Sediment transport processes and lateral facies gradients across a muddy shelf: Examples from the Geneseo Formation of central New York, United States

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ABSTRACT

Studying fine-grained siliciclastic deposits of late Middle Devonian in the northern Appalachian Basin provides an exquisite natural laboratory to observe the complex environments in which mud can accumulate. More detailed correlation and facies characterization of this succession provide a wealth of information and insight into the diverse transport mechanisms responsible for distributing clastics hundreds of kilometers away from a tectonically active source area. Commencement of the third tectophase of the Acadian orogeny and a concurrent transgression is expressed throughout the region through the development of a basin-scale unconformity (the Taghanic Onlap) above a shelf collapse (i.e., Tully Limestone) and widespread deposition of organic-matter–rich mudstones. Deposition of the lower Genesee Group is believed to reflect the coupling of this local expression of a global eustatic highstand event and contemporaneous cratonic downwarping as a flexural response of the craton to a continent–microcontinent collision. High-resolution stratigraphy has allowed differentiation of genetically related packages, composed of distinct lithofacies, with characteristic physical, biological, and chemical attributes. The present paper advances an overview of this detailed investigation based on detailed core measurement and surface correlation to assess the controlling factors on the mid-Devonian stratigraphic fill of the northern Appalachian Basin and demonstrate the distribution in mudstone facies and their relation to changing environmental conditions.

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INTRODUCTION

A long history of geological study exists for the Devonian foreland strata of the northern Appalachian Basin, representing a global reference section because of the nearly complete stratigraphic record with significant continuous sections exposed throughout the state. Units observed on this trip reflect the weathering and denudation of a renewed orogen, supplying fine-grained detritus to a rapidly subsiding foreland basin. At that time, an oblique convergence between Laurentia and Avalon terranes fostered 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 (Ettensohn, 1985, 1987; Faill, 1985; Figure 1). This event drastically reshaped the depositional and biological character of the basin, which is exemplified in a transition from platform carbonate deposition into distal offshore organic-rich facies (i.e., Tully Formation–Geneseo Formation). Tectonically induced subsidence was compounded with a eustatic sea-level rise, further supporting regional flooding of the craton and dysoxic to intermittently anoxic conditions across the basin. Moreover, the northern Appalachian Basin was situated 30°–35° south of the equator (Figure 2). As illustrated in Figure 2, some parts of Laurentia were emergent, whereas other parts were covered by a shallow sea. Globally, the Middle–Late Devonian has been characterized as being dominated by greenhouse conditions with 4–12 times present-day pCO_2 (Berner, 1990).

Changing basinal conditions along with potential global warming may have caused what is referred to as the global Taghanic Bioevent, which resulted in the demise of Middle Devonian taxa worldwide and impactful shifts in trophic and community structure (Johnson, 1970; Aboussalam, 2003; Baird and Brett, 2008). As the hinterland was carved and denuded, enhanced delivery of fine-grained detritus and terrestrial-derived nutrients fostered high surface-water algal productivity and widespread burial of organic carbon (Algeo et al., 1995). Drainage of the Acadian terrain fueled delta growth and offshore-directed sediment dispersal, which is expressed at aggradational to progradational stacking patterns observed in the Geneseo Formation. The peak of organic-carbon preservation is recognized in basal parts of the Geneseo Formation, which constitute the most distal facies deposited subsequent to this phase of tectonism. Following active thrust loading, sediment input eventually outcompetes the rate of basin subsidence, and the foreland basin fills with clastic sediments. As a result, coarser-grained facies belts migrate basinward.

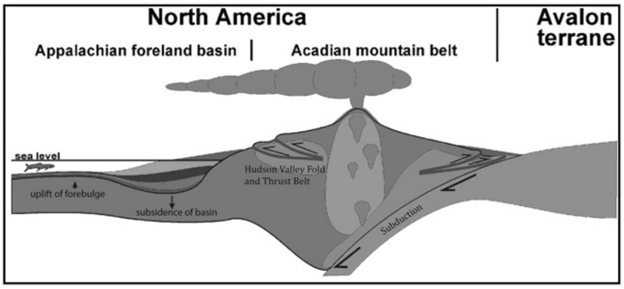

Figure 1. Idealized cross section of the Appalachian foreland basin during the Acadian orogeny. Note the collision and subduction of Avalonia to Laurentia (North America), creating a retroarc fold and thrust belt (modified from Ver Straeten, 2004).

Stratigraphic Framework

Because of the historic attention awarded to the Devonian strata of the eastern United States, a large number of lithostratigraphic, chemostratigraphic, and biostratigraphic studies enabled the development of a fully integrated stratigraphic hierarchy (Johnson et al., 1985; Baird and Brett, 1986, 2008; House and Kirchgasser, 1993; Ver Straeten, 2004; Brett et al., 2011). Inasmuch as extensive surface correlation has resulted in a high-resolution, fully integrated stratigraphic framework, an issue that persists is the abundance of unit and member names adopted by various workers.

For the purpose of this paper, the Geneseo Formation herein is subdivided into three members (i.e., Lower Geneseo Member, Fir Tree Member, Upper Geneseo Member; Figures 3, 4). Locally, the Lower Geneseo Member overlies the Tully Formation, and where the latter is absent, its basal contact is marked by a pyritic-phosphatic lag (the Leicester Pyrite Bed). The Fir Tree Member unconformably overlies the Lower Geneseo and consists of silt-rich calcareous mudstones rich in auloporid tabulate corals, ostracods, and small brachiopods. The Upper Geneseo displays dark-gray silty mudstones and muddy siltstones with abundant wave/current ripples, graded beds, and evidence of extensive reworking and erosion.

Detailed Facies Characterization

Detailing the small-scale variability observed in fine-grained strata is a critical aspect for inferring past environments of deposition. There have been significant advances over the last decade in recognizing pertinent information in terms of physical bedforms and biologic attributes in a stratigraphic context (Lazar et al., 2015). Despite these efforts to define a methodic framework to characterize mudstone-rich successions, it can be quite cumbersome and difficult, particularly in outcrop exposures. For the lower Genesee succession, samples were collected from the field for thin-section preparation as well as polishing hand samples to assist unveiling the small-scale features and linking with the outcrop expression. Throughout this succession in central New York, nine mudstone facies were identified and were used to establish a stratigraphic depositional framework (Figure 4).

Mudstone Facies of the Lower Geneseo Member

The Lower Geneseo Member stratigraphically rests above the Tully Limestone and beneath the Fir Tree Member and represents the initial phases of thrust

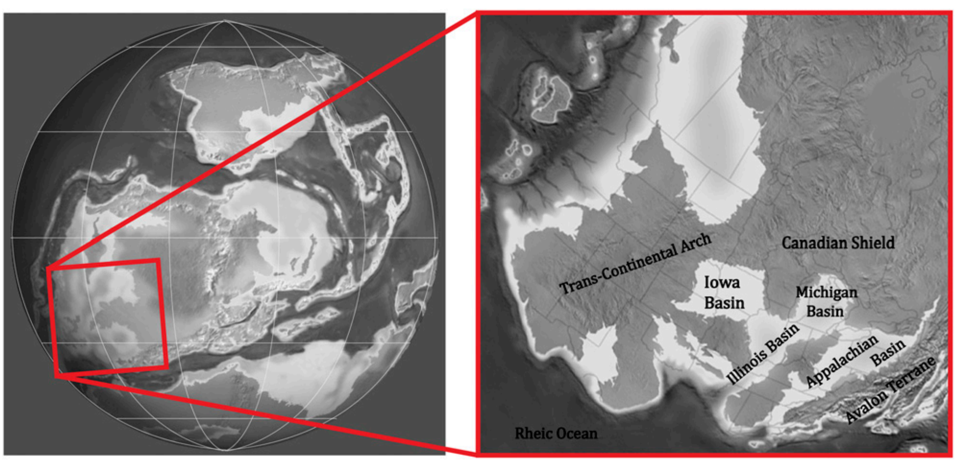

Figure 2. Middle Devonian paleogeographic map modified after Blakey (2005). Global map zooms into the eastern North America during the Middle Devonian. Various structural features and basins are outlined on the right. Note the continent–microcontinent(s) collision producing a rotational, "scissorlike" closure and uplift of the Avalon Terrane.

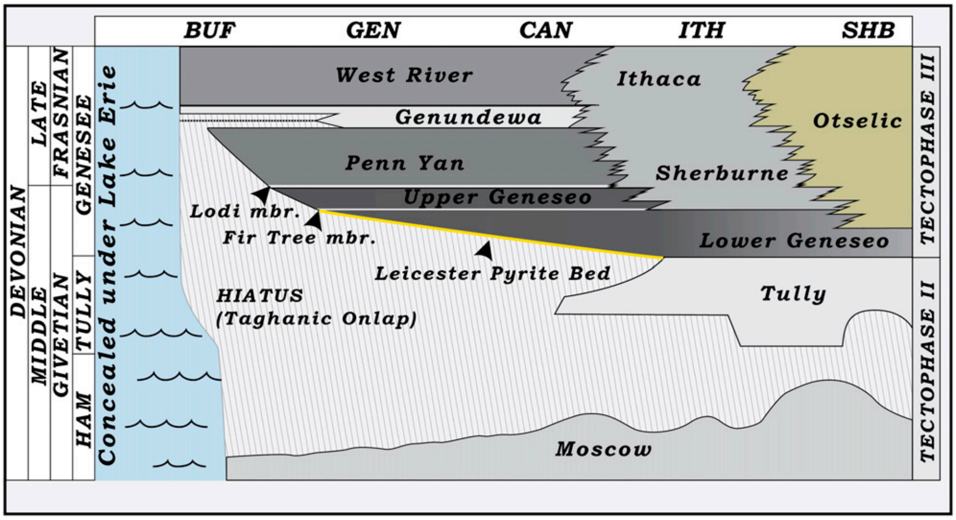

Figure 3. Generalized chronostratigraphic chart for Middle–Late Devonian strata of New York (Wilson and Schieber, 2014, 2015). The Geneseo Formation marks the onset of the third tectophase of the Acadian orogeny. Thrust loading and cratonic downwarping coincided with a major transgression (transgressive–regressive [T-R] cycle IIa). The Genesee Group onlaps the Taghanic disconformity westward; thus, the ages of the onlapping Geneseo and Penn Yan Shales become progressively younger westward. BUF = Buffalo; CAN = Canandaigua; GEN = Geneseo; ITH = Ithaca; mbr. = member; SHB = Sherburne.

loading and cratonic downwarping during the third phase of the Acadian orogeny. Consequently, orogenesis was coupled with a eustatic rise in sea level, resulting in an expansive epicontinental seaway that covered much of eastern Laurentia. As a result, extensive depositions of organic-matter–rich sediments were spread throughout the basin, and coeval deposits can be traced to the neighboring basins (i.e., Illinois and Michigan basins). Continental flooding in association with limited water circulation has been a key factor for many depositional models for Devonian organic-rich mudstones in the Appalachian Basin (Murphy et al., 2000; Werne et al., 2002; Sageman et al., 2003; Algeo et al., 2007).

The most prevalent facies throughout the Lower Geneseo Member is a banded grayish-black mudstone (BBM), and it manifests as the most organic-rich facies of the succession (Figure 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 laminaset normal grading. Many sedimentologists would be inclined to describe this facies as “finely laminated,” “homogeneous,” or perhaps even “monotonous.” That being said, careful petrographic and microscopic inspection demonstrate that deposition occurred in quite an energetic environment, because this facies preserves many features that indicate traction transport and reworking of the seabed. Upsection, basal deposits of the BBM facies grade into dark-gray mudstones with an increase in erosional contacts, current- and wave-formed features, and bioturbation intensity and diversity (Figure 6).

An interesting facies development throughout the Geneseo is the presence of intercalated silty mudstones and muddy siltstones with terrestrial phytodetritus, normal and inverse laminaset grading, convolute bedding, as well as current- and wave-formed features indicating event deposition through lateral transport (Figures 7, 8). In outcrop, this facies is typically expressed as recessive beds that interrupt the organic-rich facies of the Lower Geneseo and can be difficult to sample because of textural integrity. Stratigraphic correlation can be aided by recognizing carbonate concretion and cemented horizons that occur at multiple levels and manifest as prominent beds and ridges in outcrop.

Depositional Environment of the Geneseo Formation

Key takeaways from the preceding observations demonstrate the infilling of a rapidly subsiding foreland basin subsequent to a major orogenic event. Rejuvenation of the Acadian terrain as a clastic source supplied considerable volumes of fine-grained terrigenous sediment to the deltaic system. Although expansion of the seaway inundated a vast majority of the continent, sediment supply began to overwhelm accommodation as sediments were shed from the hinterland for dispersal to the shelf and offshore setting.

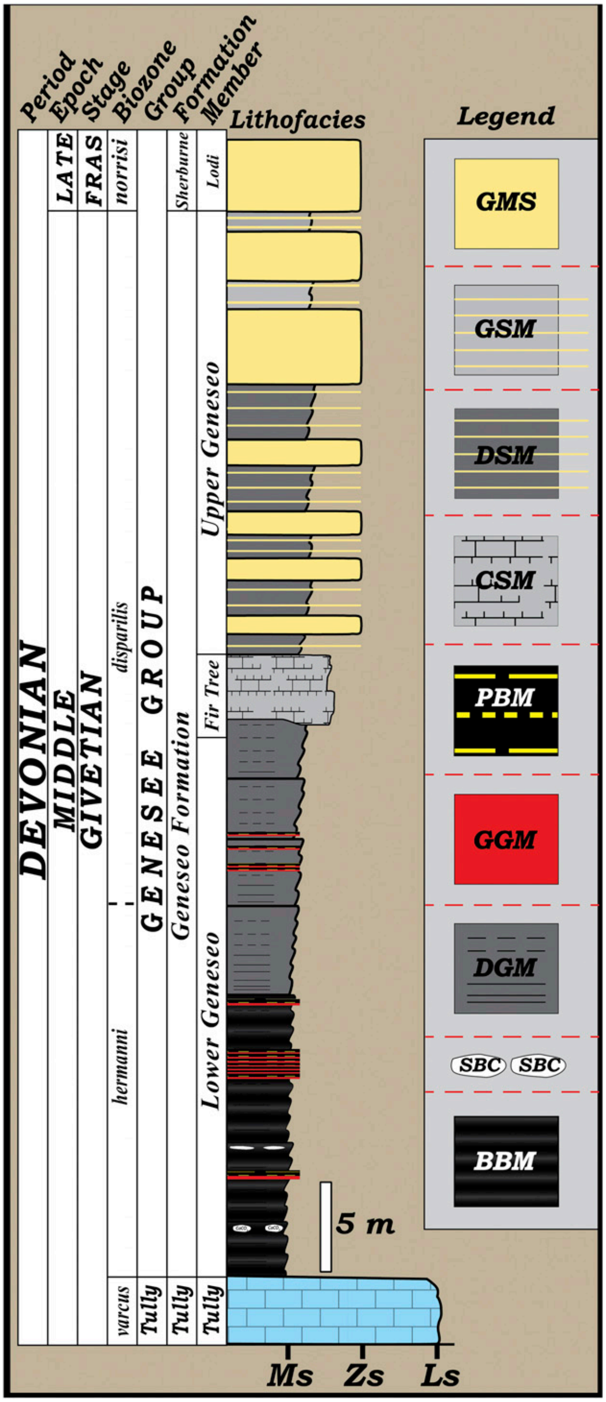

Figure 4. Lithostratigraphic section of the lower Genesee Group drafted from the Lansing drill core. Note the vertical facies progression from basal organic-rich mudstones of the Lower Geneseo to organic-lean muddy siltstones reflecting progradation of the Catskill delta. BBM = banded black mudstone; CSM = calcareous silty mudstone; DGM = dark gray mudstone; DSM = dark gray silty mudstone; GM = graded gray mudstone; GMS = gray muddy siltstone; GSBC = strongly bioturbated calcareous mudstone; GSM = gray silty mudstone; Ls = limestone; Ms = mudstone; PBM = pyritic black mudstone; Zs = siltstone.

Through many depositional processes, basinward migration of the shoreline is indicated via progradational parasequence stacking patterns and a systematic increase in benthic fauna and wave-formed features upsection. The abundance of current- and wave-related features displayed throughout the various facies suggests that deposition did not occur as a result of suspension settling in a stagnant seaway; instead, episodic storm events and bottom currents were the primary agents for sedimentation. Organic-richness of the succession, particularly in the BBM facies, appears to be a function of primary productivity as well as decreased clastic input (dilution) following the deepening event that occurred.

The Lower Geneseo Member is capped by a sequence boundary that marks a drastic seaward migration of the shoreline and resulted in deposition of the auloporid-rich, calcareous silty mudstones of the Fir Tree Member (Baird et al., 1988). Above the Fir Tree Member, the Upper Geneseo Member (also known as Hubbard Quarry Member) is observed and represents a landward migration of the paleoshoreline. However, tectonically driven sediment supply outpaced the change in accommodation, and coarser-grained facies of the Sherburne Formation interfinger with the Upper Geneseo Member (including the Fir Tree and Lodi Members; Baird et al., 1988). Thus, the Upper Geneseo Member consists of gray silty mudstones and muddy siltstones, reflecting progradation of the Catskill delta and a basinward migration of coarser-grained facies belts. Internally, the Upper Geneseo is composed of gray silty mudstones and muddy siltstones that show hummocky cross-stratification, ripple cross-lamination, climbing ripples, scour surfaces, and intense bioturbation. Depositionally, the Upper Geneseo Member records relatively continuous background sedimentation that is interrupted by major storms.

CONCLUDING REMARKS

The Geneseo Formation of New York represents a complex interplay between tectonically driven accommodation and sediment supply and eustatic sea-level rise. Throughout the deposition of this mudstone-dominated succession, the onset of the third tectophase of the Acadian orogeny put downward pressure on eastern Laurentia. The resulting

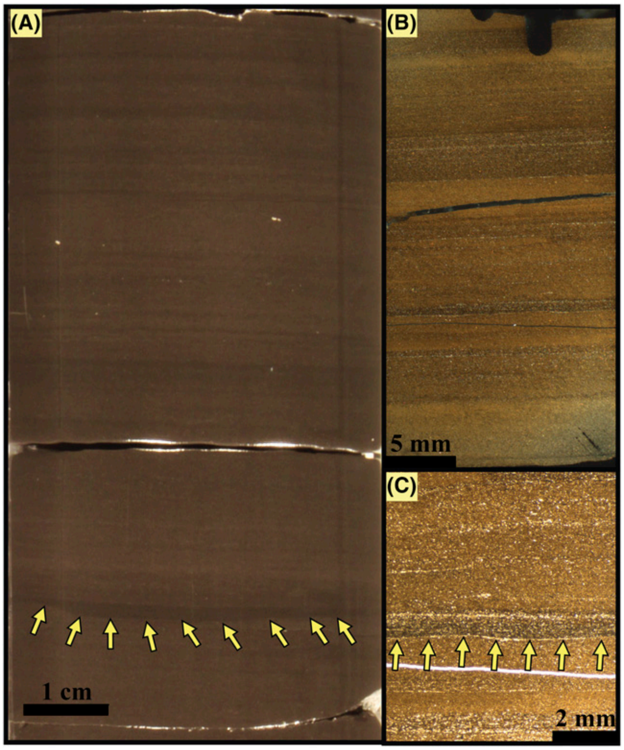

Figure 5. (A) Image of polished hand sample (contrast enhanced) of the banded grayish-black mudstone facies, showing a subtle erosional scour infilled with darker muds (arrows). (B) Photomicrograph showing predominant horizontal banding with alternating light and dark layers with subtle erosional scours and continuous to discontinuous silt laminae caused by bottom-current sorting and transport. 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. (C) Overview image of thin section with continuous to discontinuous, planar-parallel silt lamina/laminasets with scoured bases (arrows).

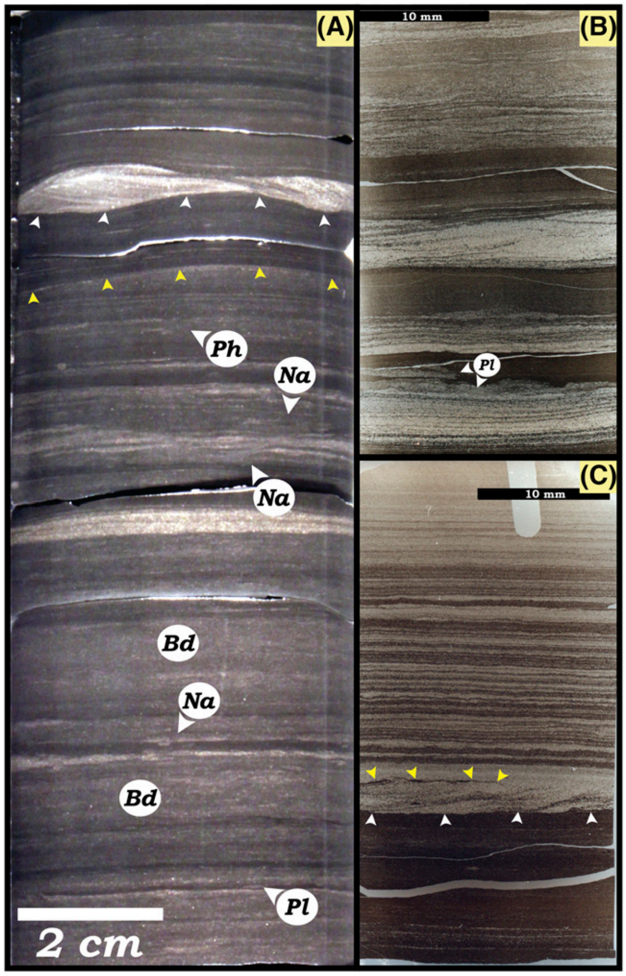

Figure 6. (A) Hand sample image (contrast enhanced) of the dark-gray mudstones (DGM) facies showing erosional features (yellow arrows), current ripples, wave ripples with arcuate scalloped topography (white arrows), laminaset grading, disrupted lamina, and bioturbation/biodeformational structures. The DGM facies contains biodeformation (Bd), navichnia traces (Na), and a suite of ichnogenera including *Planolites* (Pl) and *Phycosiphon* (Ph). The increase in bioturbation intensity (bioturbation index [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, we see planar-laminated to low-angle cross-laminated silt-rich beds that fine upward into sparsely to moderately bioturbated (BI = 2–3) DGM. 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-upward trend, which probably reflects a more proximal environment (coarser clastic influx) with extensive current reworking.

rapid subsidence of the Appalachian foreland basin allowed extensive deposition of organic-rich mudstones (Ettensohn, 1985, 1987). During active tectonism, rapid subsidence of the foreland basin followed by periods of stagnation have been key factors in depositional models for Devonian black shales of the eastern United States (Ettensohn et al., 1988; Brett and Baird, 1996). The Geneseo Formation represents the basal black shale of the third tectophase of the Acadian orogen and diachronously overlies the Tully Limestone in central New York. In western New York, this unconformity is marked by the Leicester Pyrite Bed, separating the Geneseo Formation from the underlying Windom Shale in areas where the Tully Limestone has been eroded

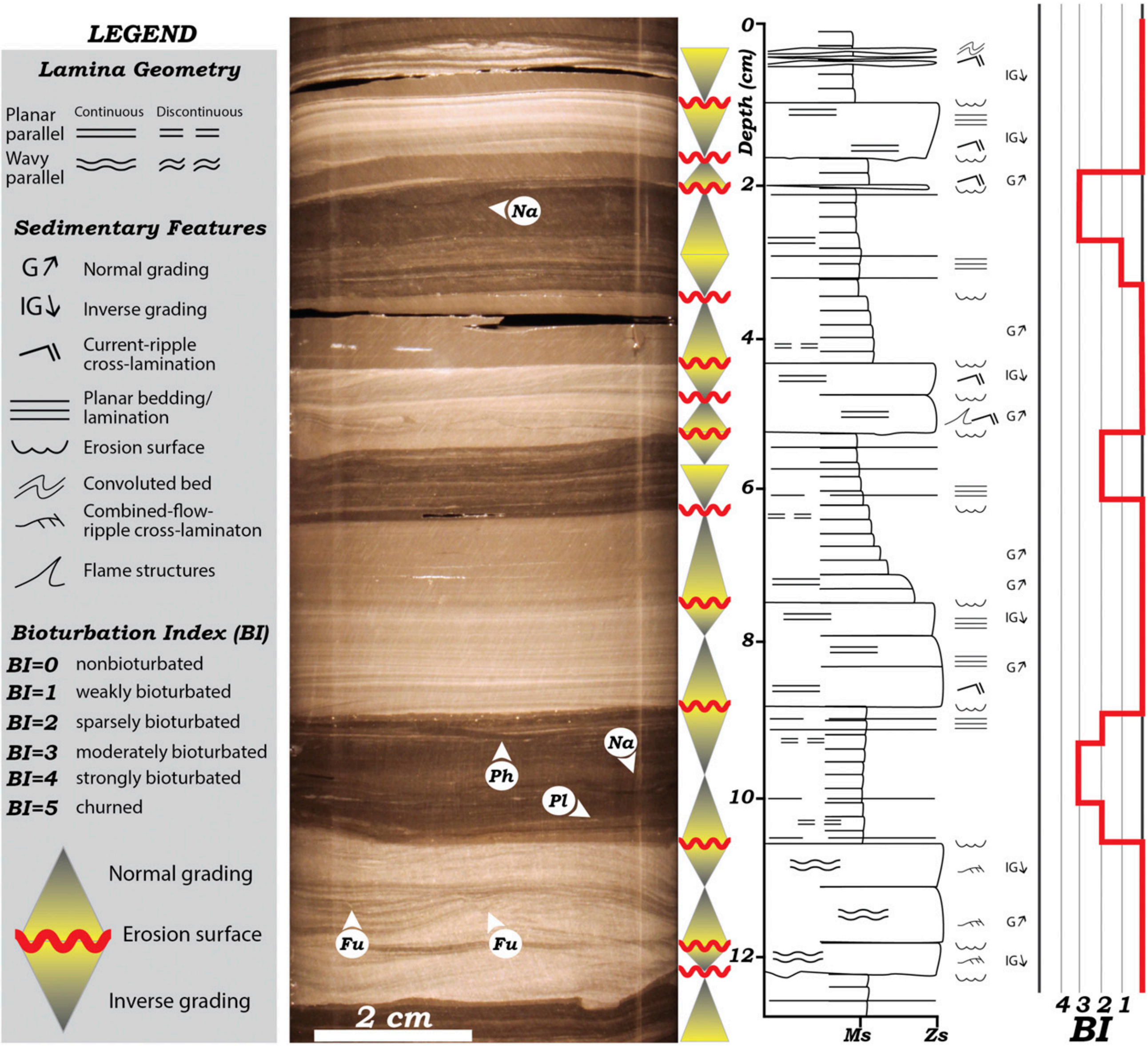

Figure 7. Photograph and detailed measured section of closely stacked hyperpycnal layers, consisting of interbedded, moderately bioturbated (BI = 3) silty mudstone and unbioturbated (BI = 0–1) muddy siltstones with erosional scours, soft-sediment deformation, normal and inverse laminaset grading, and current-, wave-, and combined-flow ripples (see legend). Various trace fossils are present, including fugichnia traces (Fu), navichnia traces (Na), *Planolites* (Pl), and *Phycosiphon* (Ph). The BI is from Taylor and Goldring (1993); it is shown as a vertical bar graph. Ms = mudstone; Zs = siltstone.

(Baird et al., 1988; Baird and Brett, 1991; Brett and Baird, 1996).

Water depths were probably greatest during the deposition of the Lower Geneseo Formation. After the major marine transgression that is marked by the Lower Geneseo, fine-grained sediments were transported westward via rapid deposition of mud blankets from density-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 was probably just beneath the sediment–water interface, only allowing organisms to penetrate a few millimeters into the sediment. Poorly defined layer boundaries and lamina disruption are suggestive of disturbance of surficial sediments by small meiofaunal organisms, such as nematodes, polychaete worms, and benthic foraminifera. The additional presence of agglutinated foraminifera and fecal pellets of benthic sediment feeders further confirms this assessment. What emerges is a picture of an

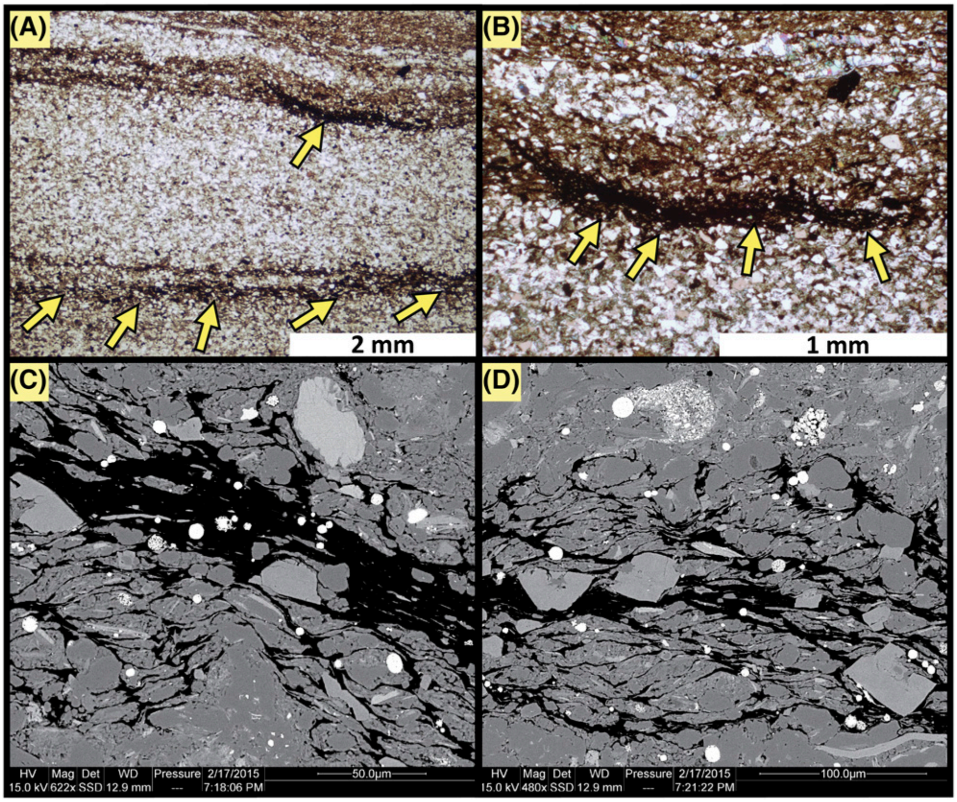

Figure 8. (A) Photomicrographs showing enrichment of terrestrial phytodetritus in clay-rich laminae of wave-aided hyperpycnal flows (yellow arrows). (B) Zoom to larger phytodetritus (>1 mm in diameter). (C) Backscatter image detailing the cellular structure of terrestrial phytodetritus. (D) Zoom to other region of backscatter image with terrestrial organic-material detailing cellular structure as well as enhanced diagenetic overprint (white pyrite framboids). Det = detector; HV = high voltage; Mag = magnification; SSD-BSD = solid state backscattered detector; WD = working distance.

oxygen-restricted (but generally not anoxic) sea floor that was intermittently swept by currents that transported mud across the sea floor. The general absence of larger trace fossils suggests that the bottom waters were generally too low in oxygen to allow colonization by larger soft-bodied metazoans but had just enough oxygen to allow small, low-oxygen–tolerant specialists to thrive.

Upsection, the Lower Geneseo Member is characterized by dark-gray shales with abundant wave and current ripples, graded beds, and increased abundance of macroscopically visible bioturbation. Thus, the Lower Geneseo displays an aggradation to progradational succession, reflecting increased sediment supply upsection and closer proximity to the shoreline upsection. Judging from sedimentary features, the sediments of the Fir Tree Limestone Member probably reflect initial deposition on a shallower-water, mud-dominated shelf. Accelerated deepening probably drowned these strata, and sediment starvation led to formation of an "overprinted" diagenetic concretionary carbonate bed. Newly generated accommodation allowed renewed deposition of organic-rich, fine-grained clastics, represented by the Upper Geneseo Member. In central New York, dark-gray silty mudstones grade vertically into dark muddy siltstones as the Sherburne Formation interfingers the Geneseo Formation. This expression represents another shallowing-upward succession as a result of progradation and increasing sediment supply.

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