Reprint of a manuscript published in Journal of Sedimentary Research, v. 85, p. 1393-1415 (2015)

Sedimentary Facies and Depositional Environment of the Middle Devonian Geneseo Formation of New York, USA

by
Ryan D. Wilson and Juergen Schieber

Department of Geological Sciences, Indiana University, Bloomington, Indiana 47405, U.S.A.
e-mail: RyanWilson@chevron.com

ABSTRACT
Detailed facies characterization of the Middle Devonian Geneseo Formation in the Northern Appalachian Basin (NAB) has revealed a rich assembly of sedimentary features and textures that suggest shelfal mud deposition in a storm-dominated, shallow epeiric sea. At the time of deposition, Acadian uplift supplied fine-grained detritus from the east and stimulated delta growth. As sediment was shed from the hinterland, autogenic processes coupled with a general rise in sea-level significantly controlled the distribution of mudstone facies.

The vertical assemblage and lateral distribution of nine mudstone facies observed in this succession indicates an overall shallowing-upwards trend (westward progradation of Catskill delta) with multiple modes of sediment transport and deposition. That the water-column became more oxygenated upsection is indicated by an increase in benthic fauna diversity (e.g., Leiorhynchus and Orbiculoides), increasing bioturbation diversity (e.g., Chondrites, Paleophycus, Planolites, Teichichnus, Thalassinoides, and Zoophycus), and a decline of organic-carbon content (via oxidation and consumption). Physical and biological attributes of this mudstone-dominated succession are used to reconstruct sedimentary processes and depositional conditions.

Although a stratified-basin model has been proposed previously for the Geneseo formation, observations made in this study do not support that interpretation. Collectively, our observations indicate shelfal mud-deposition above storm-wave base, in a relatively energetic environment with persistent lateral transport and advection by oscillatory flow, wave-induced currents, river-flood and storm-wave generated offshore-directed underflows, as well as storm setup relaxation flows.

INTRODUCTION

Characterization of mudstone-dominated systems has undergone a paradigm shift with recent advances in experimental sedimentology (Schieber, 2011; Schieber and Southard, 2009; Schieber et al., 2010; Schieber et al., 2007; Schieber and Yawar, 2009) and observations of modern muddy shelves (Allison and Nittrouer 1998; Macquaker et al. 2010; Rine and Ginsburg 1985). Flume experiments have demonstrated that even at flow velocities that transport fine and medium sand, fine-grained sediments (i.e., particles with diameter <62.5 μm) are prone to flocculate and accumulate in bed-load as migrating ripples (Schieber et al., 2007; Schieber, 2011).

Fine-grained sedimentary rocks (i.e., 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 (e.g., Passey et al. 2010). The fine-grained nature of mudstones has long nurtured the assumption that any significant turbulence in overlying waters would re-suspend accumulating muds and prevent their re-deposition (Potter et al., 1980; Stow et al., 2001). Likewise, that mudstones are apparently 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, 1988). The vast majority of sedimentologists find it a difficult task to describe mudstones that they encounter in the field or in drill core, often utilizing crude descriptors such as "black organic-rich mudstone", "undifferentiated mudstone", or "fissile shale". In addition, much of the terminology used to classify mudstones is based on weathering or compaction characteristics (e.g., fissility, color).

This study provides a detailed investigation of a presumed "anoxic" black shale succession (Baird and Brett, 1986, 1991; Formolo and Lyons, 2004) in order to present observation-based inferences of the dynamic nature of Geneseo deposition. Conceptualized facies distinctions are illustrated to provide a template for future evaluations of similar mudstone successions.

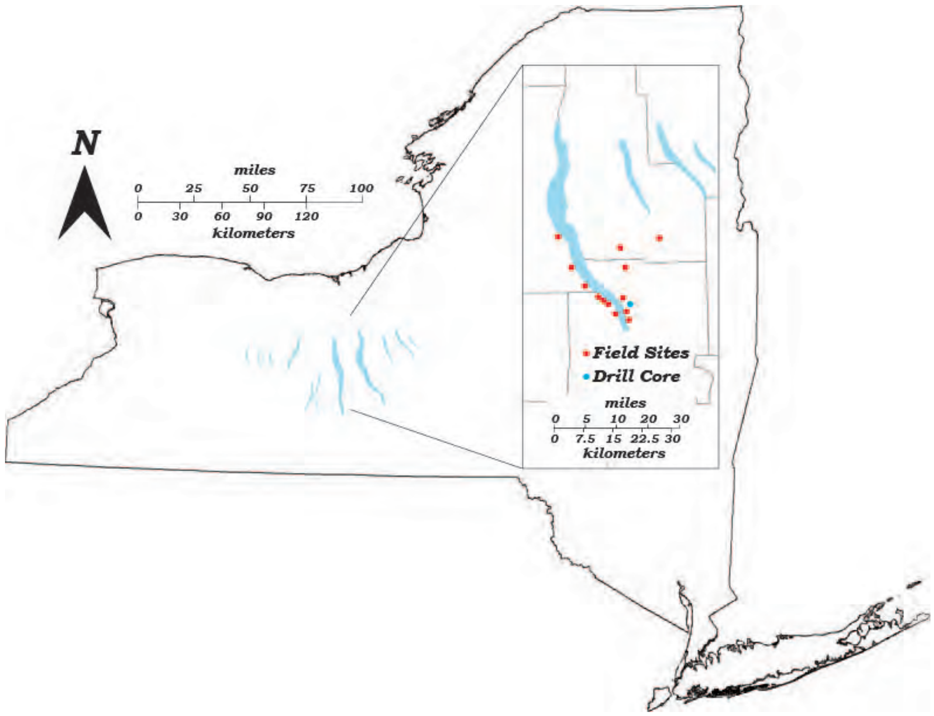

FIG. 1.—Overview map of New York and locations of outcrops and drill core (with locations of Figure 2 cross section; SHB, Sherburne; ITH, Ithaca; CAN, Canandaigua; GEN, Geneseo; BUF, Buffalo).

SAMPLING AND METHODS

This study focuses on surface exposures and a drill core in central New York (Fig. 1). Lithostratigraphic descriptions including physical and biological attributes were recorded at each locality using the methodology of Lazar et al. (2015). Samples from these localities were stabilized with epoxy resin and thin-sectioned (thickness 20–25 mm). 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.

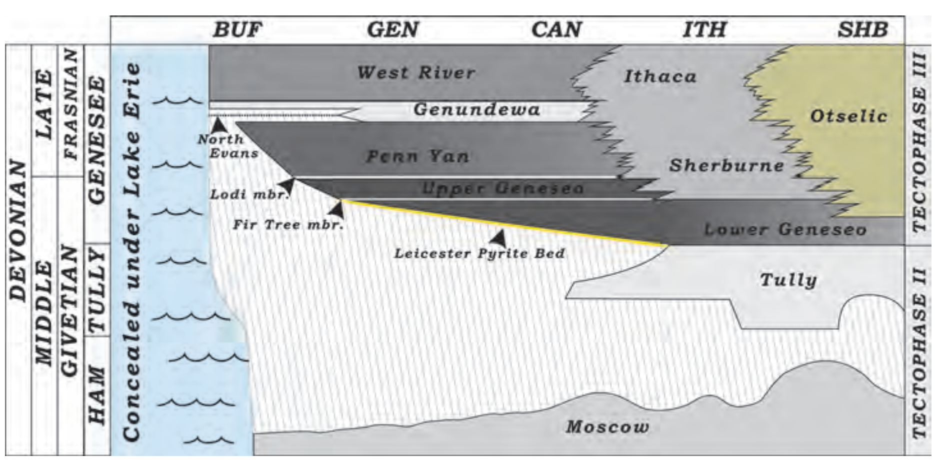

FIG. 2.—Generalized chronostratigraphic chart for Middle–Late Devonian strata of New York (SHB, Sherburne; ITH, Ithaca; CAN, Canandaigua; GEN, Geneseo; BUF, Buffalo; HAM, Hamilton Group). The Geneseo Formation marks the onset of the third tectophase of the Acadian Orogeny (Ettensohn 1987), the most pronounced thrust loading event of that orogeny. The Genesee Group onlaps the Taghanic disconformity westward; thus, the basal ages of the onlapping Geneseo 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.

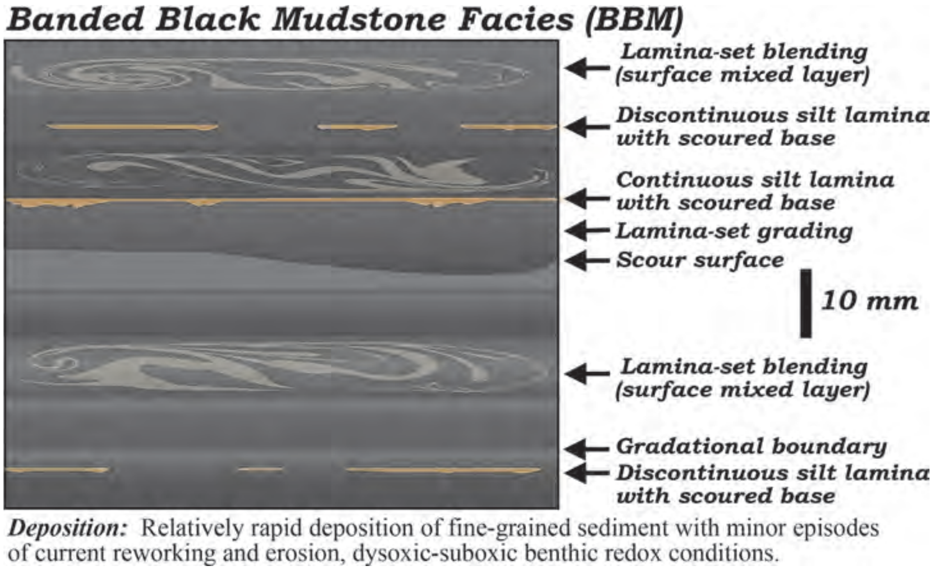

FIG. 3.—Line drawing of Banded Black Mudstone (BBM) facies detailing sedimentary features observed.

GEOLOGICAL BACKGROUND OF THE GENESEO FORMATION

Although organic-rich fine-grained deposits occur throughout earth history, there are discrete time intervals when they are more abundant. Deposition of such strata coincides with times of global sea-level rise, greenhouse climate with elevated atmospheric $p\mathrm{CO_2}$, and active volcanism (Fischer 1981). Although there are well documented glacial deposits from the latest Famennian of South America and possibly eastern North America (Isaacson and Diaz-Martinez 1995; Isaacson et al. 1999), the greater part of the Devonian supposedly reflects “greenhouse” conditions (Fischer 1981).

The Geneseo Formation was deposited during the third tectophase of the Acadian orogeny, which resulted from a continent (Laurentia)–microcontinent (Avalonia) collision (Ettensohn 1985). This collision was accompanied by magmatic-arc volcanism and formation of a retroarc fold and thrust belt (i.e., Hudson Valley Fold and Thrust Belt) that loaded the eastern edge of the North American craton. Tectonic loading produced a retroarc foreland basin that was the primary depocenter for clastics shed from the orogen (Ettensohn 1985, 1987; Faill 1985), and occurred simultaneously with a eustatic sea-level rise that is known as the Taghanic Onlap (Johnson 1970). Delta expansion, fueled by the detritus that the Acadian uplift supplied from the east, is expressed as progradational stacking patterns in the clastic wedge known as the Catskill deltaic complex.

During Middle to Late Devonian time the Northern Appalachian Basin (NAB) was located approximately 30°–35° south of the equator (Witzke and Heckel 1988). Greenhouse conditions with approximately 4–12 times present-day $p\mathrm{CO_2}$ are thought to have prevailed (Berner 1990). Environmental conditions for the NAB at this time were seasonally variable and arid to semiarid (Witzke and Heckel 1988; Woodrow 1985), and thus this region should have been extensively affected by tropical storms, a perspective that is supported by evidence for storm-influenced sedimentation throughout the NAB, such as widespread tempestites and erosional contacts (Brett et al. 2003; Miller et al. 1988; Schieber 1994, 1998). Continental flooding in association with limited water circulation has been a key component in many depositional models for Devonian organic-rich mudstones in the Appalachian Basin (Algeo et al. 2007; Murphy et al. 2000a; Sageman et al. 2003; Werne et al. 2002). In Middle to Late Devonian strata of the eastern U.S., distinct transgressive–regressive packages have been identified and correlated with global sea-level fluctuations (Brett and Baird 1996; Brett et al. 2011; Johnson et al. 1985).

Lack of surface exposure combined with lateral and vertical complexity in mudstone facies has made characterization of the internal lithostratigraphy of the Geneseo Formation (Brett and Baird 1996; Brett et al. 2011) a complicated task and has led many workers to underestimate the rate of stratal thickening and has hampered the assessment of depositional setting (Baird and Brett 1986; Baird et al. 1988; de Witt and Colton 1978; Williams 1951; Kirchgasser 1985). Whereas previous studies characterize the Geneseo Formation as a monotonous succession of nonbioturbated, finely laminated, organic-rich shale (Baird and Brett 1986; Baird et al. 1988; Brett and Baird 1996, Murphy et al. 2000b; Sageman et al. 2003; Ver Straeten et al. 2011), our detailed examination shows that most of the succession consists of weakly to sparsely bioturbated organic-rich mudstone with primary sedimentary features that formed as a result of unidirectional and/or oscillatory flow, and show multiple modes of sediment transport and deposition. Additionally, event sedimentation, as opposed to continuous deposition, is abundantly expressed through the presence of normal and inverse grading, erosional scours and truncation, as well as through post-event biogenic modification of the seabed. Bioturbation is typically expressed as top-down, and commonly consisting of more opportunistic forms (i.e., *Chondrites*, *Phycosiphon*, *Planolites*) and sediment swimming behaviors in soupy substrates (i.e., navichnia). Escape traces are also present at the bases of event deposits.

Various scenarios have been proposed for the amount and the rate at which organic material can be concentrated and preserved in mudstones. These include the lack of sufficient dissolved O_2 in the water column to prevent destruction via oxidation (Demaison and Moore 1980), enhanced primary productivity in the surface water to regulate the flux of organic matter to the sea floor (Pederson and Calvert 1990), and reduced influx of clastic sediment. The latter may actually be the main factor that controls organic matter abundance (Bohacs et al. 2005; Sageman et al. 2003).

In this study, three members are differentiated in the Geneseo Formation, spanning two depositional sequences, and nine distinct mudstone facies that have been linked to depositional environment (Fig. 2). A common argument for organic-matter preservation in Devonian mudstones of the NAB is that sedimentation could not keep pace with rapid subsidence and deepening of the water column during a tectonic event, that the basin became chemically and thermally stratified, and this allowed organic-matter enrichment under anoxic-euxinic conditions (Baird and Brett 1986, 1991; Ettensohn 1985, 1987; Ettensohn et al. 1988). In previous studies it has been argued that density stratification through establishment of a halocline (Baird and Brett 1986) and/or seasonal stratification (Murphy et al. 2000a, 2000b) were chief factors that contributed to organic-matter enrichment. Observations from this study do not support the assumption of a permanently

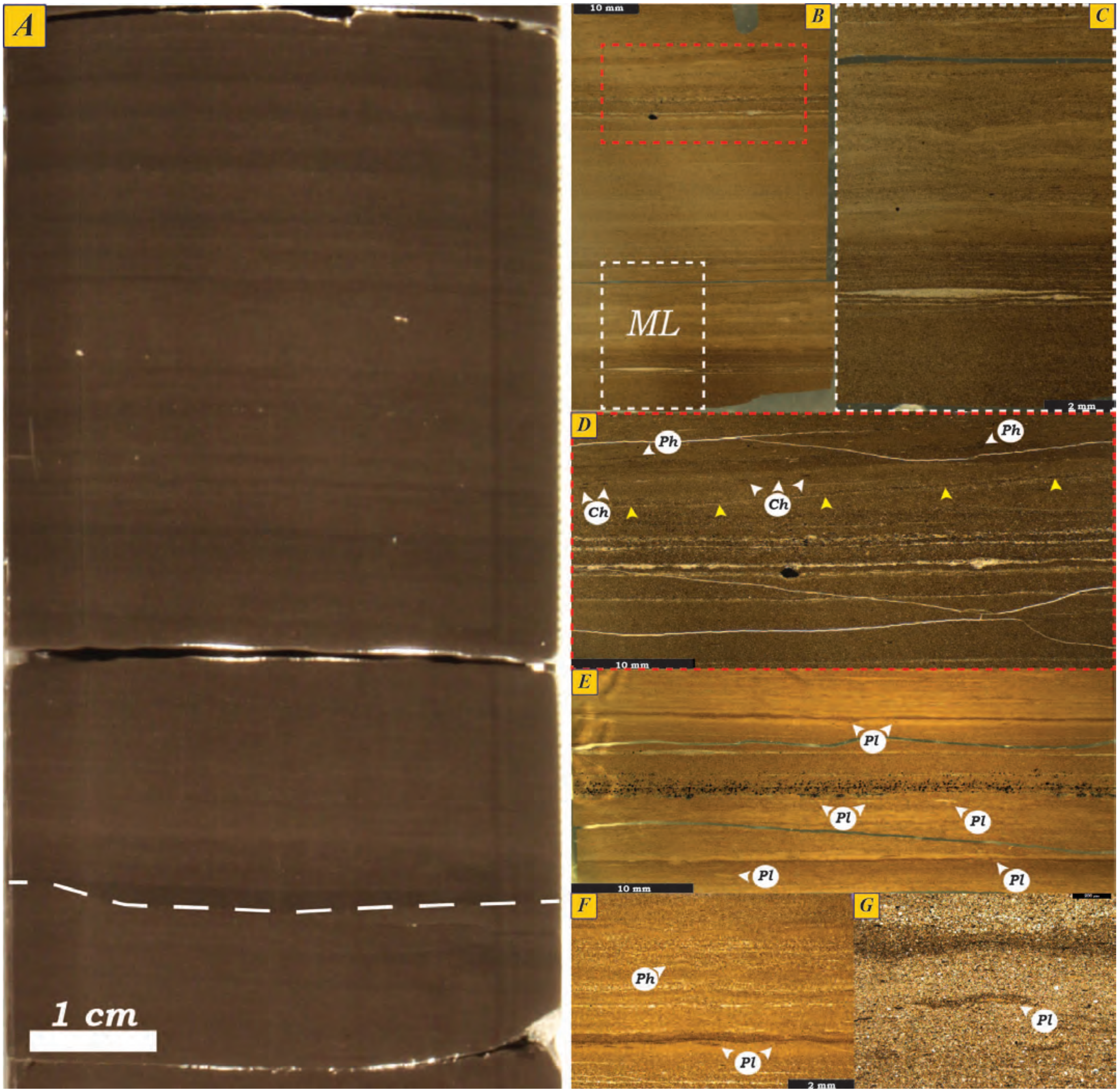

FIG. 4.—**A)** Image of polished hand sample (contrast enhanced) of the BBM facies, showing a subtle erosional scour infilled with darker muds (dashed line). Note the predominant light and dark horizontal layering with diffuse boundaries. The alternating light and dark layers are interpreted to reflect fluctuating intensity of bioturbation produced by very shallow burrowing meiofauna and surface grazing organisms such as polychaetes and nematodes. **B)** Overview image of thin section with continuous to discontinuous, planar parallel silt lamina and lamina-sets with scoured bases, and meioturbation (ML). **C)** Discontinuous silt lenses with scoured bases, with overlying gradational contacts, subtle bioturbate texture, and diffuse bed boundaries, indicating development of a surface mixed layer (ML). **D)** Overview image of thin section with continuous silt lamina–lamina-sets with basal scours. Note sub-millimeter scale *Chondrites* (*Ch*) and *Phycosiphon* (*Ph*) burrows. **E)** Overview image of thin section that shows diffuse bed boundaries and alternating light and dark bands with *Planolites* (*Pl*) burrows and abundant meioturbation. **F)** Photomicrograph showing mixed layer fabrics (BI = 2–3), disrupted silt lamina, and *Phycosiphon* (*Ph*) and *Planolites* (*Pl*) burrows. **G)** Enlarged view of *Planolites* (*Pl*) burrow with fecal pellet.

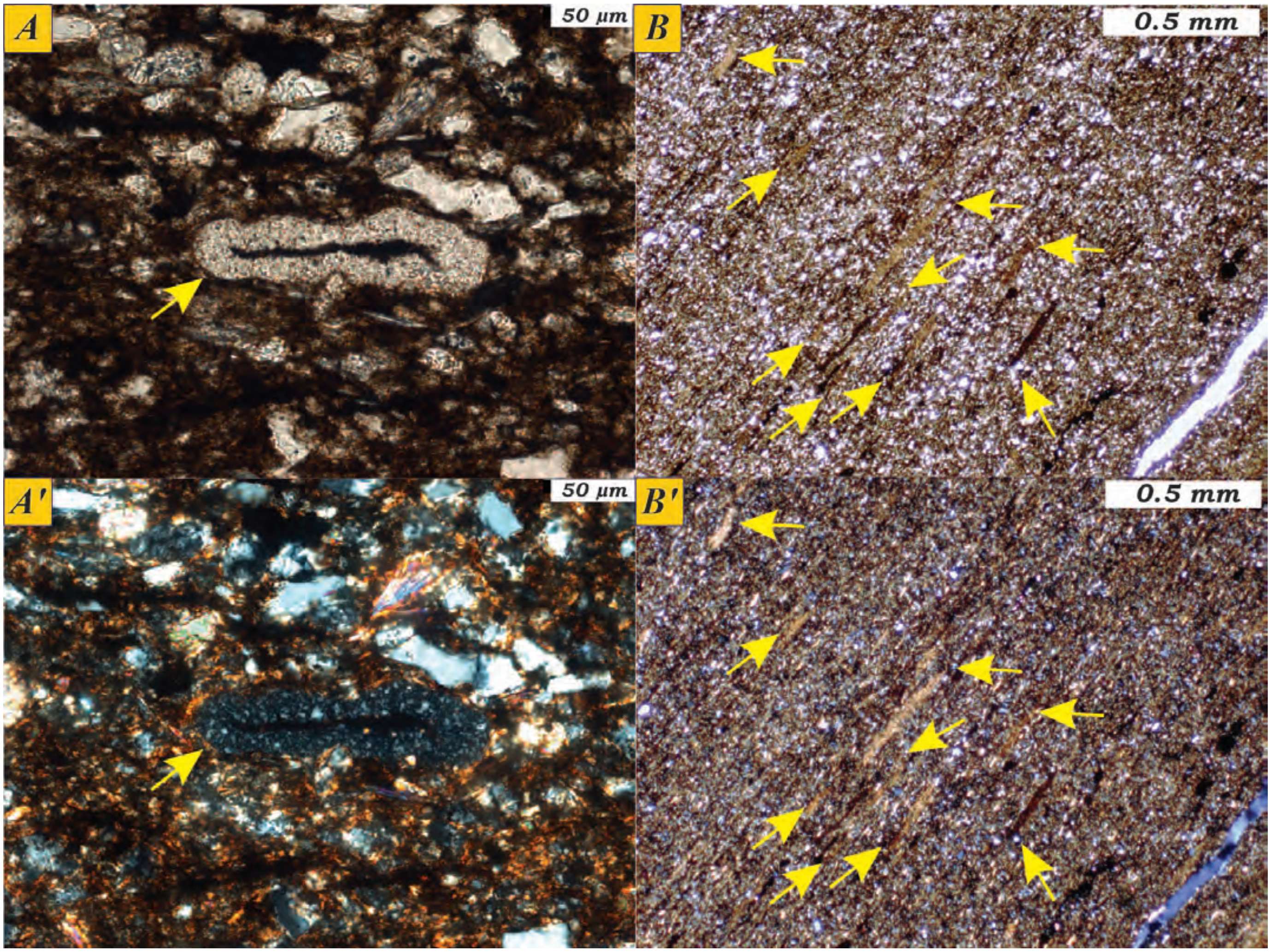

FIG. 5.—**A)** Photomicrograph showing agglutinated benthic foraminifera (yellow arrow) with partial internal fill that prevented complete collapse (plane-polarized light). Foraminifera are eukaryotic organisms, and as such require some oxygen to persist (Schieber 2012). They are very common in the Geneseo Formation, and are distinguished by the fact that they consist of an assemblage of detrital quartz grains typically smaller than 10 μm. **A′)** The same image in cross-polarized light. The foraminifera consists of tiny gray birefringent quartz grains. **B**, **B′)** Scattered benthic fecal pellets in the mudstone matrix (plane and cross-polarized light, rotated 45°). The pellets (yellow arrows) are flattened by compaction, and consist of a mixture of silt and clays that were ingested by sediment-feeding organisms. The presence of benthic life is confirmed by the common presence of benthic fecal pellets and benthic agglutinated foraminifera in these strata.

stratified water column, although seasonal stratification and marine algal blooms may have contributed to the richness in organics of this succession (up to 3 wt. % in study area). In the following paragraphs we present descriptions of Geneseo mudstone facies types, followed in each case by an assessment of what the observations tell us about depositional conditions for a given facies.

RESULTS

DESCRIPTION AND INTERPRETATION OF MUDSTONE LITHOFACIES: LOWER GENESEO MEMBER

Banded Black Mudstone (BBM) Facies

The banded black mudstone (BBM) facies is the most common facies type in the Lower Geneseo member, and is expressed as a grayish-black, weakly calcareous mudstone with distinct horizontal banding, scour surfaces, current-ripple cross-lamination, normal grading, and irregular horizontal disruption of bedding interpreted as cryptic bioturbation (Fig. 3). Cryptic bioturbation is indicated by diffuse bed boundaries between successive layers of a few millimeters thickness, and also by disrupted laminae (Fig. 4). This facies is weakly to moderately bioturbated (BI = 1–3), and shows low trace-fossil diversity, consisting mainly of sessile deposit-feeding and surface-grazing benthonic organisms (i.e., meioturbation, *Chondrites*, *Helminthopsis*, *Planolites*, *Phycosiphon*). Benthic fecal pellets and agglutinated benthic foraminifera are abundantly observed in the BBM facies (Fig. 5).

Interpretation of BBM Facies

The BBM facies reflects overall low clastic input in a distal shelf setting, with deposition occurring rapidly and episodically as mud blankets from storm-wave-induced currents. Mixing of the surficial sediment and of surficial layer boundaries by shallow burrowing benthic organisms, such as small polychaetes or nematodes (Boudreau 1998; Goldring 1995; Löhr and Kennedy 2015; Pemberton et al. 2008; Richardson et al. 1985; Uchman et al. 2008; Wheatcroft et al. 1989), was probably an important factor in facies development. Benthic redox conditions during deposition probably varied from

FIG. 6.—Carbonate concretions in the Geneseo Formation in **A)** the Cayuga Crushed Stone Quarry and **B)** the Blackchin Railroad cut (arrow points to hammer for scale).

suboxic to dysoxic (Tyson and Pearson 1991), as indicated by surficial meiofaunal mixing (e.g., by small polychaetes, nematodes, benthic foraminifera), benthic fecal pellets, and agglutinated benthic foraminifera (Figs. 4, 5). This style of surficial sediment mixing has been described in detail by authors such as Löhr and Kennedy (2015) and Pemberton et al. (2008), where small polychaetes and nematodes (only a few millimeters in length) disturb the fabric of the surface sediment sufficiently to "blend" sharp boundaries between depositional episodes. This phenomenon of meiofaunal blending also occurs in muds (Cullen 1973; Pike et al. 2001; Riemann and Schrage 1978; Schieber 2003), and is referred to herein as meioturbation. Its recognition is greatly aided by examination of polished rock surfaces and thin sections.

The shallow nature of the redox gradient that is suggested by meiofaunal reworking in the case of gradational layer boundaries (Fig. 3) is perhaps a consequence of an abundant supply of labile organic material, exhausting the supply of dissolved oxygen to the sediment. These conditions favored surface population by diminutive benthic organisms, which blended the primary sedimentary fabrics of water-rich surface muds. Because these organisms colonized a very watery substrate and were able to penetrate only to a shallow depth in the sediment ($<$ 1 cm; Bernhard et al. 2003), they did not produce large macro-burrows that remained visible after burial and compaction of sediments. Instead, the mixing of surface layer boundaries reduced primary lamina contrast (Goldring 1995). The mean thickness for the surface-mixed layer in stable oceanic environments has been estimated to be in the range of 9.8 ± 4.5 cm (Boudreau 1998), and has been related to flux of organic matter to the sea floor (Trauth et al. 1997). In the Geneseo Formation, meioturbation, though subtle, may have pervasively destroyed primary sedimentary features in the horizontal plane, and generated mm- to cm-thick horizontal "bands" of discrete composition that are easily misinterpreted as primary depositional lamination or stratification.

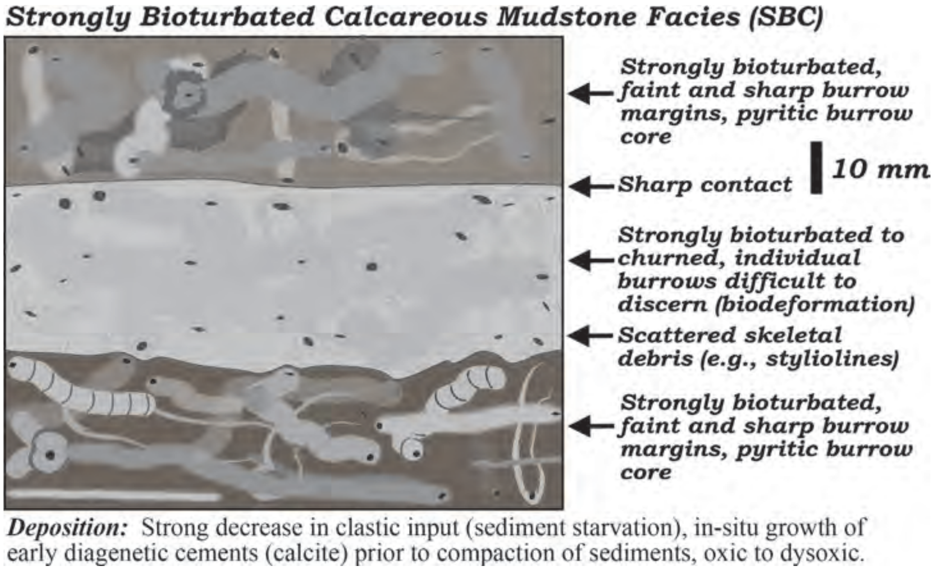

FIG. 7.—Line drawing of Strongly Bioturbated Calcareous Mudstone (SBC) facies detailing sedimentary features observed.

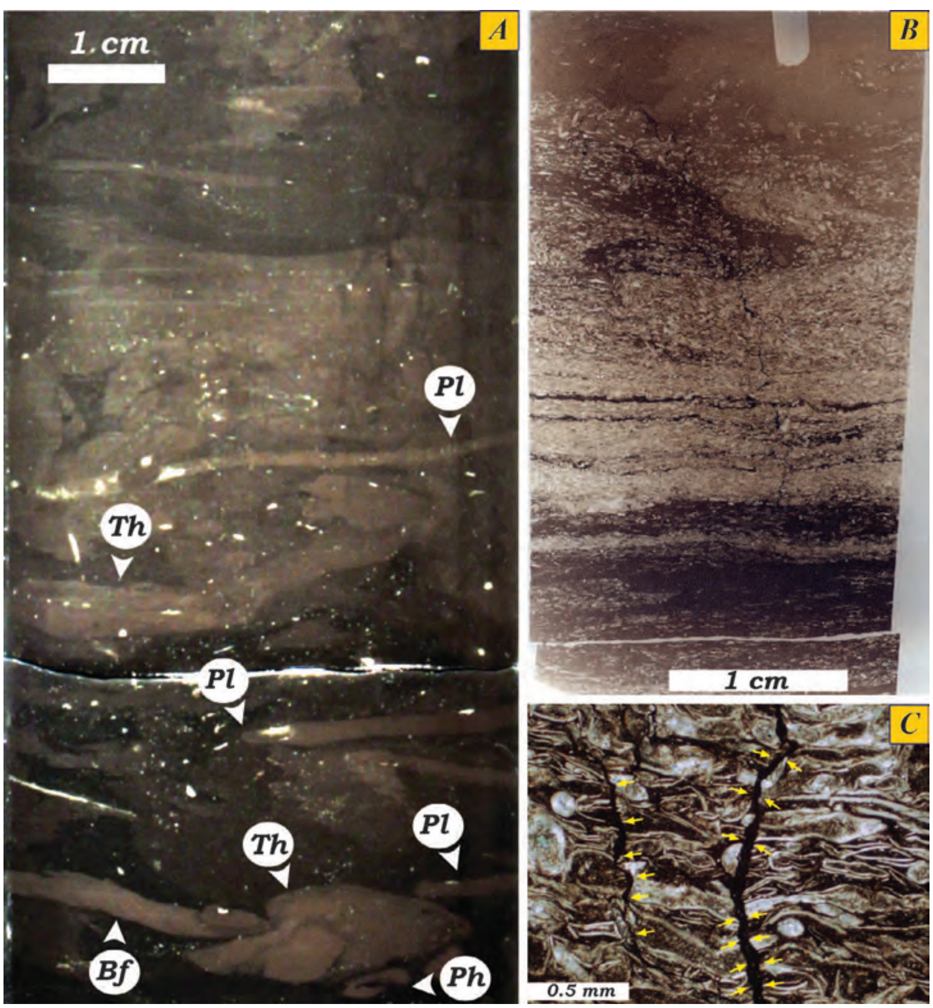

FIG. 8.—**A)** Hand-sample image (contrast enhanced) of the SBC facies, showing several generations of large horizontal, inclined, and vertical burrows with faint margins and pyritic cores. Bioturbation has obliterated primary depositional fabric and structures, and consists of a suite of backfilled meniscate burrows (*Bf*), *Planolites* (*Pl*), *Phycosiphon* (*Ph*), and *Thalassinoides* (*Th*). Bioturbation intensity (BI = 4–5) increases upwards. **B)** This facies is enriched with styliolinids that are commonly cemented. **C)** Enlarged portion of thin section showing concentration of styliolinid shell material. Note pressure-solution features (arrows), indicating significant horizontal pressure during burial.

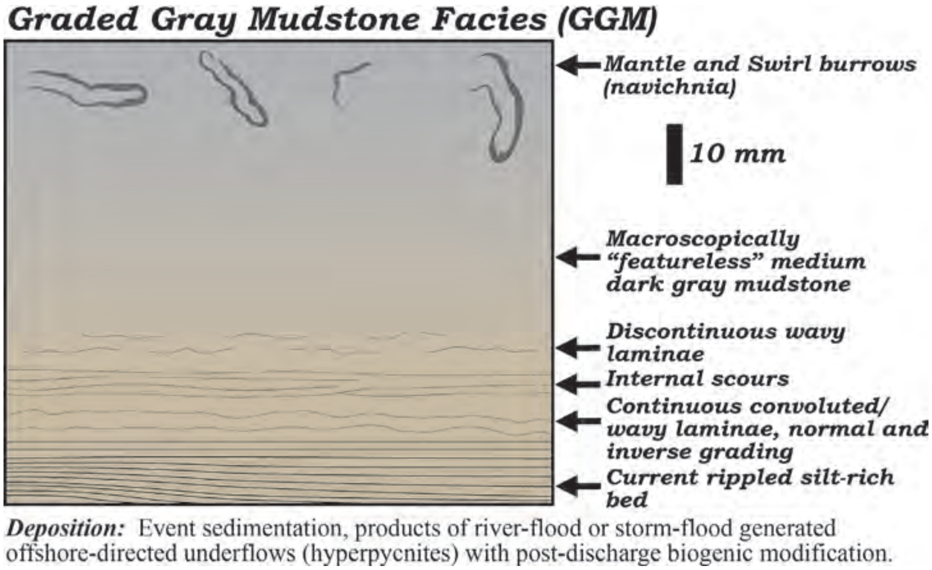

FIG. 9.—Line drawing of Graded Gray Mudstone (GGM) facies detailing sedimentary features observed.

Erosional features are present throughout this facies and can be recognized by thin continuous to discontinuous on lapping silt laminae, sharp irregular contacts, or thin continuous to discontinuous planar parallel silt laminae with irregular scoured bases (Fig. 4). Diagenetic overprints may also play a critical role in producing compositional banding, as many layers contain variable amounts of authigenic interstitial iron sulfides.

Strongly Bioturbated Calcareous Mudstone (SBC) Facies

The Lower Geneseo member contains multiple horizons of carbonate concretions (Fig. 6). Concretions of more than 40 cm in diameter have been observed, and in many places coalesce and form continuous beds. The SBC facies mudstones are brownish dark gray to brownish gray, and contain multiple generations of large horizontal, vertical, and inclined burrows, such as *Planolites*, *Phycosyphon*, and *Thalassinoides*. These burrows may show excellently preserved meniscate backfills, faint margins, and pyritic cores (Figs. 7, 8). An increase in bioturbation intensity (BI = 4–5) and diversity is observed. Cricoconarids (i.e., *Styliolina*) can be observed scattered or aligned into variably cemented shell hash beds throughout this facies (Fig. 8).

Interpretation of SBC Facies

The SBC facies records pauses in sedimentation that facilitate *in situ* precipitation of microbially mediated pore-filling carbonate cements. The abundance of styliolinid material throughout the matrix and its concentration into winnowed lags indicates that detrital input was significantly reduced, allowing pelagic "rain-out" to become enriched in the sediment. Exceptional preservation of uncompacted burrows and biodeformation suggests that cementation occurred early in depositional history, prior to burial and dewatering of sediments. Slower accumulation rates and an intermittently semi-stationary sediment–water interface allowed microbially driven carbonate precipitation (Brett and Allison 1998) to visibly contribute to the rock fabric. The presence of vertical, inclined, and horizontal burrows with multiple generations of bioturbation demonstrates the condensed nature of this interval (Brett and Allison 1998), with benthic redox conditions varying from oxic to dysoxic. The pyrite fill within burrow tubes imply that an organic slime was part of the burrow fill and formed a favorable substrate for sulfate reducing bacteria (Schieber 2002), or simply that fecal matter in the burrow fill provided a reducing micro-environment that favored sulfide precipitation. The presence of pyrite burrow tubes and pore-filling carbonate cements suggests a complex diagenetic overprint. Their early cemented large vertical, inclined, and horizontal burrows reflect a water-rich substrate of ~ 70% water content (Lobza and Schieber 1999).

Graded Gray Mudstone (GGM) Facies

The GGM facies is the most complex facies observed, in its physical expression as well as its vertical and lateral variability. The base of the GGM facies intervals is marked by a sharp erosional contact, and can contain planar parallel to current-ripple cross-lamination with internal scours, normal and inverse grading, diffuse boundaries, soft-sediment deformation (convoluted beds), and a reduction in bioturbation intensity (BI = 0–3) and diversity (Figs. 9, 10). This facies varies in thickness from 1 to 15 cm and shows a significant decrease in bioturbation intensity and diversity with respect to other mudstone facies identified. Where present, bioturbation occurs at the top of the interval (up to BI = 3), consisting principally of navichnia traces (mantle and swirl; Lobza and Schieber 1999) and appears top-down. Burrows commonly have irregular boundaries and a pyritic lining.

Interpretation of GGM Facies

On the basis of sedimentary features, texture, composition, and vertical and lateral distribution, the GGM facies appears to depict rapid deposition of high-density fluvial discharge events, producing turbulent flows that carried fine-grained detritus as offshore-directed underflows (Wilson and Schieber 2014). Thus, this facies reflects mud dispersal across and along the shelf from potentially wave-aided hyperpycnal plumes.

Sedimentary features associated with such transport include 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 a turbulent flow with waxing and waning currents (Bhattacharya and MacEachern 2009). The lateral and vertical variability records the inconsistent and chaotic nature of fluvial discharge events. The bioturbation present in the upper portions of these intervals reflects post-discharge biogenic modification by opportunistic forms.

Pyritic Black Mudstone (PBM) Facies

The pyritic black mudstone (PBM) facies is intimately associated with the GGM facies, in that it is solely observed overlying the products of fluvial

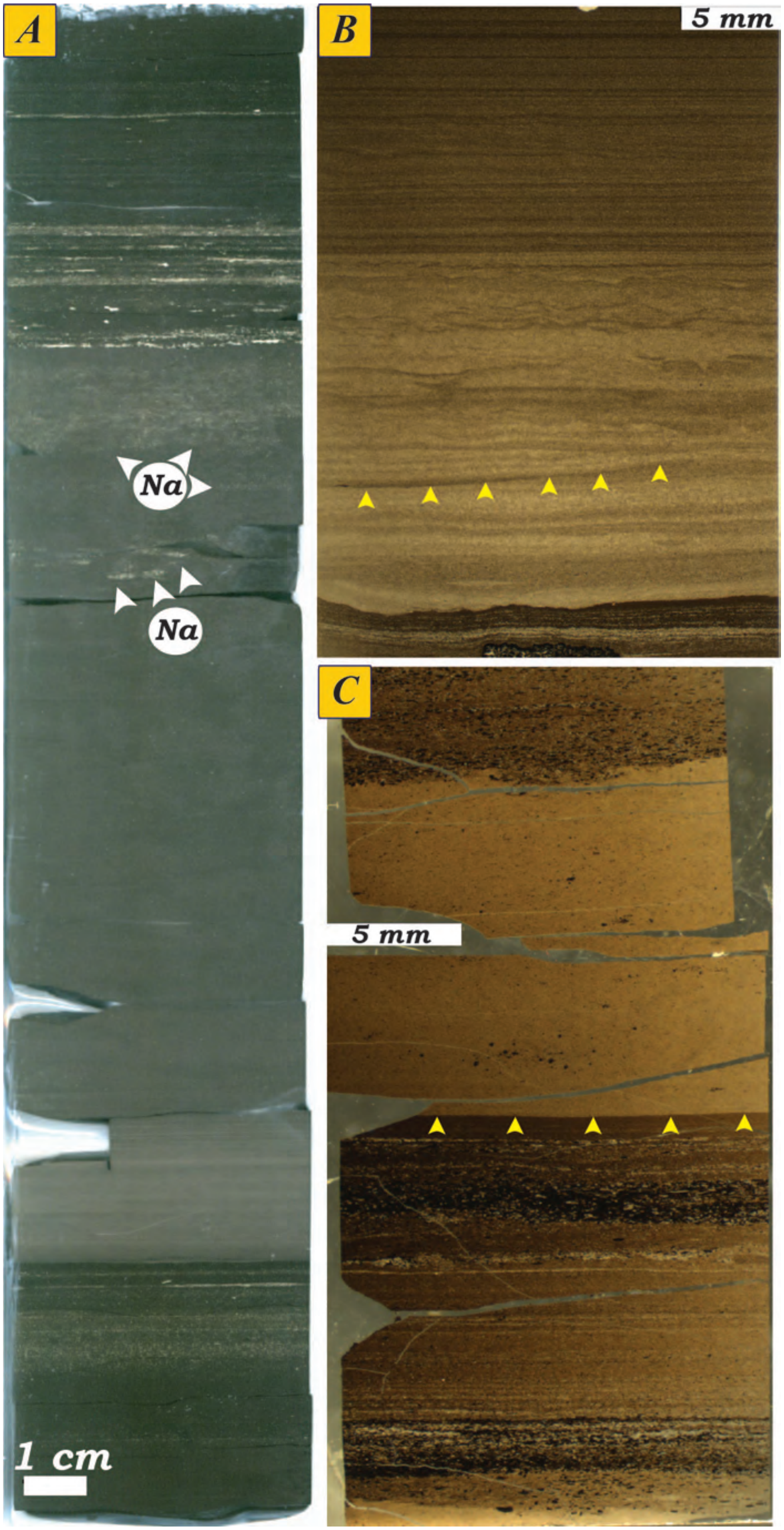

FIG. 10.—**A)** Hand-sample image (contrast enhanced) of the GGM facies showing a sharp contact with underlying pyritic black mudstone, with onlapping silt laminae that show planar parallel to low-angle cross-lamination. Planar parallel to low-angle cross-laminated silts show normal and inverse grading, with an overlying thick bed of medium dark gray mudstone with pyritic navichnia traces (*Na*) at the top. **B)** Photomicrograph showing bed-load portion of a muddy hyperpycnite (plane-polarized light). Note the irregular basal scour with overlying wavy, current-ripple cross-lamination, internal scours (arrows), and soft-sediment deformation. The basal scour is abrupt and commonly jagged, indicating erosion into firm, plastic substrate. **C)** Suspended-load portion of muddy hyperpycnite with basal scour (arrows) and top-down post-event disturbance of substrate.

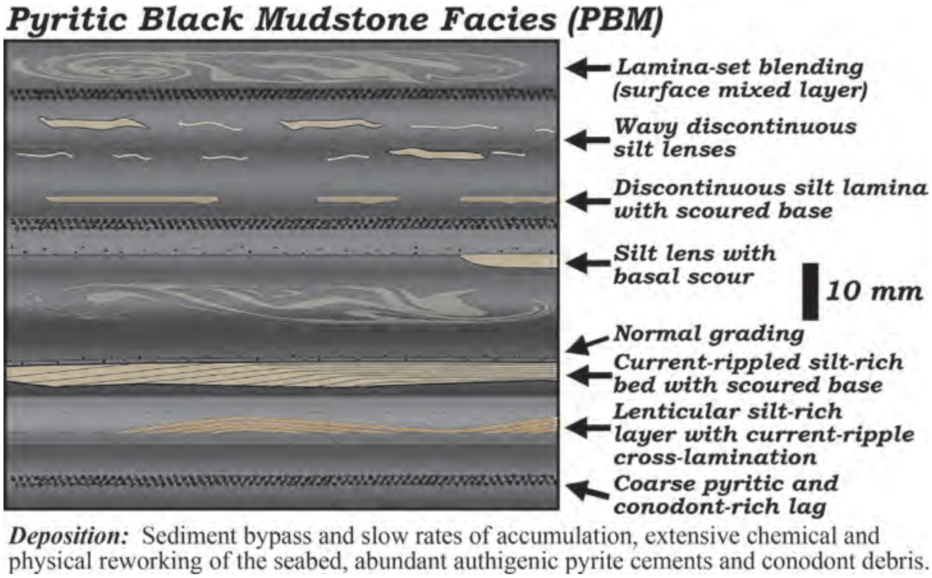

FIG. 11.—Line drawing of Pyritic Black Mudstone (PBM) facies detailing sedimentary features observed.

discharge events (Wilson and Schieber 2014). This facies shows abundant erosional features, silt-rich beds with current and wave ripple cross-lamination, normal grading, and extensive precipitation of iron-sulfide cements (Fig. 11). Trace-fossil diversity and intensity (BI = 1–3) is slightly decreased in this facies, consisting chiefly of meioturbation, *Chondrites*, and *Planolites*. Silt-rich beds with current-ripple and wave-ripple cross-lamination contain abundant diagenetic iron sulfides (Fig. 12). Petrographically, these coarser-grained beds show concentrated pyrite-replaced and cemented benthic fecal pellets and conodont skeletal debris that has been replaced by pyrite (Fig. 12). Along with benthic fecal pellets, agglutinated benthic foraminifera are also common. Additionally, coarse granular pyrite micro-concretion layers with diffuse boundaries are observed throughout clay-rich portions of this facies.

Interpretation of PBM Facies

The PBM facies is interpreted to reflect sediment bypass (low net accumulation) and extensive wave and current reworking of the seabed. Subsequent to high-density fluvial discharge events (GGM facies), areas where hyperpycnal plumes transported and rapidly deposited sediment suffered a decrease in accommodation. This resulted in sediment bypass in the proximal to medial setting, and transport of sediment to farther offshore locations. Wave and current ripples are abundantly observed in this facies, suggesting traction transport and advection of seabed sediments.

The decrease in bioturbation intensity (BI = 1–3) and trace-fossil diversity, as well as the presence of agglutinated benthic foraminifera and benthic fecal pellets, indicate a return to suboxic to dysoxic benthic redox conditions, which resulted from low net clastic accumulation and high organic flux to the seabed. The presence of iron-sulfide cementation reflects extensive chemical alteration of the substrate and a sustained position of the redox boundary near the sediment–water interface, thus allowing enrichment of early diagenetic iron-sulfide cements (Baird and Brett 1986; Schieber and Riciputi 2005). Pelagic input outcompeted detrital (clastic) input, and extensive physical and chemical reworking of the seabed resulted in sulfide precipitation in fecal matter (containing digested lipid- and protein-rich organic material) and pyritization of conodont microfossils. Pyrite and marcasite cements are more prevalent in silt-rich beds, reflecting pore-fluid enrichment in intervals with higher porosity and permeability relative to the mudstones that enclose them.

Dark Gray Mudstone (DGM) Facies

Upsection, the Lower Geneseo member is dominated by the dark gray mudstone (DGM) facies, which shows an increase in erosional features, amalgamation of beds, current, wave, and combined-flow ripple cross-lamination, normal grading, and moderate intensities of bioturbation and biodeformational structures (BI = 2–3; Figs. 13, 14). Common ichnogenera identified throughout the DGM facies include meioturbation, *Chondrites*, *Palaeophycus*, *Planolites*, *Teichichnus*, and *Thalassinoides*. In addition, flattened linguliform and rhynchonelliform brachiopods are common on bedding planes. Wave and current ripples commonly show lenticular bed geometries with arcuate scalloped topography. Graded beds are also abundantly observed with basal scours and are weakly bioturbated towards the top.

Interpretation of DGM Facies

The DGM facies reflects moderate clastic input in the distal setting with increasingly energetic conditions due to shoreline progradation. The presence of moderate bioturbation intensity and diversity with the occurrence of dysaerobic benthic fauna (e.g., *Orbiculoidea lodiensis*, *Leiorhynchus*) suggests lower oxic to dysoxic benthic redox conditions. The abundance of graded beds and current, wave, and combined-flow ripples indicate extensive lateral advection and transport. Decreased organic-carbon content in this facies reflects increased clastic dilution, as well as increased levels of consumption by benthic organisms.

DESCRIPTION AND INTERPRETATION OF MUDSTONE LITHOFACIES: FIR TREE MEMBER AND UPPER GENESEO MEMBER

Calcareous Silty Mudstone (CSM) Facies

This facies characterizes the lithostratigraphic interval that is known as the Fir Tree member of the Geneseo Formation. It shows three internal cycles (0.75 to 1.5 m thick) that show a sharp basal contact with the previous cycle, followed by gray calcareous mudstones that grade into bioturbated calcareous muddy siltstones (Baird and Brett 1986). The CSM facies is a moderately to strongly bioturbated (BI = 3–4), gray to dark gray silty mudstone, with thick silt-rich beds that show current-ripple and wave-ripple cross-lamination (Fig. 15). Common trace fossils identified throughout the CSM facies include biodeformational structures, *Planolites*, *Chondrites*, *Teichichnus*, *Thalassinoides*, and *Palaeophycus*

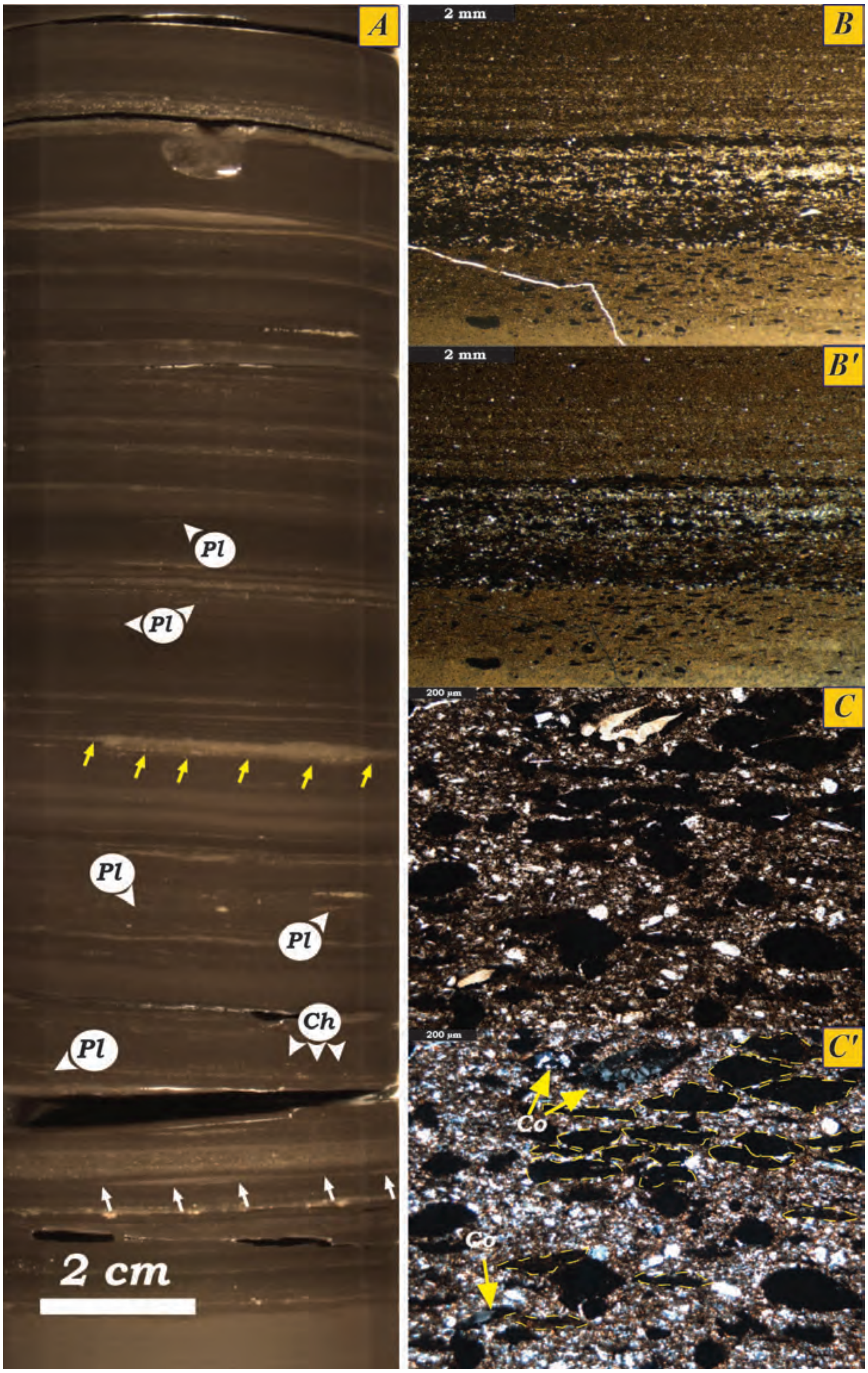

FIG. 12.—**A)** Hand-sample image (contrast enhanced) of the PBM facies showing erosional features (yellow arrows), current ripples with lenticular bed geometry, normal lamina-set grading, disrupted lamina, and pyritic cements. Many of the current ripples show draping planar parallel laminated silts (overlying yellow arrows). Silt-rich beds contain pyritic cements. Throughout the mudstone matrix, coarse granular pyrite micro-concretion bands with diffuse boundaries are observed. The PBM facies contains meioturbation as well as a less diverse suite of ichnogenera including *Chondrites* (*Ch*) and *Planolites* (*Pl*). The decrease in bioturbation intensity (BI = 1–3) and trace-fossil diversity suggests suboxic to dysoxic benthic redox conditions. **B**, **B′)** Photomicrograph showing the PBM facies with normal lamina-set grading and accumulation of reworked diagenetic pyrite (plane and cross-polarized light). **C**, **C′)** Enlarged view of a pyrite-rich layer, and it is apparent that pyrite cements are replacing conodonts (yellow arrows) and benthic fecal pellets (yellow dashed lines).

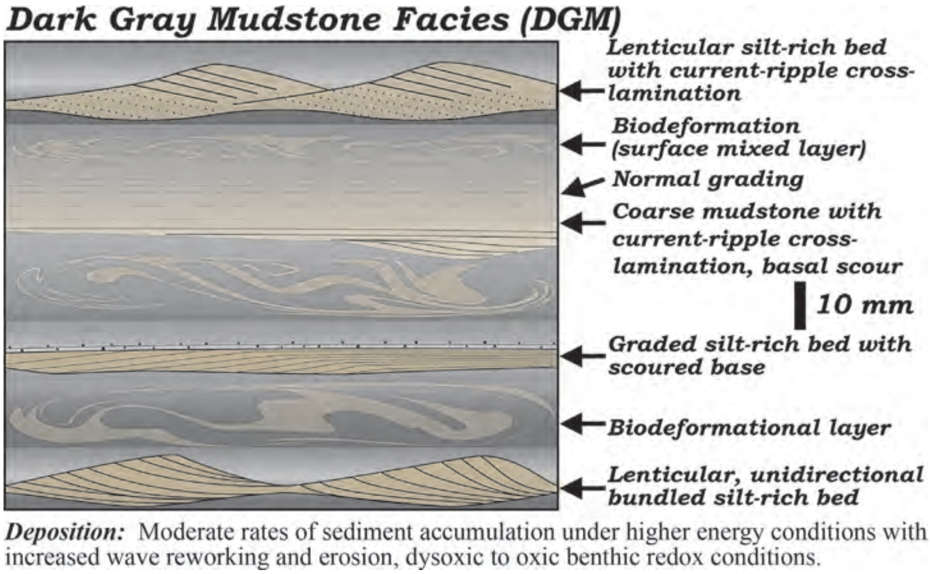

FIG. 13.—Line drawing of Dark Gray Mudstone (DGM) facies detailing sedimentary features observed.

(Fig. 16). Additionally, small brachiopods (*Ambocoelia* and *Devonochonetes*), pelmatozoans, ostracodes, and auloporid tabulate corals are present in this facies (Fig. 16). The CSM facies forms a distinct interval that is an excellent biostratigraphic marker bed due to the preservation of goniatites and is observed throughout the NAB in New York (Baird et al. 1988; Kindle 1896; Kirchgasser et al. 1988).

Interpretation of CSM Facies

The CSM facies represents varying rates of sedimentation and bypass in the medial setting, followed by flooding and sediment starvation that resulted in precipitation of pore-filling carbonate. The increased bioturbation intensity (BI = 3–4) and diversity indicates oxic benthic redox conditions. Moreover, the presence of small brachiopods, ostracodes, and auloporid tabulate corals indicates more oxygenated conditions. An increase in wave and current ripples, graded beds, and extensive erosional features further suggests extensive wave reworking and advection of the seabed in a higher energy environment.

Dark Gray Silty Mudstone (DSM) Facies

The lower portion of the Upper Geneseo member is dominated by the Dark Gray Silty Mudstone (DSM) facies, which shows an abundance of macroscopically visible bioturbation, terrestrial phytodetritus, scours, normal and inverse grading, soft-sediment deformation (convoluted beds), and current, wave, combined-flow, and asymmetric climbing ripples (Fig. 17). The bioturbation intensity varies from weakly to strongly bioturbated (BI = 1–4), and bioturbation commonly overprints primary sedimentary features. Common trace fossils include biodeformational structures, navichnia traces, fugichnia traces, *Palaeophycus*, *Phycosiphon*, *Planolites*, and *Thalassinoides*. Graded beds are observed in many places, and range in thickness from 5 mm to 15 cm. They show basal scours that are filled with planar parallel to low-angle cross-laminated silts, and grade into moderately bioturbated medium dark gray mudstones (Fig. 18).

Interpretation of DSM Facies

The DSM facies reflects a medial depositional setting with mixed-clastic input from storm sedimentation and fluvial-discharge events (Wilson and Schieber 2014). Continuous background sedimentation with extensive wave and current transport of fine-grained sediments is evidenced by the array of sedimentary features, as well as by bioturbation intensity and diversity. Rapidly deposited sediment with normal and inverse grading and current, wave, and combined-flow ripples, as well as convoluted beds, tend to have exclusively fugichnia (escaping behavior) and navichnia traces (sediment swimming behavior), these facies are interpreted to be products of prodeltaic hyperpycnal underflows. The abundantly observed wave ripples with arcuate scalloped topography are indicative of oscillatory flow and wave action.

Gray Silty Mudstone (GSM) Facies

Upsection in the Upper Geneseo member, the gray silty mudstone (GSM) lithofacies is observed. Sedimentary features observed are similar to those seen in the DSM lithofacies, but it shows an increase in silt content and bioturbation intensity and diversity, as well as a decrease in organic-matter content (Fig. 19). The GSM contains current, wave, and combined-flow ripples with irregular scours. Normal and inverse grading are present, together with terrestrial phytodetritus, internal scours, and soft-sediment deformation. The GSM facies shows a wide range of bioturbation intensity (BI = 0–5) and diversity, containing biodeformational structures, navichnia traces, fugichnia traces, *Palaeophycus*, *Phycosiphon*, *Planolites*, and *Thalassinoides*. Erosional features are abundantly present throughout this facies.

Interpretation of GSM Facies

The GSM facies reflects high sediment accumulation rates in combination with extensive wave reworking and erosion of the seabed. The variable and generally increased bioturbation intensity (BI = 0–5) and diversity suggests oxic benthic redox conditions. Intervals resulting from event sedimentation show decreased bioturbation intensity and diversity as a result of rapid burial. Increased silt content in comparison to the underlying DSM facies suggests increased proximity to the paleoshoreline.

Fluvial-discharge events (Wilson and Schieber 2014) were probably responsible for a significant proportion of the sediments in this facies, showing abundant normal and inverse graded beds with combined-flow ripples, convoluted beds, internal scours, and a decreased intensity of bioturbation (BI = 0–2) and diversity (e.g., fugichnia and navichnia traces). Storm-induced currents and storm setup-relaxation flows are probably responsible for extensive advection and bed-load transport during deposition of the GSM facies. Background deposition appears more strongly

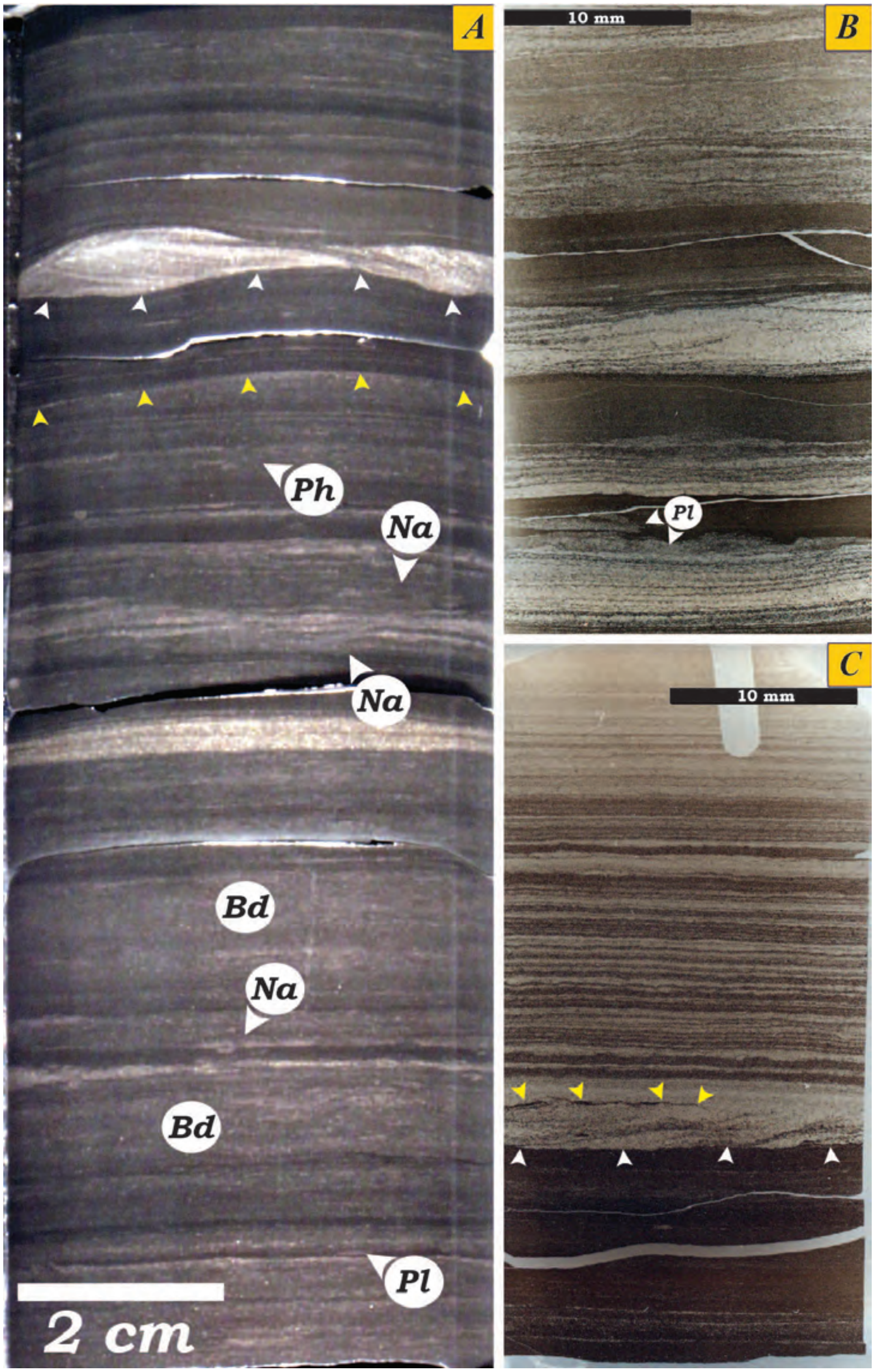

FIG. 14.—**A)** Hand-sample image (contrast enhanced) of the DGM facies showing erosional features (yellow arrows), current ripples, wave ripples with arcuate scalloped topography (white arrows), lamina-set grading, disrupted lamina, and bioturbation and biodeformational structures. The DGM facies contains biodeformation (*Bd*), navichnia traces (*Na*), and a suite of ichnogenera including *Planolites* (*Pl*), *Phycosiphon* (*Ph*). The increase in bioturbation intensity (BI = 3–4) suggests that aerobic conditions prevailed, and that the redox boundary was located deeper below the sediment surface. **B)** Photomicrograph showing the DGM facies with several graded beds. At the base are planar-laminated to low-angle cross-laminated silt-rich beds that fine upwards into sparsely to moderately bioturbated (BI = 2–3) dark gray mudstone. These graded beds probably represent distal tempestites, where storm waves suspended and transported shelfal muds offshore. **C)** Photomicrograph showing the DGM facies with current ripples, continuous planar silt laminae, and amalgamation. An interesting observation is the bundling of silt laminae upsection and an overall coarsening-upwards trend which probably reflects a more proximal environment (coarser clastic influx) with extensive current reworking.

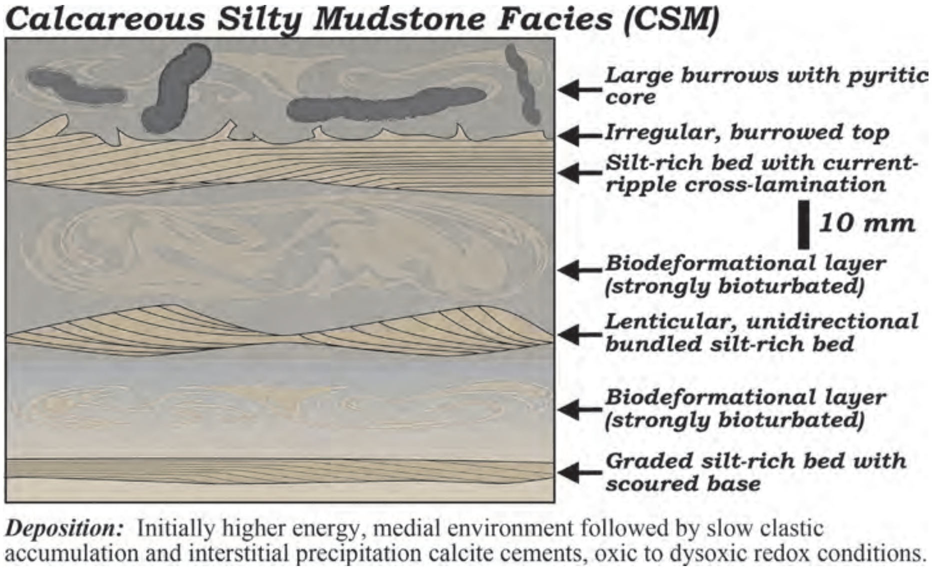

FIG. 15.—Line drawing of Calcareous Silty Mudstone (CSM) facies detailing sedimentary features observed.

bioturbated to churned (BI = 4–5), making it difficult to identify primary depositional features.

Gray Muddy Siltstone (GMS) Facies

The Gray Muddy Siltstone (GMS) facies (Fig. 20) increases in abundance and thickness in the Upper Geneseo member, and increases in abundance and thickness upsection. The GMS lithofacies is composed of thick siltstones with internal scours, hummocky cross-lamination, climbing and combined-flow ripple cross-lamination, normal and inverse laminaset grading with variable clay content, and varying degrees of bioturbation (BI = 0–4) with decreased trace-fossil diversity (Fig. 21). Common trace-fossil types include fugichnia, navichnia, *Palaeophycus*, and *Thalassinoides*.

Interpretation of GMS Facies

The GMS facies appears to reflect deposition in a storm-dominated, proximal shelf environment with high sedimentation rates with subsequent wave reworking and erosion. This facies becomes thicker and more abundant upsection (Sherburne Formation; Fig. 2). Overall, bioturbation is minimal in this facies because preservation potential is greatly decreased due to increased wave-induced winnowing and reworking, and rapid deposition and burial of the seabed. The DMS lithofacies represents the shallowest and highest-energy environment throughout the examined succession. The thick accumulation of muddy siltstones with current, wave, and combined-flow ripples records high-energy currents with a strong oscillatory component.

DISCUSSION

Through the use of sedimentary textures, features, composition, and biogenic attributes, nine facies are recognized in the Geneseo Formation of central New York. The vertical and lateral changes in mudstone lithofacies indicate a general shallowing-upwards trend, with increasing clastic input and dilution upsection (Fig. 22). Water depths were probably greatest and shoreline trajectory was at its most landward (i.e., easterly) position during the deposition of the Lower Geneseo member, particularly the BBM facies (Fig. 22). After a major marine transgression (Taghanic Onlap), offshore-directed sediment flux increased as progradation of the Catskill delta delivered fine-grained detritus across and along the Geneseo shelf (Fig. 23).

During this time interval, storm-induced waves and currents transported fine-grained sediments westward from the source area. These sediments rapidly blanketed the seafloor under prevailing suboxic to dysoxic benthic redox conditions that are indicated by decreased bioturbation intensity (BI = 1–3) and diversity (Fig. 23). This interpretation is supported by the very common presence of agglutinated benthic foraminifera and benthic fecal pellets. Organic-matter enrichment in this facies reflects minimal clastic dilution and high primary productivity, possibly aided by minor seasonal stratification (Sageman et al. 2003). The redox boundary at the time of deposition appears to have been just beneath the sediment–water interface, allowing only diminutive benthic organisms adapted to oxygen-stressed conditions (i.e., agglutinated benthic foraminifera, nematodes, polychaetes, etc.) to penetrate a few millimeters into the sediment. The presence of continuous to discontinuous silt laminae with scoured bases and current ripples throughout the BBM facies indicates that sediment accumulated and accreted laterally in bed load as migrating ripples (Schieber and Southard 2009; Schieber et al. 2007).

Growth of carbonate concretions throughout the Geneseo Formation occurred at a variety of scales, ranging from small nodules (5 cm in diameter) to discrete beds (up to 1 meter thickness). The SBC facies probably represents periods of sediment starvation and/or sediment bypass, where clastic accumulation subsided and microbially driven diagenetic reactions allowed pore-filling calcite cements to consolidate the substrate and prevent significant compaction. Before, as well as during, this interval of substrate cementation, organisms burrowed extensively into the sediment.

The GGM facies is observed throughout the Lower Geneseo member, and varies in thickness and physical expression laterally and vertically. Its sedimentary features, such 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, are all suggestive of sustained lateral sediment transport by a turbulent flow with waxing and waning currents, most likely hyperpycnites (Wilson and Schieber 2014). A critical observation 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 (Wilson and Schieber 2014). This interpretation is also supported by the observation that the deposits of hyperpycnal flows at a single location coarsen upsection, increase in thickness and abundance, and also contain more wave-formed features. Hyperpycnal mud plumes probably coincide with times of elevated fluvial discharge during flooding events, which is likely associated with changing climate or increased supply of clastics from mountain building (Wilson and Schieber 2014).

It appears that after these offshore-directed underflows deposited large quantities of fine-grained sediment; areas receiving these deposits experienced extensive bypass, and winnowing of the seabed. The PBM facies represents

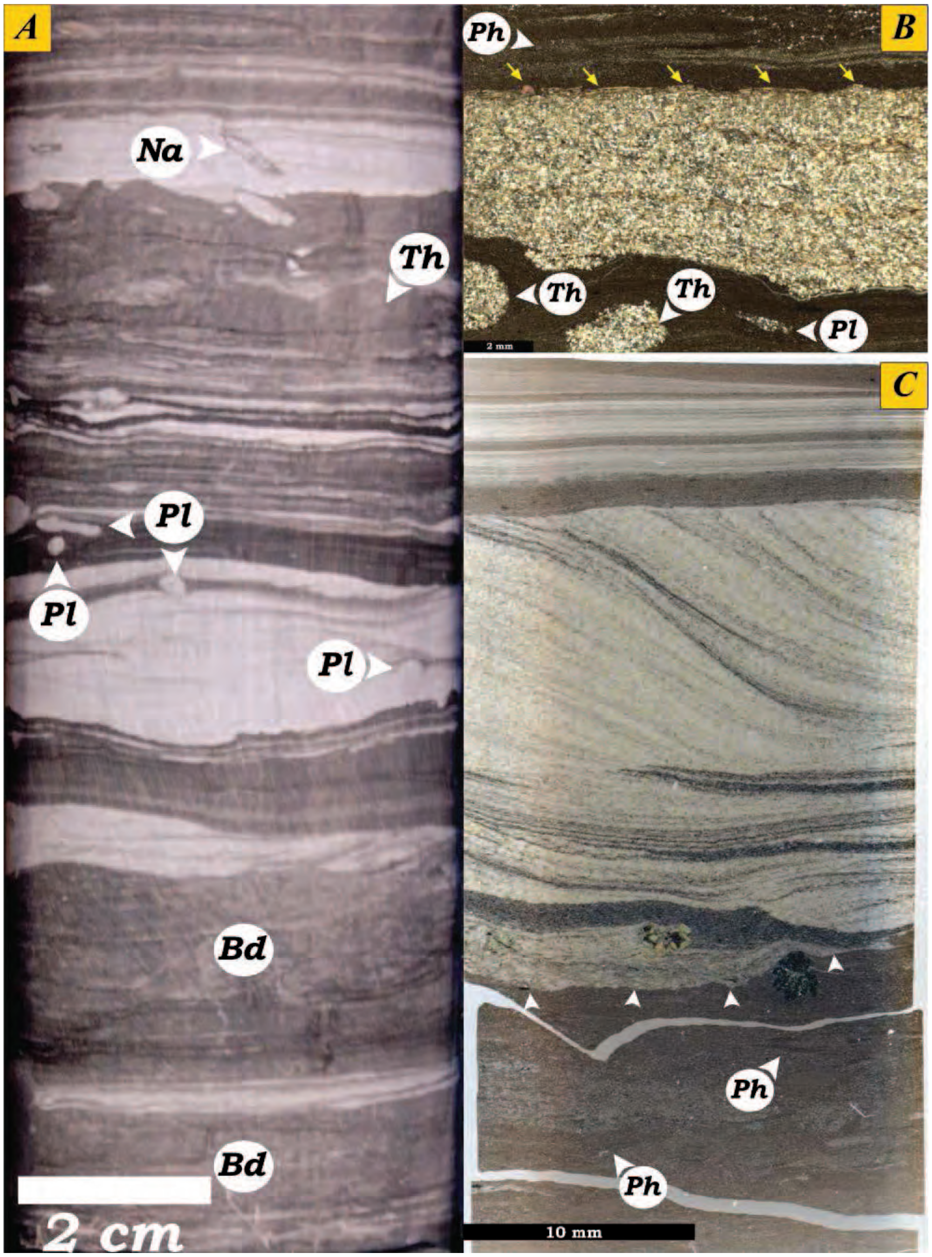

FIG. 16.—**A)** Hand-sample image (contrast enhanced) of the CSM facies showing increased erosional features, thick current ripples and wave ripples with arcuate scalloped topography, lamina-set grading, disrupted lamina, and bioturbation and biodeformational structures. The CSM facies contains biodeformational (*Bd*) features and navichnia traces (*Na*), as well as a suite of ichnogenera including *Planolites* (*Pl*), and *Thalassinoides* (*Th*). The increase in bioturbation intensity (BI = 4–5) suggests that aerobic conditions prevailed, and that the redox boundary was located deeper below the sediment surface. **B)** Photomicrograph (cross-polarized light) showing the CSM facies with deep erosional scour, silt-filled *Planolites* (*Pl*) and *Thalassinoides* (*Th*) burrows, and reworked siltstone bed containing skeletal debris (disarticulated styliolinids and brachiopods). Note that the surface of siltstone bed is marked by styliolinids and pelmatozoan debris (yellow arrows). **C)** Photomicrograph showing CSM facies, with the lower portion of the sample containing bioturbated styliolinid-rich mudstone, and an erosional contact with the overlying current-rippled interval that shows low-angle to high-angle cross lamination. Foresets of ripples contain abundant styliolinids and skeletal debris. The current ripple has an erosional cap and is overlain by planar laminated silts, suggesting that flow velocities waned after an initial erosive energy event.

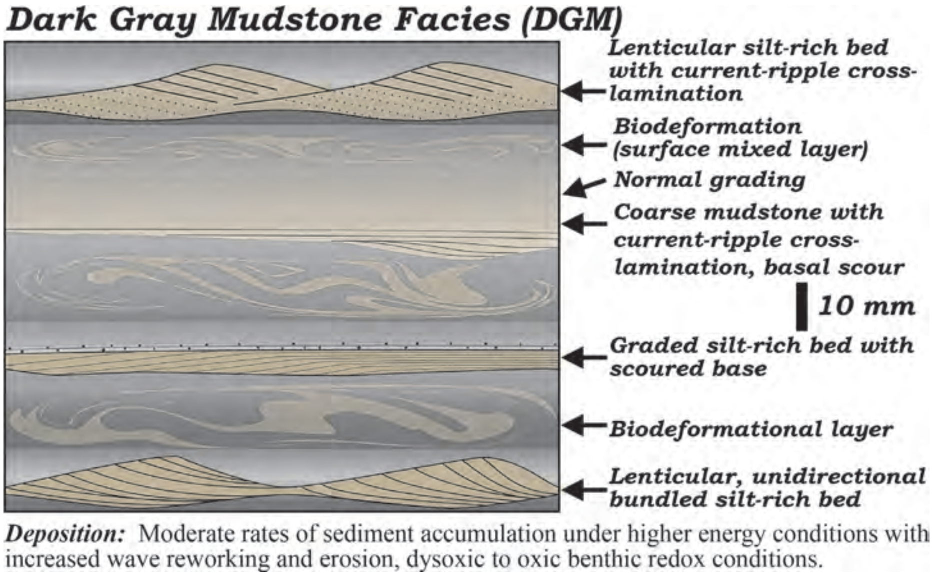

FIG. 17.—Line drawing of Dark Gray Silty Mudstone (DSM) facies detailing sedimentary features observed.

this bypass and reworking, consisting of reworked conodonts and benthic fecal pellets with substantial iron-sulfide cements, reflecting physical and chemical reworking after a depositional episode. The decrease in bioturbation intensity (BI = 1–3) and trace-fossil diversity in facies PBM indicates a return to suboxic to dysoxic benthic redox conditions, which resulted from low net clastic accumulation and elevated organic flux to the seabed.

Upsection, the Lower Geneseo member is dominated by the DGM facies, reflecting moderate clastic supply on a storm-wave-dominated, distal shelf. With an abundance of graded beds, erosional features, and current, wave, and combined-flow ripples, this facies represents increased clastic input to the distal shelf, as a result of shoreline progradation. A major shoreward shift in facies superimposed the CSM facies above organic-rich grayish-black and dark gray mudstones of the Lower Geneseo member. Exhibiting abundant erosional features, current, wave, and combined-flow ripples, this facies captures varying clastic input (high to low) and sediment bypass in a storm-wave, medial shelf. Though clastic dominated, the CSM facies contains pore-filling calcite cements that reflect sediment-starved conditions and microbial production of carbonate in the pore fluids (Brett and Allison 1998; Raiswell and Fisher 2000). Clastic starvation and/or bypass led to formation of an "overprinted" diagenetic concretionary carbonate bed.

Above the CSM facies, newly generated accommodation allowed renewed deposition of organic-rich fine-grained clastics of the Upper Geneseo member. As this newly generated accommodation was utilized and clastic input outpaced increases in accommodation, increased clastic dilution and higher energy conditions resulted, indicated by extensive erosional features, graded beds, and current, wave, and combined-flow ripples. Background sedimentation with extensive wave and current transport of fine-grained sediments is indicated by an array of sedimentary features, as well as by decreased bioturbation intensity and diversity. Wave-aided fluvial-discharge events significantly impacted sediment dispersal in the Upper Geneseo member in the medial to proximal shelf regions, indicated by terrestrial phytodetritus, normal and inverse graded beds with current, wave, and combined-flow ripples, as well as fugichnia and navichnia traces.

Farther upsection, internal scours, hummocky cross-stratification, climbing and combined-flow ripple cross-lamination, convoluted beds, normal and inverse laminaset grading with variable clay-content, and varying degrees of bioturbation (BI = 0–4) with decreased trace-fossil diversity characterize facies GSM and GMS. Delta advance is marked by a strong increase of hyperpycnites, and the accompanying increase in sedimentation rates is reflected in decreased bioturbation intensity and diversity. The latter probably were also affected by unstable salinities and increased wave action with rapid burial.

CONCLUSION

The Geneseo Formation of New York records the complex interplay between eustatic sea-level rise and tectonically driven sediment supply. In the context of global eustasy in the Devonian, it appears that the Geneseo Formation was initially deposited during a major transgression (i.e., the Taghanic Onlap; Johnson 1970) when accommodation outstripped sedimentation. This transgression coincided with the third tectophase of the Acadian Orogeny, which delivered abundant fine-grained detritus to proximal areas of the Geneseo shelf. There this detritus was subsequently reworked by wave-induced currents and storm setup-relaxation currents. As fine-grained clastics were delivered to offshore areas, input approximately balanced increases in accommodation. Together with elevated rates of primary productivity, extensive deposition of organic-rich mudstones resulted. With a westward progradation of the shoreline, fluidized muds transported as suspended-load portions of prodeltaic hyperpycnites (GGM) begin to interfinger with organic-rich facies (BBM). Basinward migration of facies belts is expressed upsection in the Lower Geneseo member as coarser-grained mudstones (DGM) with increased abundance in current- and wave-formed features, as well as increased bioturbation intensity (2–3) and diversity.

The Fir Tree carbonate interval (CSM facies) marks an initial shallowing, resulting in better-oxygenated conditions indicated by increased bioturbation intensity (BI = 3–4) and diversity, as well as increased wave reworking and erosion. After an initial shallowing, a landward migration of the shoreline fostered offshore sediment starvation and *in situ* growth of carbonate cements. After deposition of CSM facies, increasing sediment supply and seaward migration of the shoreline resulted in deposition of the DSM facies, eventually giving way to GSM and GMS as continued shoreline progradation filled the previously generated accommodation. Depositionally, the Upper Geneseo represents a combination of varying clastic input and sediment bypass, in a medial to proximal shelf setting. With extensive erosional features, and a variety of sedimentary features that indicate wave-induced and oscillatory flow, the Upper Geneseo records progradation of the Catskill delta following the Taghanic transgression and the third tectophase of the Acadian orogeny.

Though previously interpreted to represent stagnant, anoxic-euxinic basinal conditions, the Geneseo succession records instead a more energetic

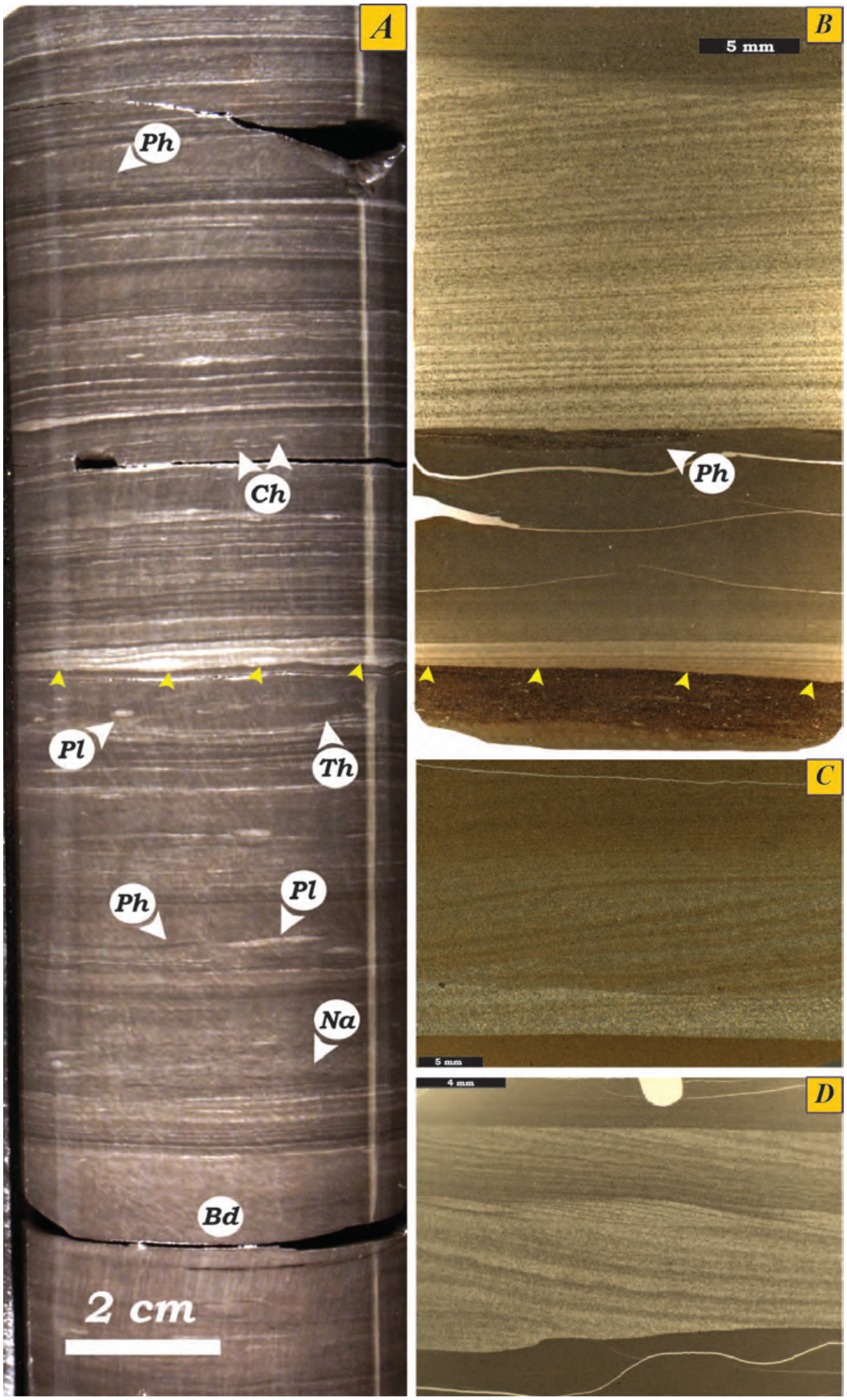

FIG. 18.—**A)** Hand-sample image (contrast enhanced) of the DSM facies showing erosional scours, current ripples with low-angle cross-lamination, normal and inverse lamina-set grading, and varying degrees of bioturbation. The DSM facies contains biodeformational (*Bd*) features and navichnia traces (*Na*), as well as a suite of ichnogenera including *Planolites* (*Pl*), *Thalassinoides* (*Th*). The increase in bioturbation intensity (BI = 4–5) and diversity indicates that aerobic conditions prevailed. **B)** Photomicrograph showing styliolinid-rich dark mudstone with truncation surface that is overlain by low-angle cross-laminated silt onlapping on that surface. Planar-laminated silts grade upwards into *Phycosiphon* (*Ph*) burrowed dark mudstone (post-event background sedimentation). An erosional contact is observed above, with onlapping laminated silts, that grade upwards into inclined laminated silts with an increase in clay content. **C)** Thin graded bed with internal scour and current-ripple cross-lamination. **D)** Silt-rich hyperpycnite with basal scour and combined-flow ripples, indicating wave-aided transport (concave-up lamina-set geometries).

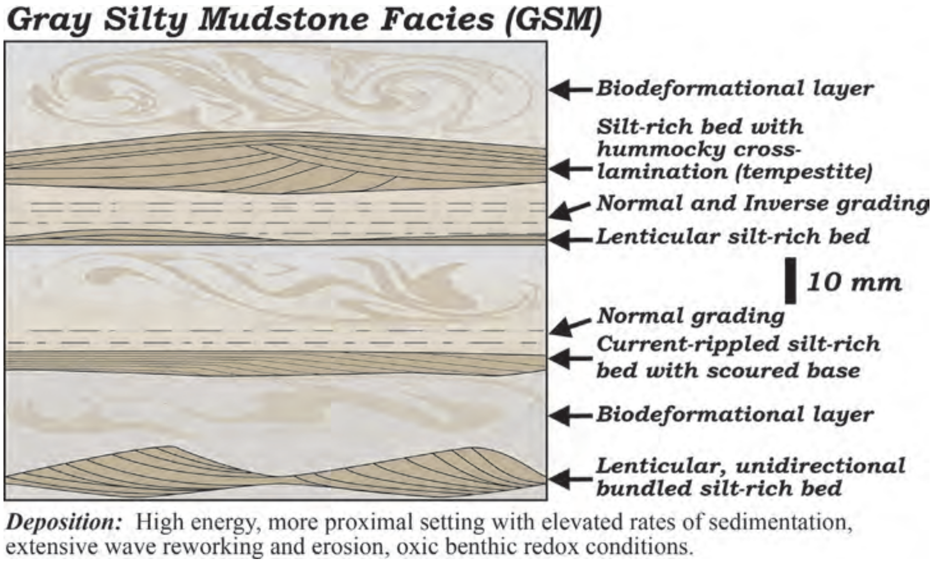

FIG. 19.—Line drawing of Gray Silty Mudstone (GSM) facies detailing sedimentary features observed.

environment with multiple modes of sediment transport and deposition (Fig. 23). The biogenic response to physical processes of deposition, such as meiofaunal sediment mixing and the wide range of locomotion and sediment feeder traces, mirrors the complex and multi-layered nature of sediment delivery. Although the Geneseo succession consists of organic-rich mudstones of source-rock quality, close inspection does not confirm the previously proclaimed stagnant and anoxic basinal conditions (e.g., Baird and Brett 1986, 1991; Ettensohn 1985, 1987; Ettensohn et al. 1988; Woodrow and Isley 1983; Woodrow 1985; Zambito et al. 2012). The described strata are yet another example of a carbonaceous mudstone succession that was deposited under more energetic conditions (Bohacs et al. 2005; Macqauker et al. 2010; Schieber and Yawar 2009) by multiple modes of sediment transport and deposition, and without the presence of anoxic bottom waters.

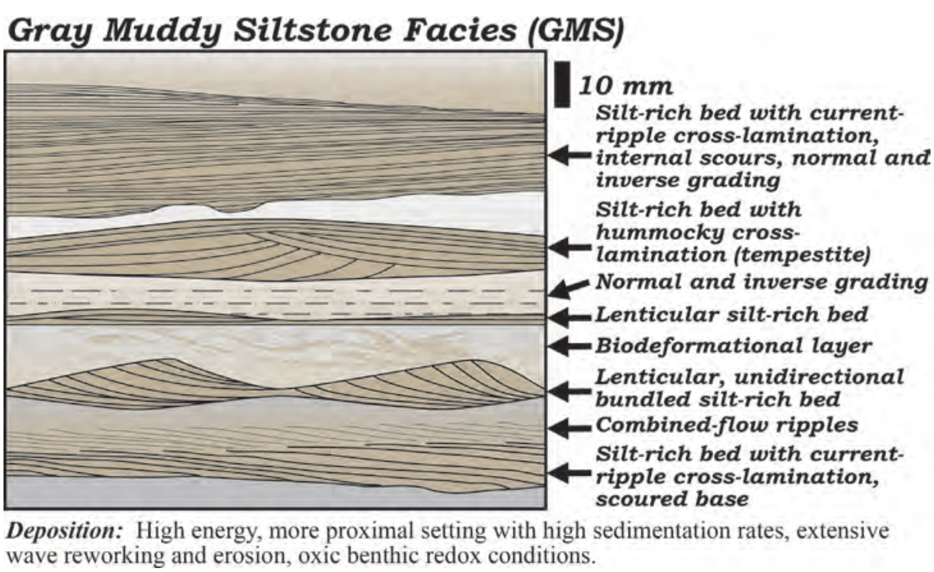

FIG. 20.—Line drawing of Gray Muddy Siltstone (GMS) facies detailing sedimentary features observed.

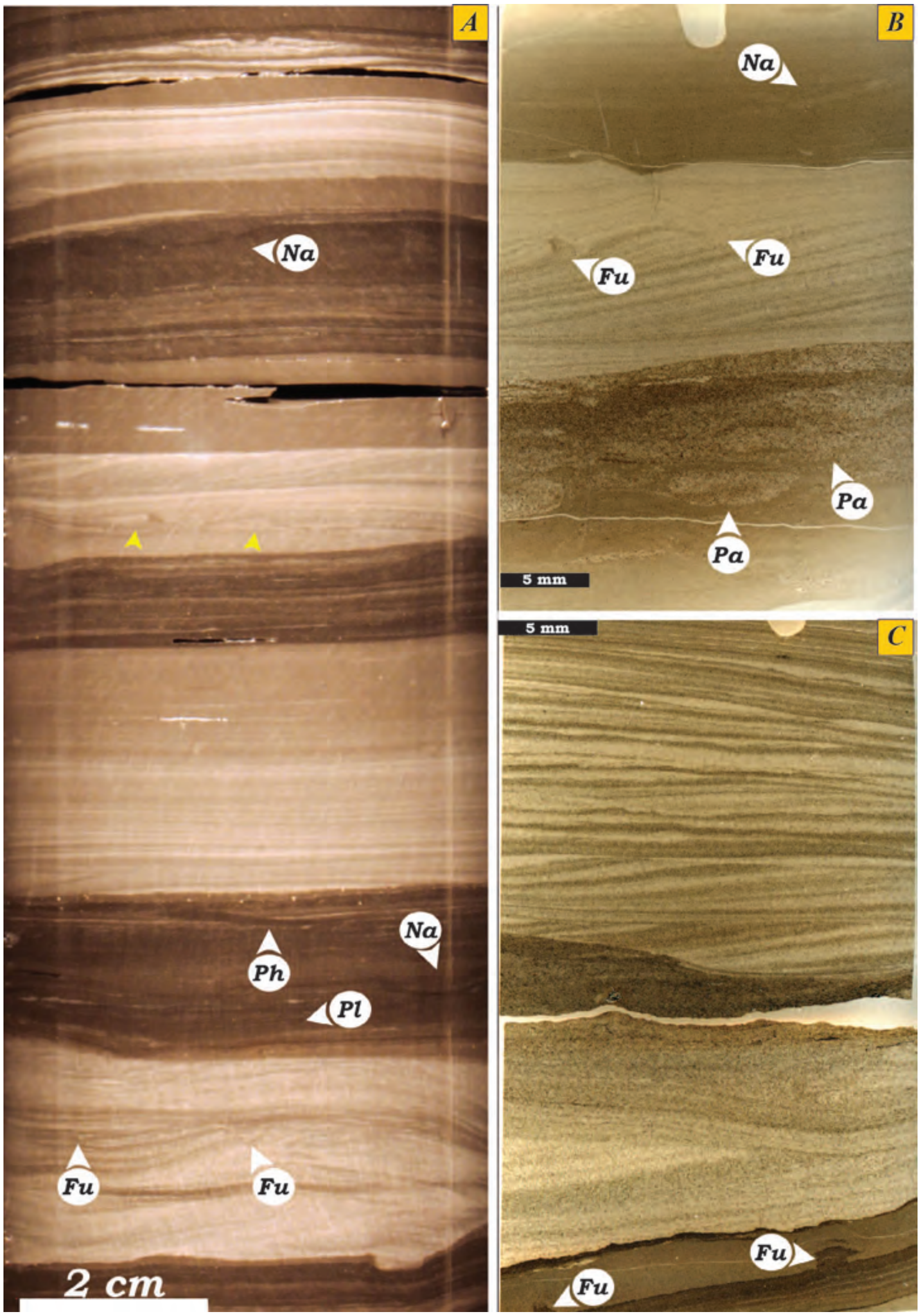

FIG. 21.—**A)** Hand-sample image (contrast enhanced) of interbedded GSM and GMS facies, showing erosional scours, current, wave, and combined-flow ripples, soft-sediment deformation (yellow arrows), normal and inverse lamina-set grading, and varying intensities of bioturbation. A variety of trace fossils are present, including fugichnia traces (*Fu*), navichnia traces (*Na*), *Planolites* (*Pl*), and *Phycosiphon* (*Ph*). **B)** Photomicrograph showing a wave ripple with escape traces (Fu), with an irregular basal scour into sandy mudstone with *Palaeophycus* (*Pa*) burrows. **C)** Another wave ripple with hummocky cross-lamination and scour overlying silty mudstones with fugichnia traces (*Fu*).

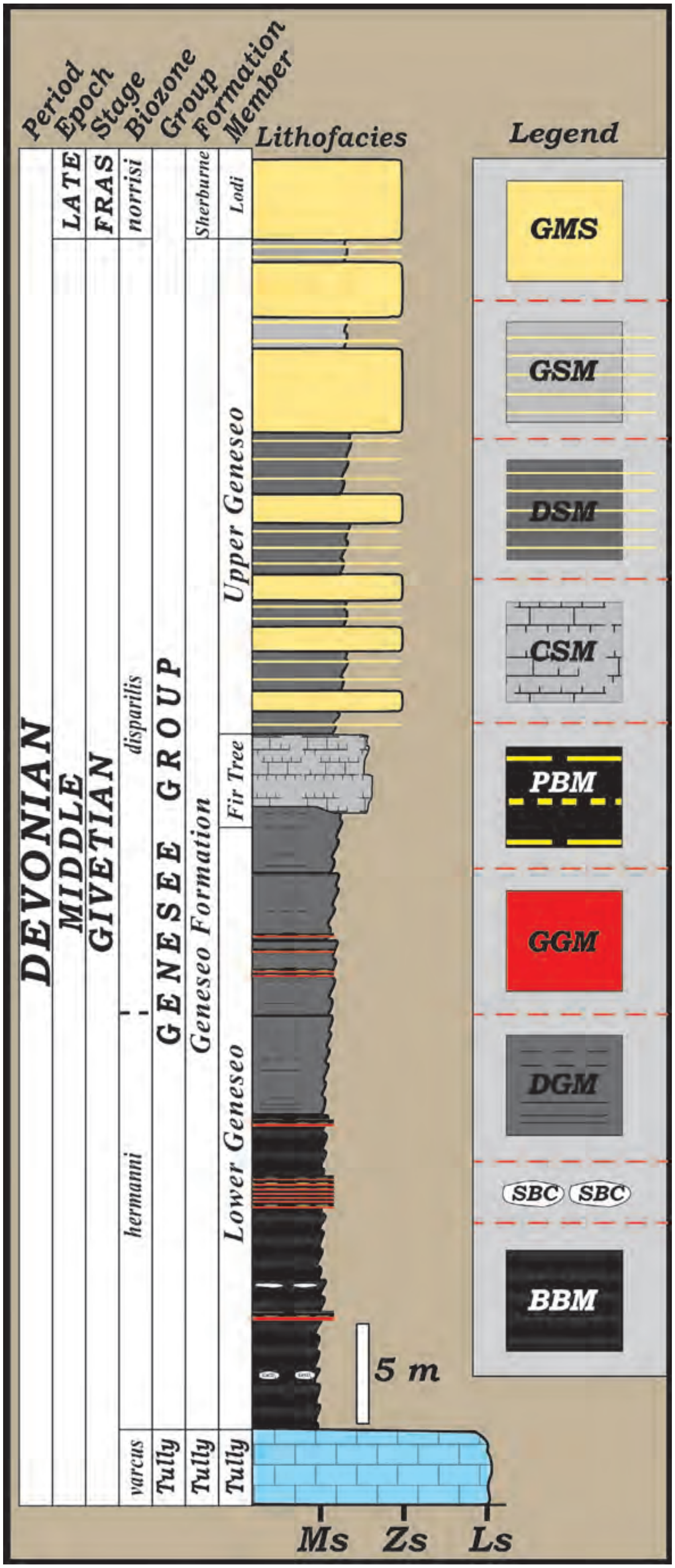

FIG. 22.—Stratigraphic column for the Geneseo Formation (Ms, mudstone; Zs, siltstone; Ls, limestone) observed in drill core (Fig. 1). Mudstone lithofacies and sedimentary features observed for the lower Genesee Group are represented.

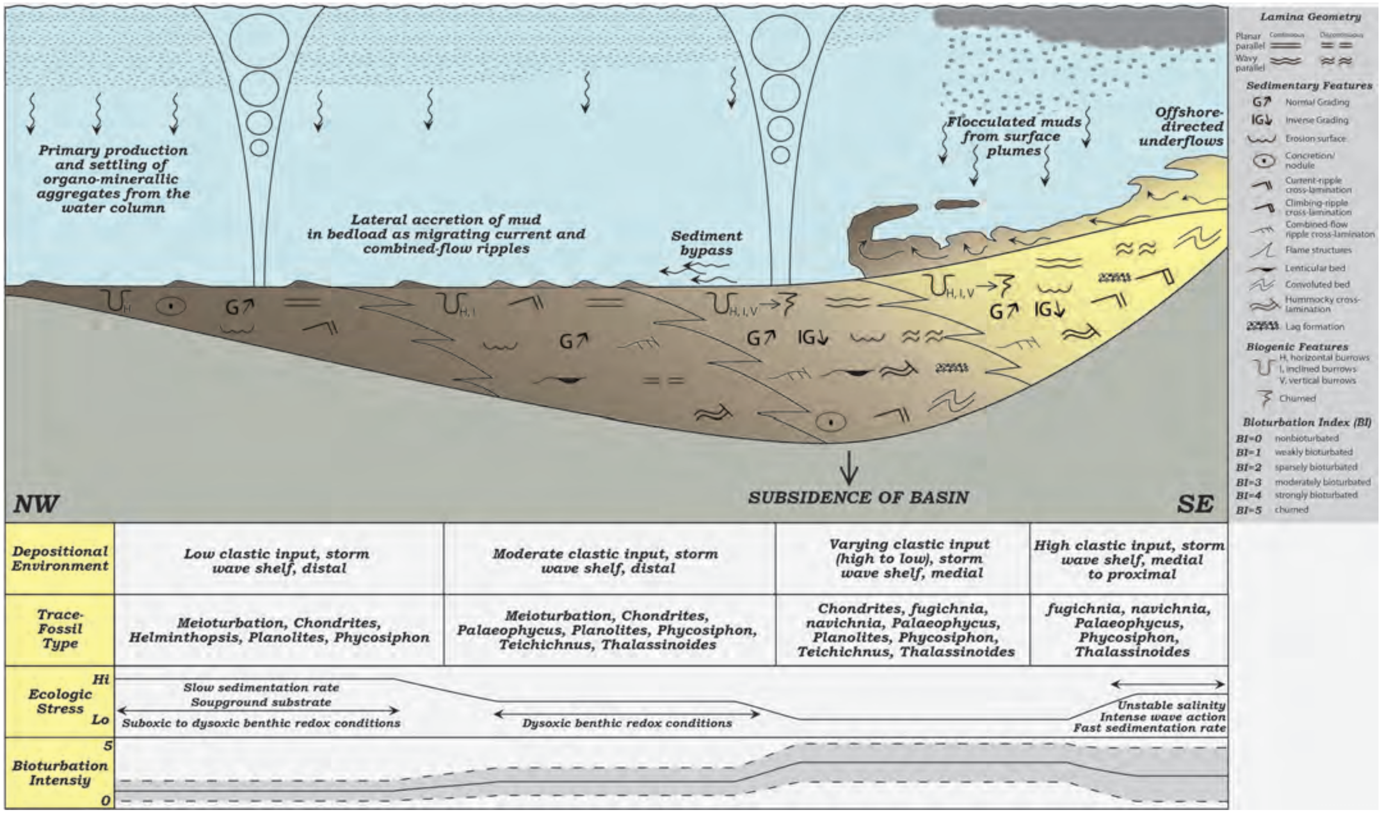

FIG. 23.—Conceptual diagram that summarizes the depositional environment, transport mechanisms, and depositional processes of the Geneseo Formation of central New York (NW to SE transect). Fluvial discharge events are shown to transport fine-grained sediment offshore as hyperpycnal flows and hypopycnal plumes. Storm processes are presumed to interact with the seafloor, causing erosion and supply sediment to the distal realm via wave-induced currents and storm setup-relaxation flows. In the distal setting, significantly decreased clastic input and heightened primary productivity in the surface waters results in enrichment of organic matter and development of a shallow redox boundary in the sediment. The chart below the diagram includes interpretations of depositional environment, ecologic stress, as well as bioturbation intensity (solid line represents mean values, gray dashed area represents possible intensities) and diversity.

ACKNOWLEDGMENTS

The authors greatly appreciate the reviews and suggestions provided by J. Bloch, C.E. Brett, G.C. Baird, J.A. MacEachern, and J.A. Rupp. We are also grateful for the technical edits provided by J.B. Southard. 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 support for RDW and laboratory facilities of the IU Shale Research Lab (http://www.shale-mudstone-research-schieber.indiana.edu/). 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

ALGEO, T.J., LYONS, T.W., BLAKEY, R.C., AND OVER, D.J., 2007, Hydrographic conditions of the Devono-Carboniferous North American Seaway inferred from sedimentary Mo-TOC relationships: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 256, p. 204–230.

ALLISON, M.A., AND NITTROUER, C.A., 1998, Identifying accretionary mud shorefaces in the geologic record: insights from the modern Amazon dispersal system: Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlung Naegele u. Obermiller, Shales and Mudstones: I, Basin Studies, Sedimentology, and Paleontology, 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: Geological Society of London, Special Publication, v. 58, p. 233–257.

BAIRD, G.C., BRETT, C.E., AND KIRCHGASSER, W.T., 1988, Genesis 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.

BERNER, R.A., 1990, Atmospheric carbon dioxide levels over Phanerozoic time: Science, v. 249, p. 1382–1386.

BERNHARD, J.M., VISSCHER, P.T., AND BOWSER, S.S., 2003, Submillimeter life positions of bacteria, protists, and metazoans in laminated sediments of the Santa Barbara Basin: Limnology and Oceanography, v. 48, p. 813–828.

BHATTACHARYA, J., AND MACEACHERN, J., 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., ed., The Deposition of Organic Carbon-Rich Sediments: Mechanisms, Models, and Consequences: SEPM, Special Publication 82, p. 61–101.

BOUDREAU, B.P., 1998, Mean mixed depth of sediments: the wherefore and the why: Limnology and Oceanography, v. 43, p. 524–526.

BRETT, C.E., AND ALLISON, P.A., 1998, Paleontological approaches to the environmental interpretation of marine mudrocks: Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlung Naegele u. Obermiller, Shales and Mudstones: I, Basin Studies, Sedimentology, and Paleontology, p. 301–349.

BRETT, C.E., AND BAIRD, G.C., 1996, Middle Devonian sedimentary cycles and sequence in the northern Appalachian Basin, *in* Witzke, B.J., Ludvigson, G.A., 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., TURNER, A.H., MCLAUGHLIN, P.I., OVER, D.J., STORRS, G.W., AND BAIRD, G.C., 2003, Middle–Upper Devonian (Givetian–Famennian) bone/conodont beds from central Kentucky, USA: reworking and event condensation in the distal Acadian foreland basin: Courier Forschungsinstitut Senckenberg, v. 242, p. 125–139.

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, v. 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.

Cullen, D.J., 1973, Bioturbation of superficial marine sediments by interstitial meiobenthos: Nature, v. 243, p. 323–324.

Demaison, G.J., and Moore, G.T., 1980, Anoxic environments and oil source bed genesis: Organic Geochemistry, v. 2, p. 9–31.

de Witt, W., and Colton, G.W., 1978, Physical stratigraphy of the Genesee Formation (Devonian) in western and central New York: U.S. Geological Survey, Professional Paper 1032-A, 22 p.

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., 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: Canadian Society of Petroleum Geologists, Memoir 14, p. 323–345.

Faill, R.T., 1985, The Acadian Orogeny and the Catskill Delta, *in* Woodrow, D.L., and Sevon, W.D., eds., The Catskill Delta: Geological Society of America, Special Paper 201, p. 15–37.

Fischer, A.G., 1981, Climatic oscillations in the biosphere, *in* Nitecki, M., ed., Biotic Crises in Ecological and Evolutionary Time: New York, Academic Press, p. 103–131.

Formolo, M.J., and Lyons, T.W., 2007, Accumulation and preservation of reworked marine pyrite beneath an oxygen rich Devonian atmosphere: constraints from sulfur isotopes and framboid textures: Journal of Sedimentary Research, v. 77, p. 623–633.

Goldring, R., 1995, Organisms and the substrate: response and effect, *in* Bosence, D.W.J., and Allison, P.A., eds., Marine Palaeoenvironmental Analysis from Fossils: Geological Society of London, Special Publication 83, p. 151–180

Isaacson, P.E., and Díaz-Martínez, E., 1995, Evidence for a middle–late Paleozoic foreland basin and significant paleolatitudinal shift, Central Andes, *in* Tankard, A.J., Suarez, S.R., and Welsink, H.J., eds., Petroleum Basins of South America: American Association of Petroleum Geologists, Memoir 62, p. 231–249.

Isaacson, P., Hladil, J., Wei, S., Kalvoda, J., Grader, G., 1999, Late Devonian–Early Carboniferous glacial sediments of South America and sea-level drops on other continents: Vienna, Geologishe Bundesanstalt Abhandlungen, v. 54, p. 239–256.

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

Johnson, J.G., Klapper, G., and Sandberg, C.A., 1985, Devonian eustatic fluctuations in Euramerica: Geological Society of America, Bulletin, v. 96, p. 567–587.

Kindle, E.M., 1896, The relation of the Ithaca Group to the faunas of the Portage and Chemung: Bulletins of American Paleontology, no. 2, 56 p.

Kirchgasser, W.T., 1985, Ammonoid horizons in the Upper Devonian Genesee Formation of New York: legacy of the Genesee, Portage, and Chemung: Geological Society of America, Special Papers, v. 201, p. 225–236.

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.

Lazar, O.R., Bohacs, K.M., Macquaker, J.H.S., Schieber, J., and Demko, T.M., 2015, Capturing key attributes of fine-grained sedimentary rocks in outcrops, cores, and thin sections: nomenclature and description guidelines: Journal of Sedimentary Research, v. 85, p. 230–246.

Lobza, V., and Schieber, J., 1999, Biogenic sedimentary structures produced by worms in soupy, soft muds: observations from the Chattanooga Shale (Upper Devonian) and experiments: Journal of Sedimentary Research, v. 69, p. 1041–1049.

Löhr, S.C., and Kennedy, M.J., 2015, Micro-trace fossils reveal pervasive reworking of Pliocene sapropels by low-oxygen-adapted benthic meiofauna: Nature Communications, v. 6, Article 6589.

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.

Miller, K.B., Brett, C.E., and Parsons, K.M., 1988, The paleoecologic significance of storm-generated disturbance within a Middle Devonian muddy epeiric sea: Palaios, v. 3, p. 35–52.

Murphy, A.E., Sageman, B.B., and Hollander, D.J., 2000a, Eutrophication by decoupling of the marine biogeochemical cycles of C, N, and P: a mechanism for the Late Devonian mass extinction: Geology, v. 28, p. 427–430.

Murphy, A.E., Sageman, B.B., Hollander, D.J., Lyons, T.W., and Brett, C.E., 2000b, Black shale deposition and faunal overturn in the Devonian Appalachian Basin: clastic starvation, seasonal water-column mixing, and efficient biolimiting nutrient recycling: Paleoceanography, v. 15, p. 280–291.

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.

Pedersen, T.F., and Calvert, S.E., 1990, Anoxia vs productivity: what controls the formation of organic-carbon-rich sediments and sedimentary rocks?: American Association of Petroleum Geologists, Bulletin, v. 74, p. 454–466.

Pemberton, S.G., MacEachern, J.A., Gingras, M.K., and Saunders, T.D.A., 2008, Biogenic chaos: cryptobioturbation and the work of sedimentologically friendly organisms: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 270, p. 273–279.

Pike, J., Bernhard, J.M., Moreton, S.G., and Butler, I.B., 2001, Microbioirrigation of marine sediments in dysoxic environments: implications for early sediment fabric formation and diagenetic processes: Geology, v. 29, p. 923–926.

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.

Raiswell, R., and Fisher, Q.J., 2000, Mudrock-hosted carbonate concretions: a review of growth mechanisms and their influence on chemical and isotopic composition: Geological Society of London, Journal, v. 157, p. 239–251.

Richardson, M.D., Briggs, K.B., and Young, D.K., 1985, Effects of biological activity by abyssal benthic macroinvertebrates on a sedimentary structure in the Venezuela Basin: Marine Geology, v. 68, p. 243–267.

Riemann, F., and Schrage, M., 1978, The mucus-trap hypothesis on feeding of aquatic nematodes and implications for biodegradation and sediment texture: Oecologia, v. 34, p. 75–88.

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, no. 33, 1 sheet.

Sageman, B.B., Murphy, A.E., Werne, J.P., Ver Straeten, C.A., Hollander, D.J., and 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, v. 195, p. 229–273.

Schieber, J., 1994, Evidence for high-energy events and shallow-water deposition in the Chattanooga Shale, Devonian, central Tennessee, USA: Sedimentary Geology, v. 93, p. 193–208.

Schieber, J., 1998, Sedimentary features indicating erosion, condensation, and hiatuses in the Chattanooga Shale of central Tennessee: relevance for sedimentary and stratigraphic evolution: Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlung Naegele u. Obermiller, Shales and Mudstones: I, Basin Studies, Sedimentology, and Paleontology, p. 187–215.

Schieber, J., 2002, Sedimentary pyrite: a window into the microbial past: Geology, v. 30, p. 531–534.

Schieber, J., 2003, Simple gifts and hidden treasures: implications of finding bioturbation and erosion surfaces in black shales: SEPM, The Sedimentary Record, v. 1, p. 4–8.

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

Schieber, J., 2012, Styles of agglutination in benthic foraminifera from modern Santa Barbara Basin sediments and the implications of finding fossil analogs in Devonian and Mississippian black shales: Springer, Anoxia, v. 21, p. 573–589.

Schieber, J., and Riciputi, L., 2005, Pyrite and marcasite coated grains in the Ordovician Winnipeg Formation, Canada: an intertwined record of surface conditions, stratigraphic condensation, geochemical "reworking," and microbial activity: Journal of Sedimentary Research, v. 75, p. 907–920.

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: SEPM, The Sedimentary Record, v. 7, 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.

Trauth, M., Sarnthein, M., and Arnold, M., 1997, Bioturbational mixing depth and carbon flux at the seafloor: Paleoceanography, v. 12, p. 517–526.

Tyson, R.V., and Pearson, T.H., 1991, Modern and ancient continental shelf anoxia: an overview, *in* Tyson, R.V., and Pearson, T.H., eds., Modern and Ancient Continental Shelf Anoxia: Geological Society of America, Special Publication 58, p. 1–24.

Uchman, A., Bak, K., and Rodríguez-Tovar, F.J., 2008, Ichnological record of deep-sea palaeoenvironmental changes around the Oceanic Anoxic Event 2 (Cenomanian–Turonian boundary): an example from the Barnasiówka section, Polish Outer Carpathians: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 262, p. 61–71.

Ver Straeten, C.A., Brett, C.E., and Sageman, B.B., 2011, Mudrock sequence stratigraphy: a multi-proxy (sedimentological, paleobiological and geochemical) approach, Devonian Appalachian Basin: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 304, p. 54–73.

Werne, J.P., Sageman, B.B., Lyons, T.W., and 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, v. 302, p. 110–143.

Wheatcroft, R.A., Smith, C.R., and Jumars, P.A., 1989, Dynamics of surficial trace assemblages in the deep sea: Deep Sea Research Part A, Oceanographic Research Papers, v. 36, p. 71–91.

WILLIAMS, G.Q., 1951, The stratigraphy of the type Ithaca Formation [Ph.D. thesis]: Cornell University, 188 p.

WILSON, R.D., AND SCHIEBER, J., 2014, Muddy prodeltaic hyperpycnites in the lower Genesee Group of Central New York, USA: implications for mud transport in epicontinental seas: Journal of Sedimentary Research, v. 84, p. 866–874.

WITZKE, B.J., AND HECKEL, P.H., 1988, Paleoclimatic indicators and inferred Devonian paleolatitudes of Euramerica, *in* McMillan, N.J., Embry, A.F., and Glass, D.J., eds., Devonian of the World: Canadian Society of Petroleum Geologists, Memoir 14, p. 49–63.

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.

ZAMBITO, J.J., IV, BRETT, C.E., AND BAIRD, G.C., 2012, The late Middle Devonian (Givetian) Global Taghanic Biocrisis in its type area (northern Appalachian Basin): geologically rapid faunal transitions driven by global and local environmental changes, *in* Talent, J.A., ed., Earth and Life: Global Biodiversity, Extinction Intervals, and Biogeographic Perturbations through Time: New York, Springer, p. 677–703.

Received 6 February 2015; accepted 8 September 2015.