Silicic Appalachian Magmatism During the Ordovician and Devonian: Perspectives from the Foreland Basin, and the Hinterland

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INTRODUCTION

At times, viscous, silica-rich molten rock in the upper portion of a magma chamber is forced upward and out of the chamber, through conduits to the surface, where volcaniclastic materials are explosively erupted through the mouth of a volcano and high into the atmosphere. Once buoyantly aloft, the extruded pumice, ash, crystals and rock fragments become sediments, and settle out close to far from the volcano, blanketing any and all environments downwind. These airborne volcanic sediments may sometimes be transported thousands of kilometers from the source volcano by wind.

The history of explosive silicic magmatism on Earth is recorded in the plutonic and volcanic igneous rocks of their source areas, in volcanic and magmatic arcs; and in sediments, modern and ancient, downwind of their eruptive centers. Reconstruction of the history of silicic paleovolcanism, especially when the igneous source areas have been deeply eroded over deep geologic time (e.g., the Appalachian mountains), may be best determined through data from both hinterland (orogenic belt) igneous and foreland sedimentary rocks.

The purpose of this article and fieldtrip is, perhaps for the first time, to bring together a diverse team of geologists and their perspectives on regional silica-rich magmatic activity during the Ordovician and Devonian Periods – from both foreland sedimentary and hinterland igneous/tectonic records.

Following an overview of volcanic tephra processes from the magma chamber to final burial in sedimentary deposits (by Ver Straeten), Paul Karabinos will present a tectonic overview of the Appalachian hinterland during the low to mid Paleozoic, and compare data on volcanism of that time from the hinterland and foreland. Scott Samson then examines the materials in foreland basin volcanic layers that yield geochronologic, isotopic and geochemical data, which in turn yield an overview of the composition, source characteristics and petrogenetic origins of Ordovician magmas in eastern North America. Baird presents a detailed analysis and discussion of the sedimentologic, preservational, and diagenetic histories of Late Ordovician airfall volcanic layers in the Mohawk Valley. Finally, Ver Straeten lays out the time-stratigraphic occurrence of foreland basin tephra layers in the Devonian of the eastern U.S., and then provides an example comparing foreland basin and hinterland data from the Lower Devonian, with implications for possible igneous sources. In turn, the field trip will stop at four localities, to examine Ordovician and Devonian airfall volcanic "tephra" layers in sedimentary rocks, and feature similar discussions.

Various terms are utilized for the volcaniclastic products of explosive volcanism (e.g., tephra, ash, tuff, bentonite, K-bentonite, and others), as seen in this paper. The term "K-bentonite" is often applied to these Paleozoic volcanic layers. However, such beds may be not only K-bentonites, as seen at Stops 1 and 2. There they occur in three to four different states; as clay-rich K-bentonites, as phenocryst-rich tuffs, and as clay-poor calcite-cemented layers in which the original glass was apparently altered to zeolite minerals instead of clays. Rather than use multiple terms that actually describe their multifarious diagenetic and sedimentologic histories, it is perhaps best to recognize their shared volcanic origin – and call them "tephras", the term chiefly utilized by modern and recent volcanologists for the products of explosive volcanism.

Technically, tephra consists of various components: volcanic glass fragments (= "volcanic ash"), pumice clasts, and crystals formed in the magma ("phenocrysts"), plus or minus country rock fragments. This is commonly termed "volcanic ash", but as just noted, ash actually represents only the fine volcanic glass component of volcaniclastic materials. "Tuff" is commonly used for coarser-grained volcaniclastic deposits. "Bentonite" is clay-rich altered tephra, in which the glassy ash is altered to smectitic clays; in "K-bentonites" or "metabentonites", clays are further altered to potassium-rich, mixed layer illite-smectite clays.

I. VOLCANIC TEPHRA EVENT PROCESSES (Chuck Ver Straeten)

Volcanic Tephra Processes

The fate of airfall volcanic tephra in sedimentary environments, the result of a single volcanic eruption, involves a vast array of igneous and sedimentary processes. From the degassing of volatiles in a magma chamber and formation of pyroclastic materials, through their explosive eruption, transport and deposition, to varied post-depositional pathways of burial and reworking that occur in sedimentary environments, preservation of a single eruptive event layer depends on so many variables. And is generally a rather unlikely occurrence. The purpose of this section is to provide a medial-level overview of processes involved from the magma chamber to final burial of airfall tephra sediments in sedimentary environments.

Eruption Processes (based on Schmincke 2004, p. 155-157)

Explosive volcanic eruptions result from complex interactions and processes that begin in the upper part of a magma chamber (Figure 1). When a magma becomes oversaturated in

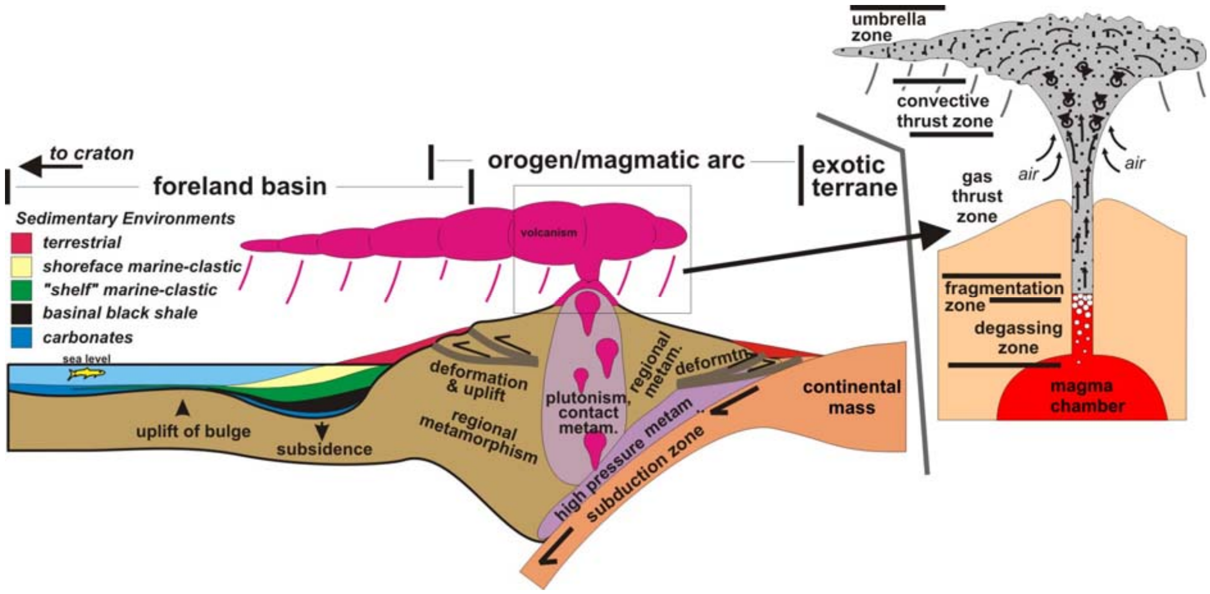

Figure 1. Settings of volcanic tephra processes. Generalized cross-section of subduction zone, orogenic belt/magmatic arc, and adjacent foreland. Inset provides close-up perspective of internal processes from magma chamber to stratosphere during explosive silicic eruption.

volatile components, gases separate out and form bubbles, which undergo expansion (“degassing zone”). This, and/or other factors, leads to expulsion of magma through conduits.

Degassing and bubble expansion continues in the rapidly rising magma. When the volume of gas bubbles approaches 65%, the magma begins to fragment (“fragmentation zone”), which leads to the formation of pyroclasts via: 1) brittle fracture of the magma from explosive “rarefaction” waves; 2) gas bubble bursting with rapid decompression of the magma; and 3) fragmentation of tephra particles in rapid flow conditions within the volcanic conduit.

Rapid gas expansion within the fragmentation zone generates a strong accelerating jet of gas and pyroclastic fragments (“tephra”, i.e., volcanic glass fragments commonly termed “ash”, pumice, and crystals, plus or minus country rock fragments) through the upper part of the conduit. The mix of gases and tephra is forcefully ejected at the mouth of the volcano and shot upward into an overlying “eruption column”.

Driven by momentum, the relatively dense mix of pyroclasts and gas is jetted into the atmosphere through the lower part of an eruption column (“gas thrust zone”). As the column continues to rise, cold air is generally incorporated into the column along its margins; the column’s density decreases as larger pyroclasts fall out, and the introduced air heats up. As a result, buoyant convective processes drive upward motion through the overlying “convective thrust zone" (upper portion of eruption column). Positive buoyancy may drive the eruption column to 30 or more kilometers into the atmosphere. At a level where the eruption column reaches neutral buoyancy, gases and pyroclastic material (tephra) spread out ("umbrella zone").

Fallout and Sedimentation Processes

Once ejected into the atmosphere, the transport, distribution and settling of airborne volcanic tephra is controlled by numerous, interacting factors. Wind is perhaps the most commonly invoked process involved. In the absence of wind, the tephra is dispersed in a bulls-eye pattern. In the presence of winds, the degree of lateral transport of pyroclastic material depends on the direction and speed of wind flow, which may simultaneously vary at different levels in the atmosphere.

Other key processes and properties controlling atmospheric transport of airborne pyroclastic material include plume height, eruption rate, tephra size distribution, duration of the eruption, and erupted volume (Mastin et al. 2009), along with wind advection, turbulent diffusion, and gravitational settling of particles and particle aggregates which is largely associated with particle diameter, density and shape; non-wind meteorological conditions can also be important (Folch and Costa 2010). Some additional key references include Fisher and Schminke (1991), Wiesner et al. (1995), Schminke (2004), and Rose and Durant (2011).

Settling through the low density medium of atmospheric gases, particles and particle aggregates settle largely following Stokes Law. Settling of airfall tephra through water has long been interpreted as strictly related to density- and shape-related factors acting upon individual grains (again, following Stokes Law). However, recent laboratory and field studies indicate that settling of tephra particles through waters is more complex (Carey 1997; Manville and Wilson 2004). Experimental analyses indicate that at the air-water interface, the settling velocity of airfall tephra undergoes a sharp decrease, resulting in high tephra concentration at the top of the water column. This dense mix of tephra particles and water leads to rapid downward transport of tephra through waters via diffuse vertical gravity currents. These flows are analogous to more horizontal density-driven turbidite flows along the sea floor (which may also happen when tephra-laden vertical density currents impinge on the sea floor).

Post-depositional Processes

Pyroclastic materials settle onto the surface of any and all depositional environments within reach of the tephra plume (Figure 1). This may include a broad variety of terrestrial and sub-aqueous (marine, lacustrine and fluvial) environments. In each of these environments, various physical, biological and chemical processes may lead to a variety of post-depositional fates. These include preservation of the fallout tephra material as deposited or with reworking of ash from the same event, resulting in preservation of only the same eruptive event deposit. Alternatively, the interaction of varied environmental processes may lead to amalgamation and/or mixing of tephra from a single event with older or younger tephra or background sediments, or total mixing of tephra materials with background sediments, sometimes to the point where the record of a volcanic contribution is lost.

In terrestrial settings, primary airfall material is commonly highly reworked and redeposited through erosion. This may occur via hydrologic runoff following rainfalls or snowmelt, landslides or mass flows on steeper slopes, redistribution by eolian processes, mixing within the sediment column via plant rooting and animal burrowing, or pedogenic (soil-forming) processes, among others. Fluvial systems redistribute both primary and reworked ash deposits, transporting the material sometimes great distances downstream, and during flood conditions out onto flood plains. Processes acting on tephra in lacustrine systems in large degree mimic those of shallower marine systems (see below), with some variations. Some key references include Mullineaux (1996); Nakayama and Yoshikawa, (1997); Riggs et al. (1997); Kataoka (2005), Kataoka et al. (2009).

In marine environments, primary airfall material is also subject to numerous processes, which may lead down various pathways of reworking and redeposition, with or without mixing of airfall tephra with background sediments. Alternatively, burial may result in preservation of the primary airfall tephra layer. Once settled onto the sea floor, a broad range of environment-related physical, biological and chemical conditions and processes may act upon, and alter the original airfall event deposit (Figure 2a). Sometimes these processes completely mix the tephra sediments with background sediments, essentially erasing and destroying the record of volcanism. These various conditions and processes may occur on the scale of day-to-day activity (e.g., tides, waves, currents, biological burrowing), as uncommon

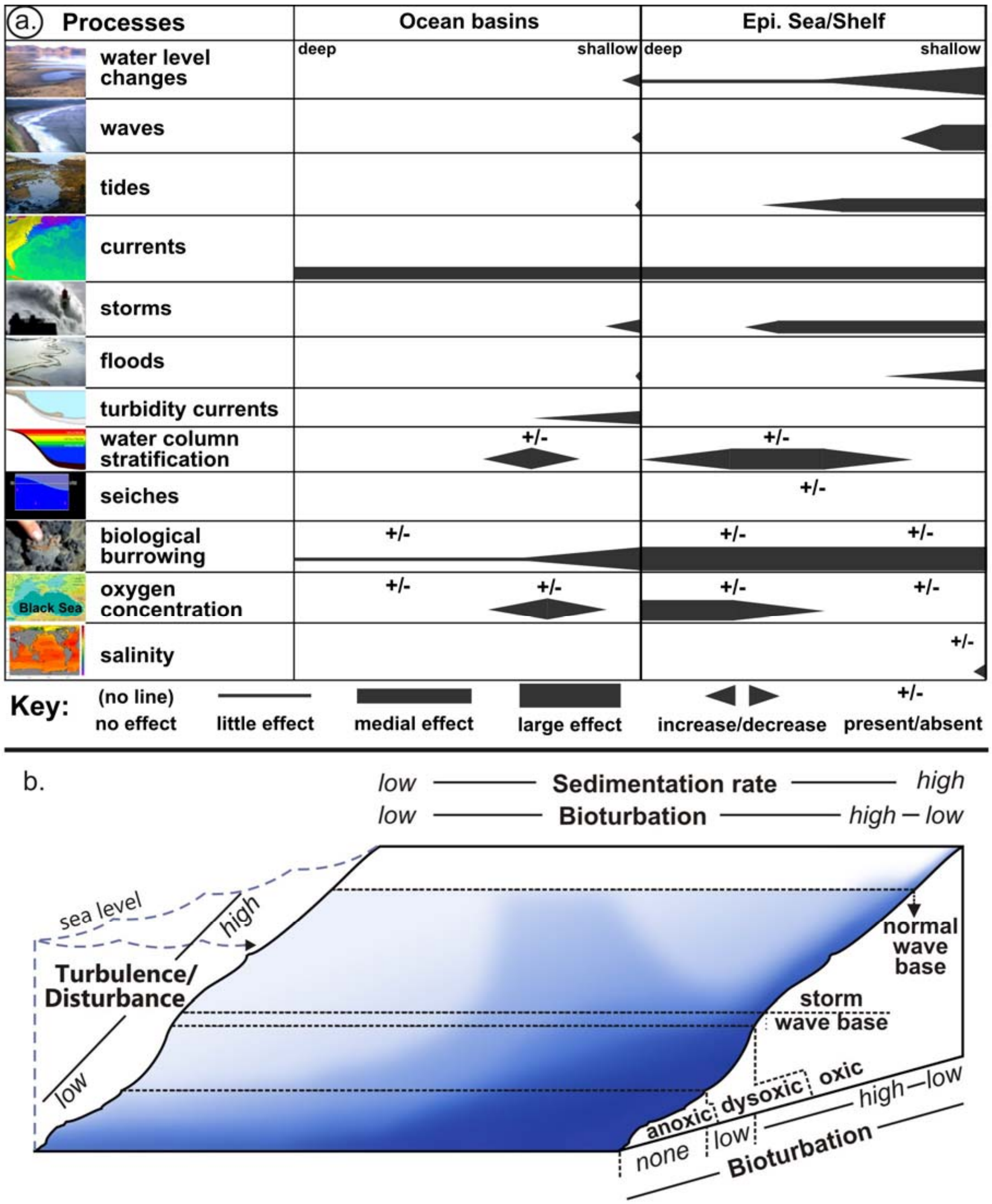

Figure 2. The preservation of tephra layers in marine environments. a) Overview of the generalized distribution of select physical, biological and chemical processes that may affect the preservation of airfall tephra layers in marine settings. Columns for ocean basins, and shelf/epicontinental sea/foreland basin settings; deeper water to left, shallower to right in each column. Thicker lines indicate stronger effects; absence of lines indicate no effect. b) Conceptual model of potential for tephra bed preservation in an epicontinental sea, accounting for sedimentation rate of background sediments, hydrodynamic disturbance, and oxygenation; bioturbation controlled by both oxygen content and sedimentation rate. Darker shades delineate areas of greater tephra bed preservation potential; lighter shades represent decreased chances of preservation.

to rare events (e.g., storms, tsunamis, gravity-driven mass flow events) or over long times spans (e.g., sea level changes, climate- or uplift-related sedimentation rate changes, water chemistry/oxygenation).

Figure 2b portrays a conceptual model of preservation potential of an airfall tephra layer in continental shelf/epicontinental sea/foreland basin settings. Darker areas represent areas of greater potential preservation of tephras. Controls are largely associated with the degree of physical or biological disturbance of sediments at and close below the sea floor, sedimentation rate, and decreasing oxygenation, typically into more basinal environments. Effects of physical processes such as day-today wave action and tides decrease with depth; in this model, bioturbation decreases with depth related to oxygen availability; but it also can decline due to high sedimentation rate. Burial, one of the most significant factors in the preservation of airfall tephra layers, especially primary (unreworked) airfall layers, is associated with increased sedimentation rates (to the right).

As can be seen in Figure 2b, the preservation potential of primary tephra beds increases in this model with greater depth, increased sedimentation rates, and decreased physical and biological disturbance (lower right); and with very high sedimentation rates at any depth, especially when combined with potentially common, episodic burial events. For more discussion of the model, see Ver Straeten (2004a).

In addition to the discussion by Baird in this paper, and publications on tephra preservation by Ver Straeten (2004a, 2007a, 2008), Benedict (2004), and Ver Straeten et al. (2005), there is an extensive and growing literature on the fate of airfall tephra deposits in Paleozoic to recent marine (and relatively similar lacustrine) settings, utilizing various detailed sedimentologic and petrologic methods, and geochemical analyses of the volcanic glass (“ash”) and/or phenocrysts contained within a single tephra layer (e.g., Huang et al. 1973; Sparks et al. 1983; Carter et al. 1995; Huff et al. 1999; Koniger and Stollhofen 2001; Reidel et al. 2001; Scasso 2001; Puspoki et al. 2005, 2008; and Allen and Freundt 2006).

In an extreme example of the post-depositional fate of an airfall tephra from a single eruption, Reidel et al. (2001) examined an airfall tephra deposit from a small lake deposit in Washington State. They found that the primary airfall portion of the layer was only two centimeters thick, at its base. Up to 17 additional meters of reworked tephra from the same eruption was redeposited in lake sediments from the surrounding watershed. Furthermore, they estimated that the reworked tephra was eroded, transported and redeposited in the small lake within one year of the original eruption.

Finally, volcanic glass ("ash") is thermodynamically unstable at surface and near-surface conditions on Earth. Over geologically short to long time spans, glass undergoes devitrification, and may be altered along several different pathways. Under various conditions, volcanic glass may alter to smectitic clays, zeolites, feldspar, or to silica minerals (e.g., amorphous silica, precursors of opal CT, or quartz), and undergo further alteration. Alternatively, tephra may become cemented early in diagenesis and be preserved. Some key references on the diagenetic alteration of volcanic glass include Marshall (1961), Hein and Scholl (1978), Fisk et al. (1998), and Jeans et al. (2000).

In summary, studies of ancient to modern airfall silicic tephra beds indicate a complex depositional history to most layers. In terrestrial and subaqueous environments, many physical, biological and chemical processes may act on primary airfall volcanic sediments; this may lead to rapid burial and preservation, amalgamation with other airfall events, partial mixing of tephra with background sediments, or complete mixing with background sediments, the latter masking the record of explosive volcanic activity in sedimentary strata.

II. INTEGRATING DATA FROM THE FORELAND BASIN AND HINTERLAND OF THE NORTHERN APPALACHIANS (Paul Karabinos)

As someone who works on metamorphosed and deformed rocks in the hinterland of the northern Appalachians, I am envious of geologists who study rocks in the foreland basin. Through careful field observations, they can determine the ages, thicknesses, and depositional environments of stratigraphic units. Correlation of units throughout the basin makes it possible to reconstruct spatial and temporal variations in thickness and facies of the sedimentary rocks, and thereby constrain the timing of subsidence in the basin. It is also possible to make inferences concerning uplift and tectonic history in the hinterland. In contrast, those of us who work in the deformed Appalachians struggle to determine the ages and estimate the thicknesses of units. When we are fortunate enough to find formational contacts, we typically struggle to identify them correctly as faults, unconformities, or conformable stratigraphic contacts. Differences in interpretation of a critical contact commonly result in heated debates. Without reliable age data, correlations between units are tenuous. However, it is the record of deformation and metamorphism in the hinterland that provides us with direct evidence of tectonic activity, even if it is difficult to decipher.

Integrating information from the foreland basin and hinterland has tremendous potential for advancing our understanding of both parts of the orogen. Evidence from the rock record in the foreland basin is commonly well constrained and detailed; it gives a clear picture of the depositional history in the basin. However, the foreland basin record does not provide direct evidence of the plate tectonic activity or geometry in the hinterland. It is a reliable time-integrated record of sediment transfer from the hinterland to the foreland that is controlled by relative elevation between the basin and the tectonically active hinterland, along with climate and drainage patterns. Thus, the foreland basin record is reliable but it does not fully explain what caused the variations in sedimentation rate. On the other hand, our knowledge of the stratigraphy, depositional setting, and tectonic affinity of rocks in the hinterland are commonly incomplete. To make up for this deficiency, however, field mapping combined with structural, metamorphic, geochemical, geophysical, geochronological, and paleomagnetic studies from the hinterland provide direct evidence for subduction, accretion of arcs and microcontinents, rifting, tectonic exhumation, and crustal thickening in the northern Appalachians. In other words, studies of the foreland basin and hinterland have complementary strengths and weaknesses.

Advances in the precise U-Pb dating of zircon have made it possible to integrate more fully data from the foreland basin and the hinterland. The recognition and precise dating of K-bentonites in the foreland basin (Tucker and McKerrow 1995; Tucker et al. 1998), combined with an expanded database of the age and tectonic significance of volcanic and plutonic rocks in the hinterland (Tucker and Robinson 1990; Karabinos et al. 1998; Bradley et al. 2000), allow us to identify some specific tectonic events that were coeval with the formation of air-fall tephras in the foreland basin. Because the dated K-bentonite layers constrain the ages of important changes in the evolution of the foreland basin, it is possible to test models of how tectonism in the hinterland affects foreland basin evolution (e.g., Ver Straeten 2010).

Long before plate tectonic theory was first applied to the Appalachians (e.g., Dewey 1969), and even before absolute radiometric ages were available, three major orogenies were recognized based on fossil dating of deformed rocks below angular unconformities: the Ordovician Taconic, the Devonian Acadian, and the Pennsylvanian to Permian Alleghenian orogenies. During the 1970s and 1980s, it was common for geologists working in western New England to ascribe deformation to either the Taconic or Acadian orogenies, both of which were considered to have consisted of several phases. This simplified view of early Paleozoic tectonism held that the Taconic orogeny resulted from the collision of Laurentia with the 'Taconic' arc (e.g., Rowley and Kidd 1981; Stanley and Ratcliffe 1985) and that the Acadian orogeny marked the collision of a microcontinent separated from Gondwana called Avalon (e.g., Rast and Skehan 1993). The Alleghenian orogeny was believed to have only affected rocks in southeastern New England.

Detailed work in New England and in the Canadian Appalachians, especially Newfoundland and New Brunswick where arcs of both Laurentian and Gondwanan affinities are better preserved, has resulted in a much more detailed and complex history of arc and microcontinent accretion, reversals in subduction polarity, and intermittent back-arc rifting (e.g., van Staal et al. 1998, Zagorevski et al. 2007). For example, we now know that Alleghenian deformation affected rocks as far west as the Bronson Hill arc in western Massachusetts (Robinson et al. 1992; Figure 3). Our expanding geochronological database in the northern Appalachians suggests that the Laurentian margin was continuously active from approximately 470 to 270 Ma. Perhaps too much effort has been expended trying to assign dated features to either the Taconic or Acadian orogeny. We should instead focus our efforts on reconstructing the rich history of tectonic events and document the evolving plate tectonic geometry during this interval. For example, a stratigrapher might use the increased influx of sediment to the foreland basin to propose a Late Ordovician to Early Silurian age for the Taconic orogeny (e.g., Rodgers 1970), whereas I would argue that from a plate tectonic perspective the Taconic orogeny, i.e. the collision of Laurentia with the Notre Dame-Shelburne Falls arc, was over before or soon after the start of the Late Ordovician (Karabinos et al. 1998, van Staal et al. 2007). As discussed below, the increase in Late Ordovician sediment flux may record changes to the continental margin following arc collision, slab

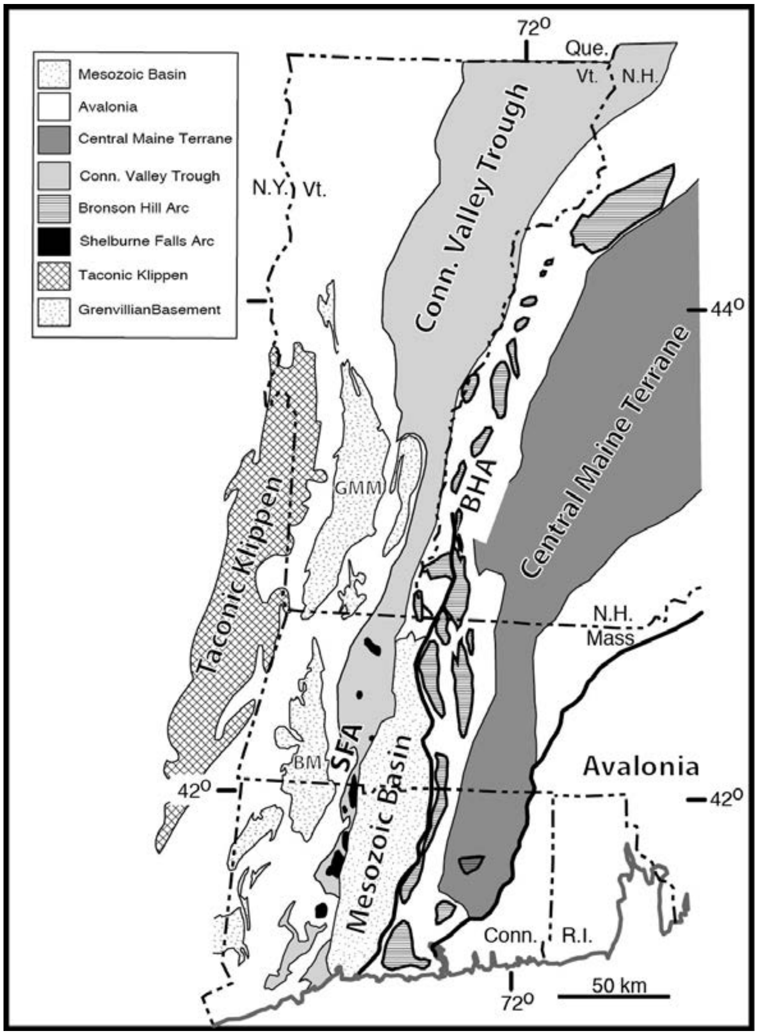

Figure 3. Tectonic map of New England. BHA- Bronson Hill arc. BM- Berkshire massif, GMM- Green Mountain massif, SFA- Shelburne Falls arc.

break-off, subduction reversal, and formation of the Bronson Hill arc along the Laurentian margin.

The formation of air-fall tephras in a foreland basin requires explosive volcanism. Island arcs (e.g., the Aleutian Islands) and magmatic arcs (e.g., the Cascade Range) are obvious settings for explosive volcanism. But hot spots beneath continents (e.g., Yellowstone) and rifting beneath continents (e.g., Valles Caldera) can also produce explosive eruptions. The transient nature of tectonically active continental margins would seem to favor arc-related eruptions as a more likely source of air-fall tephras, but other possibilities must also be considered.

If we make the reasonable assumption that the age of K-bentonites in the foreland basin can be correlated with explosive arc magmatism proximal to the active Laurentian margin, can we use tephras to date periods of increased tectonic activity (e.g., Ver Straeten 2010)? If oceanic lithosphere is subducted beneath a continental margin (e.g., Andean margin) and plate convergence rates are high, it is possible to have explosive eruptions during crustal deformation. Alternatively, if subduction polarity dips in the opposite direction, away from the continental margin and under an island arc or an impinging microcontinent (e.g., Indonesian-Australian collision), explosive eruptions should precede collision and crustal deformation, but cease soon after collision commences. This is because the subduction of oceanic lithosphere necessary to trigger melting in the overlying mantle wedge, which eventually leads to explosive eruptions, ceases soon after collision begins. Thus, it is important to not only correlate K-bentonite ages with volcanic activity in the hinterland, but also to discriminate between magmatic arcs that formed above subducting oceanic lithosphere along the continental margin from colliding arcs that overrode the continental margin.

Ordovician K-bentonites

Early Ordovician (Floian) K-bentonites have been reported by Thompson et al. (2012) from the Argentine Precordillera, a microcontinent that may have rifted from the southeastern margin of Laurentia, which later collided with Gondwana (Thomas and Astini 2003). It is unclear, however, if these older K-bentonites in the Precordillera record explosive volcanism directly related to the Appalachians. Middle Ordovician (Dapingian and Darriwilian) K-bentonites are found in North America and in the United Kingdom (Huff et al. 2010). The oldest Middle Ordovician K-bentonites in North America partly overlap with arc magmas from the Shelburne Falls arc in western New England (486 to 470 Ma, Karabinos et al. 1998), but are younger than most of the dated rocks from the Shelburne Falls arc and all of the dated rocks from the Notre Dame arc in Newfoundland (489-477 Ma, van Staal et al. 2007).

The lack of older K-bentonites corresponding to older arc magmatism in the Shelburne Falls and Notre Dame arcs may be due to the lack of a deep basin at the time of eruption to preserve the air-fall tephra, or later erosion of Early Ordovician basin deposits.

Numerous Late Ordovician K-bentonite deposits are preserved in North America (Huff et al. 2010) and many dated layers overlap in age with volcanic rocks dated in the Bronson Hill arc by Tucker and Robinson (1990), ca. 454-440 Ma. Karabinos et al. (1998) argued that the Bronson Hill arc was a peri-Laurentian arc that formed after collision of Laurentia with the Shelburne Falls arc, slab break-off, and a reversal in subduction polarity to accommodate west-dipping oceanic lithosphere under the Laurentian margin. Another interpretation is that the Bronson Hill arc is a continuation of the Popelogan-Victoria arc, which formed on a sliver of Ganderia, before it collided with Laurentia in the Late Ordovician (e.g., Zagorevski et al. 2007). In any case, coeval arc-related plutons have been dated in western Connecticut that intruded rocks of unambiguous Laurentian affinity, which had been deformed during the Taconic orogeny prior to intrusion (Sevigny and Hanson 1995), so it is almost certain that a west-dipping subduction zone existed under the Laurentian margin after collision of Laurentia and the Shelburne Falls arc. Thus, it is possible that Middle Ordovician K-bentonites in the Appalachian foreland basin were derived from two separate arc systems: one along the Laurentian margin and the other along the Ganderian margin. Collision during the Late Ordovician and Early Silurian would have presumably shut off the supply of explosive eruptions.

The increase in sediment flux from Late Ordovician into Early Silurian must reflect an increase in elevation of the hinterland relative to a subsiding foreland basin. Loading of the continental margin by the Shelburne Falls arc may account for basin subsidence, but loading occurred some 10 to 15 m.y. before the observed increase in sedimentation. Some other factor must be invoked to explain the time lag between the onset of collision and the increase in sediment influx. It is possible that crustal shortening caused by the collision of Laurentia and the Shelburne Falls arc, was augmented by buoyant uplift of the hinterland following slab break-off of dense oceanic lithosphere. The combined effect of crustal thickening and buoyant uplift may be responsible for the required increase in hinterland elevation relative to the foreland to initiate the formation of a clastic wedge. Slab break-off must have occurred prior to subduction reversal and formation of arc-related rocks along the Laurentian margin beginning at approximately 455 Ma. This late increase in hinterland elevation may have created the critical taper needed to trigger the late advance of Taconic thrust sheets in the Caradoc (e.g., Rowley and Kidd 1981; Bradley 1983). Continued crustal shortening and erosion in the hinterland and subsidence of the foreland basin during the Late Ordovician and Early Silurian may reflect either Andean-style deformation of the Laurentian margin above a west-dipping subduction zone, collision of Laurentia with Ganderia, or both.

Devonian K-bentonites

Ver Straeten (2010) showed that the foreland basin record could be used to enhance our understanding of the Acadian orogeny, and he included air-fall tephras in his analysis. There are approximately 100 K-bentonite deposits in the Devonian foreland basin. Within the Devonian sequence, numerous tephra beds form five clusters that appear to record pulses of concentrated explosive eruptions (Ver Straeten 2010) at approximately 418 Ma (Bald Hill cluster), 409 Ma (Sprout Brook cluster), 391 Ma (Tioga MCZ cluster), 390 Ma (Tioga A-G cluster), and 381 Ma (Belpre cluster).

The oldest cluster, Bald Hill, is similar in age to the Standing Pond Volcanic Member of the Waits River Formation (423 $\pm$ 4 Ma, Aleinikoff and Karabinos 1990) and a felsic sill in the Barnard Volcanic Member of the Missisquoi Formation (419 $\pm$ 1 Ma, Aleinikoff and Karabinos 1990) in Vermont. Both of these units are likely related to Late Silurian rifting and the inception of the Connecticut Valley trough. The Bald Hill cluster is also similar in age to detrital zircons recovered from the Waits River Formation (418-415 Ma; McWilliams et al. 2010).

The Connecticut Valley trough (which is the 'other' Devonian foreland basin) received large volumes of sediment until at least 405 Ma. It contains two dated tuff layers. One tuff is 407 $\pm$ 3 Ma, and in the Meetinghouse Slate Member of the Gile Mountain Formation in eastern Vermont (Rankin and Tucker 2009). The other tuff is 405 $\pm$ 4 Ma, and in the Goshen Formation in western Massachusetts (Karabinos and Aleinikoff 2011). McWilliams et al. (2010) reported detrital volcanic zircons extracted from a quartzite bed in the Gile Mountain Formation in Royalton, Vermont, that are 409 $\pm$ 5 Ma and indistinguishable in age from the tuffs. The Littleton Formation in New Hampshire also contains a 407 $\pm$ 2 Ma tuff layer (Bradley et al. 2000). These tuffs and detrital zircons are very similar in age to the Sprout Brook cluster in the foreland basin. The rocks in the Connecticut Valley trough and the Littleton Formation, however, were deformed during the Acadian orogeny shortly after deposition. A likely source for the air-fall tephras in the foreland basin and the Connecticut

Valley trough and Littleton Formation is in Maine, where the coeval Traveler and Kineo Formations form a thick succession of rhyolite (Rankin and Hon 1987; Rankin and Tucker 1995; Bradley et al. 2000).

The Acadian orogeny records the collision of Laurentia with Avalon. Bradley et al. (2000) showed convincingly that it began in the Late Silurian in the easternmost part of Maine, and that deformation migrated westward during the Early and Middle Devonian.

The three youngest air-fall tephra clusters in the foreland basin, 391 to 381 Ma, are coeval with intense Acadian deformation and metamorphism in the hinterland. Numerous $^{40}Ar/^{39}Ar$ cooling ages in this 390 to 380 Ma age range occur throughout central New England and record cooling through the closure temperatures of hornblende, biotite, and muscovite of mid-crustal rocks, and suggest that at least 10 to 15 kilometers of crust has been eroded since then. Thus, it is unlikely that any evidence for explosive eruptions would remain. If the eruptive sources of these clusters are preserved, they must be located near the suture zone between the eastern edge of Avalon and the western margin of Meguma, which collided during the Late Devonian (van Staal et al. 2009).

III. DECIPHERING THE ORIGIN, MAGMATIC EVOLUTION, AND TECTONIC SETTING OF PALEOZOIC VOLCANOES BY EXAMINING K-BENTONITES (Scott Samson)

Introduction

Widespread volcanic ash beds, or their altered equivalents (K-bentonites), are geologically useful because of their combined extensive geographic distribution and geologically instantaneous deposition. These event beds provide a tie-line, or a stratigraphic reference, which can be used to correlate the host rocks that envelop the ash bed. This, in turn, contributes to the understanding of ancient facies relationships among widespread locations. This is of particular importance in areas with little or no biostratigraphic control or for regions where there is inadequate overlap of time-diagnostic fossils (e.g., conodont bearing facies versus graptolite-bearing facies). K-bentonite correlation has thus become an extremely important aspect of stratigraphy in many areas around the globe. In New York there are numerous K-bentonites in key Ordovician and Devonian strata.

Perhaps one of the best known aspects of K-bentonites is their ability, under ideal circumstances, to provide material that is amenable to high-precision radiometric dating. Volcanic ash beds, and their highly altered (i.e. bentonite) equivalents, have proven absolutely invaluable in the calibration of the Geologic Time Scale. Combining age determinations with long-distance correlation, i.e. tephrochronology, has thus become a critical aspect of a wide variety of geological studies. What is not particularly well known about K-bentonites is their frequent ability to provide extremely important isotopic and geochemical information. This, in turn, has the potential to shed considerable light on such diverse topics as ancient magma chamber evolution, constraining potential versus impossible source regions of the K-bentonites, the tectono-magmatic setting of the volcanoes producing the ash, the degree of crustal evolution of the source regions, and finally possible constraints on paleogeography. This is an impressive list by any standard, but given that K-bentonites appear to be essentially glorified mud it is (or should be) hard to imagine the above claims are realistic! The key to accomplishing the above items is in the surviving phenocryst (and xenocryst) assemblage as discussed below.

Phenocryst Assemblage in K-bentonites

The phenocrysts in highly altered ash beds (K-bentonites, tonsteins etc.) are critical because the original volcanic glass has either largely, or entirely, been chemically modified. Most tephrochronological studies of Recent tephra are based on the unique chemical composition of the volcanic glass. However, in the Ordovician and Devonian bentonites in New York the glass has been entirely altered to clay minerals (typically illite and smectite). Thus it is the remaining chemically resistant phenocrysts that are found in many, but by no means all, K-bentonites that still preserve invaluable information about original magmatic conditions. Typically the surviving phenocrysts include quartz, zircon, and apatite. Biotite can also be found in some K-bentonites, but it is not a particularly resistant mineral and thus is often chemically altered, in some cases completely, leaving only pseudomorphs of biotite. The useful characteristics of the phenocrysts most likely to survive are given, followed by some specific examples.

Quartz

Quartz is both a physically and chemically extremely resistant mineral and thus it is not surprising that it can occur as pristine phenocrysts in altered tephra. Because it is nearly pure SiO_2 there is limited utility to determining either its major or trace element chemical composition. However, quartz phenocrysts often contain glass inclusions that in most cases represent trapped quenched melt (i.e. melt inclusions). These inclusions are thus microscopic samples of the original magma as it existed prior to the volcanic eruption producing the tephra. We now know, for example, that many of the Ordovician K-bentonites in New York are actually high K rhyolites thanks to the major element composition of the glass inclusions contained in quartz phenocrysts (Delano et al. 1994). That information, in turn, sheds some light on the source characteristics of the original magma as not all tectonic settings are conducive to generating magma with such high SiO_2 and K_2O contents.

Apatite

Apatite phenocrysts have proven to be one of the most useful aspects of bentonites in terms of unraveling details about the likely source material of the parent magma, potential links of the ash beds to exposed volcanic/plutonic terrain, and to details of magma evolution during a series of eruptions. This is possible because apatite contains high enough levels of rare earth elements and strontium to allow for the determination of the Nd and Sr isotopic composition of the phenocrysts, and hence the magma that the apatite crystallized from. This is so important because by knowing the initial $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios of the parent magma considerable information is obtained about the conditions in which that magma originated. Furthermore, in contrast to quartz, apatite incorporates a considerable number of elements into its lattice. Thus, determining the trace and minor element composition of apatite can shed further light on magmatic conditions as well as help provide a potential "geochemical fingerprint" to assess if exposed igneous regions of identical age might be the possible source location of the ancient volcanoes. Specific examples given below will help demonstrate these concepts.

Zircon

Like quartz, zircon is an extremely resistant mineral both physically and chemically and thus survives in tephra even under the most extreme diagenetic conditions. The utility of zircon phenocrysts is obvious: high precision U-Pb radiometric dates may be determined using the phenocrysts. While U-Pb dating of zircon phenocrysts may not provide much insight into magmatic characteristics, determining the presence and age of zircon xenocrysts can provide considerable information. Many of the North American Paleozoic bentonites do contain zircon xenocrysts, which adds to our information arsenal. Another utility of zircon is that the initial $^{176}Hf/^{177}Hf$ isotopic ratio can be determined for zircon phenocrysts. This information is similar to that obtained from the Nd isotopic data of apatite phenocrysts as it also provides critical information about magmatic source characteristics.

Xenocrysts

As with any igneous rock, there is the possibility of the presence of xenocrysts in bentonites. Some of the xenocrystic minerals that have been found in Ordovician bentonites besides zircon include garnet (Delano et al. 1990), hornblende and pyroxene (Samson 1996). Xenocrysts are important in that they provide a direct window into the characteristics of the magma source material.

Critical geochemical data for Ordovician volcanism in Appalachians

Most of what is known about the composition, source characteristics and petrogenetic origins of the Taconic K-bentonites in eastern North America comes from chemical and isotopic analyses of the ‘crystal cargo’ (i.e. phenocrysts and xenocrysts) of the bentonites. These data can be compared to those collected from more conventional igneous rocks to establish a larger view of Taconic magmatism. In general terms, the available geochemical data suggest that much of the Ordovician magmatism was the result of melting pre-existing continental crust. Speaking specifically about bentonites, that tephra was generated from volcanoes that were built on Proterozoic continental crust. A major source of the magmas feeding those Taconian volcanoes is inferred to be that ancient crust itself (based on data published in Samson et al. 1995; Samson 1996); this appears to be true for many other regions of exposed Ordovician igneous rocks.

Isotope Geochemistry of Ordovician Volcanic Rock/Continental Crustal Interaction

Initial isotope ratios (primarily $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$) have been determined on many of the exposed igneous and metaigneous Ordovician rocks of the Appalachians. This has also been accomplished for Taconian K-bentonites using apatite phenocrysts. Here I focus on the bentonite data, but note that the same conclusions would be reached for any volcanic rock.

The initial $^{87}Sr/^{86}Sr$ ranges from 0.70564 to 0.70905, with most samples having values close to 0.708. The initial Nd isotopic data, using †epsilon (ε_{Nd}) Nd notation, ranges from -0.9 to -5.4. These isotopic data are consistent with 'evolved' magmas (magmas that extensively interacted with continental crust), as opposed to 'juvenile' magmas, or ones that are primarily formed by melting of the mantle. For example, modern island-arc volcanic rocks have $^{87}Sr/^{86}Sr \approx 0.704$ and $\varepsilon_{Nd} \approx +5$ to +9. Mid-ocean ridge volcanic rocks have even lower Sr ratios (< 0.703) and higher ε_{Nd} values ($\geq +9$). Old continental crust has the opposite characteristics (high $^{87}Sr/^{86}Sr$ and very negative ε_{Nd}). Taconic magmatism appears to be a hybrid, and thus it is inferred that magma may originally have been mantle-derived but it became heavily contaminated by old continental crustal material.

Further evidence that continental crust must play a very important role in Ordovician magmatism is the presence of Proterozoic zircon xenocrysts in many Appalachian Ordovician igneous rocks, including the Taconic K-bentonites. A rarer, but spectacular example of xenocrysts inherited from underlying continental crust is Mesoproterozoic hornblende in some Ordovician K-bentonites of the Mohawk Valley. $^{40}Ar/^{39}Ar$ ages of 950 – 900 Ma for individual hornblende crystals suggest an interaction of Ordovician magma with Grenville basement during rapid ascent of the magma in the volcanic plumbing system (Samson 1996).

The importance of the above data lie not only in the demonstration that the Paleozoic volcanoes are built on a continental substrate, but that very important constraints are placed on potential links between the tephra and any source candidates. Any Ordovician igneous terrane that might be viewed as a potential source, such as the Bronson Hill terrane, Shelburne Falls terrane, or Stokes Domain in the northern Appalachians, or the Chopawamsic terrane and its equivalents in the southern Appalachians, must contain igneous rocks with appropriate Nd and Sr isotopic composition, must have Ordovician rocks with

Precambrian zircon xenocrysts, and must have evidence for being built on Grenville crust with a thermal history indicating cooling below ~ 500 °C around 950 Ma. This is a very powerful test on any proposition of linking foreland and hinterland units.

For additional reading on the topics examined in this section, see Samson et al. (1988 1989), Emerson et al. (2004), Carey et al. (2009), Sell and Samson (2011a,b).

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† $\varepsilon_{Nd} = 10{,}000 \times [^{143}Nd/^{144}Nd_{sample} - {}^{143}Nd/^{144}Nd_{Bulk\ Earth}]/[{}^{143}Nd/^{144}Nd_{Bulk\ Earth}]$

IV. MOHAWK VALLEY ORDOVICIAN TEPHRAS (Gordon Baird and Carlton Brett)

Introduction

Upper Ordovician deposits, comprising the Trenton Group, Dolgeville Formation, and Utica Shale have been the subject of a variety of classic paleontological, sedimentological, tectonic, and chronostratigraphic studies that span nearly two centuries of investigation. The sum gain of this work presently reveals the dynamic interaction of forearc convergence effects with platform margin-to-basin sedimentary processes. Altered volcanogenic layers ("K-bentonites" of most authors), are numerous in this succession and have figured prominently in attempts to correlate across time-variable (diachronous) facies tracts in this region (see Cisne et al. 1982; Delano et al. 1994; Goldman et al. 1994; Mitchell et al. 1994; Samson et al. 1995). Herein, we continue work by Baird and Brett (2002) and Berkley and Baird (2002) to characterize tephras in the sedimentary record from a sedimentological and diagenetic perspective. Our earlier work focused on tephra features that were useful for physical bed correlation between outcrops. In this paper, we are more interested in the intrinsic properties of these beds that relate to their sedimentological origin and diagenetic alteration. Accordingly, the first two field trip stops are directed to the study of Upper Ordovician tephra layers that accumulated in an oxygen-deficient basin setting represented by the Utica Shale. Multiple tephra beds will be seen at both localities.

Geologic Setting

The Ordovician tephra record in the Appalachian region is understood to reflect the presence of arc development and associated southeastward oceanic subduction within the

Neo-Iapetus Ocean along the southeast margin of the continent of Laurentia (proto-North America). Consumption of the oceanic lithosphere led to arc collisions with the southeast edge of Laurentia, subduction of portions of the proto-North American continental margin, and emplacement of accretionary prism complexes (Taconic allochthons) onto the Laurentian craton (Kolata et al. 1996). These events, culminating in the Upper Ordovician Taconian Orogeny, were associated with pulses of overthrusting that produced orogenic mountains, southeast of the present day Appalachians. Flexural thrust-loading, associated with this collisional phase, led to the development of a large peripheral foreland basin northwest of the mountain system, which was then filled with terrigenous sediment, mainly derived from the collisional uplifts (Cisne et al. 1982; Quinlan and Beaumont 1984; Lehmann et al 1995).

As collisional deformation advanced cratonward, the foreland basin both expanded and deepened. A cratonic shelf, recorded by richly fossiliferous shelf carbonate deposits (Trenton Group), west of the foreland basin, underwent progressive westward subsidence and drowning as a result of stepwise down-to-the-east movement along fault systems as the basin expanded (Bradley and Kidd 1991). Hence, the middle and upper parts of the Trenton Limestone pass eastward (downslope) into minimally fossiliferous slope facies (Dolgeville Formation) before grading into dysoxic basinal facies (Cisne et al. 1982; Mitchell et al. 1994; Lehmann et al. 1995; Brett and Baird 2002; Jacobi et al. 2002).

The organic-rich Utica Shale, accumulated in variably oxygen-deficient, deeper portions of the basin. The lower part of the Utica succession (Flat Creek Shale Member) is variably calcareous, and it does yield a modest benthic fauna as we will see at Stop 2. An interval of numerous ribbon limestone layers (Dolgeville Formation) overlies the Flat Creek Shale in the field trip area. This unit, visible in the high cliffs at Canajoharie Creek (Stop 2), represents a turbiditic limestone facies that correlates westward into the upper Trenton Group carbonate shoal facies (Brett and Baird 2002). Above this unit is the Indian Castle Shale Member, a black, fissile to platy shale that is stratigraphically condensed in western Mohawk Valley sections. In the Poland-Middleville-Little Falls-Dolgeville area, it disconformably overlies the Dolgeville Formation; Indian Castle Shale strata, including important tephra layers, progressively onlap westward onto this contact across this region (Baird and Brett 2001; Baird and Brett 2002). This contact (Thruway Unconformity) is spectacularly displayed along the NYS Thruway (I-90), 1.0-1.6 mile west of the Little Falls exit.

Ordovician Ash Beds: Physical Description

Volcanogenic layers

The eastern North American Upper Ordovician section has been long known for the occurrences of sedimentary layers of apparent volcanogenic origin. At least 60 diagenetically altered, airfall volcanic beds are estimated to be present within this succession (Kolata et al. 1996). Herein, we apply the more generalized term “volcanic tephra” for such beds. However, within the Mohawk Valley region, numerous similar layers are present higher in the Trenton Group, Dolgeville Formation, and Utica Shale (Cisne et al. 1982; Delano et al. 1990, 1994). These latter deposits, serving as the focus of the present study, occur within the lower and middle parts of the Upper Ordovician global Katian Series (Bergström et al. 2008). Aside from their utility in isotopic dating, volcanogenic phenocrysts in these beds also yield distinctive geochemical signatures (“chemical fingerprints”) useful, in tandem with graptolite and conodont biostratigraphy, for correlation of strata (Goldman et al. 1994; Mitchell et al. 1994; Samson et al. 1995).

Tephras In Outcrop

Approximately 30 altered tephra layers are present within the overall central Mohawk Valley, Upper Ordovician basinal facies succession, although only about 12 to 15 of these can be correlated between sections (Delano et al. 1990, 1994; Baird and Brett 2002). (1994), Baird and Brett (2001), and Baird and Brett (2002). These beds are most often expressed as bands of unctuous gray-greenish-to-china white clay that stands in dramatic contrast to enclosing limestone facies (Trenton Group or Dolgeville formation) or hard, black Utica Shale deposits (Flat Creek Shale Member, Indian Castle Shale Member successions: Figures 4, 5). Most of these beds display thicknesses in the 0.5 – 4.0 cm-range, but some, particularly the Paradise tephra bed in the basal Indian Castle Shale, exceed 14 cm. Bases of these ash layers are almost always very sharp, but the upper parts of the tephra layers usually grade conformably upward into succeeding lithologies. Weathered tephras typically form reentrants in sections (Figure 6a), often characterized by bands of plant growth on the outcrop face as can be seen along I-90 west of the Little Falls exit. Even very thin tephras are often marked

Stop 2:
Flat Creek Shale Tephra bundle at Canajoharie Creek

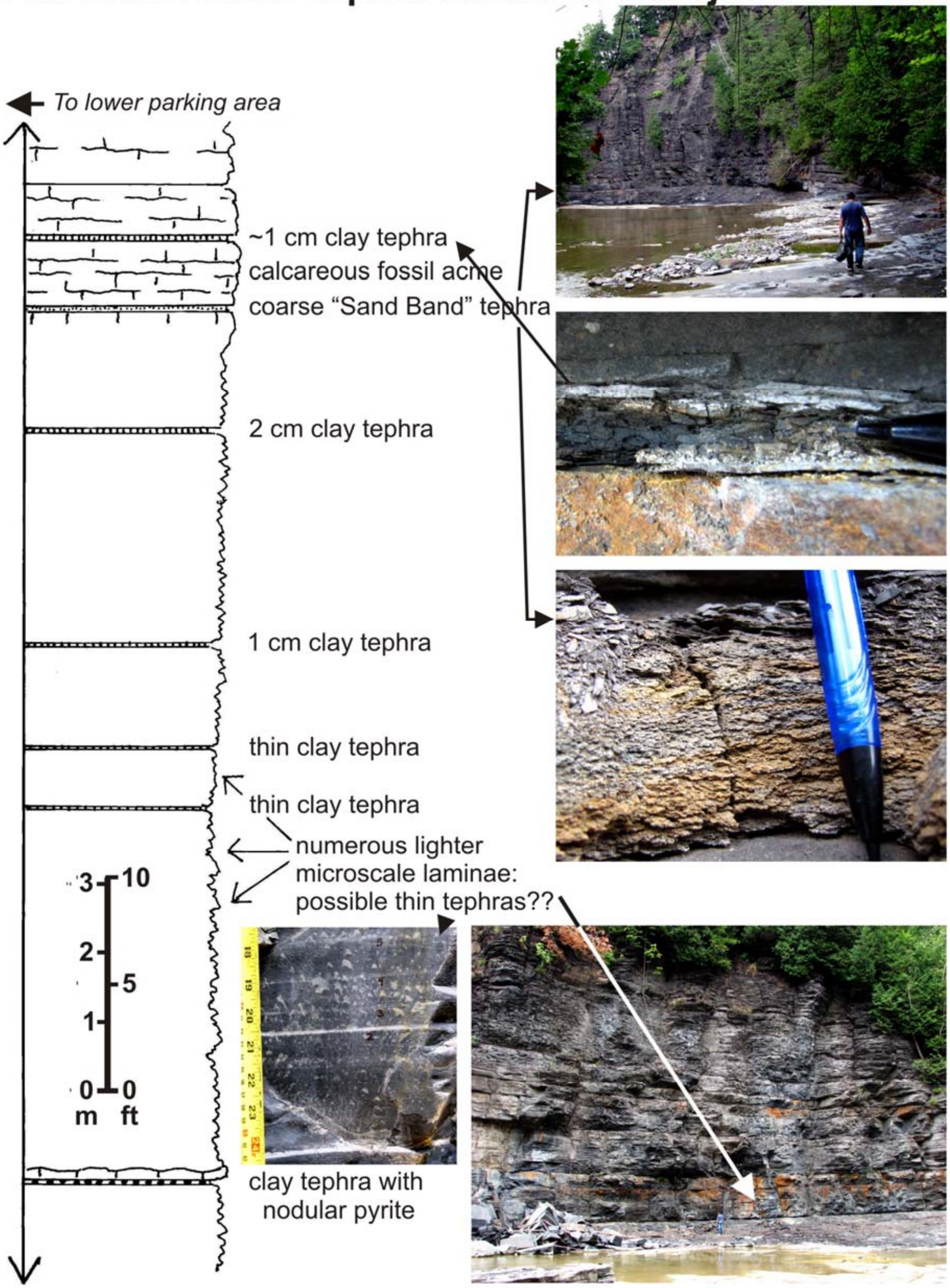


Figure 4. Schematic section of a portion of the Flat Creek Shale section in the classic Canajoharie Creek

gorge south of Canajoharie, NY (Stop 2). The top of the section shown is immediately downstream from the Wintergreen Park ingress trail from the lower parking area within the park. Two intervals of interest include a lower interval of concentrated pyrite-bearing, thin tephra layers that bleed orange on the canyon wall as they weather as well as numerous thinner beds and laminae of possible tephra origin (see inset images). Upstream, closer to the parking lot entrance, are several thicker tephra layers, including the very coarse, gritty "sand band" bed, which occurs below a fossil-rich interval (see inset images; Figure 4a,b).

by rusty, Fe-hydroxide stains in shale sections or between limestone layers. Disseminated pyrite in the clay bands degrades to rusty Fe-hydroxides on weathered surfaces, imparting an orange cast to these layers. This effect is striking in sections along I-90, west of the Little Falls exit, and along Canajoharie Creek (Stop 2). As noted above, many tephras are regionally widespread, but some vary in thickness, often within outcrops, due to low-angle tectonic slippage effects (Zambito et al. 2005; Zambito and Baird 2006). A few tephra layers are partly to entirely carbonate cemented; these concretionized occurrences can be studied on polished surfaces and in thin sections (Berkley and Baird 2002). Several thick tephra beds rest upon selectively indurated underlying layers, particularly, within the Indian Castle Shale. These "ash seats" represent dark muds that have been diagenetically altered by the overlying tuffaceous accumulation.

Mixed-layer Illite-Smectite Tephra Occurrences

Typical, "soft", clay-rich tephra beds show up as pale gray-greenish to beige-tan bands of sticky clay, which can be easily scooped out when the layers are thick. Even when such beds are sampled in the minimally weathered state, as from the bottom of a creek plunge pool, the samples have a greasy, soapy feel when handled. When these samples are rewetted, they often slake and swell to a shapeless, mud mass. This clay is the product of diagenetic alteration of unstable volcanic glass, which is initially converted to smectite. Later, following development of deeper, thermal-burial conditions, such as that associated with burial of the eastern New York Ordovician succession, the smectite was converted to a mixed-layer, illite-smectite phase (Perry and Hower 1970; Epstein et al. 1977; Delano et al. 1990).

Petrography and trace element geochemistry suggest a generally felsic to intermediate, calc-alkaline composition of the volcanic component that is consistent with the probability of an upwind arc source (Berkley and Baird 2002). Rare Earth Element (REE) analysis of these ashes shows that the clay-dominated layers, as well as calcareous ash beds, are enriched in

Stop 1
Otsquago Creek at “Pretzel Farm”

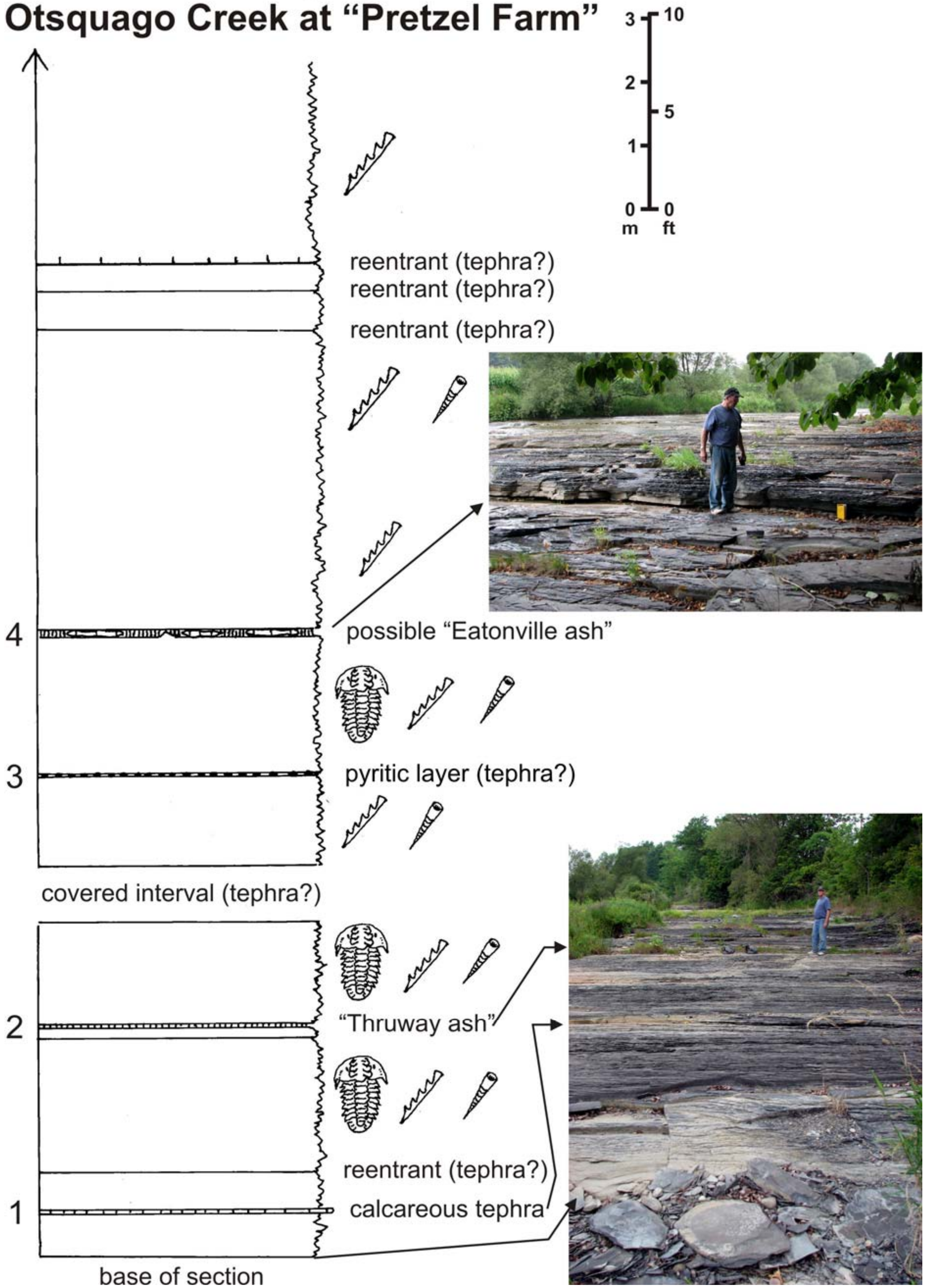


Figure 5. Stop 1 schematic section in the lower part of the Upper Ordovician Indian Castle black shale along Otsquago Creek east of Hallsville, NY ("Pretzel Farm" locality). This section is notable for several easily accessible and distinctive tephra layers. It is also an important locality for distinctive Utica Shale fossils including graptolites, flattened and current-aligned orthoconic cephalopods, as well as, the trilobite Triarthrus, which is especially common in the lower part of this section. Key tephra layers include: a 1.2 cm-thick, tabular, calcareous tephra bed displaying a rich, weakly graded concentration of phenocryst minerals as well as carbonate pseudomorphed small pumice clasts that are preserved in bas-relief along the base of the bed (lower inset image) and a thicker tephra layer displaying both carbonate and clay phases (Figure 4c,d).

light REE with moderate to pronounced Europium anomalies indicative of a felsic-to-intermediate igneous signature (Berkley and Baird 2002). Additional convincing evidence of pyroclastic origin is the variable presence of volcanogenic phenocrysts obtained from disaggregation of clay fractions. Moreover, both Utica Shale and Middle Devonian Onondaga Limestone clay tephras have yielded pumice fragments that have been geochemically analyzed (see Fenton et al. 1995). Unweathered samples of thicker, stiffer tephras often display upward-fining, graded interiors with the coarsest fraction either at or immediately above the base of the tephra layer (Figure 6a,b). The Sherman Falls tephra bed (lower part of Flat Creek Shale), the lower Wolf Hollow tephra bed (lower part of Flat Creek Shale), the Paradise tephra bed (basal part of Indian Castle Shale), and the Countrymen tephra bed (lower part of Indian Castle Shale) are thicker clay tephra units that show this internal grading texture.

Many clay-dominated tephra beds display thin planes of secondary carbonate at their bases and sometimes at higher levels within the bed (Zambito et al. 2005; Zambito and Baird 2006). These display internal slickensides indicative of tectonic shearing. Some tephras when followed along the outcrop, will expand and pinch out due to low-angle bed-slippage. Ongoing work with Jay Zambito (West Virginia University) is directed to measuring and plotting these slippage azimuths to determine their probable time of formation relative to major orogenies and ash illitization.

Calcite cemented tephras

A number of tephras in the Utica Shale succession are partly to entirely calcite cemented (Figure 6c,d,f). Where a tephra has been completely cemented, it can be easily mistaken in sections for a typical micritic limestone layer or a siltstone bed. However, close examination of such layers show that they differ from normal bedding in all facies types. Where this cemented concretionary phase is developed, the tephra is preserved as a pale, sometimes

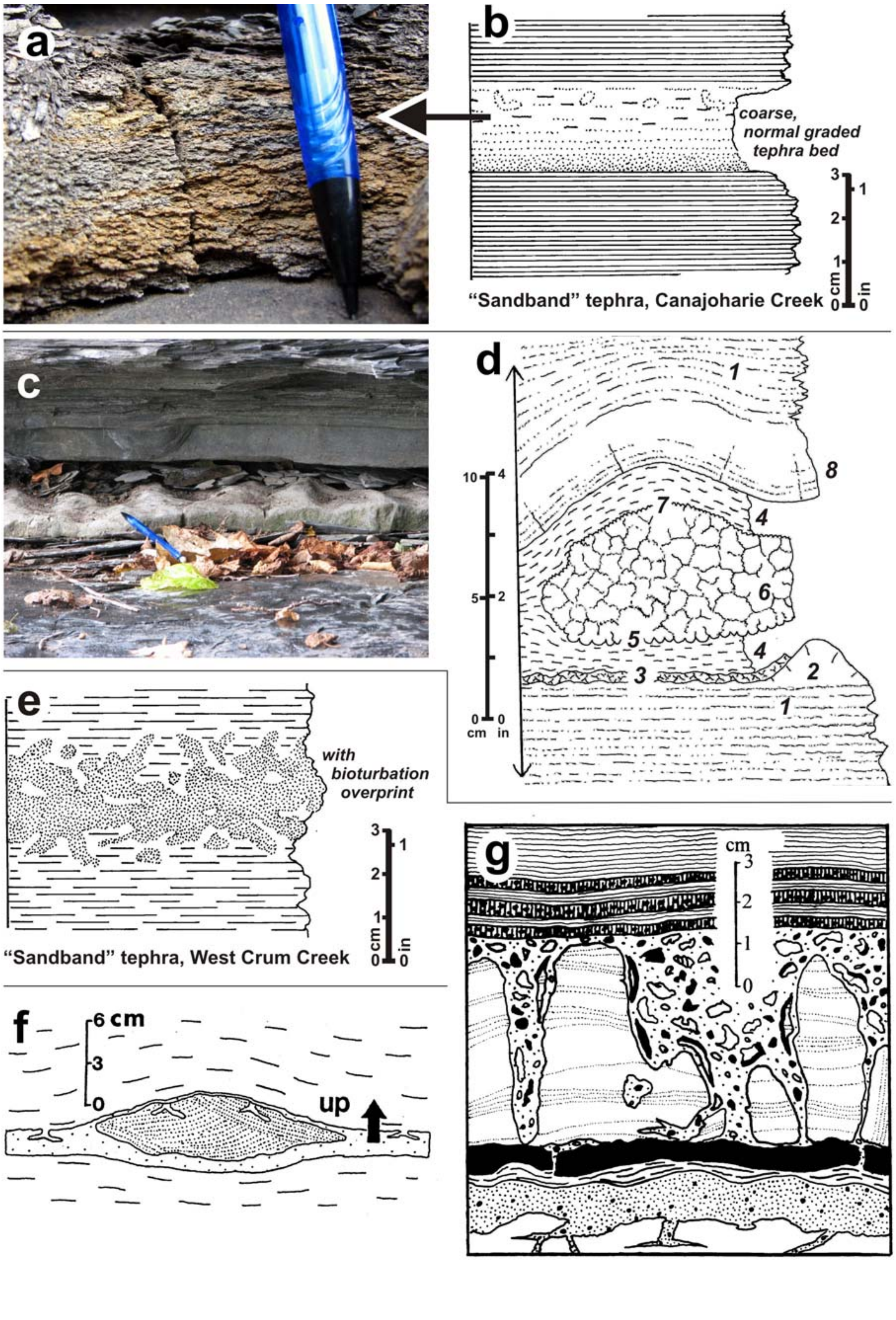

a
b
coarse, normal graded tephra bed
"Sandband" tephra, Canajoharie Creek
cm
in
c
d
1
8
7
4
6
5
4
3
2
1
cm
in
e
with bioturbation overprint
"Sandband" tephra, West Crum Creek
cm
in
f
6 cm
3
0
up
g
cm

Figure 6. Distinctive Ordovician tephra layers. a) Very coarse tephra bed ("sand band" K-bentonite) exposed at Canajoharie Creek (STOP 2); b) Schematic cross-sectional view of the sand band layer (a) showing weakly developed sedimentary grading and sharp basal, bed contact; c) Partially cemented tephra (possible Eatonville Ash bed (sensu Baird and Brett 2002) in the lower Indian Castle Shale at Otsquago Creek (STOP 1). Note pale colored, concretionary bed protruding from the outcrop reentrant. The top of this bed displays parallel ridges that may represent ripple marks; d) Schematic vertical cross-section of this same tephra bed. Note the prominent development of a laterally discontinuous concretionary bed that is surrounded by a clay tephra phase. Lettered features include: 1) enclosing black shale; 2) enigmatic concretionary? knob projecting upward into the ash bed interval from below; 3) basal zone of sparry cemented tephra phase; 4) soft, recessive, clay phase; 5) base of cemented interval displaying distinctive, pustulate, "bubbly" basal surface; 6) pale, sparry, coarsely crystalline, mosaic texture of carbonate nodule; 7) linear, parallel, ridge crests along top of nodular layer resembling "ripples"; 8) carbonate indurated shale bed displaying possible upward grading of tephra layer into overlying shale; e) Schematic, cross-sectional view of completely bioturbated sand band tephra layer as seen in equivalent, upslope, dysoxic facies at West Crum Creek west of St. Johnsville, New York; f) Cross-sectional schematic of limestone concretion within a gray clay tephra bed observed within the uppermost part of the Dolgeville Formation interval along Auries Creek upstream from (west of) the NY Route 30 A overpass bridge, south of Fultonville, NY (Baird and Brett 2002). Note development of cross-lamination indicative of lateral tephra transport by currents. Note also that this carbonate cementation preserved this sedimentary texture prior to later diagenetic alteration of the surrounding texture to clay. See text discussion (from Baird and Berkley (2002); g) Schematic cross-section of lag debris concentration associated with the Dolgeville Formation – Indian Castle Shale contact along Rathbun Brook southeast of Poland, NY. The topmost Dolgeville limestone bed in this section was subjected to intense corrosion as well as abrasion during the formation of this regional disconformity; as carbonate dissolved, insoluble material, including residual terrigenous mud, phosphatic debris, pyroclastic grains, and organic matter settled into solution fissures in a sediment-starved, dysoxic, slope setting. Tephra in this image has been variably admixed with non-ash constituents in a strongly condensed, multi-event deposit.

nearly whitish or pinkish limestone that often displays a distinctive, coarsely crystalline "mosaic" texture (Berkley and Baird 2002: Figure 6d). A given widespread tephra layer, such as the Countryman Bed, may be completely cemented in one section, non-cemented in a second, and partly cemented in a third. Partial cementation of ash is splendidly illustrated in the lower Indian Castle Member section along Otsquago Creek (Stop 1: Figures 5, 6c,d). This bed, possibly the Eatonville tephra bed (*sensu* Baird and Brett 2002; Berkley and Baird 2002), is a clay layer at one end of the exposure that passes laterally into a pale, nodular limestone layer with a distinctive coarse, internal texture of mosaic-like intergrown crystals (Figure 6c,d). Along its exterior, are protruding "popcorn-like" pustules that protrude into the surrounding clay tephra (Figure 6c,d). The pustulate concretionary surface may reflect the alteration of at least some of the volcanic ash/glass to zeolite minerals instead of smectite clays.

A second cemented tephra at Stop 1 best illustrates another aspect of the carbonate cementation process. Berkley and Baird (2002) describe remarkably well preserved glass shard textures from at least five tephras that indicate that the cementation process was early diagenetic and distinctly preceded the alteration of glass to clay. These shard textures represent glass vesicle walls replaced by smectite. Moreover, visible exteriors of apparent sand-size pumice grains, apparently preserved as pseudomorphed carbonate casts, have been recently discovered along the underside of a thin carbonate tephra layer in the lower part of the Indian Castle Shale along Otsquago Creek (see Stop 1; Figure 5). This same bed is marked by an abundance of quartz and mica phenocrysts along its base.

Inferred Tephra Sedimentology

Multi-event- and transported tephra deposits

Overview. Several thick and very widespread Ordovician tephras, most notably the Deicke and Millbrig beds in North America, have been attributed to massive eruptive episodes involving the expulsion of thousands of cubic kilometers of tuffaceous products, which display an extraordinarily broad distribution (Kolata et al. 1996). A larger number of thinner, less widely distributed tephras, comparable to tephras examined here, would have recorded great eruptions on a smaller scale or at greater distances. Although many tephras in the marine Ordovician succession display an internal upward-fining sediment texture, and many contain diverse volcanogenic phenocryst minerals, relict pumice textures, and a geochemical ash signature, a single air-fall event interpretation for all of these beds is premature (Berkley and Baird 2002). Moreover, what geological record would be expected in offshore marine settings for "big" single eruptions, such as Tambora, Krakatau, or Vesuvius, observed in historic time? Might these correspond to airfall dustings to the sea surface that are effectively erased by ocean current dispersal, bottom current transport, and bioturbation by infaunal organisms?

Tephra accumulation as background sedimentation. A specific volcanic eruption occurring today is an event emanating from a point source on a real-time frame of days to weeks for completion. Most such events should produce a discrete tephra layer, though it may be thin and prone to dilution owing to reworking by currents. Most such eruptions generate only a trace of tephra across areas hundreds or thousands of miles from the source. If a 0.5 - 1.0 cm-thick layer of tuff accumulates on the seafloor as a single event, burrowing organisms are likely to mix and blur part or all of this layer with underlying muds during a succeeding interval of hundreds of years or more. Moreover, thousands of eruptions along a very distant, upwind arc system theoretically should produce a blended ash component within slowly deposited and bioturbated marine muds on the temporal scale of geologic time. The degradative alteration of volcanic glass and feldspathic constituents in marine settings would further obscure the record of normal, real-time, volcanic events in shaly successions. The potential sedimentary record of such eruptions will be discussed at Stop 2.

Sediment traction by currents. Examination of carbonate-cemented Indian Castle tephras led to the discovery of current-generated cross-laminations in some of these beds (Figure 6f). Early diagenetic, partial to complete cementation of tephra layers preserved, not only relict, microscopic, tuffaceous textures, but also macroscopic bed-scale sedimentary structures. At Auries Creek, south of Fultonville, a thin clay tephra bed in the upper part of the Dolgeville Formation grades laterally into carbonate nodules that preserve cross-stratification generated by current traction (Figure 6f). Lateral termination of this current texture at the perimeter of this early diagenetic concretion reveals the degree of information loss as the original ash degraded to clay.

This indicates that shows that, at least, some of this tuffaceous material was moved by current traction along the sea bed. Given that the Indian Castle interval is a classic basinal black shale deposit, the cross-lamination is most likely linked to turbidity flow transport or the action of unspecified bottom currents. In the light of this discovery, it is particularly significant that these same beds, as well as almost all other tephra layers in the greater Dolgeville Formation and Utica Shale succession have knife-sharp lower contacts. This suggests that some tephras may have accumulated on scour surfaces floored by firm bottom muds.

Marine ash concentrations as lag deposits and/or time-rich facies. Several tephra beds in the greater Utica Shale succession are characterized by coarse, friable, "sandy" concentrations of volcanogenic clasts in nearly grain-supported texture throughout the tephra layer. Although these beds display variable amounts of associated soft, clay fraction, volcanogenic phenocrysts (quartz, apatite, micas, and zircons), comprise up to 25-30 % of the bed volume. Beds of this type are distinctly less common than the typical clay tephra bed, and they appear to record bigger eruptive events or ones distinctly closer to the source area.

However, we also document the occurrence of thin beds of bioturbated, coarse, volcanogenic phenocryst-rich, "sandy", dark shale or calcareous mudrock, distinctly lacking any, expandable clay fraction and containing admixed fossil debris. We interpret some of these clay-bearing and non-clay-bearing beds as representing time-rich tephra-rich lag concentrations associated with long-term sedimentary condensation and/or episodes of shorter-term bottom erosion (Baird et al. 1994; Baird and Brett 2001; Fenton et al. 1995; Berkley and Baird 2002).

The informally designated "sand band tephra" (Baird et al. 1994) particularly illustrates this condition (Figures 4, 5a,b,e). This layer, which occurs in the upper-middle part of the Flat Creek Shale, will be seen at Canajoharie Creek (Stop 2). It can be traced in sections from Florida Township, southeast of Amsterdam, westward to the vicinity of St. Johnsville. This bed ranges in thickness from 1.0 – 3.5 cm, and it displays a sharp base on underlying black shale deposits (Figure 6a,b). It is characteristically soft due to the clay component, except where it is cemented by concretionary carbonate. Viewed closely, the sand band displays a weakly graded accumulation of volcanogenic phenocrysts and exploded quartz fragments known as phenoclasts (Figure 6b). Distinctive grains including euhedral beta quartz crystals up to 1.0 mm in diameter and larger, sharp-edged, quartz phenoclast fragments up to 2.0 mm in the longest dimension. A thimble-full of distilled coarse grains can be easily isolated from the surrounding clay with the application of ultrasound. This layer can be sampled from the bed of Canajoharie Creek a short distance from our ingress route from the Wintergreen Park lower parking area at Stop 2.

To the west of St. Johnsville, the sand band grades laterally into a thin, pyroclastic shale bed distinctly lacking soft associated clay (Figure 6e). This phase, extensively bioturbated and characterized by admixed small fossils, can be seen along West Crum Creek (Figure 6e) and in a west-facing bank section along the reservoir lake on East Canada Creek above Ingham Mills. Still further west (upslope), this bed is tentatively correlated to an even thinner lag blanket of mixed pyroclastic and phosphatic debris in sections near Little Falls, on the up-thrown side of the Little Falls fault zone.

Tephra Distribution In Foreland Basin Context

The Indian Castle Shale is most condensed where it onlaps diachronously westward onto the regional, Thruway Unconformity surface, characterized by a widespread lag concentration of phosphatic debris, corroded carbonate clasts, and variable amounts of pyroclastic debris that accumulated under strongly dysoxic conditions (Figures 6g, 7). This unconformity surface is interpreted to represent an eastwardly sloping submarine ramp that marked the sediment-starved western slope of the foreland basin (Baird and Brett 2002). Tephra layers are observed to terminate westward onto this surface as the hiatus increases in time-magnitude (Figure 7). It is significant that several tephra layers (Paradise, Fishers, Eatonville, and Countryman beds) appear to thicken slightly westward towards their respective termini at the toe of the ramped erosion surface, rather than toward the east in the direction of the inferred orogen. Perhaps this eastward thinning is simply an artifact of differential tectonic compression and shearing of tephra deposits in eastern localities. However, another possibility is that tephra was differentially concentrated due to secondary reworking (downslope transport) from the adjacent ramp slope (see below).

We also observe an upward decline in the number of ashes and average thickness of tephra layers within the Utica shale succession across the Mohawk Valley region. Though there is a tendency for tephra beds to be bundled into groups of closely-spaced K-bentonite layers, both tephra bundles and isolated tephras trail off as one ascends through the Utica, such that tephras become very widely-spaced and thin in the upper parts of the Indian Castle Shale as progradational turbiditic facies of the Frankfort and Schenectady formations are approached (Baird and Brett 2002). It is particularly significant that these observations, based on outcrop work in the 1992 - 2001 period, predated examination of numerous long drill core sections by Baird, including three that extend from Grenville basement upward into the Schenectady succession (see: Baird and Brett 2006, 2008). This additional subsurface record corroborates the above observation that tephras become less common and thinner within the middle and upper portions of the Indian Castle succession. Inferential upward loss of tephra layers appears to have commenced within the upper part of the *Climacograptus spiniferus* graptolite biozone with near complete loss of observable tephras in overlying turbiditic facies (uppermost *C. spiniferus* and *Geniculograptus pygmaeus* biozones (see Goldman et al. 1994; Mitchell et al. 1994).

One explanation would be that Taconian arc activity could have slowed down or ceased following a transition from forearc subduction processes into the phase of high Taconic overthrusting. Cessation of the subduction process would have resulted in a significant reduction of, or the end of, volcanism along the proximal arc system, leading to a trailing off

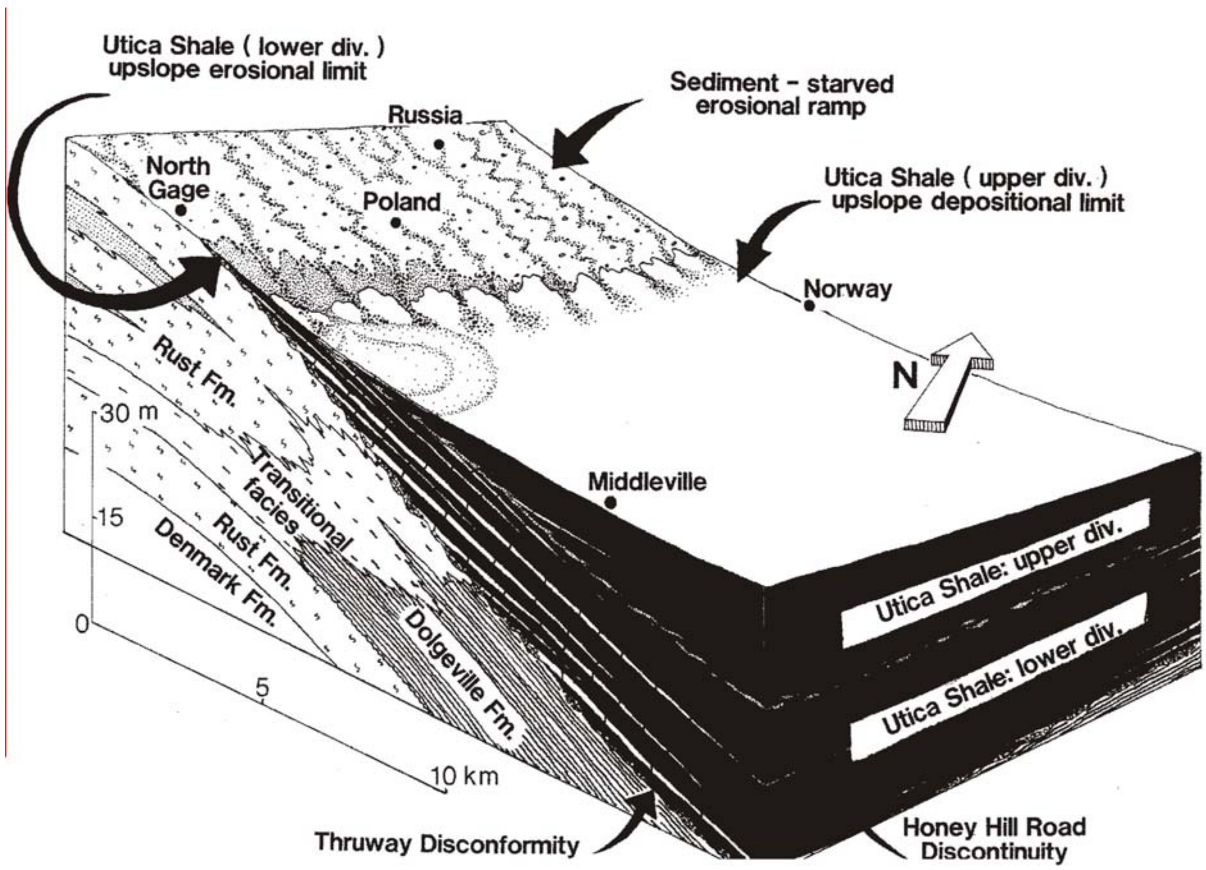


Figure 7. Process model showing onlap of condensed black Utica mud deposits onto a sediment-starved, east-facing basin margin slope during deposition of the upper part of the Indian Castle Shale. This erosional ramp corresponded to the subsiding west side of the expanding foreland basin; progressive burial of this surface produced a widespread corrosional-erosional disconformity in the westernmost Mohawk Valley region and across adjacent central New York State. Note the westward onlap of several lower Indian Castle tephras onto the older Thruway Unconformity surface (Baird and Brett (2002).

of aerial tephra supplies to the foreland basin sea. However, foreland basin sedimentary dynamics may have exerted an even greater effect. The most closely-spaced and thickest tephra layers are focused, in stratigraphically condensed, time-rich Indian Castle sections above the Thruway Unconformity in western Mohawk Valley sections (Little Falls-Middleville area; Figure 7). In this detrital mud-starved setting, tuffaceous sediment would have become more concentrated, particularly with the tractional effects of bottom currents. Moreover, several dilute tephra-rich calcareous siltstone beds in the basal 1.0-2.0 meters of the Indian Castle Shale, in sections west of the Little Falls Fault, suggest that tuffaceous material deposited on the eastward-, and southward-sloping, onlap ramp, may have been swept down that ramp and deposited as turbiditic layers within onlapping Utica black mud deposits (Figures 6g, 7). Hence, black shale deposits, comprising the basal part of the Indian Castle Shale above the Thruway Unconformity, should be particularly potassium-rich, owing both to sediment condensation and to downslope tuff transport from the nearby submarine onlap slope.

V. THE DEVONIAN TEPHRA RECORD, AND COMPARING FORELAND AND HINTERLAND RECORDS OF EXPLOSIVE VOLCANISM (Chuck Ver Straeten)

Devonian tephra beds, New York and the eastern U.S.

The convergence of multiple terranes with eastern Laurentia between the latest Silurian to early Mississippian resulted in orogenesis and magmatic arc magmatism and extrusive to explosive volcanism (Acadian orogeny; = Acadian and Neo-acadian orogenies of van Staal 2007 and van Staal et al. 2009). The orogeny developed over multiple tectonically-active to -quiescent phases (Ettensohn 1985, 2008; Ver Straeten 2010), a result of the multiple collisions and oblique convergence, seen in an overall northeast to southwest development of the orogen and sedimentation in the adjacent Acadian foreland basin system. Explosive eruption of silicic tephra in the orogen, and its subsequent transport, deposition and burial history, followed patterns outlined in the “Volcanic Tephra Processes” section earlier in this paper.

The record of explosive silicic volcanism during the Acadian Orogeny is, at least in part, recorded by airfall volcanic tephras preserved sedimentary rocks in New York and across the eastern U.S. Forty years ago, only a few such beds were known. Currently, approximately 100 volcanic airfall tephras are reported from Devonian strata in the Appalachian, Michigan, Illinois and Iowa basins (Table 1).

Many of the documented Devonian tephra beds occur within one of five clusters of relatively closely spaced beds (Table 1, Figure 8). Others, however, occur as a single isolated to a few closely spaced beds, sometimes within thick strata with no other apparent volcanogenic layers. The five clusters generally consist of 8 to 15 beds each, although in areas proximal to the apparent volcanic source, Dennison and Textoris (1988) report as many

TABLE 1. DEVONIAN AIRFALL TEPHRAS, APPALACHIAN BASIN/EASTERN U.S.

Major Devonian airfall tephra clusters:

Bald Hill K-bentonites cluster. Lower Devonian, mid Lochkovian, 417.6±1.0 Ma (Tucker et al. 1998). Up to 15 K-bentonites in cluster; NY, PA, MD, VA, WV; in NY, within Kalkberg and New Scotland Fms.; elsewhere within Corriganville and Mandata Fms. Smith et al. 1988, 2003; Shaw et al. 1991; Hanson 1995, Ver Straeten 2004a; Benedict 2004.

Sprout Brook K-bentonites cluster: Lower Devonian, lower Emsian (?), 408±1.9 Ma, (Tucker et al. 1998). Up to 15 K-bentonites in cluster; eastern NY, possibly VA and WV; In NY, in lower part of Esopus Fm.; elsewhere in basin, if present, at base of Beaverdam Mbr., Needmore Fm., Virginia. Ver Straeten 1996, 2004a&b, 2010; Benedict 2004; Ver Straeten et al. 2005.

Tioga Middle Coarse Zone cluster (recognized in Ver Straeten 2004a as separate from Tioga A-G K-bentonites cluster): lower Eifelian, 391.4±1.8 Ma, (Tucker et al. 1998); up to 32 tuffs and K-bentonites in cluster; restricted to southern part of Appalachian Basin, in parts of VA, WV outcrop belt; occurs within upper part of Needmore Fm., or "Tioga Zone". Dennison and Textoris 1970, 1978, 1987; Dennison 1983; Ver Straeten 2004a, 2007a.

Tioga A-G K-bentonites cluster (recognized by Ver Straeten 2004a as separate from Tioga Middle Coarse Zone cluster). Middle Devonian, lower Eifelian, 390±0.5 Ma, (Roden et al. 1990). Up to 9 K-bentonites in cluster; NY, PA, MD, VA, WV, OH. In NY within Onondaga Fm.; in other states within Onondaga Fm. (eastern PA), Selinsgrove Mbr., Needmore Fm. (PA, MD, VA, WV), Columbus Fm. (OH), and/or lower part of Marcellus Shale locally (PA, MD, VA, WV). Conkin and Conkin 1979, 1984; Smith and Way 1983; Way et al. 1986; Brett and Ver Straeten 1994; Ver Straeten 2004a, 2007a; Benedict 2004.

Belpre K-bentonites Cluster. Upper Devonian, Frasnian, 381.1 +/- 1.3 Ma (Tucker et al. 1998). Up to 8 K-bentonites in cluster; in Rhinestreet Fm. in western NY, and equivalent strata in TN to PA. Collins 1979; Over 2007.

Other Devonian airfall tephras:

Sub-Schoharie Fm. K-bentonite. Lower Devonian, mid Emsian. Single bed; found only in east-central NY, at Esopus-Schoharie Fms. contact; not recognized elsewhere in basin; bed rests on unconformity (shale firmground), and contains glauconite and phosphate. Hanson 1995; Ver Straeten 2004a.

Sub-Onondaga Fm. K-bentonite. Lower Devonian, upper Emsian. Single bed; found exclusively in east-central New York, at Schoharie-Onondaga Fms. contact; not recognized elsewhere in basin; bed rests on an unconformity, and contains glauconite and phosphate. Ver Straeten 2004a.

Other Onondaga Fm. K-bentonites. Middle Devonian, lower Eifelian; up to 8 separate beds scattered through Fm., not within the Tioga Middle Coarse Zone or Tioga A-G K-bentonite clusters; through NY, PA, MD, VA, WV, OH; in New York within the Onondaga Fm.; elsewhere within Onondaga Fm. (eastern PA), Selinsgrove Mbr. of the Needmore Fm. (PA, MD, VA, WV) and Columbus Fm. (OH); key references; Conkin and Conkin 1979, 1984; Ver Straeten 1996, 2004a.

Mid-Union Springs Fm. K-bentonite. Middle Devonian, mid Eifelian. Single bed; found in NY, PA, MD, VA, WV, OH; in NY in the middle of the Union Springs Fm.; elsewhere within the Marcellus Fm. (PA, VA, WV), Millboro Fm. (VA, WV) or Delaware Fm. (OH). Ver Straeten 2004a.

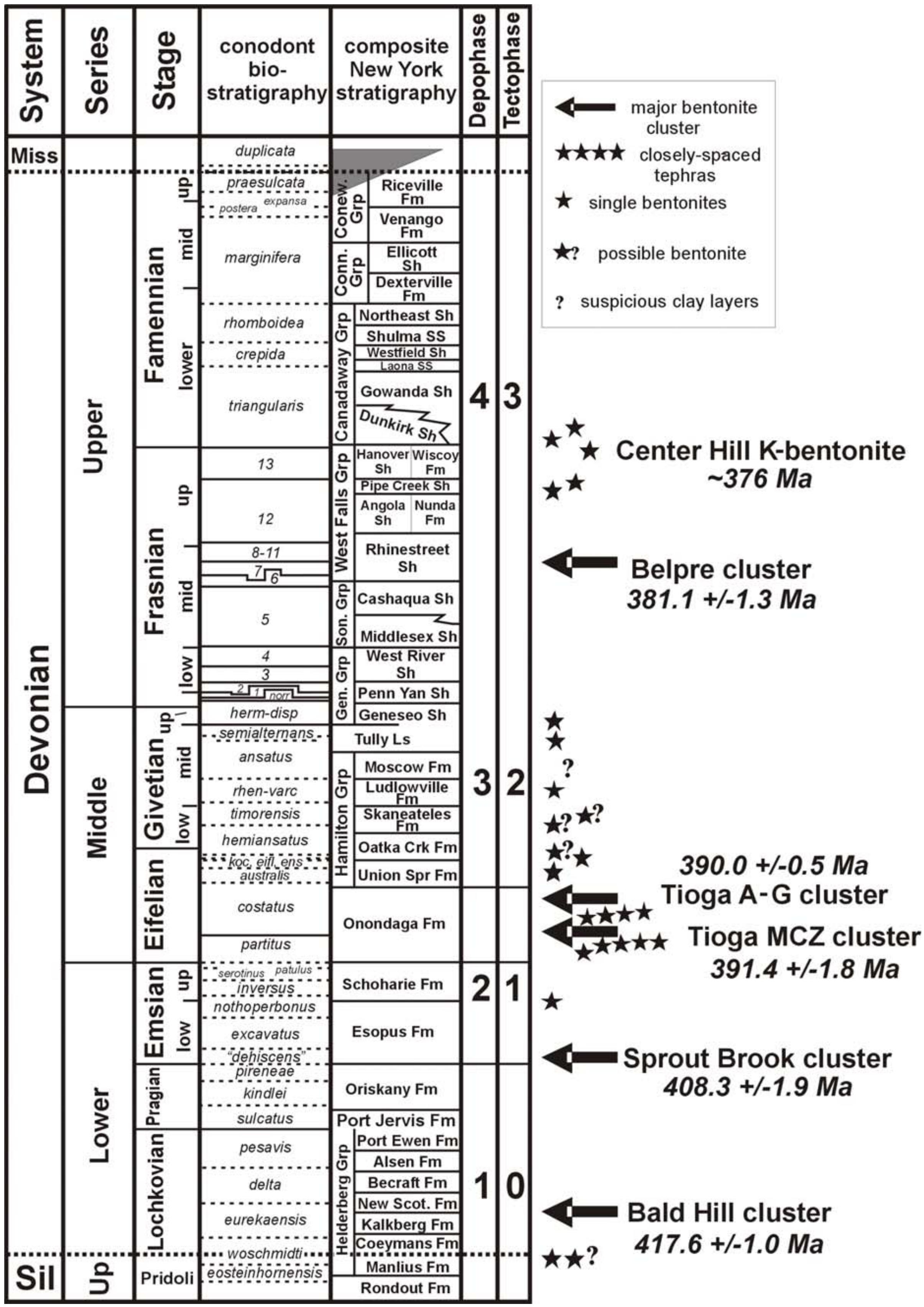
Sub-Cherry Valley K-bentonite. Middle Devonian, upper Eifelian; single bed; only recognized locally in NY. Not in VA, as reported by Ver Straeten 2004a. In NY, occurs immediately below the Cherry Valley Mbr. of the Oatka Creek Fm. Hanson 1995; Ver Straeten 2004a.

Additional Occurrences

Kashong-Windom mbrs. contact, Moscow Fm., mid Givetian, western NY. Wilcott and Over 2005.
Lower Geneseo Fm., upper Givetian, western NY. Over, Baird notes.
Lower & upper Pipe Creek Fm., upper Frasnian, western NY, possibly OH. Over et al. 1998. (2 beds?).
Center Hill K-bentonite, upper Hanover Fm., western NY; also reported in TN, possibly MI, IA. Over 2002.
Lower Dunkirk Fm., Tioga Dam, PA. D.J. Over notes.
Uppermost Olentangy Fm., OH. Over and Rhodes 2000.

Other Possible Devonian Airfall Tephra Beds

Lowest Otsego Mbr., Mount Marion Fm., lower Givetian, eastern NY. Ver Straeten 2004a.
Basal Butternut Mbr., Skaneateles Fm., Givetian, central NY. Ver Straeten notes, 1996.
"Probable bentonites", Wanakah Mbr., Ludlowville Fm., mid Givetian, western NY. Batt 1996.
Possible K-bentonites, Tully Fm., central NY, upper Givetian. Baird notes, and Ver Straeten notes, 1996.


System
Series
Stage
conodont biostratigraphy
composite New York stratigraphy
Depophase
Tectophase
major bentonite cluster
closely-spaced tephras
single bentonites
possible bentonite
suspicious clay layers
Miss
Devonian
Sil
Upper
Middle
Lower
Up
Famennian
Frasnian
Givetian
Eifelian
Emsian
Pragian
Lochkovian
Pridoli
duplicata
praesulcata
postera
expansa
marginifera
rhomboidea
crepida
triangularis
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sulcatus
pesavis
delta
eurekaensis
woschmidti
eosteinhornensis
Riceville Fm
Venango Fm
Ellicott Sh
Dexterville Fm
Northeast Sh
Shulma SS
Westfield Sh
Laona SS
Gowanda Sh
Dunkirk Sh
Hanover Sh
Wiscoy Fm
Pipe Creek Sh
Angola Sh
Nunda Fm
Rhinestreet Sh
Cashaqua Sh
Middlesex Sh
West River Sh
Penn Yan Sh
Geneseo Sh
Tully Ls
Moscow Fm
Ludlowville Fm
Skaneateles Fm
Oatka Crk Fm
Union Spr Fm
Onondaga Fm
Schoharie Fm
Esopus Fm
Oriskany Fm
Port Jervis Fm
Port Ewen Fm
Alsen Fm
Becraft Fm
New Scot. Fm
Kalkberg Fm
Coeymans Fm
Manlius Fm
Rondout Fm
Conew. Grp
Conn. Grp
Canadaway Grp
West Falls Grp
Son. Grp
Gen. Grp
Hamilton Grp
Helderberg Grp
Center Hill K-bentonite
~376 Ma
Belpre cluster
381.1 +/-1.3 Ma
390.0 +/-0.5 Ma
Tioga A-G cluster
Tioga MCZ cluster
391.4 +/-1.8 Ma
Sprout Brook cluster
408.3 +/-1.9 Ma
Bald Hill cluster
417.6 +/-1.0 Ma

Table 1. Reported Devonian Airfall Tephra Beds, Eastern U.S. Based on compilation of data from various sources, summarized in Ver Straeten et al. (2007) and Ver Straeten (2010). Modified from Ver Straeten (2010).

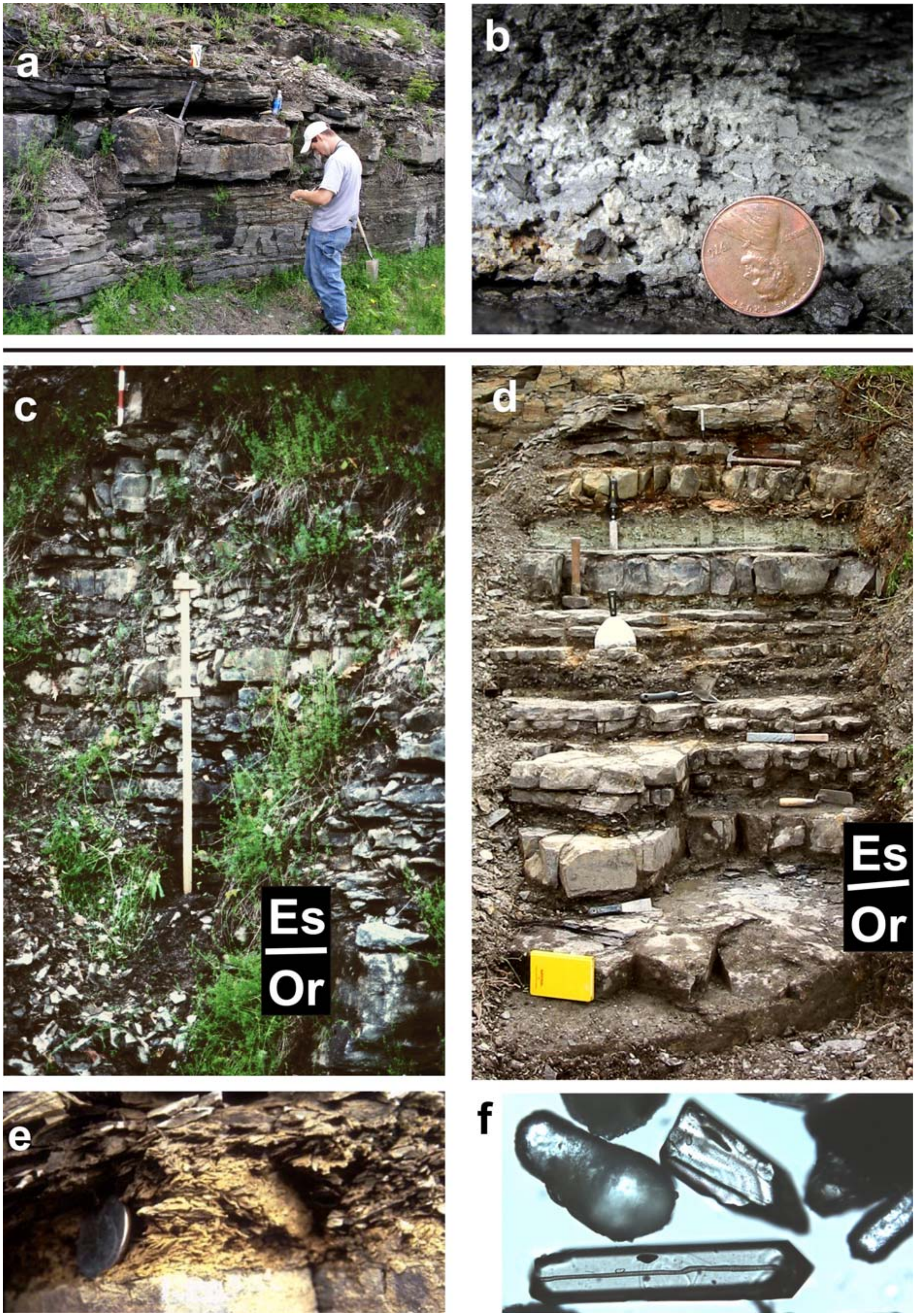
Figure 8. Stratigraphic occurrence of reported airfall volcanic tephra beds in the Devonian, eastern U.S. Major clusters marked by arrows; stars mark individual beds; stars with question marks denote possible additional beds. Occurrences plotted against generalized New York stratigraphy and biostratigraphy. Detailed information provided in Table 1. Modified after Ver Straeten (2010).

as 44 beds in the Middle Devonian Tioga Middle Coarse Zone. These tephra-rich intervals appear to indicate times of greater volcanism in the Acadian magmatic/orogenic belt (see discussion below, and in Ver Straeten 2004a).

In New York the major clusters occur, from older to younger, in the Lower Devonian Kalkberg and New Scotland formations (Bald Hill Tephras; Figures 8, 9a,b); the lower part of the Lower Devonian Esopus Formation (Sprout Brook Tephras; Figures 8, 9c-f'); apparently in the middle of Middle Devonian Onondaga equivalent strata in the Needmore Formation in Virginia and West Virginian only (Tioga Middle Coarse Zone; see note below); and in the upper Onondaga Formation (Tioga A-G Tephras; Figures 8, 10a,b,d-g); and in the Upper Devonian Rhinestreet Formation (Belpre Tephras). The Bald Hill, Tioga A-G, and Belpre tephras are found in equivalent strata around the Appalachian basin, and sometimes into the cratonic basins. In contrast, the Sprout Brook tephras and apparently the Tioga Middle Coarse Zone have a more restricted distribution (New York, and Virginia-West Virginia, respectively).

Most of the Devonian airfall tephras are preserved as altered, clay-rich K-bentonites. In the southern Appalachian basin (VA, WV) beds of the Tioga Middle Coarse Zone occur as crystal-rich sandy "tuffs", often largely comprised of biotite phenocrysts. Even in western New York, freshly exposed beds in the Tioga A-G cluster may be tuffaceous, with common to abundant fine biotites in a lithified matrix.

Geochronologic age dates for the Devonian tephras presented here are from Tucker et al. (1998). It should be noted, however, that at least some of the dates have been recalculated by different authors (e.g., Williams et al. 2000; Kaufmann 2006). Interestingly, the Geologic Time Scale of 2008 (Ogg et al. 2008) sometimes payed little attention to dated tephra numbers when assigning ages to boundaries between Devonian stages (e.g., the clearly mid Eifelian-age Tioga tephras clusters, at 390 and 391 Ma, fall within Ogg et al.'s 2008 range of ages given for the succeeding Givetian Stage).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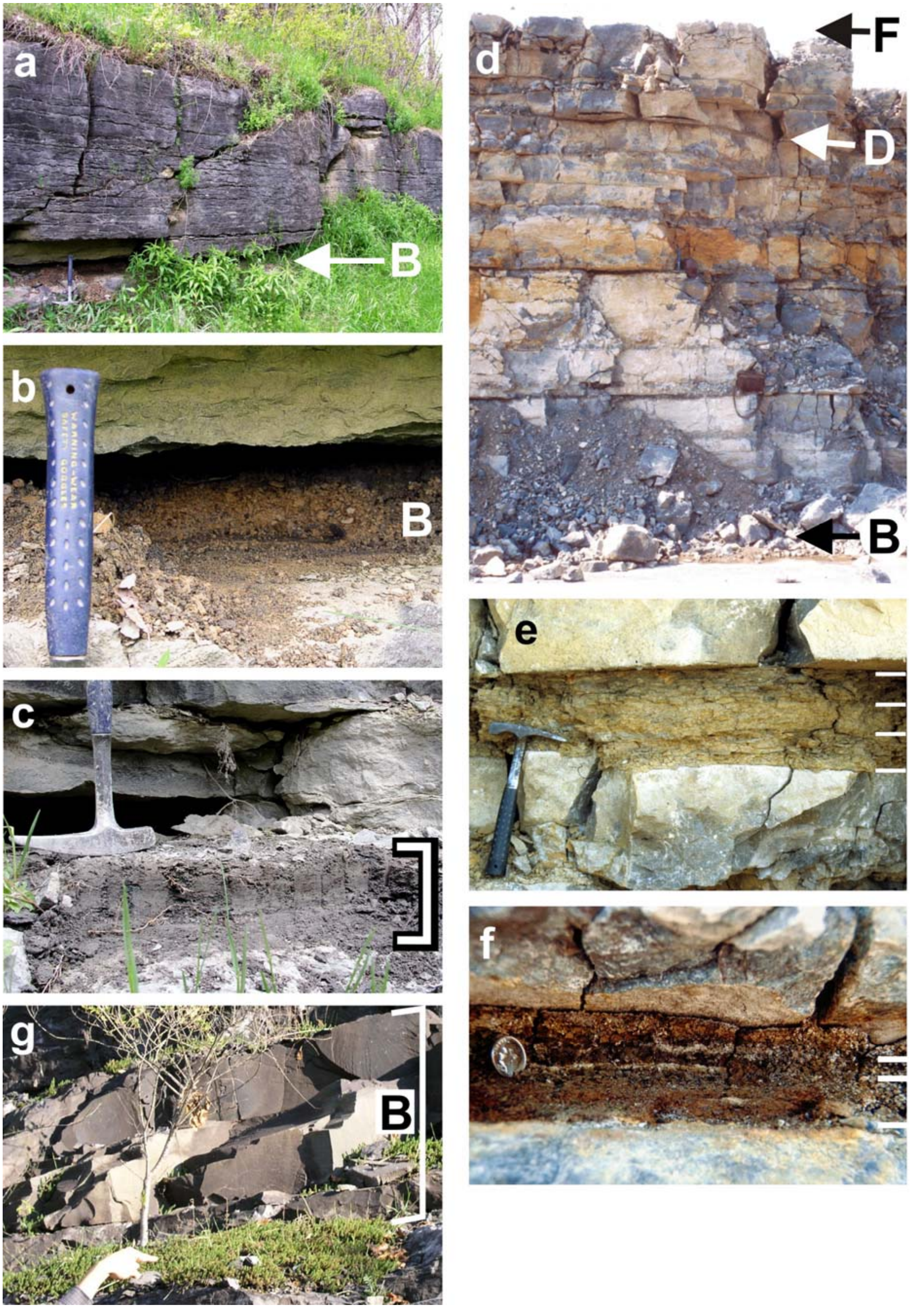
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Figure 9. Lower Devonian Tephras, Cherry Valley and other localities, eastern New York. a) Outcrop view of Rickard's original clay-rich tephra, in prominent crevice above head level. From the Bald Hill Tephra Cluster, Kalkberg Formation, Cherry Valley. b) close-up of Rickard's K-bentonite; original volcanic glass ("ash") altered to clays. Penny for scale. c) Outcrop view of lower part of the Esopus Formation, Cherry Valley. Fifteen clay beds of the Sprout Brook Tephra cluster are interbedded with shales, cherts and siliceous siltstones. Jake staff at center is 1.5 meters tall. d) Outcrop of Sprout Brook cluster 19 miles to the east-southeast, along I-88 near Cobleskill. Field book marks Oriskany-Esopus formational contact. e) Close-up of thin Sprout Brook tephra bed, along NY Rte. 23a, southwest of Catskill. Quarter for scale. f) Zircons and apatites from lower part of 12 cm-thick Sprout Brook tephra bed, 2.7 m above Oriskany Fm. at Cherry Valley. Note zoning in zircon fragment (upper center); apatites to left and right. Lower zircon is approximately 800 microns in length.

Figure 10. Middle Devonian Tephras, Onondaga Limestone, Cherry Valley and other localities. . a) Seneca Member of Onondaga Limestone at Stop 4 of this trip. Prominent crevice of Tioga B Tephra visible at base. Hammer for scale in lower left, at base of outcrop. b) Close-up view of Tioga B at Stop 4, showing 12 cm-thick K-bentonite clay bed. Deep recession due to bioerosion (decades of geologists collecting samples). c) Impure tephra at unconformable base of Onondaga Limestone, in bracketed interval. North side of Rte. 20, ca. two miles west of Stop 4. The clay-rich bed contains a mix of volcanic phenocrysts, detrital sand, and authigenic glauconite and phosphate grains, indicative of a complex history of tephra accumulation and mixing with background sediments over time. Hammer for scale. d) Complete development of Seneca Member, with Tioga tephra beds A through F. At quarry west of Honeoye Falls, Monroe County, western New York. For details, see Ver Straeten et al. (1994). Camera bag at lower prominent crevice for scale. e. Tioga B tephra bed in quarry west of Stafford, Genesee County, western New York. White bars on right delineate three distinct layers within Tioga B, a pattern seen in multiple exposures. At the Honeoye Falls Quarry (Figure 10d), Gordon Baird found two smothered fossil assemblages within the Tioga B, apparently at these same positions – these lines of evidence indicate a complex depositional history to the Tioga B tephra. f) Fresh exposure of the Tioga D tephra bed, also at Honeoye Falls quarry. White bars on right denote positions of three light gray bands of concentrated volcanic phenocrysts, each overlain by brown clays (=fine volcanic glass), again indicative of a complex depositional history prior to burial of the tephra layer. Dime for scale. g. Anomalously thick outcrop of Tioga B Tephra on south side of Interstate 80, Stroudsburg, PA (between brackets). The Tioga B at this locality is uncharacteristically thick, coarser and well-lithified. As in New York, it also features internal fossil-rich layers, sharp grain-size changes vertically, and other features that again show a complex depositional history over a broad swath of the Appalachian basin. Wrist and hand for scale in lower left.

A significant issue that is currently unresolved involves interpreted correlations of the two Tioga tephra clusters. Ver Straeten (2004a, 2007b) correlated the Tioga A-G cluster from New York and Pennsylvania with the upper of two mid Eifelian (lower Middle Devonian) tephra clusters along the Virginia-West Virginia border area, in contrast to earlier work by Dennison (e.g., Dennison and Textoris 1970, 1978, 1987; Dennison 1983), Subsequent fieldwork by Ver Straeten through Maryland and northern outcrops in Virginia and West Virginia, and discussion with T. Carr (West Virginia University) in 2011 raise questions about the correlation. Further fieldwork, possibly with geochemical fingerprinting of phenocrysts, is needed to resolve the issue.

The post-depositional history and preservation of Devonian tephra beds in the eastern U.S. has been previously examined by Ver Straeten (2004a, 2008), Benedict (2004), and Ver Straeten et al. (2005; see also Figure 10c,e-g). A strong understanding of the depositional history of the tephra beds is important, to attempt to filter out potential preservational biases in the record of explosive silicic volcanism in sedimentary successions, as outlined in the later part of the previous section. Do some conditions in sedimentary environments preferentially preserve, or alternatively destroy and alter the sedimentary record of paleovolcanism? These issues need to be examined and reasonably resolved prior to attempting to use the sedimentary airfall tephra record as a proxy for paleovolcanism. For further discussion and application to explosive Devonian volcanism during the Acadian orogeny, see Ver Straeten (2004a, 2008, 2010).

Crossing the boundary: An example comparing foreland and hinterland records of silicic magmatism

If the overall time distribution of Devonian airfall tephras in New York and the eastern U.S. is not a product of preservational biases (as discussed in the "Volcanic Tephra Processes" section above), and they do reflect a coarse record of paleovolcanism, then the major clusters should reflect times of more significant silicic magmatism in the hinterland. Therefore, one would suspect greater volcanism in the Acadian magmatic arc in the Lower Devonian at around 417 Ma (Bald Hill cluster) and 408 Ma (Sprout Brook cluster); in the Middle Devonian at around 391 Ma (Tioga Middle Coarse Zone) to 390 Ma (Tioga A-G cluster); and around 381 Ma (Belpre cluster; dates from Tucker et al. 1998, except Tioga A-G from Roden et al. 2000). The additional scattered tephra beds through the stratigraphic column may imply lower levels of background volcanism, at least at times if not continuously.

In recent years, an increasing number of plutonic and volcanic igneous rocks have been geochronologically dated in the hinterland (New England and adjacent maritime Canada), to compliment dates on the foreland basin tephras. Error bars on a relatively large number of dated lower Emsian-age igneous rocks in the hinterland overlap with the error bars on Tucker et al.'s (1998) age for the Lower Devonian Sprout Brook tephras, in the lower part of the Esopus Formation of New York (Table 2). No silicic igneous rocks of the same age are known to the author at this time south of New England.

As noted above, the Sprout Brook Tephras have a very restricted distribution across the foreland, apparently only developed in eastern New York (Ver Straeten 2004b). In the

TABLE 2. LOWER EMSIAN IGNEOUS ROCKS, ACADIAN OROGEN AND FORELAND
(WITH ERROR BARS THAT OVERLAP WITH AGE OF THE SPROUT BROOK K-BENTONITES)

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

Table 2. Lower Emsian (Lower Devonian) igneous rocks, Acadian orogen and foreland. Error bars of all units overlap with error bars of Tucker et al.'s (1998) date for the Sprout Brook K-bentonites in eastern New York. From Ver Straeten (2010).\

absence of distinct K-bentonite beds from the equivalent position to the southwest in Pennsylvania, Maryland, Virginia, and West Virginia, bulk samples of shales were collected

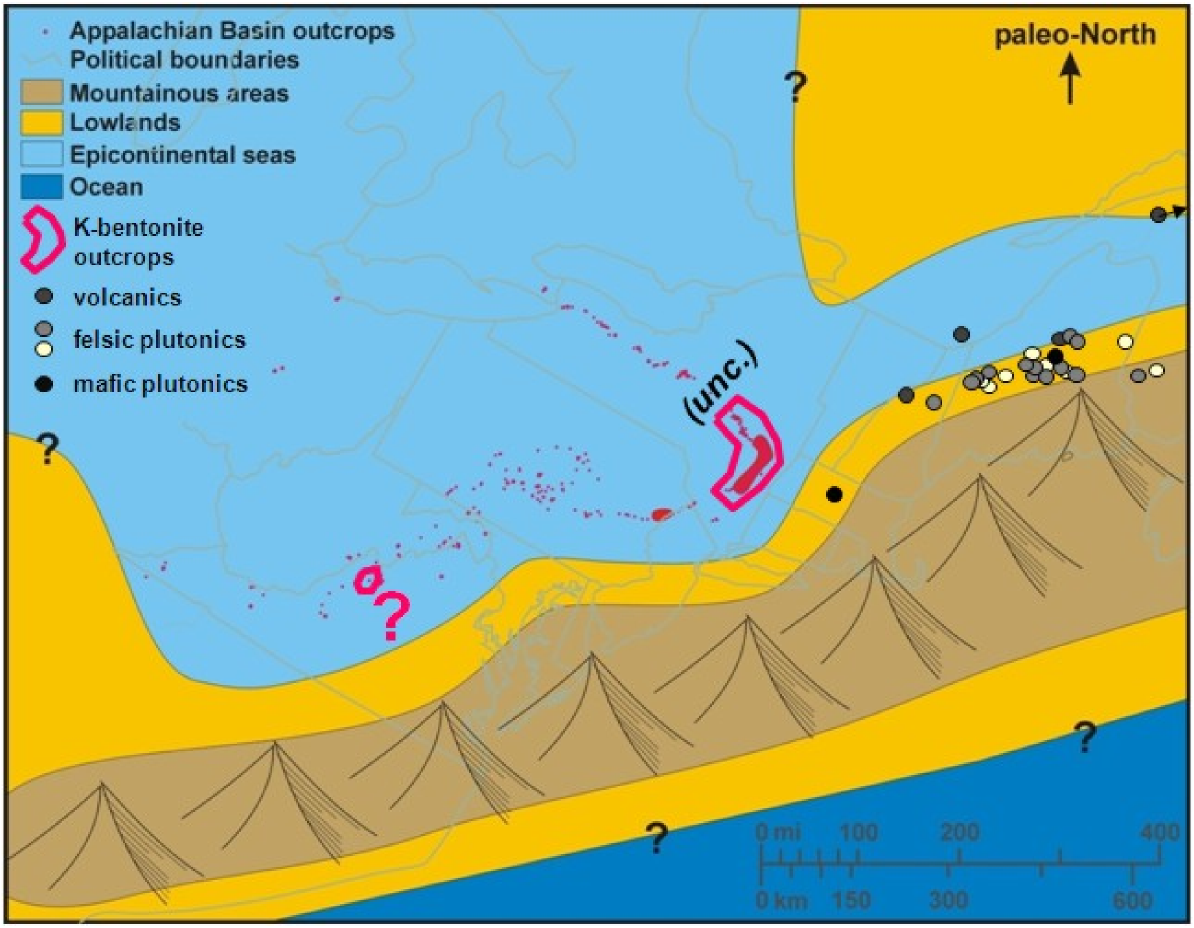

Figure 11. Lower Emsian igneous rocks, Acadian orogen and foreland. Map of distribution and type of lower Emsian–age igneous rocks within margin of errors of Tucker et al.'s (1998) age for the Sprout Brook tephra cluster in eastern New York. For details see Table 2. Positions of the front edge of the orogen and marine strata in Maine and adjacent areas are after Bradley et al. (2000). From Ver Straeten (2010).

and processed. Only one or two samples yielded apparent unabraded zircons of possible volcanogenic origin (Ver Straeten 2004b).

At least two significant non-volcanic factors could account for the restricted distribution of lower Emsian tephras across the Appalachian Basin. A first hypothesis is that tectonic-related subsidence at the onset of a new phase of Acadian uplift began earlier in the northeast part of the basin. If this is so, it is possible that the Sprout Brook Tephras were preferentially preserved in deeper water facies in eastern New York, while other portions of the basin remained longer in shallow water facies (Oriskany Sandstone), and tephra sediments became mixed with background sediments. No high resolution biostratigraphic data (e.g., conodonts, goniatites, dacryoconarids) is available to test this. However, Ver Straeten (2007b, 2009) was able to correlate all three third order (apparently global) sea level cycles that comprise the Esopus Formation from eastern New York to southwest Virginia – including the lower cycle, which features the Sprout Brook Tephras in New York. Therefore, some record of volcanism should also be preserved southwest of New York.

A second hypothesis is that enhanced preservation of the Sprout Brook beds in eastern New York could be related to higher sedimentation rates in the northeast portion of the basin. This would result in more rapid burial, leaving less time for physical and biological mixing of airfall pyroclastic sediments with background sediments at the sea floor, essentially erasing the record of volcanism – as potentially may have occurred more distal portions of the basin. However, the paucity of unabraded zircons in the shale samples from the central Appalachians makes the possibility of obliteration by mixing unlikely.

A third major hypothesis is that the restricted distribution of the Sprout Brook Tephras is related to a high concentration of lower Emsian-age silicic magmatism (at roughly 408 Ma) in New England and nearby Maritime Canada (Table 2, Figure 11). The bulk of these occur in Maine; they include the co-magmatic Katahdin Granite and Travel Rhyolite, the largest of five lower Emsian volcanic centers of the Piscataquis Volcanic Belt of north-central to western Maine (Rankin 1968). The preserved volume of ash flow tuffs of the Traveler Rhyolite is "conservatively" estimated to be 800 km^3, a "significant world occurrence of ash flow tuff" (Rankin and Hon 1987). This volume, preserved over the northeast corner of the Katahdin Pluton, is comparable with major Cenozoic tuffs in the western U.S., including the Lava Creek Tuff in the Yellowstone Caldera (more discussion in Ver Straeten 2004b). Furthermore, the approximately 3.2 kilometer-thick ash-flow tuffs of the preserved portion of the Traveler Rhyolite was deposited over an interval on the order of 1 million years (base at 407.3 ± 0.5; top at 406.7 ± 1.4 Ma; Rankin and Tucker 1995; Bradley and Tucker 2002).

The abundance of Sprout Brook age-equivalent volcanic and plutonic rocks in New England and adjacent areas in Canada, especially the great volume in the Piscataquis Volcanic Belt in Maine, suggests that the restricted distribution of New York's Sprout Brook Tephras could reflect explosive volcanic sources to the northeast (Figure 11). Considering the paleogeographic rotation of the eastern Laurentian margin at that time, and prevailing trade winds north of 30 degrees south (blowing to the west-northwest), eastern New York may have lain on the southern fringe of the prevailing pathway of airborne tephra sourced from Maine, approximately 400 to 500 km to the northeast. More distal areas of the Appalachian basin, further to the southwest, may have been beyond the margin of transport for explosive silicic pyroclastics from the Piscataquis Volcanic Belt and other northern New England sources.

SUMMARY

The Appalachian record of silicic magmatism and explosive volcanism is contained in the magmatic and volcanic rocks of the Appalachian hinterland, and in the sedimentary record of volcanic layers in the adjacent foreland, and sometimes the more distal cratonic basins beyond it. It is through a fusion of these diverse and varied data sets/perspectives from both hinterland and foreland basin records that we can approach a greater understanding of the history, character and timing of silicic magmatism and explosive volcanism in the Appalachians, through the early to mid Paleozoic.

This paper and field trip represent a first attempt at such a broader synthesis. Some key points include:

- By any name (tephra, K-bentonite, tuff), airfall volcanic layers in sedimentary rocks have a complex history, from the initiation of an eruption in a magma chamber to final burial, and diagenetic alteration.
- "Tephra" beds in sedimentary successions provide a relatively high resolution, if incomplete, record of volcanism through time. Biases of tephra event preservation in sedimentary environments must, however, be accounted for. Only rarely does a single layer represent a single eruption event; and many events are not preserved. Does the preserved tephra record provide a coarse outline of volcanism through time? If so, for example, there should be increased volcanism during the Devonian Period at around 417, 407, 390, and 381 Ma; and upper Lower Devonian tephras in eastern New York (Sprout Brook Tephra cluster) should be sourced in northern New England +/- adjacent maritime Canada.
- Geochemical tools such radiometric dating, isotopic analysis, and other geochemical data provide a range of perspectives on ancient silicic magmatism and explosive volcanism. These include age, composition, source characteristics and petrogenetic origins. For

example, strontium and neodymium isotopic analyses from apatites in Ordovician K-bentonites from the Taconic foreland, and from igneous and metaigneous rocks in the Taconic hinterland, indicate that magmatic sources were "evolved" – that the magmas extensively interacted with continental crust prior to crystallization below the surface, or to their eruption. And that the crust involved was Grenville (i.e., Laurentian).

- Late Ordovician airfall tephras in the Mohawk Valley have a complex sedimentologic, preservational and diagenetic history. Condensation processes play an important part in the post-depositional history of many layers. Volcanic glass ("ash") in some beds altered to smectite-rich clay beds, and subsequently to potassium-rich mixed layer illite-smectite clays; however, in some beds glass was altered to zeolite minerals, and/or were cemented early. Reworking and condensation on the sea floor at times led to the formation of relatively coarse-grained tuff layers. Foreland basin flexure, during the onset of new tectonic pulses, may also affect the preservation of tephra beds, which may vary laterally from proximal to distal areas across the foreland.
- Finally, foreland and hinterland data of silicic magmatism and explosive volcanism in the Ordovician and Devonian Appalachian region both have strengths and weaknesses. The integration of information from the foreland basin and hinterland, utilizing high-resolution geochronologic age dates, has tremendous potential for advancing our understanding of not only magmatic history, but also broader tectonic processes and events involving both parts of the orogen. This could possibly include significant questions such as the possibility and timing of slab break-off events, reversals in subduction polarity, and the timing of migration of the deformation front into the foreland.

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FIELD TRIP ROAD LOG

Begin trip at intersection of U.S. Rte. 20 and Otsego Co. Rte. 80 (42.837851°, -74.869873°), approximately 5.5 miles east of Richfield Springs, Otsego Co., NY.

Miles from last point	Cumulative mileage	Route description
0.0	0.0	If traveling from the west, turn left (north) onto Otsego Co. Rte. 80, and proceed ahead
1.5	1.7	Summit Lake to right
1.1	8.1	Enter Starkville
1.5	9.6	Otsego-Montgomery county line
0.9	10.5	Upper strata of Ordovician Utica Fm. on left.
1.1	12.1	Enter Hallsville

0.3	12.4	Brookman Corners; Przewtrzelski family, owners of Stop 1 (Pretzel Farm) at 121 Brookman Road
0.1	12.5-.7	Utica Shale on left, and both sides ahead.
0.2	13.0	Pullover for Stop 1 on right, before bridge

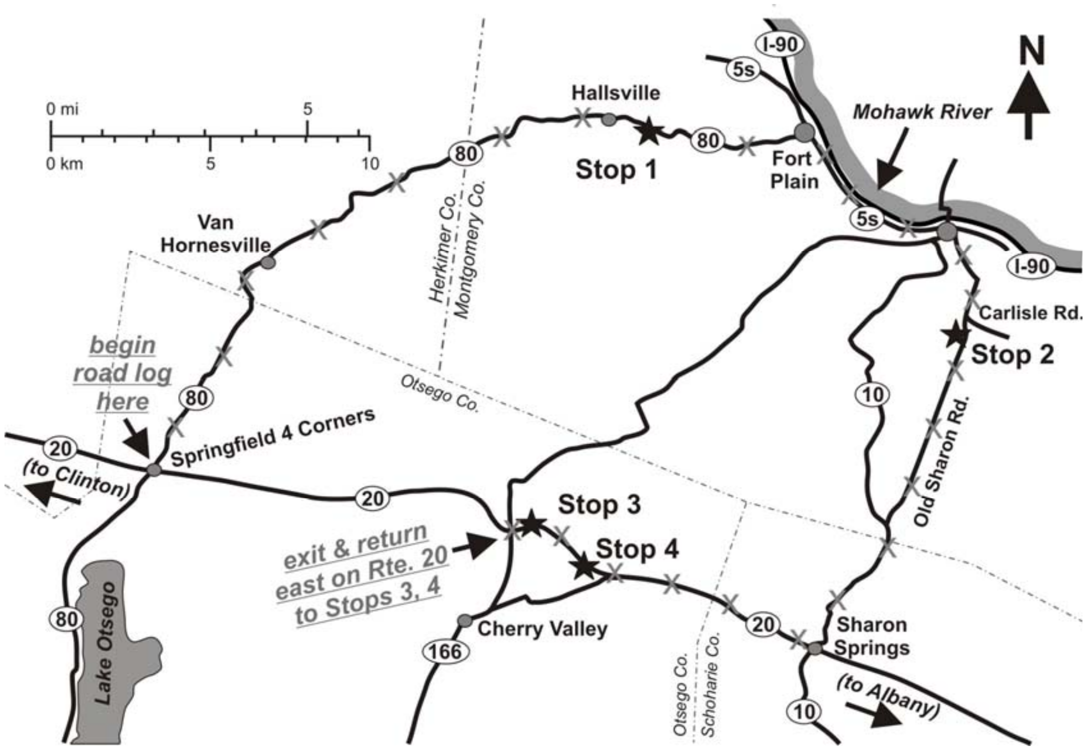

Figure 12. Map of fieldtrip route and stops. Trip begins ca. 40 miles from the Hamilton College campus.

Stop #1. Airfall volcanic tephras in Upper Ordovician Utica Shale, at Pretzel Farm, Hallsville (42.935179°, -74.692454°)

An expanse of gently westward-dipping, Upper Ordovician, black Utica Shale floors Otsquago Creek at Stop 1 (See Figure 5). This exposure displays a portion of the lower part of the Indian Castle Member that is exceptional for the abundance of classic Utica fossils such as exuviae and carcasses of the trilobite *Triarthrus*, as well as abundant orthoconic cephalopods and graptolites belonging to the *Climacograptus spiniferus* biozone (see Goldman et al. 1994; Figure 5). Several important tephra beds are present in this outcrop; these will be examined in ascending order from the downstream (east) end of this section. We will examine a thin, calcareous tephra bed near the base of this section that contains abundant volcanogenic phenocrysts and sand-size pumice clasts preserved in partial 3-D relief along the base of the layer. A higher, partially cemented tephra bed will also be a focus of examination and questions (See Figures 5, 6c,d).

---	13.0	Leave parking area, continue east on Otsego Co. Rte. 80
1.0	14.0	Contact of Ordovician-age Indian Castle Member (Utica Formation) and Dolgeville Formation in creek near red footbridge on right.

0.9	14.9	Road on right to type section of Valley Brook Shale Member, Flat Creek Formation, below Dolgeville Formation
0.2	15.9	Enter village of Fort Plain
0.6	16.8	Turn right onto NY Rte. 5S, toward Canajoharie
2.7	19.5	Enter Canajoharie
0.5	20.0	Fork to right, continue on Rte. 5S
0.2	20.2	Proceed through intersection with Rte. 10
0.1	20.3	Left onto Montgomery Street, then quick jog to left and right, onto Moyer Street (toward Wintergreen Park). Proceed uphill.
0.4	20.7	Floral Avenue on right; access to lower Canajoharie Gorge. Beekmantown Group carbonates, with large potholes, are succeeded upstream by Black River and Trenton Group carbonates.
0.4	21.1	Right onto Carlisle Road. Note flattening of road uphill, marking bedrock shift from carbonates to shales.
0.8	21.9	At fork, continue straight ahead onto Old Sharon Road.
0.1	22.0	Turn right into Wintergreen Park
0.2	22.2	Descend into valley. At stop sign, proceed ahead, then descend steep, narrow road with sharp bends.
0.2	22.4	Stop and park to right at base of slope. Follow trail to Canajoharie Creek at north end of parking area.

Stop #2. Airfall volcanic tephras in Upper Ordovician Flat Creek Shale, at Wintergreen Park, Canajoharie (at and downstream of 42.886244°, -74.564323°)

This section lies in the upper part of the gorge of Canajoharie Creek, upstream from the village of Canajoharie (see Figure 4). This is a classic Utica Shale section that exposes the entire Flat Creek Shale Member succession as well as higher strata of the Dolgeville Formation, which are visible high in the gorge face across from our entrance point. Vertical joint sets in the hard, calcareous shale are spectacularly displayed in the bank walls and creek floor along our route.

We will focus on a tephra-rich interval downstream from our point of ingress (Figure 4). Strata examined here contain graptolites belonging to the *Orthograptus americanus* biozone (Goldman et al. 1994). We will first examine several tephras exposed a short distance downstream from the path entrance that can be easily identified from the rusty stain of sulfides weathered from these layers (Figures 4, 6). Most notable among these beds is a coarse tephra layer, informally designated the “sand band” (Baird et al. 1994), that may record an episode of submarine erosion or sedimentary condensation (Figure 6a,b). This bed underlies an interval of calcareous shale and impure limestone layers containing numerous fossils, including the distinctive hemispherical bryozoan *Prasopora* and the large trilobite *Isotelus.*

Proceeding downstream, the creek canyon makes two scenic bends. On a high, east-facing wall, a cluster of orange-weathering tephra bands is conspicuously displayed. We will proceed to a minimally-weathered part of this face to look at the apparent record of countless thin laminae that record possible, “average” or “small-scale” volcanogenic events that constitute Ordovician background volcanic activity.

Return to cars, and continue south through parking area.

---	22.4	Leave parking area, proceed ahead through parking area
0.1	22.5	Left turn onto exit road, proceed uphill
0.3	22.8	Exit Wintergreen Park. Turn right and proceed south again on Old Sharon Road.
3.9	26.7	Make a very short jog to left and right at Latimer Hill Road, and continue south on Old Sharon Road
0.8	27.5	Left onto NY Rte. 10, and continue south
0.3	27.8	Enter Schoharie County
1.5	29.3	Enter village of Sharon Springs, and old spa resort town based on spring waters that surface here.
0.2	30.5	Junction with U.S. Rte. 20. Turn right/west and proceed.
0.5	32.7	Enter Otsego County
2.4	35.1	Classic Lower and Middle Devonian outcrops along Rte. 20 near Cherry Valley for next 0.6 miles. Strata include (east to west, and stratigraphically high to low) the Oatka Creek and Union Springs (="Marcellus subgroup"), Onondaga, Schoharie, Esopus, Oriskany and Kalkberg formations.
0.5	36.6	Bridge above highway
0.2	36.8	Fork right and take exit ramp for Cherry Valley/NY Rte. 166
0.1	36.9	Turn left onto Rte. 166.
0.4	37.3	Turn right onto entrance ramp for Rte. 20 east
0.2	37.5	Outcrops of Kalkberg Formation begin on right
0.1	37.6	Pull over to right and park near railroad overpass

Stop #3. Lower to Middle Devonian airfall tephra beds, U.S. Rte. 20 cuts, near Cherry Valley, NY. (between ca. 42.821797°, -74.731025° to ca. 42.822202°, -74.723747°)

Roadcuts on the south side of Rte. 20 east of Rte. 166 expose a long, nearly continuous section of the Lower Devonian Kalkberg, Oriskany, Esopus and Schoharie formations, and the Middle Devonian Onondaga Formation. Additional outcrops to the east expose the Union Springs and Oatka Creek formations (Marcellus subgroup of Ver Straeten 2007b). See Figure 13 for more details.

The Lower Devonian Kalkberg Formation, lowest in this section, features up to 15 thin volcanic airfall tuffs assigned to the Bald Hill K-bentonites (Smith et al. 1988; Shaw et al. 1991).. Rickard (1962) reported the first tephra in this interval, visible just east of the overpass as a prominent crevice, filled with light gray to tan, soapy-feeling, sticky clay about one to two meters above ground level (Figure 9a,b). Additional K-bentonitic tephras occur in the Kalkberg Formation here.

The Bald Hill Tephra Cluster is reported from New York to Virginia and West Virginia Rickard's original bed from Cherry Valley was dated by Tucker et al. (1998) at 417.6$\pm$1.0 Ma (^{207}Pb/^{206}Pb, zircons). Silicic volcanic and plutonic rocks with overlapping age dates and biostratigraphy are found in Maine and maritime Canada Up the road, lower strata of the Esopus Formation here consist of 4.4 m of interbedded cherts, K-bentonites, shales and minor thin sandstones (Spawn Hollow Member). Fifteen <1 to 14 cm-thick clay to claystone layers with zircons, apatites, and other phenocrysts indicative of a volcanogenic origin

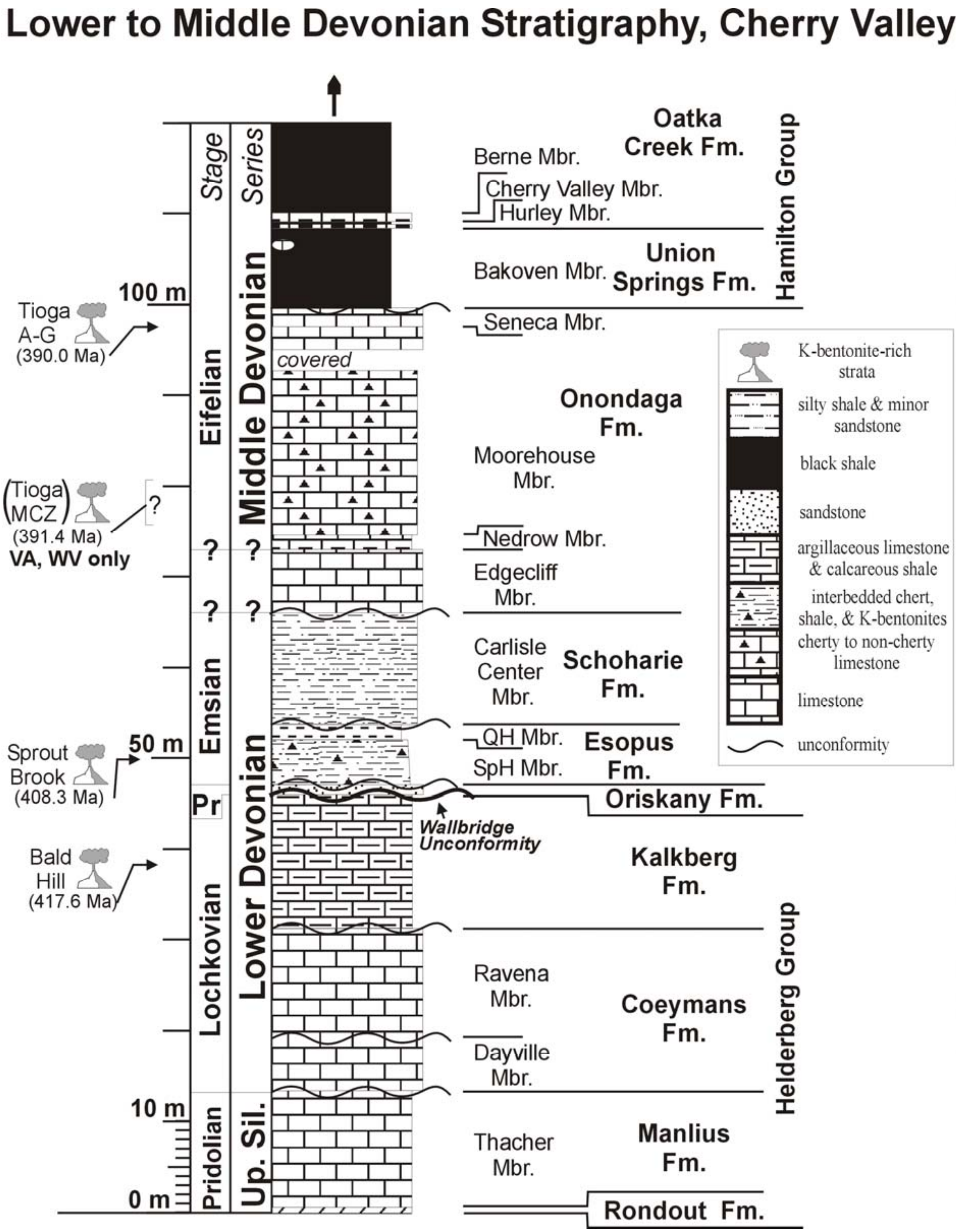

Figure 13. Upper Silurian to Middle Devonian stratigraphy near Cherry Valley, New York (Stops 3 and 4). Stop 3 examines strata of the Kalkberg through mid Onondaga formations. Stop 4 examines the topmost Onondaga Formation. Tioga Middle Coarse Zone tephra cluster is apparently found only in the southern part of the Appalachian Basin, in part of the Virginia-West Virginia outcrop belt. Abbreviations: Pr = Pragian; QH Mbr. = Quarry Hill Mbr., Esopus Fm.; SpH Mbr. = Spawn Hollow Mbr., Esopus Fm.; Up.Sil. = Upper Silurian.

(Sprout Brook K-bentonites) occur within the lower 3.6 m of the outcrop (Ver Straeten 2004b; Figure 9c). The site, now largely covered, is the type section of the Sprout Brook K-bentonites. Tephras of the Sprout Brook cluster are known only from eastern New York (Figure 9c-f). Two Sprout Brook beds from Cherry Valley were dated by Tucker et al. (1998) at 408.3±1.9 Ma ($^{207}Pb/^{206}Pb$). A number of silicic plutonic and volcanic rocks with dates that overlap that of the Sprout Brook K-bentonites are found in the northern Appalachians (e.g., the co-magmatic Katahdin Granite and Traveler Rhyolite, north-central Maine; Ver Straeten 2010; Figure 11).

Hanson (1995) reported a thin, discontinuous K-bentonite at the erosional base of the overlying sand-rich Schoharie Formation here (Carlisle Center Member). Another glauconite- and phosphate-rich clay bed marks the base of the Onondaga Limestone at Cherry Valley (Figure 10c). Best seen when dug out on the north side of Rte. 20 west of Rte. 166, the bed features a mix of detrital, authigenic, and volcanic grains (Ver Straeten 2004a).

Additional clay-dominated tephra beds occur through the lower three members of the Onondaga and equivalent units around the Appalachian basin. Most of these are difficult to find in relative shallower water facies in eastern New York, including at Cherry Valley.

Return to cars and proceed ahead (east) on Rte. 20

---	37.6	Pull onto Rte. 20 and proceed ahead
1.1	38.7	Elongate outcrop of Seneca Member on right. Black shales of Bakoven Member (Union Springs Formation, Marcellus subgroup) in covered slope above, capped at break in slope by Hurley and Cherry Valley members of the overlying Oatka Creek Formation (Marcellus subgroup).
0.4	39.1	Pull over to right and park at outcrop of Seneca Member limestone. Moorehouse Member visible in low ledges on north side of Rte. 20.

Stop #4. Airfall tephra beds of the Middle Devonian Tioga A-G cluster, U.S. Rte. 20 cut near Cherry Valley, NY.

Upper limestones of the Onondaga Formation (Figure 13) are found in this and nearby roadcuts. Topmost Moorehouse Member strata are visible on the north side of Rte 20. Two meters of the overlying Seneca Member represent the full thickness of the member locally.

The Tioga B Tephra, at the base of the Seneca Member, occurs in a deep reentrant near the base of this outcrop (Figure 10a,b). The Tioga B (anomalously thin at 12 cm here) is correlatable throughout most of the Appalachian Basin, except near Albany, and in central Ohio (Ver Straeten 2004a, 2007b).

A second thin K-bentonite, found in a crevice 0.73 m above the Tioga B is also found widely around the Appalachian Basin. A third K-bentonite was dug out 2.0 m above base of the Tioga B, at the Onondaga-Union Springs (Marcellus) contact 0.3 miles east of Stop 4.

The Tioga A-G K-bentonites occur throughout the Appalachian Basin; one of the beds has been reported from as far west as Illinois (Collinson 1968). The Middle Devonian Tioga-B K-bentonite was dated by Roden et al. (1990) at 390.0+0.5 Ma.