

Trip B-4

PALEOECOLOGY OF MIDDLE DEVONIAN BLACK AND GRAY SHALES OF CENTRAL NY

DIANA L. BOYER

Department of Earth Sciences, State University of New York at Oswego

EMILY WOOTON

Department of Earth Sciences, University of California at Riverside

INTRODUCTION

The dysaerobic zone is a broadly defined biozone that encompasses all reduced oxygen taxonomic occurrences. However, because reduced oxygen conditions include a wide range of bottom water oxygen levels, from the edge of metazoan habitability to near normal marine conditions, a single biofacies is not appropriate to describe all reduced oxygen settings. Further, reduced oxygen conditions in modern oceans are common in a broad range of physical settings and were likely common in an even more diverse range of settings in the geologic past (Tyson and Pearson, 1991; Calvert and Pedersen, 1993; Lyons, 1997; Raiswell and Canfield, 1998; Hurtgen, et al., 1999; Lyons et al, 2003; Levin, et al, 2003). The Finger Lakes region of central New York provides a unique opportunity to examine a range of interpreted relative oxygen levels preserved in black shales. Within these units, taxonomic and paleoecologic variations through the dysaerobic zone are recognized. On this trip we will explore localities representing a range of conditions through the dysaerobic zone and highlight the range of organisms adapted to low oxygen conditions and the additive pattern of diversity and life habits through these intervals.

GEOLOGIC SETTING

The Middle-Upper Devonian (Eifelian-Frasnian) sequence of New York State is an eastward thickening package of dominantly clastic rock that represents deposition in a shallow, tropical epeiric sea (Rickard, 1975; Brett, 1986). This clastic wedge of eroded material resulting from the Acadian Orogeny is known as the Catskill Delta complex and was deposited into a northeast trending forearc basin that covered much of modern-day New York, Pennsylvania, and parts of Ohio (Ettensohn, 1985a, b, 1987; Kent, 1985; Woodrow and Isley, 1983; Woodrow and Sevon, 1985; Brett, 1986; Brett and Baird, 1996). The central, deepest part of the paleo-basin, likely 100-200 m in depth at maximum flooding (McCollum, 1987; Brett, et al., 1991), trends through the area of the modern-day Finger Lakes in west-central New York (Fig. 1.1). The strata in this area are interpreted to record several transgressive-regressive cycles, marked by the deposition of fine grained clastic units, punctuated by carbonate strata interpreted to be deposited during lowstand events (Kirchgasser, et al., 1988; Brett, et al., 1991). Shale intervals are interpreted to coincide with relative deepening events due to combined tectonic and eustatic influences within the Appalachian foredeep and are interbedded with silty mudstones, siltstones, and sandstone intervals interpreted to represent deposition under shallower water depths (Ettensohn, 1985a, b, 1987; Woodrow, et al., 1989; ver Straeten and Brett, 1995; Murphy, et al., 2000 a,b; Werne, et al., 2002; Sageman, et al., 2003).

During the Middle Devonian, central New York was under a broad shallow epeiric sea. The basin was commonly occupied by dysoxic to anoxic waters throughout much of the Devonian, resulting in the deposition of numerous black to gray shales that are punctuated by carbonate beds (see Brett et al, 1991).

Mudstones examined are listed in ascending order: the Levanna member of the Skaneateles Formation, the Ledyard member of the Ludlowville Formation, the Windom Shale of the Moscow Formation, and the Genesee member of the Genesee Formation (Fig 1). These mudstones are lithologically very similar as grey to black mudstones with variable silt composition (Boyer and Droser, 2009). Clays within these units are dominantly illite with some chlorite and typically <10% carbonate composition.

DYSAEROBIC FAUNA

The dysaerobic zone is defined from ecological patterns of infaunal and macrofaunal benthos observed in modern settings that can be largely generalized by decreasing diversity, abundance, and size of individuals correlated with decreasing bottom water oxygen levels (Rhodes and Morse, 1971; Thompson et al., 1985; Savrda and Bottjer, 1986; Savrda, 1992; Wignall, 1994). Based on these patterns, a tripartite model recognizing relative oxygen levels as aerobic, dysaerobic, and anaerobic was developed and is widely used today (Rhoads and Morse, 1971; Byers, 1977).

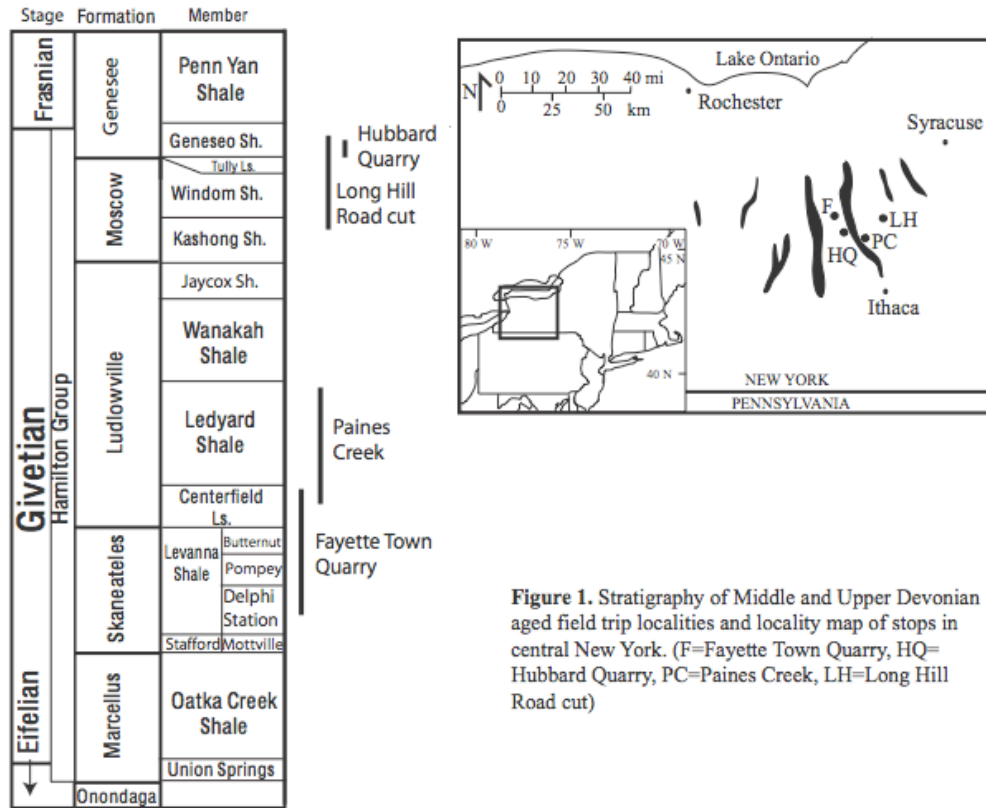


Figure 1. Stratigraphy of Middle and Upper Devonian aged field trip localities and locality map of stops in central New York. (F=Fayette Town Quarry, HQ=Hubbard Quarry, PC=Paines Creek, LH=Long Hill Road cut)

Studies in modern reduced oxygen settings reveal that particular clades, patterns of diversity, and life habits are associated with specific levels of bottom water oxygen with polychaetes, echinoderms, and mollusks generally as the taxa most tolerant to oxygen stress (Levin and Gage, 1998; Wu, 2002; Levin, 2003). Soft bodied organisms, preserved as trace fossils in the rock record, are typically the last organisms to be excluded as oxygen levels decrease to zero (Savrda, et al., 1984; Thompson, et al, 1985; Savrda, 1992). Species richness is strongly correlated with bottom water oxygen levels from a range of modern reduced oxygen settings (Diaz and Rosenberg, 1995; Levin and Gage, 1998; Wu, 2002; Levin, 2003). In modern settings, variability in dominant taxa is observed through the dysaerobic zone in association with changing levels of oxygen stress and it is unusual for one group to be dominant throughout the entire range of the dysaerobic zone (Allison, et al., 1995; Levin, 2003). Another robust ecological trend in modern settings is the persistence of deposit feeding as the dominant life habit under the most reduced oxygen levels (Wu, 2002). These established ecological patterns demonstrate the sensitivity of the biological signal to change in bottom water chemistry and allow for the recognition and interpretation of reduced oxygen conditions from the rock record (e.g. Savrda and Bottjer, 1986; Wignall, 1990; Savrda, 1992; Allison, et al., 1995; Sageman and Bina, 1997; Brett, 1998; Martin, 2004).

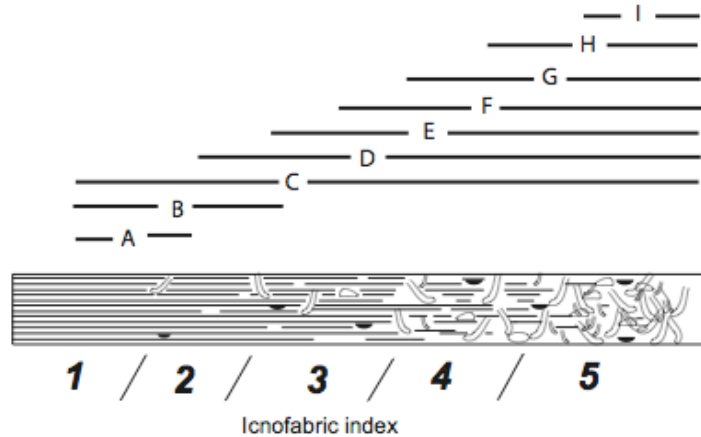
DEVONIAN DYSAEROBIC TAXA

Taxonomic Distribution

These black shale intervals are dominated by common dysaerobic taxa including species of Camarotoechioidea and Chonetoidea, *Pterochaenia*, *Lingula*, and *Orbiculoides* (Thompson and Newton, 1987; Brett, et al., 1991; Brower and Nye, 1991; Allison, et al., 1995, Boyer and Droser, 2007, 2009). At these localities, Camarotoechid brachiopods are by far the dominant group and include two common species, *Leiorhynchus quadracostata* and *Eumetabolotoechia multicostata*. They occur uncommonly in relatively dense aggregations on single bedding planes, sometimes fragmented and disarticulated indicating some reworking, but more commonly are dispersed as disarticulated, unfragmented molds. Chonetoidea brachiopods are also common at these localities. Several groups of linguliform brachiopods occur in these units including species of *Lingula* and *Orbiculoides*. They are all relatively small, flat taxa typically less than 1 cm in length. Several other brachiopod groups are recognized at these localities with increasing diversity and abundance correlative with inferred relative bottom water oxygen levels.

At least 8 taxa of bivalves are recognized at these dysaerobic sites, but *Pterochaenia fragilis* is the most common. Species of *Nuculites* and *Nuculoidea* are also commonly preserved but are not found as abundantly as *P. fragilis*.

Trilobites, including *Hollandclarkeia jennyae* and *Eldregeops rana*, are not common at these localities and gastropods occur rarely.



The distribution of benthic macrofauna at these localities has been recognized to vary in correlation with bottom water oxygen levels. Within dark shales at these localities two patterns are identified as taxa that are adapted to fully oxygenated conditions with variable, but predictable tolerance to oxygen stress, and taxa that are adapted to the lowest bottom water oxygen conditions. Figure 2 shows a schematic representation of taxonomic distribution through the dysaerobic zone with individual taxon given letter designations. This figure demonstrates patterns observed in these units that most of the taxa are fully adapted to fully oxygenated conditions, under decreasing oxygen levels, taxa with what are interpreted as successively higher oxygen thresholds are found to be excluded in a predictable order. As a result, specific combinations of taxa, rather than the occurrence of a specific taxon, are diagnostic of specific oxygen levels. This additive pattern has been recognized to persist across the paleo-basin through most of the classic Hamilton Group (Boyer and Droser, 2009). This trend of progressive loss of taxa with decreasing bottom water oxygen levels breaks down at the lowest end of the dysaerobic zone as numerous taxa are fully adapted to extremely reduced oxygen conditions. This is recognized in part by the common occurrence of monospecific assemblages (see below). *Eumetabolotoechia multicostata* has been recognized to have an extremely broad oxygen tolerance present in laminated sediments to high diversity assemblages. This is highly unusual compared to occurrences in modern marine settings.

Monospecific Assemblages

At these localities bedding planes that expose a single benthic species are common. Monospecific assemblages have been identified within these and other black shale units of the Hamilton group (Boyer and Droser, 2007). Several different taxa including *Leiorhynchus quadracostata*, *Eumetabolotoechia multicostata*, *Pterochaenia fragilis*, as well as *Lingula* and *Orbiculoides* species occur in monospecific assemblages. Interestingly, these monospecific assemblages are commonly found in association with laminated strata. The abundance of phylogenetically disparate groups that are found preserved in laminated sediments, interpreted to represent conditions at the edge of metazoan habitability, supports that numerous groups were equally well adapted to extreme oxygen stress. This is likely a result of repeated times of extremely reduced oxygen levels that are preserved as repeated black shale intervals through the middle and upper Devonian.

Table 1. Dysaerobic taxa identified at field trip localities. (LH=Long Hill Road Cut, PC= Paines Creek, F=Poormon Road/Fayette Town Quarry, HQ=Hubbard Quarry)				
	LH	PC	F	HQ
Brachiopoda				
Camarotoechids	X	X	X	X
Chonetids	X	X	X	X
Orbiculoids	X	X	X	X
Lingulids	X	X		X
Other	X		X	
Bivalvia				
<i>Pterochaenia</i>	X	X	X	
Nuculids	X	X		
other	X			
Trilobita				
<i>Eldredgeops rana</i>	X			
<i>Hollandclarkeia jennyae</i>	X	X		
Other				
Gastropod	X			

Life Habit Distributions

Within these units a range of life habits are recognized. The Rhynchonelliform brachiopods, the most abundant group in these units, are obligate epifaunal filter feeders, as well as *Orbiculoides* and the reclining Chonetes groups. Other common life habits observed at these localities include the infaunal filter feeding Lingulids, the shallow endobysate *Pterochaenia*, the infaunal deposit feeders *Nuculoidea* and *Nuculites*, deep endobysate bivalve groups, and epifaunal herbivore and/or deposit feeders including trilobites and rare gastropods.

The abundance of epifaunal filter feeders at the lowest inferred oxygen levels is in contrast to modern low oxygen settings in which deposit feeding is the dominant life habit at the lowest bottom water oxygen levels (Wu, 2002). Those groups that are restricted to the lowest inferred bottom water oxygen levels are consistently of the filter feeding life habit. The infaunal deposit feeders, deeply embedded endobysate, and mobile epifaunal groups (grazers and deposit feeders) are excluded from the lowest oxygen settings, and are found in increased abundance with increased bottom water oxygen levels. Ultimately a pattern of increased number of life habits with increasing oxygen in a predictable order is recognized and as a result life habit can be used independent of taxonomic association to identify relative variation in bottom water oxygen through the dysaerobic zone.

Black shale intervals at all of these localities preserve dysaerobic depositional conditions, but within and between these localities a range of relative oxygen levels can be recognized based on the distribution of taxa and associate life habits. Although these localities broadly represent a range of oxygen levels increasing through the trip (Hubbard Quarry extremely reduced, Paines Creek and Fayette Quarry moderately reduced, and Long Hill Road cut slightly reduced oxygen conditions), relative oxygen levels have been recognized to fluctuate on a sub-cm scale at these localities (Boyer and Droser, 2009, 2011).

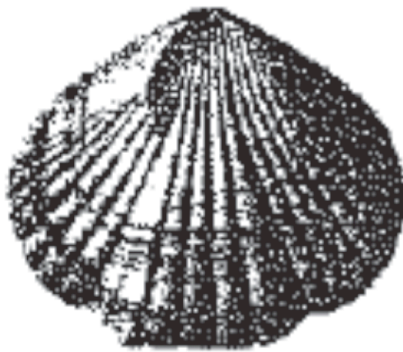
BRACHIOPOD FAUNA OF THE DYSAEROBIC FACIES



Ambocoelia umbonata



Arcuaminctes scitulus



Eumetabolotoechia multicostata



Lingula spatulata



Leiorhynchus quadricostata



Orbiculoides newberryi

ROAD LOG FOR DYSAEROBIC BLACK SHALE LOCALITIES OF CENTRAL NY

CUMULATIVE MILEAGE	MILES FROM LAST POINT	ROUTE DESCRIPTION
0.0	0.0	Start at HEROY LAB , Syracuse University (Adjacent to Carrier Dome)
0.3	0.3	Head north on Crouse Dr. toward University Pl.
0.4	0.1	Take the 1 st left onto University Pl.
0.9	0.5	Take the 1 st right onto Irving Ave
1.3	0.4	Turn left onto E Genesee St
1.5	0.2	Turn right onto S Townsend St
1.7	0.2	Turn left onto Erie Blvd E
1.8	0.1	Erie Blvd E turns slightly right and becomes Oswego Blvd
1.9	0.1	Turn left onto James St
5.6	3.7	Continue onto NY-5 W/W Genesee St
5.8	0.2	Take the NY 5 W ramp to I690/NY695/Fairgrounds/Auburn
11.6	5.8	Merge onto NY-5 W
39.5	27.9	Slight right onto NY-5 W
63.2	23.7	Turn left onto NY-89 S

STOP 1: HUBBARD QUARRY will be on the left side of the road just before the second Lucas Vineyards sign; quarry sits below the road and is obscured by high grass.

This small abandoned quarry is one of the rare exposures of the Genesee Shale, the lowest unit of the Genesee Formation, in this area. Over 3 meters of black shale are exposed. The Genesee at this locality is very black with laminated intervals that are clearly anoxic. Silt laminae range from <1 to several mm in thickness and there are some intervals of thick silt ripples preserved at this locality. There are several concretionary layers that are exposed along the floor of the quarry that preserve carbonate-concretions up to 30 cm in diameter. At this locality bedding plane assemblages, most commonly monospecific, reveal dispersed to clumped concentrations of *Leiorhynchus quadracostata*, *Lingula spatulata*, *Orbiculoidea lodensis*, and rare *Chonetes sp.*. Individuals of *L. quadracostata* can be preserved inflated and even articulated at this locality and are typically 1.5-3 cm in length. Conversely, individuals of the other brachiopod species are all consistently small (<1 cm). The stop illustrates the low end of the dysaerobic zone, although evidence of bioturbation as individual burrows or breaks in lamination are common.

63.3	0.1	Head south on NY-89 S toward Interlaken Beach Rd
63.4	0.1	Take the 1 st right onto Interlaken Beach Rd
63.5	0.1	Turn right onto County Rd 141
64.0	0.5	Take the 1 st left onto County Rd 150
64.6	0.6	Continue onto Co Rd 150/Co Route 150
71.6	7.0	Turn right onto NY-96 N
74.1	2.5	Turn right onto NY-414 N/NY-96 N
74.3	0.2	Slight right onto NY-414 N/Ovid St
81.0	6.7	Continue straight onto NY-414 N/Ovid St
81.4	0.4	Turn left onto Poormon Rd

STOP 2: POORMON ROAD – FAYETTE TOWN QUARRY will be on the left

This stop exposes the uppermost Skaneateles Formation, the Levanna Shale, and the more resistant, fossiliferous Centerfield Limestone member of the Ludlowville Formation. We will concentrate on the depauperate fossil assemblages of the black shales as an example of intermediate dysaerobic conditions (moderately reduced relative oxygen levels). At this locality, *Eumetabolotoechia multicosata*, *Arcuamminetes scitulus*, *Devonchonetes coronatus*, *Orbiculoidea newberryi* and *Pterachaenia fragilis* are commonly found in low diversity and monospecific assemblages on bedding planes. Rare individuals of *Allanella tullia*, *Emanuella subumbona* and even *Conularia sp.* have been identified from this interval. Pelagic “*Styliolina fissurella*” are abundant on some bedding planes. At some horizons, there are clearly reworked lag deposits comprised mostly of fragmented remains of *E. multicosata*, but most other individuals are well preserved molds that are likely not transported.

The Levanna Shale at this locality preserves intervals of anoxia as barren laminated shales, as well as intervals of significantly higher relative oxygen levels as indicated by horizons with moderate diversity and abundance of benthic macrofauna. Detailed trace fossil analysis supports these interpretations.

81.8	0.4	Head east on Poormon Rd toward NY-414 N/Ovid St
88.5	6.7	Turn left onto NY-414 N/Ovid St
89.1	0.6	Continue onto Cayuga St
93.6	4.5	Continue onto NY-5 E/US-20 E/Auburn Rd
111.3	17.7	Turn right onto NY-90 S
111.7	0.4	Turn left onto Moonshine Rd. Park at the end of the road

STOP 3: PAINES CREEK will be down the hill

Paines Creek is the type section for the Ledyard Member of the Ludlowville Formation and can be accessed below the closed bridge. This black shale overlies the Centerfield Limestone Member that is exposed downstream as the cap of Moonshine Falls. At this locality, approximately 4 meters of black shales of the Ledyard Member are exposed in the creek bed. Fossils are dispersed and include *Eumetabolotoechia multicosata*, *Arcuamminetes scitulus*, *Devonchonetes coronatus*, *Orbiculoidea newberryi*, *Lingula spatulata*, *Pterachaenia fragilis*, *Nuculites oblongatus*, *Nuculoidea sp.* and *Hollandclarkeia jennyae*. Benthic macrofauna at this locality are found dispersed within sediments that range from laminated through almost completely bioturbated. Monospecific occurrences are present at this locality, but there are only rare densely packed associations.

This locality again records a range or bottom water oxygen conditions from anoxic through moderately oxygenated based on the variable diversity of benthic macrofaunal, which also corresponds with ichnological data. This locality was selected to reflect intermediate conditions of oxygen stress.

112.1	0.4	Head northwest toward NY-90 S
129.5	17.4	Turn left onto NY-90 S
133.1	3.6	Turn left onto NY-38 N/Main St
134.2	1.1	Turn left onto Aurora St/County Route 43C Continue to follow County Route 43C

STOP 4: LONG HILL ROAD CUT; parking will be on the right at a gravel turnoff. Locality is on the south side of the road.

This section exposes uppermost portion of the Moscow Formation, including a near complete succession of the Windom Shale and Tully Limestone, and the overlying Genesee Shale on the south side of Long Hill Road. The black shales of the Genesee are barren at this locality. The Windom Shale preserves several coarsening upward shale-siltstone cycles through an overall shallowing succession that is overlain by the thick Tully Limestone. Within the grey shales of the Windom are moderately diverse fossil assemblages, with some dense concentrations that are interpreted to be storm events. Intervals within this succession are interpreted to represent deposition under reduced oxygen conditions at the upper end (more oxygenated) of the dysaerobic zone based on body fossil diversity and trace fossil composition.

Common benthic macrofauna within these intervals include, the Rhynchonelliform brachiopods *Eumetabolotoechia multicosata*, *Arcuaminctes scitulus*, *Devonchonetes coronatus*, *Allanella tullia*, *Ambocoelia umbonata* the “inarticulate” brachiopods *Orbiculoidea newberryi*, *Lingula punctata*, bivalves *Pterachaenia fragilis*, *Nuculites oblongatus*, and *Nuculoidea sp.* and the trilobites *Eldregeops rana* and *Hollandclarkeia jennyae*.

This locality represents the upper end of the dysaerobic zone in which oxygen conditions are not at levels interpreted to be normal marine levels due to reduced diversity and ichnological features, but are higher when compared with other black shale intervals seen on this trip.

END OF TRIP.

ACKNOWLEDGEMENTS

Acknowledgment is made to the donors of the American Chemical Society Petroleum Research Fund for partial support of this research.

REFERENCES

- ALLISON, P.A., WIGNALL, P.B., & BRETT, C.E., 1995, Palaeo-oxygenation: effects and recognition. In: D.W.J. Bosence and P.A. Allison (Editors), *Marine Palaeoenvironmental Analysis from Fossils*, pp. 97-112.
- BOYER, D.L. & DROSER, M.L., 2009, Palaeoecological patterns within the dysaerobic biofacies: Examples from Devonian black shales of New York state, *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 276, pp. 206-216.
- BYERS, C. W., 1977, Biofacies patterns in euxinic basins; a general model, *in* Cook, H. E., and Enos, P., eds., *Deep-water carbonate environments*, Society of Economic Paleontologists and Mineralogists, p. 5-17.
- BRETT, C.E., 1986, The Middle Devonian Hamilton Group of New York: an overview, *New York State Museum Bulletin*, vol. 457, pp. 1-4.
- BRETT, C.E., 1998, Sequence stratigraphy, paleoecology, and evolution; biotic clues and responses to sea-level fluctuations, *Palaios*, vol. 13 #3, pp. 241-262.
- BRETT, C.E. & BAIRD, G.C., 1996, Middle Devonian sedimentary cycles and sequences in the northern Appalachian Basin, *Geological Society of America Special Papers*, vol. 306, pp. 213-241.
- BRETT, C.E., DICK, V.B. & BAIRD, G.C., 1991, Comparative taphonomy and paleoecology of Middle Devonian dark gray and black shales facies from western New York. In: E. Landing and C.E. Brett (Editors), *Dynamic stratigraphy and depositional environments of the Hamilton Group (Middle Devonian) in New York State, Part II. Bulletin - New York State Museum*, pp. 5-36.
- CALVERT, S.E., & PEDERSEN, T.F., 1993, Geochemistry of recent oxic and anoxic sediments: implications for the geological record, *Marine Geology*, vol. 113, pp. 67-88.
- DIAZ, R.J. & ROSENBERG, R., 1995, Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna, *Oceanography and Marine Biology Annual Review*, vol. 33, pp. 245-303.
- ETTENSohn, F.R., 1985a, Controls on the development of Catskill Delta complex basin facies. In: D.L. Woodrow and W.D. Sevon (Editors), *The Catskill Delta*, Geological Society of America Special Paper, pp. 63-67.
- ETTENSohn, F.R., 1985b, The Catskill Delta complex and the Acadian Orogeny; a model. In: D.L. Woodrow and W.D. Sevon (Editors), *The Catskill Delta*, Special Paper - Geological Society of America, pp. 39-49.
- ETTENSohn, F.R., 1987, Rates of relative plate motion during the Acadian Orogeny based on the spatial distribution of black shales, *Journal of Geology*, vol. 95, pp. 572-582.
- HURTGEN, M.T., LYONS, T.W., INGALL, E.D., & CRUSE, A.M., 1999, Anomalous Enrichments of Iron Monosulfide in Euxinic Marine Sediments and the Role of H₂S in Iron Sulfide Transformations: Examples from Effingham Inlet, Orca Basin, and the Black Sea, *American Journal of Science*, vol. 299, pp. 556-588.
- KENT, D.V., 1985, Paleocoastal setting for the Catskill Delta. In: D.L. Woodrow and W.D. Sevon (Editors), *The Catskill Delta*, Geological Society of America Special Paper, pp. 9-13.
- KIRCHGASSER, W.T., BAIRD, G.C. & BRETT, C.E., 1988, Regional placement of Middle/Upper Devonian (Givetian-Frasnian) boundary in western New York State. In: N.J. McMillan, A.F. Embry and D.J. Glass (Editors), *Devonian of the world; proceedings of the Second international symposium on the Devonian System; Volume III, Paleontology, paleoecology and biostratigraphy*, pp. 113-117.
- LEVIN, L., 2003, Oxygen minimum zone benthos: Adaptation and community response to hypoxia, *Oceanography and Marine Biology Annual Review*, vol. 41, pp. 1-45.
- LEVIN, L.A. & GAGE, J.D., 1998, Relationships between oxygen, organic matter and the diversity of bathyal macrofauna. *Deep-Sea Research. Part II: Topical Studies in Oceanography*, vol. 45 #1-3, pp. 129-163.
- LYONS, T.W., 1997, Sulfur isotopic trends and pathways of iron sulfide formation in upper Holocene sediments of the anoxic Black Sea, *Geochimica et Cosmochimica Acta*, vol. 61, pp. 3367-3382.
- LYONS, T.W., WERNE, J.P., HOLLANDER, D.J., & MURRAY, R.W., 2003, Contrasting sulfur geochemistry and Fe/Al and Mo/Al ratios across the last oxic-to-anoxic transition in the Cariaco Basin, Venezuela, *Chemical Geology*, vol. 195, pp. 131-157.
- MARTIN, K.D., 2004, A re-evaluation of the relationship between trace fossils and dysoxia. In: D. McIlroy (Editor), *The application of ichnology to palaeoenvironmental and stratigraphic analysis*, Geological Society Special Publications, pp. 141-156.

- MCCOLLUM, L. B., 1987, A shallow epeiric sea interpretation for an offshore Middle Devonian Black Shale Facies in eastern North America, *Devonian of the World II*, Canadian Society of Petroleum Geologists Memoir, p. 347-355.
- MURPHY, A.E., SAGEMAN, B.B., HOLLANDER, D.J., LYONS, T.W. & BRETT, C.E., 2000a, Black shale deposition and faunal overturn in the Devonian Appalachian Basin; clastic starvation, seasonal water-column mixing, and efficient biolimiting nutrient recycling, *Paleoceanography*, vol. 15 #3, pp. 280-291.
- MURPHY, A.E., SAGEMAN, B.B., VER STRAETEN, C.A. & HOLLANDER, D.J., 2000b, Organic carbon burial and faunal dynamics in the Appalachian Basin during the Devonian (Givetian-Famennian) greenhouse; an integrated paleoecological and biogeochemical approach. In: B.T. Huber, K.G. MacLeod and S.L. Wing (Editors), *Warm climates in Earth history*. University of Cambridge, Cambridge, United Kingdom, pp. 351-385.
- RAISWELL, R. & CANFIELD, D.E., 1998, Sources of iron for pyrite formation in marine sediments, *American Journal of Science*, vol. 298, pp. 219-245.
- RICKARD, L.V., 1975, Correlation of the Silurian and Devonian rocks in New York State. New York State Museum, Map and Chart Series, vol. 24, p. 16.
- RHOADS, D.C., & MORSE, J.W., 1971, Evolutionary and ecologic significance of oxygen-deficient marine basins, *Lethaia*, vol. 4, p. 413-428.
- SAGEMAN, B.B. & BINA, C.R., 1997, Diversity and species abundance patterns in late Cenomanian black shale biofacies, *Western Interior, U.S. Palaios*, vol. 12 #5, pp. 449-466.
- SAGEMAN, B.B., MURPHY, A.E., WERNE, J.P., VER STRAETEN, C.A., HOLLANDER, D.J., & LYONS, T.W., 2003, A tale of shales; the relative roles of production, decomposition, and dilution in the accumulation of organic-rich strata, Middle- Upper Devonian, Appalachian Basin, *Chemical Geology*, vol. 195, pp. 229-273.
- SAVRDA, C.E., 1992, Trace fossils and benthic oxygenation. In: C.G. Maples, and West, R. R. (Editor), *Trace Fossils, Short Courses in Paleontology*. The Paleontological Society, pp. 172-196.
- SAVRDA, C.E. & BOTTJER, D.J., 1986, Trace fossil model for reconstruction of palaeo-oxygenation in bottom waters, *Geology*, vol. 14 pp. 3-6.
- SAVRDA, C.E., BOTTJER, D.J. & GORSLINE, D.S., 1984, Development of a comprehensive, oxygen-deficient marine biofacies model: evidence from Santa Monica, San Pedro, and Santa Barbara Basins, California Continental Borderland, *American Association of Petroleum Geologists Bulletin*, vol. 68, pp. 1179-1192.
- THOMPSON, J.B., MULLINS, H. T., NEWTON, C. R., & VERCOUTERE, T. L., 1985, Alternative biofacies model for dysaerobic communities, *Lethaia*, vol. 18, pp. 167-179.
- TYSON, R.V. and PEARSON, T.H., 1991, Modern and ancient continental shelf anoxia: an overview. In: R.V. Tyson, and Pearson, T. H. (Editors), *Modern and Ancient Continental Shelf Anoxia*. Geological Society Special Publication, pp. 1-26.
- VER STRAETEN, C.A., & BRETT, C.E., 1995, Lower and Middle Devonian foreland basin fill in the Catskill Front: Stratigraphic synthesis, sequence stratigraphy, and the Acadian Orogeny, *in* Garver, J.I., and Smith, J.A., editors, *New York State Geological Association: Annual Meeting, 67th Field Trip Guidebook*, pp. 313-356.
- WERNE, J.P., SAGEMAN, B.B., LYONS, T.W., & HOLLANDER, D.J. 2002, An integrated assessment of a "type euxinic" deposit; evidence for multiple controls on black shale deposition in the Middle Devonian Oatka Creek Formation, *American Journal of Science*, vol. 302, pp. 110-143.
- WIGNALL, P.B., 1990, Observations on the evolution and classification of dysaerobic communities. In: W. Miller, III (Editor), *Paleocommunity temporal dynamics; the long-term development of multispecies assemblies*, Special Publication. Paleontological Society, pp. 99-111.
- WIGNALL, P.B., 1994. *Black Shales*. Oxford Monographs on Geology and Geophysics, 30, Oxford, United Kingdom, 127 pp.
- WOODROW, D.L. & ISLEY, A.M., 1983, Facies, topography, and sedimentary processes in the Catskill Sea (Devonian), New York and Pennsylvania, *Geological Society of America Bulletin*, vol. 94 #4, pp. 459-470.
- WOODROW, D.L., & SEVON, W.D., 1985, Paleogeography, paleoclimate and sedimentary processes of the Late Devonian of New York State, USA, *Lethaia*, vol. 20, pp. 263-290.
- WOODROW, D.L., BRETT, C.E. & SELLECK, B., 1989, Sedimentation and basin analysis in siliciclastic rock sequences; Volume 3, Sedimentary sequences in a foreland basin; the New York System. In: P.M. Hanshaw (Editor), *Field trips for the 28th international geological congress*. Am. Geophys. Union, Washington, DC, United States, pp. 43.
- WU, R.S.S., 2002, Hypoxia: from molecular responses to ecosystem responses, *Marine Pollution Bulletin*, vol. 45, pp. 35-45.

NOTES

