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The Influence of Primary and Secondary Sedimentary Features on Reservoir Quality: Examples from the Geneseo Formation of New York, U.S.A.

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ABSTRACT

The Middle Devonian Geneseo Formation and its lateral equivalents in the Northern Appalachian Basin are regarded as crucial secondary targets to the extensively explored Marcellus subgroup. High-resolution sedimentology, stratigraphy, and petrography have yielded differentiation of genetically related packages, comprised of distinct lithofacies with characteristic physical, biological, and chemical attributes. In addition, argon ion milling and nanoscale scanning electron microscopy of shale sections has shown that the pore structure of the Geneseo derives from pores defined by phyllosilicate frameworks, carbonate dissolution, and within organic matter. Intervals of silt-rich mudstones and muddy siltstones occur in multiple facies types and "interrupt" facies, reflecting background sedimentation. These deposits and their sedimentary features are interpreted as products of high-density fluvial discharge events.

Pore morphology and distribution correlates with distinct mudstone lithofacies as a result of small-scale compositional and textural characteristics. Phyllosilicate framework pores are small triangular openings (100–1500 nm wide) and are the dominant pore type observed in hyperpycnites. Organic matter porosity is common (10–500 nm pore size) and dominates the organic-rich facies that represents "background" sedimentation with high organic content. Carbonate dissolution pores (50–500 nm wide) are observed in calcareous intervals and reflect partial dissolution of carbonate grains during catagenetic formation of carboxylic/phenolic acids.

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INTRODUCTION

Characterizing the microstructure of fine-grained sediments and sedimentary rocks has been of interest to both academic and industry researchers, spanning a multitude of fields and applications (Bennett et al., 1991). At present, most research regarding the genesis and preservation of shale porosity is aimed at documenting its variability in morphology and structure (Loucks et al., 2012; Driskill et al., 2013; Rine et al., 2013). The underlying causes of pore structure and preservation in unconventional reservoirs, however, are still poorly understood. The goal to provide predictive capabilities away from data control, to enhance basin-scale characterization of shale formations, is still elusive.

Application of shale sedimentology and petrography is highly relevant for maximizing the benefits of technological advances in the production of hydrocarbons from tight reservoirs. Unconventional reservoir character varies at the millimeter to kilometer scale vertically and laterally. Yet, although it is generally acknowledged that variations in mudstone properties have a dramatic effect on producibility of tight reservoirs, the underlying controls are not well understood.

Middle to Upper Devonian organic-rich shales of the Northern Appalachian Basin have been extensively evaluated for economic viability as unconventional resources. Throughout the exploration of these targets, lateral variability in thickness, mechanical properties, and organic content is not adequately explained with existing depositional models that view these deposits as the result of slow, consistent sediment accumulation in a stratified water column with anoxic conditions throughout the basin. At closer inspection, an array of sedimentary features suggest multiple modes of sediment transport and deposition in a complex depositional environment (Wilson and Schieber, 2014). These features include scour surfaces, normal and inverse lamina-set grading, current- and wave-formed features, and varying intensity and diversity of bioturbation. The variability preserved in these strata, although at times quite subtle, requires detailed sedimentologic and petrographic evaluation from the macro- to nanoscale to arrive at an integrated reservoir characterization (Bohacs et al., 2012).

The Middle Devonian Geneseo Formation of New York is a clastic-dominated, organic-rich mudstone succession that records the westward progradation of the Catskill Delta during the third tectophase of the Acadian Orogeny (Figure 1). During this tectonic event, crustal downwarping due to thrust-loading along the eastern edge of Laurentia generated

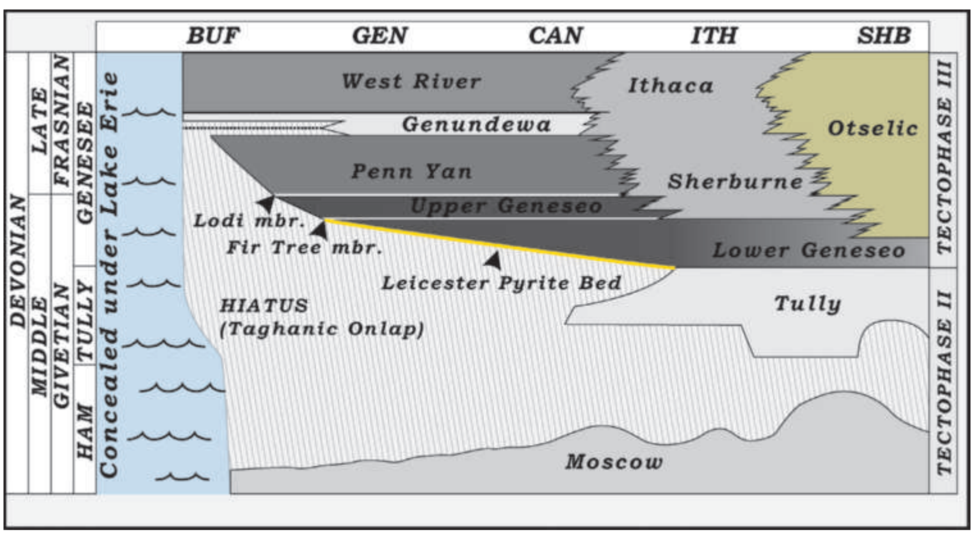

Figure 1. Generalized chronostratigraphic chart for Middle-Late Devonian strata of New York (SHB = Sherburne, ITH = Ithaca, CAN = Canandaigua, GEN = Geneseo, BUF = Buffalo, HAM = Hamilton Group). The Geneseo Formation marks the onset of the third Tectophase of the Acadian Orogeny (Ettensohn, 1987), the 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 Kirchgasser et al. (1997) and includes data from Baird and Brett (1986, 1991), Baird et al. (1988), Kirchgasser et al. (1988), Bridge and Willis (1991, 1994), Brett and Baird (1996), and Brett et al. (2011).

accommodation in the Appalachian Basin for easterly derived clastics (Ettensohn, 1985). The succession consists of a multitude of mudstone facies, and through the use of physical, biologic, and chemical attributes (Wilson and Schieber, 2015), can be differentiated into genetic packages based on their stratal geometry and parasequence development (Wilson, 2012).

Recent recognition of wave-aided hyperpycnites in the Geneseo indicate dynamic sediment redistribution and transport in this organic-rich mudstone succession (Wilson and Schieber, 2014; Wilson and Schieber, 2015). River-flood and storm-wave generated offshore-directed underflows were responsible for transporting large volumes of fine-grained sediment and phytodetritus to offshore regions. These rapidly deposited organic-lean intervals, dominated by clay- and silt-sized particles and terrestrial phytodetritus, greatly affect reservoir quality in the proximal- to medial-shelf settings.

Nanometer-scale imaging of shale porosity was aided by argon ion milling to produce smooth and mechanically unaltered surfaces for electron microscopy. This technique has been utilized in the material sciences for decades and allows precise etching of a surface using a highly collimated argon beam (Dolph and Santeufemio, 2014). Scanning electron microscopy of the Geneseo Formation allowed definition of three principal pore types: (1) phyllosilicate framework (PF) pores that are triangular openings (100–1500 nm wide) defined by clay and mica flakes, (2) organic matter (OM) pores in kerogen particles and organo-clay aggregates (10–500 nm wide), and (3) carbonate dissolution (CD) pores. Porosity in the Geneseo is directly related to facies development within a sequence stratigraphic framework and corresponds to composition, texture, and organic richness.

METHODOLOGY

Materials for this study were sampled and prepared at the Indiana University Shale Research Lab. A drill core from Lansing, New York, U.S.A. (Figure 2), was measured in detail, and samples were collected to capture changing sedimentologic character. The bioturbation index (BI) of Taylor and Goldring (1993) was used to quantify bioturbation intensity. Samples were cut with a rock saw and sent to Wagner Petrographic for thin sectioning. In addition, 5 × 5 mm slices were mounted, and ion milled for SEM analysis. The possibility that artificial pores might be produced in OM due to ion-beam heating was a serious concern. We adopted the following procedure to eliminate misinterpretation of artifacts. First, samples were given a multistep low-pressure mechanical polish to 0.1 μm, rinsed and cleansed gently with distilled water, blown dry with compressed air, and then examined and photographed with the SEM (FEI

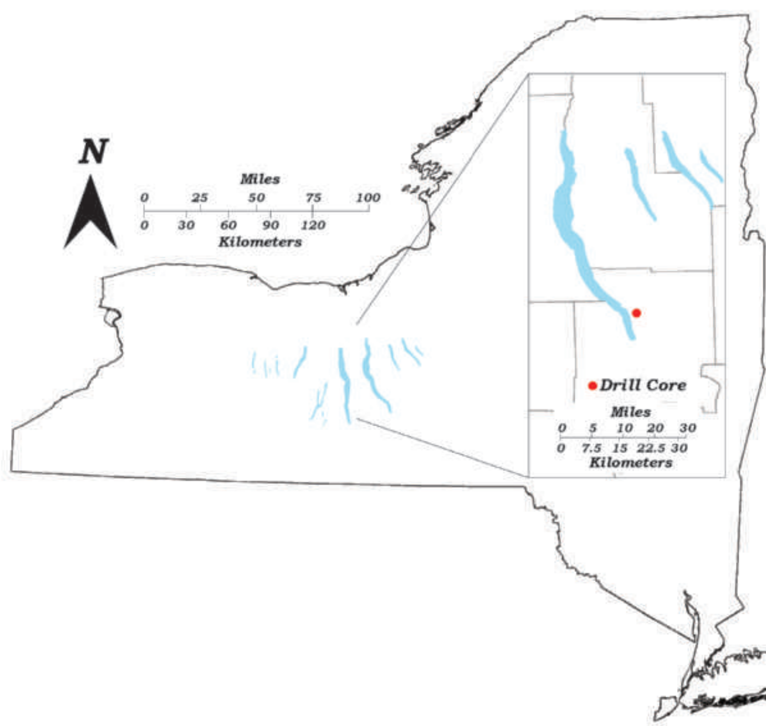

Figure 2. Overview map of New York and drill core location on the southeastern edge of Cayuga Lake in Lansing, New York.

Quanta 400 FEG). Second, after first-pass ion milling with a Gatan 600 DuoMill™, samples were examined again with the SEM, and the same areas as previously examined were photographed a second time. Third, photographs of mechanically polished versus ion-milled surfaces were compared. In this way, we were able to verify that the pores that we saw clearly once samples had been ion milled were already visible on mechanically polished surfaces. Use of the Gatan 600 DuoMill™ did not produce noticeable changes of pore distribution or pore size at room temperature operations. Using the Gatan 600 DuoMill™, slices of shale (up to 12.5 mm across) were ion milled to produce smooth and mechanically unaltered surfaces for analyzing pores and grains in the nanometer-size range.

To further verify the quality of our large diameter polishes, we used a Gatan Ilion™ edge mill to make polishes of a subset of 10 samples (duplicates from the set of 28 samples examined initially). The Gatan Ilion™ is a cross-beam ion mill that produces a high-quality polished area of about 0.3–2 mm^2, and the sample stage can be cooled with liquid nitrogen (LN_2). In contrast to the Gatan 600 DuoMill™, the Gatan Illion™ has narrow and sharply focused argon ion beams, and this makes its polishing action considerably more aggressive than that of the Gatan 600 DuoMill™. The milled area is substantially smaller than the area achieved with the Gatan 600 DuoMill™, but the generated surfaces are of excellent flatness.

The milled sample surfaces were examined without conductive coating with an FEI Quanta 400 FEG in low vacuum mode. We used noncoated samples because coating artifacts are in the same size range (nm's to 10s of nm's) as the pores that we were interested in observing. Operation in low vacuum mode does cause beam dissipation and loss of resolution, and we counteracted this effect by choosing close working distances and comparatively high beam voltages (typically 15 kV). The latter can potentially cause damage to organic material in the specimen, but was permissible because of the comparatively high maturity of the studied samples. Energy-dispersive x-ray spectroscopy was used to examine the composition of sedimentary particles.

SEDIMENTOLOGIC AND STRATIGRAPHIC EXPRESSION

The Geneseo Formation is a highly variable mudstone-dominated succession that represents the onset of the third tectophase of the Acadian orogeny (Ettensohn, 1985), as well as a general rise in eustatic sea level (Johnson, 1970). The combination of crustal downwarping with a eustatic sea-level rise caused the development of an expansive seaway that covered much of eastern North America. At this time, fine-grained detritus was shed from eastern source areas and delivered to the marine realm by a multitude of transport mechanisms that fueled the growth of the Catskill Delta.

The Geneseo Formation as described herein (Wilson and Schieber, 2015) is differentiated into three lithostratigraphic members: (1) the Lower Geneseo Member, (2) the Fir Tree Member, and (3) the Upper Geneseo Member (Figures 1, 3). Several mudstone facies can be identified in this succession on the basis of sedimentary structures, textural changes, composition, and biogenic attributes (Figure 4; Wilson and Schieber, 2015). The Geneseo Formation disconformably overlies the Tully Limestone, and where the latter is absent, the disconformity is in many places marked by a pyritic–phosphatic lag, the Leicester Pyrite Bed (Figure 3). The Lower Geneseo Member consists primarily of weakly to sparsely bioturbated (BI = 1–2), organic-rich banded mudstones with relict lamination and cryptobioturbation (Figure 4). Upsection, the Lower Geneseo Member grades into dark gray mudstones that show an increase of current- and wave-formed features, erosional contacts, as well as increased bioturbation intensity (BI = 3–4). Argillaceous limestones and calcareous silty mudstones of the Fir Tree Member separate the Lower and Upper Geneseo members. The Upper Geneseo Member consists primarily of dark gray silty mudstones and muddy siltstones (Figure 5) with abundant current- and wave-formed features, normal and inverse grading, erosional contacts, terrestrial phytodetritus (Figure 6), and decreased bioturbation intensity (BI = 0–2).

In the Geneseo Formation, the lithostratigraphic framework and facies distribution documents a general westward migration of the paleoshoreline over time. This inference is corroborated by an upsection increase in wave-formed features, silt-sized particles, bioturbation intensity and diversity, and a decrease in organic richness. Throughout the succession, complexly graded mudstones and siltstones are interbedded with the "background" organic-rich mudstones of the Lower and Upper Geneseo members. As discussed below, the sedimentary structures in these interbeds suggest that they originated as storm-wave-induced fluvial discharge events (hyperpycnal flows) that carried sediment several 10s to 100s of kilometers offshore (Wilson and Schieber, 2014).

Hyperpycnal flows occur when the density of riverine suspensions is higher than that of the waterbody

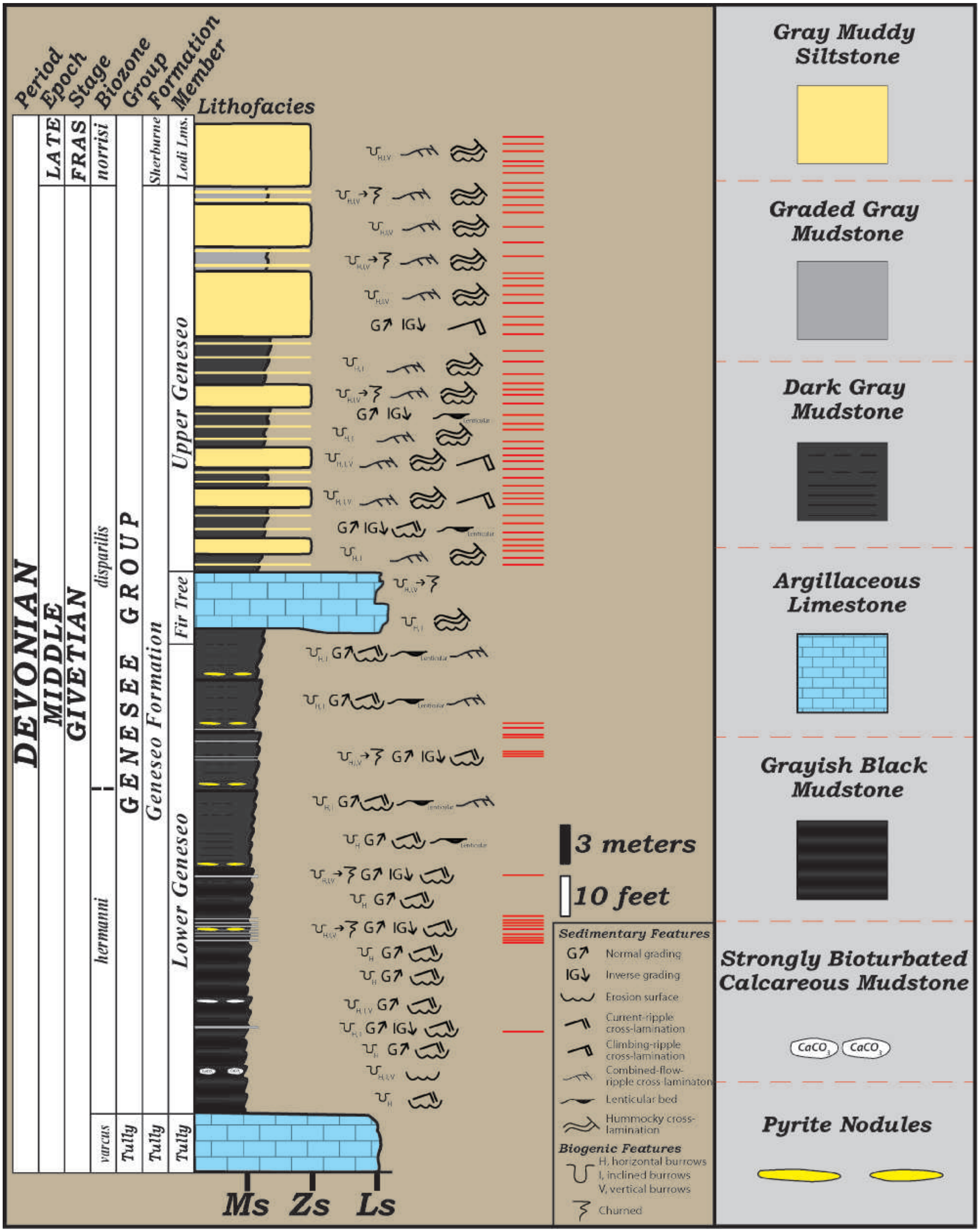

Figure 3. Stratigraphic column for lower Genesee Group strata (Ms = mudstone, Zs = siltstone, Ls = limestone) observed in drill core (location in Figure 2). Generalized lithostratigraphy and sedimentary features observed for the lower Genesee Group are represented, as well as vertical distribution of hyperpycnites recognized in the drill core (red horizontal lines from Wilson and Schieber, 2014).

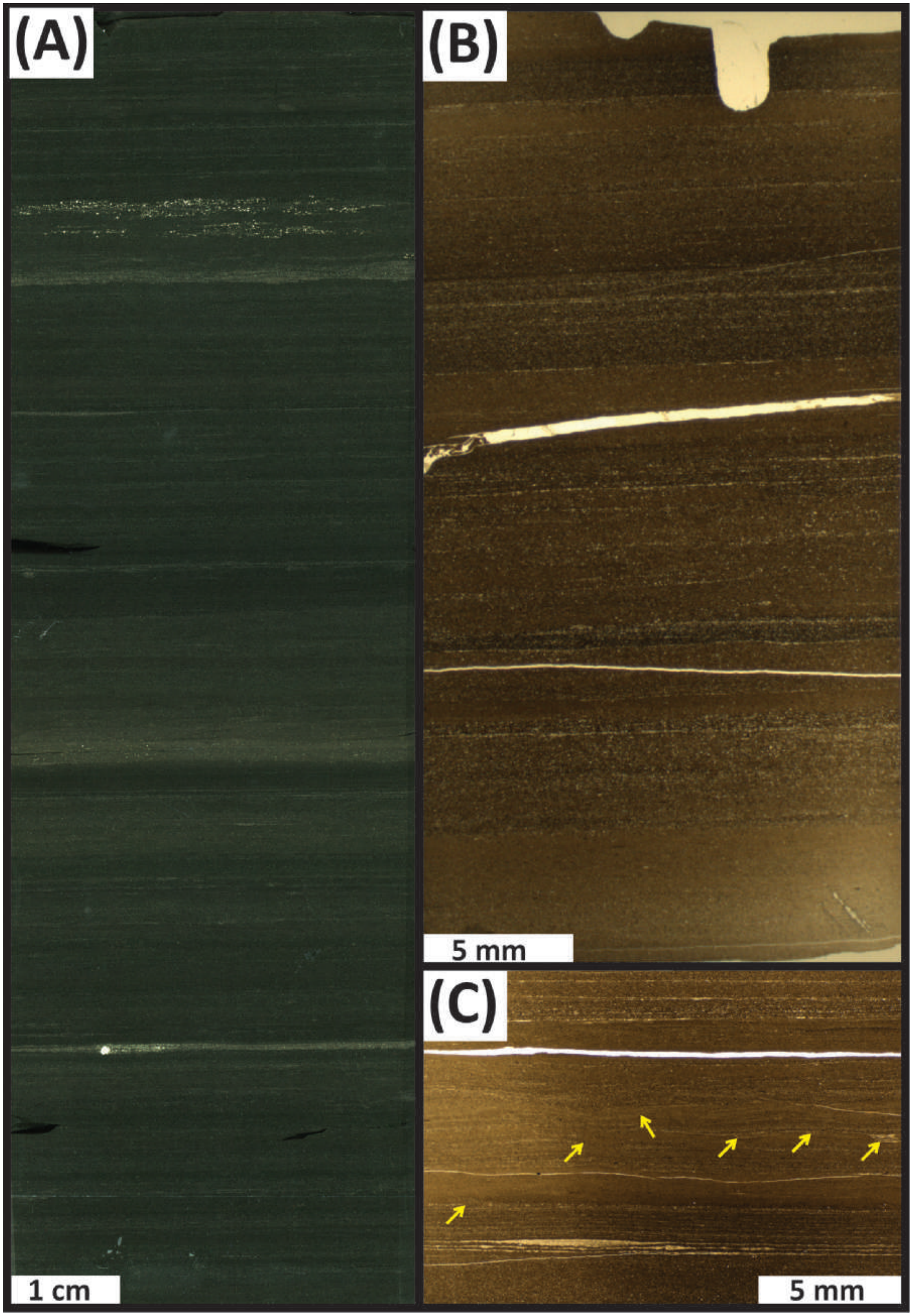

Figure 4. (A) Polished drill core showing diffusely banded and pyritic grayish-black shale, reflecting slowly accumulating fine-grained clastics and organic enrichment in "background" facies. (B) Photomicrograph of "background" banded grayish-black shale with alternating light and dark layers with subtle erosional scours and continuous to discontinuous silt laminae due to bottom current sorting and transport. (C) Photomicrograph of banded grayish-black shale with continuous to discontinuous silt laminae with scoured bases, as well as evidence of surficial traces by meiofauna (cryptobioturbation; yellow arrows).

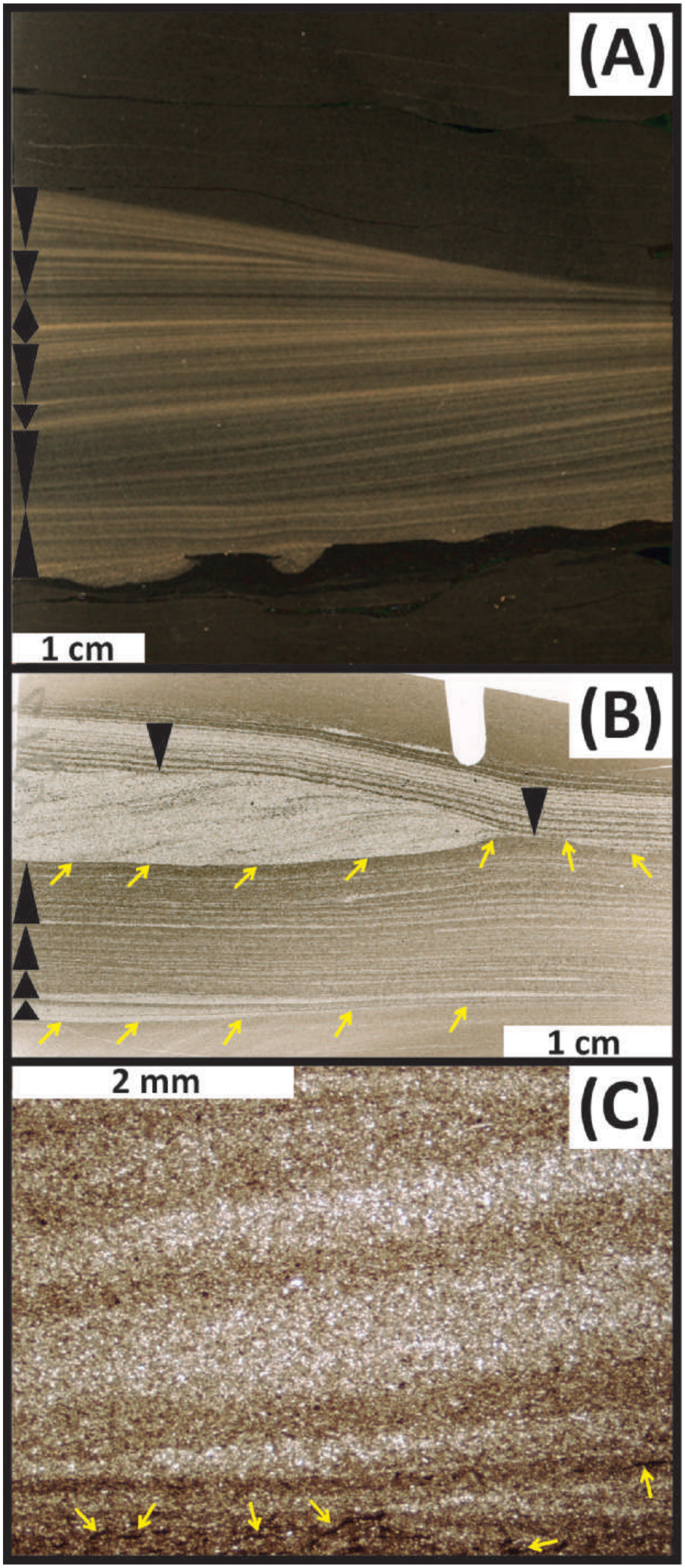

Figure 5. (A) Polished drill core showing a nonbioturbated silt-rich hyperpycnite with exquisite preservation of basal arcuate scalloped topography, normal and inverse lamina-set grading (black triangles), internal scours, and planar-parallel to low-angle cross-lamination, suggestive of sustained lateral sediment transport by turbulent flows with waxing and waning currents. (B) Photomicrograph of a rapidly deposited muddy hyperpycnite with multiple scales of normal and inverse grading (black triangles), internal scours, and planar-parallel to low-angle cross-lamination. (C) Photomicrograph of a silt-rich hyperpycnite with low-angle cross-lamination and terrestrial phytodetritus in the basal portion of the deposit (yellow arrows).

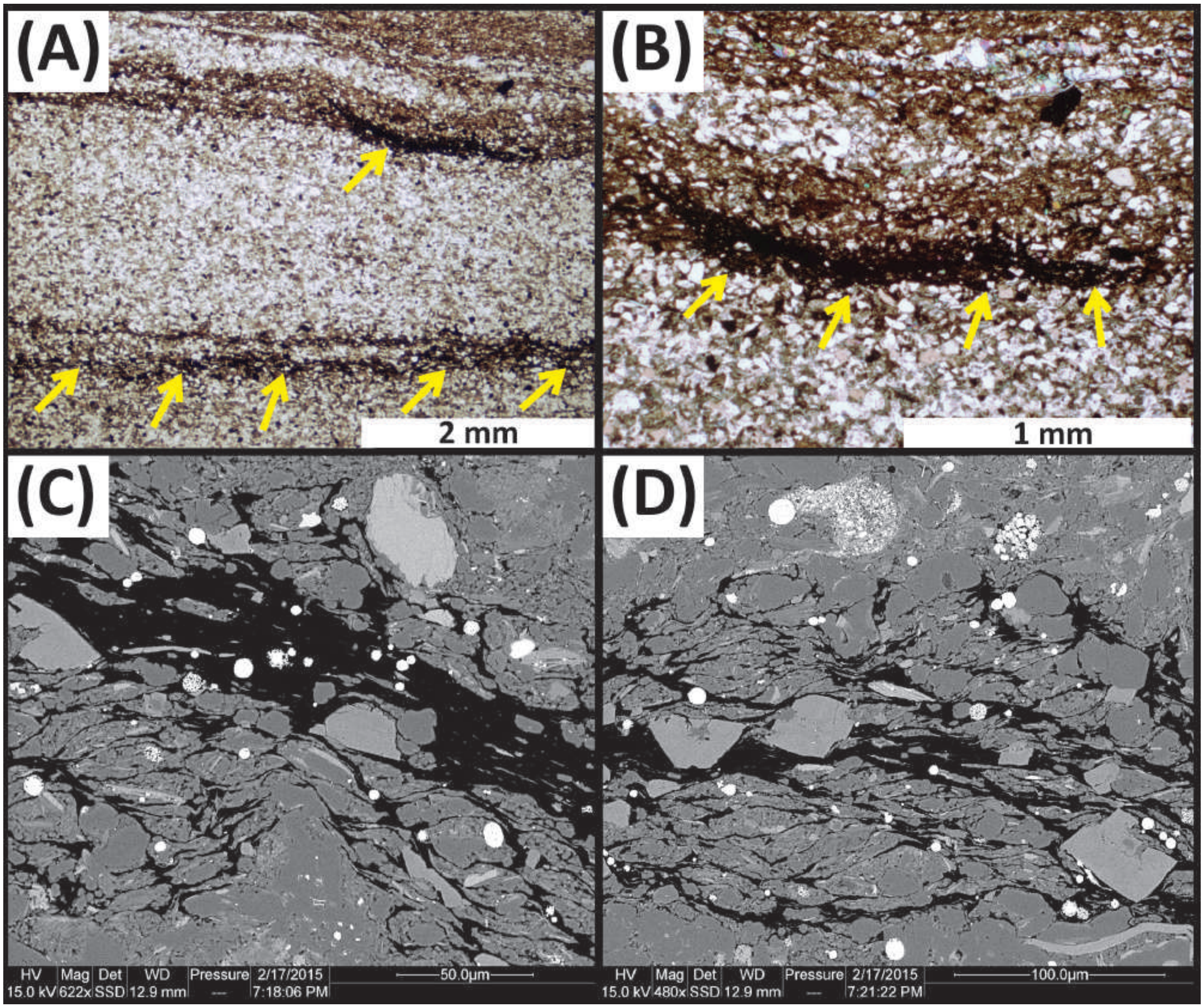

Figure 6. (A) and (B) Photomicrographs showing terrestrial phytodetritus in clay-rich portions of hyperpycnites (yellow arrows). (C) and (D) Backscatter image detailing the cellular structure of terrestrial phytodetritus.

into which the river flows, be it fresh (i.e., lacustrine) or marine waters. This disparity in density results from changing salinity and temperatures between the two water masses, as well as from the suspended sediment load (Felix et al., 2006). The generation of river-fed hyperpycnal turbidity currents requires slopes greater than 0.7° (Bentley, 2003; Friedrichs and Scully, 2007; Bhattacharya and MacEachern, 2009). On low-gradient deltas (slopes < 0.3°), such flows can be maintained because of wave and tidal processes that enhance turbulence at the seabed and may produce fluidized muds for offshore transport (e.g., Syvitski, 1991; Bentley, 2003; Wright and Friedrichs, 2006; Friedrichs and Scully, 2007; Varban and Plint, 2008).

PORE TYPES AND DISTRIBUTION

Understanding the intrinsic porosity of hydrocarbon-bearing shales is critical to better identify potential reservoir lithofacies, as well as understanding the fluid flow within them. Scanning electron microscopy of ion-milled samples allowed definition of three principal pore types found in the Geneseo: (1) PF pores, (2) OM pores, and (3) CD pores. Phyllosilicate framework pores are triangular openings (100–1500 nm wide) that are delineated by phyllosilicate flakes. 1Organic matter pores that occur in kerogen particles and organo-clay aggregates (10–500 nm wide) are most likely related to hydrocarbon

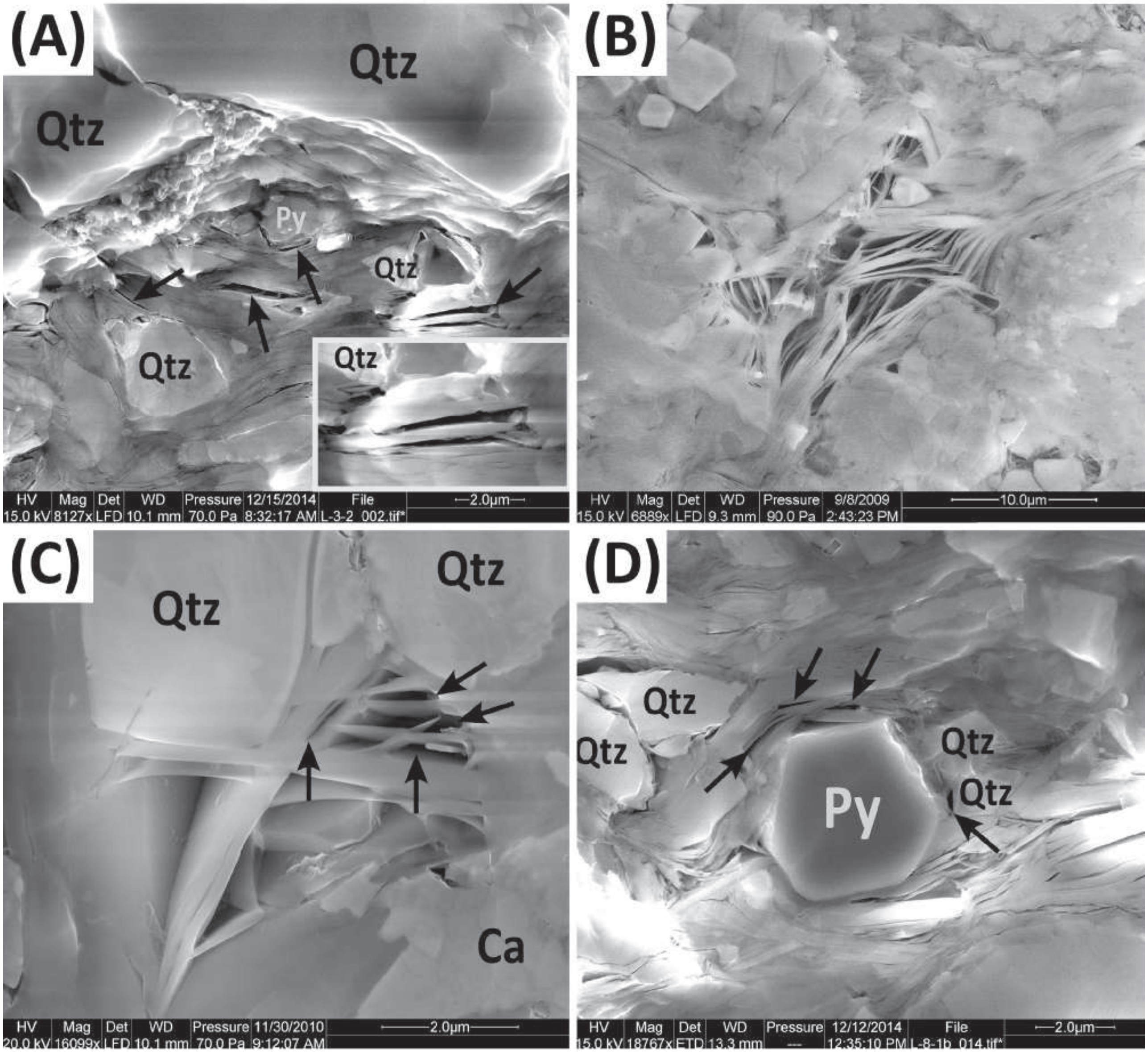

Figure 7. (A) Dispersed quartz (Qtz) silt grains, calcite (Ca), and pyrite (Py) creating pressure shadow, allowing only partial collapse of original phyllosilicate fabric. PF pores are triangular openings that reflect pre-existing grain orientation (up to 4 μm across). (B) Composite PF porosity with large open pores. (C) and (D) PF pores developed within pressure shadows, large open pores with phyllosilicate being "clamped" and "propped" due to diagenetic mineral growth (all secondary electron images).

generation and expulsion (Schieber, 2010). Carbonate dissolution pores are caused by partial dissolution of carbonate grains (50–500 nm wide) and probably related to late diagenetic carboxylic and phenolic acids (Schieber, 2010, 2013).

Of these three pore types, the PF pores are the most ubiquitous and present the largest pore openings observed (up to 1500 nm; Figures 7–9). They consist of triangular openings that are defined by a clay mineral framework and are best developed in pressure shadows adjacent to larger and compaction-resistant grains (pyrite, quartz, calcite) and in compaction-protected spaces between such grains. Diagenetic mineral growth (quartz, dolomite, pyrite) also enhances PF pores by "clamping" clay flakes in place prior to compaction (Schieber, 2013) or by acting

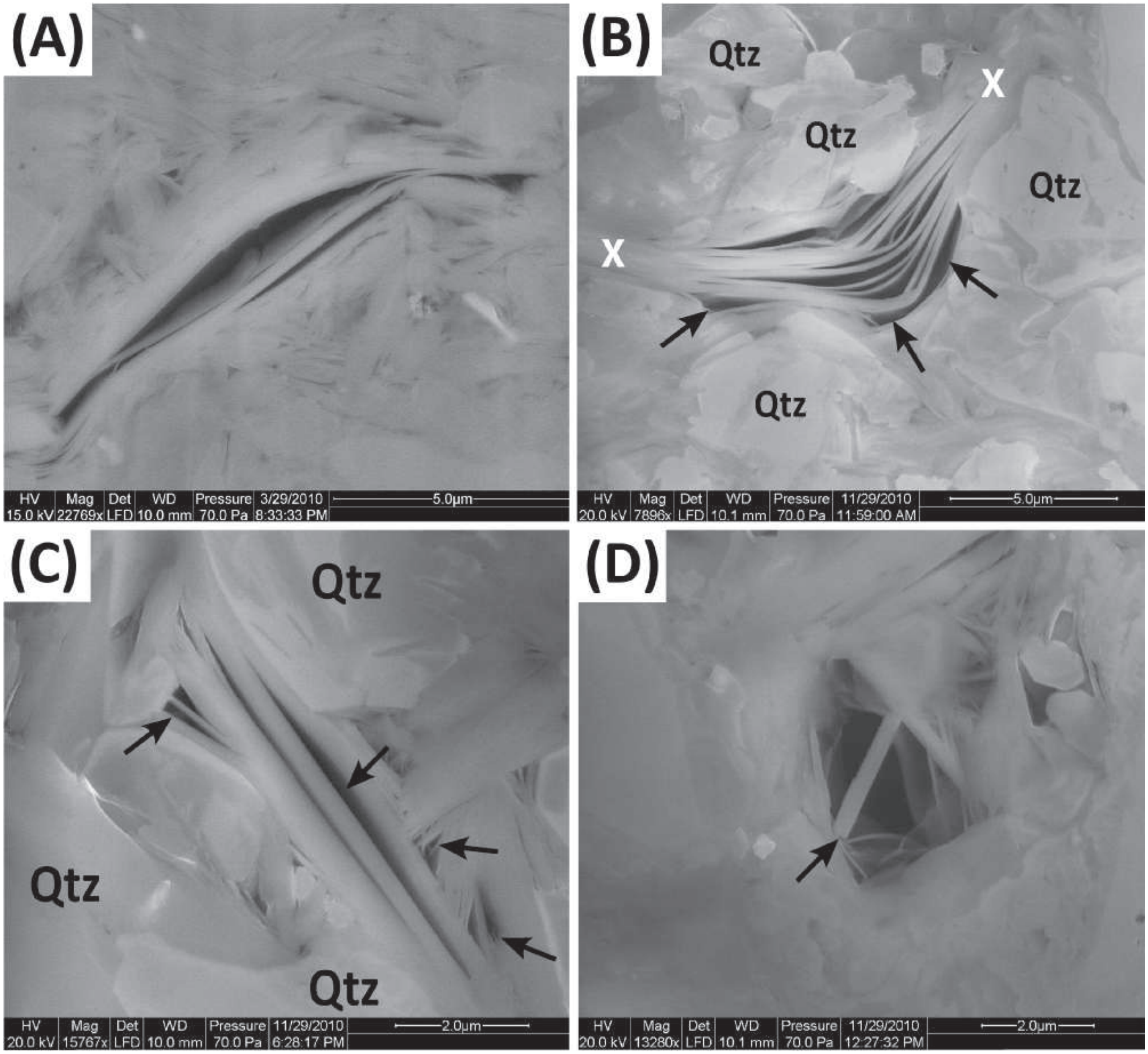

Figure 8. (A) Variably sized PF porosity, (B) quartz grains (Qtz) with diagenetic overgrowth prevent fabric collapse and allow PF pores (arrows) to stay open and clamp the fringes of phyllosilicates (white X), and (C) propping of PF pores and clamping of clay flakes (arrows). (D) PF pores developed within pressure shadows of larger silt grains show large open pores with diagenetic phyllosilicate "clamping" and "propping" of pores (arrow) by diagenetic minerals (all secondary electron images).

as a proppant that prevents collapse of triangular openings (Figures 8, 9). Phyllosilicate framework pores are abundantly observed in hyperpycnal intervals with increased contents of silt and terrestrial phytodetritus. Increased silt content provides compaction-resistant grains to create pressure shadows that prevent collapse of PFs. Furthermore, these intervals contain less labile organic material (prone to form OM pores upon heating) due to clastic dilution and rapid sedimentation.

Organic matter pores dominate in the "background" organic-rich mudstones that were not affected by fluvial-sourced sedimentation and clastic dilution. They are associated with OM in the form

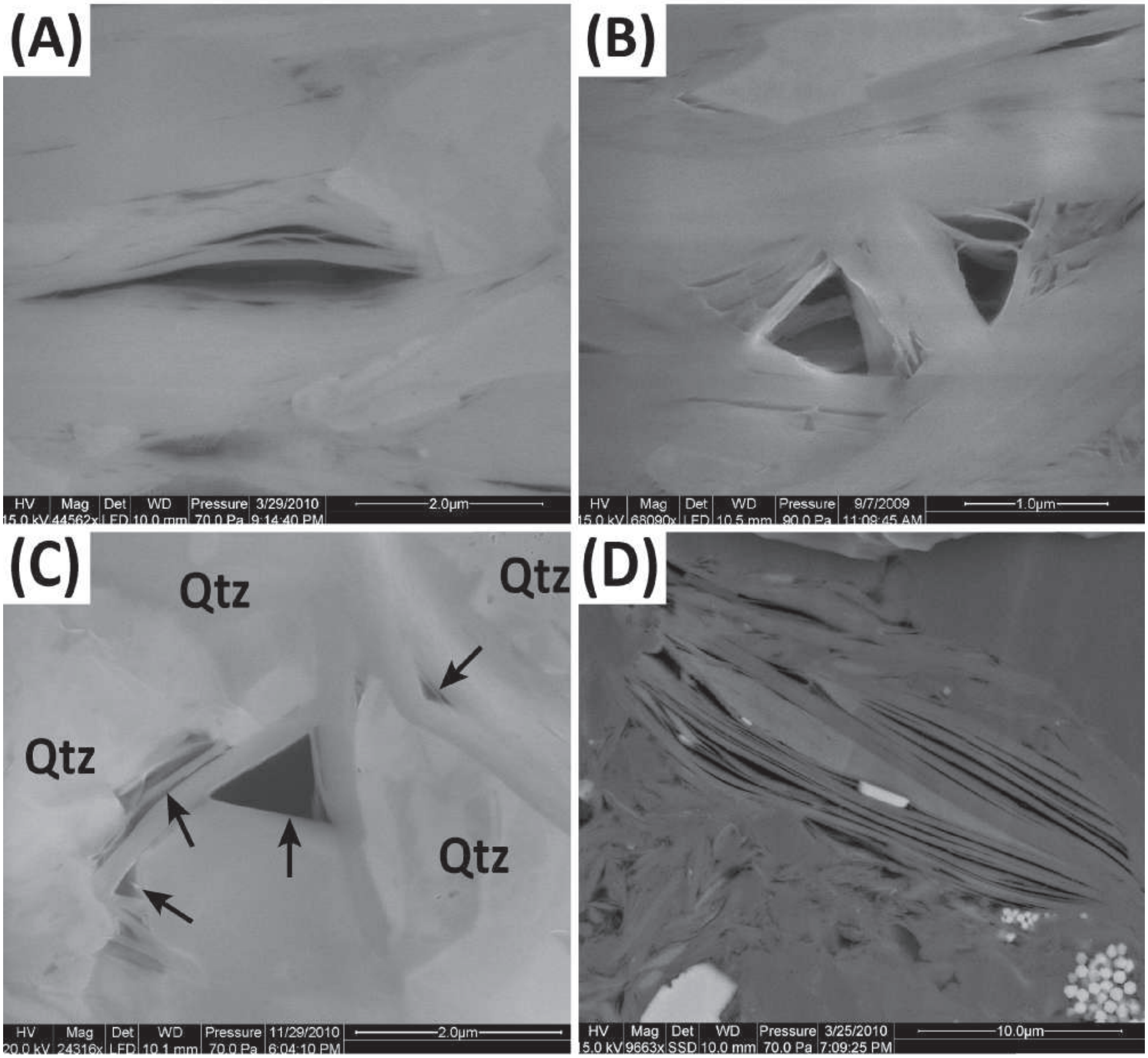

Figure 9. (A), (B), and (C) Secondary electron images showing examples of PF framework porosity where dispersed quartz (Qtz) silt grains create pressure shadows that allow for only partial collapse of original phyllosilicate fabric (arrows). PF pores are triangular openings that reflect pre-compaction grain orientations. (D) Backscatter electron image of composite PF porosity with large linear open pores with minor infill of pyrite.

of kerogen particles (Figures 10, 11). All samples collected for this study are overmature, thus hydrocarbons were generated and have migrated from the succession (R_0 = 1.4–1.6; Weary et al., 2000). The removal of hydrocarbons from kerogen is most likely responsible for the OM pores that we now observe in Geneseo kerogen particles. Pore development in Geneseo OM is quite variable and most likely reflects different diagenetic reactivity of the various organic macerals that were originally buried within these sediments. Generally speaking, amorphous kerogen (MacGowan and Surdam, 1990; Schieber, 2010, 2013) appears to be developing micropores upon maturation (Figure 10), whereas structured kerogen (e.g., Tasmanites cysts, terrestrial phytodetritus) does not develop visible porosity at the same stage of heating (Schieber, 2013).

Carbonate dissolution pore development starts along the margins of carbonate grains. In rare cases, the entire grain may be dissolved, leaving a void

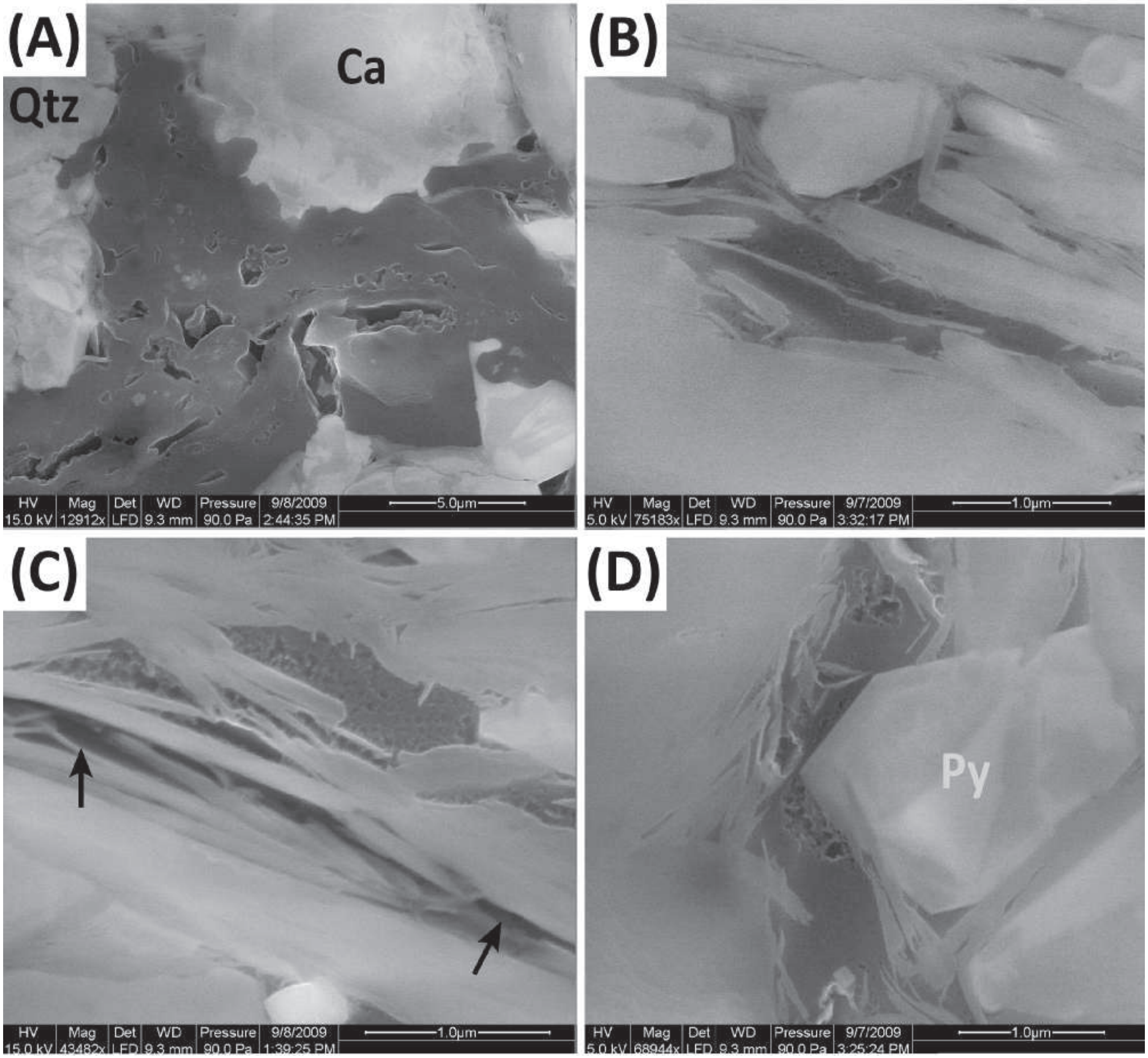

Figure 10. (A), (B), (C), and (D) Secondary electron images showing examples of OM porosity resulting from thermal cracking of labile organics and subsequent migration of hydrocarbons to infill nearby open porosity (arrows). Continued pressure and temperature allows further development of kerogen micropores. Kerogen particles fill primary PF framework porosity, thus it is essential for compaction-resistant grains such as quartz (Qtz), calcite (Ca), or pyrite (Py) to be present in shale matrix for pressure envelopes to preserve open phyllosilicate porosity.

space with a remnant skeleton of the original grain (Figure 12c, d). Carbonate dissolution is probably related to the formation of carboxylic and phenolic acids in the course of OM diagenesis (MacGowan and Surdam, 1990; Surdam et al., 1991). The observation that CD pores have not collapsed or filled with secondary cements also indicates that these pores formed relatively late in burial history.

DISCUSSION

Porosity within the Geneseo Formation of New York correlates directly with distinct lithofacies associations that resulted from changing intra- and extrabasinal controls. Shelfal mud deposition within storm-wave base is documented by sedimentary features that indicate a relatively energetic environment

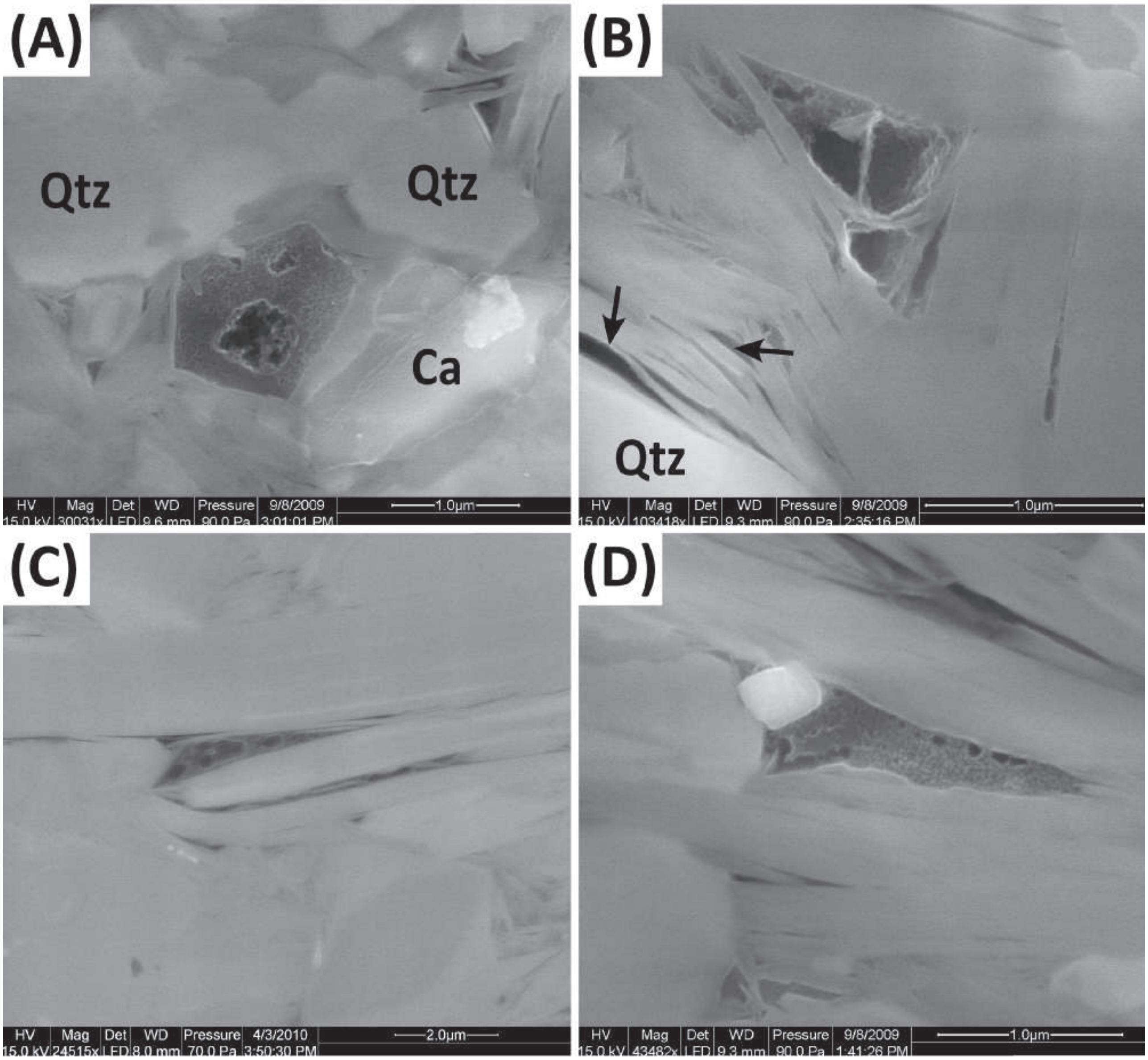

Figure 11. (A), (B), (C), and (D) Examples of OM porosity in "background" facies of the Geneseo succession, indicating thermal cracking of labile organics and generation of microporosity. Kerogen particles fill primary PF framework porosity (arrows) that relies on the presence of compaction-resistant grains such as quartz (Qtz) and calcite (Ca) to be present in shale matrix for pressure envelopes to preserve open phyllosilicate porosity (all secondary electron images).

with consistent 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. Through changing transport mechanisms and sediment flux, the sediment matrix varies in texture and composition and introduces the initial components for diagenetic and catagenetic alteration (Berner, 1980). Substrate consistency, porosity, pH, and organic content are all factors with significant implications for postdepositional alteration during burial, and thus, porosity development.

In facies associations that reflect "background" sedimentation (Figure 4), organic-rich black and dark gray mudstones show dominantly OM porosity (Figures 10, 11). This is because of the presence and maturation of labile organics and subsequent generation of hydrocarbons. Micropores develop in kerogen particles during thermal cracking and migration of hydrocarbons into framework porosity.

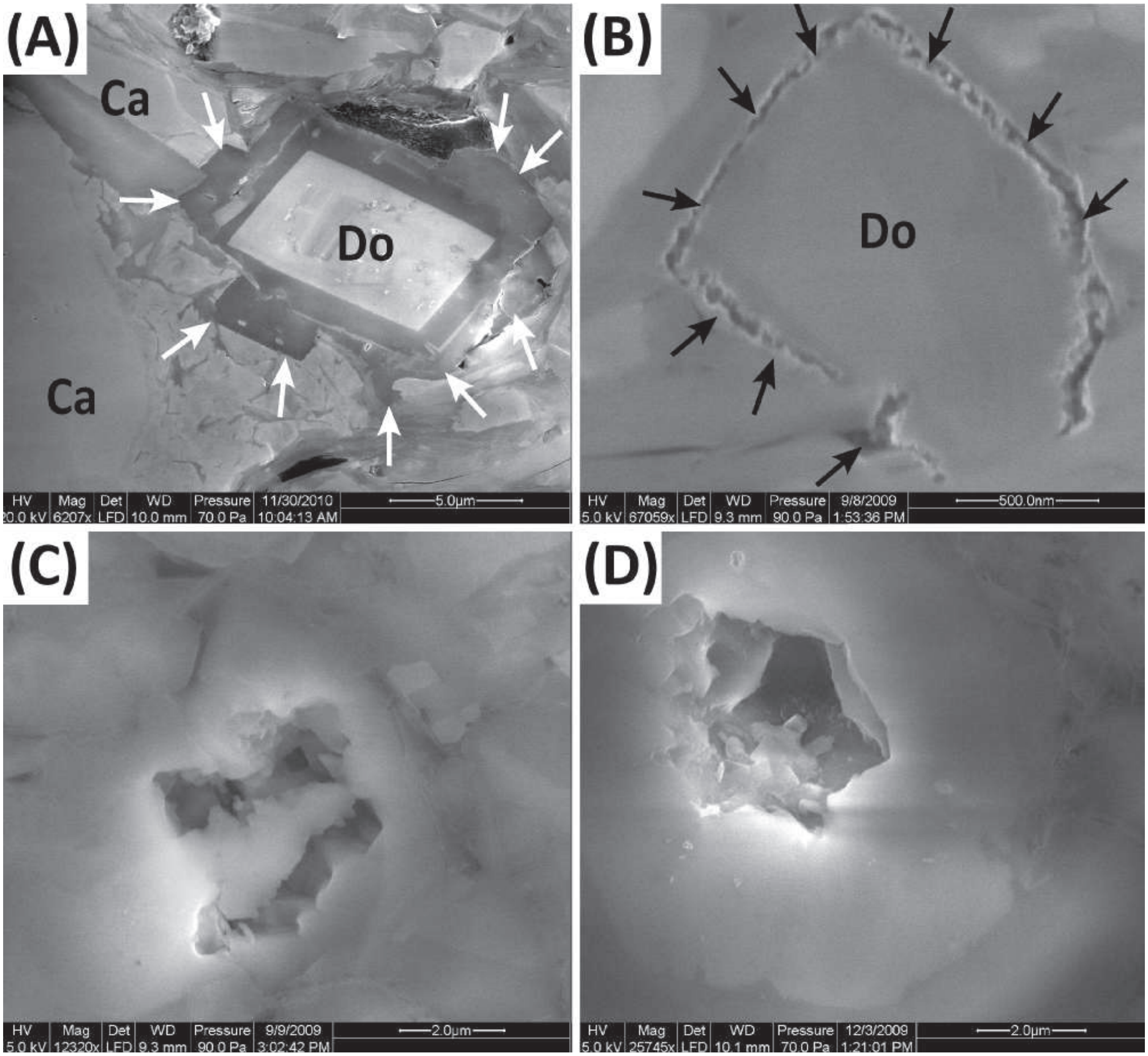

Figure 12. (A) Zoned dolomite showing multiple growth generations around calcite (Ca) grain. Dolomite (Do) cements invade open porosity during late-stage growth (arrows). (B), (C), and (D) Examples of CD porosity where carboxylic and phenolic acids created secondary porosity along the margins as well as removing entire grains to form “honeycomb” texture (all secondary electron images).

In organic lean intervals that reflect rapid deposition of coarser clastic material (Figure 5) and phytodetritus (Figure 6) from hyperpycnal plumes, PF pores dominate (Figures 7–9). This is due to an increase in rigid textural components as well as insignificant contributions of labile organics. As a result of coarser grain transport from fluvial discharge events, fine-grained portions of these event deposits have “floating” grains that facilitate the development of pressure shadows and prevent collapse of clay fabrics. Phyllosilicate framework pores remain fully open and also show “clamping” and “propping” by diagenetic mineral growth (Schieber, 2013).

The areal extent of hyperpycnal flows is rather channelized and focused into specific regions that are controlled by proximity to river-mouth, paleohydrologic controls, as well as pre-existing topography (Mulder et al., 2003; Bhattacharya and MacEachern, 2009). In localities where dispersal of sediment from hyperpycnal flows is negligible, deposition of organic-rich “background” facies prevails, due to lack of clastic dilution and elevated accumulation of

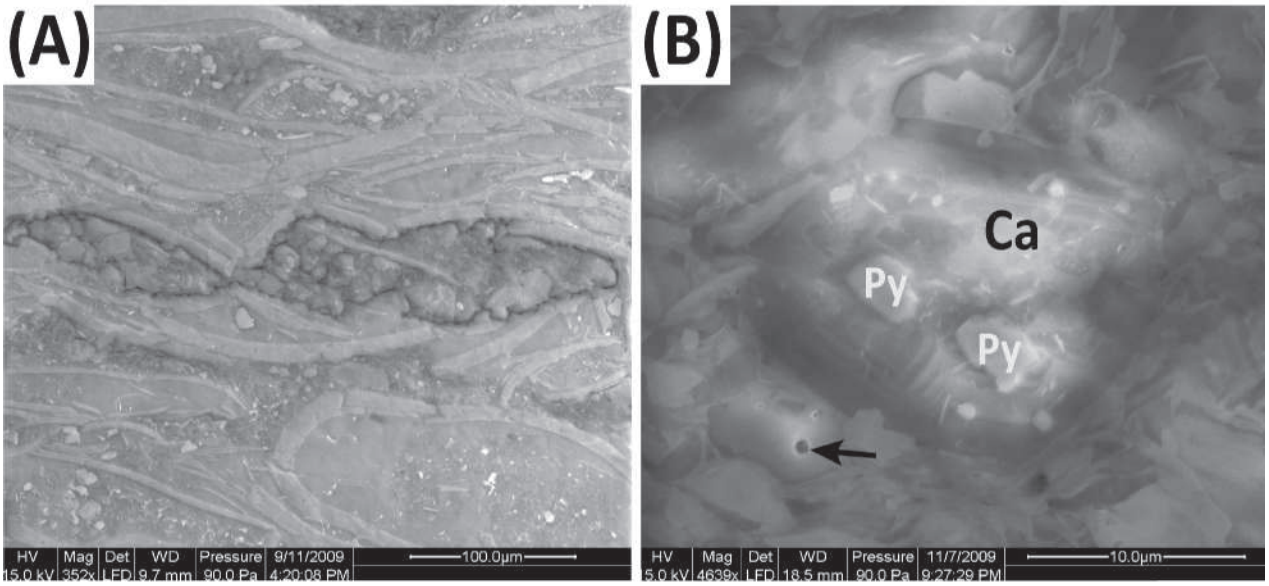

Figure 13. (A) Carbonate-cemented interval with densely packed fragments of ostracods, winnowed into a skeletal lag. Porosity in this sample is significantly reduced from void filling of early diagenetic calcite cements. (B) Detail of tight calcite (Ca) cementation. Minor rounded pores (arrow) are probably from fluid inclusions that were milled open (all secondary electron images).

organic material to the seabed. Because of decreased dilution, as well as accumulation of finer-grained clastics in medial to distal shelf settings, development of PF pores is minimal. Existing framework porosity is filled with migrated hydrocarbons and subsequently results in development of OM micropores in those places. Moreover, because slow sediment accumulation favors in situ growth of cements (i.e., silica, calcite, and dolomite), this further reduces porosity in "background" facies (Figure 13). However, secondary porosity due to dissolution of carbonate cements and grains (organic acid production) may enhance porosity of such cemented intervals (Figure 12). Overall, however, CD pores in the Geneseo are less common than the other two pore types and do not appear to have good connectivity.

CONCLUSIONS

Fluvial discharge events are increasingly being recognized in deep-time marine shelfal strata and represent an important source of fine-grained sediment to the offshore setting. Understanding these dispersal mechanisms and how they influence depositional regimes of mudstone-rich strata is essential for understanding unconventional reservoirs and to improve prediction away from data control.

This study reports SEM observations of multiple pore types from a fluvial-influenced organic-rich mudstone succession and supports the notion that depositional environment and transport mechanisms strongly affect reservoir quality and distribution. In the Geneseo Formation, the totality of shale porosity depends on compositional parameters that permit pressure shadow preservation of PFs (i.e., larger hard grains), organic maturation that generates acidity and secondary porosity (CD pores), and hydrocarbon migration that results in micropores in OM (OM pores).

Depositional processes control the initial "ingredients" and conditions for porosity development and distribution. Documentation of wave-aided hyperpycnal flow deposits in a tight shale reservoir provides a conceptual basis for developing more sophisticated approaches to the vertical and lateral prediction of compositional attributes, textural characteristics, and ultimately porosity and porosity type.

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