The Classic Devonian of the Catskill Front: A Foreland Basin Record of Acadian Orogenesis

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INTRODUCTION

Foreland basins sedimentary rocks preserve a record of the evolution of a mountain belt. Indeed, adjacent to ancient, deeply eroded orogens like the Devonian Acadian mountain belt, the foreland basin sedimentary succession is a key source of data on the timing and character of orogenic events and processes long since eroded away.

Making viable interpretations of orogenesis from foreland basin sedimentary rocks is, of course, not simple and straightforward. For example, look at the evolving understanding of Devonian volcanic ash beds ("tephras", "tuffs", "K-bentonites") and their implications for explosive Acadian volcanism, one of the author's primary research interests (Ver Straeten, 2004a, 2008; Ver Straeten et al., 2005).

Prior to the mid-1970s, only a few thin volcanic tephras were known from Devonian strata across eastern North America. Now approximately 100 beds are known from the Devonian of the Appalachian basin. Older perspectives interpreted each bed to represent a single explosive volcanic eruption. Microstratigraphic and geochemical study of the beds, however, indicate that many are multi-event layers, with a history of amalgamation of multiple eruptions, resedimentation on the sea floor, and/or mixing with detrital sediments. Furthermore, it is unknown how many tephra layers, erupted over ca. 60 million years, were not preserved in the sedimentary rock record. The question then arises, does the existing record of foreland basin tephras yield a viable proxy of Acadian volcanism through time, despite biased and incomplete preservation of individual eruptions?

This field trip and paper examine the Devonian (+/- Upper Silurian) sedimentary rock succession in the Catskill Front of eastern New York, with additional perspectives from across New York and the Appalachian basin. Through a review of the existing literature, and presentation of new data, the author hope to produce a detailed, yet broad perspective of the implications of data from the foreland basin on the Acadian orogeny in the northeastern U.S. It is, of course, a progress report on the subject, a single author's perspective on what is known at this time, and resulting interpretations. Much more and varied work is needed.

This paper and field trip will present an overview of the Acadian orogeny and its foreland basin. It will then focus on a set of sedimentary rock characters that potentially provide regional perspectives on Acadian orogenesis. These include: 1) sedimentation and sea level history; 2) clastic rock composition; 3) volcanic tephra beds; and 4) soft sediment deformation. These four types of information may, and generally indeed do, permit interpretation of the developmental history of the Acadian orogen and the evolution of the Acadian foreland basin.

The Acadian Orogeny. As defined by some workers, the Acadian Orogeny was a major Late Silurian to Devonian-age mountain-building event in eastern North America. There are other perspectives: van Stall et al. (in press) recognize two separate events, the Acadian and Neo-Acadian orogenies. For the present paper, the Acadian orogeny will be treated as a single event. Long thought to be a Devonian-only event, recent dating of igneous rocks in Maine and adjacent areas indicate a Late Silurian beginning (Bradley et al., 2000). The orogeny is generally interpreted to have been the result of oblique collision of eastern North America (Laurentia) with one or more landmasses (e.g., Avalon, Rast and Skehan, 1993; Avalon and Meguma terranes, van Staal et al., in press), or a series of terranes. It should be noted, however, that Murphy and Keppie (2005) have recently proposed 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.

Acadian orogenesis resulted in construction of an elongate mountain chain that extended from Newfoundland to Alabama. It is characterized by significant plutonic/volcanic activity, regional metamorphism, and large scale deformation along the orogen. Post-orogenic processes and events have destroyed or buried much of the rock record of the event, especially in the central to southern Appalachians.

The Acadian Orogeny is generally interpreted to have resulted in a general southward-progressive, oblique collision against the eastern Laurentian margin, which extended from the Mid-to-Late Silurian to Late Devonian or Early Mississippian (Rogers, 1967; 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 at successive Laurentian promontories (Gaspe Peninsula, New York, Virginia, and Alabama Promontories, northeast to southwest, respectively; Thomas, 1977) with a probable single Avalon plate. Other authors proposed collision of separate Avalonian blocks during the Acadian Orogeny (e.g., Rast and Skehan, 1993). Additional select references on the Acadian orogeny include Bradley (1983), Osberg et al. (1989), papers in Roy and Skehan (1993), Rast and Skehan (1993), Robinson et al. (1998), Tucker et al. (2001), and Bradley and Tucker, 2002).

Bradley et al. (2000) provided a detailed history of cratonward advancement of the Acadian orogenic front across Maine and adjacent areas of New England and Canada. Their results, a synthesis of geochronologic, sedimentologic/stratigraphic, biostratigraphic, igneous, and structural data, indicate that between the Late Silurian and the earliest Late Devonian (ca. 40 m.y.), the Acadian deformation front migrated over 240 km cratonward (non-palinspastic distance) from coastal Maine into Quebec. A similar developmental history likely characterized the orogeny across central to southern New England, impacting foreland basin evolution in the New York region.

Foreland Basins. Foreland basins are elongate troughs, or "moats", that form on continental crust between orogenic belts and adjacent cratons (Dickinson 1974; Miall, 1995; DeCelles and Giles, 1996). The geometry of a basin is the result of one or more interacting factors, including orogenic loading, +/- subduction-related geodynamics, mantle processes, in plane stresses, and redistribution of the load via sedimentation (e.g., Beaumont, 1981; Jordan, 1981; Beaumont et al., 1988; Mitrovica et al., 1989; Cloetingh, 1988; Jordan and Flemings, 1991). The interaction of multiple processes with plates of varying flexural rigidity result in a complex history of foreland basin flexure (DeCelles and Giles, 1996; Gurnis, 1992).

Foreland basin systems have been described by DeCelles and Giles (1996) as consisting of four distinct depozones. These comprise the wedge-top, foredeep, forebulge, and back-bulge basin, from the orogenic front to the craton, respectively (DeCelles and Giles, 1996). These zones, summarized below from DeCelles and Giles (1996), may shift laterally through time.

The wedge-top is the most proximal zone of sediment deposition, comprising the front of the orogenic fold-thrust belt (DeCelles and Giles, 1996). It is characterized by deposition of coarse sediments which 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 approximately 100 – 300 km wide, with a cumulative sedimentary fill 2-8 km thick. The sedimentary fill is sometimes distinguished as earlier or more distal deeper water "flysch" and more proximal shallow marine to terrestrial "molasse" sediments. The bulk of the sediment is derived from 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, and a few tens to hundreds of meters high. It commonly is an area of little to no deposition and/or erosion, characterized by unconformities; if flooded, carbonate platforms may develop over the bulge. Forebulges generally migrate laterally through time, associated with changes in flexural kinematics in a foreland basin system.

The back-bulge basin of foreland basin systems is a zone of sediment accumulation between the forebulge and craton, with a relatively low subsidence rate. Sediment may be derived from the orogenic belt, but also from the

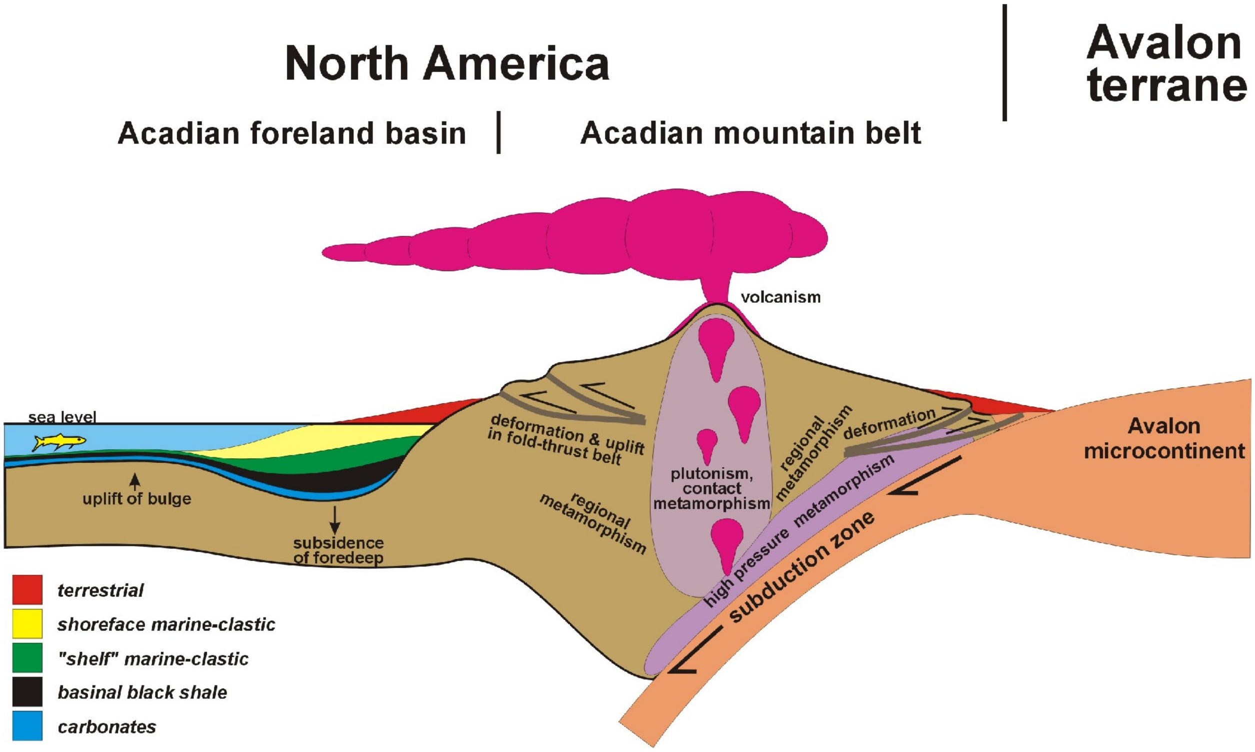

Figure 1. Idealized cross-section of the Acadian orogen and foreland basin.

craton, the forebulge and in situ carbonate production, if it is flooded by marine waters. It is characterized by a relatively thin, tabular-layered sedimentary succession.

The Acadian Foreland Basin and the Appalachian Basin. The Acadian foreland basin was an elongate trough, formed during the Late Silurian to Devonian, due to load-induced subsidence adjacent to the rising Acadian orogen (Figure 1). The basin was oriented approximately northeast to southwest during the Devonian, and extended from Newfoundland to northern Georgia and Alabama. The Appalachian basin portion of the foreland is variously interpreted to have been positioned between approximately 25-40 degrees south of the equator during the Devonian (van der Voo, 1983; Witzke and Heckel, 1988; Scotese and McKerrow, 1990). Additional select references on the Acadian foreland basin include Rogers (1967), papers in Woodrow and Sevon (1985), Ettensohn (1985), Woodrow (1985), Rust et al. (1987, 1989), Lawrence and Rust (1988), Osberg et al. (1989), and Bradley et al. (2000).

The Acadian foreland is generally interpreted to have been a collisional-related foreland basin (Miall, 1995). Ongoing debate about the direction of subduction (e.g., Bradley, 2000; versus van Staal, 2007; van Staal et al., in press) does not permit interpretation of whether the Acadian foreland was a retroarc or peripheral foreland basin.

An important perspective sometimes overlooked in discussions pertains to the issue of the Acadian versus the Appalachian basin. The "Appalachian basin" is only a part of the greater Acadian foreland basin. The former represents a body of rock preserved through the states of New York, New Jersey, Pennsylvania, Maryland, Virginia, West Virginia, Tennessee, Ohio, and parts of southern Ontario. The greater Acadian foreland basin system occurred from Newfoundland to Alabama, and in our region, extended into New England. Today, the proximal portion of Acadian foreland basin system has been removed by uplift and synorogenic to post-orogenic weathering and erosion.

Previous Work. Since the mid-1800s, the Upper Silurian to Devonian succession in the Catskill Front has been the focus innumerable studies. The succession overlying the Taconic unconformity in the area comprises nearly 2.7 km of sedimentary rocks of Uppermost Silurian through Late Devonian age (Pridoli through Frasnian stages; Figures 2-6). The bulk of the rocks are clastic (mudrocks, sandstones, and minor conglomerates); three packages of carbonates

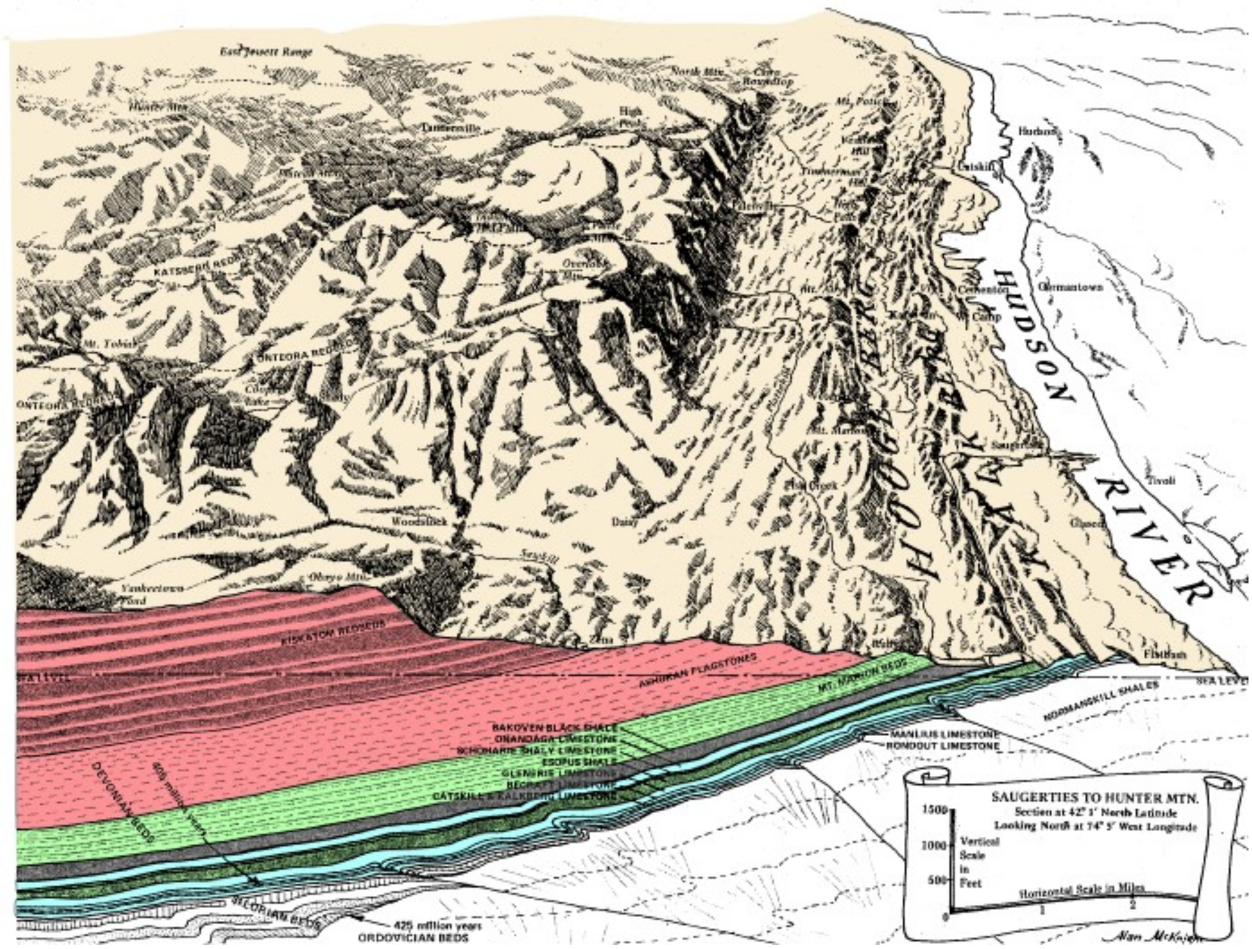

Figure 2. Cross section of the Catskill front. Physiographic map and cross-section of the Hudson Valley and Catskill Front, showing bedrock and relation to topography. Stratigraphic terminology on figure after Chadwick (1944); in modern terminology, Catskill Shaly=New Scotland; Kiskatom=Plattekill and Manorkill; Onteora=Oneonta; and Katsberg=Walton formations. Onandaga=Onondaga. Note that the Mount Marion Formation near Kingston includes much of the lower part of strata shown as Ashokan Formation. Original drawing by Alan McKnight.

occur low in the succession (Helderberg Group, Glenerie Formation, and Onondaga Formation). They were deposited over a period of approximately 45 million years (Tucker et al., 1998; Kaufmann, 2006; Ogg et al., 2008). The strata are divided into 15 formations, most of which consist of relatively thin but distinctive units in the lower part of the succession (Table 1).

The rocks represent a broad range of depositional environments from supratidal to deep ramp marine carbonate facies, and clastics of marine to terrestrial origin, from basinal black shales to shoreface sandstones to fluvial-dominated channel and floodplain facies.

Overall, the succession records initial marine carbonates (Rondout Formation and Helderberg Group), a hiatus of a few million years (Wallbridge unconformity of Sloss, 1962), thin chert-rich carbonates overlain by a first, relatively thin wedge of clastics, and a gradational return to carbonate deposition (Glenerie, Esopus, Schoharie and Onondaga formations; total thickness of lower strata = ca. 275 m). The succeeding second wedge of clastics, approximately 2.4 km thick, consists of a lower package of marine strata (>500 m thick) and overlying terrestrial strata, which extend

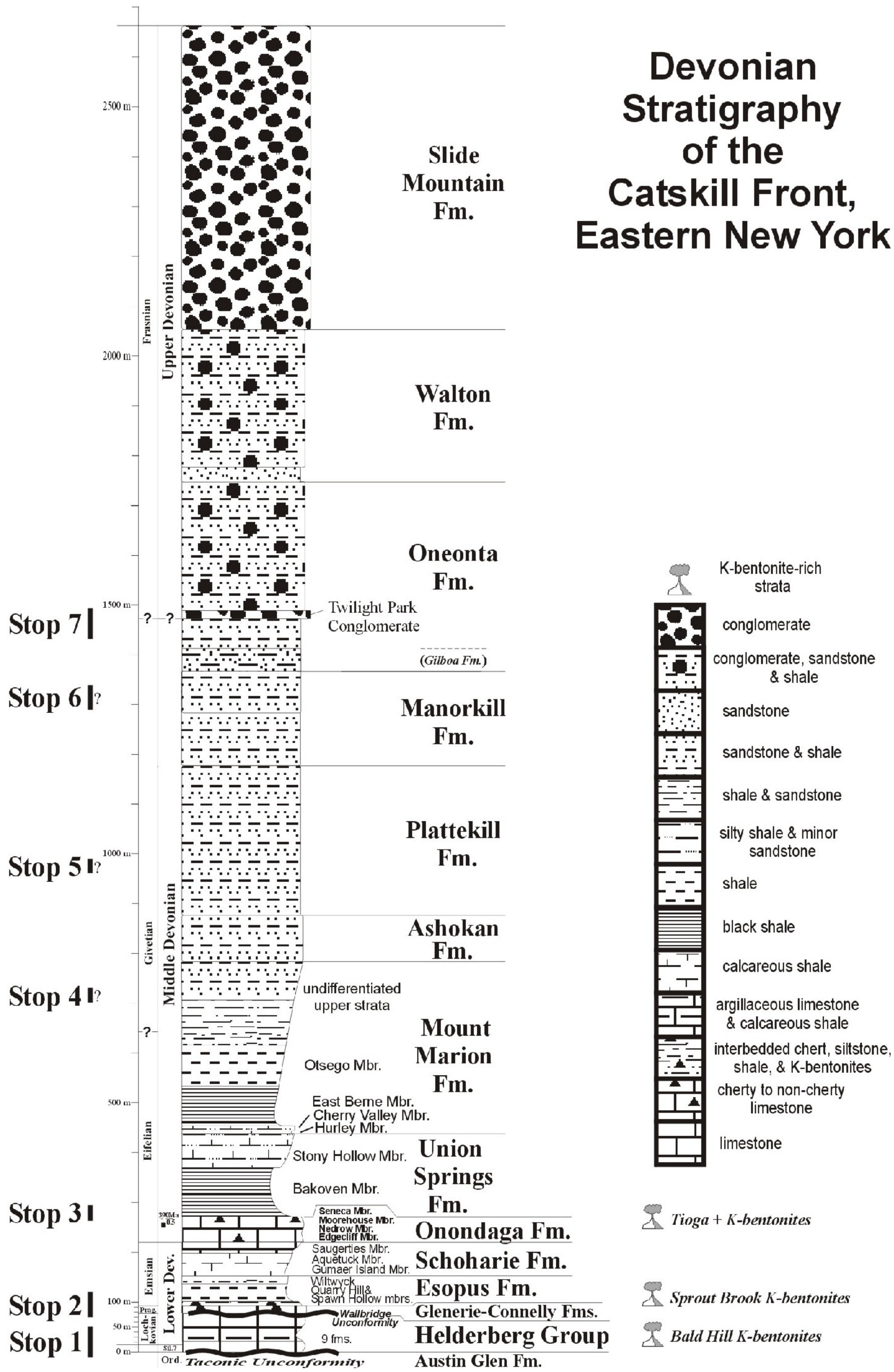

Figure 3. Stratigraphy of the Catskill Front. Composite section of >2.6 km of uppermost Silurian and Lower to Upper Devonian strata, from the Taconic unconformity (Catskill) to the top of Slide Mountain. Stratigraphic positions of Stops 1-8 shown on left. Data from Rickard (1962), Hodgson (1970), Rehmer (1976), the author's field notes, Feldman (1985), the author's field notes, Chadwick (1944), and Fletcher (1967), from low to high, respectively. Unidentified formations overlying the Taconic unconformity include, from low to high: Upper Silurian Rondout Formation; Helderberg Group strata, including possibly Upper Silurian-age Manlius Formation, and Lower Devonian Coeymans, Kalkberg, New Scotland, Becraft, Alsen and Port Ewen formations.

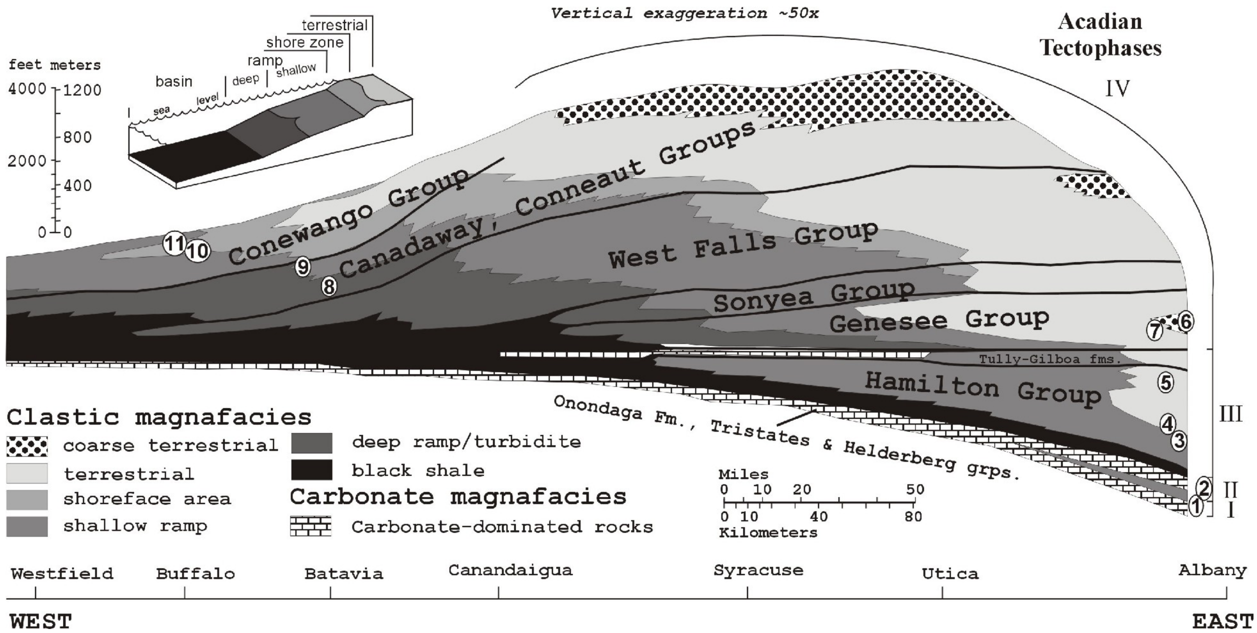

Figure 4. Cross-section of the Catskill delta complex. Figure depicts preserved Devonian strata along the New York-Pennsylvania border. Transect is roughly perpendicular to strike of the basin and the Acadian orogenic belt. Vertical exaggeration ~50x. Modified after Rogers et al. (2000). Cities across bottom of figure occur longitudinally at or north of the transect. Circled numbers 1-11 denote position of conglomerate samples in this study. Roman numerals I-IV denote strata associated with Ettensohn's (1985) Acadian tectophases.

to the top of Slide Mountain, the highest peak in the Catskills. Additional information on the Silurian-Devonian strata in the Catskill Front, along with key references, is provided in Table 1.

RESULTS

Sedimentation and Sea Level History

Major Sedimentation Trends. The Devonian succession in New York can essentially be viewed as three major alternations of carbonates (+/-quartz arenites) and terrigenous clastic sedimentary rocks. The carbonates and quartz arenites comprise sediments derived from within the sedimentary basin. The terrigenous clastics, alternatively, were transported into the basin from external sources. These very basic concepts are at the core of this paper and field trip.

Initial Upper Silurian to Lower Devonian carbonates (Rondout Formation and Helderberg Group) are overlain by a major (Wallbridge) unconformity. A succeeding quartz arenite-carbonate suite (Oriskany-Glenerie-Connelly formations) is followed by a first major, if relatively thin, package of synorogenic clastics (Esopus Formation). A gradation from mixed clastic-carbonate to fully carbonate deposition (Schoharie to Onondaga formations) is, in turn, succeeded by a second package of clastic rocks (Hamilton Group).

In central New York, Hamilton clastics are overlain by a third carbonate unit (Tully Formation), succeeded once more by a third package of clastic rocks (Geneseo Formation and succeeding strata), which continue into the lower Mississippian beyond the borders of New York. Note that all of the previous mentioned strata were deposited in marine settings.

In eastern New York, lower Hamilton marine rocks grade upward into terrestrial strata, and the third marine carbonate unit is not developed. Terrestrial facies (Plattekill to Slide Mountain formations) characterize the rest of the Devonian succession in the Catskills.

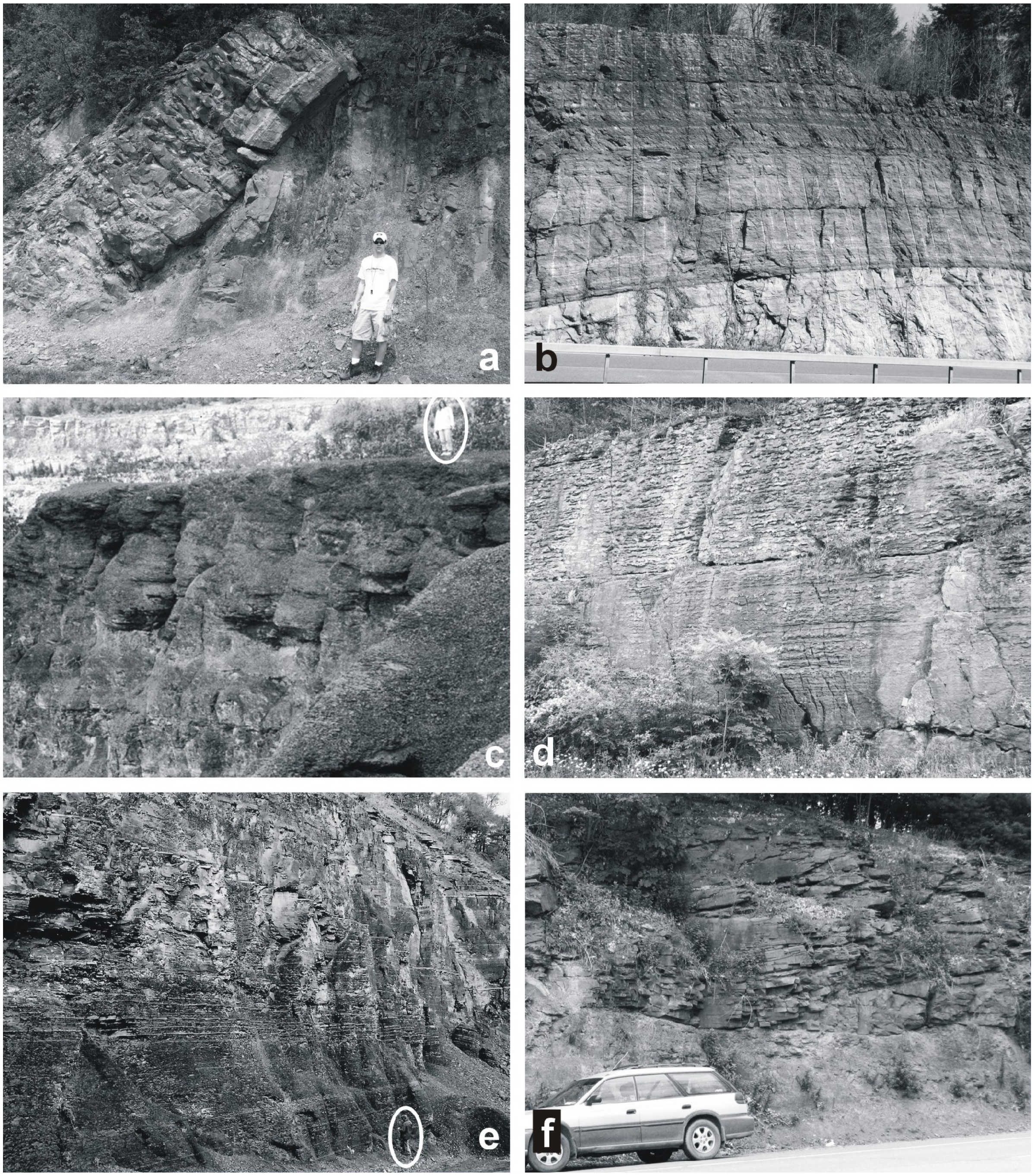

Figure 5. Strata of the Catskill front I. Photo figure of select strata, Catskill front: a) Taconic unconformity, Rte. 23, Catskill. Ordovician Austin Glen Formation below angular unconformity, uppermost Silurian Rondout Formation above; b) upper Helderberg Group limestones, Rte. 199, Kingston. Lower Devonian Becraft, Alsen and Port Ewen formations, from low to high; c) middle of Lower Devonian Esopus Shale, near Hudson, Columbia County. Quarry Hill Member; person (circled) for scale; d) chert-rich Middle Devonian Edgecliff Member, Onondaga Limestone, Rte 23 and Kings Highway SW of Catskill. Note multiple layers of chert. Exposed strata are ~11 m thick; e) shales and thin sandstones, upper East Berne Member, Middle Devonian Mount Marion Formation, near Quarryville, Ulster Co. Person (circled) for scale); f) Middle Devonian Ashokan Formation, along Rte. 28, northwest of Kingston. Floodplain paleosols (below) and channel sandstones (above).

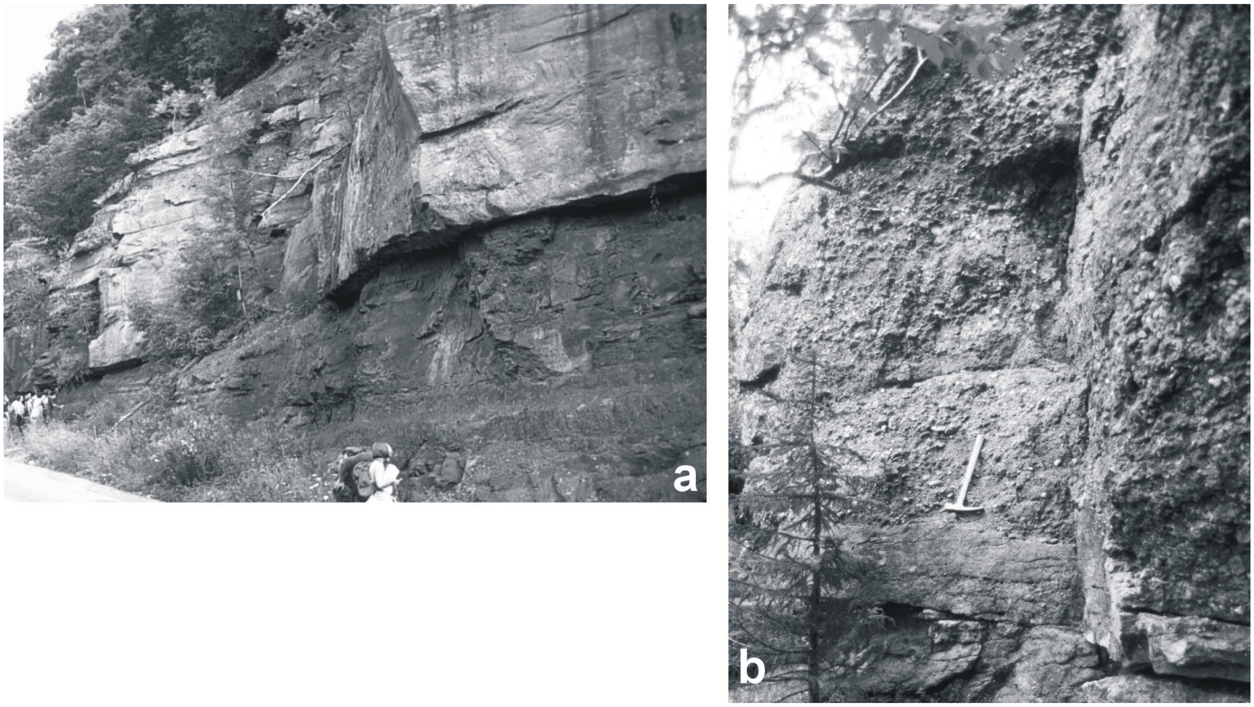

Figure 6. Strata of the Catskill front II. Photo figure of select strata, Catskill front: a) upper Manorkill (Middle Devonian) or lower Oneonta Formation (Upper Devonian?), Rte. 23, Kaaterskill Clove, Greene Co. Red floodplain paleosols (below) and gray channel sandstones (above); b) Upper Devonian (?) Twilight Park Conglomerate, Oneonta Formation, at Sunset Rock, North-South Lakes State Campground (north of North Lake). Conglomerate over pebbly sandstone. Large rock hammer for scale.

Post-Wallbridge Lower to Middle Devonian carbonate (+/- quartz arenite) suites are characterized by three key patterns (Figure 7): 1) a relatively widespread distribution; 2) a relatively tabular thicknesses, and: 3) relatively shallow water litho- and biofacies. This is most clearly shown by the Onondaga Limestone east-west across the state (Figure 7). Similar patterns are seen in the Tully Limestone in central New York; they break down laterally, however, as the Tully passes into thicker, proximal sandstones to the east, and disappears beneath an unconformity to the west. The shallow water Oriskany Sandstone and correlatives do not appear to be widespread or tabular in distribution across the state. However, local pockets of Oriskany across central to western New York indicate that it once was deposited across the area, but later eroded beneath a pre-Onondaga unconformity.

In contrast, those same three characters show opposing patterns in the clastic rocks immediately above the carbonate-rich packages (Figure 7). These initial clastics (Esopus, Union Springs and Geneseo formations) are characterized by: 1) relatively restricted distribution (toward the orogen); 2) distinctive wedge-shaped thicknesses (thickening toward the orogen), and; 3) relatively deep water, dark gray to black shale facies and depauperate dysoxic to anoxic biofacies.

These three key characters undergo sharp, abrupt changes across the contact of the carbonate to initial clastics units. Strata above the initial clastics, however, display an overall, gradational shift to increased $CaCO_3$/decreased detrital content, a more widespread distribution, a more tabular geometry, and a trend toward shallower water litho- and biofacies (Figure 7).

Sea Level History. Studies of the Devonian succession in New York and, in some cases, across the Appalachian basin have outlined a history of relative sea level cycles, or, in sequence stratigraphic terms, third order depositional sequences (e.g., Johnson et al., 1985; Dorobek and Read, 1986; House and Kirchgasser, 1993; Brett and Baird, 1996; Filer, 2002; Ver Straeten, 2007a; see Figure 8).

Internatl. Stage (Series)	For-mation	Lithology	Fauna/ flora	Thickness	Environments	Key refs.
Frasnian (Up Dev)	Slide Mountain	ss, cgl; minor red/green sh/mudst	fish, terr. plants,	610 m[3]	terrestrial; fluvial channels & flooplains	Burtner 1963, 1964; Fletcher 1964, 1967; Gale 1985
Frasnian (Up Dev)	Walton	ss, red/green/dk gray sh/mudst, minor cgl	fish, terr. plants,	305 m[3]	terrestrial; fluvial channels & floodplains, minor lacustrine?	Burtner 1963, 1964; Fletcher 1964, 1967; Gale 1985; Gordon 1986
Frasnian (Up Dev)	Oneonta	ss, minor cgl, red/green/dk gray sh/mudst	fish, terr. plants, arthropods	274 m[3]	terrestrial; fluvial channels & floodplains, minor lacustrine?	Burtner 1963, 1964; Fletcher 1964, 1967; Lucier 1966; Johnson 1968; Johnson & Friedman 1969; Nickelsen 1983; Gale 1985; Bridge & Gordon 1985; Bridge & Nickelsen 1985; Gordon 1986
Givetian (Mid Dev)	Manorkill	ss, red/green/dk gray sh/mudst	fish, terr. plants, arthropods	189 m[3]	terrestrial; fluvial channels & floodplains, minor lacustrine	Burtner 1963, 1964; Fletcher 1964, 1967; Lucier 1966; Way 1972; Gale 1985; Willis 1986; Willis and Bridge 1988; Bridge & Willis 1994
Givetian (Mid Dev)	Plattekill	ss, red/green/dk gray sh/mudst	fish, terr. plants	305 m[3]	terrestrial; fluvial channels & floodplains, minor lacustrine	Burtner 1963, 1964; Fletcher 1964, 1967; Lucier 1966; Way 1972; Gale 1985; Willis 1986; Willis and Bridge 1988; Bridge & Willis 1994
Givetian (Mid Dev)	Ashokan	dk gray/green sh/mudst, ss	fish, terr. plants	152 m (Kingston), 91 m (Kiskatom)[4]	largely terrestrial (coastal lowlands); fluvial channels & floodplains, lacustine & palustrine	Burtner 1963, 1964; Wolff 1967, 1969
Eifelian-Givetian (Mid Dev)	Mount Marion	Black/gray sh/mudst, ss, minor cgl	normal marine	~425 m[5] (Kingston; thins to north)	marine: clastic anoxic basin to shoreface; local terrestrial tongue	Wolff1967, 1969; Griffing & Ver Straeten 1991; Ver Straeten 1994, 2007a; Ver Straeten & Brett 1995
Eifelian (Mid Dev)	Union Springs	black sh, buff calc sh to fine ss	restricted to normal marine	~175 m[5] (Kingston; thins to north)	marine: anoxic to dysoxic clastic basin	Griffing & Ver Straeten 1991; Ver Straeten et al., 1994; Ver Straeten & Brett 1995; Ver Straeten 2007a
Eifelian (Mid Dev)	Onondaga	ls (wacke- to grainstones)	normal marine	ca. 50 m[6]	marine: shallow carbonate "shelf"[10]	Oliver 1956; Ver Straeten & Brett 1995; Ver Straeten 2007a
Emsian (Low Dev)	Schoharie	ls, sh, chert, some clastic sh	normal marine	26.7 m[7]	marine: mixed carb-clastic "shelf"	Johnsen 1957; Ver Straeten & Brett 1995; Ver Straeten 2007a
Emsian (Low Dev)	Esopus	sh/mudst, siltst, ss		[8]	marine: clastic basin to "shelf"	Rehmer 1976; Ver Straeten & Brett 1995; Ver Straeten 2007a

Table 1. (continues) Upper Silurian & Devonian Strata of the Catskill Front.

Internatl. Stage (Series)	For-mation	Lithology	Fauna/ flora	Thickness	Environments	Key refs.
Pragian (Low Dev)	Glenerie[2] Oriskany Connelly	ls & chert quartz SS quartz cgl	normal marine	4.6 m[9] (Glenerie)	marine: shoreface to shallow shelf	Hodgson 1970; Ver Straeten & Brett 1995; Ver Straeten 2007a
Pragian (Low Dev)	Port Ewen	ls (mudstones to packstones), some clastic sh	normal marine	2.1 m[9] (thickens to south)	marine; deeper carbonate "shelf"	Rickard 1962; Mazzo & LaFleur 1984; Ebert 1984, 1987
Lochkovian (Low Dev)	Alsen	ls (wacke- to packstones), minor clastic sh	normal marine	9.8 m[9]	marine; shallow carbonate "shelf"	Rickard 1962; Ebert 1984, 1987
Lochkovian (Low Dev)	Becraft	ls (grainstones)	normal marine	14.6 m[9]	marine; carbonate shoal	Rickard 1962; Ebert 1984, 1987
Lochkovian (Low Dev)	New Scotland	lLs (mudstones to packstones), some clastic sh	normal marine	30 m[9]	marine; deeper carbonate "shelf"	Rickard 1962
Lochkovian (Low Dev)	Kalkberg	ls (wacke- to packstones), minor clastic sh	normal marine	16.5 m[9]	marine; shallow carbonate "shelf"	Rickard 1962
Lochkovian (Low Dev)	Coey-mans	ls (grainstones)	normal marine	4.3 m[9]	marine; carbonate shoal	Rickard 1962; Ebert and Matteson 2003
Pridoli?[1] (Up Sil?)	Manlius	ls (mudstones to wackestones), minor clastic sh	restricted marine	15.5 m[9]	marine; carbonate tidal	Rickard 1962; Ebert and Matteson 2003
Pridoli?[1] (Up Sil?)	Rondout (upper part)	dolst, basal ss	?	1.2 m[9]	coastal margin; carbonate, minor clastic supratidal	Rickard 1962;

Table 1. (continued) Upper Silurian & Devonian Strata of the Catskill Front. *For all strata in the Catskill Front, see also Chadwick (1944).*

[1] Previously assigned to the Devonian (e.g., Rickard 1975), recent work by Ebert (e.g., Ebert and Matteson, 2003) suggests a Silurian age.

[2] North of Catskill, the Glenerie Ls. undergoes facies change into the Oriskany Sandstone; south of Kingston, the Glenerie Ls. is underlain by the Connelly Cgl., which replaces it completely in the Skunnemunk outlies south of Kingston.

[3] Thicknesses from Fletcher (1967)

[4] Thicknesses at type area (near Kingston) and Catskill Front (near Kiskatom), from Chadwick (1944)

[5] Estimated thicknesses at Kingston, from Rickard (1989)

[6] Thickness at Saugerties (NYS Thruway cuts), from Feldman (1985)

[7] Thickness at Rte. 23 (W of Catskill), from Ver Straeten and Brett (1995)

[8] Thickness from Rte 23a (SW of Catskill), from Rehmer (1976)

[9] Thicknesses from Austin Glen (W of Catskill), from Rickard (1962)

[10] Strata not deposited on actual continental "shelf", but in foreland basin/epicontinental sea setting, with a shallow to deep ramp-like basin morphology.

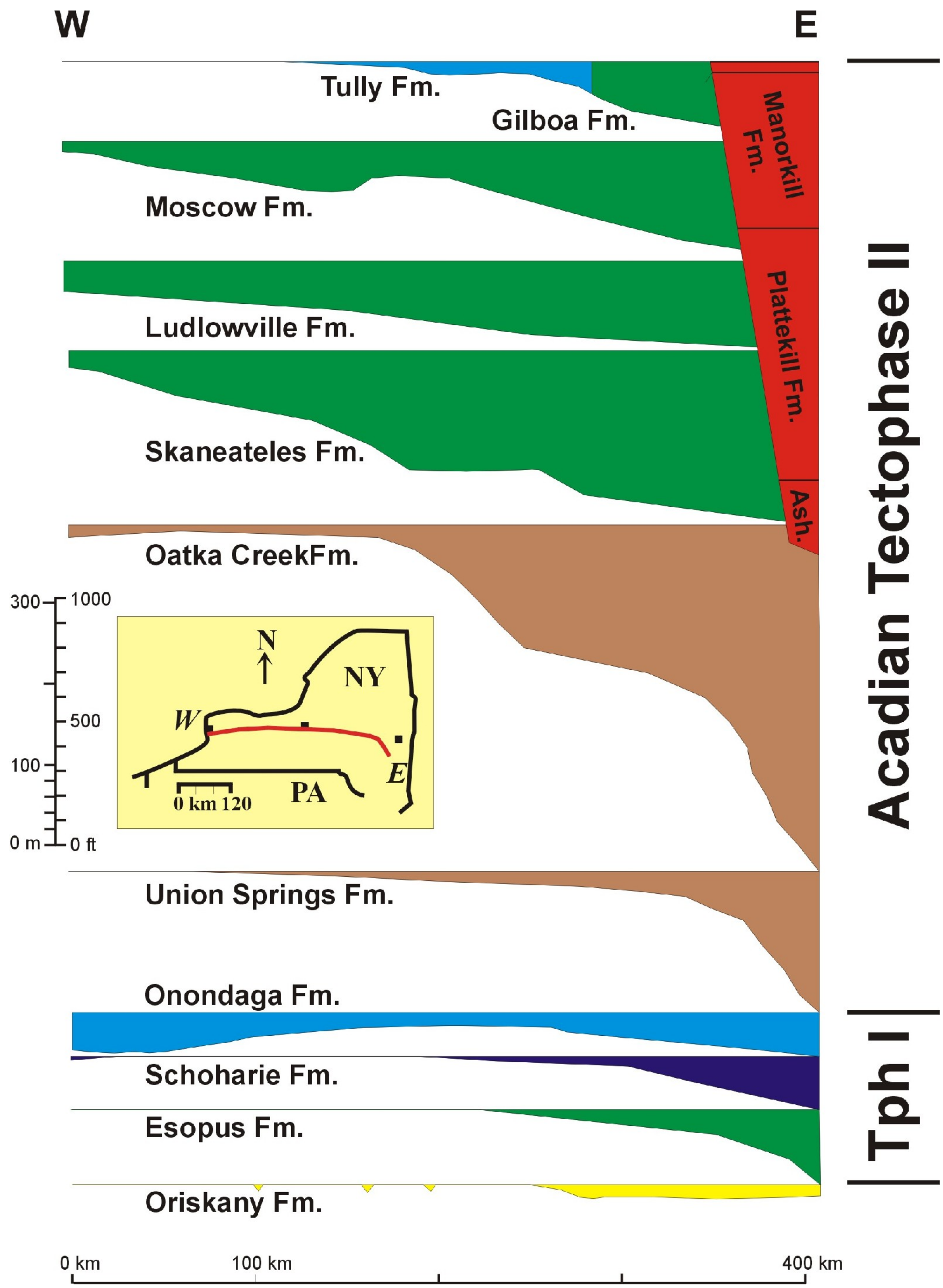

Figure 7. Stratal geometry of upper Lower and Middle Devonian units, New York. Geometry and generalized facies of strata along the New York outcrop belt between Catskill front (east) and Buffalo (west). Note relatively tabular geometry of the Onondaga and Tully formations, in contrast with the Esopus, Union Springs and Oatka Creek-Mount Marion formations. Modified from Ver Straeten and Brett (1995), with additional data from Rickard (1989; Oatka Creek to Moscow fms.), Heckel (1973; Tully Fm.) and Fletcher (1967; Ashokan to Manorkill Fms.). Correlationa between the marine and terrestrial units remain tentative to unknown.

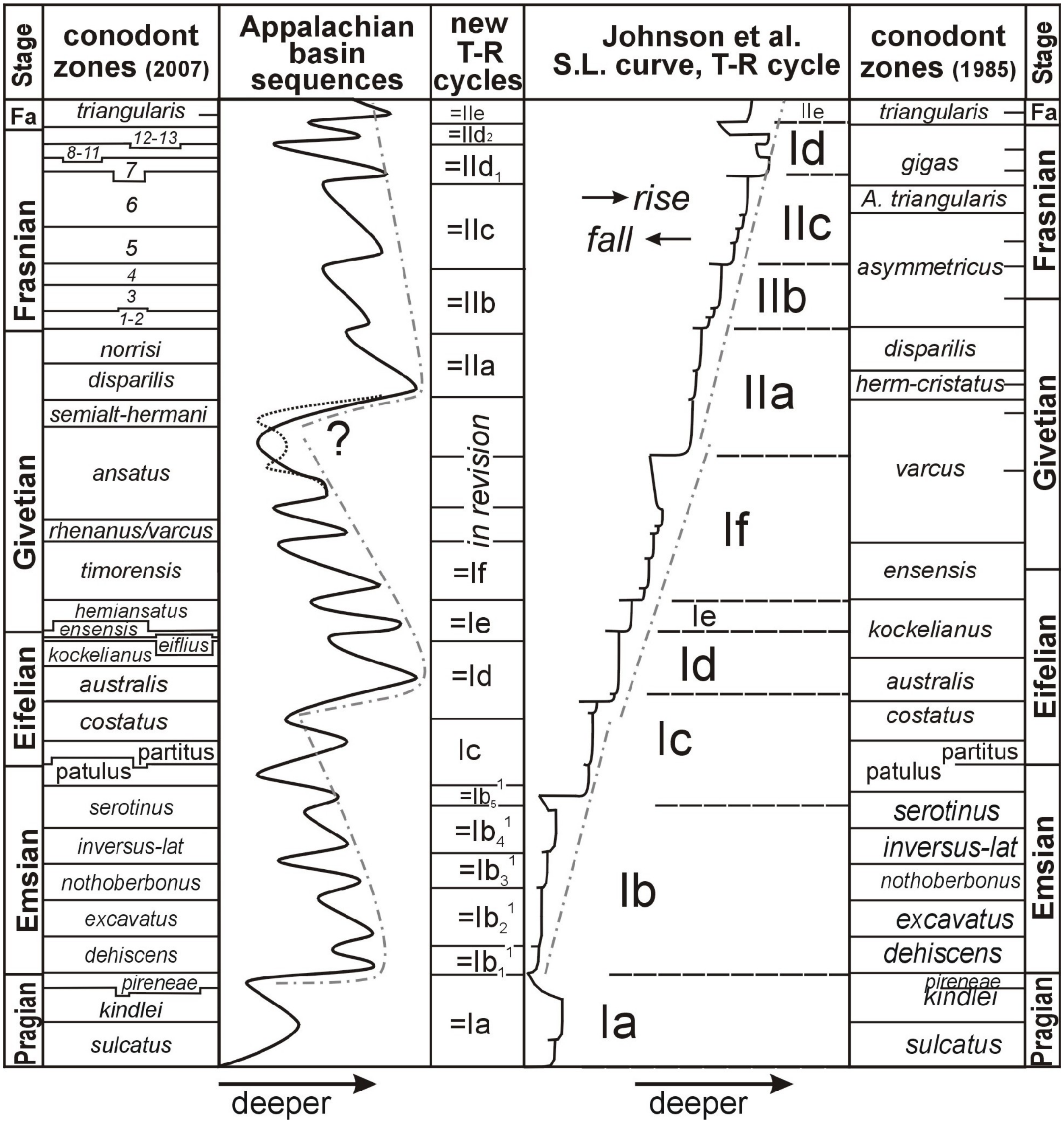

Figure 8. Devonian depositional sequences/sea level cycles. Comparison of Pragian through lower Famennian relative sea level curve (Appalachian basin) and Euramerican eustatic sea level curve (of Johnson et al., 1985). Appalachian curve/sequences include refinements on original Euramerican T-R cycles. 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 transgressions in the lower Emsian, mid Eifelian, and upper Givetian, followed by overall regressions. These cycles represent Ettensohn's (1985) Tectophases I, II and III (part). Divergence of sea level curves at tectophase-scale cycles is indicative of Acadian influence on relative sea level. Data for Appalachian basin cycles from Johnson et al. (1985), Dorobek and Read (1986), House and Kirchgasser (1993), Brett and Baird (1996). Filer (2002), Ver Straeten (2007a, in press).

In the area of this field trip, Uppermost Silurian to Lower Devonian strata of the Helderberg Group, Oriskany Sandstone and Esopus and Schoharie formations comprise 8 major sequences; two in the Helderberg Group (Rondout to basal Becraft fms.; lower Becraft to Port Ewen fms.), one absent locally, but developed in more basinal settings of the Oriskany Sandstone across the basin; and five in the Esopus and Schoharie formations (Ver Straeten, 2007a). The latter five represent a new interpretation by the author, based on basinwide correlation of Emsian-age Esopus and Schoharie strata, initial field study in Nevada, and comparison with data from Europe and North Africa, along with recent geochronologic age data (Tucker et al., 1998; Kaufmann, 2006) that project a duration of 15 to 17 million years for the Emsian stage.

Seven sequences subdivide the Middle Devonian record across the Appalachian basin (Brett and Baird, 1996; Ver Straeten, 2007a). The lower one occurs within the lower to middle Onondaga Limestone; upper Onondaga strata and the overlying Union Springs Formation (lower part of the Marcellus "shale") comprise a second sequence. Younger cycles are represented by each of four overlying Hamilton Group formations, and the Tully to Geneseo formations. In the field area, only the lower three are identified. As Hamilton strata pass into terrestrial facies above the Mount Marion Formation, the additional Middle Devonian sequences have not been delineated (Ashokan through Manorkill formations). Similarly, multiple Upper Devonian stratigraphic sequences have not been delineated in the terrestrial facies of the Oneonta through Slide Mountain formations.

Johnson et al. (1985) outlined a Euramerican sea level history for the mid Lower to Upper Devonian strata (Pragian to Famennian stages; Figure 7, right side). Although modified and refined since its first publication by numerous workers globally, their interpretations still form the basic standard for Devonian sea level cyclicity.

Clastic Rock Petrology

Previous Results. Between the 1960s and 1980s, a number of petrographic studies examined the mineralogy of New York's Lower to Upper Devonian clastics. These focused predominantly on the terrestrial rocks of the Catskill Front, from the Plattekill Formation upward. Much of the data is found in unpublished theses. Most studies focused on thin section analyses of sandstones (e.g., Burtner, 1964; Lucier, 1966; Way, 1972; Ethridge, 1977; Gale, 1985), but also included analyses of the clay mineralogy of mudrocks (e.g., Friend, 1966; Wolff, 1967; Leibling and Schirp, 1976, 1980; Hosterman and Whitlow, 1983). Petrology of the conglomerates has received less attention; however, some compositional data is reported (e.g., Nickelsen, 1983; Smith and Jacobi, 1998).

Petrographic data from the Lower Devonian Esopus Formation, the initial package of clastic sedimentary rocks, have a relatively quartz-rich composition (Rehmer, 1976). Excluding fine clay matrix from the data, a single sandstone sample analyzed by Rehmer (1976) was dominated by quartz (77.8%), with only very minor amounts (3.0 to 0.6%) of coarse muscovite, along with plagioclase and K-feldspars, pyrite, chert, and calcite and dolomite. Trace amounts of glauconite, biotite, epidote and zircon were also present. Her analyses of Esopus siltstones yielded relatively similar results (e.g., quartz between 64.2 and 72.8%, excluding matrix). The quartz in the Esopus is dominantly clear, monocrystalline, and unstrained. Detrital phyllosilicates generally comprise >3% of the rock, including matrix; muscovite is more common that chlorite or biotite. Silt-sized shale or phyllitic rock fragments are found, but cannot be distinguished. However, rare micaceous fragments with crinkle-fold textures suggest input of at least some low-grade metamorphic rocks (Rehmer, 1976).

The most abundant grains in the Middle to Upper Devonian sandstones are monocrystalline and polycrystalline quartz, foliated metamorphic rock fragments, and sedimentary rock fragments; these comprise at least 80% of sandstones (Gale, 1985). Metamorphic rock materials include slate, phyllite and possible schistose fragments; sedimentary rocks grains found include shale, siltstone, sandstone and carbonate, along with chert. Other minor components, in decreasing concentration include plagioclase feldspars, with rare orthoclase feldspars and igneous (plutonic/volcanic) rock fragments (Gale, 1985). Chlorite is the chief micaceous mineral present, followed by muscovite and sericite, with only minor biotite (Lucier, 1966).

The matrix in the sandstones, previously interpreted to largely consist of clays, was shown by Gale (1985) to predominantly be comprised of deformed, ductile lithic fragments. Therefore, compositionally the sandstones are litharenites to sublitharenites, not graywackes.

Sandstone compositional trends through the succession (upper Mount Marion to Slide Mountain formations) show no major vertical changes. Smith's (1970) examination of lower Middle Devonian sandstones (upper Mount Marion through Plattekill formations) found some decrease in quartz content (monocrystalline + polycrystalline quartz + chert). This was accompanied by an increase in metamorphic rock fragments and matrix.

Gale (1985) noted some distinctive vertical trends through the overlying Plattekill to Slide Mountain formations. These included: 1) a general increase of mono- and polycrystalline quartz upward; 2) a net upward decrease in foliated metamorphic rock fragments; and 3) an upward increase in grain size. This expanded upon the similar results of Lucier (1966) for the Plattekill and Manorkill formations, who also noted overall vertical decreases in chert and plagioclase feldspar in those strata.

Combined data from Smith (1970) and Gale (1985) indicates an arc of initial decreasing, then increasing quartz content through the Middle to Upper Devonian succession. Chert concentration itself, however, decreases upward through the succession from the upper Mount Marion Formation.

Mudrock studies (Friend, 1966; Wolff, 1967; Rehmer, 1976; Leibling and Schirp, 1976; Hosterman and Whitlow, 1983) indicate that the clay mineral suite in Devonian fine-grained strata is largely comprised of illite and chlorite, with subordinate amounts of mixed-layer illite-smectite and kaolinite. This parallels clay mineral data from the sandstone studies. The chlorite is largely derived from low-grade metamorphic rocks (Leibling and Schirp, 1976, 1980). Hosterman and Whitlow (1983) examined Middle to Late Devonian black marine mudrocks (Marcellus to Cleveland shales) in New York and across the Appalachian basin. They noted an upward decrease in chlorite, accompanied by upward increase of mixed layer illite-smectite. Hosterman and Whitlow's (1983) mudrock analysis reported that kaolinite was largely restricted to younger Devonian shales (Rhinestreet Formation and younger); however, Gale found a decreasing kaolinite content above the Plattekill Formation.

Although Friend (1966) suggested that clays from the Manorkill Formation were largely unaltered, Hosterman and Whitlow's (1983) comprehensive study of the marine black shales stated that the existing illite (2M) and mixed layer illite-smectite clays are largely diagenetic in origin, derived from older illite (Md) and smectite. Interestingly, they also report that at least some of the chlorite was originally derived from smectite.

More recent studies, utilizing other analytical approaches, add additional perspectives to the composition and provenance of these Acadian-derived synorogenic clastics. New approaches include dating of detrital micas and zircons, and rutile geochemistry.

Aronson et al. (1994), using K-Ar methods, dated detrital white micas from Upper Devonian to Lower Mississippian clastics of the Catskill delta complex (NY and OH). The micas all yielded Devonian age dates between 406 – 380 Ma, with a single outlier of 419 Ma (with margins of error of +/- 7-20 m.y.). Micas from the Walton Formation in eastern New York produced an age of 401 +/- 7 Ma. They interpreted their results to indicate that rocks subjected to regional metamorphism or plutonism (>350^{o} C) during the Acadian orogeny were the dominant source of sediments during deposition of the Catskill Delta.

McLennan et al. (2001) examined U-Pb ages of detrital zircons from a sample of the Frasnian-age lower Walton Formation (near Monticello, Sullivan Co., NY). A single sample of red sandstone yielded 41 zircons, from which they obtained a bimodal set of SHRIMP U-Pb ages of 1.23-1.00 Ga (Grenville age) and 470-420 Ma (which they termed "Taconian" in age; it actually encompasses the Middle Ordovician through most of the Silurian Periods, much of it post-dating the Taconian orogeny). They found no detrital zircons of unambiguous Acadian age in their sample.

Certain geochemical characteristics of rutile make it useful in provenance studies, including its ability to act as a geothermometer. Zack et al., (2004) examined the geochemistry of detrital rutiles from the same outcrop of the Upper Devonian Walton Formation sampled by McLennan et al. (2001). Detrital rutiles from their sample were derived from a broad range of low to high (greenschist/blueschist to granulite) grade metamorphic rocks, subjected to temperatures between <450^{o} and 1050^{o} C. Significantly, coarser grained rutiles (ca. 60% of rutile grains analyzed) derived from high-grade (granulite facies) metamorphic rocks.

Sample number	1	2	3	4	5	6	7	8	9	10	11
Sample (100 count analysis, or %)	Connelly Cgl.	Kanuse SS	upper Mt. Marion Fm.	Ashokan Fm.	basal Moscow Fm.	Twilight Park Cgl. (% of 400 clasts)	Cgl., top of Platte Clove	Avg. cgl comp, Rushford Fm[1]	low Cattaraugus cgl., Alma, NY	Wolf CreekCgl.[2]	Killbuck Cgl.[2]
Age	upper Pragian	basal Eifelian	lower Givetian	lower Givetian	mid Givetian	~lower Frasnian	~lower Frasnian	lower Famennian	mid Famennian	mid Famennian	mid Famennian
vein quartz	100	100	40	*	56	66%	47	*	83	98	97
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	2
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	*	*	*	1	*	*	*	*	*	*	1
calc. nodule clast	*	*	*	99	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	*

Table 2. Composition of some Devonian conglomerates, New York State. Preliminary results of Lower to Upper Devonian (Pragian to Famennian) conglomerate analysis in New York State, with data from Smith and Jacobi (1998; sample 8). Based on a 100 clast count, or % of total clasts counted. Abbreviations: c = common; p = present; nod. = nodule.

[1] mean % of 11 conglomerates, Upper Devonian Rushford Fm, from Smith and Jacobi (1998)

[2] samples from NY State Museum collection; inaccurate locality data

[3] total quartz = monocrystalline, polycrystalline and undulatory quartz.

Stratigraphic and geographic positions of samples denoted by numbers on Figure 4.

New Results: Devonian Conglomerates. Up to the present, no systematic analysis of conglomerates is reported from the Devonian Catskill delta complex in New York. Their presence are noted in publications, but few studies examine clast composition in detail (however, see Allen and Friend, 1968; Nickelsen, 1983; Smith and Jacobi, 1998; Friedman, 1998). Recent study provides an overview of compositional changes of conglomerates through the Devonian succession in New York.

Table 2 presents data for 11 conglomerate beds, including results from the two previously noted studies. The conglomerates were deposited in eastern and western New York through approximately 40 million years (upper Pragian to middle Famennian stages, ca. 410-370 Ma). Grain composition through the succession comprise extra- and intrabasinal clasts, including vein quartz, sedimentary and low-grade metamorphic clasts, intraformational nodules and mud clasts, and fossil material. Compositions were generally determined using a standard 100 clast count method, via naked eye, 10x hand lens, or a binocular microscope. Photographs of select conglomerate beds can be seen in Figures 9 and 10.

The coarse clastic beds in Table 2 were variously deposited in shallow marine to fluvial environments. The majority of beds are true conglomerates; some terrestrial beds, however, feature abundant angular, blocky calcareous nodules of pedogenic origin (Figure 9d), and are better defined as breccias. Some conglomerates consist largely to fully of intrabasinal clasts, including reworked nodules of varying composition or ripped-up mud fragments (Figure 9c, d, e). Other ones are chiefly to fully composed of extrabasinal granules, pebbles and/or cobbles. Older and younger beds analyzed are oligomictic in composition, characterized by dominantly quartz grains (e.g., vein quartz +/- chert; Figures 9a, 10c). The intervening beds have a petromict (polymict) character (Figures 9b, 10b), with more diverse clast types including quartz, chert, and pre-lithified sandstone/siltstone pebbles. Many samples are paraconglomerates, with a significant amount of finer-grained (sand- to clay-sized) matrix. Clasts are dominantly pebble-sized, except for granule-dominated sample 2.

Initial Lower and Middle Devonian conglomerates (Samples 1, 2; Oriskany-equivalent Connelly Formation and lower Onondaga-equivalent Kanouse Formation) are composed exclusively of white vein quartz. Succeeding samples, however, show diverse types of clasts, including of both sedimentary and low-grade metamorphic composition. Chert content is highest in Sample 3 (Middle Devonian Mount Marion Formation), where its abundance is roughly equal with macrocrystalline quartz; a small number of sandstone clasts also occur in Sample 3. Chert concentration declines above the Mount Marion conglomerates. Stratigraphically higher beds, from the Upper Devonian Oneonta through Slide Mountain formations, feature significant percentages of sandstone clasts, some of which commonly feature chlorite. Red sandstone clasts, similar to red sandstones in the Devonian Catskill succession, are common in the Slide Mountain Formation (Fletcher, 1967).

The youngest conglomerates studied, from the Late Devonian of western New York, feature abundant white vein quartz (Samples 8-11, Figure 10c). In the two youngest samples, vein quartz concentration approaches the purely vein quartz composition of the two oldest conglomerates (samples 1 and 2).

Volcanic Airfall Tephras in the Foreland Basin Fill. Explosive plinian-type volcanic eruptions result in atmospheric transport of fine ash and crystals, which settle out across all environments downwind. The resulting ash layers, which are subjected to various physical, biological and chemical processes in the respective environments, may or may not be preserved in the rock record. These beds are diagenetically altered over deep time, and become rich in clays or other mineral phases to which other terms are sometimes applied (e.g., bentonite, K-bentonite, tonstein). The author follows the usage of USGS volcanologist A.M. Sarna-Wojcicki (pers. comm., 2008), and applies the term “tephra” to ancient volcanic airfall beds in sedimentary rocks.

Though they comprise a small proportion of sedimentary rocks, volcanic airfall tephras provide key beds for analyses of a rock succession. Regional correlation and geochronologic age-dating of airfall tephras provide high resolution timelines to analyze the relative and geochronologic timing of events and processes active in both a foreland basin and the adjacent orogen (e.g., tectonic flexure, changes in sedimentation, timing and character of explosive volcanic activity).

Approximately 100 tephras, occurring as clay-rich K-bentonites or coarse-grained tuffs, are now known from the Devonian (+/- uppermost Silurian) of the Appalachian basin (Figures 11-12). These include five clusters of 6-15 or

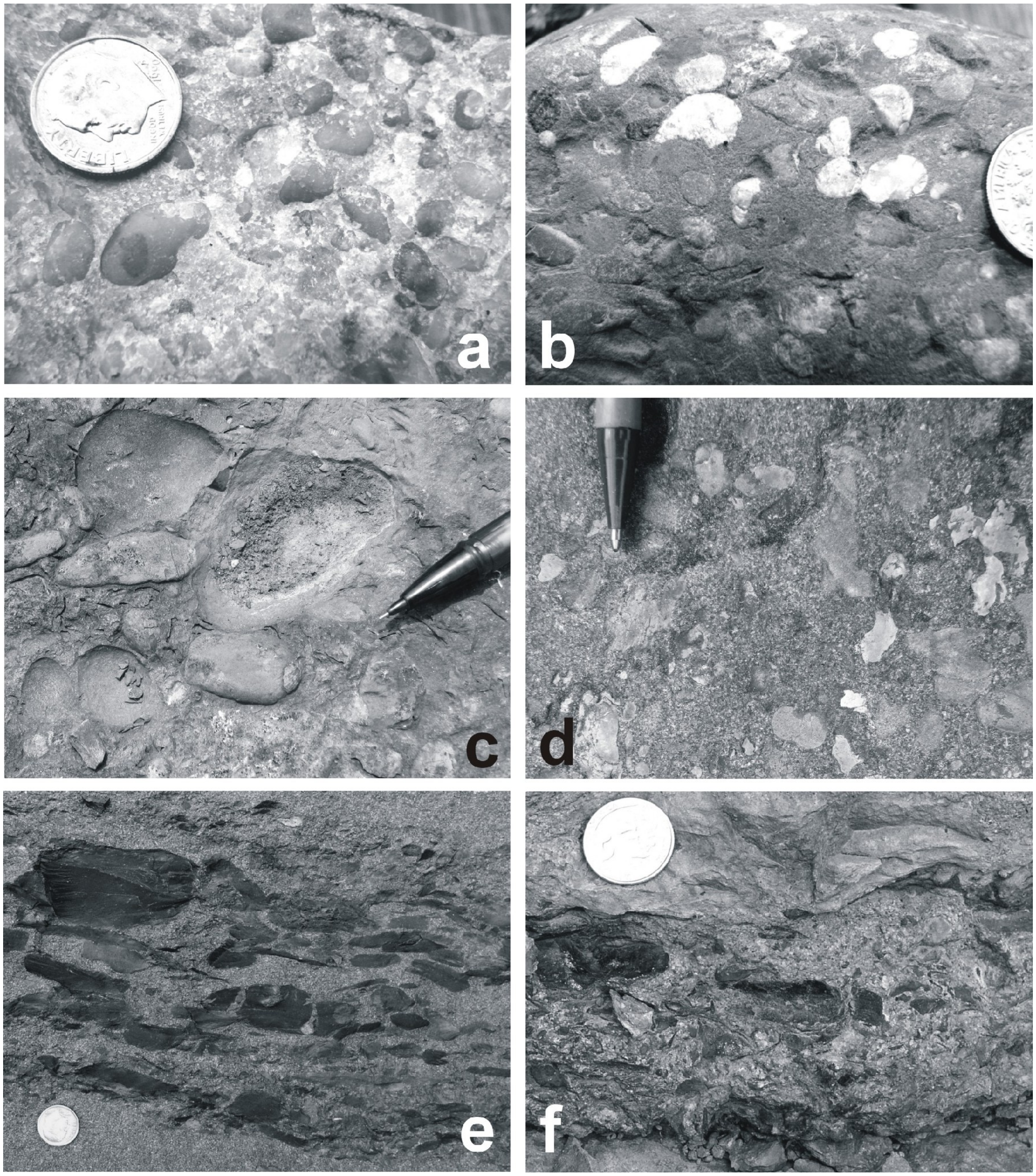

Figure 9. Devonian Conglomerates I. Photos of Devonian conglomerates: a) Milky quartz pebble conglomerate, Lower Devonian Connelly Formation. Pebbles slightly stained by iron. Along west side of NYS Thruway, Schunnemunk Outlier, Orange Co.; b) polymict, extraformational conglomerate, upper part of the Middle Devonian Mount Marion Formation, near Catskill. Mix of milky quartz and chert, with sandstone and reworked nodules. Dime for scale; c) intraformational conglomerate of reworked nodules, upper Mount Marion Formation, along Rte. 23, near Leeds (Stop 5). Pencil tip for scale; d) intraformational breccia of calcareous nodules in sandstone, reworked from terrestrial paleosols. Plattekill Formation, Catskill Creek at Rte. 32, Cairo. Point of pen for scale; e) intraformational conglomerate of dark gray mud clasts in sandstone, reworked from floodplain deposits. Loose block of unknown Upper Devonian sandstone, Oneonta or Walton Formation. Dime for scale; f) intraformational biogenic conglomerate of fish bones, plant debris, and possible charcoal. Manorkill Formation, quarry north of Windham. Quarter for scale.

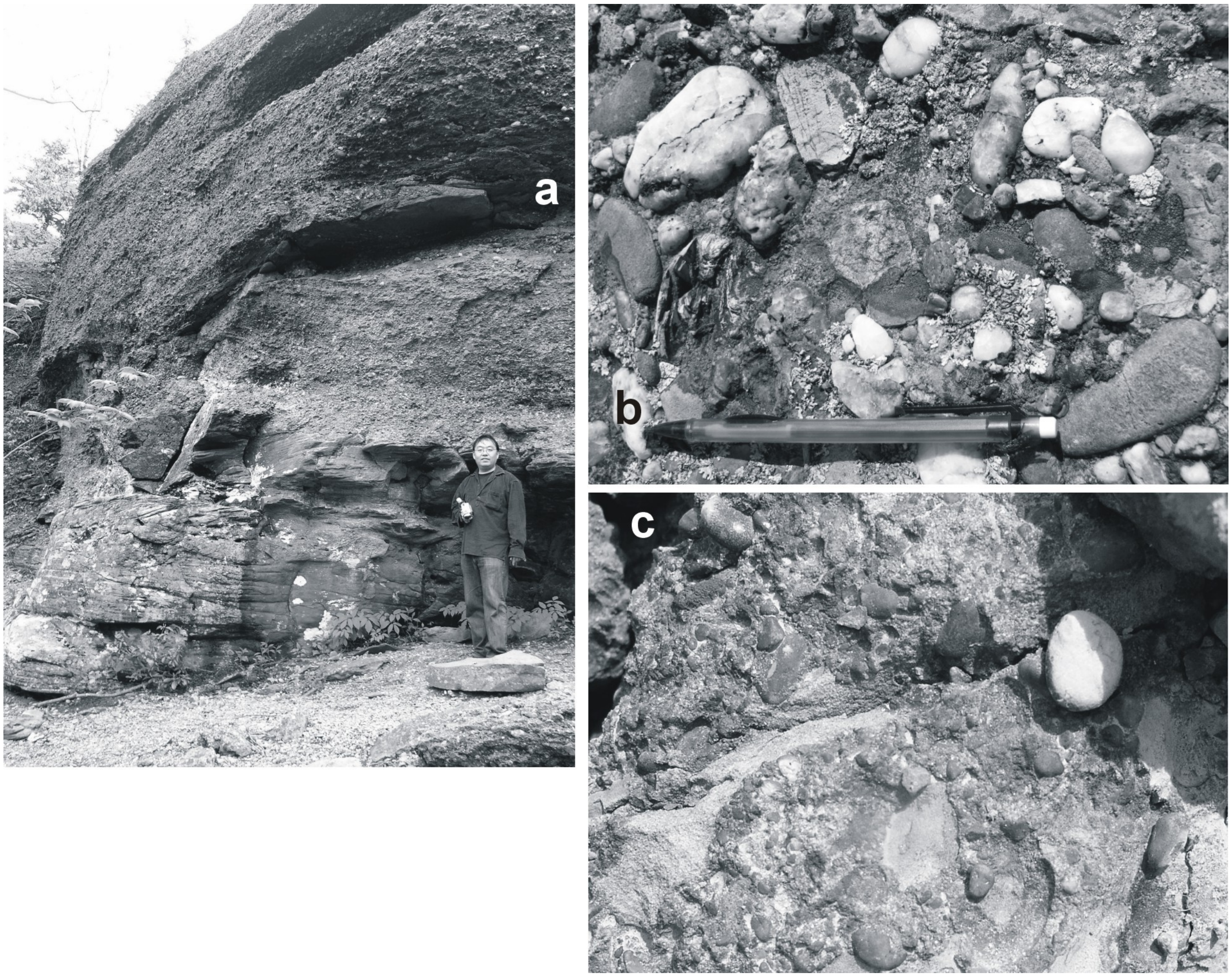

Figure 10. Devonian conglomerates II. Photos of Devonian conglomerates: a) Outcrop of Upper Devonian (Frasnian) Twilight Park Conglomerate (Oneonta Formation), at Sunset Rock, North-South Lake (Stop 8); b) polymict, extraformational conglomerate of mixed clast types. Mix of milky quartz and sandstone clasts, with other less common clasts. Twilight Park Conglomerate, at Sunset Rock, North-South Lake (Stop 8). Pencil for scale; c) Milky quartz-rich extraformational conglomerate, with lesser amounts of sandstone clasts, wood and charcoal. Upper Devonian (Famennian) Cattaraugus Formation, near Allentown, Allegany Co. western NY. Larger pebble is approximately 1 cm in length.

more closely-spaced beds (Figures 12, 13a, b); additional single beds or lesser clusters occur through parts of the succession (Figure 13c-f). Some are found widely across the eastern U.S. (e.g., one or more beds of the Eifelian Tioga A-G zone, and the Frasnian Center Hill K-bentonite), whereas others are only regionally to locally recognized. At present, Lower to lower Middle Devonian (Lochkovian- through Eifelian-age) tephras have been more extensively documented. Additional work is needed through upper Silurian and upper Middle to Upper Devonian strata. The highest concentration of documented tephra beds are in Eifelian strata (>50 beds) across the basin; in contrast, some intervals have as yet yielded few if any beds.

Key references on Devonian tephras include Dennison and Textoris (1970, 1978) Dennison (1983). Conkin and Conkin (1979, 1984), Smith and Way (1983), Way et al. (1986), Smith et al. (1988, 2003), Shaw et al. (1991), Hanson (1995), Ver Straeten (1996, 2004a, b, 2008), Over and Rhodes (2000), Shaw (2003), Ebert and Matteson (2003), Wilcott and Over (2005), Ver Straeten et al. (2005, 2007a), and Over (2007). Information from other geologists include personal communications with G. Baird, D.J. Over, and P. Rubin (2007).

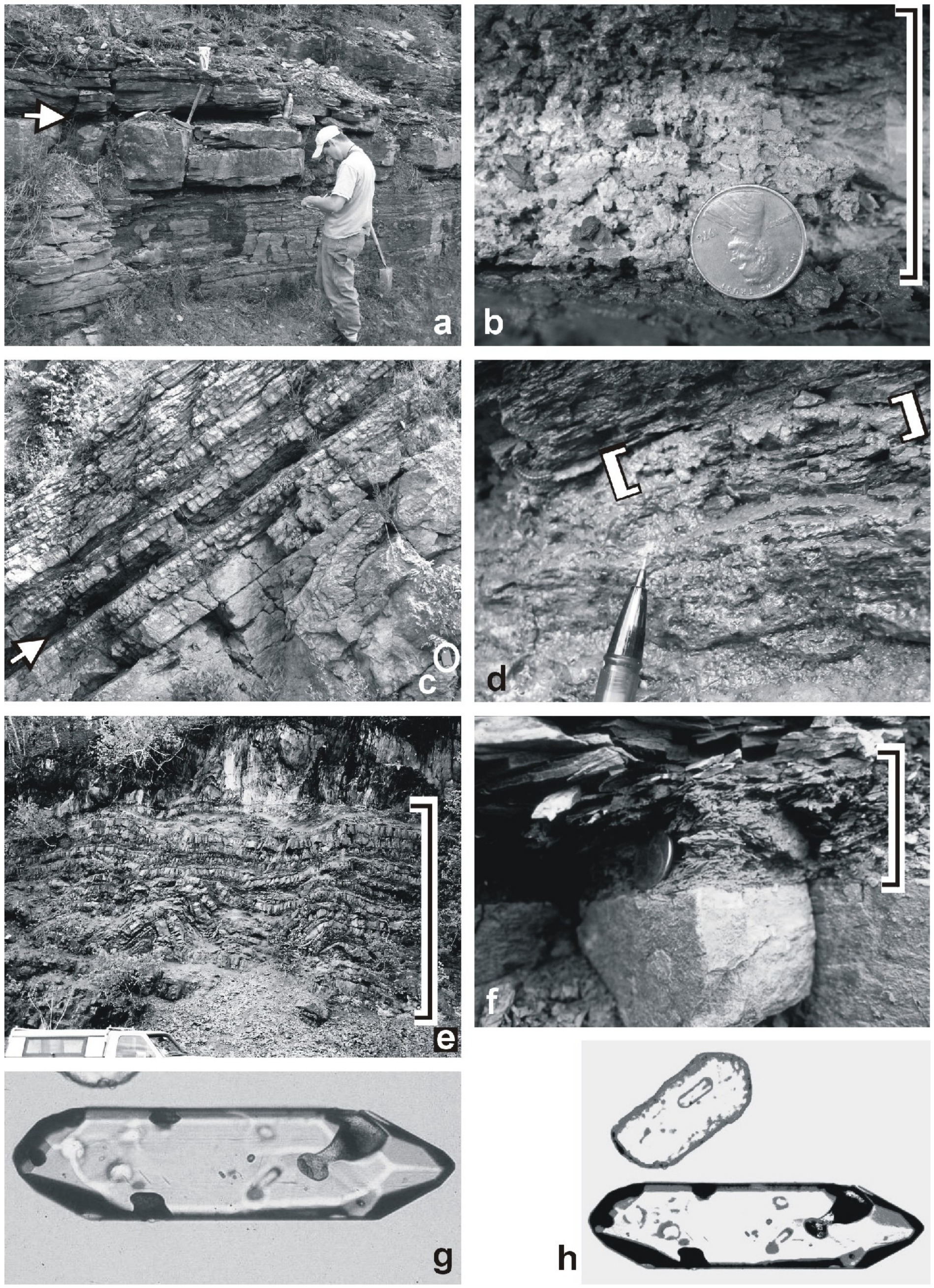

Figure 11. Devonian volcanic tephras I. Devonian airfall tephra beds in foreland basin sedimentary rocks, eastern New York: a) Arrow points to Bald Hill K-bentonite C. Lower Devonian Kalkberg Formation, Rte. 20, Cherry Valley, Otsego Co.; b) close up of clay to claystone of Bald Hill K-bentonite C (bracketed), at same outcrop; c) a thin Bald Hill K-bentonite bed within prominent dark gray shale bed. Middle of Lower Devonian Kalkberg Formation, Rte. 23 Catskill (Stop 1). Fieldbook in lower right (circled) for scale; d) close up of same thin Bald Hill K-bentonite bed as previous photo (bracketed). Pencil tip for scale; e) interval with 15 Sprout Brook K-bentonites. Spawn Hollow Member, Lower Devonian Esopus Formation, Rte. 23a SW of Catskill (Stop 2). Top of pickup truck for scale. f) close-up of a thin Sprout Brook K-bentonite (bracketed), from same outcrop. Dime for scale, just left of center; g) close-up of zircon from a Sprout Brook K-bentonite bed, showing inclusions. Scale not known; h) close-up of same zircon crystal, with apatite crystal.

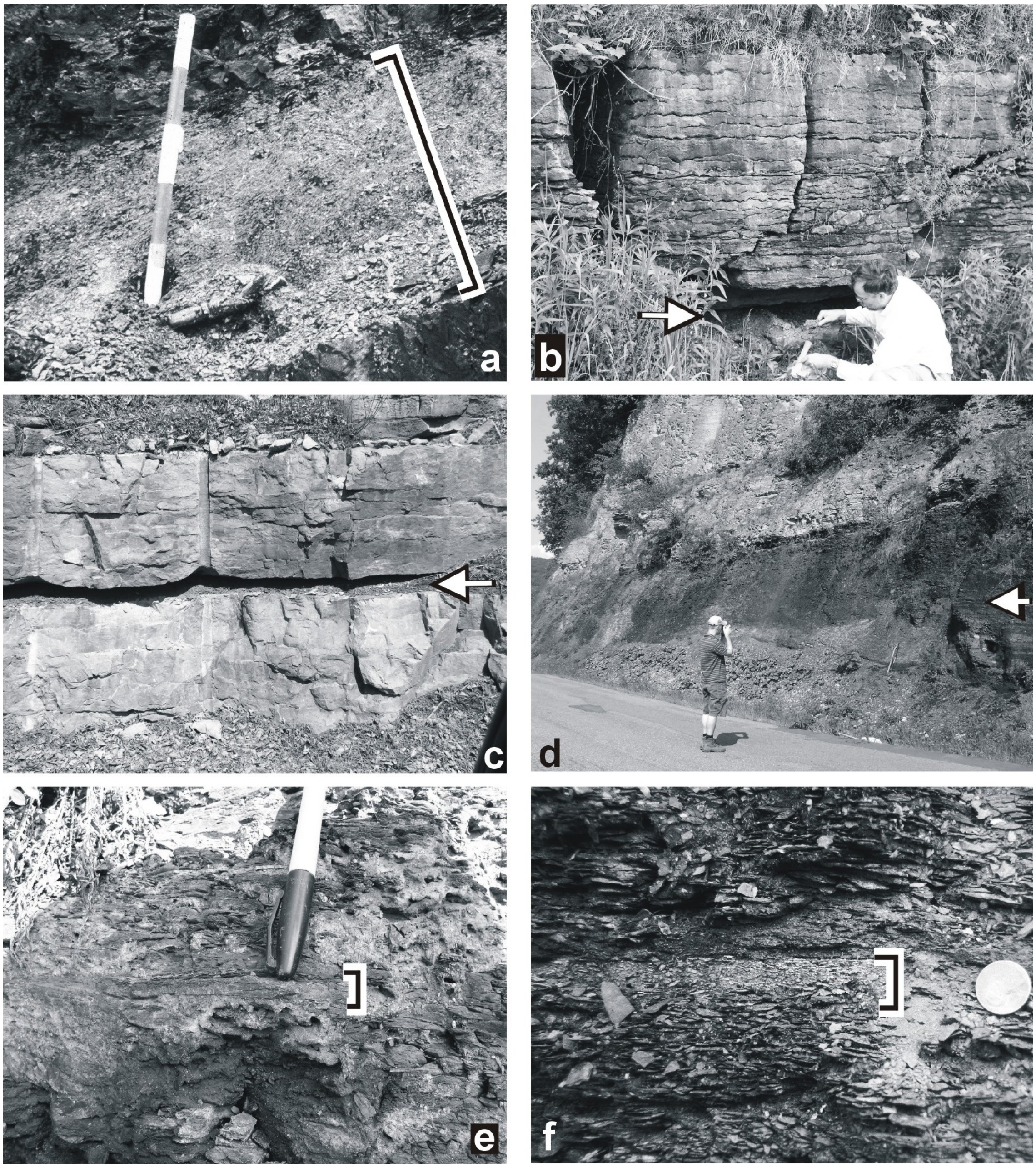

Figure 12. Devonian volcanic tephras II. Devonian airfall tephra beds in foreland basin sedimentary rocks, eastern New York: a) Topmost Sprout Brook K-bentonite (bracketed), from same outcrop as Figure 12e, f. Bed locally thins and thickens along the outcrop, associated with structural deformation of strata. Bands on stick = 10 cm; b) Tioga B K-bentonite in recessed interval, from Tioga A-G K-bentonites cluster. At base of Seneca Member, Middle Devonian Onondaga Formation, Rte. 20 cuts at Cherry Valley. George Shaw for scale; c) arrow points to thin (ca. 7 cm-thick), unidentified K-bentonite in upper part of Onondaga Formation (Moorehouse Member). Rte. 85, north of Clarksville, Albany Co.; d) arrow points to mid-Union Springs K-bentonite of Ver Straeten (2004a). In upper part of Bakoven Member, below contact with Stony Hollow Member, Middle Devonian Union Springs Formation. Along City View Terrace, off Rte. 28, northwest of Kingston; e & f) close-up of mid-Union Springs K-bentonite at same outcrop. Brackets denote position of cm-scale bed. In photo f, the bed is distinctly replaced by pyrite. Marker pen and penny for scales.

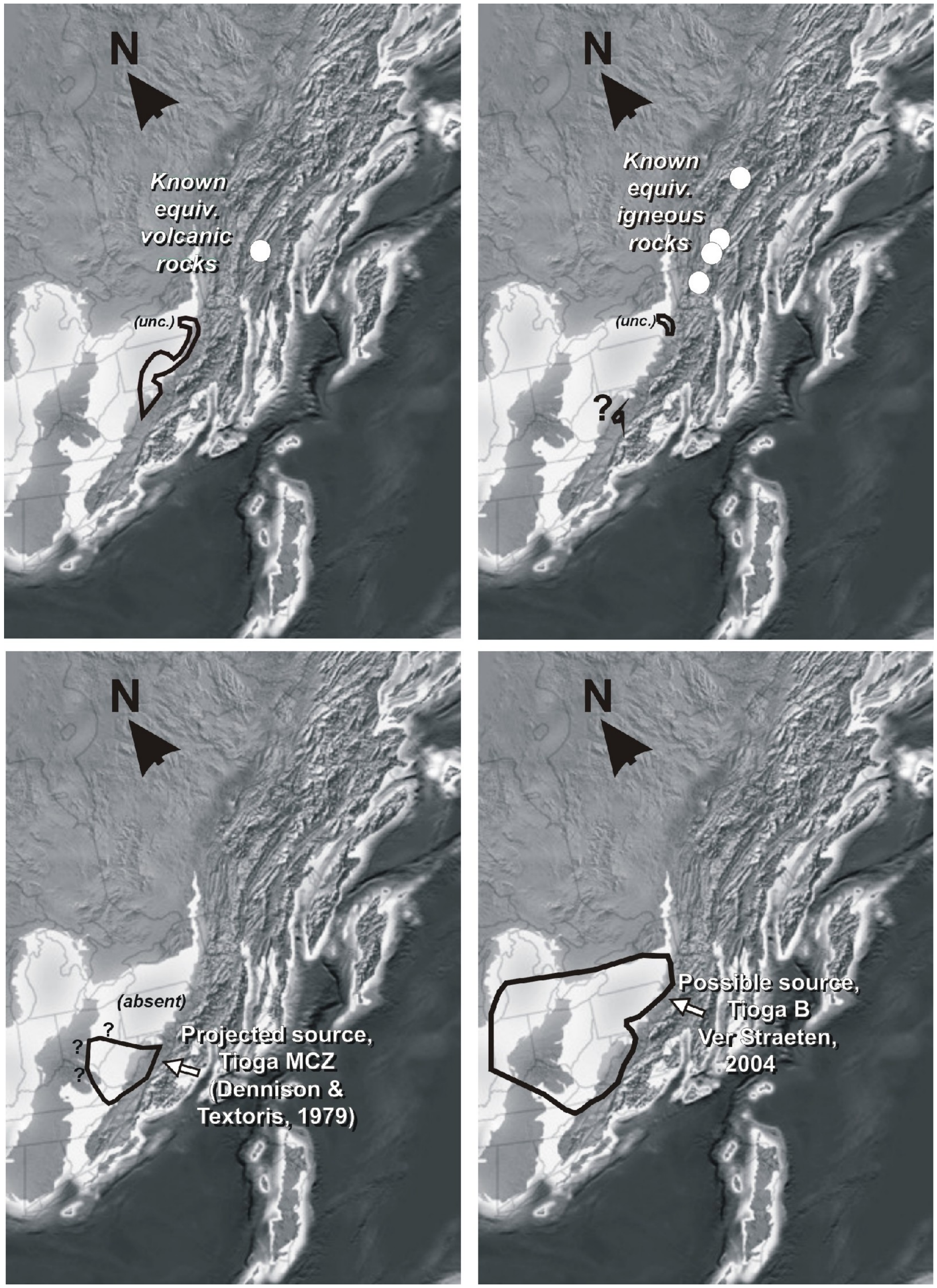

Figure 13. Lower to Middle Devonian tephra clusters, Appalachian basin, and possible source areas. Map distribution of the Bald Hill, Sprout Brook, Tioga Middle Coarse Zone, and Tioga A-G tephra clusters are plotted over a paleogeographic map of eastern Laurentia in the Middle Devonian. Potential source areas in a and b based on known age-equivalent volcanic and plutonic rocks in the Acadian orogen and greater Acadian foreland basin; projected source areas in c and d after Dennison and Textoris (1978) and Ver Straeten (2004a). Base map from Blakey (http://jan.ucc.nau.edu/~rcb7/namD385.jpg).

Most of the Devonian airfall tephras occur as clay rich beds; the clays are derived from alteration of volcanic glass. In contrast, some beds are essentially sandstones, formed of sand-sized minerals (phenocrysts) that were ejected from the magma chamber with volcanic ash during eruptions. The clay-rich beds are generally termed K-bentonites or metabentonites, due to the high content of potassium-rich illite; sandy phenocryst-rich beds may be termed "tuffs". Early diagenetic weathering of the abundant volcanic glass in the K-bentonites would have initially yielded smectitic clays (e.g., montmorillonite), which over deep time were altered to illite or mixed layer illite-smectite. Colors of the clay beds may vary, but commonly have a yellow-tan appearance. The clay rich K-bentonites beds commonly form recessions within the surrounding strata. Most all beds also at least a small percent of phenocrysts; these generally appear pristine and unabraded, euhedral in form or broken and shattered, with sharp edges. Common phenocrysts include zircon, apatite and bipyramidal quartz +/- quartz shards. Geochemical analysis of melt inclusions within metastable quartz crystals indicate that source magmas for the Bald Hill, Sprout Brook, and Tioga A–G clusters were of a high-silica rhyolitic composition (Hanson, 1995).

The Major Clusters Of Lochkovian To Eifelian Airfall Tephras. The Lower Devonian (Lochkovian) Bald Hill K-bentonites cluster comprises of up 15 airfall tephras (Figure 11a-d). They occur widely across the Appalachian foreland basin, from New York to Virginia and West Virginia (Smith et al. 1988, 2003; Shaw et al. 1991). One of the beds yielded a U-Pb age of 417.6 +/- 1.0 Ma (Tucker et al. 1998). In New York, they occur within the Kalkberg and New Scotland formations. The documented distribution of the Bald Hill K-bentonites across the Appalachian basin is shown in Figure 13a.

The Lower Devonian (lower Emsian) Sprout Brook K-bentonites, also consist of up to 15 airfall tephra beds (Ver Straeten, 2004b; Figures 12e-h, 13a). U-Pb dating of zircons yielded an age of 408.3 +/- 1.9 Ma (Tucker et al. 1998). They occur in the lower part of the Esopus Formation (Spawn Hollow Mbr.), in eastern New York (from Cherry Valley, Otsego Co. eastward). Locally in Virginia, a bed of mixed terrigenous and volcanic grains has been found in the same position, in the lower part of the Needmore Formation (lower part of the Beaverdam Member; Conkin and Conkin, 1979; Ver Straeten, 2004b). The Sprout Brook K-bentonites appear to be restricted to the northeastern part of the Appalachian basin (Figure 13b).

The Middle Devonian (lower Eifelian) Tioga Middle Coarse Zone of Dennison and Textoris (1970, 1978) is restricted to the southern part of the basin, where it is characterized by three prominent tuff beds, with up to 29 additional minor beds. Zircons from one bed have been dated at 391.4 +/-1.8 Ma (Tucker et al., 1998). The Tioga Middle Coarse Zone occurs in upper strata of the Needmore Formation, correlative with the lower part of the Moorehouse Member of the Onondaga Formation in New York (Ver Straeten 2004a, 2007a). Figure 13c illustrates the distribution of the Tioga Middle Coarse Zone across the Appalachian basin.

The Middle Devonian (lower Eifelian) Tioga A-G K-bentonites cluster (Smith and Way, 1983) consists of eight to nine beds that are widely correlatable through the Appalachian basin, from New York to southwestern Virginia, and into central Ohio (Ver Straeten, 2004a, 2007a). The Tioga B bed yielded an age of 390 +/- 0.5 Ma (Roden et al. 1990). In the northern part of the basin the A-G cluster occurs in the upper part of the Onondaga Formation and basal Union Springs Formation (Figure 13b); to the south they are found in the Selinsgrove Member (PA) or calcareous shale and limestone member of the Needmore Formation, and/or the lower part of the Marcellus Shale or Millboro Formation (MD, VA, WV). In Ohio they occur in the upper part of the Columbus Formation and lower part of the Delaware Formation (Ver Straeten, 2007a; DeSantis et al., 2007). At least one Tioga bed has been identified as far west as the Illinois basin. The distribution of the Tioga A-G cluster is shown in Figure 14d.

The Sprout Brook K-bentonites are the best represented tephras in the Catskill Front (Figures 12e-h, 13a). Though not commonly exposed, a number of complete outcrops can be found from Columbia and Greene to Otsego counties (including Stop 2). Up to 15 K-bentonites are interbedded with siliceous siltstones, impure cherts and minor shales in the lower part of the Spawn Hollow Member (lower part of the Esopus Formation). They commonly appear as yellow-tan unlithified clay beds, ranging in thickness from >1cm to ~20 cm, except where they are structurally modified in deformation zones (e.g., Stop 2, Figure 13a).

Independently derived correlations of Sprout Brook K-bentonites are shown in Figure 14 (Ver Straeten et al., 1993). The figure shows an upper set of physical correlations made by the author, and a lower set of independently derived correlations based on the geochemistry of glass inclusions in quartz phenocrysts by B. Hanson (Hanson, 1995). Clear physical and geochemical correlations closely match for outcrops in the Hudson Valley. However, correlations to the west (e.g., Knox, Cherry Valley) by either method was less clear.

Close observation of the columns in Figure 14 from the Hudson Valley delineates distinct packages of tephra beds with siliceous siltstones, cherts and minor shales. Six such packages seem to occur through the interval of the Sprout Brook K-bentonites.

Soft Sediment Deformation. Some Devonian strata in the Catskill Front show clear indications of deformation previous to lithification (Figure 15). These are marked by distorted to convolute layering, ball and pillow structures, and other features characteristic of soft sediment deformation zones (SSDs). SSDs commonly, though not exclusively, occur in beds of alternating grain size (e.g., muds and sands/carbonates), and may form through several different mechanisms.

At present, observations in eastern New York by previous workers and the author indicate a concentration of SSDs in the upper part of the marine succession (ca. upper middle Mount Marion Formation; "storm rollers" of Chadwick, 1944; Wolff, 1967; Stop 4, Figure 15a-e). Higher in the succession, in terrestrial strata, Fletcher (1967) reported SSDs in the base of the Oneonta Formation, and Gordon (1986) reported rare load casts and convolute bedding; in addition, some "highly disturbed" zones of Willis and Bridge (1998) may represent additional SSD zones. The author has locally noted SSDs in the Manorkill Formation (Stop 6) and the lower Oneonta Formation (Stop 7; Figure 15f, g).

Through the entire Devonian succession in the Catskill Front, however, SSDs are rarely observed or reported. Though this may in small part due to the difficulty of recognizing SSDs in homogenous facies (e.g., mudrock-only lithologies), it largely reflects their absence.

In upper middle to upper parts of the Mount Marion Formation, SSDs can be seen all along the outcrop belt from Kingston to the Helderbergs (Figure 15a-e). One area to observe multiple SSDs in the Mount Marion Formation is along and adjacent to NY Rte. 28 northwest of Kingston (Ulster Co.). Stratigraphically lower SSDs in this succession are seen along Moray Hill Road, near Stony Hollow, where three deformed zones can be seen in the upper approximately 12.5 m of a road cut. The lowest SSD zone comprises a 0.6 m-thick bed of internally-deformed sandstones; lower and upper bounding strata are undeformed. The middle zone features isolated pillows of sandstone in a sandy mudstone through a 20-30 cm-thick interval, underlying an undeformed argillaceous sandstone unit. The upper zone is not so subtle; the deformed zone is up to 3.3 meters thick, with contorted laminations and bedding, ball and pillow structures with a distinct wrinkled surface that marks the passage of fluidized muds +/- water along their margins. Also visible are four large, isolated sandstone boudins, ranging from 0.35 x 2.2 m to 0.50 to 4.3 m in size (Figure 15e). Three of the boudins are horizontal, but one is distinctly tilted at an angle. In at least one spot, a zone of plastic deformation is dissected by small vertical to near-vertical faults,

Northwest of Moray Hill Road on Rte. 28, additional outcrops show increasing degrees of soft sediment deformation up through the succession. One very large pillow, or "bowl", is visible in one of the middle outcrops (Figure 15a). A stratigraphically higher outcrop, a short distance northwest, features multiple zones of SSDs.

Similar features are noted where upper-middle Mount Marion strata are exposed, such as NY Rte. 23 near Quarryville (Greene Co.), NY Rte. 32 east of Westerlo (Albany Co.), and along the Hamilton escarpment in the Helderbergs (Albany Co.). Many of these SSDs are associated with interbedded sandstone and shale layers.

A different style of soft sediment deformation is visible in the upper part of the Mount Marion Formation off of NY Rte. 23, northwest of Catskill (Stop 4). Along the south side of the 12.3 m-thick outcrop, the uppermost, 0.9 m-thick sandstone bed features obvious SSD features (Figure 15b). Ball and pillow deformation and contorted strata is accompanied by a wrinkled surface, indicative of the plastic flow of fluidized sediments along the surface of the ball sediments. In this case, it appears that no mud was involved in the deformation. Instead, liquification of the sands following a triggering event led to dewatering, repacking of the sand grains, and deformation. An additional SSD occurs in sandstones about 40 cm below the base of the uppermost sandstone bed.

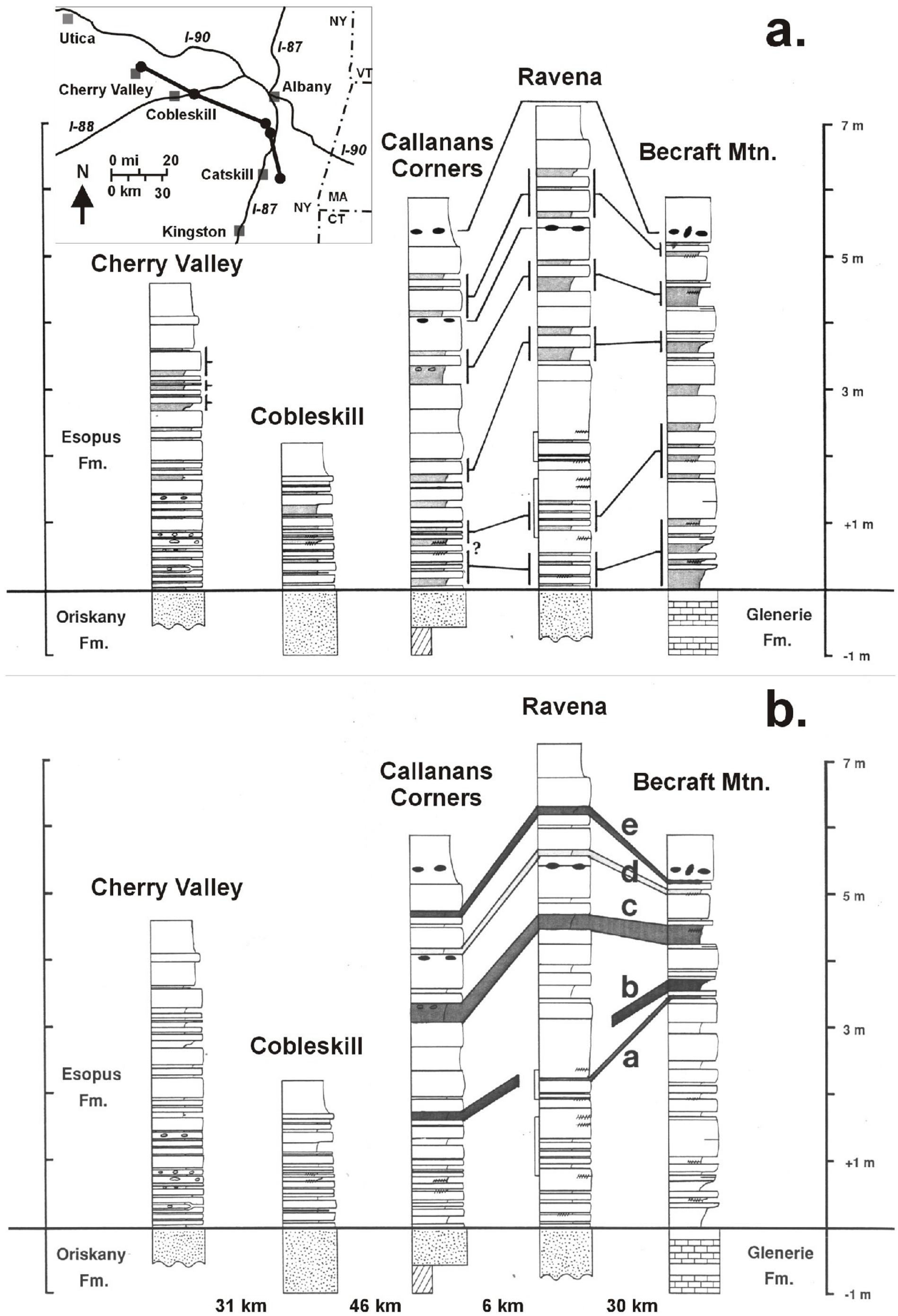

Figure 14. Correlations of the Sprout Brook K-bentonites, eastern New York. Independently-derived correlations of the Sprout Brook K-bentonites cluster: a) physical correlations, by the author; b) geochemical correlations by B. Hanson. Originally presented by Ver Straeten et al. (1993). Both methods yielded essentially the same results in the three easternmost outcrops; correlations to the west are less clear. Geochemical correlations based on composition of rhyolitic inclusions within volcanogenic quartz within individual Sprout Brook beds (Hanson, 1995). Note distinct packages of K-bentonites, separated by marine strata, which can be correlated physically in easternmost outcrops.

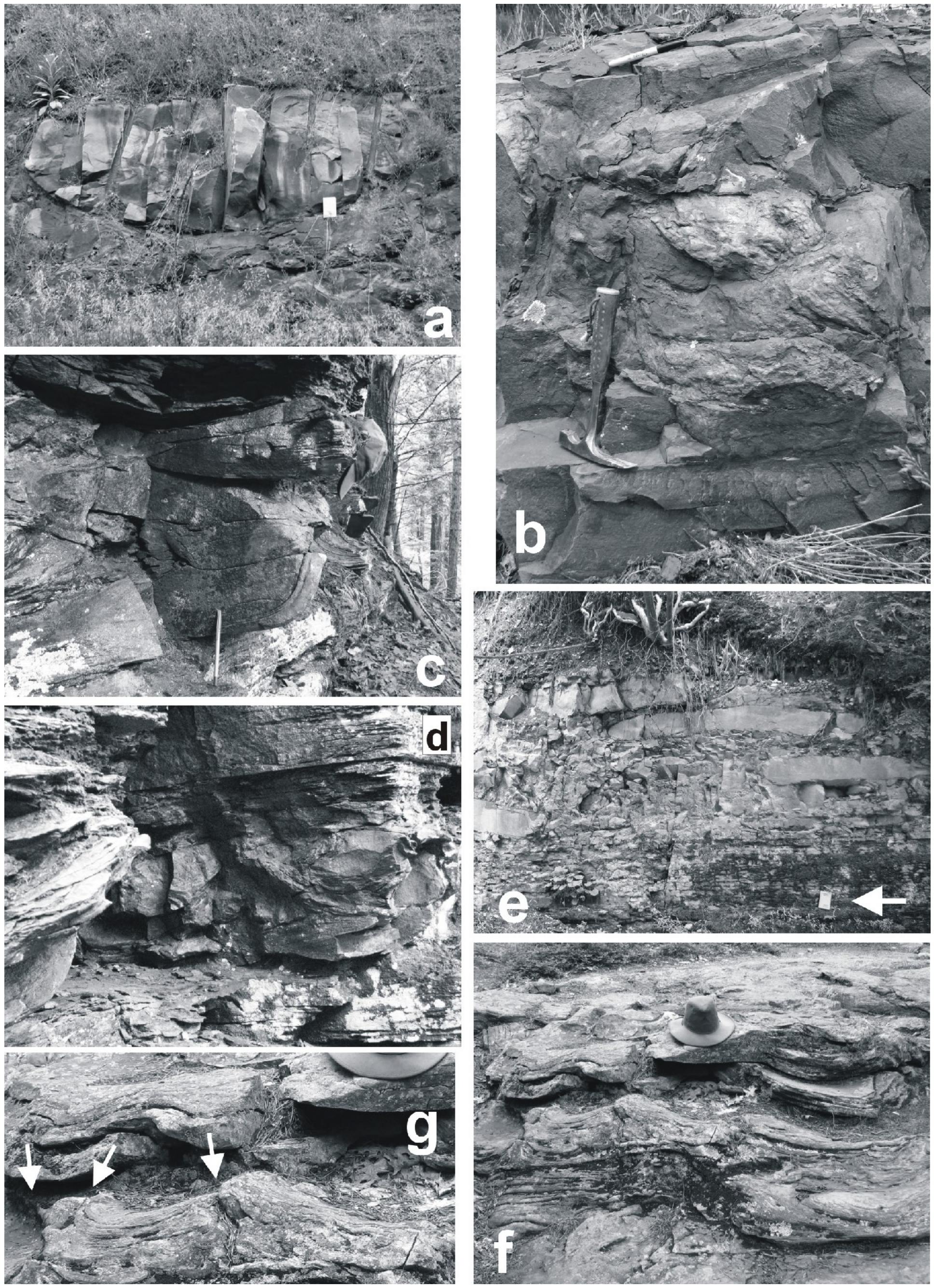

Figure 15. Soft-sediment deformation features, Catskill front. a) large dish/pillow structure of sandstone in mixed sandstone and shale. Upper middle part of the Middle Devonian Mount Marion Formation, Rte. 28, northwest of Kingston. Fieldbook for scale, at lower right of dish; b) pillow-like structures, with "wrinkled" surfaces, developed in sandstone-only strata. Upper part of the Mount Marion Formation, Rte. 23 near Leeds (Stop 5); c) various soft sediment deformation structures in mixed sandstone-shale facies. Upper middle part of the Mount Marion Formation, on the author's land, East Berne, Albany County. Pen for scale at lower center; d) structurally complex SSD zone, between undisturbed strata of similar facies; same outcrop as photo c; e) large, isolated sandstone boudins within ca. 3.5 m-thick deformed zone. Upper middle part of the Mount Marion Formation, Moray Hill Rd., NW of Kingston. Field book in lower right for scale; f) SSDs in sandstone only fluvial channel facies. Lower part of Upper Devonian (?) Oneonta Formation, along trail to Artists Rock and Sunset Rock, North-South Lake. Note rough similarity of structures to trough cross-bedding; however, margins of troughs are vertical water escape structures.

In the Oneonta Formation, along the crest of the Catskill Escarpment, one or more SSDs have been noted in Kaaterskill Clove and near North-South Lake (Fletcher, 1967; Gale, 1985; this paper; Stop 7, Figure 15f, g). When first viewed along the trail to Artists Rock at North-South Lake, one interval of sandstones appear to feature numerous trough cross-beds. However, a closer examination indicates that the edges of the troughs are at near-vertical to vertical angles, far beyond the angle of repose. Those edges actually represent dewatering structures, and the troughs, at least in part, represent lows where sand grains settled lower, via foundering and post-liquifaction repacking into more condensed deposits.

One of the interesting characters of many SSDs in the Catskill Front is their occurrence within specific layers, surrounded by layers of similar lithology throughout the rest of an outcrop. Most or all of the surrounding strata show no deformation.

DISCUSSION

Sedimentation and Sea Level History

Sedimentation Trends and the Acadian Orogeny. The major carbonate-quartz arenite and initial terrigenous clastic packages of strata above the Wallbridge unconformity feature markedly different patterns of sediment type, depth-related facies, and stratal distribution and geometry.

Variations in sediment type between the intrabasinal carbonates (+/-quartz arenites) versus extrabasinal clastics are, of course, related to changes in sediment source/provenance. Most of the carbonate is derived from biogenic production of shell matter by marine organisms (e.g., brachiopods, crinoids). Quartz arenites, including quartz conglomerates, are largely derived from reworking of supermature sediments within or on the fringes of the basin. Terrigenous clastics, in contrast, derived from erosion of previously existing rocks eroded from regional highlands and transported into the basin

The relatively widespread distribution of the limestones of the Helderberg Group, along with the Glenerie-Oriskany, Onondaga, and Tully formations reflect widespread shallow seas, characterized by relatively high carbonate production rates by shelly organisms living in shallow, relatively clastic-free tropical seas. The distinct wedge-shaped geometries, especially of the initial clastics overlying the carbonates indicate the influx of detrital materials eroded from a regional source area, accompanied by close to full cessation of carbonate production with clastic input.

The contrasting pattern of relatively shallow versus deep water litho- and biofacies of carbonate versus initial clastic deposits is associated with flexure of the crust underlying the foreland basin system. Crustal loading associated with orogenic buildup leads to subsidence of the crust, the shutoff of the carbonate production, and initial sediment starvation with transgression. Subsequent low sedimentation rates of suspended fine-grained sediments, combined with deposition/preservation of organic matter in deep water anoxic sediments, leads to the formation of basinal black shales.

Another contrast between the carbonate versus initial clastic suites is the widespread nature of the former and the more proximally-restricted distribution of the latter. Carbonate production, active across the basin during limestone deposition, shut down with the onset of clastic deposition, even in distal, clastic-starved areas of the foredeep basin in New York.

These major patterns, associated with development of three to four separate clastic wedges punctuated by carbonates, were interpreted by Ettensohn (1985) to reflect tectonically-active to -quiescent phases ("tectophases") during the Acadian orogeny. He proposed four separate Acadian tectophases, from the upper Lower Devonian through Lower Mississippian. The onset of tectonism in each tectophase resulted in subsidence of the basin foredeep and deposition of the basinal dark gray to black shales. Subsequent development through a tectophase culminated in a return to tectonic quiescence and deposition of carbonates. In general, Ettensohn's (1985) basic model still appears to explain a number of trends in the foreland basin sedimentary rock record. The relationship of his model to data and interpretations by researchers working in the orogen itself is still largely unclear to the author. More discussion of sedimentary evidence of orogenesis and the tectophase model are needed with peers working in the orogenic belt.

We now know that Acadian orogenesis begin in Late Silurian in Maine and New England (e.g., Bradley et al., 2000), and progressively migrated cratonward through the Lower to Upper Devonian. The earlier initiation of the orogeny was not readily visible to Ettensohn (1985). This is now understood by the author to be due to: 1) early in the Acadian event, the orogen, its deformational front, and most of the Acadian foreland basin system (wedge-top, foredeep and forebulge) were still geographically positioned in New England to easternmost New York, and; 2) Ettensohn (1985, 1987) was working with data from the eroded remnant of the greater Acadian foreland basin, which starts on the west side of the Hudson River, far cratonward of the Late Silurian interface of the orogen and foreland. During the initial stages of the Acadian orogeny, the Catskill front was geographically situated in the far cratonward backbulge basin of the foreland basin system – marked by deposition of the Rondout and Helderberg carbonates. Portions of the early Acadian foredeep are preserved in northern New England, in thick, flysch units like the Lower Devonian Littleton Formation of Vermont and New Hampshire.

Through time, the orogenic front and successive portions of the foreland basin (wedge-top, foredeep, and forebulge) migrated cratonward, some of which passed west of the position of today's Hudson River. By the Late Devonian, the wedge-top portion of the basin, characterized by deformational thrusting and uplift, may have migrated into the Catskill Front. Interpretation of this is dependent on whether any of the structural deformation in the Catskill Front is of Devonian/Acadian age – a point of ongoing of debate (e.g., Geiser and Engelder, 1983; Marshak, 1986; Marshak and Tabor, 1989; Zadins, 1989).

Eustatic and Tectonic Effects on Relative Sea Level. Two of the most important factors affecting relative sea level change are global eustatic sea level processes and regional, tectonic-induced subsidence. There have been many debates over the relative effects of these two processes in foreland basin systems. A series of third order depositional sequences/sea level cycles from the Devonian Appalachian basin Devonian are outlined in Figure 8. Many of the sequences have been correlated outside of the basin (e.g., Johnson et al., 1985; House and Kirchgasser, 1993; Bartholomew, 2006), indicating their global, eustatic nature. Figure 8 compares relative sea level curves for the Appalachian basin sequences and Johnson et al.'s (1985) Euramerican curve. The Appalachian basin sequences show some refinements over the Euramerican curve (e.g., base of transgressions placed at position of lowstand or initial transgressive litho- and biofacies; cycles added where Johnson et al., 1985 overgeneralized the sea level history). Accounting for these refinements, data from New York and globally indicate correlation of individual sequences/cycles (e.g., House and Kirchgasser, 1993; Brett and Baird, 1996; Over, 2002; Filer, 2002; Ver Straeten, 2007a). However, where the Euramerican curve shows overall transgression from the middle Lower Devonian to middle Upper Devonian, the Appalachian basin curve is marked by three major transgressive to regressive pulses, superposed over the record of third order cyclicity. These are the effects of tectonically-induced loading and subsidence in the foreland basin. The three major transgression mark the onset of three separate Acadian tectophases (Tectophases 1 to 3 of Ettensohn, 1985). Of importance, it is clear that these major subsidence events are superposed over the distinct record of eustatic sea level cycles in the foreland basin.

Clastic Rock Petrology and Provenance Changes in detrital grain mineralogy through foreland basin successions provide information about changes of the rocks exposed within source areas through time (provenance). The presence of abundant quartz, K-rich feldspars and granitic rock fragments, or minerals such as staurolite, kyanite and high grade metamorphic rocks fragments indicate very different rocks exposed in their respective sedimentary source areas. These may reflect changes of provenance, although the record may also be affected by grain size variation, transport distance, or depositional environment (Gale, 1985).

Conglomerates Discussion. The new conglomerate analysis presented here provides additional perspectives on changing clastic composition and provenance over approximately 40 million years, (ca. 410 to 370 million years ago). Initial vein quartz conglomerates (mid Lower Devonian Connelly Conglomerate and uppermost Lower to basal Middle Devonian Kanouse Sandstone) at ca. 410 and 395 Ma were likely derived from erosion of intrabasinal sources, such as the Silurian Shawangunk and correlative Green Pond Formations in southeastern New York and adjacent New Jersey.

Succeeding quartz- and chert-rich polymict conglomerates in the upper Mount Marion Formation (Sample 3, ca. 388 Ma) clearly indicate a change in source area. The introduction of the chert and sandstone clasts, not present in the lower samples, is the result of deposition of synorogenic sediments from outside the basin. The varied colors of the cherts (i.e., gray, light gray to white, dark gray to black, and red) imply the erosion of multiple levels of strata in the source area. Variously colored cherts are found in Cambrian and Ordovician strata east of the Hudson River – although no green cherts, characteristic of some of those rocks (e.g., Mount Merino Member, Normanskill Group) have been noted.

The overlying Upper Devonian conglomerates of the Oneonta Formation (Samples 6 and 7, ca. 384 Ma) to Slide Mountain Formation (based on general statements in Fletcher, 1967; Gale, 1985; ca. 376 Ma) are characterized by abundant quartz and sandstone clasts. Chert content has declined to almost negligible amounts. Chlorite is found in a number of the sandstones, which may indicate low grade metamorphism of some of the strata, or incorporation of low-grade metamorphic sediments into the sandstones. The latter could have happened during the Lower to Middle Devonian, off to the east before the foredeep of the basin migrated westward into the Hudson Valley area. Their occurrence could be explained by uplift, exposure and erosion of those sandstones above thrust fault slices in the wedge-top of the foreland basin system. This would be consistent with Fletcher (1967) proposal that the red sandstone pebbles in the Slide Mountain Formation may have been cannibalized from Devonian sedimentary rocks further to the east. However, further petrologic and possibly palynological study is needed to resolve this issue.

The four Famennian-age conglomerates (ca. 376-370 Ma) from western New York are quartz-rich (83-98%), especially the two younger mid-Famennian samples. These nearly compare to the oldest conglomerates in the succession, which were 100% macrocrystalline vein quartz. However, the composition of the younger Famennian conglomerates may have biasing influences different from all of the older samples. Clastics in western New York may have been derived from a broader or different source area along the orogen (e.g., beyond eastern New York and/or Pennsylvania outcrops), yielding a different pebble composition from those in the Catskill Front. Their occurrence far into the foredeep basin also implies a greater transport distance for the clasts. The conglomerate from the lower Cattaraugus Formation, near Amla, New York lies approximately 340 km west of Catskill escarpment. How far it would be to similar sources of clasts southeast of the Pennsylvania outcrop belt is unknown to the author. Long distance transport through high gradient wedge-top to low gradient delta plain streams wear down and destroy less durable clasts (e.g., Cameron and Blatt, 1971; Ethridge, 1977; Davies and Moore, 1970). So, the great transport distance would favor the preservation of highly durable quartz pebbles over other clasts. How much influence this had on the composition of the Famennian conglomerates in New York is unknown. However, at least in part, it likely represents a continuance of increasing quartz content noted in the Catskill Front through the Middle to Upper Devonian Plattekill through Slide Mountain formations.

To summarize, extrabasinal Devonian conglomerates record changing input of coarse clastics into the Catskill Front and beyond. Initial milky quartz gravels (at ca. 410 and ca. 395 Ma, upper Pragian and lower Eifelian) were succeeded compositionally by mixed chert- and quartz-rich gravels (at ca. 388 Ma, lower Givetian), to slightly increasing quartz-rich gravels with abundant sandstone-/metasandstone-rich pebbles (ca. 383 to 376 Ma, lower Frasnian). Through the latter interval, increased numbers of red sandstone pebbles in the gravels appear to indicate erosion and cannibalization of Acadian-derived sandstones (Fletcher, 1967). These would have most likely been exposed by thrusting in the proximal wedge-top depozone of the foreland, and subsequently transported into the foredeep. The youngest conglomerates from this study (ca. 376-370 Ma, lower to mid Famennian) continue the arc of increasing quartz content, culminating in nearly pure milky quartz compositions approaching those of the lowest conglomerates.

Sandstone and Mudrock Provenance. Sandstone petrographic studies of the Lower to Upper Devonian Catskill Delta succession (e.g., Lucier, 1966; Allen and Friend, 1968; Way, 1972; Rehmer, 1976; Ethridge, 1977; Gale, 1985) repeatedly found little to no mineralogical evidence of significant igneous or medium to high grade metamorphic rocks exposed within Acadian drainage basins supplying sediments to the Catskill Front. Instead, the mineralogical evidence largely points to exposure and erosion of low-grade metamorphic rocks (up to greenschist grade) and sedimentary clastics and minor carbonates within the source area. Some very minor exceptions to this pattern were reported by some authors in the sandstones. For example, Lucier's (1966) data on heavy minerals in five samples found traces of medium to high grade metamorphic and igneous rocks (e.g., staurolite, hypersthene, hornblende and diopside-augite). In addition, Allen and Friend (1968) report clasts of pyroclastic tuffs and metamorphic granulites in the Twilight Park Conglomerate.

The low-grade metamorphic and sedimentary rock grains predominantly found in the Middle to Upper Devonian sandstones are lithologically similar to Cambrian to Ordovician sedimentary to low grade metamorphic rocks now exposed in eastern New York (Lucier, 1966; Fletcher, 1987). However, unlike proposed by Lucier (1966) and others authors, it seems unlikely that those rocks were exposed at the surface in eastern New York between approximately 388 to 375 million years ago.

Hosterman and Whitlow (1983), in their study of Middle to Upper Devonian marine shales, hint at a another, disguised sediment source. Their analytical results led them to interpret that during the Devonian, much of the illite and mixed layer illite-smecite now in the rocks was originally composed of illite and smectite clays. As smectite clays form from the weathering of feldspars, volcanic ash, and other similar rocks, their occurrence would indicate a more significant input of sediment from igneous sources than generally interpreted.

In support of Hosterman and Whitlow's (1983) interpretation of substantial smectite content in the Devonian rocks, paleosol studies in the Catskill magnafacies of New York and Pennsylvania note the abundance of vertisols, along with entisols, inceptisols, and alfisols (Driese and Mora, 1993; Mora and Driese, 1999; Oliver and Terry, 2009). Modern vertisols are characterized by a relatively high content of smectite (montmorillonite) clays. Vertical cracks, and deformational features such as pedogenic slickensides, bowls/gilgai/pseudoanticlines and other structures are diagnostic features of vertisols. These result from wetting and drying of the soils (commonly seasonal), and resultant expansion and contraction of the smectitic clays. Though substantial amounts of smectite are not preserved in the Catskill succession today, the widespread occurrence of vertisols also appear to indicate its strong presence during the Devonian.

Apparent substantial smectite content in the strata during the Devonian appear to indicate a hidden source of igneous-derived sediment. Interestingly, Hosterman and Whitlow (1983) note the similar alteration of Devonian airfall tephras to K-bentonites. These beds, originally composed of volcanic glass and phenocrysts, were diagenetically altered to smectitic clays, and then further altered to mixed layer illite-smectite clays and illite.

To summarize, these clay mineralogy and paleosol studies indicate that during the Devonian, fine-grained sediments in New York and the Appalachian basin had a significant component of smectitic clays, apparently derived from the weathering of igneous rocks or volcanic ash. This sharply contrasts with the data from sandstones and conglomerates outlined above, which portray a source very restricted to sedimentary to low grade (slate to greenschist) metamorphic facies.

More recent provenance studies, using different techniques, also portray a more complex picture of sediment provenance in the Catskill front and adjacent areas. Aronson et al.'s (1994) dates of detrital micas (mostly 406-387 Ma) from Upper Devonian to Lower Mississippian clastics in New York and Ohio appear to indicate the much of the Catskill clastic wedge have an Acadian-age provenance. They calculated that Taconic- and Grenville-age sources could comprise no more than about 30% and 5% of sedimentary sources, respectively.

McLennan et al.'s (2001) U-Pb ages of detrital zircons from lower Walton Formation yielded SHRIMP U-Pb ages of 1.23-1.00 Ga (Grenville age) and 470-420. In the absence of clear Acadian age detrital zircons in their single sample, they projected that Acadian sediments appear to recycle pre-existing, pre-Devonian rocks from along the continental margin of Laurentia.

Zack et al.'s (2004) geothermometry analysis of detrital rutiles from the same outcrop as McLennan et al. (2001) indicated that the rutiles were derived from a broad range of low to high (greenschist/blueschist to granulite) grade metamorphic rocks. The authors interpret the rutiles to be eroded from Pre-Cambrian gneissic terranes, and deposited in pre-Taconian orogeny sedimentary successions. During the Devonian, they were eroded from post-Grenville/pre-Taconian sedimentary or sub-greenschist grade metasedimentary rocks in the Acadian orogen.

Two recent studies of Devonian to Pennsylvanian sedimentary successions in the eastern U.S. (Thomas et al., 2004; Eriksson et al., 2004) hypothesize that synorogenic foreland basin sediments incorporate clastic detritus from the erosion of previous orogenic events, but not from the current orogeny. This appears to agree overall with the data and interpretations of McLennan et al. (2001), and the numerous petrologic studies of Middle to Upper Devonian strata in the Catskill Front (e.g., Burtner, 1964; Lucier, 1966; Fletcher, 1967; Gale, 1985). However, all of these studies are in sharp contrast with the results of Aronson et al.'s (1994) detrital micas dates, and projected dominance of Acadian sources of sediment during deposition of the Catskill delta.

As pointed out by McLennan et al. (2001) these contrasting data and interpretations are in part a result of analysis of very different detrital grains (e.g., zircons versus white micas), which may have different deep versus shallow sources in an orogen, and be biased by weathering/abrasion and transport processes. It is intuitive that Acadian-age, non-volcanic zircons would be sourced from deeply buried igneous or metamorphic rocks, whereas Acadian-age white micas could be readily sourced from shallowly buried, low-grade metamorphosed rocks. Deep Acadian sources, exposed at present in New England, would not have been unroofed during the Devonian. In contrast, Upper Silurian to Middle Devonian synorogenic sediments, or Taconic metamorphics re-exposed to >350°C temperature conditions during the Acadian orogeny, would be less deeply buried, and become exposed and weathering in the orogen.

And, as also pointed out by McLennan et al. (2001), while highly durable zircons last through multiple events that recycle sediments, micas are readily weathered, or broken down by transport processes, and disappear relatively quickly. One would expect to find older zircons in clastic sediments, but less so older micas.

Another key issue in this debate may be the small number of analyses performed, on a stratigraphically- and regionally-limited number of samples. A more systematic geochemical and geochronologic analysis of the Lower to Upper Devonian succession in the Catskill Front (and other areas) is needed.

One more point should be expressed on this issue. Low grade metamorphic rocks are known to be the source of a significant component of Catskill delta sediments. While interpreted to be Taconian in age by earlier workers (e.g., Burtner, Lucier etc.), Aronson's dates constrain their source to be largely Acadian. Where would such Devonian sediments be sourced from?

The author provides the following hypothesis as a plausible explanation. Early in the Acadian orogeny, a massive volume of Upper Silurian to at least Lower Devonian synorogenic sediments were deposited in the foredeep basin in New England (e.g., Littleton Formation). A great thickness of these was deposited over the top of the rocks of the Taconian orogen in the basin foredeep. As the Acadian orogenic front migrated cratonward through time, these early foredeep sediments, and underlying rocks, were subjected to regional metamorphism. Later in the orogeny, these early Acadian synorogenics would have been uplifted along thrust sheets and exposed in the wedge-top of the foreland basin, and cannibalized, providing unaltered to low-grade metamorphosed Acadian sediments to younger Acadian synorogenic sediments. Although some older rocks may have been thrust to the surface, much of what should have been exposed in the orogenic front should have been the younger Upper Silurian to Lower Devonian rocks. This thick younger succession would largely have to be unroofed first to get to underlying Taconian-age rocks.

The author finds it most plausible that the fine-grained sediments, sedimentary and low-grade metamorphic rock fragments, and conglomerate clasts in the Catskill Front were derived from Acadian, not Taconian sources. At least in part, older more durable grains, like zircons and rutile, were likely eroded from pre-Devonian sources early in the orogen, and deposited in the Devonian succession of the early Acadian foredeep, and later uplifted and cannibalized.

In summary, the provenance of at least Middle to Upper Devonian sandstones and mudrocks in the Catskill Front appear to be derived largely from sedimentary and low grade metamorphic rocks in the Acadian orogen. Between approximately 388 and 376 million years ago (Mount Marion to Slide Mountain formations), there were no major changes in sediment composition, and hence no major changes in rock types exposed and eroding within the paleodrainage basin feeding into the Catskill Front. In contrast with previous interpretations, it seems plausible that Catskill delta clastics were largely derived from Acadian sources, not Taconian. Little if any significant magmatic or high-grade metamorphic rocks were exposed in the orogen, within the paleodrainage basin. A hidden source of abundant smectitic clays, derived from weathering of igneous rocks, may have come from airborne volcanic ash.

Foreland Basin Tephras and Acadian Volcanism/Magmatism. At this time, more than 80 beds of volcanic airfall origin are documented from Lower and Middle Devonian Lochkovian to Eifelian stages) strata across the Appalachian basin. Additional beds are known from the upper Middle to Upper Devonian, but more work is needed in that interval. Stepping back, however, what are the broader implications of this data for the history of Acadian paleovolcanism? Can the record of tephra beds preserved in foreland basin sediments be used as a proxy for the timing and character of explosive plinian volcanism in a magmatic belt like the Acadian orogen?

Tephra Beds as a Proxy for Paleovolcanism. The traditional view of volcanic airfall tephras (including the New York's Devonian K-bentonites) is that a single tephra bed is the result of a single volcanic eruption. Recent studies, however, indicate that many beds have a complex depositional history, resulting from reworking of tephra sediments and/or the amalgamation of multiple eruptive events into a single layer. Furthermore, a broad range of physical, biological, and chemical processes active in individual environments can lead to preservation, mixing or destruction of airfall tephra layers.

Ver Straeten (2004a) explored these issues and their implications for explosive Lower to Middle Devonian volcanism in the Acadian orogen (see also Ver Straeten, 2005, 2007b, 2008; Benedict, 2004; and Ver Straeten et al., 2005). Based on the record of tephras in the foreland basin fill, and recognizing potential preservational biases in that record, Ver Straeten (2004a) proposed that the mid-Lochkovian, lower Emsian and lower to middle Eifelian stages were times of increased volcanism in the mountain belt. These times correspond to deposition of the Bald Hill, Sprout Brook, and Tioga Middle Coarse Zone and Tioga A-G tephra clusters. Ongoing search of the literature on Devonian magmatism and volcanism from the Acadian orogen seems to support those interpretations (see lower Emsian discussion below).

As noted in the provenance discussion, other lines of evidence (smectite clay mineralogy and vertic palesols) appear to indicate the presence of an otherwise disguised igneous source in the Devonian strata. This could be derived from weathered igneous rocks in the orogen, reworking of pre-Acadian sedimentary rocks in the orogen rich in smectite/igneous minerals, or weathered Acadian-derived volcanic ash deposited by airfall in the foreland basin

Lower Emsian magmatism and volcanism in the Acadian Orogen. Figure 14 appears to indicate that packages of multiple Sprout Brook K-bentonites can be physically correlated from the Catskill front to Helderbergs in eastern New York. This is dependent on the separation of a few closely-spaced K-bentonites from others by thicker beds of background siliceous siltstones to cherts. Thickest siltstone/chert beds appear to underlie the insertion of the sets of thin K-bentonites.

These patterns resemble small-scale parasequences, developed in clastic-dominated facies. Increased sedimentation of marine sediments during a fall to lowstand of sea level (small-scale falling systems and lowstand systems tracts in sequence stratigraphy terms) would yield thicker siliceous siltstones to cherts. Succeeding sea level rise (a small-scale transgressive systems tract) and resultant shutoff of clastic sedimentation would allow for accumulation of whatever alternative sediment was available in the environment. It this situation, that would be airborne volcanic tephra from a single to multiple volcanic eruptions in the orogenic belt. The accumulation of exclusively volcanic tephra could occur over sediment-starved intervals of time because no other sediment was available. A detailed discussion of tephra deposition and sediment condensation in a context of sea level change is provided in Ver Straeten (2008).

The lower part of the Esopus Formation (Spawn Hollow Member) marks a major sea level rise, via a combination of a third order eustatic sea level rise, and superposed tectonically-induced basin subsidence (Ver Straeten, 2007a; Figure 8). Shutoff of carbonate production, and relative clastic sediment starvation due to sea level rise could potentially result in periods of time where the only sediment available for deposition in the environment might be airfall volcanic ash (Brett and Baird, 1990; Puspoki et al., 2008; Ver Straeten, 2008).

Supporting evidence for application of such a model in lower Esopus time come from geochemical analysis of apatite phenocrysts from the Sprout Brook K-bentonite beds by Benedict (2004; and in Ver Straeten et al., 2005). His work indicates that a single tephra bed sometimes yields phenocrysts with different geochemical signatures. Those signatures imply deposition of ash from different volcanic sources, or at least different eruptive events, within a single bed.

Puspoki et al. (2008) carefully documented such a case of enhanced sedimentation of tephra from multiple eruptions with clastic sediment starvation during a major Miocene transgression. In their remarkable study, deposition during some parasequences consisted wholly of volcanic ash sediments; the delineation of individual parasequences was in some cases only possible by the degree of weathering and alteration of volcanic to clays at transgressive surfaces.

Let's extend this line of thought further. If the patterns of a few clustered Sprout Brook tephras (separated by thicker beds of marine deposits) are interpreted to represent small-scale cycles, the sections at Becraft Mountain to Callanans Corners could possibly represent six such cycles. If each cycle is interpreted to represent a Milankovitch precessional cycle, of approximately 23,000 years duration, then the entire Sprout Brook succession could represent 23,000 x 6 = approximately 138,000 years. If individual couplets of K-bentonite + background marine beds represent a single parasequence and the six packages represent approximately 100,000 year Milankovitch eccentricity cycles, then the succession would comprise on the order of 600,000 years.

Where is all of this volcanic ash coming from? Is there supporting data in the Acadian orogen to interpret such ongoing and extensive volcanism during deposition of the Sprout Brook K-bentonites?

Lower Emsian-age igneous rocks occur in both the greater Acadian foreland basin and the Acadian orogen. A number of these have an overlapping error range with the Sprout Brook K-bentonites cluster in the Appalachian basin (408.3 +/- 1.9 Ma; Tucker et al. 1998). These include at least six different deposits of volcanic rocks, and numerous plutons in New England, Quebec and New Brunswick (e.g., Bradley et al., 2000; Ver Straeten, 2004b).

The Sprout Brook K-bentonites, in the lower part of the Esopus Formation (Spawn Hollow Mbr.), are found in northeastern New York (Ulster and Otsego counties; Ver Straeten, 2004b). Locally, in the southern part of the basin, beds with mixed volcanogenic and detrital grains, are found (Conkin and Conkin, 1979; Ver Straeten 2004b).

A relatively large number of lower Emsian volcanic and magmatic rock units with an overlapping error range with the Sprout Brook K-bentonites (ca. 409 to 405 Ma) are reported from the Acadian orogen, chiefly from Maine (see references below). Theses include the Traveler, Kineo and other rhyolitic ashflow tuffs erupted from five major volcanic centers in north-central to western Maine. All along the belt, the rhyolites are underlain by quartz-rich sandstones (Matagamon Formation) equivalent to the Oriskany Formation in New York (Boucot, 1969; Rankin, 1968, Rankin and Hon, 1987). Furthermore, some of the rhyolites are overlain by marine sedimentary rocks correlative with the Schoharie Formation in New York (Boucot, 1969).

The widely known Mount Katahdin in north-central Maine is one of the lower Emsian granitic plutons. Katahdin's northeastern flank is draped by its co-magmatic ash flow tuffs (Traveler Rhyolite; Rankin, 1968). Rankin and Hon (1987) conservatively estimate the preserved volume of the Traveler Rhyolite alone is approximately 800 km^3. This volume compares with major Cenozoic tuffs in the western U.S. (e.g., Timber Mountain, Paintbrush, and Lava Creek tuffs, 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 nearby 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.

The ages of numerous additional lower Emsian-age felsic plutons in Maine and New Hampshire are reported by Bradley et al. (2000). Further plutonic rocks with dating errors that overlap with the Sprout Brook K-bentonites are reported by Tucker and Robinson (1990), Bevier and Whalen (1990), Rankin and Tucker (1995), Robinson and Tucker (1996), Ludman and Idleman (1998), Solar et al. (1998), Eusden et al. (2000), and Tucker et al. (2001).

More lower Emsian volcanogenic strata from Acadian foreland basin deposits on the Gaspe Peninsula, Quebec, in northern New Brunswick, and in New Hampshire, (Billings, 1937, 1956; Douglas, 1970; Boucot, 1970, pers. comm., 1993; Poole and Rogers, 1972; Doyon and Valiquette, 1987; Tucker and Rankin, in Bradley et al., 1999; and Wilson, 2004).

No igneous rocks of Emsian age are known from south of New England. This may be associated with erosion and/or cover by younger rocks. However, with close to no record of airfall tephras in the southern part of the Appalachian basin, it is possible that there was only minor explosive lower Emsian-age volcanic activity in the southern Acadian orogen.

The high concentration of Lower Emsian magmatic and volcanic rocks in the northern Appalachians, combined with the restricted distribution of airfall 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). Devonian-age westward directed transport by winds would have carried tephra plumes from New England out over the northeastern edge of the Appalachian basin, where it would have been deposited in the seaway in present-day eastern New York.

Soft Sediment Deformation = Seismites? The purpose of this section is to examine potential causes of soft sediment deformation in the Catskill succession, and how they may potentially relate to Acadian orogenesis. Too little detailed information is yet available to make clear interpretations; it is hoped this will draw attention to such features, and lead to further investigation.

The deformation of unlithified sediments may result from various processes. These include the formation of a density inversion via rapid deposition of dense sediments over dilute water-rich sediments; repacking of under-compacted sediment layers; the escape of gases from sediments; sliding or slumping of sediments; impacts or earthquake/seismic shocks; waves or flood surges; tsunamis and density flows; and pressure changes on the sea floor from storm currents (Jones and Omoto, 2000; McLaughlin and Brett 2004; Montenat et al., 2005). They commonly occur (though not exclusively) in beds of alternating grain size (e.g., muds and sands or carbonates), which are sensitive to changes in sediment yield strength (Montenat et al., 2005). Sediments by themselves do not deform without a trigger to reduce their yield strength. According to Jones and Omoto (2000), deformation of unconsolidated sediment requires: 1) a deformation mechanism, which enables the material to be deformed; 2) a driving force, which brings about deformation; and 3) a trigger, which initiates 1, 2, or both.

In recent years, some SSDs have been interpreted to be the result of seismic shocks, generated by earthquakes. Termed "seismites", they form due to powerful shocks that strongly affect water-saturated sediments, triggering a thixotropic reaction, which leads to liquification of sediments. Deformation then results from the expulsion and or intrusion of fluidized materials (Montenat et al., 2005). Selected references on seismites include Sims (1975), Pope et al. (1997), Jones and Omoto (2000) McLaughlin and Brett (2004), Montenat et al. (2007).

Key features of seismite beds include convolute bedding/laminations; ball and pillow/"thixotropic bowls"/"saucer" structures; mudstone/sandstone volcanoes/diapirs; boudins and brecciated fabrics; inclined blocks; and truncation surfaces (McLaughlin and Brett 2004; Montenat et al., 2005). Sims (1975) discussed criteria for correlating soft sediment deformation structures with seismic events. These include: 1) Proximity to active seismic zones; 2) presence of potentially liquefiable sediments; 3) similarity to structures formed experimentally; 4) structures related to liquefaction; 5) structures restricted to single stratigraphic intervals correlatable over large areas; and 6) absence of slope influence and failure. When interpreting ancient SSDs, criteria number 1 is often difficult to assess; geologists rely more on the other criteria, including their correlatability over large areas.

The SSDs in the Mount Marion and Oneonta formations in the Catskill front (Figure 15) meet many of the criteria for seismites. Their internal structures appear to be related to liquification of the sediments, and they feature structures (e.g., ball & pillows) similar to experimentally-generated forms. Furthermore, they are largely restricted to relatively thin intervals, separated from other occurrences in similar facies, and adjacent under- and overlying beds appear undeformed.

The sedimentary conditions needed to commonly form SSDs in shallow marine and terrestrial facies (e.g., fluid muds below rapidly deposited sands) occur extensively, especially in the upper Mount Marion Formation. However, deformed zones are generally uncommon. As noted by McLaughlin and Brett (2004) this pattern is indicative of a limited frequency of triggering events capable of deforming the strata.

Some SSDs in both marine and terrestrial strata in the area occur within sandstone-only layers (e.g., Figure 15b, f, g; Stops 4 and 7), where the sands did not founder into fluid-rich muds. This would seem to call for a significant triggering event to initiate liquefaction, settling and tighter repacking of the sand grains, along with dewatering. Powerful seismic shocks, generated by along the Acadian deformation front, would provide a likely trigger to deform these sediments.

One key line of evidence for interpreting the Catskill SSDs as seismites, however, is still undocumented. It is unknown whether individual SSDs can be correlated from outcrop to outcrop, across broad areas. And at least in the upper part of the Mount Marion Formation, the author's experience indicates that it may be difficult to establish such correlations, due in part to the homogeneity of facies, an apparent lack of distinctive marker beds, the thickness of the interval, and its limited exposure.

Although the geographic distribution of these soft-sediment deformational units are unknown, others in the Devonian succession of New York have relatively widespread distribution. Sutton and Lewis (1966) report soft-sediment deformation in the Upper Devonian (Frasnian) Point Bluff Siltstone Bed in western New York. They found SSD at all studied localities over a ca. > 775 km^2 area of outcrop of the thin (ca. 12 cm-thick) unit. This is very likely a previously unreported seismite related to Acadian earthquake activity, either in the orogenic belt or along faults active at that time in western New York. In another study, Smith and Jacobi (1998) document soft sediment deformation in Upper Devonian (Famennian) strata of the Canadaway Group, and interpret them to be seismites related to syn-depositional movement along the Clarendon-Linden fault system.

The stratigraphic distribution of the SSDs in the Catskill Front present an additional possible line of support for their interpretation as seismites. The examples from the Mount Marion and lower Oneonta formations occur in strata associated with the early stages of Acadian tectophases, as outlined by Ettensohn (1985). If the tectophase model is viable, these strata should represent times of increased seismic activity, with renewed or at least increased uplift and deformation in the orogenic belt.

In summary, SSDs in the Catskill Front potentially represent seismites, formed in unlithified sediments. If they are seismites, they provide insights into the timing of Acadian seismic activity. More work is needed documenting their character, distribution and, importantly, their correlatability across the region.

SUMMARY

This paper has been an attempt to provide a broad perspective of the Acadian orogeny, based on a synthesis of new and old data from New York's portion of the Acadian foreland basin. Approximately 2.7 km of Upper Silurian and Devonian strata in the Catskill front, deposited through roughly 45 million years (ca. 420 – 375 Ma) provide a key source of data about the timing and character of orogenic and foreland basin evolution, erosional unroofing the orogen, explosive volcanism, and perhaps seismic activity.

Beginning in the Late Silurian, collision of the North American margin and another landmass initiated the Acadian orogeny in the northeastern U.S. Uplift and loading in the orogen led to subsidence and development of an adjacent foreland basin system (wedge-top, foredeep, forebulge and back-bulge basin). A tremendous volume of sediments eroding off the orogen was deposited across the foreland.

Initially, the orogen and foreland basin were largely developed in New England. Through time, both the orogen and foreland migrated cratonward. As a result, initial foreland basin deposits were thrust up and exposed, some of them subjected to low-grade metamorphism, and then eroded and transported via rivers to cratonward.

Following the Taconian orogeny, the area of today's Catskill front was elevated and eroding from the Late Ordovician through much of the Silurian. However, in the Late Silurian, approximately 420 million years ago, the eastern New York high subsided and was submerged. Through deposition of the Rondout Formation and Helderberg Group, eastern New York was positioned in the distal, cratonward margin of the foreland basin system, in a back-bulge basin. Following Helderberg time, the forebulge region of the foreland migrated into and through the Catskill front; however, Oriskany time was an interval of relative quiescence in the mountain belt, and the forebulge was relatively subdued as it moved through the region. With the onset of a new tectonically active phase of the orogeny in later parts of the Early Devonian, the cratonward margin of the basin foredeep migrated into eastern New York, and the first major wedge of synorogenic clastics were deposited (Esopus Shale), followed by a gradational return to carbonate deposition during another period of relative tectonic quiescence (Schoharie to Onondaga formations).

The onset of another tectonically active phase of the Acadian orogeny (ca. 390 Ma) led to subsidence and black shale deposition (lower Hamilton Group, Union Springs Formation), and cratonward migration of the complete foredeep of the foreland basin system into the Catskill Front. Within a few million years, the foredeep became overfilled to above sea level with mud and sand, and the Catskill front became terrestrial. The beginning of a third major tectonically active phase in the orogen is less visible in the Catskill Front, but is recorded in the marine basin at about 385 Ma, with deposition of the black Geneseo Shale.

In New York, we have insufficient data to interpret much of the older history of the Acadian orogen. But beginning in the middle Lower Devonian, we see that three tectonically active to quiescent phases (Tectophases I-III of Ettensohn, 1985) began at about 408, 390, and 385 Ma.

The sediments eroding off the orogen and being shed into the Catskill front through the Middle to Upper Devonian indicate that rocks exposed in the source area were predominantly low grade metamorphic (up to greenschist-grade) and sedimentary rocks. They were most likely derived from older Devonian foreland basin sediments, not Cambrian-Ordovician as proposed in older studies.

The foreland basin record of volcanic airfall tephras appears to indicate that there were peaks of explosive volcanic activity in the Acadian orogen at approximately 417, 408, and 391-390 Ma. Interestingly, these appear to correspond with the beginnings of tectonically active stages in the mountain belt.

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FIELD TRIP ROAD LOG

Mileage	
0.0	Start at Plattekill Parking Lot, on the SW corner of Plattekill Ave. and Manheim Ave. (NE corner of the SUNY-New Paltz campus). Turn right onto Plattekill Ave.
0.0	Immediately, at stop sign, turn left onto Manheim Blvd.
0.2	Turn right at light onto Rtes. 32 & 299
1.0	Get into right lane.
1.1	Turn right at entrance to NY State Thruway.
1.3	Get toll card at booth.
1.4	Fork right for I-87/NYS Thruway Northbound (toward Albany).
5.9-7.3	Outcrops of Martinsburg Formation. Interbedded turbidites and shales.
6.4	Catskills visible ahead.
7.3	Cross over Wallkill River.
9.9	Cross over Rondout Creek. Begin climb up onto Devonian bedrock.
11.1	Lower Devonian Glenerie Formation.
11.8	Lower Devonian New Scotland Formation?
12.5	Lower Devonian, upper part of New Scotland to Becraft formations.
13.0	New Scotland Formation.
13.4	New Scotland to Becraft formations.
14.8-15.6	Lower Devonian Schoharie Formation
15.7	Middle Devonian Onondaga Limestone (Edgecliff Member).
16.0	Onondaga Limestone (Nedrow to Moorehouse members).
16.8	Cross over Esopus Creek.
17.0	Bypass Kingston exit.
17.6-18.3	Middle Devonian Union Springs Formation (Stony Hollow Member).
19.0	Esopus Creek on right.
19.5	Cross under Rte. 209, with a classic set of Lower to Middle Devonian road cuts along it.
19.8	Cross over Sawkill Creek.
19.9	Middle Devonian Mount Marion Formation (East Berne Member).
22.0	Mount Marion ahead on left. Type section of Mount Marion Formation.
22.7	Cross over Plattekill Creek.
23.1	Stony Hollow Member again.
25.3	Mount Marion to left.
26.2	Note large quarry on north flank of Mount Marion. East Berne and Otsego members, Mount Marion Formation.
27.1	Bypass Saugerties exit. Most complete section of Onondaga Limestone in eastern New York, visible along Thruway and northbound entrance; Schoharie Formation visible at far end, right side.
28.5-29.1	Excellent section of Lower Devonian Becraft, Alsen, Port Ewen, and Glenerie formations.
29.8	Schoharie Formation (Aquetuck & Saugerties members).
32.6	Schoharie Formation.
33.2	Extensive limestone quarries in Lower Devonian Helderberg Group beyond ridge to right.
34.6	Becraft Formation (?).
34.5	Schoharie Formation.
35.3	Schoharie Formation +/- uppermost underlying Esopus Formation.
35.5	South end of long exposure along abandoned Thruway exit, ending at Stop 2 of this trip. Strata visible from Thruway include Schoharie and Esopus formations. Complete section of Esopus exposed.
36.2	Onondaga to Schoharie formations.
37.0-37.2	Schoharie exposed on southbound side of Thruway.

36.8 Onondaga Formation.
37.4 Cross over Kaaterskill Creek.
37.6 Schoharie Formation on west side, Onondaga Formation on east side.
38.1 Schoharie Formation.
38.3-39.5 Esopus Formation (mostly Quarry Hill Member, in middle of formation).
39.6 Cross over Catskill Creek.
39.7 Becraft to New Scotland formations.
40.0 Exit NYS Thruway at Catskill. New Scotland Formation along exit ramp.
40.5 Pay toll. New Scotland Formation on left.
40.7 Turn left onto Rte. 23b, toward Catskill.
40.8 New Scotland Formation on left, Kalkberg Formation on right.
41.0 Pull over and park on shoulder. Cross and continue ahead on Rte. 23b, then walk up exit ramp off of Rte. 23 to prominent angular Taconic unconformity.

STOP 1. TACONIC UNCONFORMITY AND HELDERBERG GROUP LIMESTONES, CATSKILL (45 MINUTES). This classic locality has been the subject of many field trips. For this trip, we will visit two road cuts along Rte. 23: a) exit ramp to Leeds/Rte. 23b, off of Rte. 23 westbound; and b) the succession on the north side of Rte. 23 west of Rte. 23b. We will largely focus on various features with implications for Acadian orogenesis, as interpreted from the sedimentary rock record. These include the Taconic unconformity and Manlius-Coeymans contact, carbonate deposition in a back-bulge basin of the foreland basin system, volcanic tephra beds (K-bentonites), and possible Devonian deformation of the "Little Mountains Fold-Thrust Belt" here.

Near the base of the succession, the prominent angular unconformity (Taconic unconformity) places supratidal dolostones and sandstones (Upper Silurian (?) Rondout Formation) over deep water turbidite sandstones and shales (Middle Ordovician Austin Glen Formation). The hiatus represents approximately 30 million years of time, and marks a series of events associated with the Taconian orogeny. This history begins with deep water deposition of synorogenic clastics, overthrusting of the rocks from western Massachusetts into eastern New York, and later uplift of the area due to erosional unroofing and rebound of the Taconian orogen through the latest Ordovician to Late Silurian. The latter resulted in the elevation of eastern New York above sea level throughout most of the Silurian, and restriction of the sea to western +/- central New York during most of the Silurian. Transgression of marine waters over eastern New York in the latest Silurian to earliest Devonian is at least in part due to tectonic-induced subsidence and migration of the foreland basin to the east. This was associated with collision and crustal loading during Late Silurian, with the onset of the Acadian orogeny on the far margin of eastern North America.

The limestones, dolostones and minor shales of the Rondout Formation and Helderberg Group along Rte. 23 here comprise a carbonate ramp succession. They were deposited in the back-bulge basin of the greater Acadian foreland basin, at a time when the orogen and the main body of the foreland basin were still far to the east. The strata examined on this trip (Rondout, Manlius, Coeymans, Kalkberg, New Scotland, and Becraft formations) record an overall deepening- to shallowing up succession through supratidal, tidal, shoal, and shallow to deep ramp facies (Rondout to lower New Scotland fms.), followed by a gradational shallowing up to shoal to tidal facies (middle New Scotland to lower Becraft formations). In sequence stratigraphic terms, the succession comprises comprise a single "third order" depositional sequence, and the lowstand base of a second sequence. In total, the Rondout-Helderberg succession represents two major "third order" sea level cycles/depositional sequences.

The Manlius-Coeymans contact in the Catskill area was interpreted by Chadwick (1944) to represent an erosional hiatus. However, the wider distribution and implications of this break has only been recently documented by Ebert and Matteson (2003). Their detailed work through the two formations has documented at least two significant unconformities, including the formational contact. Noting a subtle but documented angularity to the unconformity, Ebert and Matteson (2003) interpret its formation to be associated with the orogen-ward migration of a bulge-like feature, associated with early stages of the Acadian orogen on the distant margin of North America near the Silurian-Devonian boundary.

Ancient volcanic airfall tephra beds, altered to clay-rich K-bentonites, occur in the Kalkberg and New Scotland formations along Rte. 23. This cluster of approximately 15 beds, termed the Bald Hill K-bentonites, are widely reported across the Appalachian basin, from eastern New York to Virginia and West Virginia. They preserve a record of explosive, plinian-type volcanism in the Acadian orogen. Additional K-bentonites have been noted in the Manlius Formation at other localities (Ebert and Matteson, 2003; P. Rubin, pers. commun. 2007).

The age of deformation of the strata along Rte. 23 is the subject of debate. Some workers (e.g., Marshak, 1986; Marshak and Tabor, 1989; Zadins, 1989) interpreted the folding and faulting to be Devonian, at least in part. In contrast, Geiser and Engelder (1983) interpret the structures to have formed later, during the Late Carboniferous-Permian Alleghanian orogeny. It is possible that both orogenic events led to the deformation. At present, the timing of deformation is unclear.

	At end of Stop 1a, return to cars.
41.3	Proceed ahead on Rte. 23.
41.4	Cross over NYS Thruway.
41.5	Beginning of another classic cut through the "Little Mountains" fold-thrust belt.
41.8	Cross over Catskill Creek. Downstream the creek passes for approximately 1 mile through the gorge of Austin Glen, descending stratigraphically through Lower Devonian to uppermost Silurian strata of the Esopus through Rondout formations, and into the Ordovician Austin Glen Formation. Classic, beautiful site.
41.9	Esopus through basal Onondaga Formations (Stop 1B of Ver Straeten and Brett, 1995).
42.4	Turn left at light, onto Cauterskill Road.
43.7	Cross over NYS Thruway.
43.8	Schoharie Formation.
44.1	Onondaga Formation.
45.0	Cross over Kaaterskill Creek. Ordovician Austin Glen Formation exposed in creek bed to left.
45.05	Turn right at stop sign, continuing on Cauterskill Road. Kaaterskill Creek will follow road for some distance.
46.1-.6	Onondaga Limestone. Section between 46.5-.6 exposes Edgecliff, Nedrow and lower Moorehouse members.
46.9	Fork left onto Rte. 23a.
47.1	Park along shoulder, and walk ahead to prominent outcrop.

STOP 2. LOWER DEVONIAN RAMP CARBONATES AND THE INITIAL ACADIAN CLASTIC WEDGE, THE SPROUT BROOK K-BENTONITES, AND THE WALLBRIDGE UNCONFORMITY (45 MINUTES). This is another classic Devonian locality, chiefly noted for its prominent structural folds. However, several additional characters of the outcrop provide a record Acadian Lower Devonian activity in the Acadian mountain belt. These include the Wallbridge unconformity; a carbonate-quartz arenite suite of rocks succeeded by the first major influx of Acadian synorogenic sediments; migration of the foreland basin foredeep into the Catskill Front; and a second major cluster of altered volcanic tephra beds. The Glenerie-Esopus contact at this outcrop lies approximately 90 m stratigraphically above the Taconic unconformity, seen at Stop 1.

The units visible at Stop 2, from low to high include the top of the Port Ewen Formation, the Wallbridge unconformity, local chert facies of the Glenerie, and a rare, complete section of the overlying Esopus Formation. At the far end of the outcrop, along the NYS Thruway, lower strata of the Schoharie Formation are visible.

The top of the Port Ewen Formation, a shaly limestone analogous to the New Scotland formation, directly underlies the Wallbridge unconformity here. The Wallbridge, which marks one of the major Phanerozoic sea level lowstands in North America (Sloss, 1963), is of relatively short duration in the Hudson Valley. Deposition across the interval is continuous in the Port Jervis area, where New York, New Jersey, and Pennsylvania meet.

Immediately overlying the Wallbridge unconformity is a conglomeratic lag bed at the base of the Glenerie Formation. The conglomerate in the area of Catskill is largely composed of phosphatic pebbles with scattered milky quartz. To the south, beginning near Kingston, a conglomerate unit of milky quartz wedges in below the Glenerie. This unit, termed the Connelly Conglomerate, is the oldest conglomerate found in the New York Devonian (Table 2). Its quartz composition (>99% milky quartz) contrasts with younger pebbly to conglomeratic strata in the Catskill front, which feature a more diverse composition (Table 2). The conglomeratic base of the Glenerie locally near Catskill is dominated by chert; to the south, it transitions into silica-rich limestones, and to the north to the quartz sand-rich Oriskany Sandstone.

Glenerie-Esopus contact is relatively gradational at Stop 2 and in the eastern New York region. Elsewhere across the central to southern part of the basin, the contact is generally more sharp (Ver Straeten, 2007a). It marks a time of foundering of widespread shallow marine ramp conditions, and progressive subsidence and migration of the foreland basin foredeep into eastern New York, during the onset of the first Acadian Tectophase recognized by Ettensohn (1985). In reality, at least one previous tectonically active to quiescent "tectophase" likely occurred during the Late Silurian to Early Devonian parts of the Acadian orogeny.

The mudstones, shales, siltstones and sandstones of the Esopus Formation mark the first significant influx of Acadian synorogenic clastics into the Catskill Front and the Appalachian basin. Migration of the orogenic front across New England has by the Emsian Stage moved far enough cratonward for the foredeep segment of the foreland basin system to migrate west of the present day Hudson River. Petrologic data from Rehmer (1976) indicates that fine sandstones to siltstones of the Esopus are rich in quartz (~33-55%), with a high concentration of matrix (~19-49%), and minor amounts of fragmentary mica and chlorite, detrital and diagenetic chert, and pyrite.

Detailed work by the author on Emsian-age (upper Lower Devonian) strata of the Esopus and Schoharie formations and equivalent strata across the Appalachian basin (Ver Straeten, 2007a), along with geochronologic age dating (Tucker et al., 1998; Kaufmann, 2006), outline a longer, more complex history to the Emsian stage in the eastern U.S. than has been appreciated . U-Pb dating indicates a duration on the order of 15-18 million years for the Emsian (Tucker et al., 1998; Kaufmann, 2006), and that it's global sea level history comprises five major third order cycles (Ver Straeten, in press), not one as previously interpreted by Johnson et al. (1985).

To the author, one of the key stories linking the foreland and orogenic belt is tied a series of thin, tan-colored clay beds in the lower part of the Esopus Formation here (Spawn Hollow Member). These are the Sprout Brook K-bentonites, 15 altered volcanic tephras dated at 408.1 +/- 1.5 Ma (Tucker et al., 1998). In contrast with other Devonian clusters of K-bentonites in the Appalachian basin, these are geographically restricted to eastern New York (Ver Straeten, 2004a, b). The age of the Sprout Brook K-bentonites cluster overlaps with dates of numerous volcanic and plutonic rocks in the northern Appalachians, predominantly in Maine (e.g., Bradley et al., 2000; and additional references in main body of this paper). This includes the Katahdin Granite and co-magmatic Traveler Rhyolite of central Maine; the Traveler alone, from only one of many volcanic centers of lower Emsian age, is conservatively estimated to have a volume on the order of the largest Cenozoic-age tuffs in the western U.S. (Rankin and Hon, 1987; Ver Straeten, 2004b). It is plausible that explosive, plinian-type volcanoes in northern New England were the source of the tephra deposited in eastern New York.

As at Stop 1, the age of deformation of the strata here is unknown. An interesting point here is the relationship of deformation to the Sprout Brook K-bentonites. The soft, unlithified clay beds form a sharp rheological contrast with their interbedded thin chert and shale beds. Slippage largely appears to follow the clay beds, which in places appear to have been squeezed through the folds ("like toothpaste"). This is well seen in the uppermost K-bentonite, which varies in thickness from zero to over 1.5 meters along the outcrop over the central anticline. The K-bentonites probably helped concentrate deformation along this zone in the Catskill Front and into the subsurface, the position of a major decollement in the Catskill Front/Little Mountains fold-thrust belt according to Marshak (1986).

	At end of Stop 2, return to cars.
47.1	To continue, pull ahead and turn around near base of outcrop. Proceed west on Rte. 23a.
47.3	Pass Cauterskill Road.
47.4	Cross over NYS Thruway. Prominent exposures of Lower Devonian Schoharie Formation.
47.6	Pass Old Kings Highway on left. Topmost Schoharie and Edgecliff Member of Middle Devonian Onondaga Limestone exposed along beginning of Road (Stop 3B of Ver Straeten and Brett, 1995).

47.65 PARKING OPTION 1 FOR STOP 3: Pull onto shoulder and park. *If you wish to use option 2 for parking, proceed ahead on Rte. 23.* Folded Nedrow and Moorehouse members (Onondaga Limestone) exposed on left. To proceed from here to Stop 3, carefully walk 0.3 miles ahead to east (proximal) side of bridge over Kaaterskill Creek. Walk down steep slope on south (left) side of bridge to exposure along creek.

47.95 Cross over Kaaterskill Creek. Drive across valley of easily eroded Bakoven Member black shales.

48.45 Turn around at intersection of Rte. 23 and Underhill Rd. Then return east on Rte. 23

48.6 PARKING OPTION 2 FOR STOP 3: Pull onto shoulder and park in grassy area. To proceed from here to Stop 3, carefully walk 0.3 miles ahead to the far side of bridge over Kaaterskill Creek. Walk down steep slope on south (left) side of bridge to exposure along creek.

STOP 3. MIDDLE DEVONIAN RAMP CARBONATES AND THE SECOND ACADIAN CLASTIC WEDGE, AND TEPHRAS (30 MINUTES). Note: No hammers or collecting from the Onondaga-Bakoven contact – it is a rare exposure. The creek exposure is on private property - ask permission for access.

Strata exposed at Stop 3 include the uppermost limestones of the Middle Devonian Onondaga Formation and overlying black shales of the Bakoven Member of the Union Springs Formation (lower part of the Marcellus subgroup of Ver Straeten and Brett, 2006). At least one K-bentonite of the Tioga A-G K-bentonite cluster is exposed here. The first part of the outcrop is along Kings Highway and Rte. 23a, where the lower to middle Onondaga Formation is exposed (Edgecliff, Nedrow and Moorehouse members). Walk westward down the hill to the south side of the bridge over Kaaterskill Creek, where the top Onondaga (Seneca Member?) and lower Bakoven Shale are exposed along the creek. This outcrop lies approximately 270 m stratigraphically above the Taconic unconformity, seen at Stop 1.

Above the Esopus Formation at the previous stop, the Schoharie Formation is transitional from extrabasinal clastics to intrabasinal carbonates. This shift culminates in deposition of the Middle Devonian Onondaga Limestone. Onondaga-equivalent carbonate-rich facies occur widely across eastern North America; they mark a shutdown of clastic sedimentation in the northern Appalachian basin, although to the south in deeper parts of the basin (PA through VA-WV), the interval marks more of a decline in % clastic content, and deposition of mixed carbonate-clastic facies.

Base of Onondaga is a lowstand of sea level. In the Schunnemunk outlier north of NYC, and in the area of Palmerton, eastern PA, lower Onondaga +/- upper Schoharie strata are represented by shallow marine quartz sandstones conglomerates. Exclusively quartz pebbles also occur scattered through strata at two positions within the Schoharie Formation. Furthermore, rare quartz pebbles have also been found in the same position in the Moorehouse Member and equivalent strata in central New York and central Pennsylvania. Curiously, widespread occurrence of quartz-rich strata are a contrast with the synorogenic sediments of the Esopus Shale below. Conditions that permitted progradation of Esopus extrabasinal clastics no longer existed.

Here at Stop 3 we stand at a major depositional shift, where relatively shallow marine carbonates are succeeded by basinal organic-rich black shales (by some estimates representative of ca. 100-200 m depth). A prominent bone-rich phosphatic lag interval at the formational contact marks a period of sediment starvation across the transition. A similar lag bed occurs along the Onondaga-Bakoven contact into western New York, overlying progressively younger uppermost Onondaga strata in that direction. The top of the Onondaga progressively youngs to the west, indicated but by the progressive upward appearance of the Tioga B, B', C, D, E, and F K-bentonites with the thickening of upper Onondaga (Seneca Member) strata to the west. This younging is associated with earlier foundering and subsidence of the foredeep of the foreland basin in eastern New York; subsequently, the shallow Onondaga ramp progressively subsided to the west, due to loading and uplift during the onset of Acadian Tectophase II of Ettensohn (1985).

The Onondaga to lower Union Springs Formation and equivalent strata across eastern North America are well known for the occurrence of the Tioga K-bentonites. Actually, the so-called "Tioga" interval comprises two major clusters of volcanic tephras (Ver Straeten, 2004a, 2007a). In the northern and central part of the Appalachian basin, an upper cluster of eight beds (Tioga A-G K-bentonites) occurs widely in upper Onondaga and Union Springs-equivalent strata. A lower cluster of up to 32 beds, previously correlated with the Tioga A-G K-bentonites, is found only in middle Onondaga-equivalent strata in the southern part of the Appalachian basin (Virginia and West Virginia; Ver Straeten, 2004a, 2007a). The lower cluster has been dated at 391.4+/-1.8 Ma (Tucker et al., 1998), the upper one at 390+/- 0.5 Ma (Roden et al., 1990). They appear to be sourced from volcanic centers in northern Virginia and southeast of the Stroudsburg, PA area, respectively (Dennison and Textoris, 1970, 1978; Ver Straeten, 2004a). At Stop 3, some of the long bedding planes exposed along Rte. 23a may represent thin K-bentonites. Along the creek exposure, a thin centimeter-thick clay bed 35 cm below the contact is a K-bentonite. Another thicker bed, possibly the widely known Tioga B K-bentonite bed from the base of the Seneca Member in New York, is covered just above the base of a small gully closer to the bridge.

At end of Stop 3, return to cars. *If you used the first option for parking, follow directions to Underhill Rd., turn around and follow directions from 48.6 miles.*

48.6 Proceed ahead, eastward, on Rte. 23a.
49.4 Cross over NYS Thruway again.
49.5 Fork left onto Cauterskill Road, then immediately turn left again at stop sign.
50.1 Kaaterskill creek visible along road again, on left.
51.4 Turn left at bridge, and remain on Cauterskill Road.
52.6 Cross over NYS Thruway.
53.5 Pass Vedder Mountain Road on left
53.55 Turn left onto Vedder Road.
54.4 Exposures of upper part of the Mount Marion Formation on left.
54.6 Pull onto shoulder of Vedder Road and park.

STOP 4. NEARSHORE MARINE CLASTICS, UPPER MOUNT MARION FM. (30 MINUTES). This stop examines shallow marine clastics (upper part, Middle Devonian Mount Marion Fm.), not far below the transition into terrestrial strata (Ashokan Fm. and higher strata). Exposed along Rte. 23 are approximately 12.3 m of sandstone-dominated strata. Well defined hummocky cross beds, indicative of storm processes low in the outcrop are replaced above by mega-ripples (dunes), suggesting an overall shallowing up succession. Intraformational conglomerates and soft sediment deformation zones are also visible in the upper part of the outcrop. The strata at Stop 4 are approximately 750 m stratigraphically above the Taconic unconformity at Stop 1.

Two sandstone beds with reworked, intraformational pebbles and brachiopods are visible in the upper part of the outcrop. Along Catskill Creek, approximately 0.8 km to the north-northwest, a conglomerate with abundant macrocrystalline milky quartz and chert, with lesser numbers of sandstone and other clasts, was reported by Wolff (1967) and exposed in the late 1980s. It is presently covered in the creek bed. The author has noted multiple thin, sometimes lensing conglomerate beds in the upper Mount Marion Formation along and in the forest off of Rtes. 28 and 28a northwest of Kingston. They also mark the progradation of gravels into the Catskill Front at approximately 388 Ma, possibly concentrated into beds during the lowstand or basal transgressions of small scale (fifth to sixth order) cycles (e.g., Bergman and Walker, 1987; Smith and Jacobi, 1998).

Compositionally (Table 2), these conglomerates contrast sharply with the only white quartz pebble compositions of conglomerates and scattered pebbles in older strata (Connelly Formation; Schoharie Formation; Kanouse, Palmerton and Onondaga/upper Needmore formations) in New York and Pennsylvania. The relatively high concentration of various-colored cherts in the conglomerates also contrast with relatively chert poor compositions of overlying conglomerates in the Devonian succession. This indicates a relatively significant source of chert in rocks exposed in the Acadian orogen at this time. The upper Mount Marion conglomerates

Smith's (1970) petrographic studies of upper Mount Marion sandstones in the Catskill front found that the sands were composed of a mix of mono- and polycrystalline quartz, chert, metamorphic and sedimentary rock fragments with less abundant chlorite, other micas, and plagioclase feldspars. His reported average compositions for the upper Mount Marion strata ("Solsville" and overlying "Pecksport" equivalents, 5 and 8 samples, respectively) are: Quartz + chert = 50.0 & 37.4%; matrix = 9.1 & 13.2%; rock fragments = 37.6 & 41.1%; and carbonate = 1.6 & 8.3%. The presence of slate and phyllite fragments, along with recycled sandstone and limestone grains indicated erosion of low grade metamorphic and sedimentary rocks in the Acadian orogen by approximately 388 Ma.

On the south side of the outcrop, along Vedder Road, two zones of soft sediment deformation can be seen in the upper part of the outcrops (Figure 15b). These potentially represent "seismite" beds, formed when severe seismic shocks from the Acadian orogen triggered liquification of the loosely packed sands, and their subsequent, more condensed repacking, and expulsion of excess water.

The first outcrop west of Five Mile Woods Road, on the south side of Rte. 23, exposes roughly five meters of interbedded sandstone and dark gray mudstones. Two sandstone bodies (ca. 1.5 and 3 m-thick) are not notably cross-bedded or erosively based; small delicate traces in the intervening mudstones may represent small plant root traces. The outcrop may be the lowest terrestrial deposits exposed along Rte. 23. If so, it could represent a thin tongue of terrestrial facies within the upper Mount Marion Formation, as seen near Kingston (Stop 8 of Ver Straeten and Brett, 1995), or deposits low in the overlying Ashokan Formation.

Strata from the lowest redbeds to the top of Slide Mountain, the highest peak of the Catskills, comprise approximately 1.9 km thickness of Middle to Upper Devonian strata (lower Givetian to upper Frasnian stages, Rickard, 1975). They were almost exclusively deposited in fluvial-dominated, terrestrial environments. These strata will be seen at subsequent Stops 5-7, and in road cuts along the route.

	At end of Stop 4, return to cars.
54.6	Proceed ahead on Vedder Road.
54.65	Turn right onto Five Mile Woods Road, then turn left onto Rte. 23 (westbound).
55.0	Interbedded sandstones and shales on south side of Rte. 23.
56.2	Lowest exposure of terrestrial "redbeds" of Plattekill Formation along Rte. 23. Lower red and green mudrocks (including paleosols) deposited on floodplain, overlain further along road by channel sandstones. Outcrops for next ~10 miles (to ~66.1 miles) are in the Plattekill Formation.
57.8	Intersections with Silver Spur Road. Good exposure of Plattekill Formation along Silver Spur Road to left.
59.2	Intersection with Rte. 32, which joins Rte. 23 here for a short distance. **For a "pit stop" at McDonalds, turn left onto Rte. 32 south, and then right into parking lot.**
60.0	Very good exposures of Plattekill Formation. Pull onto shoulder and park for optional stop.

(OPTIONAL) STOP 5. MIDDLE DEVONIAN FLUVIAL CHANNEL AND FLOODPLAIN DEPOSITS (30 MINUTES). This outcrop of the Middle Devonian Plattekill Formation exposes typical terrestrial facies of the Catskill delta complex, as developed in the Catskill front. The strata at Stop 5 are roughly a little less than one kilometer stratigraphically above the Taconic unconformity (Stop 1).

Along the outcrop (ca. 11.6 m-thick), two channel sandstone bodies and two sandy to muddy floodplain deposits, including ancient soils (paleosols) are visible. Fining up pairs of channel sandstones to floodplain deposits in the Catskills are interpreted to represent thousands to tens of thousands of years (Bridge, 2000).

The lower "mudrock" unit (ca. 2.0 m-thick) is characterized by dark gray to gray shales that grade upward into interbedded thin sandstones and green mudstones. The upper 40 cm have a blocky texture and feature small-scale slickensided surfaces (pedogenic slickensides), associated with soil development.

Lower strata of the overlying sandstone body (ca. 4.2 m-thick) grade laterally between gray sandstones, dark gray shaly sandstones, and intraformational conglomerates, of which at least one is dominated by calcareous nodules, eroded and reworked from erosion of paleosols upstream, Cross-bedded sandstones above feature more than one channel (multi-storied) up through the succession.

The top of the channel is marked by a 0.7 m-thick interval of more tabular sandstone beds, which grade upward into ca. 1.2 m of red mudrock-dominated strata, deposited across a floodplain after migration of the channel. Centimeter-scale vertical traces, often green in color represent root traces of *Eospermatopteris*-type cladoxylopsid trees, similar to the famous tree stumps found near Gilboa, higher in the Catskills. In places, the roots have extensively bioturbated the sediments. In addition, the upper 40-60 centimeters feature multiple "dish/gilgai/pseudoanticline" soil deformation structures, and pedogenic slickensides occur through the strata. These features form by wetting and drying of expandable smectite (montmorillonite) clay rich, fine-grained sediments, and indicate the development of vertic paleosols.

The upper unit (ca. 3.5 m exposed) is another multi-storied channel sandstone body. Mudrock lenses occur locally along the outcrop, and prominent, down-cutting erosional surfaces are overlain by additional channel deposits. The sandstone bodies are interpreted to be deposited in single channel, sinuous ("meandering") rivers, which migrated across vegetated alluvial plains (Bridge, 2000).

Sandstone petrologic studies by Gale (1985) through the Plattekill to Slide Mountain formations in the Catskills found that composition of the sandstones is relatively consistent. Mono- and polycrystalline quartz, foliated metamorphic rock fragments and sedimentary rock fragments comprise 80% or more of the sandstones (Gale, 1985). Low in the succession (e.g., Plattekill Formation), sandstones contain a greater percentage of foliated metamorphic rock fragments and a correlative lower concentration of quartz. The sandstones are relatively clay poor, and are best defined as lithic to sub-lithic arenites (Gale, 1985). Overall, the sand-size fraction increases in grain-size upward through the succession, as environments change from lowland to transitional lowland-upland alluvial plain environments.

Plattekill Formation sandstones analyzed by Gale (1985; 10 samples) feature concentrations of foliated metamorphic rock fragments between 19-47%, in sharp contrast with the Slide Mountain Formation (3-17%; 5 samples); total macrocrystalline quartz (mono- + polycrystalline) in the Plattekill comprises 25-50 % of the rock, compared with 47-62% in the Slide Mountain Formation. In addition to quartz, metamorphic rock fragments and sedimentary rock fragments (10-23%), lesser amounts of chert (0.4-3.6%), plagioclase and orthoclase feldspars (0.2-1.9%), along with chlorite and micas, illite and kaolinite are found in Plattekill Formation sandstones (Gale, 1985).

Analysis of the clay minerals in the Catskill succession, and marine strata beyond, indicate a dominance of illite with lesser amounts of chlorite and minor kaolinite (e.g., Friend, 1966; Hosterman and Whitlow, 1983). However, vertic paleosols, as relatively well developed in the upper floodplain deposit, form in smectite-rich sediments. These clays, which swell and shrink with wetting and drying, are derived from igneous sources. The abundance of vertic paleosols in the Catskill succession appear to represent an otherwise hidden component of sediments derived from igneous sources. The sources could be derived from weathering of plutonic or volcanic rocks in the source area, or from volcanic ash erupted from explosive volcanic eruption in the Acadian orogenic belt.

At this time, only intraformational conglomerates/breccias are known by the author in the Plattekill Formation (Figure 9d). The clasts in these beds consist of reworked calcareous nodules ("peds") reworked from paleosols, or chips of mud. They commonly occur in the base of channel sandstone deposits.

	At end of Stop 5, return to cars.
60.0	Proceed ahead on Rte. 23.
60.3	Continue straight ahead. Rte. 32 turns to right (North). More excellent exposures of Plattekill Formation are visible along Catskill Creek, 1.4 miles north. Outcrops include well exposed bedding plane and cross-sectional exposures of fluvial channel sandstones and floodplain mudstones. Also found (some distance upstream of abandoned dam) is a ~1.5 m-thick interval of carbonate-rich facies, capped by a thin (ca. 20 cm-thick) limestone bed indicative of lacustrine facies in floodplain environments. NOTE: Exposures along the creek are on private property. And pay attention to extensive No Parking signs along Rte. 32 near Catskill Creek.
60.6	Get into left lane.
60.85	Stop sign at intersection with Rte. 145. Proceed ahead.
61.0	Exposures of Plattekill Formation along Rte. 23.
61.5	Peaks of Acra Point, Burnt Knob, and beyond, Windham High Peak (3524') visible in distance.
66.1	Cairo-Durham town line. Approximate position of Plattekill-Manorkill ("Moscow") formational boundary, according to Fisher et al., (1970).

66.9 Good exposures of Manorkill Formation along south side of road, near interesting and unusual buildings. Additional exposures of the Manorkill along highway ahead.

68.0 Fork right into large parking area. Pull ahead and park.

LUNCH STOP (20 MINUTES).

STOP 6. FLOODPLAIN AND CHANNEL SANDSTONE DEPOSITS, EAST WINDHAM (45 MINUTES). Over 60 m of mudrocks, sandstones and a thin limestone bed in the Manorkill Formation at Stop 6 represent deposition in floodplain, fluvial channel, and lacustrine environments on the subaerial delta plain of the Catskill delta complex. It is possible that a part of the section may represent some brackish water conditions however. This outcrop is roughly 1.25 km stratigraphically above the Taconic unconformity at Stop 1.

Low in the part of the outcrop facing the parking area, another red paleosol zone with green, cm-scale diameter root traces of cladoxylopsid trees is visible, more easily seen than those at the last stop. Additional paleosols along the outcrop show varying development (Mintz et al., 2006). Along the outcrop, floodplain deposits vary between red, green, yellow-tan and dark gray/black mudstones and lesser fine-grained sandstones. Several sandstone bodies occur along the outcrop also, though few are thicker than 1-2 m.

Around the bend and uphill from the parking area, a prominent sloping-to-the-right interval of yellowish-green strata is succeeded by a zone of thin sandstones and dark gray mudrocks, at a distinctly different angle to the underlying beds. A number of isolated soft sediment deformation pillows occur along the outcrop within the lower approximately 1-3 m of the upper unit.

Higher in the section, downhill from the first driveway uphill of the bend, a prominent, thin ledge of limestone sticks out from the outcrop. Fallen slabs of the bed can be seen in the talus. Light gray to brown-gray, varyingly smooth to knobby in appearance, the fauna noted in the bed consists of ostracodes. Mintz et al. (2006) state that the bed appears to have been pedogenically modified and brecciated. It is over and underlain by red to green paleosols.

Apparent lacustrine (lake) and palustrine (wetland) facies, including similar thin limestones, are not often discussed but not unknown in Upper Devonian Catskill magnafacies (DeMicco et al., 1987; Dunagan and Driese, 1999). Similar limestones are documented from Devonian terrestrial facies in Canada, Great Britain and Australia (e.g., Donovan, 1975). They are generally interpreted to have formed toward the center of ponds and lakes, beyond the transport of fine-grained clastics. Carbonate is derived from calcareous, photosynthetic algae (e.g., charophytes). The author has found multiple apparent freshwater limestones in the Plattekill and Manorkill formations along the Catskill Front. Lacustrine and palustrine/wetland environments comprise an interesting and relatively overlooked facies in the Catskill Front, which deserves more attention.

A short distance above the limestone, along the lower part of a driveway, an interval of olive-colored, mudrock-dominated strata above the limestone, best seen along the lowest part of a driveway, features common fish bone material, ostracodes and desiccation cracks. Also found in the interval are *Spirophyton* trace fossils, which have been interpreted by some to have lived in freshwater setting (Bridge and Gordon, 1985; DeMicco et al., 1987), but by others (Gordon, 1988; Miller, 1991) to indicate brackish water conditions. Miller (1991) proposed that the animals producing *Spirophyton* lived in ephemeral ponds on the coastal floodplain, with fluctuating fresh- to brackish water salinities, perhaps tied to floods of brackish water that flowed upstream and spread across floodplains during major storms.

As in other fluvial-dominated strata of the Catskills, Manorkill Formation sandstones analyzed by Gale (1985; 3 samples) feature common mono- and polycrystalline quartz (29.6-60.0%), and foliated metamorphic and sedimentary rock fragments (30.4-41.8% and 9.3 to 22.0%, respectively). lesser amounts of chert (0.2-0.7%), plagioclase and orthoclase feldspars (1.6-4.3%), along with chlorite and micas, illite and kaolinite are found in Manorkill sandstones (Gale, 1985). This represents a subtle shift toward increased quartz content from the underlying Plattekill Formation. With the exception of a single bed at or near the base of the Manorkill Formation, conglomerates known to the author at this point are intrabasinal ones, with reworked mud or pedogenic carbonate nodules.

At end of Stop 6, return to cars.

68.0	Drive ahead to exit from parking area. Then, TURN LEFT, and return back downhill on Rte. 23 toward Cairo.
69.1	Peak of Burnt Knob and/or Acra Point ahead.
75.4	Intersection with Rte. 145.
75.9	Intersection with Rte. 32, which joins Rte. 23 for 1.1 miles. Village of Cairo on right.
77.0	Turn right, and follow Rte. 32 south.
77.25	Stop light, village of Cairo on right.
79.0	Channel sandstones of Plattekill Formation. All exposures along Rte. 32 ahead are in the Plattekill Formation.
82.4	Area between here and turn at Rte. 23a are called the Kiskatom Flats, which we'll see from above at Stop 7.
84.8	Turn right onto Rte. 23a, toward Palenville and Kaaterskill Clove.
85. 7	Note rise of the highway, ascending up alluvial fan out front of Kaaterskill Clove.
87.1	Stop light in Palenville.
87.6	Enter Kaaterskill Clove.
88.0	Lower bridge in Kaaterskill Clove. Cross over Kaaterskill Creek. Excellent exposures of Plattekill Formation upstream, including channel sandstones, floodplain deposits, and at least one more apparent freshwater limestone.
88.3	Area of "High Rocks" of Chadwick (1944, Fig. 47).
89.0	Middle bridge in Kaaterskill Clove. Excellent exposures of red mudstone/paleosol facies of Manorkill Formation at and above bridge.
90.5	Upper bridge in Kaaterskill Clove. Excellent exposures of Oneonta Formation upstream, along trail to base of Kaaterskill Falls.
90.7	Parking area for trail to Kaaterskill Falls.
90.8	Classic exposures of Oneonta Formation along road, with well developed paleosols.
91.4	Twilight Park entrance on right, near village of Haines Falls.
91.6	Top of Kaaterskill Clove
92.1	Turn right onto North Lake Road.
93.9	Bypass road to Kaaterskill Falls to right.
94.4	Entrance to North-South Lake Campground, in Catskill Park. Drive ahead to booth and pay entrance fee ($8/car at time of field trip). Proceed forward to parking area for North Lake. At stop sign ahead, continue ahead to North Lake.
96.1	Parking area for North Lake and trails along the Catskill Escarpment.

REST STOP: Restrooms on the east side of the parking area at North Lake.

Stop 7. UPPER DEVONIAN CLASTICS, NORTH-SOUTH LAKE (1.5 HOURS). Note: No hammers or collecting at this stop (a Catskill Park campground, run by NYS-DEC).

At this stop, we will walk north along the Catskill escarpment to Artists Rock and Sunset Rock. The rocks exposed comprise lower strata of the Upper Devonian Oneonta Formation, and will include the Twilight Park Conglomerate Member (at Sunset Rock). The latter outcrop is approximately 1.5 km stratigraphically above the Taconic unconformity at Stop 1. Another ~1.2 km of strata overlie the Twilight Park Conglomerate, to the top of Slide Mountain, the highest peak in the Catskills.

The Escarpment trail going north from the parking area at North Lake slowly rises upward through a major sandstone ledge that caps the Catskill escarpment here. Termed the "Kaaterskill Sandstones" by Chadwick (1944), they form the lower part of the Upper Devonian Oneonta Formation. Sandstones dominate the strata along the trail to Artists Rock. An abandoned trail a short distance beyond Artists Rock exposes red mudstones that lie between major sandstone packages.

Partway along the trail to Artists Rock, shortly after a several-meter rise up through the lower Oneonta sandstones, an odd set of sedimentary structures occur in the sandstones in the trail. At first glance, they appear to be trough cross beds. On closer observation, however, the edges of the troughs are vertical to near vertical, well beyond the angle of repose. The vertical edges are water-escape structures, along the margins of foundered bowls of sandstone. This represents another soft sediment deformation zone, developed in sand-only facies (as found at Stop 4). The author has not examined their correlatability, although previous workers have noted disturbed soft sediments elsewhere in the area, in the lower part of the Oneonta Formation. If the feature is relatively widespread, it could possibly represent a "seismite", triggered by a significant seismic shock during the Acadian orogeny. Without more evidence (e.g., correlatability across a broad area), this is only conjecture.

Mono- and polycrystalline quartz comprise approximately 37.9-59.1 % of the rock in petrographically analyzed sandstones of the Oneonta Formation (Gale, 1985). The concentration of foliated metamorphic and sedimentary rock fragments (15.7-33.4% and 8.7 to 21.1%, respectively) have decreased relative to underlying strata, while the concentration of quartz has increased. The concentration of other components (e.g., chert, feldspars, chlorite and micas, etc.) remain about the same as in the underlying Manorkill and Plattekill formations.

There is a rise of approximately 530 m (1750') from the Kiskatom Flats below. In the distance to the east, the Taconic Mountains are visible along the New York-Massachusetts border; high peaks of the Berkshire Mountains (including Mount Greylock) locally project above the Taconics. Farther to the north/left, the Green Mountains are visible in Vermont. These highlands today expose low grade metamorphic rocks (e.g., slates and phyllites in the Taconics; some schist in the higher Berkshires and Greens). However, those rocks would have been deeply buried under younger rocks during the Devonian Acadian orogeny.

At Sunset Rock, up the trail beyond Artists Rock, a 23 m-thick outcrop of the Twilight Park Conglomerate (member of the Oneonta Formation) is very well exposed. The unit marks the first major progradation of clastics into the Catskill front from the Acadian orogen. Bridge and Nickelsen (1985) hypothesized that the progradation was due to increased slope due to tectonic changes, stating that climate did not appear to vary through the interval. In this case, a base-level drop associated with a significant sea level fall was not discussed. Bridge and students generally dismiss eustatic sea level controls over processes active in the terrestrial settings of the Catskill magnafacies. However, Devonian workers (e.g., House and Kirchgasser, 1993; Brett and Baird, 1996; Bartholomew, 2006; Ver Straeten, 2007a, in press) have now established significant eustatic control over sea level changes in New York's marine succession. And that tectonic patterns of flexure are superposed over the record of third order sea level cycles/stratigraphic sequences (Figure 8).

The author proposes a counter hypothesis, that Twilight Park gravels may have prograded basinward during one of the major sea level falls near the Middle-Upper Devonian boundary. As there is no tight control over where the Middle-Upper Devonian boundary actually occurs in the Catskill front, that sea level drop could be one of a few near the boundary.

Petrologically, clastic rocks of the Catskill front indicate that rocks exposed in the Acadian orogen consisted of dominantly low grade (up to greenschist) metamorphic and sedimentary rocks. Rare igneous- or high grade metamorphic-derived sediments indicate only very minor exposure of such rocks. A hidden source of more igneous than previously thought seems to be indicated by common vertic paleosols, which form in smectite clay-rich sediments (smectite clays are derived from the weathering of igneous rocks, including volcanic ash).

A number of previous authors hypothesized that Cambrian and Ordovician rocks in the Taconics region were the source of the Devonian Catskill delta sediments. However, beginning in the Late Silurian, the Acadian orogen and the associated foreland basin developed on the far margin of eastern North America. Through the Lower Devonian, massive volumes of Acadian-derived sediments were deposited in the foredeep basin in New England, while the Hudson Valley was positioned in the back bulge basin to cratonward edge of the foredeep of the foreland basin system. As the orogen progressively migrated cratonward toward eastern New York, Devonian sediments in that early Acadian foredeep basin (e.g., Littleton Formation of New England) were caught up in the deformational front of the orogen (e.g., wedge-top of the foreland basin system). Some of the Lower Devonian foredeep sediments were metamorphosed; metamorphosed or not, the foreland basin strata were thrust up, eroded and transported into the Catskill front. The clastic wedge, of which 2.7 kilometers thickness is preserved in the Catskills, by the latest Devonian apparently distributed muds as far west as northern Iowa (B. Witzke, pers. commun., 1999). Possibly by the Late Devonian, folding and thrusting of the foreland basin wedge-top may have migrated west of the Hudson River.

	At end of Stop 7, return to cars.
96.1	Return to Rte. 23a in Haines Falls.
100.2	Intersection with Rte. 23a in Haines Falls. Turn left, unless driving west through the Catskills to get home.
105.1	Stop light in Palenville. To proceed to the NYS Thruway southbound at Saugerties, fork right onto Rte. 32a, then Rte. 32 south. To proceed to the NYS Thruway northbound at Catskill, fork left and remain on Rte. 23a to Rte 9W, then Rte. 23 west, and then Rte. 23b to the Thruway entrance.

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