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Shale Microfabrics and Pore Development – An Overview with Emphasis on the Importance of Depositional Processes

Juergen Schieber
Indiana University, Bloomington, IN 47401, USA
jschiebe@indiana.edu

Summary

In shale successions, pores that control gas production are a direct outcome of processes that are active during deposition and diagenesis. These intrinsic pores are typically in the micrometer to nanometer size range and unrelated to processes that produce fragmentation-related porosity later in burial history.

Examination of shale successions that span most of the Phanerozoic shows that there is only a finite number of pore types, in spite of considerable variability in composition, depositional setting, and compaction history (Fig. 1). Shale pores occur in open spaces of the grain fabric (framework pores), can be integral to certain grain types (intrapores), and be due to dissolution of grains (solvopores). An additional pore type can occur in organic matter (macerapores). Grain and fabric shrinkage during core storage and sample processing produce pores as well (desipores), and their accurate identification is critical for accurate petrographic pore assessment. The most common framework pores are defined by phyllosilicates (clays, micas) and carbonate grains (biogenic, diagenetic), and intrapores are largely due to cavities in biogenic debris. Solvopores predominantly are encountered in association with calcite and dolomite grains, although other minerals (feldspar, pyrite) may show dissolution effects as well. Macerapores are predominantly associated with kerogen blebs and organo-clay aggregates, and pore development is maceral selective.

When organic matter content and shale maturity are considered, the following relationships emerge: 1) at high organic matter content (>10% TOC) many framework pores are filled with amorphous kerogen (bituminite) in immature shales; 2) in mature shales this interstitial organic matter develops macerapores that increase in abundance with the degree of maturity. In shales with comparatively low TOC (less than 7%) a large proportion of the framework pores remain open, are likely connected, and potentially able to transmit gas. Framework pores defined by phyllosilicates become more common as clay content increases, but more critically, their abundance hinges on the presence of pressure shadows generated adjacent to "hard" grains (quartz, feldspar, dolomite, calcite, pyrite) that resist compaction. Solvopores appear to form late in diagenetic history, and the requisite pH drop was likely due to the formation of carboxylic and phenolic acids when kerogens reacted with silicates in a briny solution at elevated temperatures (~ 80° to 120° C). At low carbonate contents (a few %) solvopores constitute only isolated porosity, but in shale intervals that contain abundant carbonate, and where carbonate grains are concentrated into laminae, solvopores are probably are an important facilitator of gas migration.

SEM study of ion milled flume sediments shows that the mode of mud deposition, namely whether deposition occurs via still water settling or from bedload floccules, significantly impacts the clay fabric, the potential to preserve framework pores, and the likely pore size distribution. Thus, conditions and environment of shale deposition have most likely a bearing on producibility and possibly even on organic matter content and gas content.

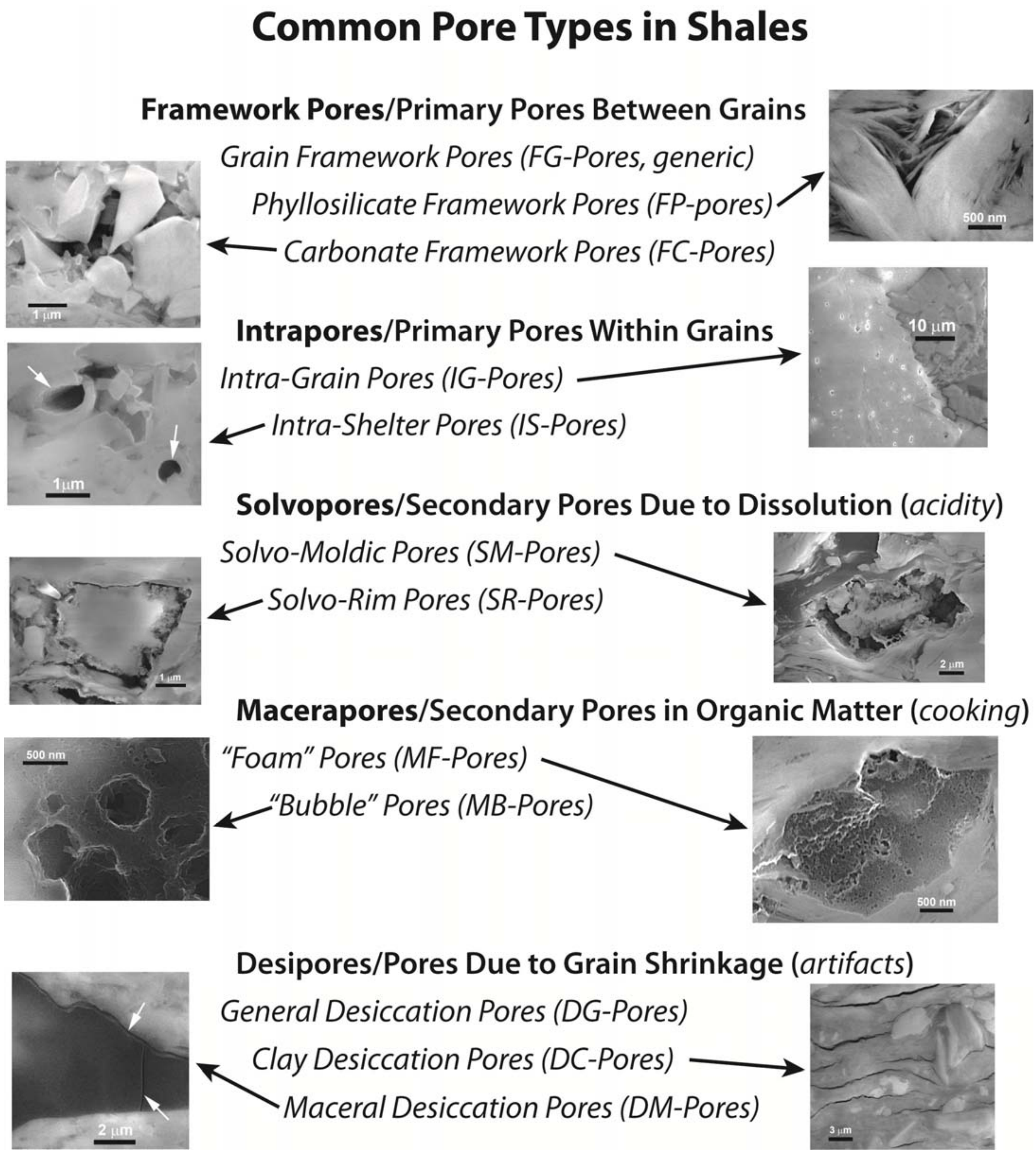

Figure 1: An overview of pore types observed in shale successions. On first approximation framework pores probably reflect the original depositional arrangement of detrital grains (clay, carbonate), but may be overprinted by diagenetic growth of clays and carbonate grains. Of intrapores, only those defined by fossil debris are likely important. Both framework and intrapores can at first pass be considered primary porosity, whereas solvopores and macerapores constitute secondary porosity. Desipores appear all to be artifacts and should be readily identified in ion milled sections. Cold-milling with a liquid nitrogen cooled stage can eliminate/reduce artifacts caused by sample heating during milling.

Methods

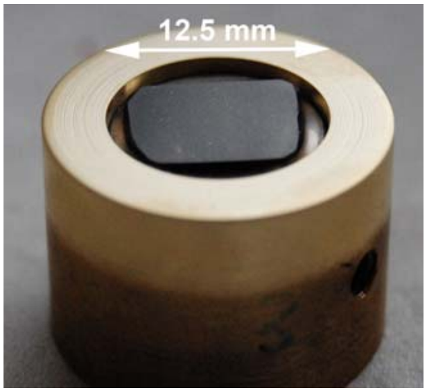

Figure 2: Large diameter ion milled sample in custom made holder that allows milling of samples up to 12.5 mm diameter. Judicious use of gun alignments, milling angle, and milling time allows the surface to be milled to a degree of smoothness that permits assessment of pore type and pore distribution across the entire surface. Most examples shown in Fig. 1 were milled with that method.

Cambrian through Cretaceous samples were collected from drill cores stored at the core library of the Indiana Geological Survey, the New York State Geological Survey, and from fresh outcrops. Samples for TEM observation (JEOL 1200 EX STEM) were thinned mechanically and then ion milled with a Gatan 600 Duomill. Large samples (12.5 mm diameter; Fig. 2)) for SEM observation were mounted in custom designed sample holders and ion milled with a Gatan 600 Duomill. Small SEM samples were mounted to a Tantalum sample holder/blade and ion milled with a Gatan Ilion edge mill. Both Gatan mills have liquid nitrogen cooled sample stages. Milled surfaces were then examined by SEM without conductive coating (FEI Quanta 400 FEG, low vacuum mode). All samples were viewed on surfaces oriented perpendicular to bedding.

Observations on Rocks

Phyllosilicate framework (FP) pores are the ubiquitous pore type in clay bearing samples and consist of triangular openings that are defined by a lattice-work of randomly oriented clay mineral platelets (Fig. 3).

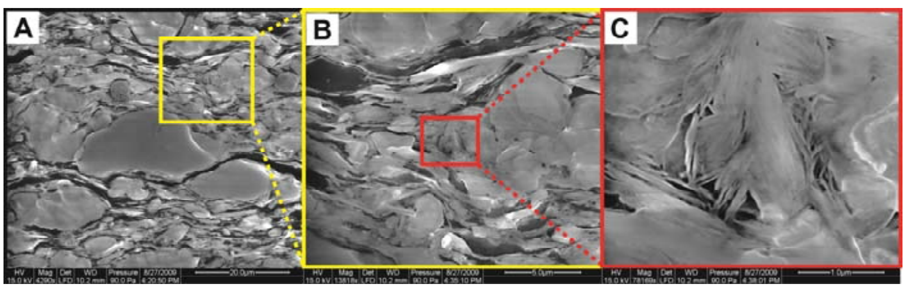

Figure 3: Fabric and FP-pores in New Albany Shale. (A) Low magnification SEM image shows planar fabric due to compaction and compression around resistant larger grains. (B) Enlarged view, planar-compressed fabric still dominant. Dark streaks are kerogen. (C) Further enlargement. Shows randomly oriented clays that define triangular openings.

The defining clay mineral platelets, typically at most a few microns in size, appear to have multiple origins. Features that suggest a “depositional” origin of FP-pores, related to depositional processes such as flocculation, include bending and splintering due to compaction, as well as piercing and differential compaction when oriented near-vertical (Fig. 4).

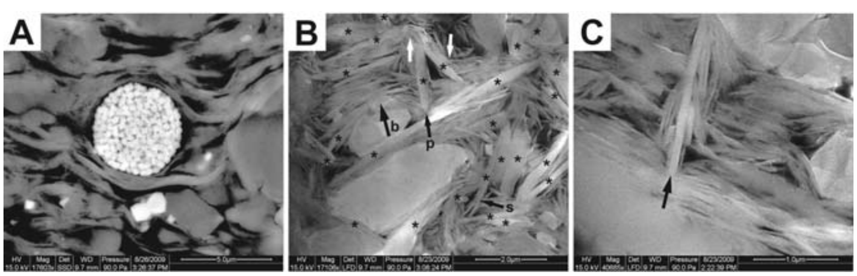

Figure 4: (A) SEM BSE image that shows bending of large detrital clays and mica flakes around pyrite framboid (center) and quartz grains. (B) Random clay fabric & FP-pores. Clay flakes marked * are considered detrital, and define framework of compaction protected space. Black arrows: b = compactional bending of clays, s = splintering of clay flake due to compression, p = piercing by clay flake. White arrows = “wrapping” of clays due to compaction. (C) Subvertical clay flake (arrow) pierces underlying clays due to compaction. All images New Albany Shale.

Although compaction will tend to collapse original open clay fabrics, factors that help preserve FP-pores include pressure shadows between and adjacent to compaction resistant grains and diagenetic mineral growth. Diagenetic mineral growth (Fig. 6) can keep FP-pores open by propping open the space between clay flakes, and also by cementing in place the ends of clay flakes ("clamping"). Whereas presumed “detrital” FP-pores as described above are largely in the 50-1000 nm size range, smaller FP-pores in the 10-50 nm range are common in diagenetic clay fabrics.

Implications of Flume Studies

Flume experiments suggest that low energy settings are not a prerequisite for mud accumulation, and represent a paradigm shift in mudstone sedimentology that has far reaching implications (Schieber et al., 2007; Schieber & Southard, 2009). For example (1) many laminated shales, long thought to represent quiescent conditions, may instead reflect mud accretion by currents; (2) the majority of these laminated shales are carbonaceous; and the latter then begs the question (3) whether there is a fabric difference between flow deposits and quiet water settled muds (Fig. 5), and (4) whether these fabric differences also affect carbon burial/degradation and porosity.

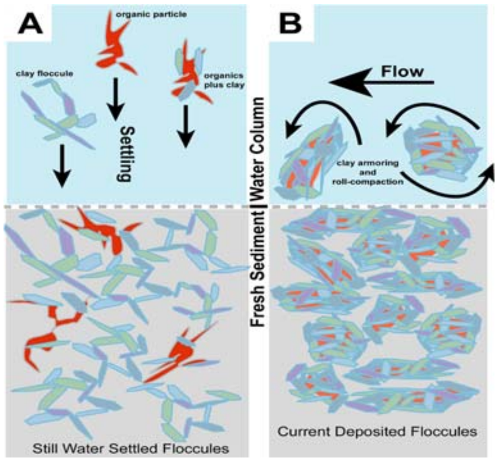

Figure 5: (at left) Contrasting sediment fabrics due to the difference between (A) simple settling and (B) accretion of mud bed from flow deposited floccules carried in bedload.

From studies of flume generated fabrics it is clear that the fabric of current deposited muds differs from those that form via stagnant settling (Fig. 6).

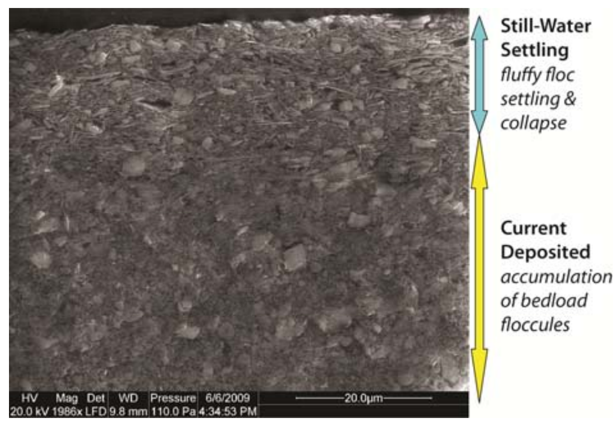

Figure 6: (at right) Fabric contrast in flume produced muds between still water settled clays (top, parallel alignment of clays) and clays deposited from migrating ripples (bottom, random orientation of clays).

It is therefore plausible that flow-imposed fabric differences induce marked disparities with regard to the size distribution of preservable FP-pores (Fig. 7), as well as the relationship between kerogen and detrital components and thus the character and distribution of macerapores in the final deposits. Thus, in studies of shale gas producibility and likely gas recovery, conditions and environment of shale deposition need to be factored in for a comprehensive evaluation.

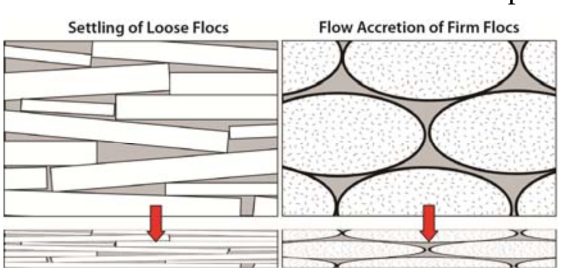

Figure 7: (at left) The impact of loose floccule settling and rolling-floc accretion on likely pore sizes and rock properties. Compacting (red arrows, bottom) and already parallel aligned loose floc deposit will likely produce abundant tiny pores in the 10’s of nm range, whereas compaction of a layer of bedload floccules potentially allows preservation of pores in the micron range.

Acknowledgements

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