Journal of Sedimentary Research

Journal of Sedimentary Research, 2014, v. 84, 866–874
Current Ripples
DOI: http://dx.doi.org/10.2110/jsr.2014.70

1926 SEPM Society for Sedimentary Geology

MUDDY PRODELTAIC HYPERPYCNITES IN THE LOWER GENESEE GROUP OF CENTRAL NEW YORK, USA: IMPLICATIONS FOR MUD TRANSPORT IN EPICONTINENTAL SEAS

RYAN D. WILSON AND JUERGEN SCHIEBER
Department of Geological Sciences, Indiana University, Bloomington, Indiana 47405, U.S.A
e-mail: rydawils@indiana.edu

ABSTRACT: **Recent studies of marine continental shelves show that hyperpycnal flows are responsible for offshore transport of large volumes of sediment. Detailed facies analysis and petrography of the lower Genesee Group in the Northern Appalachian Basin (NAB) shows a wealth of sedimentary textures and fabrics that indicate mud deposition by lateral transport across and along the shelf under energetic conditions. Intervals of silt-rich mudstones and muddy siltstones with internal scours, diffuse stratification, soft-sediment deformation, normal and inverse lamina-set grading, and a reduced intensity and diversity of bioturbation occur in multiple facies types and "interrupt" what appears to be the overall background sedimentation. These intervals and their sedimentary features are interpreted as products of high-density fluvial discharge events, which generated turbulent flows that carried fine-grained clastics several tens of kilometers offshore from the paleoshoreline.**

Recognizing these sediments as products of river-flood- and storm-wave-generated offshore-directed underflows challenges previous depositional models for organic-rich mudstones in the lower Genesee succession, which call for clastic starvation and suspension settling of clay and silt in a deep stratified basin. Rapid deposition of fine-grained intervals from hyperpycnal plumes in a setting favoring preservation of organic-rich mudstones calls for a reappraisal of the depositional setting of not only the Genesee Group, but also of comparable mudstone successions in the Appalachian Basin and elsewhere.

INTRODUCTION

Interpreting the depositional processes of mudstone-dominated systems has seen a paradigm shift through recent experimental studies (Schieber et al. 2007; Schieber and Southard 2009; Schieber and Yawar 2009; Schieber et al. 2010; Schieber 2011a) and observations of modern muddy shelves (Rine and Ginsburg 1985; Allison and Nittrouer 1998; Macquaker et al. 2010). Fine-grained sedimentary rocks (shales, claystones, mudstones, siltstones, etc.) constitute approximately two thirds of all sedimentary rocks (Potter et al. 2005). Yet, when compared to sandstones and carbonates, the processes that govern their transport and deposition remain poorly understood. Current efforts by the petroleum industry to develop unconventional hydrocarbon reservoirs in mudstone successions have given impetus to better understand the nature and origin of these rocks (Passey et al. 2010). The small grain size of these sediments (< 62.5 μm) has long nurtured the assumption that any significant turbulence in overlying waters would resuspend accumulating muds and prevent their deposition (e.g., Potter et al. 1980; Stow et al. 2001).

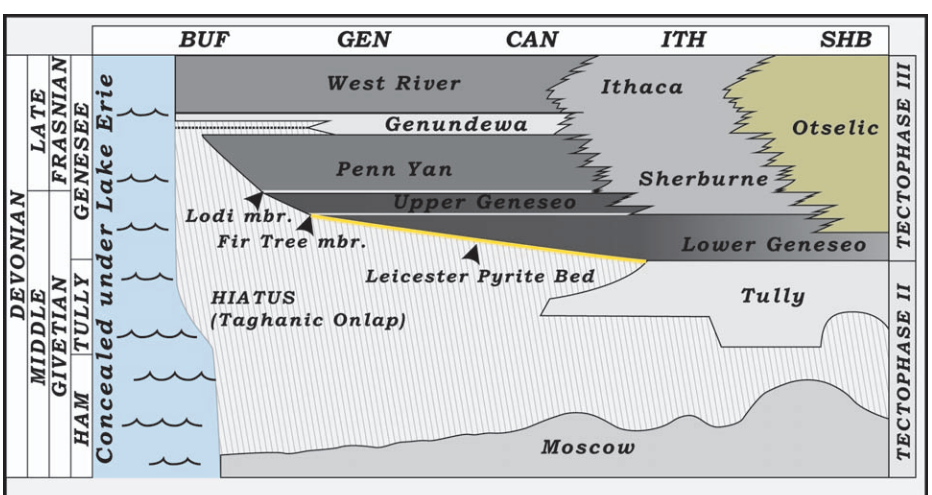


FIG. 1.—Generalized chronostratigraphic chart for Middle–Late Devonian strata of New York (SHB, Sherburne; ITH, Ithaca; CAN, Canandaigua; GEN, Geneseo; BUF, Buffalo; HAM, Hamilton Group). This study focuses on the lower Genesee Group (Givetian) of central New York. The Geneseo Formation marks the onset of the third tectophase of the Acadian Orogeny (Ettensohn 1987), the most pronounced thrust loading event of this orogeny. The Genesee Group onlaps the Taghanic disconformity westward, thus, the ages of the onlapping Geneseo and Penn Yan shales become progressively younger westward (Kirchgasser et al. 1988). Figure is modified from Rogers et al. (1990) and Kirchgasser et al. (1997), and includes data from Baird and Brett 1986, 1991; Baird et al. 1988; Brett and Baird 1996; Brett et al. 2011; Bridge and Willis 1991, 1994; and Kirchgasser et al. 1988.

Published Online: October 2014

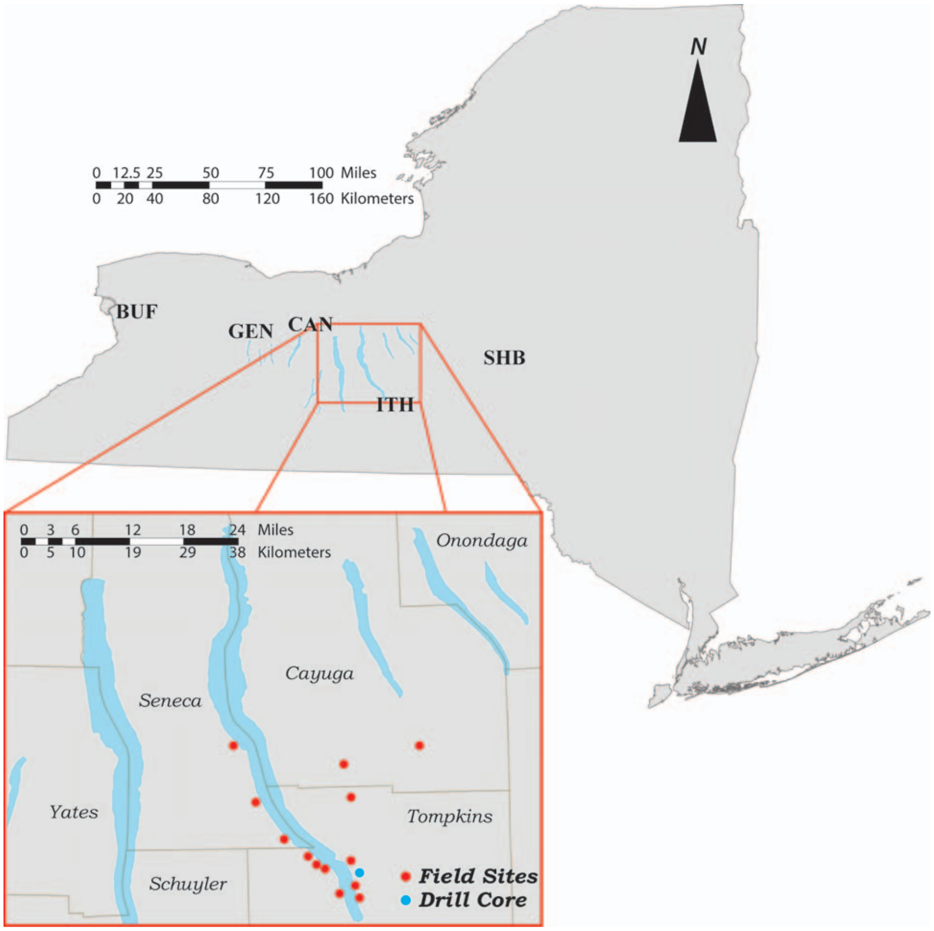


FIG. 2.—Overview map of New York and locations of outcrops and drill core (with locations of Figure 1 cross section; SHB, Sherburne; ITH, Ithaca; CAN, Canandaigua; GEN, Geneseo; BUF, Buffalo).

Likewise, that mudstones are monotonous in appearance and contain little in terms of physical sedimentary structures is another oversimplification that still influences how depositional environments of mudstone-dominated systems are evaluated (Cluff 1980; Ettensohn 1985, 1987, 1988).

Johnson (1970) considered that the Geneseo Formation (Fig. 1) was deposited in a deep anoxic basin following a major transgression. This transgression coincided with the onset of the third tectophase of the Acadian Orogeny, an event that has been interpreted as the cause for deepening of the basin, stratification of the water-column, and a drastic decrease in sediment supply (Ettensohn 1985, 1987, 1994). However, the abundant silt-rich mudstones and muddy siltstones in the Geneseo contain a rich assembly of sedimentary features and textures that permit the development of a more sophisticated and realistic depositional model. The present study area is located up to 130 km from the eastern paleoshoreline of the basin (Dennison 1985), where coeval fluvial formations (Oneonta Formation; Fig. 1) have been extensively studied (Bridge and Willis 1991, 1994).

In prior studies, the siltstone intervals in the lower Genesee Group were interpreted as "classical" turbidites that resulted from slope failure and/or resuspension of sediments on the basin margin slope by internal waves that traveled along the pycnocline within the water column (Woodrow and Isley 1983; Woodrow 1985; Ettensohn 1985, 1987; Baird and Brett 1986, 1991; Ettensohn et al. 1988). However, the presence of normal and inverse lamina-set grading, internal scours, combined-flow ripples, and concave-up geometries indicate sediment transport in high-density turbulent flows that waxed and waned (Bhattacharya and MacEachern 2009). Interpreting the latter as hyperpycnites allows a new perspective on these deposits, greatly facilitates understanding the observed vertical and lateral variability, and enables a better characterization of fine-grained sediment transport mechanisms in the Appalachian Basin and other marine shelf environments.

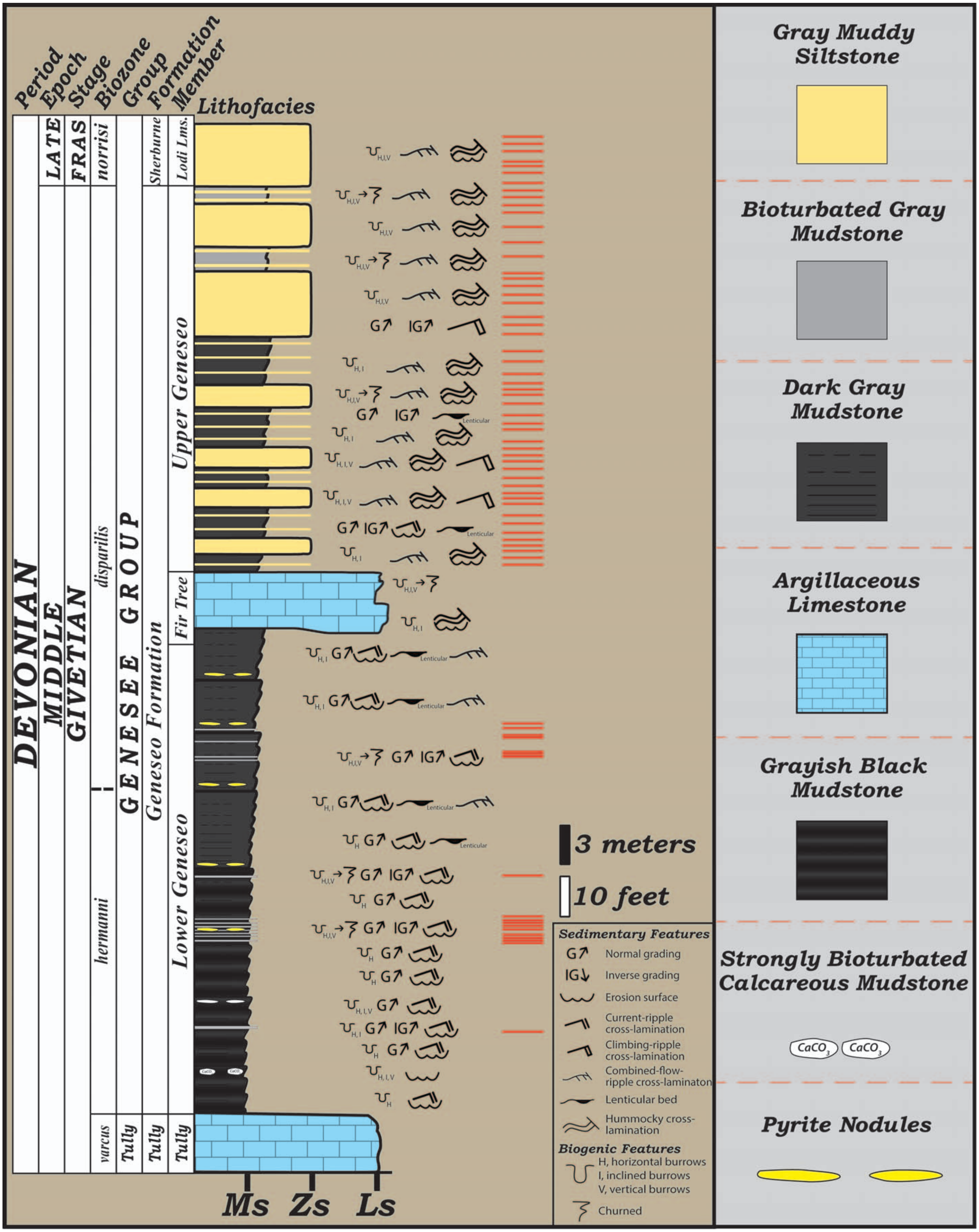
METHODS

The present study relies on observations from exposures surrounding Cayuga Lake and a single drill core from Lansing, New York (Fig. 2). Lithostratigraphic profiles were recorded at each locality and samples stabilized with epoxy resin and thin-sectioned (thickness ~ 20–25 μm). Hand specimens were slabbed with a rock saw and then smoothed and polished with grinding wheels of successively finer grit sizes (60–1200). High-resolution images of polished slabs and thin sections were acquired by standard photography and with a flatbed scanner (1200–2400 dpi resolution).

Through variable lighting, as well as wet vs. dry imaging, detailed image sets of sedimentary features at the hand specimen scale were acquired. Thin sections (~ 200) were used to examine microfacies variation, small-scale sedimentary features (lamina truncations, graded beds, stratification styles, etc.), compositional and textural changes, and bioturbation styles. The bioturbation index (BI) of Taylor and Goldring (1993) was used to quantify bioturbation intensity. Drill-core, hand-specimen, and thin-section descriptions were combined to comprehensively evaluate centimeter- to decimeter-scale heterogeneity, lithofacies, and stratal architecture.

OBSERVATIONS

In the lower Genesee Group, several mudstone facies can be identified on the basis of sedimentary structures, textural changes, composition, and


Period
Epoch
Stage
Biozone
Group
Formation
Member
Lithofacies
DEVONIAN
LATE
MIDDLE
FRAS
GIVETIAN
norrisi
disparilis
hermanni
varcus
GENESEE GROUP
Tully
Sherburne
Geneseo Formation
Tully
Lodi Lms.
Upper Geneseo
Fir Tree
Lower Geneseo
Tully
Ms
Zs
Ls
Lenticular
3 meters
10 feet
Sedimentary Features
G↗ Normal grading
IG↓ Inverse grading
Erosion surface
Current-ripple cross-lamination
Climbing-ripple cross-lamination
Combined-flow-ripple cross-laminaton
Lenticular bed
Hummocky cross-lamination
Biogenic Features
H, horizontal burrows
I, inclined burrows
V, vertical burrows
Churned
Gray Muddy Siltstone
Bioturbated Gray Mudstone
Dark Gray Mudstone
Argillaceous Limestone
Grayish Black Mudstone
Strongly Bioturbated Calcareous Mudstone
CaCO3
CaCO3
Pyrite Nodules

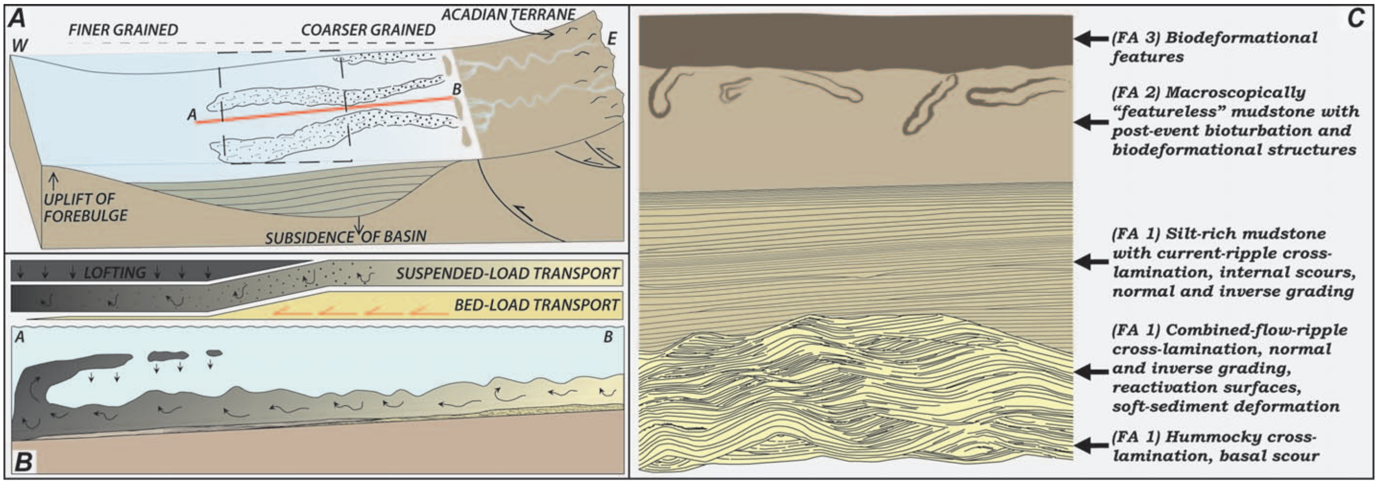


FIG. 4.—**A)** Idealized sketch of the Northern Appalachian Basin during the Devonian (study area projected as dashed box), with river-fed hyperpycnal flows displayed (A–B cross section used in Part B). **B)** Conceptual diagram showing the internal arrangement of facies deposited from sustained hyperpycnal flows in a marine environment, including bed-load transport (FA 1), suspended-load transport (FA 2), and lofting (FA 3; modified from Zavala et al. 2011). **C)** Idealized sketch of a lower Genesee muddy hyperpycnite, with the succession of bedforms and facies types typically observed.

biogenic attributes (Fig. 3; Wilson 2012). The Geneseo Formation disconformably overlies the Tully Limestone; and where the latter is absent, the disconformity is in many places marked by a pyritic–phosphatic lag, the Leicester Pyrite Bed (Fig. 1). The lowermost portion of the Geneseo Formation consists primarily of weakly to sparsely bioturbated (BI 1–2), organic-rich banded mudstones with relict lamination and indications of surficial sediment mixing by benthos. Upsection, the Lower Geneseo Member grades into dark gray mudstones that show an increase of current- and wave-formed features, erosional contacts, and increased bioturbation intensity (BI 3–4) and diversity (e.g., *Chondrites*, navichnia traces, *Planolites*, and *Phycosiphon*). Argillaceous limestones and calcareous silty mudstones of the Fir Tree Member separate the Lower and Upper Geneseo members. The Upper Geneseo Member consists of dark gray silty mudstones that grade upsection into gray silty mudstones and muddy siltstones with abundant current- and wave-formed features, erosional contacts, and increased bioturbation intensity (BI 3–5) and diversity (e.g., navichnia traces, *Paleophycus*, *Planolites*, *Phycosiphon*, *Teichichnus*, *Thalassinoides*). Whereas the parasequences that constitute the lower Genesee Group are developed as classical coarsening-upwards packages (Bohacs et al. 2005), their predictable vertical facies succession (Fig. 3) appears randomly interrupted by complex graded beds with internal scours.

Three distinct facies associations (FA) can be identified within these "random" beds, including (FA 1) muddy siltstones and silty mudstones with evidence of oscillatory flow and unidirectional traction transport, (FA 2) macroscopically "featureless" mudstones with diffuse stratification, and (FA 3) dark gray to grayish black mudstones with biodeformational features (Fig. 4). Thicker deposits of this type typically show all three facies subdivisions, while thinner deposits are typically expressed as (FA 2) macroscopically "featureless" mudstones and/or (FA 3) dark gray to grayish black mudstones with extensive biodeformational features. The "random" beds in question have sharp bases with arcuate scalloped topography, show soft-sediment deformation (convolute bedding), normal and inverse grading, internal scours, current-ripple cross-lamination, and hummocky cross-lamination, and range in thickness from 1 to 15 cm (Figs. 4, 5, 6). Towards the eastern sediment source, these presumed hyperpycnite deposits increase in thickness, are coarser grained (up to 100 μm), and are associated with more wave-formed features (oscillatory flow), more convolute bedding, more terrestrial phytodetritus, as well as decreased bioturbation intensity (BI 0–3) and diversity (e.g., fugichnia traces and navichnia traces). Additional sedimentary features are asymmetrical climbing ripples and combined-flow ripples with low-angle erosional contacts, "bundle-wise" stacking of foreset laminae with cross-stratal offshoots, lamina onlapping, and concave-up geometries (Figs. 5, 6).

In contrast to underlying and overlying strata reflecting background sedimentation, bioturbation intensity is significantly reduced in these intervals (isolated feeding structures), and internal microstratigraphy is preserved in exquisite detail. Upsection, these complex graded beds increase in thickness and abundance as organic-rich mudstones of the Geneseo Formation grade into silt-rich mudstones and muddy siltstones of the overlying Sherburne Formation (Fig. 1).

DISCUSSION

Hyperpycnal flows occur when the density of riverine suspensions is higher than that of the waterbody into which the river flows, be it fresh (i.e., lacustrine) or marine waters. The density contrast is due to the suspended sediment load, as well as differences in salinity and temperature of the two water masses (Felix et al. 2006). The generation of river-fed hyperpycnal turbidity currents requires slopes greater than 0.7° (Bentley 2003; Friedrichs and Scully 2007; Bhattacharya and

←

FIG. 3.—Stratigraphic column for lower Genesee Group strata (Ms, mudstone; Zs, siltstone; Ls, limestone) observed in drill core (Fig. 2). Generalized lithostratigraphy and sedimentary features observed for the lower Genesee Group are represented, as well as vertical distribution of hyperpycnites recognized in the drill core (red horizontal lines). Note the nonsystematic vertical distribution of hyperpycnites in the Lower Geneseo Member, where organic-rich banded mudstones grade vertically into dark gray mudstones with increase in wave- and current-produced features. The Upper Geneseo Member displays an increased frequency of hyperpycnites as dark gray mudstones grade vertically into gray muddy siltstones.

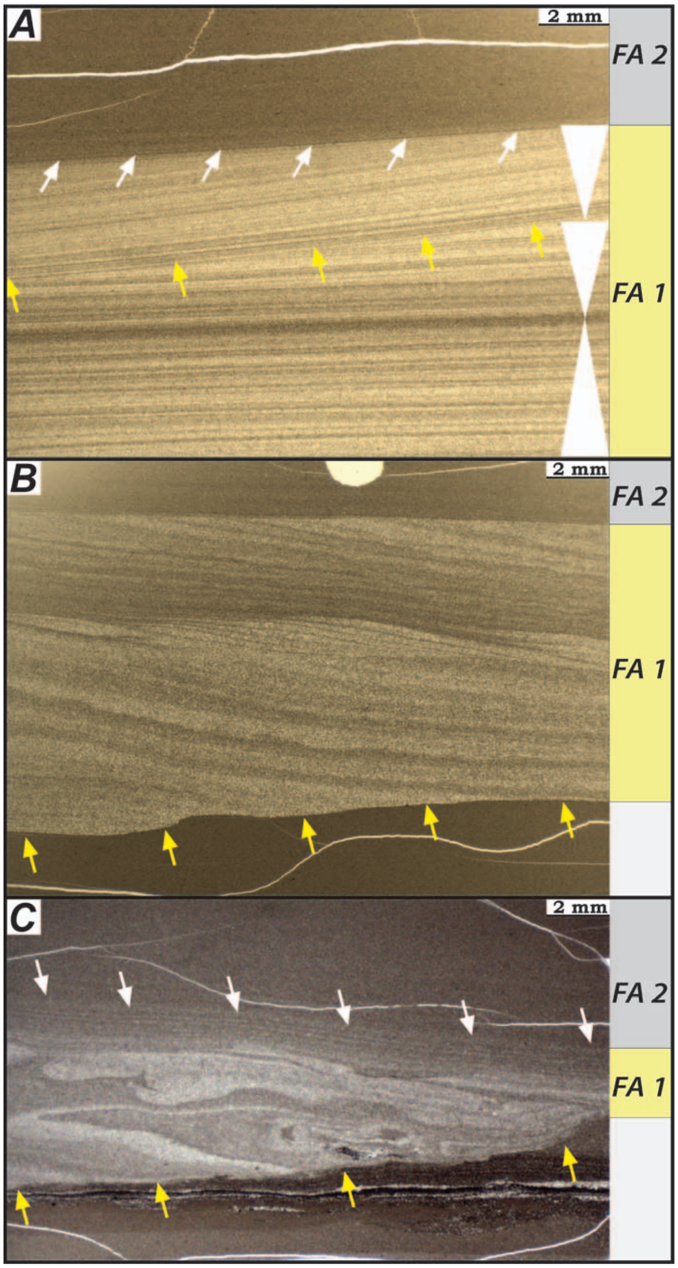


FIG. 5.—**A)** Silt-rich muddy hyperpycnite showing continuous planar parallel to low-angle cross-lamination, normal and inverse grading (normal and inverted triangles), and internal scours (yellow arrows; with facies associations outlined). **B)** Silt-rich hyperpycnite with basal scour and combined-flow ripples, indicating wave-aided transport (concave-up lamina-set geometries). **C)** Thin graded bed with basal scour (yellow arrows) and soft-sediment deformation (convoluted laminae), reflecting high sedimentation rate with internal shearing and frictional drag on the stationary seabed. Note draping parallel-laminated silts (white arrows), suggesting decreased sediment flux and waning current transport.

MacEachern 2009). On low-gradient deltas (slopes $< 0.3^\circ$), such flows are still feasible if wave and tidal processes sufficiently enhance turbulence at the seabed and facilitate downslope transport of fluidized muds (e.g., Bentley 2003; Friedrichs and Scully 2007; Varban and Plint 2008; Wright and Friedrichs 2006).

In studies by Mulder and Alexander (2001) and Mulder et al. (2003), sedimentary features associated with such transport were identified as lamina-set and bed-set geometries with internal scours, diffuse bedding, normal and inverse grading, soft-sediment deformation (convolute bedding), and planar-parallel to low-angle cross-lamination, suggestive of sustained lateral sediment transport by turbulent flows with waxing and waning currents. Rapid deposition of suspected hyperpycnite intervals in the Geneseo is indicated by the general lack of benthic fauna, decreased bioturbation intensity and diversity, as well as the presence of soft-sediment deformation (exclusive to these intervals). In the lower Genesee Group, the three FAs identified in the complex graded beds described above contain all of these features (Fig. 4), and are consistent with facies associations of hyperpycnites observed elsewhere (Zavala et al. 2011). FA 1 contains all of the wave- and current-aided traction transported features, FA 2 represents the suspended-load aspect of hyperpycnal flows, where waves and currents support a dense fluid-mud layer to move along and across the shelf (Kineke et al. 1996), FA 3 reflects buoyancy reversal in the hyperpycnal flow that resulted in the finest material being lifted from the flow to subsequently settle from suspension. Preservation potential of this latter FA is low, because the low density of the deposit makes it susceptible to resuspension and transport (Zavala et al. 2011). A critical observation in support of a hyperpycnite model is the lateral and vertical variability in the abundance and thickness of graded intervals, which indicates an overall shallowing-upwards trend and basinward migration of the shoreline. These trends are corroborated by the observation that the deposits of hyperpycnal flows at a single location will coarsen upsection, increase in thickness and abundance, and also contain more wave-formed features (Fig. 3). The abundance of wave-formed features in the interpreted hyperpycnites of the lower Genesee, such as hummocky cross-lamination, concave-up lamina-set geometries, and combined-flow-ripple cross-lamination (Figs. 5, 6, 7) is consistent with storm-aided transport of hyperpycnal plumes (Friedrichs and Wright 2004; Higgs 1990), a common process on low-gradient deltas with slopes $< 0.3^\circ$ (Bhattacharya and MacEachern 2009).

The presence of hyperpycnites several tens of kilometers offshore on the Geneseo shelf indicates an influence of storm waves (Bhattacharya and MacEachern 2009). The observed internal scours (Figs. 5, 6, 7) can be interpreted as high-energy fluvial discharge events with progressive erosion of underlying strata (Fig. 4), whereas the absence of extensive bioturbation in these beds probably reflects rapid sedimentation, presence of soupy substrates, reduced salinity of interstitial water, and burial of bedforms (MacEachern et al. 2005; Bhattacharya and MacEachern 2009). The bioturbation observed in the upper portions of hyperpycnites in the lower Genesee can be interpreted as post-discharge biogenic modification (Fig. 8; Cutter and Diaz 2000). Other mechanisms that could potentially produce such deposits are "classical" surge-type turbidites (Woodrow and Isley 1983; Woodrow 1985; Ettensohn 1985, 1987; Baird and Brett 1986, 1991; Ettensohn et al. 1988), wave-enhanced sediment gravity flows (WESGFs; Macquaker et al. 2010), or possibly storm-driven nearshore sediment reworking and offshore transport (Aigner and Reineck 1982). WESGFs are wave-generated fluidized muds, have the potential to deposit large volumes of mud as fine-grained graded beds, and supposedly show a "triplet" succession of sedimentary features (Macquaker et al. 2010) that resembles some of the interpreted hyperpycnites in the Geneseo. However, WESGFs are generally thinner than the beds discussed in this study, measuring less than 5 cm thickness in rock-record examples (Macquaker et al. 2010). Also, unpublished results from flume studies (Schieber 2011b) indicate that the "triplet" succession that is supposedly diagnostic for WESGFs can be deposited from either continuous or decelerating flows of muddy suspensions that had significantly lower sediment concentrations than the 10 grams per liter threshold for fluidized muds. The fact that these experiments produced the "diagnostic" WESGFs triplet (i.e., scoured base with current ripple cross lamination, planar-parallel-laminated silts and muds, and

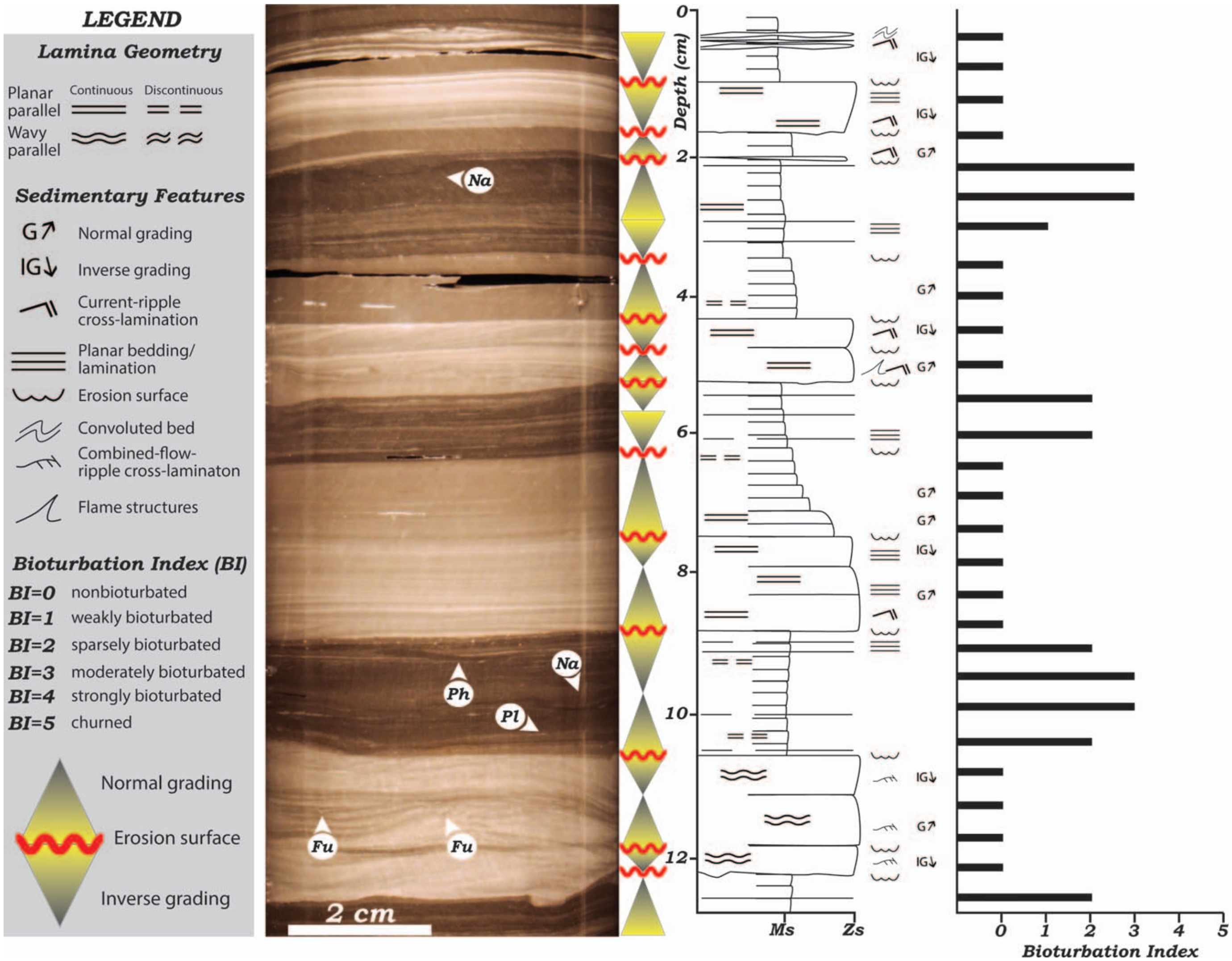


FIG. 6.—Photograph and detailed measured section (Ms, mudstone; Zs, siltstone) of closely stacked hyperpycnal layers, consisting of interbedded moderately bioturbated (BI 3) silty mudstone (FA 2) and nonbioturbated (BI 0–1) muddy siltstones with erosional scours, current-, wave-, and combined-flow ripples, soft-sediment deformation, and normal and inverse lamina-set grading (FA 1; see legend). A variety of trace fossils are present, including fugichnia traces (*Fu*), navichnia traces (*Na*), *Planolites* (*Pl*), and *Phycosiphon* (*Ph*). Bioturbation index from Taylor and Goldring (1993) is shown as a vertical bar graph.

homogenized muds; Macquaker et al. 2010) suggests that the ''triplet'' succession is not diagnostic of a singular process. In the case of the ''random'' beds from the lower Genesee Group of central New York, the collective presence of inverse and normal grading, internal scours, and wave-formed features requires a process that allows for quasi-steady lateral flow, meaning that flow velocity can increase and decrease gradually with time (Mulder and Alexander 2001; Mulder et al. 2003). Given the vertical and lateral distribution of these deposits, as well as associated changes in sedimentary features, hyperpycnal flows, reflecting the sporadic nature of fluvial discharge events, appear to be the most likely process that allows for that kind of variability.

CONCLUSION

Although descriptions of ancient muddy hyperpycnites are still rare, several examples have recently been described from strata of the Cretaceous Western Interior Seaway (e.g., Pattison et al. 2007; Soyinka and Slatt 2008; Bhattacharya and MacEachern 2009), suggesting that the ''rarity'' is more a matter of nonrecognition than of actual absence. Identifying such deposits in the NAB, a substantially older mudstone-rich foreland basin, suggests that hyperpycnites may actually be much more common in the rock record than previously recognized. With regard to interpretations of the sedimentary history of Devonian black shale successions in the NAB, the observations presented here cast doubt on previous assessments that assumed that organic-rich muds of the Genesee Group accumulated in a quiescent, deep-water environment. The observations presented in this study imply a significantly shallower and more energetic setting in which high-energy events associated with river floods transported and deposited large volumes of sediment across and along the Devonian shelf.

As elaborated above, the interpreted muddy hyperpycnites of the lower Genesee Group increase in thickness and abundance upsection, and show a parallel increase in grain size and wave-related sedimentary features, and a decrease in bioturbation intensity and trace-fossil diversity. Collectively these observations are consistent with increasing proximality upsection as a consequence of westward shoreline progradation.

The tectonic activity that coincides with deposition of the Geneseo Formation (onset of third tectophase of the Acadian Orogeny) provides a

FIG. 7.—Outcrop appearance of a silt-rich hyperpycnite with a basal scour, hummocky cross-lamination, and current-ripple cross-lamination showing normal and inverse grading (normal and inverted triangles).

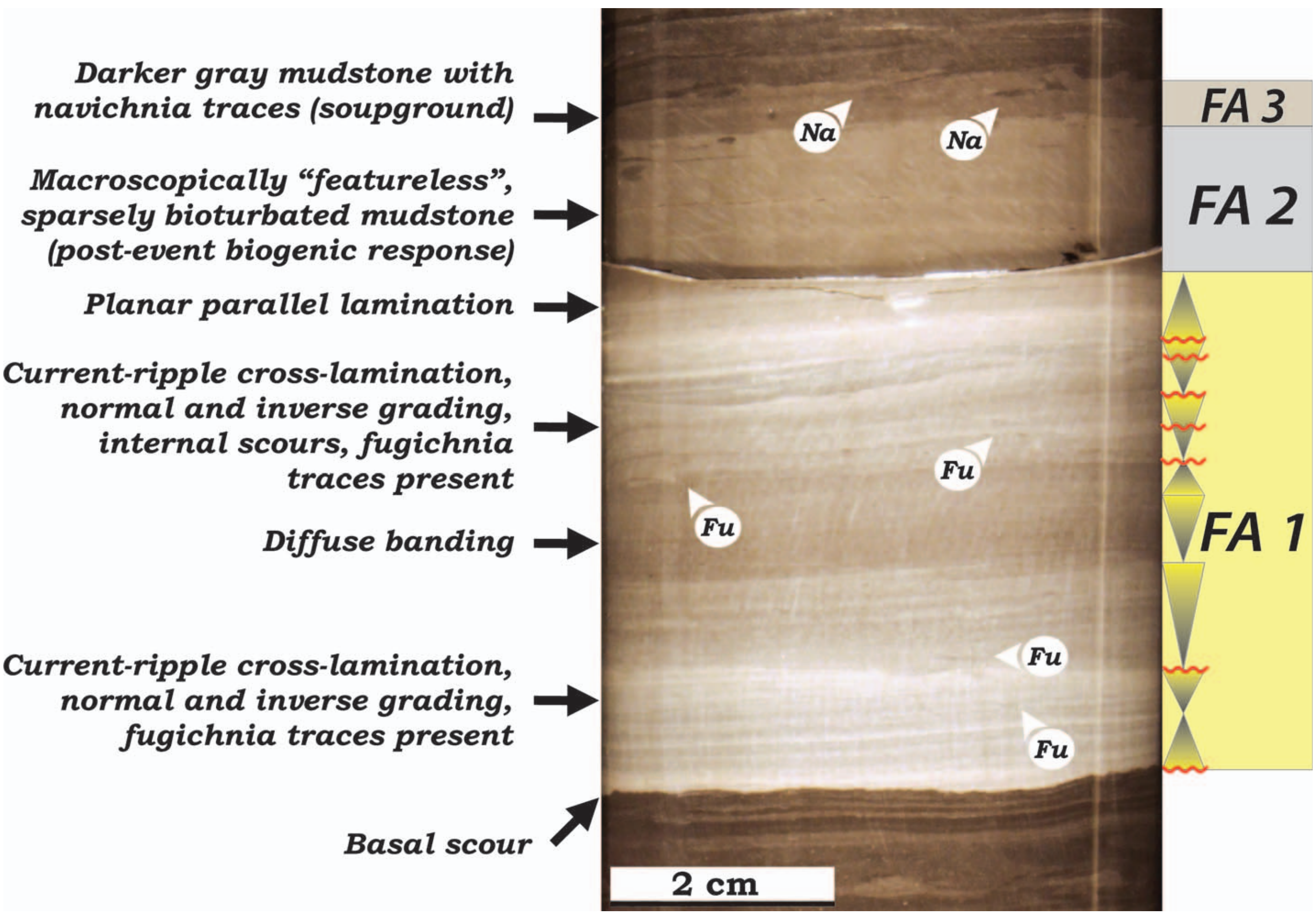


FIG. 8.—Photograph showing the product of a sustained hyperpycnal flow in the Geneseo Formation, with sedimentary features and facies divisions outlined (reference legend from Fig. 6).

plausible cause for an increase in sediment supply, increased fluvial sediment discharge, and shoreline progradation. In addition, the proposed muddy hyperpycnites may also reflect seasonal increases in runoff and storm activity due to changing environmental and climatic conditions. Erosional and wave-related features indicate that deposition of the lower Genesee Group occurred above storm wave base for the most part, and was strongly influenced by fluvial-discharge events.

The conclusions from this study provide a new perspective for potential environments of deposition of organic-rich mudstones in an allegedly quiescent, anoxic foreland basin. There is no longer a need for a deep, stratified basin wherein sediment transport was driven by internal waves that eroded and mobilized deep water slope sediments (e.g., Woodrow and Isley 1983; Woodrow 1985; Ettensohn 1985, 1987; Baird and Brett 1986, 1991; Ettensohn et al. 1988), and where anoxia were critical for preservation of organic matter. The described strata are yet another example for a carbonaceous mudstone succession that was deposited under comparatively energetic conditions (Bohacs et al. 2005; Schieber and Yawar 2009; Macqauker et al. 2010), reflects multiple modes of sediment transport and deposition, and records significant carbon burial without a need for anoxic conditions.

ACKNOWLEDGMENTS

The authors are indebted to J.A. MacEachern and J.P. Bhattacharya for their helpful comments on the initial draft, as well as providing insight for future work. We would also like to acknowledge K.M. Bohacs, B.A. Cheadle, and J.B. Southard for providing valuable suggestions and reviews of the manuscript. The authors are grateful to the sponsors of the Indiana University Shale Research Consortium (Anadarko, Chevron, ConocoPhillips, ExxonMobil, Shell, Statoil, Marathon, Whiting, and Wintershall), which provided student support. Field work and analytical supplies were supported through student research grants awarded to RDW by the Geological Society of America, SEPM (Society for Sedimentary Geology), the Indiana University Department of Geological Sciences, and the American Association of Petroleum Geologists (Pittsburgh Association of Petroleum Geologists Named Grant, Richard W. Beardsley Named Grant).

REFERENCES

Aigner, T., and Reineck, H.E., 1982, Proximality trends in modern storm sands from the Helgoland Bight (North Sea) and their implications for basin analysis: Senckenbergiana Maritima, v. 14, p. 183–215.

Allison, M.A., and Nittrouer, C.A., 1998, Identifying accretionary mud shorefaces in the geologic record: insights from the modern Amazon dispersal system, *in* Schieber, J., Zimmerle, W., and Sethi, P.S., eds., Mudstones and Shales: Recent Progress in Shale Research: Stuttgart, Schweizerbart Publishers, p. 147–161.

Baird, G.C., and Brett, C.E., 1986, Erosion on an anaerobic seafloor: significance of reworked pyrite deposits from the Devonian of New York state: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 57, p. 157–193.

Baird, G.C., and Brett, C.E., 1991, Submarine erosion on the anoxic sea floor: stratinomic, palaeoenvironmental, and temporal significance of reworked pyrite–bone deposits, *in* Tyson, R.V., and Pearson, T.H., eds., Modern and Ancient Continental Shelf Anoxia: Geological Society of London, Special Publication 58, p. 233–257.

Baird, G.C., Brett, C.E., and Kirchgasser, W.T., 1988, Genesis and geochronology of black shale–roofed discontinuities in the Devonian Genesee Formation, western New York State, *in* McMillan, N.J., Embry, A.F., and Glass, D.J., eds., Devonian of the World: Canadian Society of Petroleum Geologists, Memoir 14, p. 357–375.

Bentley, S.J., Sr., 2003, Wave–current dispersal of fine-grained fluvial sediments across continental shelves: the significance of hyperpycnal plumes, *in* Scott, E.D., Bouma, A.H., and Bryant, W.R., eds., Siltstones, Mudstones and Shales: Depositional Processes and Characteristics: SEPM, Miscellaneous Publication, CD-ROM, p. 35–48.

Bhattacharya, J.P., and MacEachern, J.A., 2009, Hyperpycnal rivers and prodeltaic shelves in the Cretaceous seaway of North America: Journal of Sedimentary Research, v. 79, p. 184–209.

Bohacs, K.M., Grabowski, G.J., Carroll, A.R., Mankiewicz, P.J., Miskell-Gerhardt, K.J., Schwalbach, J.R., Wegner, M.B., and Simo, J.A., 2005, Production, destruction, and dilution: the many paths to source-rock development, *in* Harris, N.B., ed., The Deposition of Organic Carbon-Rich Sediments: SEPM, Special Publication 82, p. 61–101.

Brett, C.E., and Baird, G.C., 1996, Middle Devonian sedimentary cycles and sequences in the northern Appalachian Basin, *in* Witzke, B.J., and Day, J., eds., Paleozoic Sequence Stratigraphy: Views from the North American Craton: Geological Society of America, Special Paper 306, p. 213–241.

Brett, C.E., Baird, G.C., Bartholomew, A.J., DeSantis, M.K., and Ver Straeten, C.A., 2011, Sequence stratigraphy and a revised sea-level curve for the Middle Devonian of eastern North America: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 304, p. 21–53.

Bridge, J.S., and Willis, B.J., 1991, Middle Devonian near-shore marine, coastal and alluvial deposits, Schoharie Valley, central New York State: New York State Geological Association, Guidebook 63, p. 131–160.

Bridge, J.S., and Willis, B.J., 1994, Marine transgressions and regressions recorded in Middle Devonian shore-zone deposits of the Catskill clastic wedge: Geological Society of America, Bulletin, v. 106, p. 1440–1458.

Cluff, R.M., 1980, Paleoenvironment of the New Albany Shale group (Devonian–Mississippian) of Illinois: Journal of Sedimentary Petrology, v. 50, p. 767–780.

Cutter, G.R., and Diaz, R.J., 2000, Biological alteration of physically structured flood deposits on the Eel margin, northern California: Continental Shelf Research, v. 20, p. 235–253.

Dennison, J.M., 1985, Catskill Delta shallow marine strata, *in* Woodrow, D.L., and Sevon, W.D., eds., The Catskill Delta: Geological Society of America, Special Paper 201, p. 91–106.

Ettensohn, F.R., 1985, Controls on development of Catskill Delta complex basin-facies, *in* Woodrow, D.L., and Sevon, W.D., eds., The Catskill Delta: Geological Society of America, Special Paper 201, p. 65–77.

Ettensohn, F.R., 1987, Rates of relative plate motion during the Acadian Orogeny based on the spatial distribution of black shales: Journal of Geology, v. 95, p. 572–582.

Ettensohn, F.R., 1994, Tectonic control on formation and cyclicity of major Appalachian unconformities and associated stratigraphic sequences: SEPM, Concepts in Sedimentology and Paleontology, v. 4, p. 217–242.

Ettensohn, F.R., Miller, M.L., Dillman, S.B., Elam, T.D., Geller, K.L., Swager, D.R., Markowitz, G., Woock, R.D., and Barron, L.S., 1988, Characterization and implications of the Devonian–Mississippian black-shale sequence, eastern and central Kentucky, USA; pycnoclines, transgression, regression and tectonism, *in* McMillan, N.J., Embry, A.F., and Glass, D.J., eds., Devonian of the World: Canadian Society of Petroleum Geologists, Memoir 14, p. 323–345.

Felix, M., Peakall, J., and McCaffrey, W.D., 2006, Relative importance of processes that govern the generation of particulate hyperpycnal flows: Journal of Sedimentary Research, v. 76, p. 382–387.

Friedrichs, C.T., and Scully, M.E., 2007, Modeling deposition by wave-supported gravity flows on the Po River prodelta: from seasonal floods to prograding clinoforms: Continental Shelf Research, v. 27, p. 322–337.

Friedrichs, C.T., and Wright, L.D., 2004, Gravity-driven sediment transport on the continental shelf: implications for equilibrium profiles near river mouths: Coastal Engineering, v. 51, p. 795–811.

Higgs, R., 1990, Is there evidence for geostrophic currents preserved in the sedimentary record of inner to middle-shelf deposits?—Discussion: Journal of Sedimentary Petrology, v. 60, p. 630–632.

Johnson, J.G., 1970, Taghanic onlap and the end of North American Devonian provinciality: Geological Society of America, Bulletin 81, p. 2077–2106.

Kineke, G.C., Sternberg, R.W., Trowbridge, J.H., and Geyser, W.R., 1996, Fluid-mud processes on the Amazon continental shelf: Continental Shelf Research, v. 16, p. 667–696.

Kirchgasser, W.T., Baird, G.C., and Brett, C.E., 1988, Regional placement of Middle/Upper Devonian (Givetian–Frasnian) boundary in western New York State, *in* McMillan, N.J., Embry, A.F., and Glass, D.J., eds., Devonian of the World: Canadian Society of Petroleum Geologists, Memoir 14, p. 113–117.

Kirchgasser, W.T., Brett, C.E., and Baird, G.C., 1997, Sequences, cycles and events in the Devonian of New York State: an update and overview: New York State Geological Association, Guidebook 69, p. 5–121.

MacEachern, J.A., Bann, K.L., Bhattacharya, J.P., and Howell, C.D., 2005, Ichnology of deltas, *in* Giosan, L., and Bhattacharya, J.P., eds., River Deltas: Concepts, Models, and Examples: SEPM, Special Publication 83, p. 49–85.

Macquaker, J.H.S., Bentley, S.J., and Bohacs, K.M., 2010, Wave-enhanced sediment-gravity flows and mud dispersal across continental shelves: reappraising sediment transport processes operating in ancient mudstone successions: Geology, v. 38, p. 947–950.

Mulder, T., and Alexander, J., 2001, The physical character of subaqueous sedimentary density flows and their deposits: Sedimentology, v. 48, p. 269–299.

Mulder, T., Syvitski, J.P.M., Migeon S., Faugéres, J.C., and Savoye, B., 2003, Marine hyperpycnal flows: initiation, behavior and related deposits. A review: Marine and Petroleum Geology, v. 20, p. 861–882.

Passey, Q.R., Bohacs, K.M., Esch, W.L., Klimentidis, R.E., and Sinha, S., 2010, From oil-prone source rock to gas-producing shale reservoir: geologic and petrophysical characterization of unconventional shale-gas reservoirs: Society of Petroleum Engineers, Paper 131350-MS, 29 p.

Pattison, S.A.J., Ainsworth, R.B., and Hoffman, T.A., 2007, Evidence of across-shelf transport of fine-grained sediments: turbidite-filled shelf channels in the Campanian Aberdeen Member, Book Cliffs, Utah, USA: Sedimentology, v. 54, p. 1033–1064.

Potter, P.E., Maynard, J.B., and Pryor, W.A., 1980, Sedimentology of Shale: New York, Springer-Verlag, 306 p.

Potter P.E., Maynard J.B., and Depetris P.J., 2005, Mud and Mudstones: Introduction and Overview: New York, Springer, 297 p.

RINE, J., AND GINSBURG, R., 1985, Depositional facies of a mud shoreface in Surinam, South America: a mud analogue to sandy shallow-marine deposits: Journal of Sedimentary Petrology, v. 55, p. 633–652.

ROGERS, W.B., ISACHSEN, Y.W., MOCK, T.D., AND NYAHAY, R.E., 1990, New York state geological highway map: New York State Museum and Science Service, Educational Leaflet 33, 1 sheet.

SOYINKA, O.A., AND SLATT, R.M., 2008, Identification and micro-stratigraphy of hyperpycnites and turbidites in Cretaceous Lewis Shale, Wyoming: Sedimentology, v. 55, p. 1117–1133.

SCHIEBER, J., 2011a, Reverse engineering mother nature: shale sedimentology from an experimental perspective: Sedimentary Geology, v. 238, p. 1–22.

SCHIEBER, J., 2011b, Implications of flume studies for shallow marine mud deposition and the stratigraphic record [abstract]: American Association of Petroleum Geologists, Annual Meeting in Houston, Abstracts Volume 987116, p. 160.

SCHIEBER, J., AND SOUTHARD, J.B., 2009, Bedload transport of mud by floccule ripples: direct observation of ripple migration processes and their implications: Geology, v. 37, p. 483–486.

SCHIEBER, J., AND YAWAR, Z., 2009, A new Twist on mud deposition: mud ripples in experiment and rock record: The Sedimentary Record, v. 7, no. 2, p. 4–8.

SCHIEBER, J., SOUTHARD, J.B., AND THAISEN, K., 2007, Accretion of mudstone beds from migrating floccule ripples: Science, v. 318, p. 1760–1763.

SCHIEBER, J., SOUTHARD, J.B., AND SCHIMMELMANN, A., 2010, Lenticular shale fabrics resulting from intermittent erosion of water-rich muds: interpreting the rock record in the light of recent flume experiments: Journal of Sedimentary Research, v. 80, p. 119–128.

STOW, D.A.V, HUC, A.Y., AND BERTRAND, P., 2001, Depositional processes of black shales in deep water: Marine and Petroleum Geology, v. 18, p. 491–498.

TAYLOR, A.M., AND GOLDRING, R., 1993, Description and analysis of bioturbation and ichnofabric: Geological Society of London, Journal, v. 150, p. 141–148.

VARBAN, B.L., AND PLINT, A.G., 2008, Palaeoenvironments, palaeogeography, and physiography of a large, shallow, muddy ramp: late Cenomanian–Turonian Kaskapau Formation, Western Canada foreland basin: Sedimentology, v. 55, p. 201–233.

WILSON, R.D., 2012, Facies analysis and sequence stratigraphy of the Middle Devonian (Givetian) Geneseo Formation of New York: implications for accommodation during a eustatic sea-level rise [M.S. thesis]: Indiana University, 193 p.

WOODROW, D.L., 1985, Paleogeography, paleoclimate, and sedimentary processes of the Late Devonian Catskill Delta, *in* Woodrow, D.L., and Sevon, W.D., eds., The Catskill Delta: Geological Society of America, Special Paper 201, p. 51–63.

WOODROW, D.L., AND ISLEY, A.M., 1983, Fades, topography, and sedimentary processes in the Catskill Sea (Devonian), New York and Pennsylvania: Geological Society of America, Bulletin, v. 94, p. 459–470.

WRIGHT, L.D., AND FRIEDRICHS, C.T., 2006, Gravity-driven sediment transport on continental shelves: a status report: Continental Shelf Research, v. 26, p. 2092–2107.

ZAVALA, C., ARCURI, M., MEGLIO, M.D., DIAZ, H.G., AND CONTRERAS, C., 2011, A genetic facies tract for the analysis of sustained hyperpycnal flow deposits, *in* Slatt, R.M., and Zavala, C., eds., Sediment Transfer from Shelf to Deep Water: Revisiting the Delivery System: American Association of Petroleum Geologists, Studies in Geology 61, p. 31–51.

Received 20 January 2014; accepted 1 July 2014.