

ASSOCIATION BETWEEN WAVE- AND CURRENT-AIDED HYPERPYCNITES AND FLOODING SURFACES IN SHELFAL MUDSTONES: AN INTEGRATED SEDIMENTOLOGIC, SEQUENCE STRATIGRAPHIC, AND GEOCHEMICAL APPROACH

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ABSTRACT: The Middle to Late Devonian lower Genesee Group of New York has been the focus of sedimentologic, stratigraphic, and paleoecologic studies for over 150 years. Documentation of fluvial discharge events in this succession supports the growing realization that mudstone sedimentation in shelf seas is much more dynamic than commonly appreciated. Although this process has been observed on modern shelves, so far only few examples have been reported from ancient shelf strata. Integrated sedimentologic, sequence stratigraphic, and geochemical data suggest that organic-rich mudstones of the Genesee Formation were strongly influenced by fluvial-discharge events that carried fine-grained clastics and phytodetritus as turbulent flows from river-mouth regions onto the shelf. These discharge events appear to occur most abundantly during initial flooding at parasequence boundaries, a depositional context that resulted in increased coastal erosion processes and enhanced continental runoff.

In this study we explore the potential relationships between flooding events and depositional processes that govern the transport and deposition of organic-rich, fine-grained clastics in shelfal settings. In addition, we document how stable carbon isotopes and X-ray fluorescence analyses allow chemical fingerprinting of fluvial input events in an ostensibly monotonous succession of organic-rich mudstones. Isotopically, the organic material within hyperpycnal layers shows a dominantly terrestrial signature ($\delta^{13}\text{C}_{\text{org}} = -26.5\text{‰}$) and contrasts strongly with the dominant marine signature ($\delta^{13}\text{C}_{\text{org}} = -30\text{‰}$) of the Genesee organic-rich succession. The less negative $\delta^{13}\text{C}_{\text{org}}$ values of hyperpycnal layers (organic-lean, gray silty mudstones) are associated with elevated Zr/Al, Ti/Al, and Si/Al ratios, decreased Fe_T/Al , and lower trace-metal concentrations. Intervening intervals of organic-rich, sparsely to weakly bioturbated, pyritic and banded black mudstones show more negative $\delta^{13}\text{C}_{\text{org}}$ values, and are associated with decreased Zr/Al, Ti/Al, and Si/Al ratios, increased Fe_T/Al , and trace-metal enrichment. Recognizing wave-aided hyperpycnal input hundreds of kilometers away from the paleoshoreline suggests that deposition of basinal organic-rich mudstones occurred within storm-wave base and preservation of organic-matter richness is dominantly controlled by dilution.

INTRODUCTION

Fine-grained sedimentary rocks (shales, claystones, mudstones, siltstones, etc.) constitute approximately two thirds of the sedimentary column (Potter et al. 2005). Understanding their depositional processes has evolved with recent advances in experimental sedimentology (Young 1977; Schieber et al. 2007; Baas et al. 2009; Schieber and Southard 2009; Schieber and Yawar 2009; Schieber et al. 2010; Schieber 2011) and observations of modern muddy shelves (Rine and Ginsburg 1985; Allison and Nittrouer 1998; Macquaker et al. 2010; Dashtgard and MacEachern 2016). Widespread deposition of organic-rich fine-grained sediments appears to occur during time intervals that reflect times of global sea-level rise, greenhouse climate with elevated atmospheric $p\text{CO}_2$, and extensive volcanism (Fischer 1981). One of these time intervals is the late Devonian, during which many of the black, organic-rich mudstones observed in the eastern and central United States were deposited.

The Devonian Period marks many changes in marine and terrestrial ecosystems, most notably the proliferation of vascular plants that led to enhanced weathering and nutrient flux to the oceans (Algeo et al. 1995; Berner 2005), and likely enabled globally extensive deposition of organic-rich black mudstones. Although both phytoplankton and land plants preferentially incorporate ^{12}C into their biomass during photosynthesis, land plants use stomata to regulate gas exchange with the atmosphere, and thus are not as influenced by ambient CO_2 concentration as are marine photoautotrophs. The isotopic consequences of this effect allow the differentiation of marine vs. terrestrial organic-matter input (Maynard 1981), and are further enhanced during periods of high atmospheric $p\text{CO}_2$ (Arthur et al. 1988).

The chosen interval of study is a late Middle Devonian organic-rich succession (Fig. 1) that has been studied throughout New York (Fig. 2) through surface exposures and drill-core characterization (Wilson and Schieber 2014, 2015, 2016, 2017). The aforementioned studies investigate sediment transport processes and redefine depositional environments in the mudstone-dominated Genesee Group, as well as develop a sequence stratigraphic framework (Wilson and Schieber 2014, 2015, 2017). Moreover, implications for sediment transport mechanisms and unconven-

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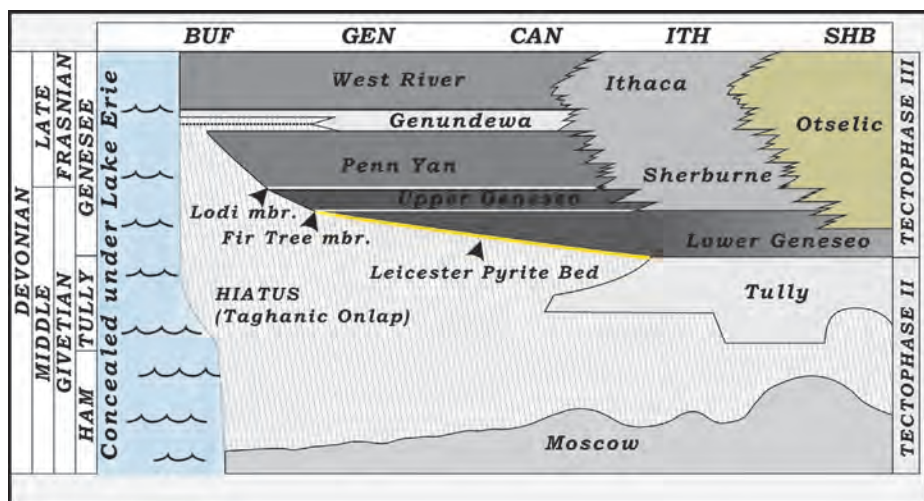


FIG. 1.—Generalized chronostratigraphic chart for Middle–Late Devonian strata of New York (SHB, Sherburne; ITH, Ithaca; CAN, Canandaigua; GEN, Genesee; BUF, Buffalo; HAM, Hamilton Group). The Genesee Formation marks the onset of the third tectophase of the Acadian Orogeny (Ettensohn 1987), the most pronounced thrust loading event of that orogeny. The Genesee Group onlaps the Taghanic disconformity westward; thus, the basal ages of the onlapping Genesee and Penn Yan shales become progressively younger westward (Kirchgasser et al. 1988). Figure is modified from Rogers et al. (1990) 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.

tional reservoir presence, quality, and distribution are addressed (Wilson and Schieber 2016). These investigations have resulted in a facies model for the Genesee Formation wherein lithofacies variability is directly linked to changing paleoenvironmental stresses during the drainage of an active tectonic source region that supplied the advancing Catskill deltaic complex. The present paper aims to address the geochemical relationships

to varying depositional processes in the offshore deltaic setting, as well as expand the relationship of fluvial-discharge events in a sequence stratigraphic framework.

Stratigraphically, the Lower Genesee Member overlies the Tully Limestone and underlies the Fir Tree Member (Fig. 1), and represents the initial phases of thrust loading and cratonic downwarping during the

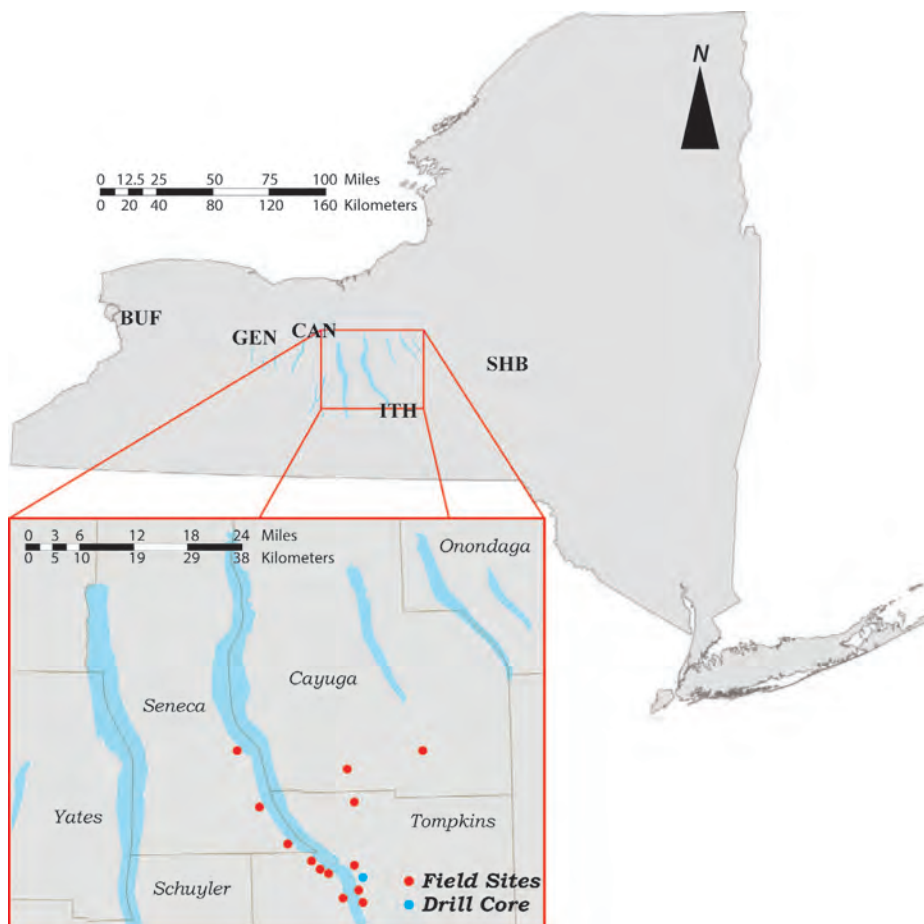


FIG. 2.—Overview map of New York and the outcrops visited near Cayuga Lake (blue) as well as drill-core location (red).

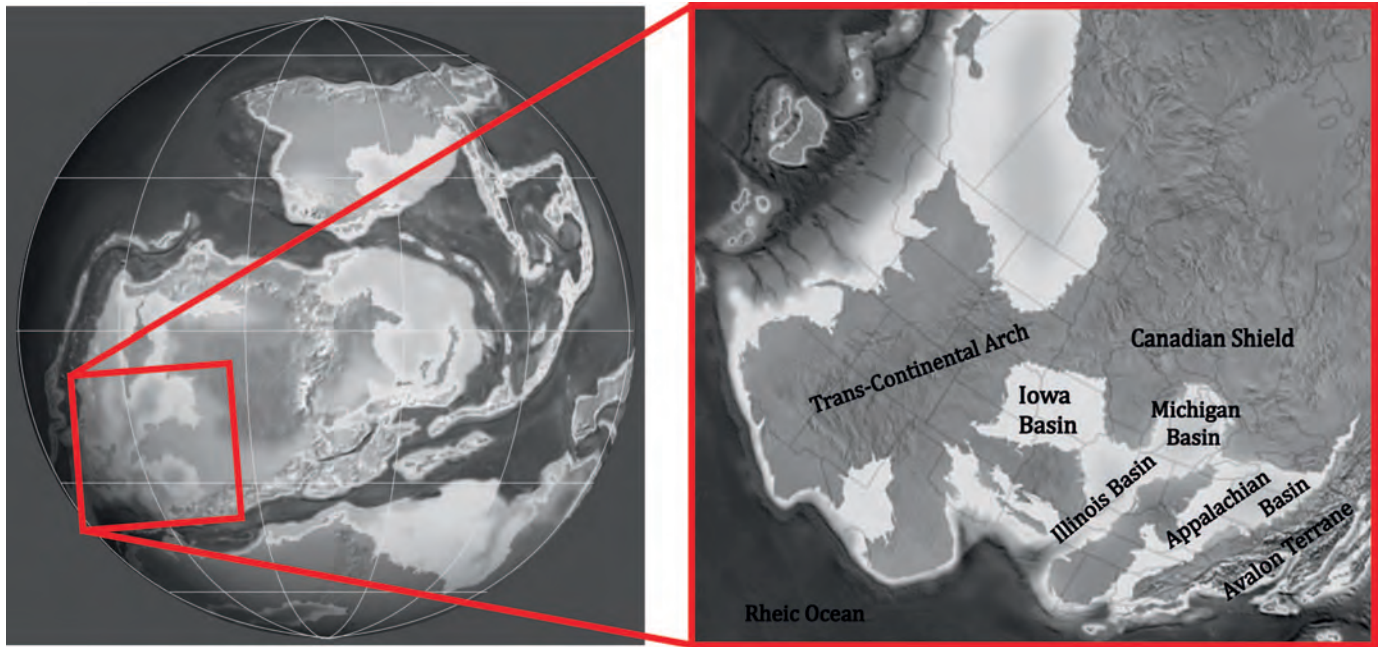


Fig. 3.—Middle Devonian paleogeographic map modified after Blakey (2005). Global map zooms into the Eastern North America during the Middle Devonian. Various structural features and basins are outlined on the right. Note the continent–microcontinent(s) collision producing a rotational “scissor-like” closure and uplift of the Avalon Terrane.

third phase of the Acadian orogeny. Orogenesis was coupled with a prolonged Devonian rise of eustatic sea level (Johnson et al. 1985), resulting in an expansive epicontinental seaway that covered much of eastern Laurentia (Fig. 3). The Tully–Genesee contact has been recognized as the maximum flooding surface of a Middle Devonian transgressive–regressive cycle (Fig. 4; Johnson et al. 1985; Brett et al. 2011; Wilson and Schieber 2017). Above this contact, careful correlations of parasequences in the Lower Genesee Member, as identified by coarsening-upwards packages and systematic shifts in facies tracts, show aggradational to progradational stacking, indicative of a highstand systems tract (Wilson and Schieber 2017). The most prevalent facies throughout the Lower Genesee is a banded grayish black mudstone (BBM) that is also the most organic-rich facies of the succession (Fig. 5). The BBM facies shows meioturbational fabrics and is texturally a fine to medium mudstone with erosional contacts and current-ripple cross-lamination with abundant lamina-scale normal grading. Upsection, the basal deposits of the BBM facies grade into dark gray mudstones (DGM) with an increase in erosional contacts, current- and wave-formed features, and increased bioturbation intensity and trace-fossil diversity. The Lower Genesee Member is capped by a sequence boundary that marks a drastic seaward shift of the shoreline, resulting in deposition of the aulopod-rich, calcareous silty mudstones of the Fir Tree Member (Baird et al. 1988).

Within this organic-rich interval, complexly graded layers record short-lived pulses of high-energy events with sedimentary structures that are thought to be associated with wave-aided hyperpycnal flows (Wilson and Schieber 2014, 2015). Diagnostic sedimentary features of wave- and current-aided fluvial discharge events include basal scours, normal and inverse lamina-scale grading, flame structures, asymmetrical climbing current ripples and combined-flow ripples with low-angle erosional contacts, “bundle-wise” stacking of foreset laminae with cross-stratal offshoots, concave-up geometries, and concentration of terrestrial phytodetritus (Fig. 6; Bhattacharya and MacEachern 2009; Wilson and Schieber 2015). Basal portions of these deposits in many places show hummocky cross-

lamination, climbing-current-ripple cross-lamination, wave-modified current-ripple cross-lamination, and combined-ripple cross-lamination, indicating that these low-density suspensions were sustained for significant distances via bidirectional and unidirectional transport (Wilson and Schieber 2014). From these observations, a facies model was developed (Fig. 6) that captures lateral variability in sedimentary structures and post-event biogenic activity in the context of hyperpycnal depositional events. This model differentiates these complexly graded layers into a basal wave- and current-aided fraction (FA 1), a finer-grained suspended-load fraction (FA 2), and a buoyancy-reversal fraction (FA 3; Fig. 6).

The development of reliable geochemical proxies to assess paleodepositional conditions for organic-rich sediments has been a critical topic of research for several decades, including what information can be discerned about such conditions with a multi-proxy approach (Lewan 1986; Arthur and Sageman 1994, 2005; Jones and Manning 1994; Carroll and Bohacs 2001; Werne et al. 2002; Sageman et al. 2003; Bohacs et al. 2005; Algeo and Maynard 2008). In this study, we follow an approach that was developed for the Appalachian and Illinois basins to differentiate land-derived from marine organic matter inputs (Maynard 1981). Carbon isotope samples were collected vertically throughout the mudstone succession and combined with high-resolution X-ray fluorescence analysis and detailed petrographic characterization, in order to better capture the dynamic relationships between organic-matter accumulation and depositional processes. By integrating our geochemical indices with previous studies of the Genesee Formation, where a sedimentological case is made that fluvial-sourced injections of sediment are added to an organic-rich background sedimentation (Wilson and Schieber 2014), our observations and conclusions support an emerging alternative hypothesis that posits that the Devonian organic-rich mudstones of the eastern US were deposited in a broad, expansive, shallow epeiric sea wherein lateral sediment transport was driven largely by storm waves and sustained advective currents (Conant and Swanson 1961; McCollum 1988; Schieber 1994, 2003, 2016; Schieber and Riciputi 2004; Wilson and Schieber 2014, 2015, 2017).

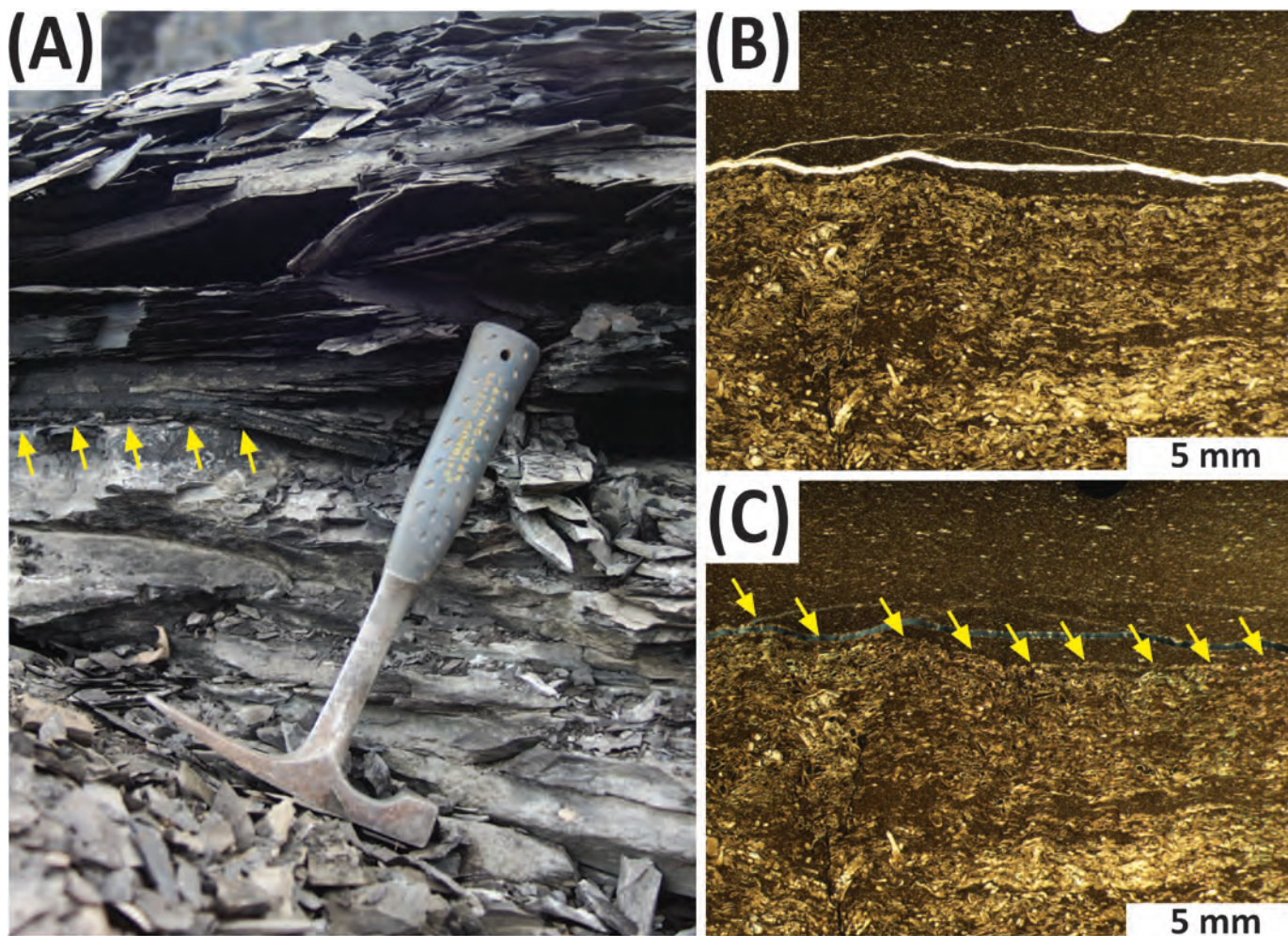


FIG. 4.—(A) The upper Tully–Genesee contact at the Cayuga Crushed Stone quarry (rock hammer for scale). (B, C) Photomicrograph of this contact. Note irregular sharp boundary (yellow arrows) separating the underlying densely packed, well sorted, styliolinid packstones of the Tully Formation with the overlying Genesee Formation consisting of grayish-black, fine to medium mudstones with agglutinated benthic foraminifera.

METHODS

For the present study, observations from the Genesee Formation were made on exposures in upstate New York near Cayuga Lake, as well as a drill core from Lansing, New York (Fig. 5). Lithologic profiles were recorded for each outcrop exposure and drill core at the centimeter scale. Observations of texture, sedimentary features, bioturbation index, ichnogenera, diagenetic overprint, and bed thickness/shape/and continuity were recorded (Wilson and Schieber 2015). Samples were stabilized with epoxy resin and thin-sectioned. Hand-specimens were slabbed with a diamond blade and then smoothed and polished with grinding wheels of successively finer grit sizes (60–1200 mesh). High-resolution images of these samples were compiled via standard photography and a flatbed scanner (1200–2400 dpi). Through variable lighting, as well as wet vs. dry imaging, detailed image sets of sedimentary features at the hand specimen scale were acquired.

For geochemical analyses, samples were selected from drill core at 40 cm intervals. Samples were ground with a SPEX 8000 ball mill with a steel vial for 10–15 minutes, weighed into a polyethylene centrifuge tube (~1 gram), and subsequently acidified for 24 hours with 1N hydrochloric acid (HCl). Subsequently, samples were centrifuged for 10 minutes and the

supernatant was drained. Deionized water was added and mixed with each sample and centrifuged three times to remove remaining HCl from the ground sample. Samples were subsequently frozen, and freeze-dried to remove liquids. The samples were then weighed into tin capsules (~0.30 µg), placed into the autosampler of the elemental analyzer, and combusted. Stable-isotope ratios of organic carbon ($\delta^{13}\text{C}_{\text{org}}$) were determined using a ThermoFinnigan Delta Plus XP mass-spectrometer connected to a Costech Elemental Analyzer. The carbon-isotope composition of the resulting CO_2 gas was measured against internal laboratory standards (e.g., acetanilide, $\delta^{13}\text{C}_{\text{org}} = -29.85\text{‰}$) that had been calibrated with the Vienna Peedee Belemnite (VPDB) isotopic standard. Total carbon and sulfur were determined with a C-S Eltra Analyzer on powdered samples. For XRF, outcrop and drill-core samples were slabbed and polished to reduce surface topography and then analyzed with an ITRAX core scanner at 4-mm resolution at the Large Lakes Observatory in Duluth, Minnesota.

RESULTS

In central New York state, the Genesee Formation consists of multiple mudstone facies (Fig. 2), and shows an overall shallowing-upwards trend that represents the westward progradation of the Catskill delta (Ettensohn

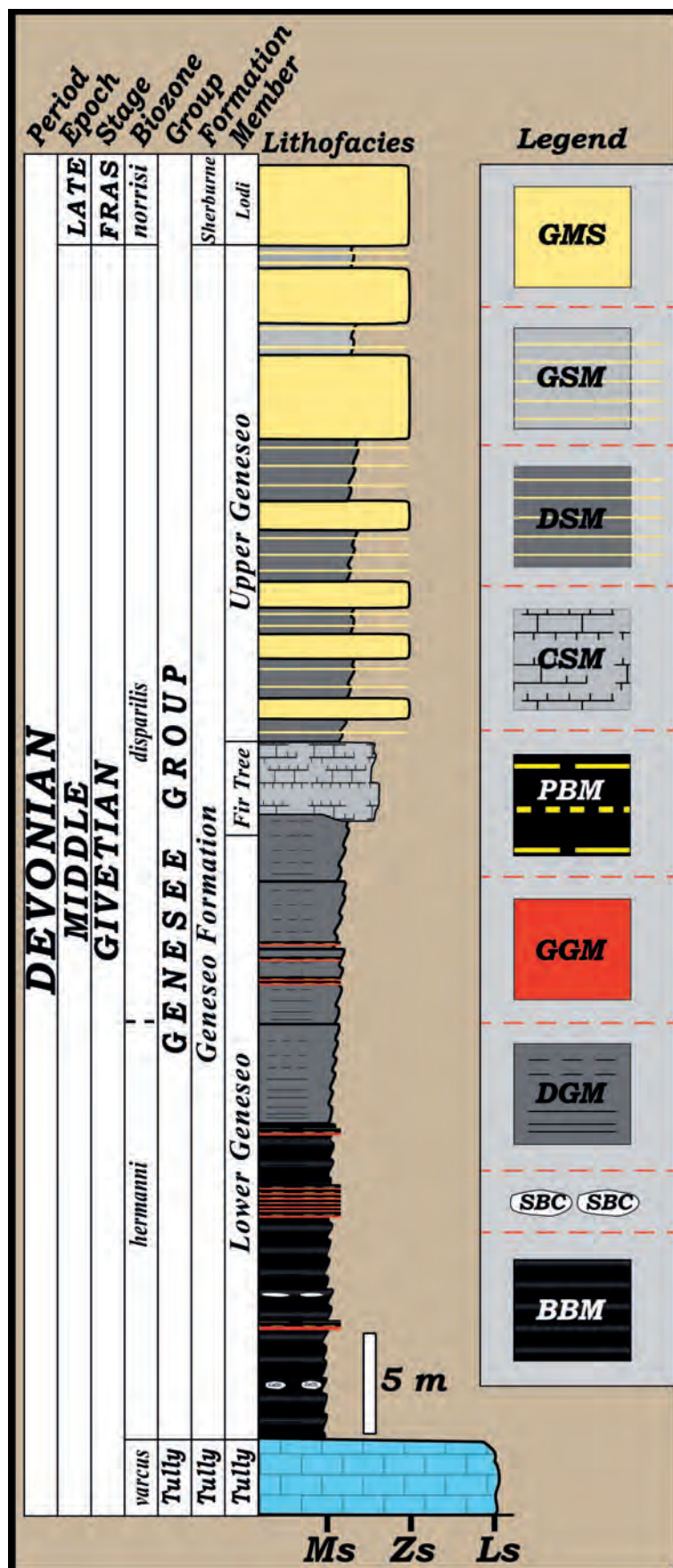


FIG. 5.—Lithologic section of the lower Genesee Group drafted from the Lansing drill core. Note the vertical facies progression from basal organic-rich mudstones of the Lower Genesee to organic-lean muddy siltstones reflecting progradation of the Catskill delta. BBM, banded black mudstone; CSM, calcareous silty mudstone; DGM, dark gray mudstone; DSM, dark gray silty mudstone; GGM, graded gray mudstone; GMS, gray muddy siltstone; SBC, strongly bioturbated calcareous mudstone; GSM, gray silty mudstone; Ls, limestone; Ms, mudstone; PBM, pyritic black mudstone; Zs, siltstone.

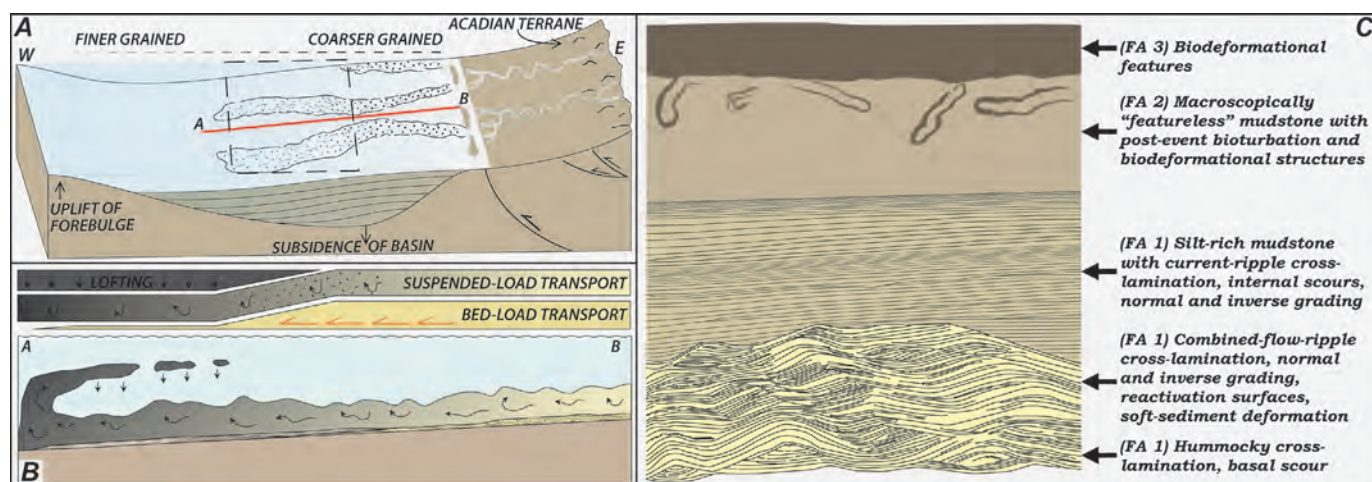


FIG. 6.—**A**) Idealized sketch of the northern Appalachian Basin during the Devonian (study area projected as dashed box), with river-fed hyperpycnal flows displayed (A–B cross section used in Part B). **B**) Conceptual diagram showing the internal arrangement of facies deposited from sustained hyperpycnal flows in a marine environment (modified from Zavala et al. 2011), including bed-load transport (FA 1), suspended-load transport (FA 2), and lofting (FA 3). **C**) Idealized sketch of a lower Genesee muddy hyperpycnite, with the succession of bedforms and facies types typically observed (adapted from Wilson and Schieber 2014).

1985; Wilson and Schieber 2014). The Genesee–Tully contact has been correlated regionally across the northern Appalachian Basin (Brett and Baird 1996; Brett et al. 2011). This contact is a sharp, erosional boundary that separates the underlying platform carbonates of the Tully Formation from the overlying organic-rich, grayish black, sparsely bioturbated (BI = 0–2) with low trace-fossil diversity (e.g., *Chondrites*, *Helminthopsis*, and *Planolites*), fine to medium mudstones of the Genesee Formation (Fig. 4). The basal deposits of the Genesee are thin-bedded, fine-mudstones (i.e., claystones) with a characteristic textural banding that reflect very shallow-penetration surface-grazing organisms such as polychaetes and nematodes, fostering the development of a surface mixed layer (see Boudreau 1998) where small meiofauna disturb the surface sediment sufficiently to “blend” sharp boundaries between depositional events (Pemberton et al. 2008; Löhr and Kennedy 2015; Wilson and Schieber 2015). Upsection, the Lower Genesee Member coarsens into moderately bioturbated (BI = 3) dark gray mudstones with erosional scours, current ripples, combined-flow ripples, and wave ripples (Fig. 5). Common ichnogenera identified throughout the dark gray mudstones include *Chondrites*, *Palaeophycus*, *Planolites*, *Teichichnus*, and *Thalassinoides*. Moreover, flattened linguliform and rhynchonelliform brachiopods are common on bedding planes. The Lower Genesee Member is capped by a regionally extensive sequence boundary that marks a major seaward advance of the shoreline, resulting in deposition of the aulopod-rich, calcareous silty mudstones of the Fir Tree Member (Baird et al. 1988).

Throughout the succession, numerous complexly graded layers have been recognized as sustained wave- and current-aided hyperpycnites and categorized on the basis of physical and biological criteria to develop a facies model with three distinct facies associations (Fig. 6; Wilson and Schieber 2014). Facies association 1 can be recognized by nonbioturbated (BI = 0) siltstones with the presence of basal scours, normal and inverse grading, hummocky cross-lamination, climbing-ripple cross-lamination, combined-flow ripples (Fig. 7), as well as an abundance of terrestrial plant material (Fig. 8). Facies association 2 consists principally of non-bioturbated (BI = 0), diffusely stratified mudstones, and facies association 3 consists of dark gray to grayish black nonbioturbated to sparsely bioturbated mudstones (BI = 0–2). Bioturbation is not prevalent in hyperpycnal intervals, with the greater part of the deposit showing undisturbed, perfectly preserved sedimentary features. When present,

bioturbation occurs at the top of the interval (BI = 0–2), consisting principally of *navicchia* traces (mantle and swirl; Lobza and Schieber 1999) and appears top-down. Burrows commonly have irregular boundaries and a pyritic lining.

To further investigate the depositional environment and sequence stratigraphic framework for this succession, carbon isotopes of organic matter and X-ray fluorescence analyses were conducted. The $\delta^{13}\text{C}_{\text{org}}$ values of identified hyperpycnal layers show significant excursions toward less negative values (–26.5‰) compared to the interstratified organic-rich mudstones (–30‰; Fig. 9). Moreover, excursions toward less negative values appear to interrupt deposition of organic-rich intervals with decreased intensity of bioturbation coupled with decreased diversity of trace-fossil suites, and appear concentrated with the presence of early diagenetic nodules and cements (Figs. 9, 10). In the study area, the Genesee reaches total-organic-carbon (TOC) contents of up to 2.3 wt. % (average 1.4%). Intervals with more negative isotopic values are associated with organic-rich mudstones at or just above parasequence boundaries (i.e., flooding surfaces).

Identifying parasequences in offshore mudstone-rich strata requires detailed observations of sedimentary features, textural and compositional trends, diagenetic overprint, bioturbation intensity and trace-fossil diversity, and fossil assemblages (Bohacs et al. 2005). Parasequence boundaries are identified on the basis of an abrupt transition from organic-lean, moderately to strongly bioturbated (BI = 3–4) coarse mudstones with wave- and current-formed features below to more organic-rich, sparsely bioturbated fine to medium grayish black mudstones above. Parasequence boundaries (i.e., flooding surfaces) in the Genesee are commonly marked by concretionary zones (i.e., carbonate and/or pyrite concretions), as well as an abrupt change to more thin-bedded clay-rich mudstones (i.e., claystones) with subtle horizontal trace fossils (*Helminthopsis* and *Planolites*) and meioturbation. A parasequence expression in the Genesee progresses from basal clay-dominated mudstones with discontinuous to continuous, planar parallel laminations that are sparsely to weakly bioturbated (BI = 1–2; Fig. 10). Multiple beds and bed-sets stack vertically with increased current- and wave-ripple lamination, increased erosional scours, and increased bioturbation intensity and ichnological diversity upsection.

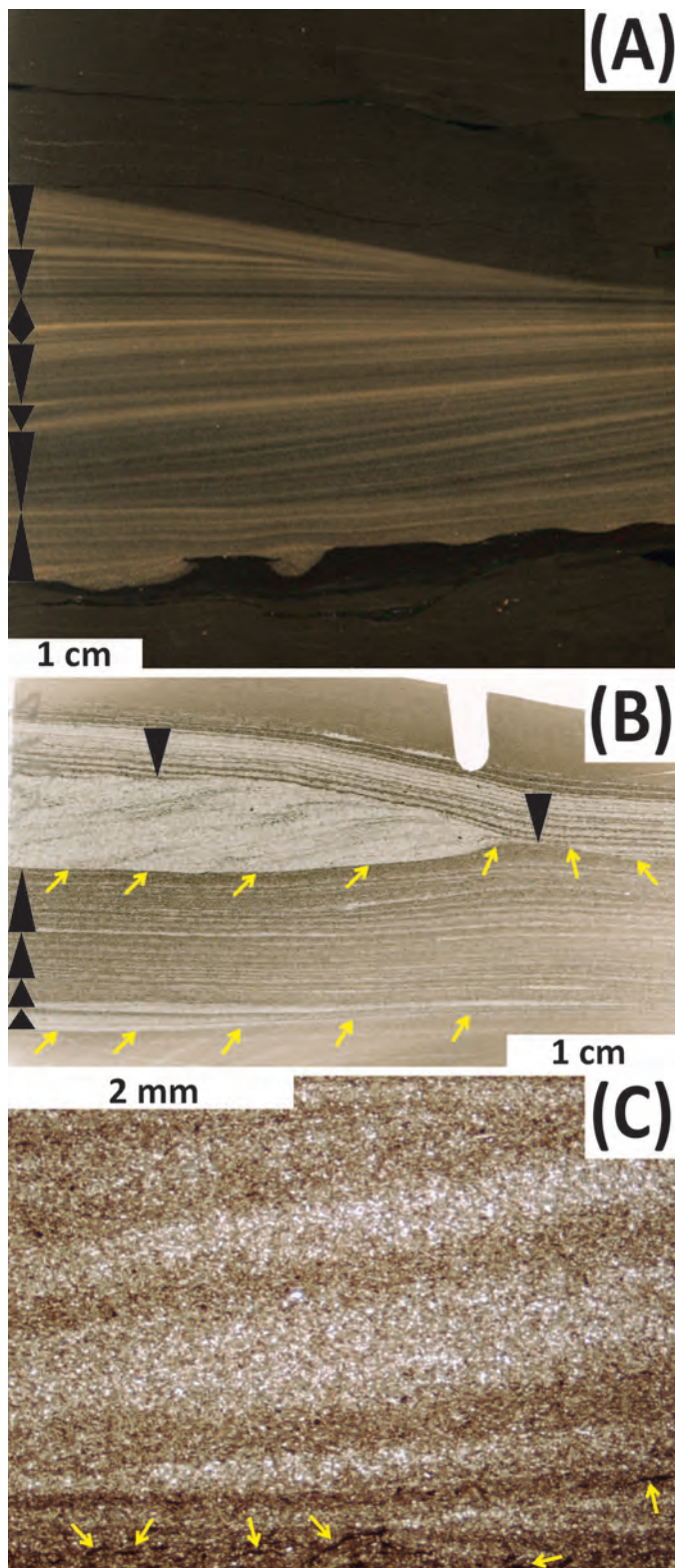


FIG. 7.—**A)** Polished drill core showing a nonbioturbated (BI = 0) silt-rich hyperpycnite with exquisite preservation of basal arcuate scalloped topography, normal and inverse lamina-set grading (black triangles), internal scours, and planar-parallel to low-angle cross-lamination, suggestive of sustained lateral sediment transport by turbulent flows with waxing and waning currents. **B)** Photomicrograph of a rapidly deposited muddy hyperpycnite with multiple scales of normal and

X-ray fluorescence analysis provides an independent tool for recognition of muddy hyperpycnites from more slowly accumulating organic-rich mudstones. Organic-rich facies show decreased Zr/Al, Ti/Al, and Si/Al, increased Fe_T/Al, and enrichment of redox-sensitive trace metals in organic-rich, sparsely to weakly bioturbated pyritic and banded black mudstones (Fig. 11). In contrast, the less negative carbon isotope values of presumed hyperpycnite intervals are associated with elevated Zr/Al, Ti/Al, and Si/Al, with decreased Fe_T/Al, and lower concentrations of redox-sensitive trace metals, and occur in nonbioturbated to weakly bioturbated (BI = 0–1) organic-lean, muddy siltstones to moderately to strongly bioturbated (BI = 3–4) gray mudstones (Figs. 11, 12). Fine-scale textural and compositional variations can be observed in the elemental profiles (Figs. 11, 12).

DISCUSSION

The combination of sedimentologic data and geochemical indices used in this study provides for alternative methods to detect fluvial discharge events in organic-rich mudstones of the Genesee Formation. The carbon-isotope values of organic matter appear to act as a reliable proxy for organic-matter type and distribution (Maynard 1981). Throughout the study interval, $\delta^{13}\text{C}_{\text{org}}$ values largely show “marine” values (–30‰) that are punctuated intermittently by excursions towards “terrestrial” values (–26.5‰). These carbon-isotope excursions coincide with facies associations that have been interpreted as the result of sustained hyperpycnal-flow events (Wilson and Schieber 2014) that transported terrestrial phytodetritus into the offshore realm. An interesting observation is that hyperpycnal flows appear to be focused on intervals in the succession that coincide with interpreted marine flooding surfaces (i.e., parasequence boundaries). This relationship is extremely important for the environmental conditions that facilitate density contrast between riverine input and the connecting waterbody, and enable offshore-directed flow of hyperpycnites. This density contrast is especially sensitive to increased discharge of terrestrial matter and commonly occurs during major storms (Bhattacharya and MacEachern 2009).

There have been a series of independent studies, ranging from paleoecological to stratigraphic investigations, that suggest that the Genesee Formation was deposited during a highstand systems tract (HST) subsequent to a major transgression (i.e., the Taghanic Onlap; Johnson 1970). The latter is marked by a widespread hiatus and the formation of a subaqueous unconformity between the Genesee Formation and the underlying Tully Formation (Fig. 4; Brett et al. 2011). As the Catskill deltaic system advanced, Genesee deposition recorded aggradational–progradational stacking of genetically related bed-sets (i.e., parasequences). For the Genesee Formation, it appears that the hyperpycnal input is highest near parasequence boundaries (i.e., flooding surfaces). For instance, 10 m above the Tully (Fig. 9), multiple hyperpycnites are highly concentrated into thinly stacked layers at a parasequence-set boundary, presumably marking a change from aggradational to progradational stacking patterns as well as a facies change from BBM to DGM. This is further corroborated by a shift towards more negative $\delta^{13}\text{C}_{\text{org}}$ values coupled with increased TOC at the boundary. Another location of highly concentrated fluvial-discharge events occurs 8 m below the Fir Tree Member, which appears to coincide with another increase in TOC and shift towards more negative $\delta^{13}\text{C}_{\text{org}}$ values.

← inverse grading (black triangles), internal scours, and planar-parallel to low-angle cross-lamination. **C)** Photomicrograph of a silt-rich hyperpycnite with low-angle cross-lamination and terrestrial phytodetritus in the basal portion of the deposit (yellow arrows).

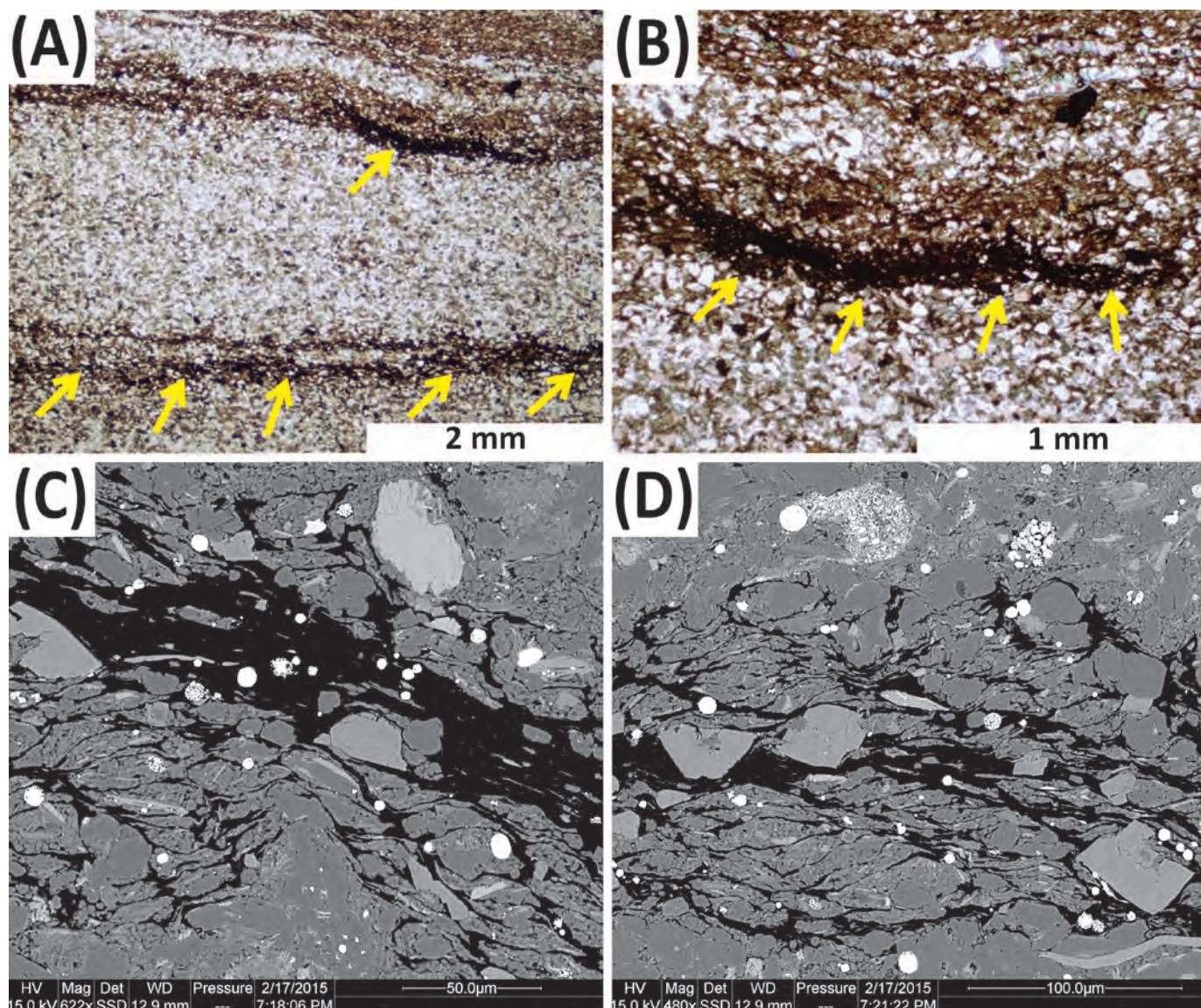


FIG. 8.—**A, B**) Photomicrographs showing terrestrial phytodetritus in clay-rich portions of hyperpycnites (yellow arrows). **C, D**) Backscatter image detailing the cellular structure of terrestrial phytodetritus.

This apparent close coupling between flooding events and offshore-directed fluvial discharge has many implications in terms of spatial and temporal character of the deposits. Previously, it has been an understood paradigm that flooding surfaces imply a landward shift of the shoreline that sequesters clastics in nearshore regions (i.e., estuaries and bays). An important yet neglected topic of discussion, however, is the various processes that break up terrestrial material (i.e., soil and plant material) for transport to the distal shelf setting. Apart from human-induced processes, the two primary causes of coastal erosion are rising sea level and coastal storms (Lisle 1982; Fletcher 1992). Whereas the storms provide the energy to accomplish the geomorphic work, it is the increase in sea-level that provides the impetus for change. The impact of sea-level rise will vary locally with relief, lithology, terrain, wave impingement, and vertical relief (e.g., tectonics). Whereas these previous factors all contribute to the erodibility of soil, it is the storm behavior that facilitates soil erosion processes in nearshore and coastal environments. Storms as an ancillary

process also facilitate across-shelf transport of eroded materials to the offshore setting as waves impinge on the shoreline and induce peak discharge from fluvial inputs. Further, storm-related soil erosion results from energy transmitted from associated rainfall and wind, an effect that is strongly intensified on steeply sloping terrains.

Whereas the aforementioned processes dominantly occur in the terrestrial setting adjacent to the shelf sea, they can be regarded as compounding elements in the genesis and distribution of fluvial injections throughout the Genesee Formation. During sea-level rise associated with parasequence formation, coastal soils are exposed to wave attack, and material that is eroded from slopes (soil and terrestrial organic matter) and accumulates in valleys and river banks requires shorter transport distances to the sea. During a storm event, this enhances the efficacy of elevated rainfall and discharge to transport eroded materials and nutrients to the river mouth. High concentrations of suspended material in storm-related

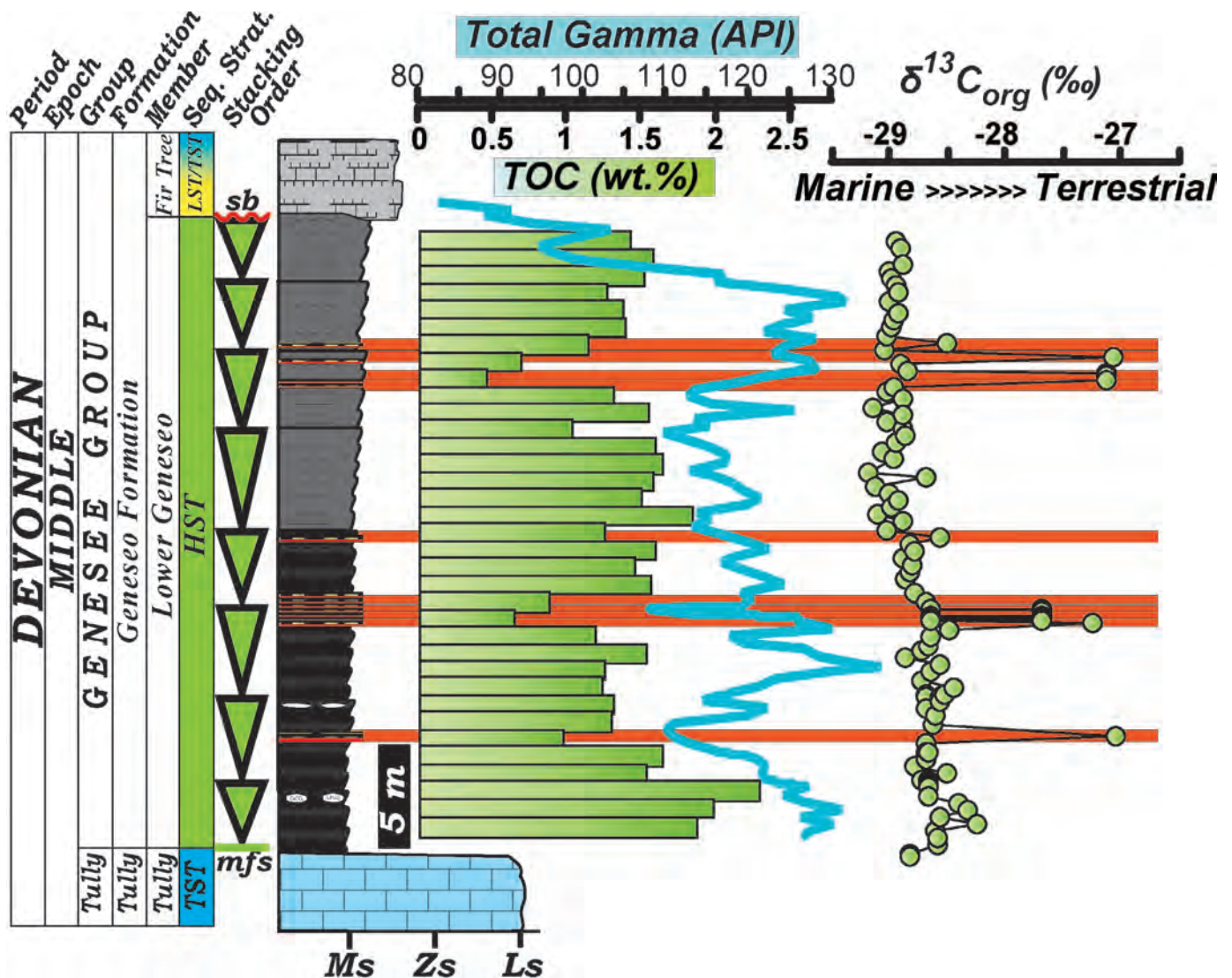


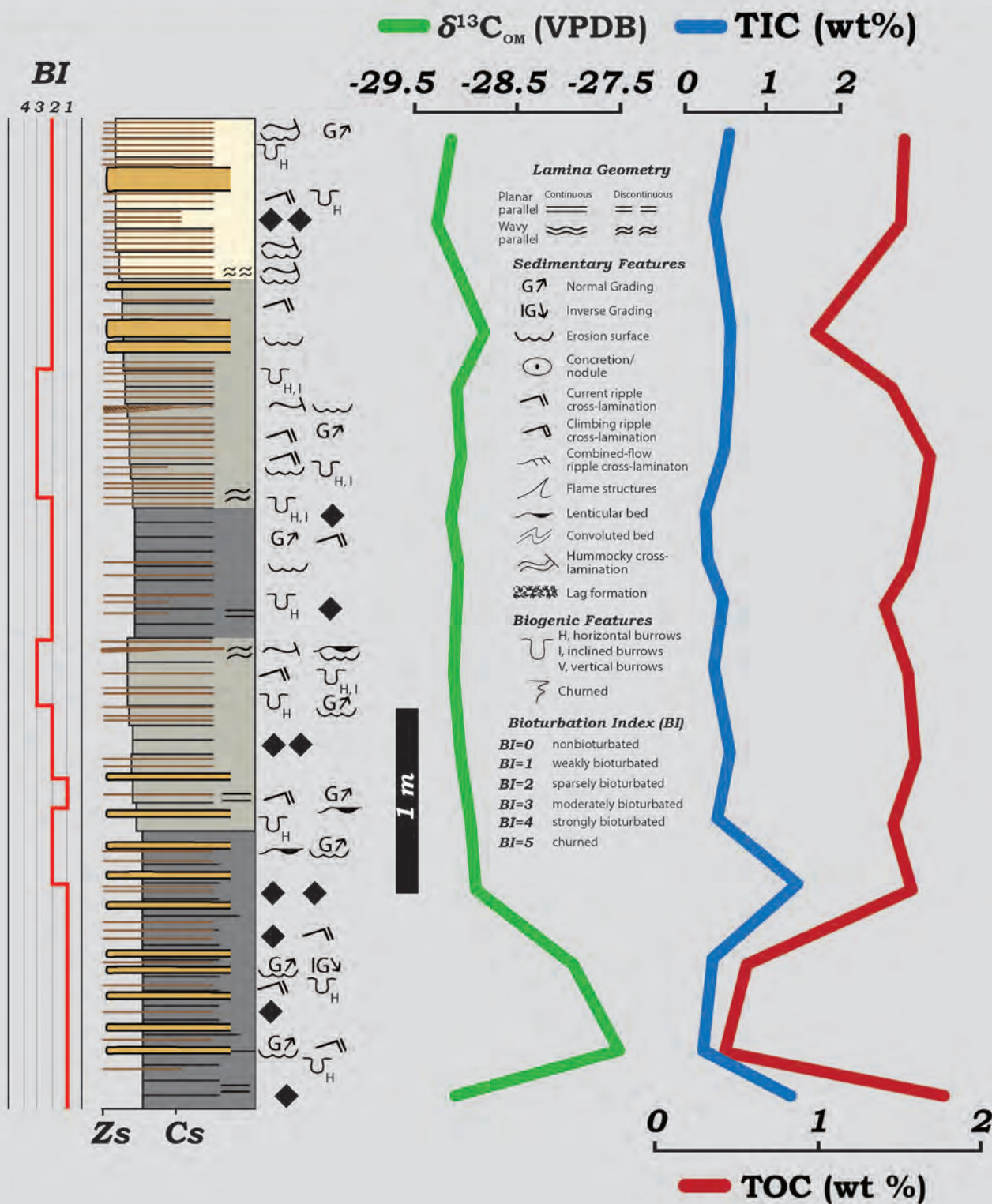
FIG. 9.—Detailed measured section (Ms, mudstone; Zs, siltstone; Ss, sandstone) of the Lower Genesee Member observed in a single drill core, including major sequence stratigraphic subdivisions (Seq. Strat.) and parasequence stacking patterns (upside-down triangle). Geochemical profiles shown include total-organic-carbon (TOC), the stable-carbon-isotope ratios of organic carbon ($\delta^{13}C_{org}$), and total sulfur (TS). Yellow horizontal lines highlight identified hyperpycnites in this drill core, showing decreased bioturbation intensity and trace-fossil diversity, normal and inverse lamina-set grading, internal scours, as well as current- and wave-formed features.

peak discharge are essential to generate the density contrast needed for the initiation of hyperpycnal flows (Mulder and Alexander 2001).

The XRF chemical profiles provide an independent perspective for sediment addition by hyperpycnal flows, and can thus assist in the recognition of hyperpycnal deposits in the absence of carbon-isotope data. This is particularly apparent in the bedload facies association (FA1) of interpreted hyperpycnites (Wilson and Schieber 2014), where the direct linkage to a terrestrial source of these sediments is reflected in increased Zr/Al and Ti/Al ratios. Higher values of these ratios suggest less heavy-mineral fractionation because of shorter transport and a ratio closer to source-area compositions (Nesbitt and Young 1982; Arz et al. 1998; Chen et al. 2013). Likewise, rivers are also the major source of Fe supply to the oceans, and their Fe/Al ratios reflect terrigenous sediment provenances (e.g., Lamy et al. 2000). The patterns observed in Figures 11 and 12 suggest that iron that was delivered as grain coatings of fluvial sediment (Glaser 1969; Shluger and Roberson 1975). Once these coatings dissolved,

Fe concentrations in pore waters rose, and due to sulfide production in associated carbonaceous muds, pyrite was precipitated into directly associated underlying and overlying strata (Fig. 11) or within porous portions of the hyperpycnite beds themselves (Fig. 12). That suspended-load portions of hyperpycnal intervals (FA 2) typically show diminished but otherwise consistent values of “detrital” element ratios (Figs. 11, 12) is to be expected, because of the common source for the bed-load and suspended-load component of typical hyperpycnites (Mulder and Alexander 2001; Bhattacharya and MacEachern 2009). Non-lithogenic particles of biologic origin are the main contributors of redox-sensitive trace elements to modern marine sediments (e.g., Nameroff et al. 2002), and in ancient strata these elements are typically associated with slowly deposited organic-rich mudstones (e.g., Jones and Manning 1994). These general principles are consistent with the observed low trace-metal values in rapidly deposited hyperpycnal intervals, and enrichment of trace metals in slowly accumulating organic-rich “background” mudstones.

Parasequence Expression



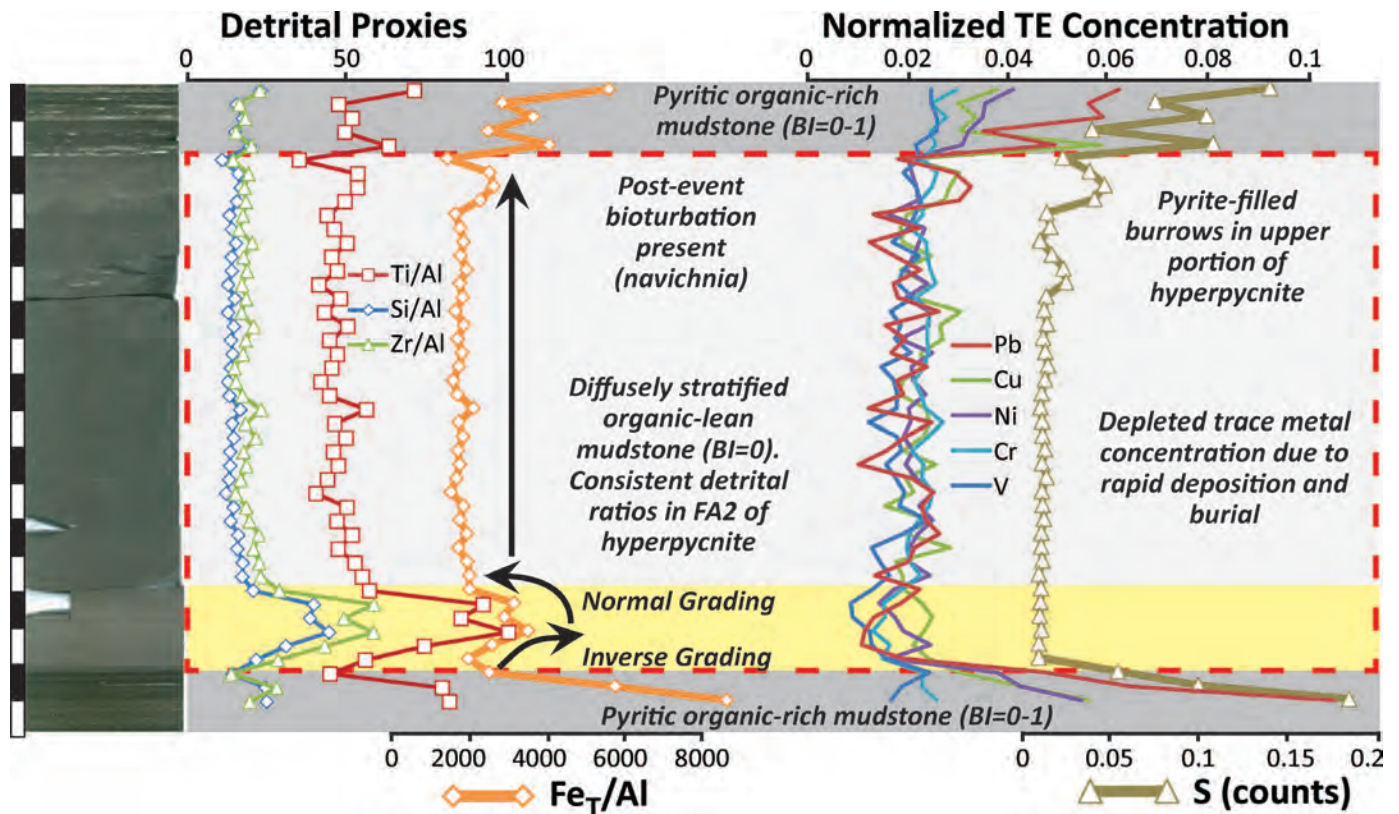


FIG. 11.—Elemental profiles for a hyperpycnal interval (red dashed box) interspersed within pyritic organic-rich mudstone facies ($BI = 0-1$), reflecting “background” sedimentation consisting of diffuse boundaries and continuous to discontinuous silt laminae (gray background). Note the small-scale inverse to normal lamina-set grading observed in the detrital fraction within the basal portion of hyperpycnite (FA1; yellow background). Above the bed-load portion of hyperpycnites, very consistent values are observed in elemental data representing fluidized muds (FA2; white background) with navichnia traces at the top of the deposit (post-event bioturbation). Redox-sensitive trace metals are elevated in the underlying and overlying pyrite-rich banded black mudstones. Each scale bar is 1 cm.

CONCLUSIONS

As shown for the Genesee Formation of New York, combining geochemical data with detailed facies characterization and stratigraphic observations can be a powerful tool for effective reconstruction of paleodepositional environments within fine-grained sedimentary successions. Understanding the nested cyclicity in organic-rich successions is critical for developing a robust sequence stratigraphic framework. Appreciating these relationships also facilitates the understanding of facies development, stacking patterns, and stratal architecture, important components when implementing a genetic framework for predictions away from data control. Moreover, the identification of multiple parasequences and parasequence-sets with characteristic stacking patterns, facies, facies associations, and stratal geometry can be combined into process-based models for depositional tracts.

Through the use of carbon-isotope geochemistry, punctuated river-flood- and storm-wave-generated offshore-directed underflows can be recognized due to the predominance of terrestrial phytodetritus. Additionally, rapid deposition of fluvial-sourced muds (silt-rich) is reflected in the elemental

data as an increase in the detrital proxies. Even normal and inverse grading can be discerned through these proxies, characteristics that are diagnostic of sustained hyperpycnal flows. Redox-sensitive trace-metal concentrations are significantly decreased when compared to what is considered background sedimentation (Fig. 11), due to rapid accumulation and a lack of labile organics to fuel microbial degradation and subsequent diagenetic cementation in the substrate. Post-event bioturbation appears to inflict ecologic stressors as recorded in decreased bioturbation intensity ($BI = 0-1$) and decreased trace-fossil diversity, consisting primarily of navichnia traces (mantle and swirl; Lobza and Schieber 1999). This is a product of hyperpycnal emplacement resulting in short-lived periods of salinity reduction during deposition (not typical of most conventional turbidites; Föllmi and Grimm 1990), and so may delay the initial post-event colonization of the resulting event bed. Further, these deposits preclude or inhibit certain ichnogenera observed in the slowly accumulating background organic-rich mudstones (i.e., *Chondrites*, *Helminthopsis*, and *Planolites*) that might otherwise be a component of the suite.

Though fluvial-discharge processes are sporadic, the present study illustrates the organization of these events in a sequence-stratigraphic

FIG. 10.—Parasequence expression illustrating physical features, bioturbation index (BI), carbonate percent (TIC), total-organic-carbon content (TOC), and carbon isotope values of organic matter ($\delta^{13}C_{OM}$). Note basal portion of parasequence showing decreased bioturbation intensity and trace-fossil diversity, as well as less negative carbon-isotope values due to the presence of current-aided hyperpycnal flows with terrestrial phytodetritus.

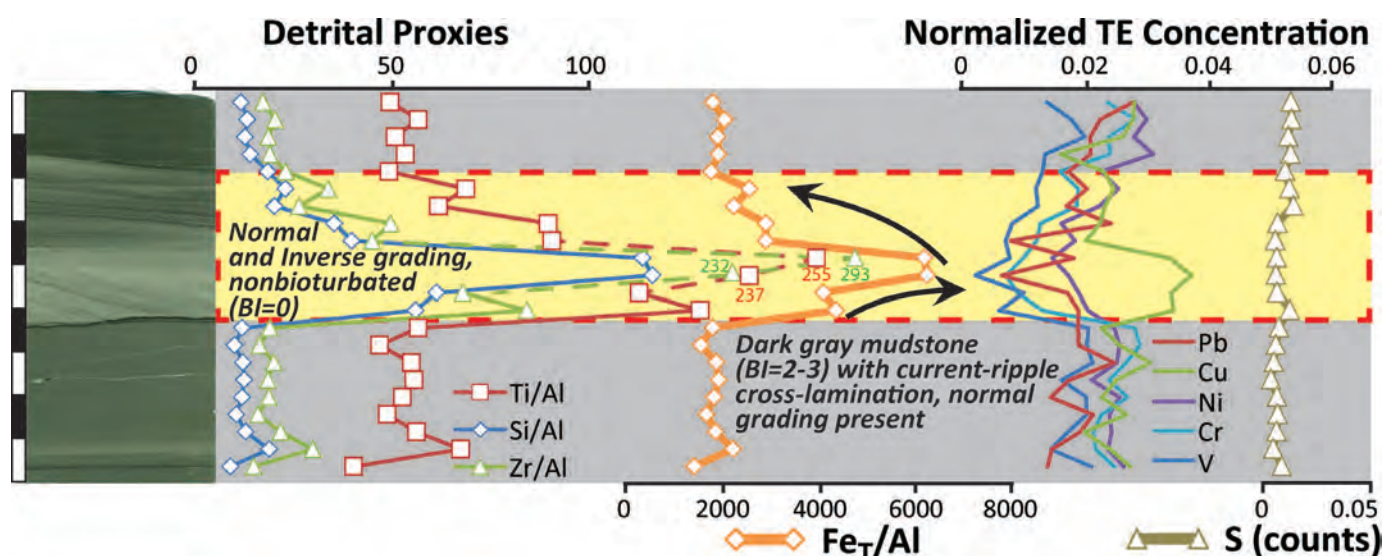


Fig. 12.—Elemental profiles for a hyperpycnal interval (BI = 0; red dashed box) interspersed within sparsely to weakly bioturbated (BI = 2–3) dark gray mudstones with current-ripple lamination and normal grading reflecting background sedimentation (gray background). Note the small-scale inverse to normal lamina-set grading and high-angle cross-lamination observed in the detrital fraction in the basal portion of hyperpycnite (FA1, yellow background). Each scale bar is 1 cm.

framework, wherein initial flooding may have facilitated the erosion of exposed continental soils and weathered products. Combined with major storms, high-concentration fluvial injections occurred throughout the Catskill delta, interrupting deposition of distal organic-rich sediments. The presence of hummocky cross-lamination and combined-flow ripples indicates that these flows were sustained above storm-wave base, and the high degree of lateral continuity of the deposits suggests that they were wave-aided and distributed as unconfined flows.

The illustrated analytical approach provides us with an understanding of depositional processes that accounts for the variability observed in this succession, and we propose that this methodology can be effectively applied to other mudstone-rich strata that may have been subject to hyperpycnal sediment inputs, in order to detect presence, distribution, and dispersal patterns of the hyperpycnal component.

ACKNOWLEDGMENTS

The authors are grateful to external reviewers Carlos Zavala and Piret Plink-Björklund for their critiques and suggestions which greatly improved the manuscript. We are especially indebted to associate editor James MacEachern for his detailed commentary regarding ichnogenes observed and relationships in bioturbation associated with wave- and current-aided hyperpycnal flows. We recognize the sponsors of the Indiana University Shale Research Consortium, which provided student support. Field work and analytical supplies were supported through student research grants awarded to Ryan D. Wilson 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).

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Received 25 April 2017; accepted 2 September 2017.