STRATIGRAPHY AND PALEONTOLOGY OF THE FRASNIAN-FAMENNIAN BOUNDARY INTERVAL (UPPER DEVONIAN) IN TIOGA, NORTH-CENTRAL PENNSYLVANIA

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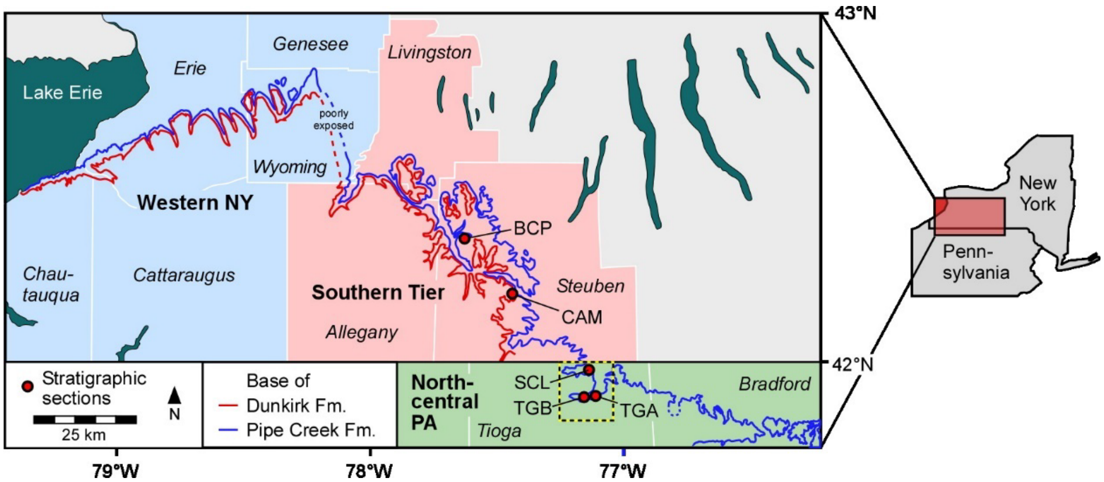
ABSTRACT

Late Frasnian and early Famennian strata are exposed in road cuts in Tioga County in north-central Pennsylvania, providing the opportunity to observe sedimentological and paleontological changes associated with the Late Devonian mass extinction in relatively shallow-marine, siliciclastic-dominated paleoenvironments. In Pennsylvania, these strata are assigned to the Lock Haven Formation/Group, and correlations with the Upper Devonian of New York are possible using brachiopod biostratigraphy and carbon isotope stratigraphy. Specifically, we correlate stratigraphic sections in Tioga with the Wiscoy, Pipe Creek, Canaseraga, Dunkirk, and Caneadea formations of New York. The dark gray, silty shales of the Pipe Creek Formation (the temporal equivalent of the Lower Kellwasser event, the first pulse of the Frasnian-Famennian mass extinction) are exposed and easily accessible, although the Upper Kellwasser-equivalent Point Gratiot Bed has not yet been recognized in the area. Across the basin, many brachiopod species go extinct in the Lower Kellwasser event, although the Upper Kellwasser event is more muted. Skeletobionts do not suffer an obvious extinction, although their patterns of abundance shift, and patterns of extinction in other marine invertebrates have not been studied in detail. The transition to the marginal marine and non-marine facies of the Catskill Formation can be seen at Tioga in Famennian strata.

INTRODUCTION

The Upper Devonian in New York and Pennsylvania is represented by a thick package of siliciclastic sediments that were shed into the Appalachian foreland basin from the Acadian mountains, located to the modern-day east (Ver Straeten, 2009). These sediments record a range of fascinating events in the history of life, including several mass extinctions and the spread of plants and animals on land. Here, we focus on the stratigraphy and paleontology of the upper Frasnian-lower Famennian strata exposed in Tioga County, Pennsylvania, which record the Late Devonian (Frasnian-Famennian) mass extinction in relatively shallow-marine paleoenvironments (Bush et al., 2015, 2017, 2023; Beard et al., 2017; Pier et al., 2021; Brisson et al., 2023). Higher in the section at Tioga, one can also observe the transition to the marginal-marine and terrestrial facies of the lower Catskill Formation.

The Frasnian-Famennian (F-F) boundary is exposed in an outcrop belt that runs from western New York through the "Southern Tier" of New York and into north-central Pennsylvania (Text-fig. 1). The outcrop belt exposes an offshore-onshore paleoenvironmental transect, transitioning from offshore shales in the west to terrestrial facies in the east. Until recently, however, the F-F transition was not studied in detail in shallow-marine strata. Although these rocks are often extremely fossiliferous, there are many challenges to working on them: (1) It can be challenging to correlate outcrops, which are often geographically scattered and generally expose small segments of the total stratigraphy. Facies can change considerably from locality to locality. (2) The most useful fossils for biostratigraphy, like conodonts and ammonoids, are rare in shallow-marine facies, although brachiopods and other benthic macrofauna are common. (3) Preservation of common fossils like brachiopods is highly variable. Only rarely can fossils be extracted easily from the rock, and many are moldic. Collection, preparation, and identification of fossils is generally labor-intensive. (4) The taxonomy of many groups requires updating, and (until recently), one mostly had to rely on 19th century lithographs



Text-fig. 1. Map of the study area showing the bases of the Pipe Creek Formation (blue line) and Dunkirk Formation (red line). County names are in italics. Three regions mentioned in the text are indicated by color: western New York in blue, the Southern Tier in pink, and north-central Pennsylvania in green. The dotted rectangle surrounds the three sections in Pennsylvania that are the focus of this field trip. See Table 1 for locality information. Modified from Bush *et al*. (2023) with permission, based originally on Pepper and de Witt (1950, 1951), Rickard and Fisher (1970), Woodrow (1968), and Bush et al. (2015).

from James Hall (e.g., Hall, 1867) and reprints thereof (Linsley, 1994) for identification. (5) Formation names for these strata change across the New York-Pennsylvania border.

In a series of papers, we have been addressing some of these issues, although much work remains. We have suggested new west-east correlations based on carbon isotope stratigraphy, brachiopod biostratigraphy, and limited conodont biostratigraphy (Bush et al., 2015, 2017, 2023). We have better documented the stratigraphic ranges of brachiopods through the F-F interval via bed-by-bed collecting through longer stratigraphic sections, supplemented by additional collections from smaller outcrops (Bush et al., 2015, 2017, 2023; Pier et al., 2021). This work has suggested that the positions of the two pulses of the F-F extinction, the Lower and Upper Kellwasser events (LKW and UKW), were incorrectly identified in shallow-water settings in many previous stratigraphic studies. We have not addressed most of the taxonomic problems in the fauna, and the genus assignments of many species need to be evaluated, although we have at least provided photographs of brachiopod species from the F-F boundary interval (Bush et al., 2017, and see below).

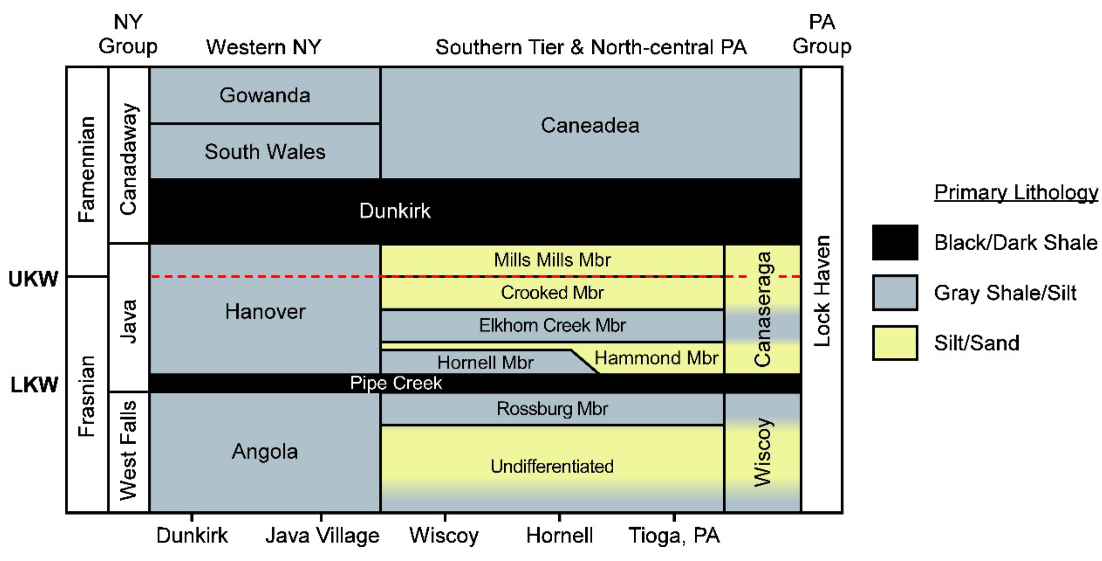
Stratigraphic sections around Tioga, Pennsylvania are of particular interest because they represent the most onshore localities in the outcrop belt at which the F-F interval has been studied in any detail (Text-fig. 1). The Tioga sections are easily accessible at roadcuts, whereas most longer sections through the F-F interval in New York are exposed along stream cuts on private land. (Roadcuts are also present, of course, in New York, but it is difficult to examine extended stratigraphic intervals because the strata are more-or-less flat-lying. In Tioga County, the strata are gently folded, and longer stratigraphic intervals are accessible along some roadcuts.) However, the section along Route 15 in Tioga (TGA) will become less accessible when this road becomes Interstate 99, as has already happened north of the border in New York.

Table 1. Locality information for stratigraphic sections referenced in this chapter.

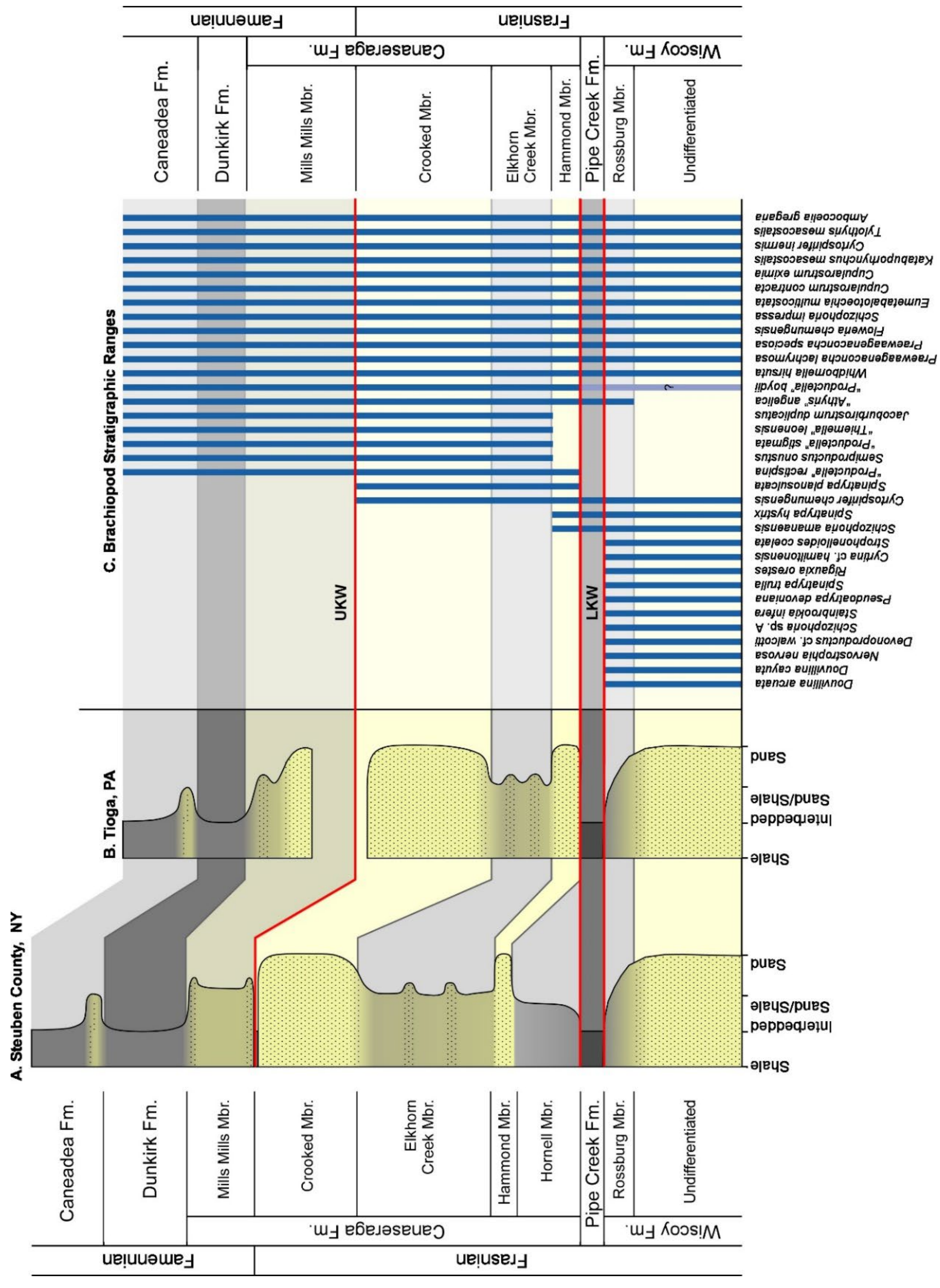
Site	Location	Latitude	Longitude
BCP	Tributary of Big Creek, Hornell, NY	42.3635°	-77.6446°
CAM	Tributary of Canisteo River, Cameron, NY	42.2001°	-77.4370°
SCL	Rt. 49, south side of Cowanesque Lake, PA	41.9816°	-77.1492°
TGB	Rt. 287, Tioga, PA	41.9069°	-77.1624°
TGA	Rt. 15, Tioga, PA	41.9115°	-77.1241°

CORRELATION

Over (1997, 2002) identified the temporal equivalents of the LKW and UKW events in deeper-water environments of western New York using conodont biostratigraphy; specifically, the Pipe Creek Formation is equivalent to the LKW and a black shale bed in the upper Hanover Formation is equivalent to the UKW (the Point Gratiot Bed; Over et al., 2013). Correlation of the Frasnian-Famennian boundary interval between western New York and shallower-water facies the Southern Tier (Text-fig. 1) has been somewhat controversial. Here, we use the correlations proposed by Bush et al. (2015, 2023) and Beard et al. (2017) (Text-fig. 2), which have been used in several recent studies (Bush et al., 2017; Pier et al., 2021; Kerr et al., 2022; Brisson et al., 2023). For a more detailed discussion of the rationale for these correlations, as well as the history of correlation, see Bush et al. (2023) and references therein, as well as discussions by Smith and



Text-fig. 2. Revised correlations of upper Frasnian-lower Famennian strata in New York and north-central Pennsylvania based on Bush *et al*. (2015, 2023) and Beard *et al*. (2017). The red dotted line marks the Point Gratiot Bed of (Over *et al*. 2013), which is the Frasnian-Famennian boundary and UKW. Mbr = Member, UKW = Upper Kellwasser equivalent, LKW = Lower Kellwasser equivalent. Reproduced from Bush et al. (2023) with permission.



Text-fig. 3. Generalized stratigraphy in Steuben County, New York (**A**) and Tioga County, Pennsylvania (**B**), along with and stratigraphic ranges of rhynchonelliform brachiopods (except chonetids) (**C**). Modified from Bush et al. (2023). Stratigraphic ranges are ranged-through based on our data and published reports, and some genus names require revision. Fm. = Formation, Mbr. = Member, UKW = Upper Kellwasser equivalent, LKW = Lower Kellwasser equivalent.

sections with those in the Southern Tier of New York (Text-fig. 1).

Uppermost Frasnian and lowermost Famennian strata around Tioga are assigned to the Lock Haven Formation (Faill and Wells, 1977), which is generally equivalent to the Chemung magnafacies of New York. Correlative strata in New York are divided into numerous formations, and the difference in stratigraphic terminology complicates any discussion of the Frasnian-Famennian boundary and extinction. To facilitate stratigraphic and paleontological studies that cross the border, Beard et al. (2017) and Bush et al. (2023) suggested promoting the Lock Haven to group status in this region and dividing it into the same formations used in the Southern Tier of New York (also see Woodrow, 1968). They also divided the Canaseraga Formation and part of the Wiscoy Formation into members (Text-fig. 2); the TGB section in Tioga was proposed as the type section for several of these (Bush et al., 2023).

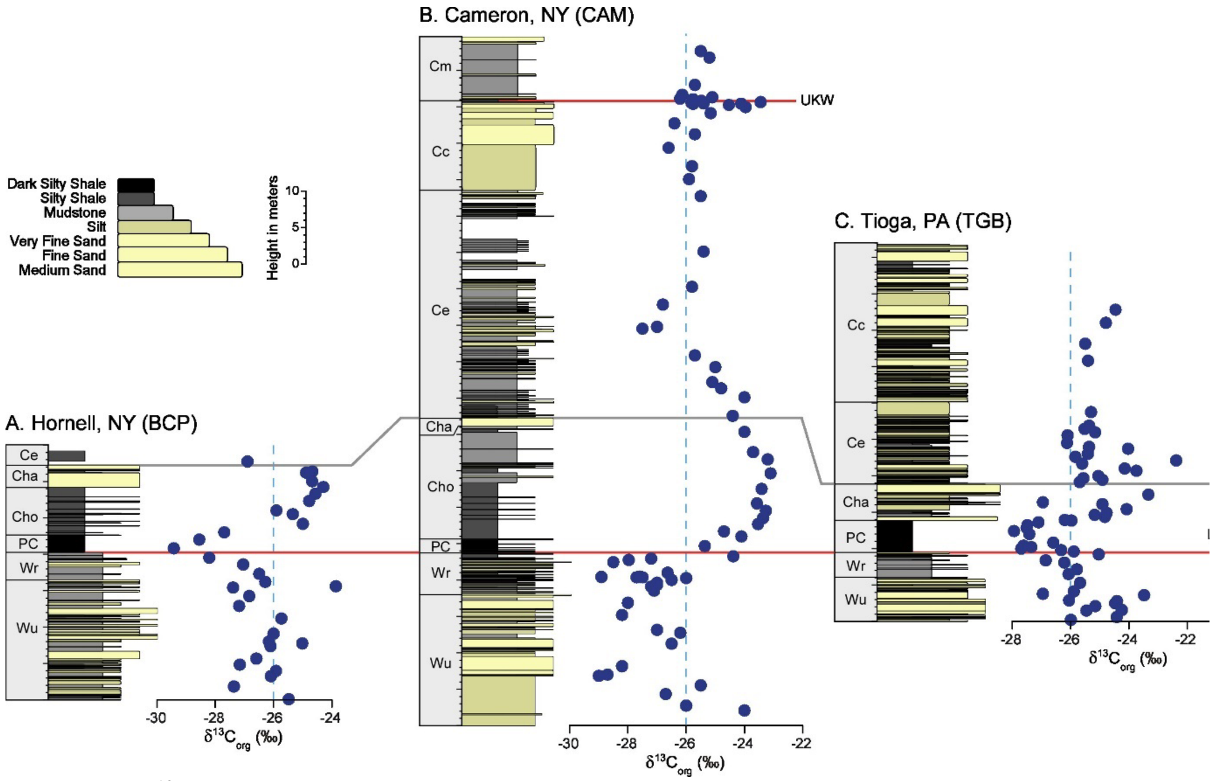
Given their more proximal location, the sections at Tioga are somewhat coarser-grained than those in the Southern Tier, and the facies tend to represent somewhat shallower environments. The general stratigraphic architecture is similar, with one major exception: an interval of several meters of gray shale that directly overlies the Pipe Creek in New York (the Hornell Member of Bush et al., 2023; also see Gallucci et al., 2016) is missing at Tioga. Instead, the dark gray shales of the Pipe Creek transition abruptly into sands of the Hammond Member (Text-figs. 2, 3), although ripped up shale clasts are present in its base (Beard et al., 2017). Beard et al. (2017) and Bush et al. (2023) suggested that these gray shales were removed by erosion.

CORRELATION OF THE LOWER KELLWASSER INTERVAL

Brachiopods have been extremely useful in regional correlations; in particular, there is significant turnover across the LKW event (i.e., from the Wiscoy Formation to the Canaseraga Formation; Text-fig. 3). This turnover has been recognized for many years, even if the details were not well documented; for example, Chadwick (1935) described a “faunal disjunction” in which a fauna “characterized by *Strophonella caelata*, *Douvillina mucronata* (*cayuta* auct.), *Leptostrophia nervosa*… gives place abruptly upward to a different society in which the above named species and many others fail to re-appear. Instead, species like *Athyris angelica*… are found in these overlying beds”. The faunal transition associated with the LKW (Text-fig. 3) is easily recognized at the TGB section, although not all species are present.

At locations around the world, the two KW events are marked by positive carbon isotope excursions (e.g., Joachimski and Buggisch, 1993; Stephens and Sumner, 2003; Chen et al., 2005; Buggisch and Joachimski, 2006). Murphy et al. (2000) and Lash (2017) demonstrated these excursions in organic carbon from locations in western New York, and Bush et al. (2023) identified them at the Cameron (CAM) section in the Southern Tier. Here, we compare the carbon isotope profile from Cameron to preliminary data from Tioga (TGB) and Hornell, NY (BCP) that show the LKW excursion. Methods for carbon isotope measurements follow Bush et al. (2023).

At BCP and TGB (as well as at Walnut Creek in western New York; Lash 2017), there is an initial negative excursion within the dark shales of the Pipe Creek Formation, although this excursion is not clearly manifested at CAM, where the Pipe Creek was not collected in great detail (Text-fig. 4). A broad positive excursion follows in the overlying strata. The excursion at TGB is stratigraphically less expanded than at CAM and, arguably, of lesser magnitude. However, at CAM, the highest $\delta^{13}C_{org}$ values occur within the gray shales of the Hornell Member, which, as discussed above, are missing at TGB, likely due to erosion. Thus, part of the $\delta^{13}C_{org}$ excursion is likely missing at Tioga.



Text-fig. 4. $\delta^{13}C_{org}$ profiles through late Frasnian-early Famennian sections in the Southern Tier of New York and north-central Pennsylvania. **A**, Section BCP in Hornell, New York. **B**, Section CAM in Cameron, New York. **C**, Section TGB in Tioga, Pennsylvania. See Text-fig. 1 for location map. UKW = Upper Kellwasser equivalent, LKW = Lower Kellwasser equivalent, Wu = undifferentiated Wiscoy Formation, Wr = Rossburg Member (Wiscoy), PC = Pipe Creek Formation. Members of the Canaseraga Formation: Cho = Hornell, Cha = Hammond, Ce = Elkhorn Creek, Cc = Crooked, Cm = Mills Mills.

Correlation of the Upper Kellwasser Interval

Turnover in brachiopods is less obvious at the UKW event, with a couple species going extinct and, as far as we know, no new species showing up immediately thereafter (Text-fig. 3). Most notably, *Spinatrypa planosulcata*, the last atrypid in the basin, goes extinct. *S. planosulcata* is present at the TGB section, above the Pipe Creek, but it is not present anywhere at the overlying TGA section, suggesting that the base of the latter probably post-dates the UKW. If UKW-equivalent beds are present at TGB, they have not yet been identified; it is possible that neither Tioga section includes this interval.

The base of the TGA section is silty, but the lithology transitions into a dark shale after about 11 meters. This shale is quite thick, and must be the Dunkirk Formation, which is highest major dark shale unit in the Upper Devonian of New York (and, presumably, north-central Pennsylvania). The section continues to be shale- or mudstone-dominated until the transition to the overlying Catskill Formation, the basal portion of which is well exposed.

SEDIMENTOLOGY

The Tioga sections consist of siliciclastic sediments deposited in the Acadian Foreland Basin. Paleoenvironments were deeper in western New York and shallower to the modern-day east, eventually transitioning from marine to non-marine. Over the course of the Late Devonian, the clastic wedge prograded westward. Sediment accumulation rates were quite high, with the two Kellwasser events separated by up to 60 m of strata (Beard et al., 2017).

The Lock Haven strata at Tioga consist of shallow-marine, storm-dominated strata and offshore muds. Beard et al. (2017) assigned the strata at the TGB and TGA sections to facies ranging from middle shoreface to outer shelf, descriptions of which are given in Table 2. The TGA section also exposes a considerable thickness of the Catskill Formation above the Lock Haven. The sections are described in more detail under the stop descriptions at the end of this chapter.

Table 2. Descriptions and interpretations of sedimentary facies from Tioga, Pennsylvania based originally on Beard et al. (2017). Reproduced from Bush et al. (2017), with permission.

Sand-dominated facies

	Lithology	Features	Interpretation
S1	Medium-bedded sandstone with discontinuous coarser laminations	Mud rip-up clasts, swales, dune/ripple cross-stratification	Middle Shoreface
S2	Medium- to thick-bedded, fine-grained sandstone, < 20% mudstone	Swales, hummocks, oscillatory or combined flow ripples	Middle Shoreface
S3	Thin- to medium-bedded, fine-grained sandstone with 20–50% mudstone	Swales, hummocks, oscillatory or combined flow ripples	Lower Shoreface
S4	Very fine-grained, muddy sandstone, medium- to thick-bedded	Structureless, dewatering structures, concretions, increasing mud upwards	Shoreface, rapid deposition
S5	Scour-based, medium- to thick-bedded fine-grained sandstone	Plane-laminated or cross-stratified assoc. with 3D dunes, plant debris with iron staining, wave-ripples	Shelf Channel

Mud-dominated facies

	Lithology	Features	Interpretation
M1	Gray–brown mudstones with thin beds of siltstone to fine-grained sandstone	Plane-laminations, oscillatory or combined flow ripples (sandstones)	Inner Shelf
M2	Gray, fissile, silty mudstone	May have regularly spaced bedding-parallel red banding	Outer Shelf
M3	Dark gray, fissile silty mudstone	May have regularly spaced bedding-parallel red banding	Outer Shelf, dysoxic–anoxic

PALEONTOLOGY/MASS EXTINCTION

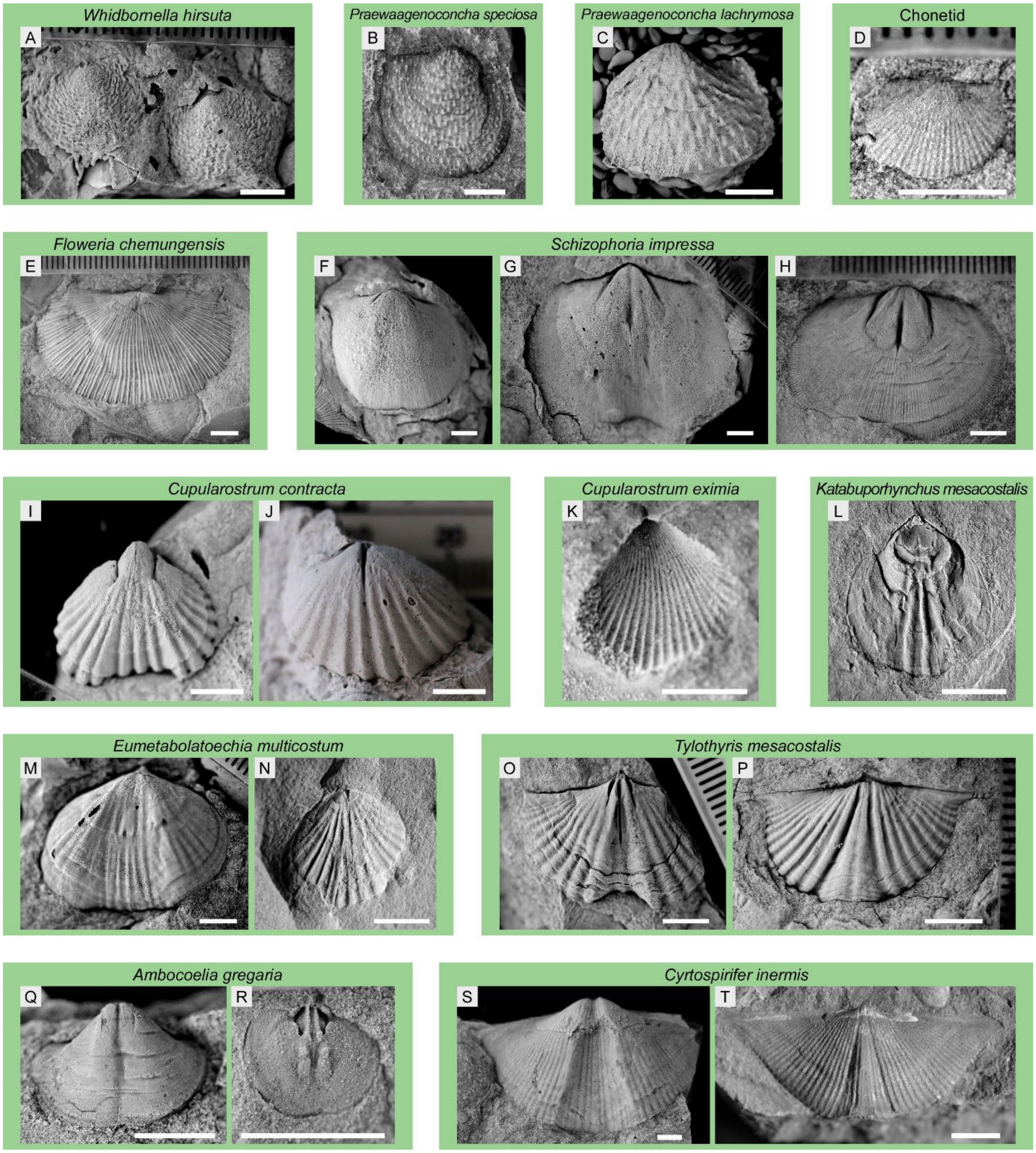
The Late Devonian (Frasnian-Famennian) mass extinction consists of two pulses, the Lower and Upper Kellwasser events (LKW and UKW; e.g., Schindler, 1993; McGhee, 1996; House, 2002). Correlation of the F-F boundary interval in the highly fossiliferous strata of the Southern Tier and north-central Pennsylvania has permitted a number of new analyses of these events; so far, these analyses have focused on rhynchonelliform brachiopods (minus chonetids, which can be difficult to identify in these rocks when poorly preserved) and on their skeletobionts.

Numerous species of brachiopod survive both extinction pulses (Text-figs. 3, 5; note that some photographed specimens are from Tioga but some are from other localities). About half the brachiopod species present in the Wiscoy Formation go extinct in the Lower Kellwasser event (Text-figs. 3, 6) (Pier et al., 2021; Brisson et al., 2023). At Tioga, the Pipe Creek Formation (LKW equivalent) consists of several meters of dark-gray, silty shale that bears a low density of small body and trace fossils; Beard et al. (2017) interpreted it as representing a dysoxic but not permanently anoxic depositional environment (cf. Boyer et al., 2014, 2021; Haddad et al. 2018). At Tioga, a couple species (*Spinatrypa hystrix* and *Schizophoria amanaensis*) last occur in the Hammond Member, which sits right above the Pipe Creek (Text-fig. 3). If one interprets the LKW event as corresponding only to the shales of the Pipe Creek Formation, then these species go extinct shortly after the event. However, if one interprets the event as encompassing the entirety of the LKW biogeochemical disturbance (e.g., the carbon isotope excursion, which persists into the Hammond Member), then these species could be considered victims of the LKW event. Either way, analyses by Pier et al. (2021) suggest that the victims of the extinction were primarily those that may have been adapted to warmer waters, consistent with arguments for global cooling as an extinction kill mechanism (e.g., Copper, 1998; Joachimski and Buggisch, 2002). None of the strophomenids or atrypids present in the Wiscoy persist above the Pipe Creek and/or Hammond.

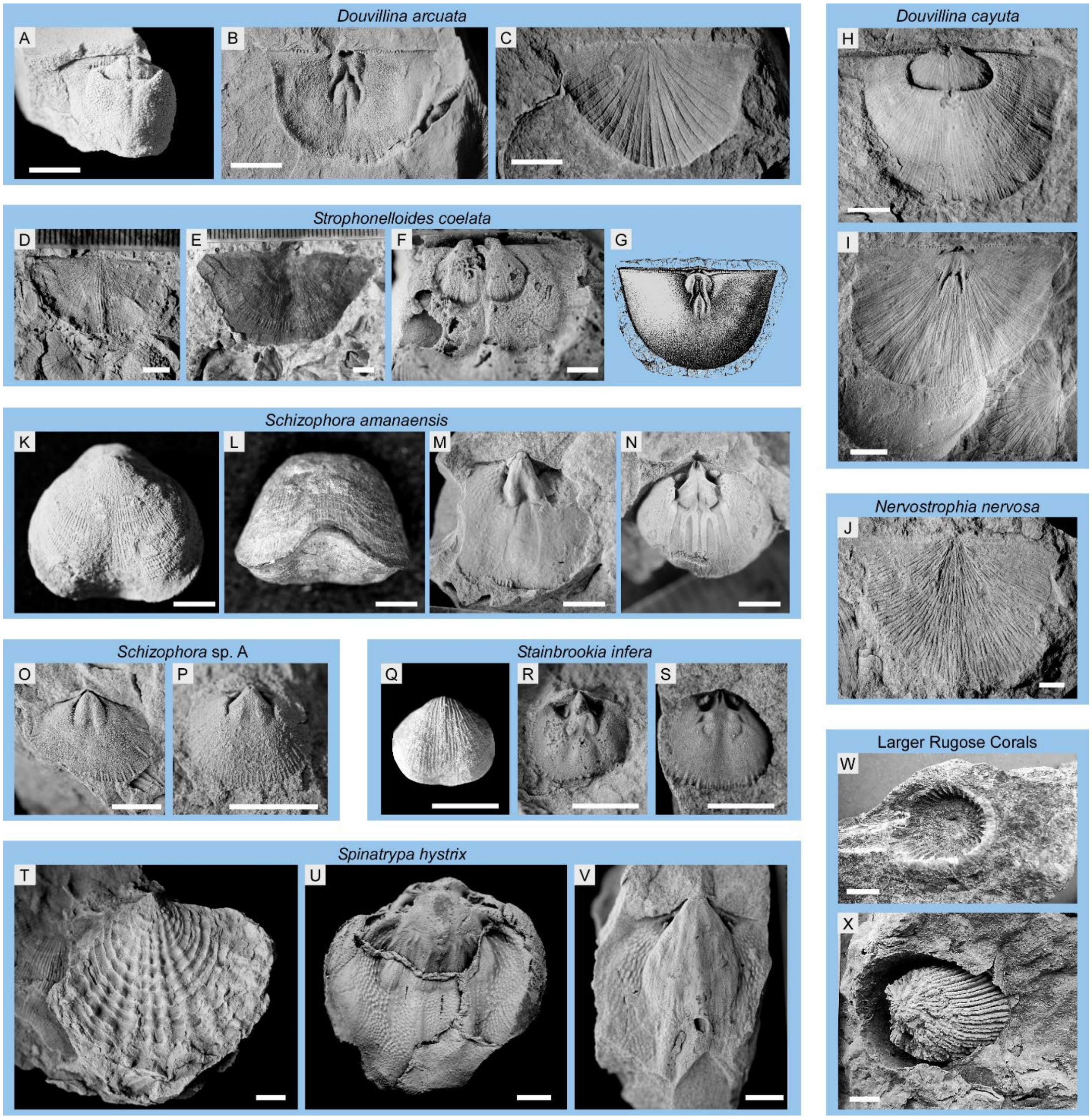
The extinct brachiopods were largely replaced above the LKW by new species (Text-figs. 3, 7), which included a number of productids and the last atrypid in the basin, *Spinatrypa planosulcata*. As far as we have been able to determine, only two brachiopod species go extinct at the UKW event: *S. planosucata* and *Cyrtospirifer chemungensis* (Text-fig. 8). Thus, the LKW event was much more pronounced in this region than the UKW event.

Brisson et al. (2023) compared the onshore-offshore distributions of the survivors of the LKW in the Wiscoy and Canaseraga formations (i.e., before and after the extinction) using ecological gradient analysis. They found that survivors tended to exhibit niche conservatism, meaning that they lived in the same habitats before and after, even though much of the fauna changed around them due to extinction and migration.

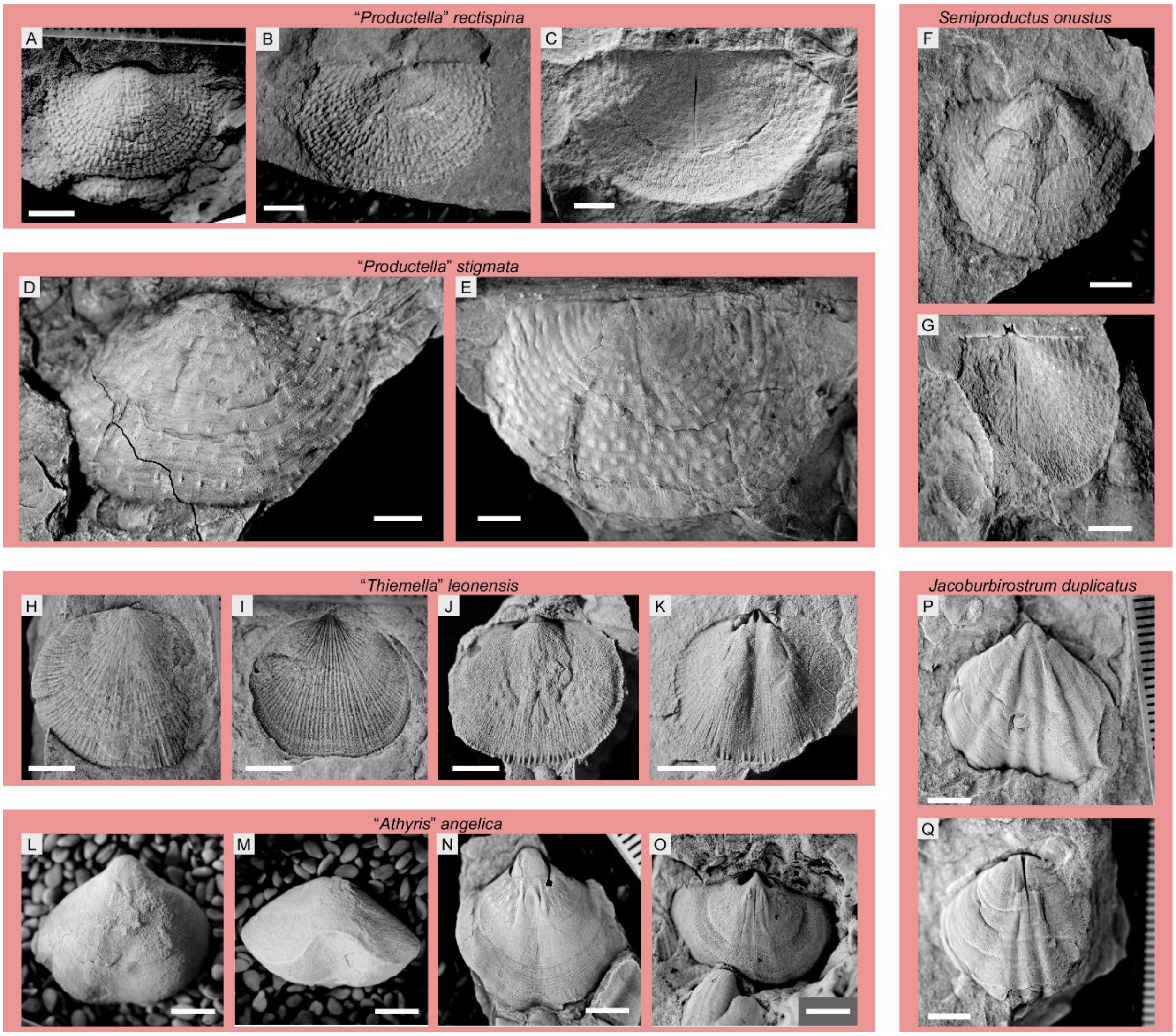
Kerr et al. (2022) examined the fate of the skeletobionts that encrusted and bored brachiopod shells (Text-fig. 9) across the LKW at a stratigraphic section in Cameron, New York (CAM in Text-fig. 1). They identified seven major types of skeletobiont, including microconchids, stenolaemate bryozoans, ctenostome bryozoans, hederelloids, and several types of borings attributed to sponges. Initial analyses suggest that skeletobiosis was more common on larger shells and that borings were less common (or less commonly preserved) in mudstones. All skeletobiont types survived the LKW, although the total frequency of encrustation/boring declined and the relative abundance distribution shifted. The exact drivers of these patterns will be addressed in further studies that will include fossils from Tioga.



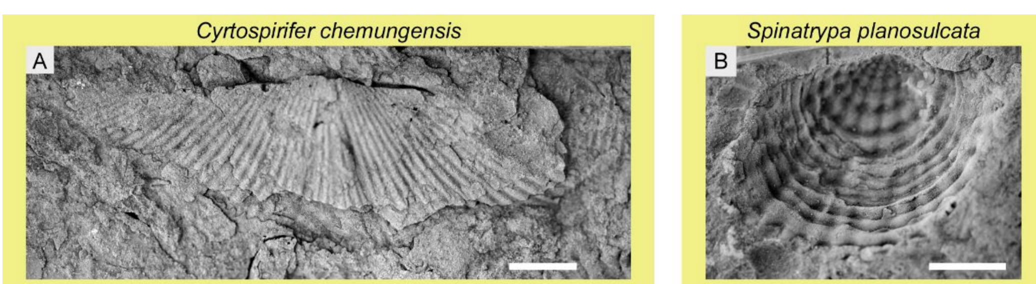
Text-fig. 5. Brachiopods that range through the study interval. Scale bars = 5 mm. Photos reprinted from Bush et al. (2015, 2017), who give more detailed locality information. **A**, Dorsal molds, CAM 20. **B**, Ventral view, CAM 152. **C**, Ventral, CAM 132. **D**, Ventral, CRR. **E**, TGA. **F**, Dorsal internal mold, TGA 1. **G**, Ventral internal mold, SGU. **H**, Ventral internal mold, PCE-1. **I**, Ventral internal mold, Rt. 119, Cameron, NY. **J**, Dorsal internal mold, TGB 49. **K**, External mold, TF. **L**, BCP 149. **M**, Ventral internal mold, SWA. **N**, Dorsal internal mold, BCP 150. **O**, Ventral internal mold, PCR. **P**, Dorsal internal mold, PCR. **Q**, Ventral, BCP 141. **R**, Dorsal internal mold, BCP 106. **S**, Ventral, CAM 155. **T**, Dorsal, CAM 155.



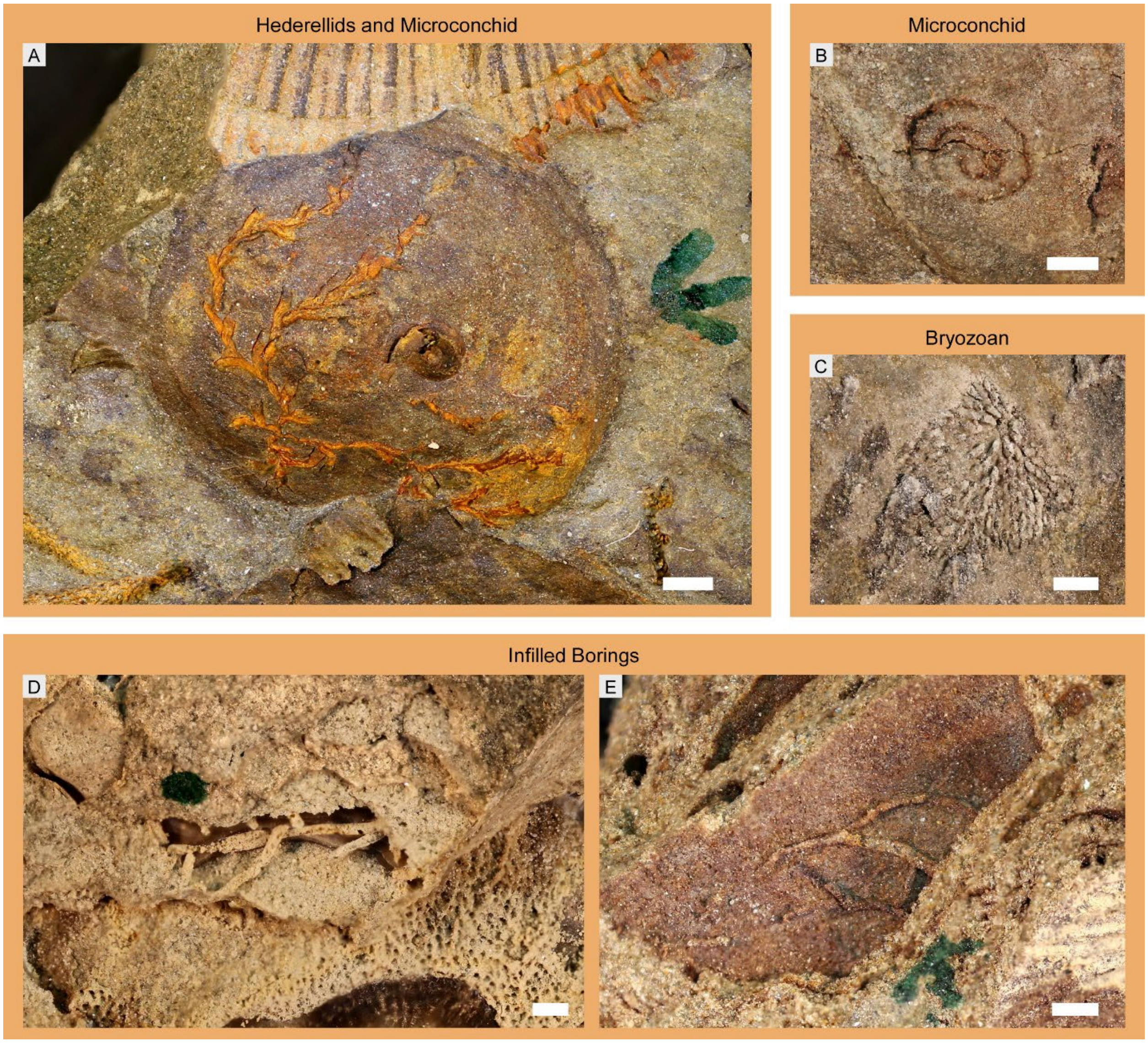
Text-fig. 6. Brachiopods (and corals) that went extinct in the Lower Kellwasser interval (last occurrence in the upper Wiscoy Formation or the Hammond Member of the Canaseraga Formation). Scale bars = 5 mm. Brachiopod photos reprinted from Bush et al. (2015, 2017), who give more detailed locality information. **A**, Ventral, BCP 106. **B**, Dorsal, CAM 43. **C**, Dorsal, CAM 43. **D**, Ventral, CAM 12. **E**, Dorsal, ADR. **F**, Ventral, CAM 12. **G**, Dorsal (Hall, 1867). **H**, Ventral, WEL. **I**, Dorsal, WEL. **J**, BPH. **K**, Ventral, HNS. **L**, Anterior, HNS. **M**, Ventral, DAN 30. **N**, Dorsal, BCP 134. **O**, Ventral, CAM 23. **P**, Dorsal, BCP 53. **Q**, Ventral, HNS. **R**, Ventral, DAN. **S**, Dorsal, BRC. **T**, Ventral, TGB. **U**, Ventral, loc? **V**, Ventral, BCP 7. **W**, TGB 5. **X**, Mold, TGB 5.



Text-fig. 7. Brachiopods from the Canaseraga Formation that survive the Upper Kellwasser Event. Scale bars = 5 mm. Photos reprinted from Bush et al. (2015, 2017), who give more detailed locality information. **A**, Ventral, CSA. **B**, Dorsal, CAM 79F. **C**, Dorsal, CAM 110. **D**, Ventral, PD. **E**, Dorsal, PD. **F**, Ventral, TGA. **G**, Dorsal, CAM 108. **H**, SLD-2013. **I**, Loc. unknown. **J**, Ventral, CAM 132. **K**, Dorsal, BCP. **L**, Ventral, TGA 13R. **M**, Anterior, TGA 13R. **N**, Ventral, CAM 120. **O**, Dorsal, CAM 145. **P**, Ventral, PCR. **Q**, Dorsal, PCR.

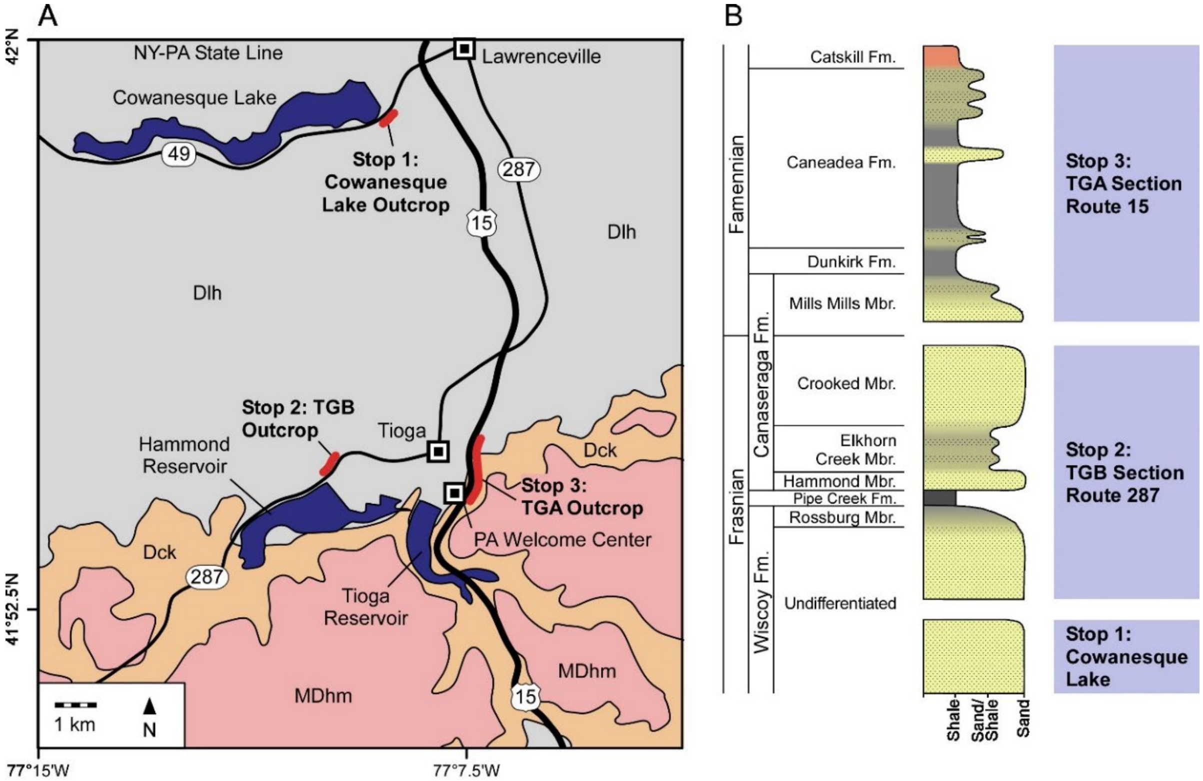


Text-fig. 8. Victims of the Upper Kellwasser event. Scale bars = 5 mm. Photos reprinted from Bush et al. (2015, 2017). **A**, CAM 135. **B**, CAM float.



Text-fig. 9. Molds of skeletobionts on brachiopod shells from the Frasnian-Famennian boundary interval. All specimens from the CAM locality (Cameron, New York). Scale bars = 1 mm. See Kerr et al. (2022) for more information.

ROAD LOG

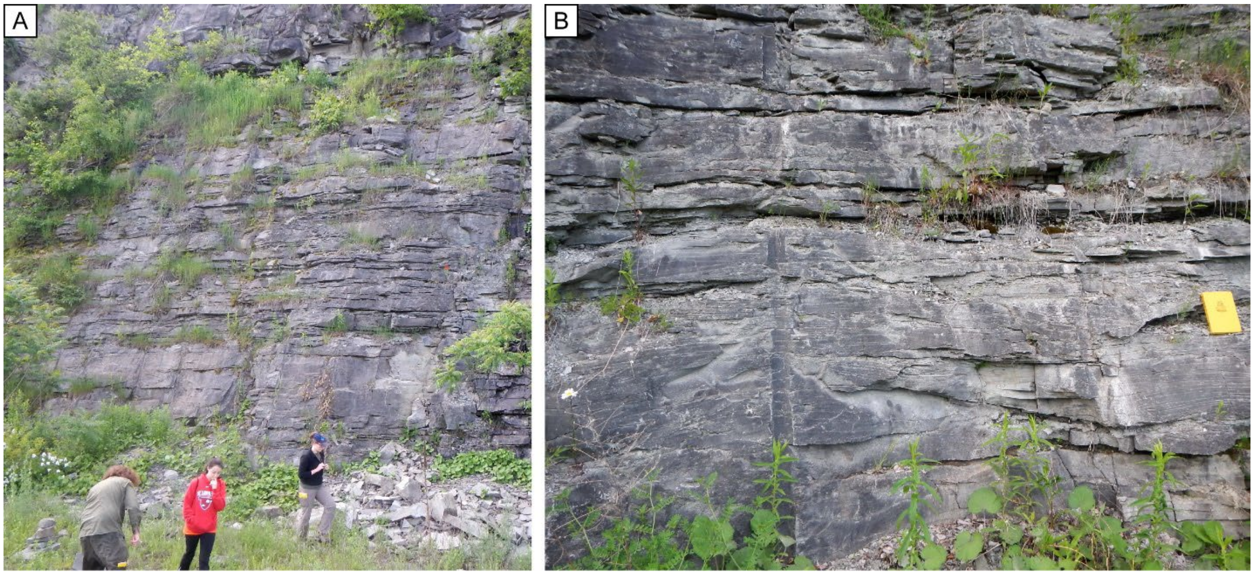


Text-fig. 10. Field trip stop information. **A**, Geologic map of the Tioga, Pennsylvania region (close-up of the dotted rectangle in Text-fig. 1). Modified from Bush et al. (2017) with permission of NYSGA. Based on information in Berg et al. (1980) and Beard et al. (2017). Dlh = Lock Haven Group. Dck = Catskill Formation. MDhm = Huntley Mountain Formation. **B**, Generalized stratigraphy of field trip stops.

STOP 1
ROUTE 49, COWANESQUE LAKE, PENNSYLVANIA
41.9816°, -77.1492°

This outcrop of Wiscoy Formation-equivalent strata just south of the New York-Pennsylvania border (Text-figs. 10, 11) is similar to several large outcrops north of the border along I-99/Rt. 15. Parking is much easier at this locality. The strata display hummocky and swaley cross-stratification, similar to facies S2-S3 of Beard et al. (2017) (Table 2). Facies S2 includes medium- to thick-bedded, fine-grained sandstone with abundant swales and < 20% interbedded mudstones; Beard et al. (2017) interpreted it as a middle shoreface environment. Facies S3 has thin- to medium-bedded sandstones and a greater percentage of interbedded mud (20-50%), and it was interpreted as lower shoreface.

This outcrop gives a good view of the undifferentiated portion of the Wiscoy, the top of which is exposed at the next stop (TGB). Thus, these are the lowest strata visited on this trip. Fossils include brachiopods, bivalves, and trace fossils. The brachiopods are typical of the Wiscoy and include *Douvillina arcuata*, *D. cayuta*, *Schizophoria amanaensis*, *Schizophoria* sp. A, *Whidbournella hirsuta*, *Strophonelloides coelata*, *Whidbornella hirsuta*, *Spinatrypa hystrix*, *Cupularostrum contracta*, chonetids, and others (Text-figs. 5, 6).



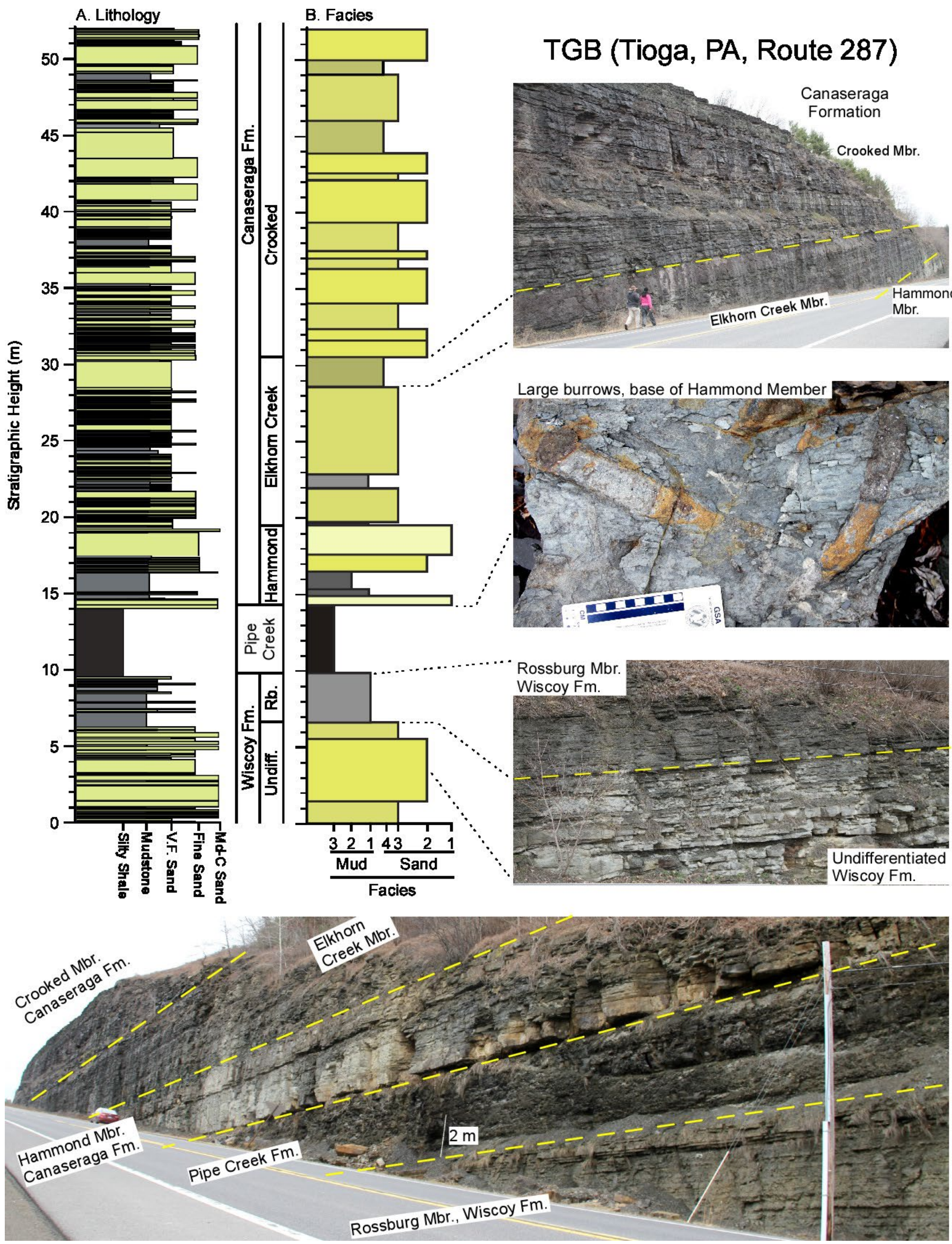
Text-fig. 11. Outcrop along Rt. 49 near Cowanesque Lake, Pennsylvania (SCL in Text-fig. 1 and Table 1).

STOP 2
ROUTE 287, TIOGA, PENNSYLVANIA
41.9069°, -77.1624°

This outcrop, referred to as TGB by Bush et al. (2015) and others, shows the uppermost Wiscoy Formation, the entirely of the Pipe Creek, and much of the Canaseraga Formation (Text-fig. 10, 12). It is the type section of the Hammond, Elkhorn Creek, and Crooked members of the Canaseraga Formation (Beard et al., 2017; Bush et al. 2023). The following descriptions of these stratigraphic units are based on the facies descriptions of Beard et al. (2017) and subsequent discussions by Bush et al. (2017, 2023) (see Text-fig. 12 for section and Table 2 for facies descriptions). The Lock Haven sections at Tioga were previously discussed by Berg et al. (1981, pp. 153-158), Castle (2000), and Bush et al. (2015), and Pier et al. (2021) and Brisson et al. (2023) discuss the record of the LKW extinction at TGB and other sections.

Wiscoy Formation, undifferentiated: The base of the TGB section belongs to the undifferentiated portion of the Wiscoy Formation (Text-fig. 12). It consists of swaley, fine-grained sandstones with varying amounts of interbedded mudstone, interpreted as lower to middle shoreface (facies S2-S3, swaley-bedded, fine-grained sandstones with variable proportions of mud interbedded). Fossils include *Strophonelloides coelata*, *Schizophoria amanaensis*, *Spinatrypa hystrix*, *Douvillina arcuata*, *Cyrtospirifer inermis*, *Floweria chemungensis*, and rugose corals (Text-figs. 5, 6).

Wiscoy Formation, Rossburg Member: The upper several meters of the Wiscoy are assigned to the finer-grained Rossburg Member, which at TGB consists of mudstone with thin siltstone and sandstone interbeds, interpreted as inner shelf (facies M1 in Beard et al. 2017). Macrofossils are rare to absent in these beds, although bioturbation is common.



Text-fig. 12. TGB section, Route 287, Tioga, Pennsylvania. **A**, Lithology. **B**, Facies analysis of Beard et al. (2017) (see Table 2). Modified from Bush et al. (2017), with permission.

Pipe Creek Formation: The Pipe Creek is about four meters thick at TGB; it consists of dark gray, silty shale interpreted a low-oxygen, offshore setting (facies M3 in Beard et al., 2017). bivalves, and lingulid brachiopods can be found in the unit (Beard et al., 2017).

Canaseraga Formation, Hammond Member: At TGB, the Hammond Member directly overlies the Pipe Creek, although the gray shales of the Hornell Member separate them at more distal sections. The Hammond includes the most coarse-grained strata at TGB, which Beard et al. (2017) interpreted as representing a middle shoreface environment (facies S1). At Tioga, the base of the lowest Hammond sandstone bed is covered by large burrows, possibly *Teichichnus* isp. and *Thalassinoides* isp., which probably represent animals deposit-feeding on the organic-rich muds of the Pipe Creek following the return of normal oxygen levels (Text-fig. 12). Trace fossils are common elsewhere in the Hammond as well. The coarsest sandstone beds at the base of the Hammond are capped by granule-rich bed bearing rippled bedforms (Beard et al., 2017, fig. 6A,B) that may represent a transgressive ravinement surface (cf. Castle, 2000; Plint, 2010; McClung et al., 2013).

Floweria chemungensis is abundant in the Hammond, and the large bivalve *Grammysia* is also notable at some horizons. The Hammond also contains the last representatives of species like *Spinatrypa hystrix* and *Schizophoria amanaensis*. As discussed by Pier et al. (2021), these species could be considered survivors of the LKW, as they persist above the Pipe Creek Formation, or they could be considered victims, if the extinction interval extends above the Pipe Creek (i.e., if the extinction interval is marked by the biogeochemical disturbances indicated by the carbon isotope excursions) (for a general discussion, see Holland and Patzkowsky, 2015).

Canaseraga Formation, Elkhorn Creek Member: The transition from the Hammond to the Elkhorn Creek represents a deepening; the most common facies is S3, representing the lower shoreface (thin- to medium-bedded, fine-grained, sandstones with swales and hummocks, interbedded with 20–50% mudstone; Text-fig. 12, Table 2). This interval contains a diverse fauna, including brachiopod species that first appear in the Canaseraga, such as *Spinatrypa planosulcata* (Text-fig. 8B), "*Productella*" *rectispina*, and *Semiproductus onustus* (Text-fig. 7). Long-ranging brachiopods such as *Floweria chemungensis*, *Whidbornella hirsuta*, *Cyrtospirifer inermis*, *Tylothyris mesacostalis*, and *Cupularostrum contracta* are also common, among others (Text-fig. 5). Glass sponges have also been found (Bush et al., 2017, fig. 53), among other marine invertebrates.

Canaseraga Formation, Crooked Member: The Crooked Member at TGB is sandier than the underlying Elkhorn Creek (largely facies S2, middle shoreface) and represents a slight shallowing (Text-fig. 12). *Cyrtospirifer inermis* (Text-fig. 5S, T) begins to dominate the fossil assemblages, with *Cupularostrum contracta* (Text-fig. 5I, J) remaining somewhat common as well. Several noteworthy beds are marked in Text-fig. 12B as facies S4, which consists of muddy, fine-grained sand characterized by dewatering structures and convoluted bedding. Beard et al. (2017) interpreted these beds as representing the rapid deposition of mud and sand that were loaded prior to dewatering. Brachiopods are often present in these layers.

The Point Gratiot Bed (F-F boundary bed) should be located at the top of the Crooked Member (Beard et al., 2017; Bush et al. 2023). We have not identified it at TGB, although we do not know exactly what it would look like in this onshore setting. It is possible that it sits in the gap between the TGB section and the overlying TGA section.

***Summary of TGB Stratigraphy*:** The lower 10 m of the section represent increasing water depth, with the transition from the swaley, sandy sediments of the undifferentiated Wiscoy Formation to the bioturbated muds and thin siltstones of the Rossburg Member to the offshore, dysoxic Pipe Creek Formation. The silty shales of the Pipe Creek transition abruptly to the middle shoreface sands at the base of the Hammond, suggesting a forced regression. Additional large changes in water depth are suggested by the coarse-grained bed with large ripples, which may represent a transgressive ravinement surface (cf. Castle, 2000; Plint, 2010; McClung et al., 2013), followed by mudstone, then the middle shoreface sediments of the upper Hammond Member. Facies changes are more subdued and gradual in the rest of the section, which generally coarsens upward from the Elkhorn Creek Member to the Crooked Member.

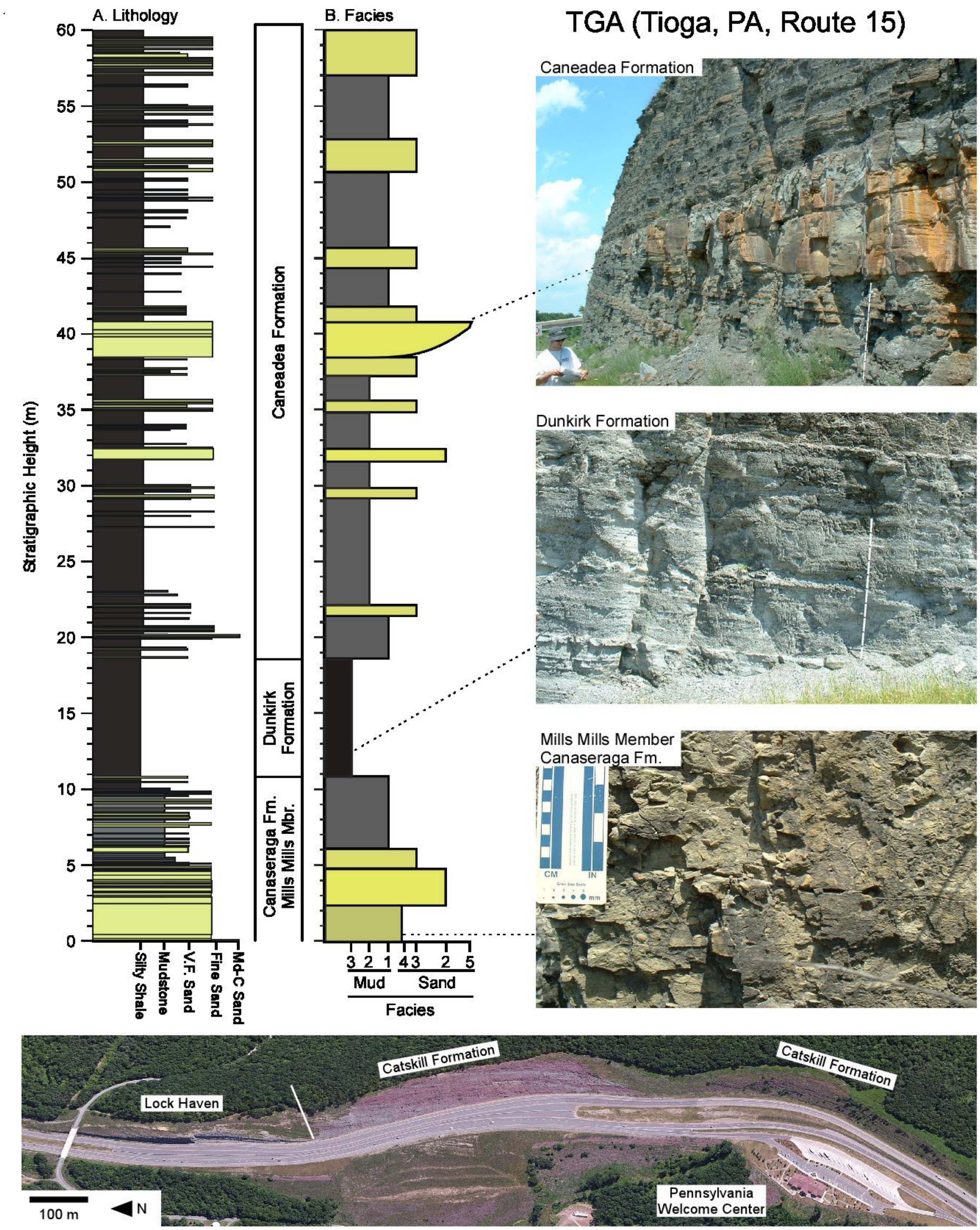
STOP 3
ROUTE 15, TIOGA, PENNSYLVANIA
41.9115°, -77.1241°

This outcrop, referred to as TGA by Bush et al. (2015) others, exposes the uppermost ~10 meters of the Canaseraga Formation (Mills Mills Member), the entirety of the Dunkirk and Caneadea formations, and the basal portion of the Catskill Formation (Text-fig. 13). Stratigraphic units are described below in ascending order (see Table 2 for facies descriptions for the Lock Haven). For previous discussions of this outcrop see, for example, Berg et al. (1981, pp. 148-152), Slingerland and Loulé (1988), Castle (2000), Oest (2013), McLaurin (2013), Bush et al. (2015, 2017), and Beard et al. (2017) (also, see Woodrow, 1989, for similar outcrops by the Tioga Dam).

Canaseraga Formation, Mills Mills Member: The basal ten meters of the section are correlated with the Mills Mills Member, the lowest stratigraphic unit in the Famennian (Text-fig. 13). The correlation is based on the position relative to the Dunkirk Formation, the lack of any bed that is obviously correlated with the Point Gratiot Bed (UKW equivalent), and the lack of any fossils like *Spinatrypa planosulcata* that would indicate a late Frasnian age. This interval fines from facies S2 and S3 (middle to lower shoreface) to M1 (inner shelf) and thence into the Dunkirk. Common brachiopods include "*Athyris*" *angelica*, *Tylothyris mesacostalis*, *Praewaagenoconcha speciosa*, *Floweria chemungensis*, *Schizophoria impressa*, "*Productella*" *rectispina*, *Cupularostrum contracta*, *Ambocoelia gregaria*, *Cupularostrum eximia*, and *Semiproductus onustus* (Text-figs. 5, 7). Other marine invertebrate fossils are common, including bivalves, bryozoans, and crinoid columnals.

Dunkirk Formation: The Dunkirk Formation is the uppermost thick black shale unit in the Upper Devonian of New York; here, it consists of dark gray, silty shale, and Beard et al. (2017) interpreted it as an offshore, dysoxic paleoenvironment. It generally lacks macrofossils, although fossils similar to those in the underlying Mills Mills Member occur near the base, suggesting a gradual decrease in oxygen during the Mills Mills – Dunkirk transition.

Caneadea Formation: The Caneadea consists largely of gray shale with frequent silty-sandy interbeds; we place its base at the first package of coarser beds above the more consistent dark shales of the Dunkirk Formation (Text-fig. 13). It generally coarsens upward towards the base of



Text-fig. 13. TGA section, Rt. 15 (future I-99), Tioga, Pennsylvania. **A**, Lithology. **B**, Facies analysis (see Table 2). Modified from Bush et al. (2017), with permission. Facies analysis from Beard et al. (2017). Bottom panel: Imagery ©2017 Google, Map data ©2017 Google. Staff = 2 m with 20 cm divisions.

shelf) with an increase in S3 (lower shoreface) toward the top. Tabulation of fossils from the section is in progress, but in general, shallow-water species like *Cyrtospirifer inermis* and *Cupularostrum contracta* become more common towards the top, consistent with a shallowing trend. At 40 m, there is a thick sandstone interval with a scoured base, plane laminations, cross beds, ripples, and abundant plant material that Beard et al. (2017) interpreted as a shallow shelf channel.

Catskill Formation: The base of the Catskill in Pennsylvania is typically placed at the base of the first substantial interval of reddish mudstone (e.g., Faill and Wells, 1977). The lowermost Catskill at Tioga consists of about 60 m of alternating red and gray strata that are similar to the Irish Valley Member described elsewhere in Pennsylvania, and the overlying strata are similar to the Sherman Creek Member (McLaurin, 2010), although these members have never been formally recognized in this part of the state.

The most detailed study of the lower Catskill at Tioga was performed by Slane and Rygel (2009), although their full study has not been published. They reported that

> The Tioga outcrop records the intertonguing relationship between drab marine mudrocks and sheet sandstones of the underlying Lock Haven Formation and terrestrial redbeds in the lower ~60% of the Catskill Formation. Terrestrial redbeds at this location are composed of red mudrock (~50%) with abundant, immature paleosols and scattered thin channel bodies. Thin, transitional redbed intervals at the contact between terrestrial and marine facies contain articulate brachiopods, *Lingula*, and vertical, *Skolithos*-like trace fossils. Although obvious indicators of tidal influence are lacking, sheet and channel sandstones exhibit bimodal (N-S) paleoflow indicators, suggesting a subtle tidal influence…. Exposures of the Catskill Formation near Tioga were deposited in a muddy, lower delta plain that prograded into a relatively calm, shallow marine environment. Transitional redbed intervals with marine body fossils and *Skolithos*-like trace fossils may represent a muddy tidal flat at the terrestrial-marine interface.

Slingerland and Loulé (1988) interpreted the depositional environment of this section as a muddy shoreface, transitioning to tidal flats and tidal-channel-fill sequences towards the top of the outcrop. For other discussions of these units, see, for example, Berg et al. (1981), McLaurin (2013), Oest (2013), Bush et al. (2017), and Daeschler et al. (2019); for more information on the lower Catskill Formation in Pennsylvania, see Arndt et al. (1962), Walker (1971), Walker and Harms (1971), Rahmanian (1979), Cotter and Driese (1998), and Slingerland et al. (2009).

Several types of brachiopod are present in some beds, including lingulids, *Cyrtospirifer inermis*, and *Cupularostrum eximia*. Trace fossils are abundant in the float; for example, Bush and Goldstein (2023) reported on some gregarious funnel-shaped burrows. Fish remains are also present here and at other outcrops of the Catskill in the area (e.g., Davis et al., 2004; Friedman and Daeschler 2006; Daeschler and Cressler III, 2011; Long and Daeschler 2013; Broussard et al., 2018, 2020; Daeschler et al., 2019; Downs and Daeschler, 2022), and early tetrapods have been found in the Fammenian of the region (e.g., Daeschler et al., 1994; Daeschler, 2000).

***Summary of TGA Stratigraphy*:** The basal portion of the Route 15 outcrop documents an increase in water depth from the Mills Mills Member (uppermost Canaseraga Formation) into the offshore environments of the Dunkirk (Text-fig. 13). The paleoenvironment shallows from the

Dunkirk into the Caneadea, which is mostly mudrock-dominated with sandy interbeds. An increase in *Cyrtospirifer inermis* towards the top of the Caneadea suggests some amount of shallowing, followed by more abrupt shallowing at the transition to the Catskill. The lower portion of the Catskill alternates among shallow marine facies and transitional marine-non-marine facies, with non-marine facies becoming more common upwards.

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