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Revised correlation of the Frasnian–Famennian boundary and Kellwasser Events (Upper Devonian) in shallow marine paleoenvironments of New York State

Andrew M. Bush [a,b,*], Jayme D. Csonka [b], Graziella V. DiRenzo [a,1], D. Jeffrey Over [c], J. Andrew Beard [b]

[a] Department of Ecology and Evolutionary Biology, University of Connecticut, 75 North Eagleville Road, U-3043, Storrs, CT 06269-3043, USA
[b] Center for Integrative Geosciences, University of Connecticut, 354 Mansfield Road, U-1045, Storrs, CT 06269-1045, USA
[c] Department of Geological Sciences, SUNY College at Geneseo, Geneseo, NY 14454, USA

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ABSTRACT

The Frasnian–Famennian boundary (Upper Devonian) is exposed in a 200 km-long outcrop belt in New York State, with deeper paleoenvironments to the west and shallower ones to the east. Geochronology in the eastern end of the outcrop belt has been based primarily on lithostratigraphic correlation with western sections, which were dated using conodonts. We collected conodonts and brachiopods from several measured sections and numerous other localities, and these collections suggest that these east–west lithostratigraphic correlations require revision. We correlate the Wiscoy Formation with the upper Angola Formation and the Canaseraga with the upper Hanover. Thus, the Canaseraga Formation contains the Frasnian–Famennian boundary and Upper Kellwasser Event, and the dark shale above the Wiscoy is equivalent to the Pipe Creek Formation and Lower Kellwasser Event. These new correlations imply that the Lower Kellwasser Event had greater impact on the shelly benthos of New York than the Upper Kellwasser, at least for the subset of taxa examined here. All strophomenid brachiopods and rugose corals were extirpated at the Lower Kellwasser, along with numerous other brachiopods. The final species of atrypid brachiopod persisted to the Upper Kellwasser.

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1. Introduction

Extinction events in the Late Devonian caused considerable biotic turnover and ecological change (e.g., Schindler, 1993; McGhee, 1996; Copper, 2002; House, 2002; McGhee et al., 2004; Sallan and Coates, 2010; Christie et al., 2013; McGhee, 2013). Two of these extinctions, the Lower and Upper Kellwasser Events (LK and UK), occurred during the late Frasnian and coincided with the deposition of the Lower and Upper Kellwasser limestones, organic-rich deposits found across Europe and northern Africa (Joachimski and Buggisch, 1993; Schindler, 1993). At several deep-water locations in western New York State, Over (1997, 2002) identified the temporal equivalents of the Kellwasser Events using conodont biostratigraphy. To the east of these locations, shallower-water facies are exposed, macrofossils are common, conodonts are rare, and geochronology is based primarily on lithostratigraphic correlations with the deeper-water sections in western New York (Chadwick, 1935; Pepper and deWitt, 1950, 1951; Rickard, 1964, 1975; Smith and Jacobi, 2000). However, new collections of brachiopods and conodonts indicate that the Frasnian–Famennian (F–F) boundary and the Kellwasser Events have generally been misplaced in the shallow-water, "Chemung" paleoenvironments at the eastern end of the outcrop belt. We suggest alternate correlations that will serve as the basis for future studies of Late Devonian extinction dynamics in the Appalachian Basin.

2. Geologic setting and stratigraphy

During the Late Devonian, sediments shed from the Acadian Mountains were deposited in the Appalachian Foreland Basin as part of the prograding clastic wedge of the "Catskill Delta" (Woodrow and Sevon, 1985; Filer, 2003; Ver Straeten, 2009). Upper Frasnian and lower Famennian strata are exposed in New York in an outcrop belt stretching from Lake Erie in the west to the Pennsylvania border south of Corning (Fig. 1A, B), with paleoenvironments shallowing eastwards. The stratigraphy and paleoecology of these strata (and correlative rocks to the south) have been addressed by numerous authors, including McGhee (1976), McGhee and Sutton (1981, 1983, 1985), Sutton and McGhee (1985), Roen and deWitt (1984), Van Tassell (1987), Warne and McGhee (1991), Castle (2000), Murphy et al. (2000), Smith and Jacobi (2001), Day and Over (2002), Filer (2002, 2003), Rode and Lieberman (2004),

* Corresponding author at: Department of Ecology and Evolutionary Biology, University of Connecticut, 75 North Eagleville Road, U-3043, Storrs, CT 06269-3043, USA. Tel.: +1 11 1 860 486 9359; fax: +1 11 1 860 486 6364.
E-mail addresses: andrew.bush@uconn.edu (A.M. Bush), jayme.csonka@uconn.edu (J.D. Csonka), gdirenzo@umd.edu (G.V. DiRenzo), over@geneseo.edu (D.J. Over), james.beard@uconn.edu (J.A. Beard).
[1] Present address: Department of Biology, University of Maryland, 4219 Biology–Psychology Building, College Park, MD 20742, USA.

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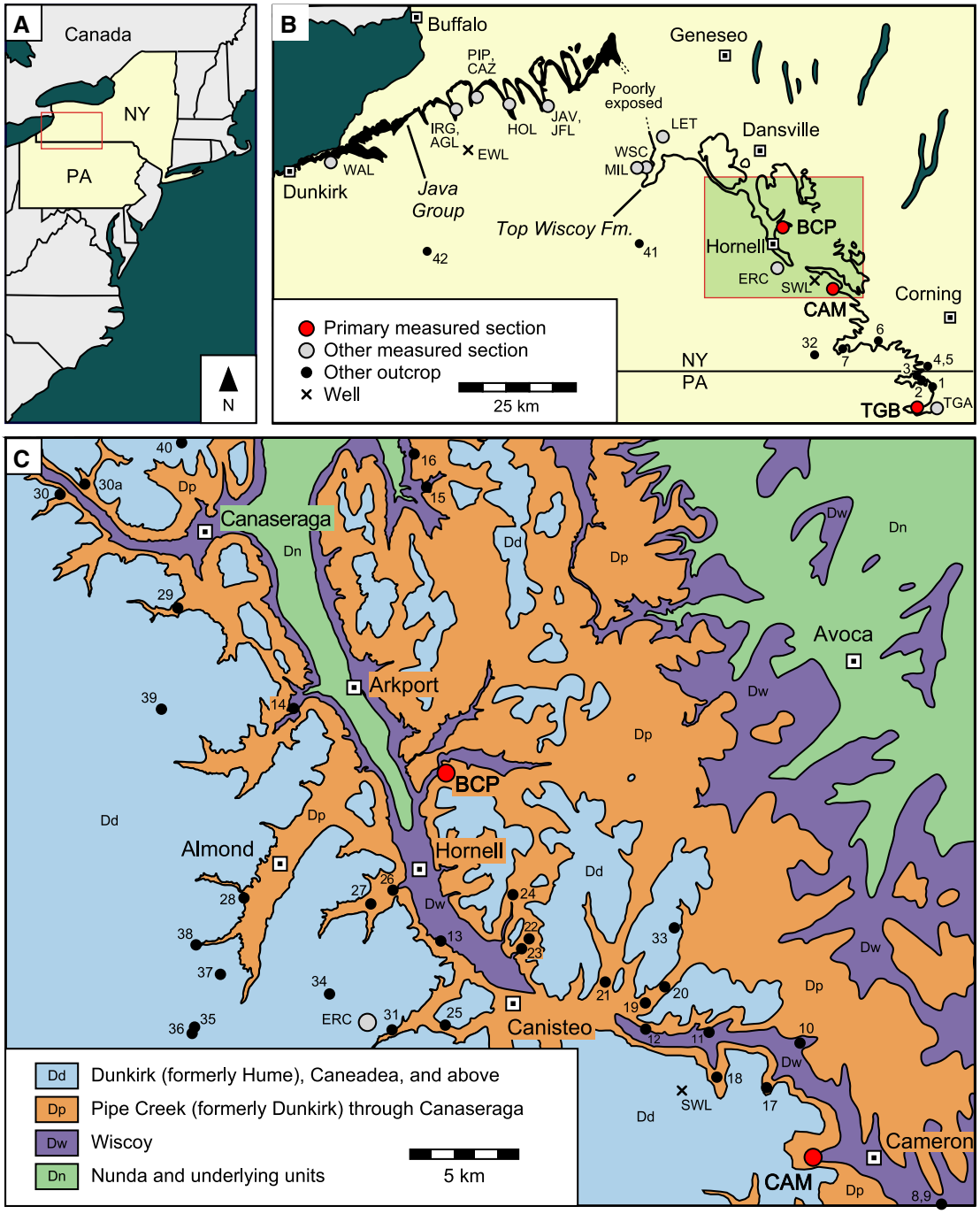

Fig. 1. Locality maps. A) Eastern United States with the field area in New York and Pennsylvania highlighted. B) Expanded view of the highlighted region from panel A. In western New York, the Java Group is marked in black. The base of the group (northern boundary) is defined by the Angola–Pipe Creek contact (LK equivalent). The top of the group (southern boundary) is marked by the Hanover–Dunkirk contact, which is slightly above the UK equivalent (Over, 1997). In the eastern end of the outcrop belt, the contact between the Wiscoy and the overlying shale is marked; previously, this contact was correlated with the Hanover–Dunkirk contact in the west, but we correlate it with the Angola–Pipe Creek contact. C) Detailed geologic map of the region highlighted in panel B. Stratigraphic assignments reflect the new correlations proposed here. Sampling locations and abbreviations are listed in Tables 1 and 2. The "primary measured sections" (BCP, CAM, and TGB) were sampled bed-by-bed for fossils, and the "other measured sections" are discussed or figured but not necessarily sampled intensively for fossils. "Other outcrops" were sampled for fossils but the sections were not measured.
Geologic maps based on Pepper and deWitt (1950), Pepper (1954), and Rickard and Fisher (1970).

Stigall Rode and Lieberman (2005), Bond and Wignall (2008), Bush and Brame (2010), Christie et al. (2013), and McClung et al. (2013).

In western New York, upper Frasnian and lower Famennian strata include shales assigned to the Angola, Pipe Creek, Hanover, Dunkirk, South Wales, and Gowanda formations (Fig. 2). Over (1997, 2002) identified the Pipe Creek as the temporal equivalent of the LK and a thin black shale interval in the Hanover located 3 m or less below the contact with the Dunkirk as the UK equivalent. The Upper Devonian is poorly exposed in parts of Wyoming County, but outcrops become common again in the Genesee River valley and eastwards (Fig. 1B; see also Fig. 1 of Pepper and deWitt, 1950).

In the eastern part of the outcrop belt, silt- and sand-rich strata of the Nunda, Wiscoy (Fig. 3D), and Canaseraga (Fig. 3B) formations are separated by gray and dark gray shales (Fig. 3A, C) that have been

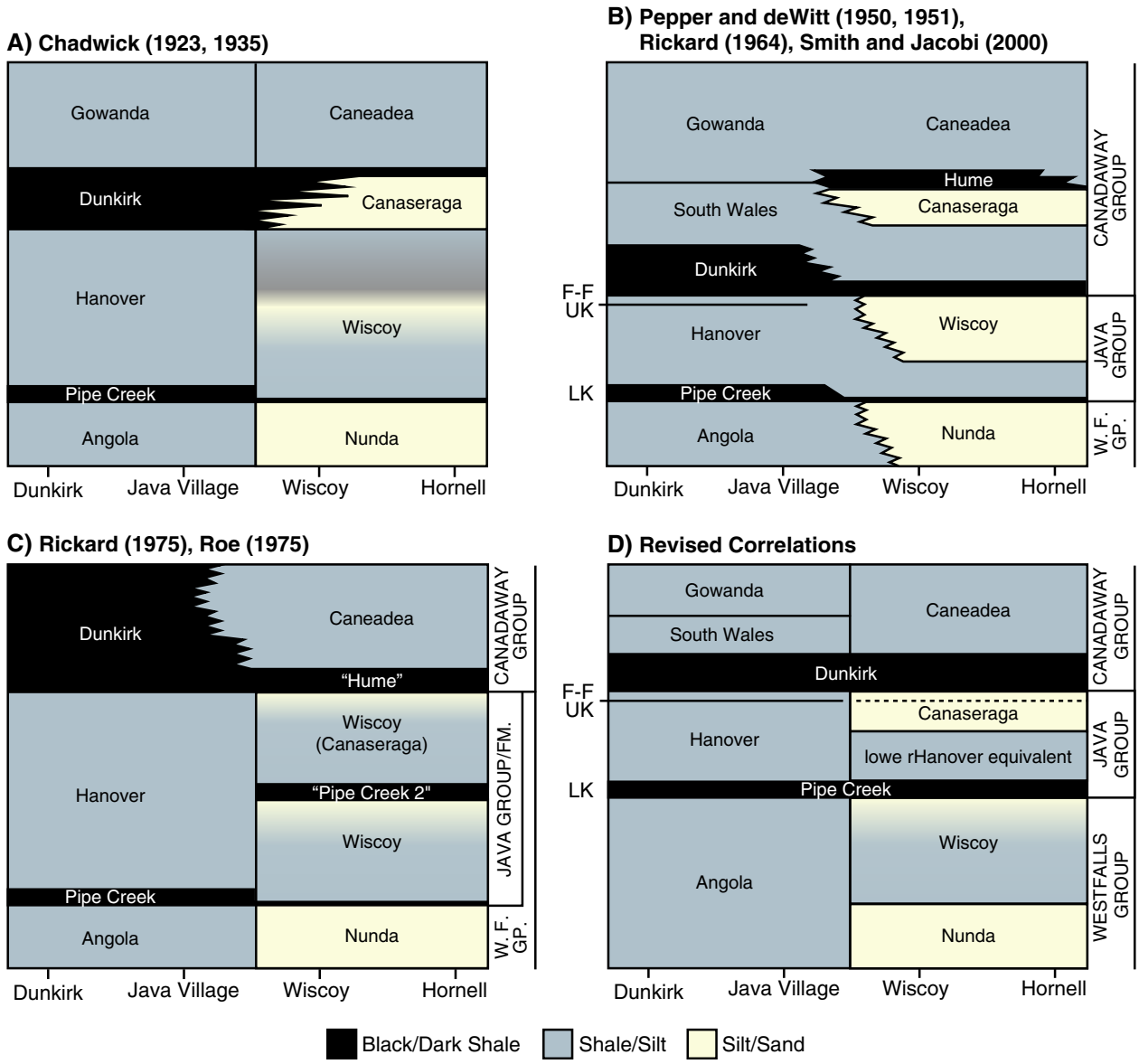

Fig. 2. Correlations between the western and eastern portions of the outcrop belt. A) Chadwick (1923, 1935). B) Pepper and deWitt (1950, 1951), Rickard (1964), Rickard and Fisher (1970), and Smith and Jacobi (2000, 2001). C) Rickard (1975) and Roe (1975). D) Revised correlations proposed here. Panels A, B, and C are composites of similar (though not necessarily identical) correlations from multiple sources. F–F: Frasnian–Famennian boundary. UK: Upper Kellwasser equivalent. LK: Lower Kellwasser equivalent.

correlated with the shales in the west in various ways by different authors, reflecting the challenges of correlation when facies changes are substantial and biostratigraphic and other geochronological data are absent. Chadwick (1919, 1923, 1924, 1935) correlated the Pipe Creek of western New York with a shale bed above the Nunda, and he correlated the Hanover and Dunkirk with the Wiscoy and Canaseraga, respectively (Fig. 2A). At the time, the Wiscoy referred to all of the shalier strata along Wiscoy Creek (WSC in Fig. 1B; Clarke, 1899; Clarke and Luther, 1908)—that is, all strata below the Canaseraga (Mills–Mills of Smith and Jacobi, 2000).

Like Chadwick, Pepper and deWitt (1950, 1951) and Pepper (1954) placed the Pipe Creek atop the Nunda, but they placed the Dunkirk and the top of the Wiscoy lower in the section and named the black shale on top the Canaseraga the Hume (Fig. 2B). These basic correlations have been used by many authors since (e.g., Rickard, 1964; Smith and Jacobi, 2000, 2001, 2006) and were ensconced in the geologic map of New York (Rickard and Fisher, 1970).

However, these correlations did not receive universal support. After examining numerous well logs and outcrops, Roe (1975) correlated the Dunkirk with the Hume Shale, in contrast with Pepper and deWitt (1950, 1951) (Fig. 2C). The Pipe Creek remained correlated with the shale above the Nunda, such that all strata above the Nunda and below the "Hume" were correlated with the Hanover (similar to Fig. 2A, but with the Canaseraga equivalent to the upper Hanover, not the Dunkirk). In the eastern portion of the outcrop belt, Roe (1975) referred to the dark shale that Pepper and deWitt (1950, 1951) called the Dunkirk as the "Pipe Creek 2", and he treated the Canaseraga as part of the Wiscoy Formation (Fig. 2C). These correlations were followed by Rickard (1975), and, implicitly, by McGhee and Sutton (1981). Roe's (1975) work was never published, and neither he nor Rickard (1975) provided a detailed justification for including the Canaseraga in the Wiscoy. As a result, the rationale for these correlations has remained murky, and, furthermore, it is not always clear which definition of the Wiscoy is employed in some subsequent works. Smith and

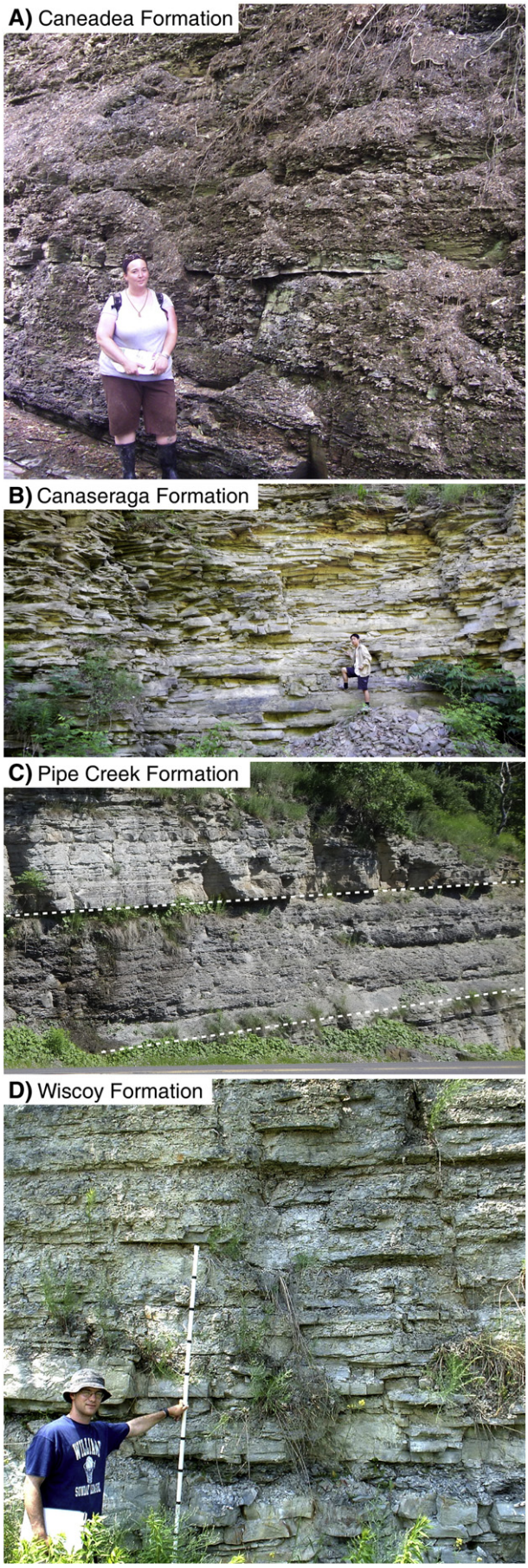

Fig. 3. Outcrop photographs in descending stratigraphic order. A) Caneadea Formation, location ERC (creek west of Ells Road near intersection with Purdy Creek Road, south of Hornell, NY). B) Canaseraga Formation, location 20 (CSB, Campbell Creek Road east of Canisteo, NY). C) Pipe Creek Shale (outlined unit) and adjacent strata, ~9–19 m at section TGB (Rt. 287, Tioga, PA). The Pipe Creek is 4.4 m thick. D) Upper Wiscoy Formation, ~5.0–7.5 m at section TGB. Staff ruled in 20-cm increments. See Fig. 1 for map and Tables 1 and 2 for further locality information.

Jacobi (2000) criticized Rickard's (1975) placement of the "Hume" directly on top of the Wiscoy, because these units (as often defined) are separated by more than 50 m of strata at Wiscoy Creek (WSC and MIL, Fig. 1). However, Roe's (1975) work suggests that these strata were not omitted per se; rather, the Wiscoy was defined to encompass the Canaseraga. Here, we follow Pepper and deWitt's (1950) definition for the top of the Wiscoy (Fig. 2B) because it corresponds to a major lithologic transition that is recognizable across the region (see Smith and Jacobi, 2000, 2001, for further details).

The base of the Canaseraga Formation has also been defined in various ways. Chadwick (1923) proposed the name "Canaseraga ss" for strata between the Wiscoy and the Gowanda. Chadwick (1924) elaborated further, proposing the name "Canaseraga sandstone" for the "150 feet of heavy arenaceous beds" exposed along Slader Creek near Canaseraga, New York (location 29 on Fig. 1C). Given the original meaning of the Wiscoy, discussed above (Clarke, 1899; Clarke and Luther, 1908), and the description of the type section, Chadwick's Canaseraga sandstone only included the sandy interval referred to as "Mills–Mills" by Smith and Jacobi (2000, 2001, 2006). However, Pepper and deWitt (1951) also included an interval of interbedded shales and thin siltstones that underlies the more massive silt/sandstones. Smith and Jacobi (2000, 2001) used the informal name "Mills–Mills Formation" to distinguish the sandy beds, later proposing it as a formal name (Smith and Jacobi, 2006).

Here, we define the Canaseraga as equivalent to the "Mills–Mills" as illustrated by Smith and Jacobi (2001). The base of the Canaseraga is best placed at the base of the sandy beds, where it marks a major lithologic transition that is easily recognizable across the outcrop belt. This placement also matches the original definition of Chadwick (1923, 1924) by our interpretation.

3. Methods

Fossils were collected bed-by-bed through measured sections in Hornell (BCP), Cameron (CAM), and Tioga, Pennsylvania (TGB), that expose the upper Wiscoy Formation and overlying strata (see Table 1 and Fig. 1 for locality information). Section TGB was illustrated previously by Berg et al. (1981, p. 156) and Castle (2000, p. 907) and is mapped as the Lock Haven Formation, a name applied to Upper Devonian shallow marine strata in Pennsylvania (Berg et al., 1980). Section CAM was previously shown by Pepper and deWitt (1951), who extrapolated the lithology of some covered intervals. These prior works did not include detailed faunal data. Additional samples from numerous other locations that expose the Wiscoy and overlying strata were also examined (Fig. 1, Table 2), some of which were used previously by Christie et al. (2013).

International biostratigraphic correlation in the Upper Devonian is based primarily on conodonts (e.g., Ziegler, 1962; Klapper, 1989; Ziegler and Sandberg, 1990; Klapper et al., 1994; Klapper, 1997; Over, 1997, 2002), and several were located via visual inspection of rock samples. Rhynchonelliform brachiopods were extremely abundant at many of our localities and have been used previously for regional correlations within the Appalachian Basin (e.g., McGhee, 1976; McGhee and Dennison, 1980; Dutro, 1981; Brame, 2001). The atrypid brachiopods are of particular biostratigraphic value because they go extinct by the F–F boundary (Copper, 1998; Day, 1998). For this study, we tabulated occurrences of strophomenid, orthid, atrypid, athyrid, and a subset of spriferid and spiriferinid brachiopods. Taxa were identified with reference to type material and previous works (Hall and Whitney, 1858; Hall, 1867; Hall and Clarke, 1892, 1894; Williams, 1908; Clarke

Table 1
Locality information for stratigraphic sections and wells. See Fig. 1 for map.

Site	Name	Latitude N	Longitude W	Source
Primary sections (faunal data shown in Fig. 4)				
TGB	Tioga, PA, Rt. 287	41°54.423′	77°09.715′	Bush et al. (this paper)
CAM	Cameron	42°12.008′	77°26.219′	Bush et al. (this paper)
BCP	Big Creek	42°21.810′	77°38.675′	Bush et al. (this paper)
Additional sections				
TGA	Tioga, PA, Rt. 15	41°54.690′	77°07.446′	Bush et al. (this paper)
ERC	Ells Road Creek	42°15.303′	77°40.773′	Bush et al. (this paper), Pepper and deWitt (unpublished)
LET	Letchworth Park	42°35.15′	78°01.13′	Pepper et al. (1956)
WSC	Wiscoy Creek	42°30.280′	78°5.014′	Smith and Jacobi (2001)
MIL	Mills–Mills	42°30.050′	78°7.218′	Smith and Jacobi (2001)
JFL	Johnson's Falls	42°43.75′	78°27.17′	Pepper et al. (1956)
JAV	Java Village	42°40.33′	78°26.08′	Pepper and deWitt (1950, 1951)
HOL	Holland	42°42.25′	78°33.83′	Pepper and deWitt (1950, 1951)
CAZ	Cazenovia Creek	42°47.17′	78°41.25′	Pepper et al. (1956)
PIP	Pipe Creek	42°41.75′	78°41.25′	Pepper and deWitt (1950, 1951)
AGL	Alice Glen	42°43.17′	78°45.00′	Pepper and deWitt (1950)
IRG	Irish Gulf	42°32.33′	78°45.25′	Pepper and deWitt (1950, 1951)
WAL	Walnut Creek	42°32.33′	79°10.08′	Pepper and deWitt (1950, 1951)
Well logs				
SWL	Steuben Co. well log	42°14.155′	77°30.764′	Empire State Oil and Gas Information System (2013)
EWL	Erie Co. well log	42°32.495′	78°42.016′	Empire State Oil and Gas Information System (2013)

and Swartz, 1913a,b; Caster, 1930; Stainbrook, 1940; Butts, 1941; Stainbrook, 1942, 1945; Williams, 1953; Greiner, 1957; Cooper and Dutro, 1982; Rossbach, 1992; Linsley, 1994; Day and Copper, 1998; Brame, 2001; Day and Over, 2002; Stigall Rode, 2005). Many of the species are long overdue for taxonomic revision, but for now we use previously published names pending revisions. Rugose corals were noted but not identified specifically; for information on Chemung rugose corals, see Stumm (1960) and Sorauf (1978, 1987). Bivalves, bryozoans, nautiloids, gastropods, and crinoid debris were present but not examined in detail.

Brachiopods were preserved as molds or as calcite shells, which generally could not be extracted from the matrix. Many specimens were exposed using hammers, chisels, and a hydraulic rock splitter, and some were further prepared with a vibropick. Some samples were treated in dilute HCl to reveal molds. Whole shells could be extracted easily from the matrix at several localities that exposed the uppermost 5 m of the Wiscoy Formation (e.g., locations 13, 16, and BCP).

4. Data

Numerous macrofossil species last occurred near the top of the Wiscoy at sections BCP, CAM, and TGB (Fig. 4); these include all strophomenid brachiopods (e.g., Fig. 5A–D) and rugose corals, both of which suffered globally in the Frasnian extinctions (e.g., Sorauf and Pedder, 1986; Rong and Cocks, 1994) and do not occur above the Wiscoy in New York (Dutro, 1981; Oliver and Sorauf, 1981, 1983).[2] Two atrypid species were found in the Wiscoy (*Pseudoatrypa devoniana* and *Spinatrypa hystrix*; Fig. 5E), neither of which continued into the overlying strata. Other victims include several orthids (Fig. 5G–O), a spiriferid, and a spiriferinid. Species that ranged through the entire interval (e.g., *Tylothyris mesacostalis*, *Schizophoria impressa*) were excluded for clarity (Fig. 4). At TGB, *S. hystrix* and *Schizophoria amanaensis* also occurred just above the dark shale that overlies the Wiscoy (Fig. 4C). However, these fossils were worn and occurred in a high-energy, rippled conglomerate that was unique in the section. This is the only location where these taxa occurred above this shale, and we interpret them as reworked due to their physical appearance and the sedimentology of the enclosing bed.

The dark shale above the Wiscoy is overlain by interbedded shales and silts, referred to the South Wales Formation by Smith and Jacobi (2000, 2001). Several species first occur in these beds (Fig. 4), including *Spinatrypa* cf. *planosulcata* (Fig. 5F), "*Thiemella*" *leonensis* (Fig. 5P–R), and "*Athyris*" *angelica*. This turnover in the brachiopod fauna can be recognized across the eastern portion of the outcrop belt (Table 2).

At the Mills–Mills locality on Wiscoy Creek (MIL in Fig. 1B), the Canaseraga Formation consists of two sandy intervals separated by an interval of interbedded shales, siltstones, and sandstones (see Fig. 6d of Smith and Jacobi, 2001). Unfortunately, the Wiscoy Creek section has few body fossils, and we have not yet examined a fossiliferous section through the entirety of the Canaseraga in shallower-water settings, presumably because the finer-grained interval is often poorly exposed. However, outcrops of the sandy beds are plentiful (e.g., Fig. 3B), and, based on current collections, *Spinatrypa* cf. *planosulcata* occurs in the lower, but not the upper, sandy beds of the Canaseraga, as determined by contact with under- and overlying strata.

The stratigraphic ranges of brachiopods observed here (Fig. 6) are somewhat different from previous range compilations. For example, some species that we found in the Wiscoy were reported previously to last occur in the Nunda (Dutro, 1981), including *Stainbrookia infera* (Fig. 5J–L) and *Strophonelloides coelata* (Fig. 5B). Several taxa previously reported from the Wiscoy were not observed (e.g., *Cariniferella*; Dutro, 1981; McGhee and Sutton, 1981).

At section BCP in Hornell, the conodont *Palmatolepis winchelli* (Fig. 7A) was recovered from the dark shale above the Wiscoy (Fig. 4A). *Ancyrognathus symmetricus* (Fig. 7B) was recovered from the "Hume" Shale at Mills–Mills (MIL in Figs. 1B and 8).

5. New correlations

Based on the biostratigraphic work by Over (1997), the correlations used by Pepper and deWitt (1950, 1951), Rickard (1964), Rickard and Fisher (1970), and Smith and Jacobi (2000, 2001) imply that the F–F boundary and UK event should lie at or near the top of the Wiscoy Formation (Fig. 2B), so the overlying strata should contain no Frasnian taxa unless there was reworking. However, the conodont *P. winchelli* (Fig. 7A), a wide-ranging upper Frasnian taxon known from the

[2] Dutro (1981) indicated that *Douvillina arcuata*, a strophomenid, might extend above the Wiscoy, but marked post-Wiscoy occurrences with a question mark. We have not observed this species above the Wiscoy in our collections or museum collections.

Table 2
Localities sampled for faunal data, with the occurrences of biostratigraphically informative species of strophomenid, orthid, atrypid, athyrid, and selected spriferid and spiriferinid brachiopods. Rugose corals are indicated but not identified. See Fig. 1 for map. The ranges of most taxa shown here are also shown in Fig. 5. Cyrtospiriferid brachiopods were generally not included in this study pending further study; however, two Famennian species are included in this table because they are easily recognized and are among the first new taxa to appear in the Famennian.

Map Number	Location	Latitude N	Longitude W	Rugosa	*Nervostrophia nervosa*	*Strophonelloides coelata*	*Douvillina cayuta*	*Douvillina arcuata*	*Cyrtina cf. hamiltonensis*	*Orthid sp. A*	*Stainbrookia infera*	*"Spirifer" williamsi*	*Pseudoatrypa devoniana*	*Spinatrypa hystrix*	*Schizophoria amanaensis*	*Spinatrypa cf. planosulcata*	*"Thiemella" leonensis*	*"Athyris" angelica*		*"Cyrtospirifer" sulcifer*	*Cyrtospirifer vandermarkensis*
Wiscoy Formation																					
1	PUP	41°57.769'	77°07.254'				X							X							
2	SCL	41°58.896'	77°08.951'			X		X						X							
3	NCL	41°59.258'	77°10.326'							X											
4	NYP	42°00.417'	77°07.800'					X		X				X							
5	WCR	42°00.670'	77°08.248'			X		X						X							
6	BPH	42°04.394'	77°17.953'	X	X		X			X			X	X							
7	RGR	42°02.681'	77°25.306'	X				X	X					X							
8	CML 1	42°10.275'	77°21.697'				?	?		X											
9	CML 2	42°10.586'	77°21.904'			X		X						X							
10	ORE	42°15.181'	77°26.545'											X							
11	HAN	42°15.378'	77°29.957'	X		X		X				X		X							
12	ADR	42°15.430'	77°32.156'			X		X						X							
13	HNS	42°17.649'	77°38.678'	X				X			X				X						
14	BRC	42°23.325'	77°43.643'					X							X						
15	KHC	42°28.895'	77°39.203'											X							
16	DAN	42°29.615	77°39.920'	X			X	X		X	X			X	X						
"lower Hanover equivalent" and Canaseraga Formation																					
17	RSC	42°14.038'	77°27.956'															X			
18	MHC	42°14.650'	77°29.614'													X		X	X		
19	CSA	42°16.123'	77°32.201'													X	X		X		
20	CSB	42°16.458'	77°31.490'													X	X		X		
21	SGL	42°16.533'	77°33.526'													X			X		
22	HAC	42°17.727'	77°35.923'													X		X	X		
23	HCR2	42°17.426'	77°36.187'															X			
24	CHC	42°18.698'	77°36.436'													X		X	X		
25	PCR	42°15.570'	77°38.827'														X				
26	CCH	42°18.954'	77°40.230'														X	X			
27	CHR	42°18.593'	77°40.964'														X				
28	MHV	42°18.544'	77°45.203'														X	X			
29	SLD	42°25.871'	77°46.985'													X	X	X	X		
30	SKI	42°28.609'	77°51.441'													X			X		
30a	EHR	42°28.545'	77°50.612'														X				
31	BLK	42°15.391'	77°40.452'														X	X			
Dunkirk Formation and above																					
--	TGA	41°54.690'	77°07.446'															X		?	
32	GRN	42°01.439'	77°30.573'																	X	
33	BVS	42°17.941'	77°30.952'																		
--	ERC	42°15.303'	77°40.773'																		
34	ELL	42°16.237'	77°42.485																		
35	ALF	42°15.507'	77°46.986'															X			X
36	ALT	42°15.338'	77°47.102'															X			X
37	SHE	42°16.784'	77°46.110'															X			X
38	MHV2	42°17.682'	77°46.628'															X		X	
39	BRN	42°23.209'	77°47.982'																		
40	SHR	42°30.148'	77°47.496'																		
--	MIL	42°30.050'	78°07.218'																		
41	WHC	42°19.311'	78°06.416'															X			
42	GHC	42°18.285'	78°50.614'																	X	

Pipe Creek and upper Hanover further to the west (Over, 1997), occurs in the dark shale above the Wiscoy (Fig. 4A). In addition, atrypid brachiopods—which elsewhere go extinct at the end of the Frasnian (e.g., Copper, 1998; Day, 1998)—persist into the lower Canaseraga Formation, at least 60 m above the Wiscoy at Cameron (Fig. 4B).

Characteristic Frasnian taxa could occur in strata commonly mapped as lower Famennian for several reasons. The strata could be Frasnian in age, or nominally Frasnian taxa could have survived into the Famennian in this part of New York. Alternatively, the fossils could have been reworked upwards from the Wiscoy. However, the fossils occur high above the Wiscoy at multiple localities (Fig. 4) and do not show signs of reworking; indeed, some atrypid specimens have delicate spines preserved. We also find it unlikely that New York was a "refugium" for both conodonts and brachiopods that are known to go extinct elsewhere at the end of the Frasnian. Miscorrelation is therefore highly probable in Fig. 2B.

The Famennian conodont *A. symmetricus* (Fig. 7B) was recovered in the "Hume" Shale, which overlies the Canaseraga, at Mills–Mills (MIL in Figs. 1B and 8). This is the first record of this species from New York, but it is known from Upper *triangularis* Zone strata of the Dunkirk-equivalent lower Gassaway Member of the Chattanooga Shale in Tennessee (Over, 2007). *Spinatrypa* cf. *planosulcata* (Fig. 5F) occurs as high as the lower sandy beds of the Canaseraga Formation (Figs. 4B and 6), suggesting that these beds are Frasnian. It has not been found in the upper sandy beds, but it is unknown if it persists into the muddier beds between the two sandy intervals due to poor exposure. These fossils constrain the F–F boundary to the base of the Hume, the upper sandy beds of the Canaseraga Formation, or the finer interval between the lower and upper sands. We tentatively place the F–F boundary and UK equivalent in the shalier interval between the two sandy pulses of the Canaseraga (Fig. 8), consistent with the disappearance of atrypids from the lower to upper sands and the placement of the boundary below the Hanover–Dunkirk contact in the western sections studied by Over (1997, 2002). However, exact placement of the boundary in the eastern portion of the outcrop belt requires additional analysis of complete sections.

The "Hume" shale and overlying gray shales of the Caneadea sit at or near the base of the Famennian according to our biostratigraphic data, suggesting that they are temporally equivalent to the Dunkirk, South Wales, and Gowanda formations of western New York, providing support for the correlation of these units by Roe (1975) (Fig. 2C). The Dunkirk marks the most extensive transgression since the Rhinestreet event and the last thick transgressive shale of the Upper Devonian in New York (Rickard, 1964, 1975; Filer, 2003), and the Hume–Caneadea shale succession is extremely thick. For example, there is ~50 m of uninterrupted shale at section ERC (Fig. 8), and the next 50 m is dominated by shale with some beds of silt or fine sand (also see Fig. 5 in Smith and Jacobi, 2001). In contrast, the shale above the Wiscoy is much thinner (Fig. 8). These revised correlations solve the odd geometry of the "Hume" Shale on some previous correlation charts, which show it pinching out both landward and basinward (Fig. 2B); in Fig. 2D, it is simply the eastward extension of the Dunkirk (also see Roe, 1975; Rickard, 1975).

Occurrences of brachiopods and conodonts indicate that the dark shale above the Wiscoy and below the Canaseraga is upper Frasnian, not Famennian as implied in Fig. 2B. Roe (1975) and Rickard (1975) also placed it in the Frasnian (Fig. 2C), but they did not correlate it with any of the named black shales from western New York, and Rickard (1975) showed it pinching out both landward and basinward, similar to the "Hume" Shale in Fig. 2B. We propose that the shale above the Wiscoy correlates with the Pipe Creek Formation (LK equivalent), in contrast with previous interpretations. It is approximately the same thickness as the Pipe Creek in western New York (up to 7 m in the west and up to 15 m in the east; Fig. 8), and, as in western New York, it is a "persistent, massive, petroliferous black shale" (Pepper and deWitt, 1950). Previously, the Pipe Creek was placed above the Nunda in the eastern part of the outcrop belt, but there is no dark shale at this horizon from Hornell eastwards; Pepper and deWitt (1950) and Pepper (1954) presumed that it pinched out. However, it is persistent and easily recognizable in deeper-water settings in New York, and Filer (2002, 2003) found that it persisted shorewards in the subsurface of West Virginia. Likewise, the shale above the Wiscoy (as we define it) is regionally extensive and easily recognizable in the shallower end of the outcrop belt, but was not correlated with a major dark shale interval in western New York by Rickard (1975). With the new correlations (Fig. 2D), the Pipe Creek is recognizable throughout New York and into northern Pennsylvania (Figs. 3C, 4 and 8).

In sum, the following correlations are proposed between the western and eastern portions of the New York outcrop belt (Figs. 2D and 8): (1) the Wiscoy Formation correlates with the upper part of the Angola, not with the Hanover; (2) the dark shale above the Wiscoy correlates with the Pipe Creek, not the Dunkirk; (3) the strata overlying this dark shale ("lower Hanover equivalent" in Figs. 2D, 4 and 8) correlate with the lower Hanover Formation, not the South Wales; (4) the Canaseraga is coeval with the upper Hanover Formation; (5) the "Hume" Shale is equivalent to the Dunkirk; and (6) the Caneadea is correlative with the South Wales and Gowanda Formations. Given these revised correlations, the Wiscoy and Canaseraga formations should be reassigned to the West Falls and Java groups, respectively (Fig. 2D).

6. Subsurface

Filer (2002) recognized 11 late Frasnian transgressive–regressive cycles in gamma-ray logs from the Appalachian Basin, including western New York and West Virginia (see also Roe, 1975; Roen and deWitt, 1984). We downloaded well logs from the Empire State Oil and Gas Information System (2013) to determine whether these cycles could be recognized in the more onshore environments of the eastern portion of the New York outcrop belt. Black shales are indicated by elevated gamma-ray radiation and clean sands by lower values (Filer, 2002).

In western New York, the Dunkirk manifests as a persistent shift to high gamma ray values that marks the top of Filer's (2002) cycle 11 (Fig. 9A, which shows the same log as Fig. 2 of Filer, 2002). The Pipe Creek defines the base of cycle 8 and is marked by a thinner interval of positive values. Both of these deflections are apparent in a log from Steuben County (Fig. 9B) that was recorded 7 km from CAM (Fig. 4B) and 4 km from the Roosa School section of Pepper and deWitt (1951), which is similar to CAM. The pronounced shift to elevated values at the base of the Dunkirk is obvious, and the Pipe Creek lies within a broad elevated interval that also includes the shaly strata of the upper Wiscoy and lower Hanover equivalent. Cycles 9 and 10 are also visible, as is the broad interval of low values that comprises cycle 7. The cm-scale lithologic log of the CAM section (Fig. 9C) corresponds well with the nearby Steuben County well log. The outcrop section does not extend to the top of the Canaseraga or to the overlying Dunkirk Shale, but the shale outcrops nearby (ERC in Figs. 1 and 8). Several of the cycles are also apparent in gamma-ray logs measured by Castle (2000) from the Tioga outcrops; the Pipe Creek shows up as a strong but thin deflection towards high values and the Dunkirk as a persistent interval of high values (Fig. 9D). These results reinforce the potential of gamma-ray logs as a useful tool in further correlations of these strata at other sites in New York and Pennsylvania.

7. Remaining questions

Additional conodonts from the eastern end of the outcrop belt would be useful in validating these correlations, although they are rare and difficult to locate in coarser siliciclastic sediments. Carbon isotope chemostratigraphy could provide an independent check on the proposed correlations and positions of the Kellwasser Events (e.g., preliminary results presented by Beard et al., 2014). Detailed correlation of the Wiscoy Creek section with sections to the west (e.g., Java Village) could be helpful as well. Critically, the position

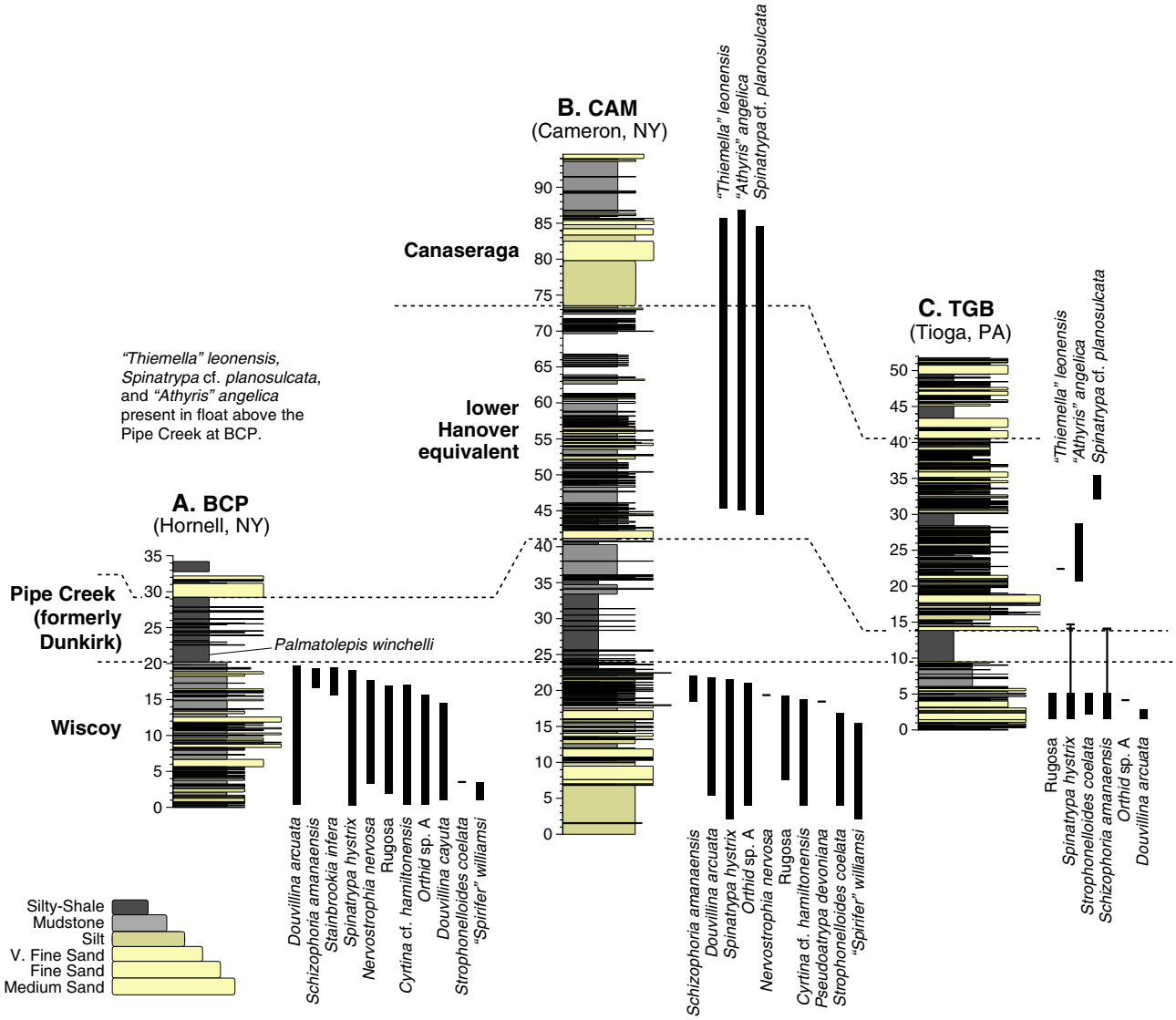

Fig. 4. Stratigraphic distribution of key fossil taxa in the upper Wiscoy Formation and overlying strata. A) Big Creek, Hornell, NY (BCP). B) Cameron, NY (CAM). C) Rt. 287, Tioga, PA (TGB). See Fig. 1 and Table 1 for locations. Height in meters. Ranges include strophomenid, orthid, atrypid, athyrid, and selected spriferid and spiriferinid brachiopods that first or last occurred in these sections; long-ranging taxa that span the entire stratigraphic interval are excluded for clarity. The distribution of rugose corals is also shown.

of the UK needs to be identified precisely in the eastern portion of the outcrop belt. Presuming that these revised correlations are confirmed, the east–west correlations within the West Falls and Canadaway Groups should be re-examined as well. Previously, the uppermost Angola was correlated with the Nunda, but if it correlates with the Wiscoy, then the Nunda must be correlative with another portion of the Angola (Fig. 2D). The Caneadea has been divided into several members (Smith and Jacobi, 2000), and further work could provide more detailed correlations with the South Wales–Gowanda succession in the west.

Correlations with the central and southern Appalachians could also be re-examined. In West Virginia, McGhee (1977) placed the F–F boundary within the Pound Member of the Foreknobs Formation, which is typically considered correlative with the Wiscoy of New York. Biostratigraphic evidence presented here suggests that the Pound actually correlates with the Canaseraga because the lower portion of each contains the last *Spinatrypa* and the first "*Athyris*" *angelica* (Figs. 4 and 6). In his analysis of gamma-ray logs, Filer (2002) correlated the Pound with the upper portion of the Hanover Formation, which again would make it correlative with the Canaseraga given the correlations outlined in Fig. 2D. Correlations between New York and Pennsylvania should be re-evaluated as well (e.g., Warne and McGhee, 1991).

Revised correlations could also provide new insights into Upper Devonian sedimentology and sequence stratigraphy. Smith and Jacobi (2000, 2001) analyzed the sedimentology and sequence stratigraphy of the F–F boundary interval in Allegheny County, but expanding their analyses to the other sections discussed herein would be valuable. Using the older correlations, they noticed dramatic changes in the thicknesses of some units across the basin and suggested that they resulted from syndepositional faulting that caused variable accommodation space, but the role of faulting should be evaluated in light of these new correlations. Baird and Jacobi (1999) described a sandstone bed that occurred within the Pipe Creek Shale in the South Wales–Varysburg region of New York, to the west of our field area. In some localities, most or all of the lower Pipe Creek appeared to have been removed by erosion during or prior to deposition of this sandstone. Given the revised correlation of the Pipe Creek (Fig. 2D), this depositional event could be re-evaluated across the basin. Finally, Boyer and Seeger (2012) examined oxygen levels during the deposition of the UK in western NY using geochemical proxies and ichnofabrics, and

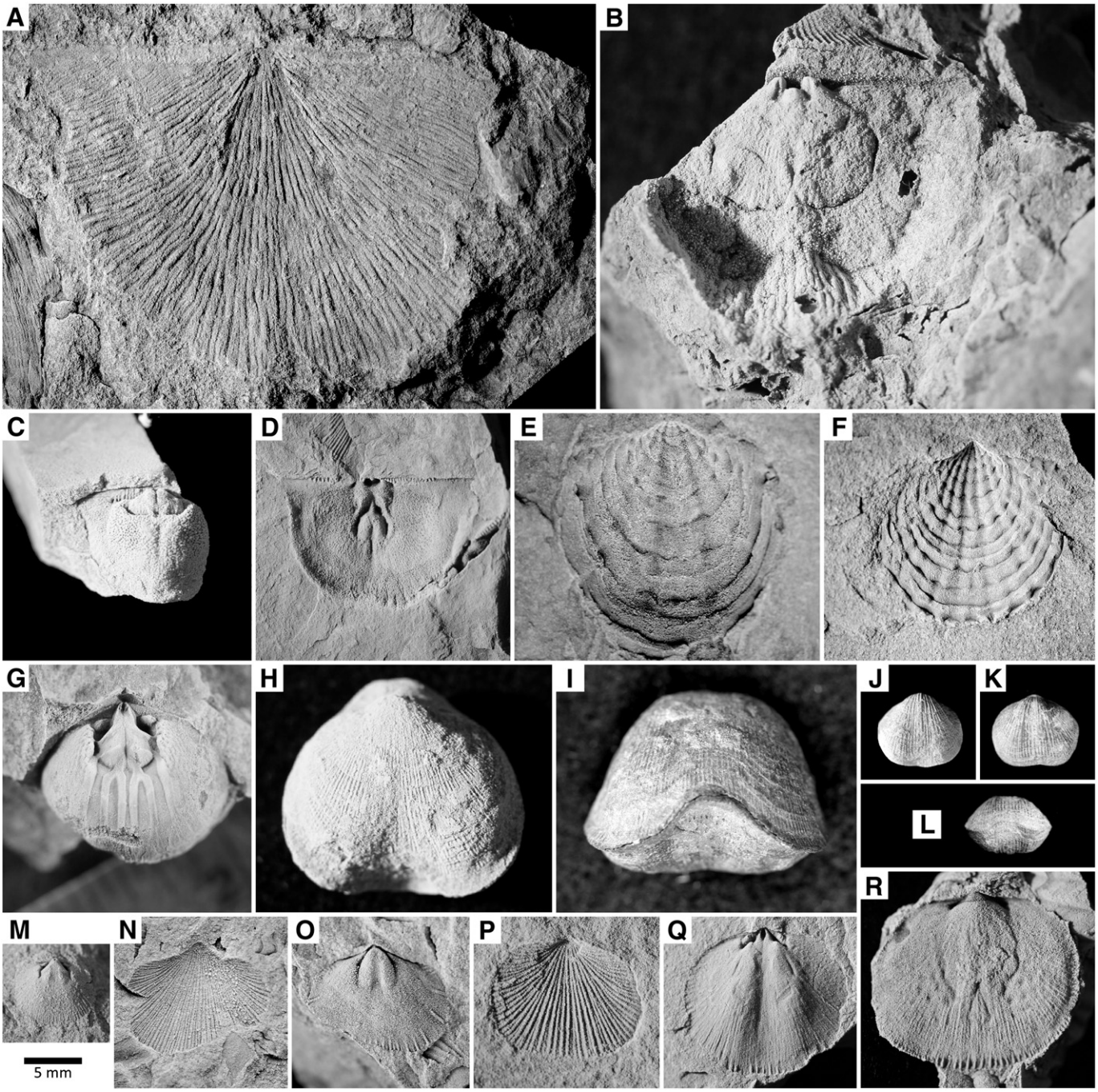

Fig. 5. Brachiopods from the F–F boundary interval of New York. A) *Nervostrophia nervosa*, mold, location 6 (BPH). B) *Strophonelloides coelata*, interior mold, ventral valve, sample TGB 5. C) *Douvillina arcuata*, interior mold, ventral valve, sample BCP 106. D) *Douvillina arcuata*, interior mold, dorsal valve, sample CAM 43. E) *Spinatrypa hystrix*, exterior mold, location 12 (ADR). F) *Spinatrypa* cf. *planosulcata*, exterior mold, sample CAM 134. G) *Schizophoria amanaensis*, interior mold, dorsal valve, sample BCP 134. H–I) *Schizophoria amanaensis*, ventral and anterior views, location 13 (HNS). J–L) *Stainbrookia infera*, ventral, dorsal, and anterior views, location 13 (HNS). M) Orthid sp. A, interior mold, dorsal valve, sample BCP 53. N–O) Orthid sp. A, exterior and interior molds, ventral valve, sample CAM 23. P) "*Thiemella*" *leonensis*, exterior mold, location 25 (PCR). Q) "*Thiemella*" *leonensis*, interior mold, dorsal valve, location BCP, float. R) "*Thiemella*" *leonensis*, interior mold, ventral valve, sample CAM 132. Specimens were coated with ammonium chloride and are shown at the same scale.

these studies could be extended into shallower water using these correlations.

8. Implications for Kellwasser extinctions

We ascribe the extinction at or near the top of the Wiscoy Formation to the LK event, not the UK, as implied by some previous correlations (Fig. 2B). At this horizon, all strophomenid brachiopods and rugose corals were extirpated (Figs. 4 and 6). In other regions, strophomenids do not suffer as extensively at the LK, but suffer additional extinctions at the UK (e.g., Cooper and Dutro, 1982; Day, 2010). All existing atrypids also went extinct, although *Spinatrypa* cf. *planosulcata* appears in the overlying strata, presumably through migration. Several other species of brachiopods last occur in the upper Wiscoy as well. These likely reflect extinction and not facies control because the Canaseraga and underlying Hanover-equivalent beds represents a range of facies generally similar to that of the Wiscoy, and we have sampled both intervals at many localities along a depth transect (Fig. 1, Table 2). Possible

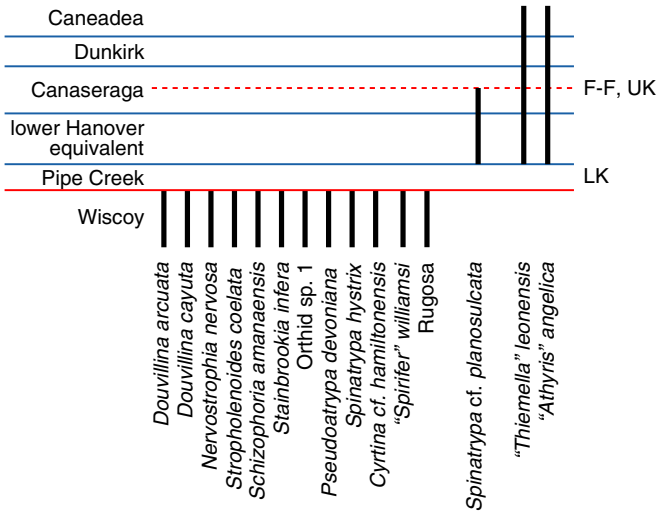

Fig. 6. Summary of stratigraphic ranges of selected biostratigraphically important brachiopods in the upper Frasnian–lower Famennian of New York. F–F: Frasnian–Famennian boundary. UK: Upper Kellwasser equivalent. LK: Lower Kellwasser equivalent.

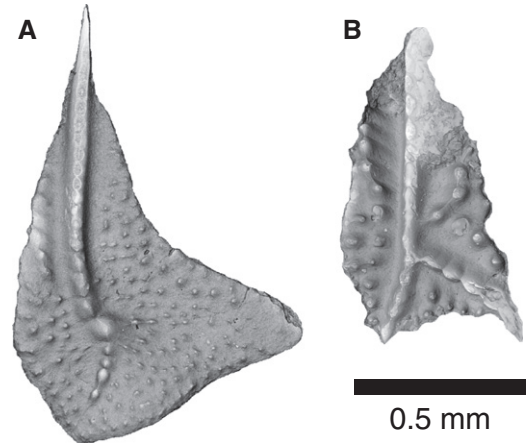

Fig. 7. Conodonts from the F–F boundary interval of New York. A) *Palmatolepis winchelli*, sample BCP 140 (see Fig. 4A). C) *Ancyrognathus symmetricus*, "Hume" Shale (equivalent to the Dunkirk Formation; Fig. 2D), location MIL in Fig. 1 (Mills–Mills, NY).

exceptions include *S. amanaensis* and *S. infera*, which appear to have had a narrow environmental range, only occurring in the transgressive interval in the upper ~5 m of the Wiscoy. At least within the subset of macrofaunal taxa considered here, the UK extinction appears to have had less effect than the LK in New York (Fig. 6).

The LK extinction was previously placed at the top of the Nunda, and according to Dutro (1981), numerous species last occur in this unit. Dutro emphasized that his results were preliminary pending further field work and taxonomic revision, and we have found several species in the Wiscoy that he shows last occurring in the Nunda; detailed comments on turnover from the Nunda to the Wiscoy require further field work.

9. Conclusions

Upper Frasnian and lower Famennian strata of New York State were miscorrelated between deeper-water sections in the west and shallower-water sections in the east. New collections of conodonts and brachiopods from shallow-water, "Chemung" paleoenvironments indicate that the dark shale above the Wiscoy Formation is correlative with the Pipe Creek and that the "Hume" is correlative with the Dunkirk. Thus, extinctions at the top of the Wiscoy correspond with the Lower Kellwasser Event, not the Upper Kellwasser. These extinctions are substantial and include all rugose corals and strophomenid brachiopods. The Upper Kellwasser Event and Frasnian–Famennian boundary are hypothesized to fall within the Canaseraga Formation, although additional work is needed to place the boundary precisely. These correlations establish a temporal framework for further studies of biotic change and mass extinction in shallow-water facies of the Appalachian Basin.

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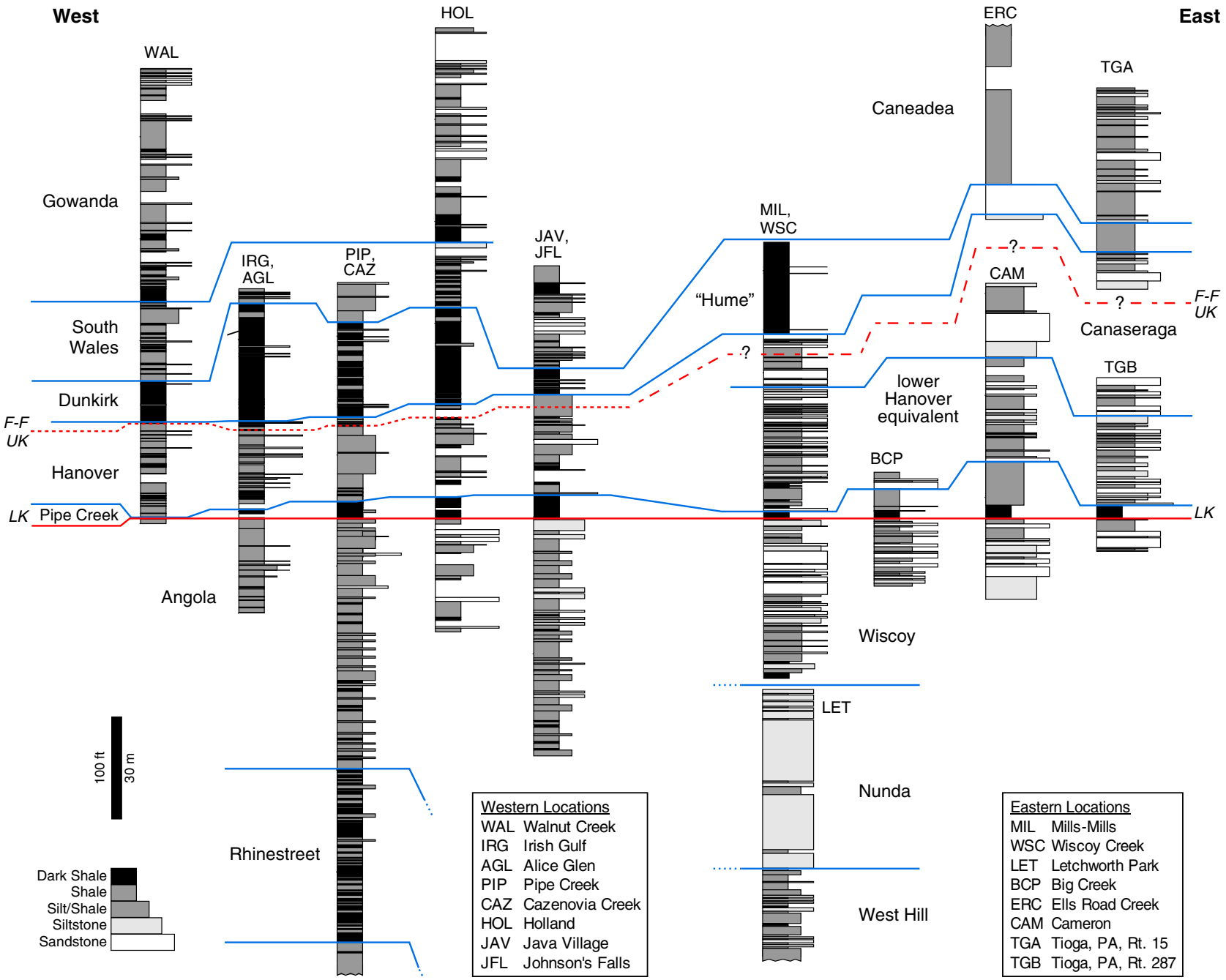
Fig. 8. Stratigraphic sections from the F–F boundary interval in New York and northern Pennsylvania showing the correlations proposed here (i.e., the shale above the Wiscoy correlates with the Pipe Creek, not the Dunkirk; Fig. 2D). The exact position of the F–F boundary in the eastern part of the outcrop belt is not well constrained. See Fig. 1 and Table 1 for locations and sources of data. F–F: Frasnian–Famennian boundary. UK: Upper Kellwasser equivalent. LK: Lower Kellwasser equivalent.
Data from Pepper and DeWitt (1950, 1951), Pepper et al. (1956), Over (1997), Smith and Jacobi (2001), and our own field work.


West
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WAL
IRG, AGL
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Dunkirk
F-F UK
Hanover
LK
Pipe Creek
Angola
Rhinestreet
"Hume"
Caneadea
lower Hanover equivalent
BCP
Wiscoy
LET
Nunda
West Hill
Canaseraga
100 ft
30 m
Dark Shale
Shale
Silt/Shale
Siltstone
Sandstone
Western Locations
WAL Walnut Creek
IRG Irish Gulf
AGL Alice Glen
PIP Pipe Creek
CAZ Cazenovia Creek
HOL Holland
JAV Java Village
JFL Johnson's Falls
Eastern Locations
MIL Mills-Mills
WSC Wiscoy Creek
LET Letchworth Park
BCP Big Creek
ERC Ells Road Creek
CAM Cameron
TGA Tioga, PA, Rt. 15
TGB Tioga, PA, Rt. 287

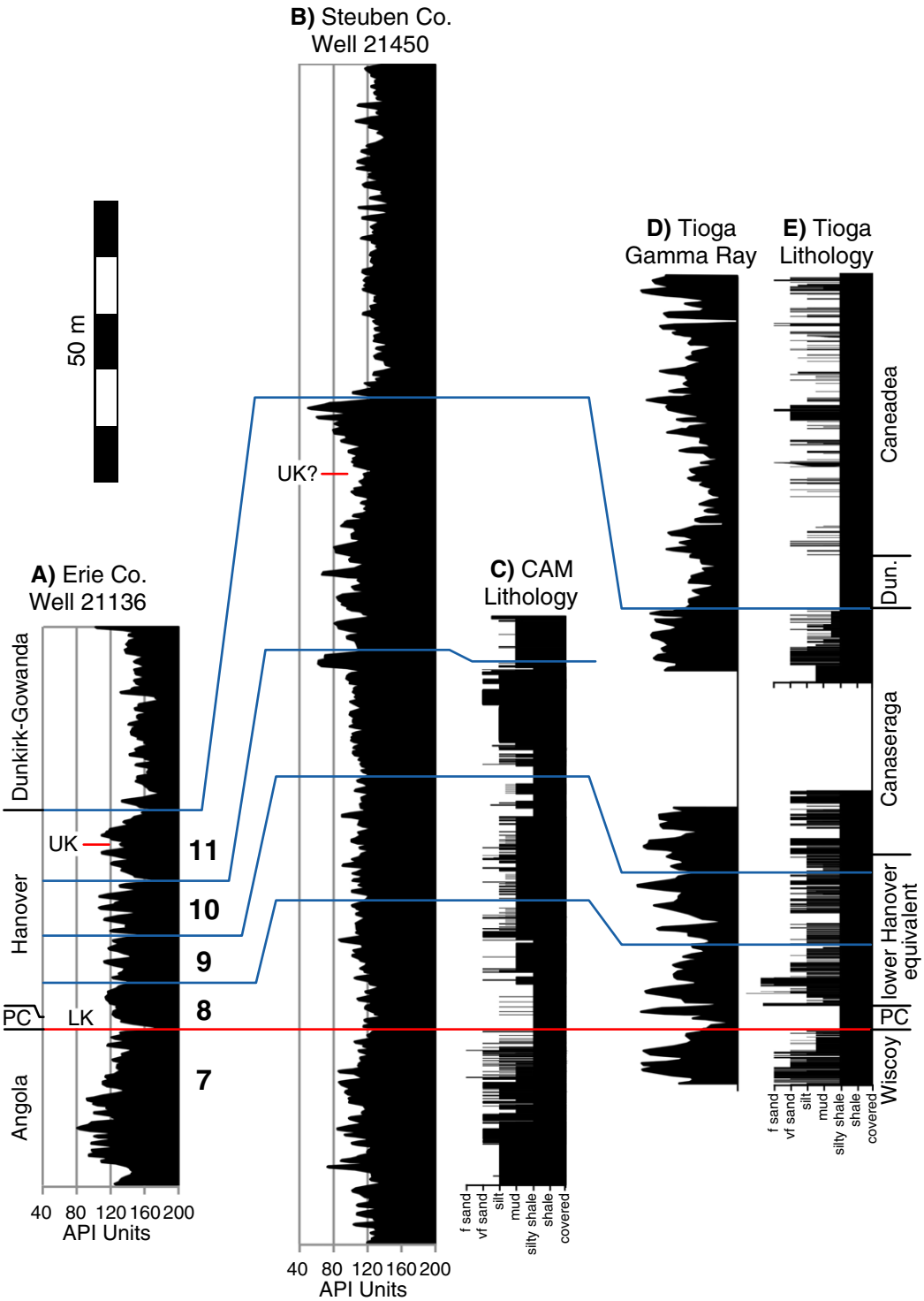

Fig. 9. Subsurface data. A) Gamma-ray log from Erie County well 21136 (see Fig. 2 of Filer, 2002). Numbers 7–11 correspond with Filer's (2002) transgressive–regressive cycles. B) Gamma-ray log from Steuben County well 12145. C) Lithologic log from CAM outcrop (Cameron, NY; see Fig. 4B). D) Gamma-ray log from Tioga, PA outcrops (TGB, lower, and TGA, upper). E) Lithologic logs of Tioga outcrops (see Fig. 4C). PC: Pipe Creek. UK: Upper Kellwasser equivalent. LK: Lower Kellwasser equivalent.
Data in panel D is from Castle (2000). Subsurface gamma-ray logs downloaded from the Empire State Oil and Gas Information System (2013).

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