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A role for organic petrology in integrated studies of mudrocks: examples from Devonian black shales of the eastern US

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Abstract

Over the years, the study of mudrocks has lagged far behind that of other lithologies, a circumstance that is in part due to their fine-grained nature, and in part due to economic realities. Yet, within petroleum systems mudstones are usually the main source of hydrocarbons and typically are also important as hydrocarbon seals. Recent work on Late Devonian mudstones from the eastern US shows that much progress can be made through an integration of outcrop study, macro- and micropaleontology, ichnofossils, gamma ray spectroscopy, microscopic examination of thin sections in transmitted and reflected light, electron microscopy (SEM, BSE), electron microprobe, carbon and sulfur isotopes, and organic geochemistry.

Erosion surfaces within this black shale succession have been traced over large distances and provide the foundation for a sequence stratigraphic re-interpretation of these rocks. Evidence of storm wave reworking of the seabed, as well as the realization that benthic colonization was much more widespread than previously believed, suggest that anoxic conditions in the water column were not a controlling factor in the accumulation of the large quantities of organic matter found in these shales.

These distal Devonian shales accumulated slowly and allowed accumulation of large proportions of organic matter. In modern settings of abundant organic matter accumulation, the original material is broken down by bacteria within a matter of months into a mass of largely unidentifiable organic particles and extracellular bacterial slime. Although one can still find identifiable material within this mass, slime and amorphous material strongly dominate. After burial and maturation this material turns into the various organic macerals that organic petrologists are accustomed to describe. One might wonder in this context, how much information about the origin of a given mudstone unit can we hope to extract through organic petrology?

In order to illustrate how organic petrology of mudrocks can contribute to their better understanding, Late Devonian black shales of the eastern US will be examined from a sedimentological perspective. Combining sedimentologic and geochemical data with basic observations on organic petrology, illustrates how the latter can contribute to more realistic scenarios of black shale genesis.

Keywords: Black shale; Sequence stratigraphy; Anoxia; Petrology; Organic

1. Introduction

The factors that lead to the deposition of carbonaceous mudstones and shales (collectively referred to as black shales in the rest of the paper) have been a matter of long debate. For a time, the main argument seemed to be between those that assumed that bottom water

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anoxia were crucial to preserve organic matter at the seafloor, and those that held the view that high productivity in the surface waters was sufficient to lead to substantial burial of organic matter (Macquaker and Gawthorpe, 1993; Oschmann, 1988, 1991; Demaison and Moore, 1980; Demaison, 1991; Heckel, 1991; Byers, 1977; Pedersen and Calvert, 1990; Calvert, 1987; Calvert and Pedersen, 1992; Wetzel, 1991; Wignall and Hallam, 1991). More recent studies of black shales show increasingly that understanding their origin is not as simple as the distinction of anoxia vs. productivity control (Schieber, 1994a, 1999; Murphy et al., 2000; Tyson and Pearson, 1991), and that only a detailed and holistic examination of composition, sedimentology, paleoecology, and geochemistry is likely to give us an understanding of the underlying causes of black shale formation.

In this paper, I endeavor to illustrate the intricacies and potential pitfalls of black shale investigations with examples from the Late Devonian succession of the eastern US, an area where my students and I have made considerable progress in understanding sedimentary dynamics and environmental constraints on black shale formation (Schieber, 1998a,b; Schieber and Baird, 2001). As the study of sandstones and carbonates has shown very convincingly, a sedimentary deposit is far better understood through the summation of the histories of its individual particles, than through the measurement of bulk properties (Potter et al., 1980). Yet when it comes to the organic content of black shales, an important component that may range from a few percent to several percent, this is the typical state of affairs. The data most commonly reported in the literature are the total organic content (TOC), followed by the bulk carbon isotope ratio, hydrogen index (HI), and oxygen index (OI). Detailed and systematic examination of the organic particles, with on eye towards their origin and diagenetic history, could open up a whole new dimension for the study of black shales and has a potential to settle questions left unresolved by other methodologies.

2. New insights into sedimentology and stratigraphy of Devonian black shales

The Devonian black shales of the southeastern US are part of an epicontinental succession that was deposited over vast areas of the North American craton (De Witt et al., 1993) and form the distal end of a westward thinning clastic wedge. They are known as the Chattanooga Shale in Tennessee and central Kentucky, as the New Albany Shale in western Kentucky, Indiana, and Illinois, and as the Ohio Shale in eastern Kentucky and Ohio (Fig. 1). These shales overly a regional unconformity and in the central portion of the study area, where they straddle the Cincinnati Arch, they rarely exceed 10 m in thickness. Westward and eastward from there, into the Illinois and Appalachian Basins, respectively, their thickness gradually increases.

Although long thought of as the deposit of a deep stagnant basin (e.g., Potter et al., 1982; Ettensohn, 1985), recent investigations show that the Chattanooga Shale accumulated in relatively shallow water, prone to influence by storm waves and episodic erosive events (Schieber, 1994a,b, 1998a). Erosive events of variable strength and/or duration are indicated by truncation surfaces beneath which from a few centimeters to more than a meter of section is missing (Fig. 2). Hummocky cross-stratified sand/silt beds, and fine grained tempestites (Figs. 3 and 4) suggest

Fig. 1. Map of the eastern US with location of study area marked.

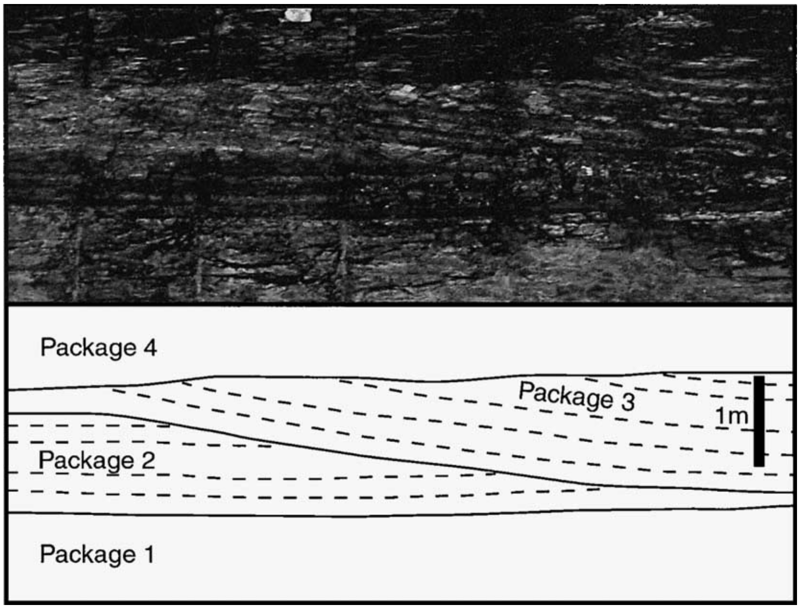

Fig. 2. Erosion surfaces within Late Devonian black shales of central Kentucky. The line drawing at the bottom shows shale packages delineated by erosion surfaces. Dashed lines indicate orientation of shale beds in packages 2 and 3.

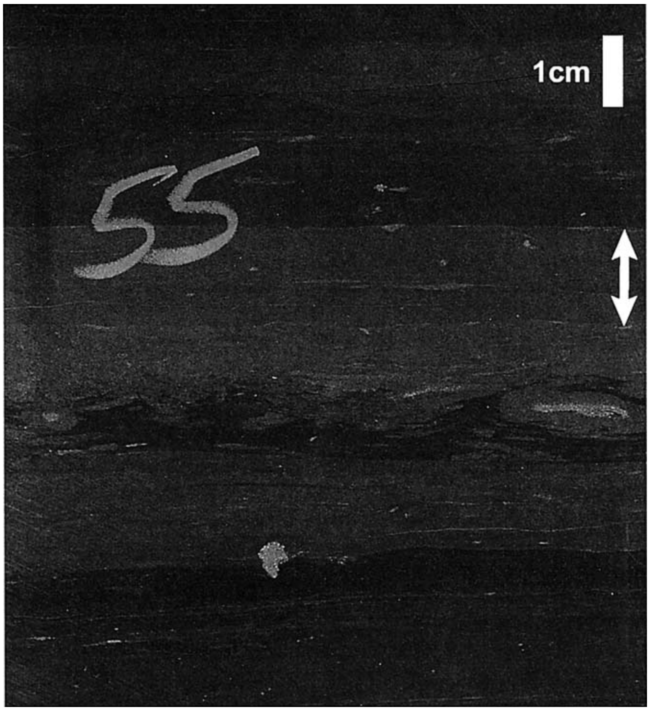

Fig. 3. Mud tempestite in the New Albany Shale. The slightly lighter shale layer marked with a double arrow is draped across a bioturbated horizon. Overlying black shales are also bioturbated. The essential absence of bioturbation in the marked layer indicate that it is an event deposit. This layer closely resembles distal storm deposits shown by Aigner and Reineck (1982).

Fig. 4. Graded silt/mud couplet in the New Albany Shale (silt = arrow (a); mud = arrow (b)). The black shale is subtly bioturbated and homogenized, whereas the couplet has a clear lower boundary and primary features (load casts, lamination) well preserved. The lack of homogenization indicates that this is an event deposit. The event deposits in Fig. 3 and this figure closely resemble the distal storm deposits that Aigner and Reineck (1982) described from muddy shelf deposits of the North Sea.

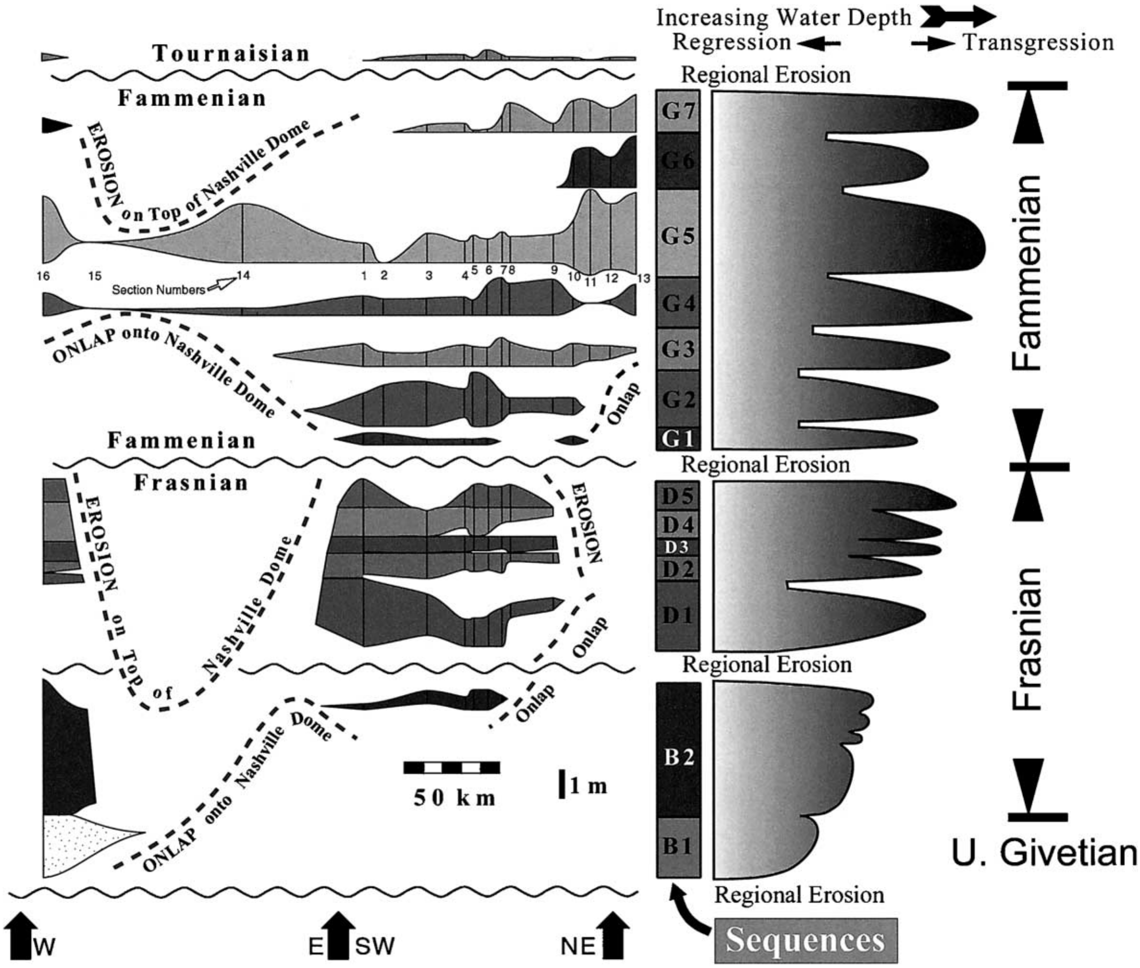

Fig. 5. Sequence stratigraphic overview for the Chattanooga Shale in Tennessee. The succession consists of three packages that can be further subdivided on the basis of erosion surfaces, such as that seen in Fig. 2.

that the seabed was close to or within reach of storm waves (Schieber, 1994a, 1998a).

Sedimentologic study of the Chattanooga Shale also revealed that previous stratigraphic correlations between the western and eastern portion of the Nashville Dome (Conant and Swanson, 1961) had been in error. Tracing of major erosion surfaces within the Chattanooga Shale showed them to be continuous over large distances. These erosion surfaces are therefore viewed as sequence boundaries (Vail et al., 1991) and have been utilized to redefine the internal stratigraphy of the Chattanooga Shale (Schieber, 1998b, Fig. 5).

3. The behavior of modern organic-rich muds

Observations of organic-rich muds were made in a modern very small pond, approximately 1 m in diameter and 1 m deep. Leave litter that accumulates in the pond during the fall rots and gradually renders the lower portions of the pond anoxic. In a way, we have here a miniature "Pontus Euxinus" (as the Black Sea was called by the ancients). The black organic muck at the bottom of the pond, although of very limited lateral extent, could be viewed as a potential precursor to a black shale.

For further examination, several glass jars were filled with this material and taken to the laboratory. The first expectation was that this mixture of water and organic debris should behave pretty much like a liquid, and it did so initially, when it was sufficiently agitated. A few minutes after setting the jars down, however, an interface formed between a black organics–water mixture (the muck) at the bottom, and a clear layer of water above (Fig. 6A). A short while later, I also noticed that the muck/water interface seemingly did not obey the laws of gravity. The muck resisted gravitational deformation when a jar was tilted, and instead exhibited jelly-like behavior (Fig. 6). When placed under the microscope, it became clear that the muck behaved that way because the discrete organic particles seen megascopically were coated with extracellular bacterial slime. The latter conclusion stems from two observations: (1) with a phase contrast microscope live bacteria (sessile as well as motile) are abundant in this low density coating, and (2) this extracellular slime is only found in the presence of bacteria. Formation of slime bridges (Fig. 7) between adjacent particles leads to formation of rapidly settling flocs initially, and to a jelly-like consistency after settling of the flocs. When compared with the settling behavior of a clay–water mixture, the organic muck settles much faster, and also exhibits mechanical strength much earlier in settling history (Fig. 8). In an experiment, the resistance to deformation illustrated in Fig. 6 allowed the deposition of an 8-mm thick layer of sand on top of this very watery muck (88% water content) very soon (1.5 h) after the onset of settling. A comparable clay–water mixture, in contrast, can barely support a 1-mm thick sand layer 5.5 h after the onset of settling (water content 82%; Barret and Schieber, 1999).

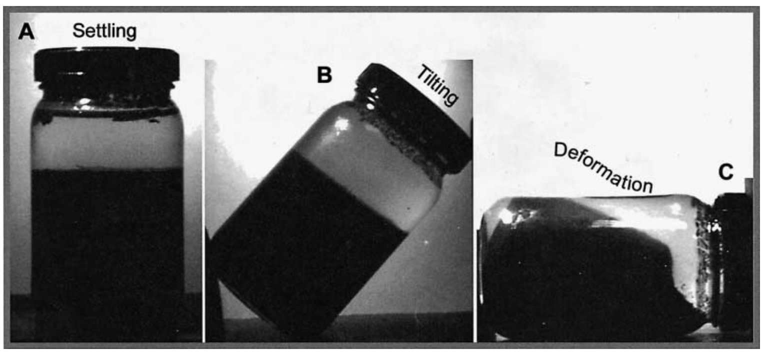

Fig. 6. Organic pond muck in a glass jar. (A) After about 30 min of settling; (B) tilting the jar does not produce a tilt of the water/sediment interface, even though the sediment consists to 88% of water; (C) rotating the jar by 90° causes gravity-induced deformation of the "organic jelly."

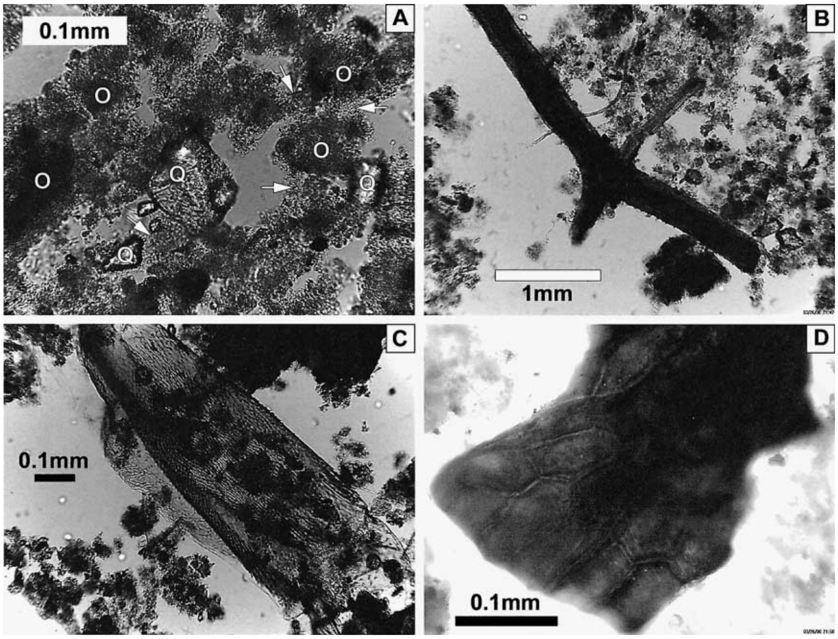

Fig. 7. Photomicrographs of pond muck. (A) Amorphous organic particles (marked O) and mineral grains (marked Q) that are connected by slime bridges (arrows); (B) the more degradation resistant ribs and veins of a leaf; (C) a piece of an insect leg; (D) a piece of a leaf cuticle with cell impressions.

The gel-like nature of above organic muds will probably remind organic petrologists of behavior expected from colloidal humic gels that form due to the degradation of plant matter in peats (Taylor et al., 1998). In the latter case, however, one might expect to still see relict structures such as cell walls (Taylor et al., 1998). Yet, even under high magnification, the particles in the organic muck showed no structure. Considering the very short degradation history of the leaf litter and its oxygen restricted setting, observations made here suggest that very early in sediment history bacterial slime controls sediment behavior, whereas humification and gelification become important factors as this material continues to degrade. This issue requires more research, and sedimentologists would definitely benefit if organic petrology could provide clues about processes that operate at the very sediment surface.

Gel-like behavior of freshly deposited organic muds may also have relevance for the interpretation of thin coaly streaks commonly found in Devonian black shales. Coaly matter in these shales can either be found as identifiable compressed tree trunks of the *Callixylon* variety (Conant and Swanson, 1961), or as thin streaks of a few mm thickness (Fig. 9). The latter are commonly interpreted as the compressed remains of smaller pieces of wood, such as twigs and stems, and are common within sandy–silty lag deposits (Fig. 9). However, when wood compacts in other sandy deposits, such as fluvial channel sands, we typically see concave impressions of tree trunks and branches. These concave impressions may be covered by a thin coaly layer, and the concavity itself is filled with deformed sediment layers. The reason for this is as follows: (1) at time of deposition, the wood (log or branch) takes up a cylindrical space, (2) sediment layers are draped across the upper (convex) surface, (3) once the wood undergoes humification/gelification and compacts (it becomes a thin coaly layer), the underlying sediment retains the concave shape of the erstwhile log, whereas the overlying sediment layers sag downwards and undergo soft sediment deformation. By analogy, if thin coaly streaks in sandy lag deposits (Fig. 9) represent fossil pieces of wood, they should show comparable deformation of overlying

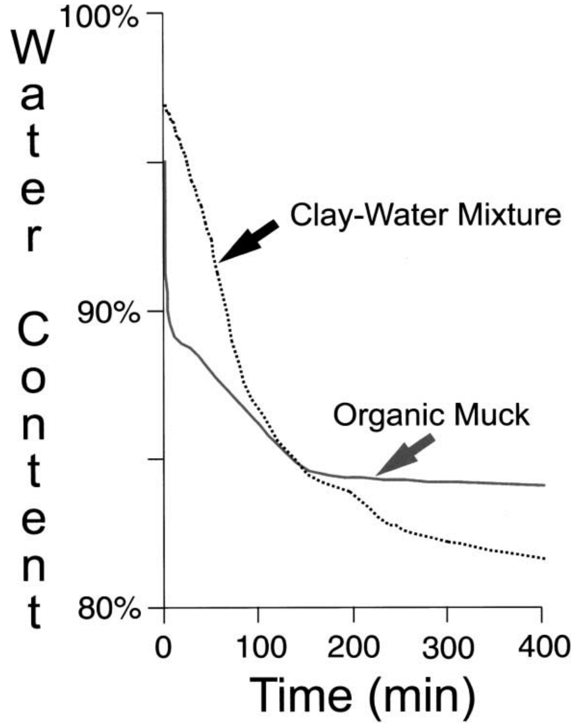

Fig. 8. The settling curves for organic pond muck (gray line) and a clay–water mixture (dotted line) of comparable density. The organic muck settles much faster and reaches stability earlier than the clay water mixture.

sediment layers, as well as a concave base. The fact that they do not show either feature indicates that they may not represent fossil wood after all.

These coaly streaks show shrinkage cracks as typically observed in telogelinite, suggestive of derivation from completely gelified plant tissues (Taylor et al., 1998). If not formed from compressed and gelified pieces of wood, we have to wonder in what other way they could have formed. Internally these coaly streaks show layer-parallel horizons of pyrite framboids, suggesting an existence as layers of essentially pure organic material. Under blue fluorescent light, they show a brownish fluorescence that is comparable to bituminite elsewhere in these shales. The fact they were able to support overriding rippled sand and silt layers suggests resistance to deformation. Judging from observations made on our organic pond muck (Figs. 6 and 8) it could be that thin coaly streaks in Devonian black shales originated in the following manner: (1) initial accumulation of layers of organic debris that is stabilized by microbial slime, (2) followed by compaction and further maturation of these layers that leads to streaks of bituminite.

When examining the muck under the microscope, I also realized that over the course of a mere 6 months, a large portion of the original leaf litter had changed from recognizable components to amorphous dark particles that provide no visual clues of their origin (Fig. 7). Although one can search and find identifiable material, such as leaf cuticles (Fig. 7D), ribs and veins of leaves (Fig. 7B), and may be a fish bone or an insect part (Fig. 7C), microbial decay has transformed the bulk of the material into dark amorphous organic matter. This is a sobering realization when one has the hope to find clues to the origin of the organic content of black shales from the petrography of organic macerals. The preponderance of seemingly structureless organic matter (mostly bituminite) within the matrix of carbonaceous shales (e.g., Williams and Douglas, 1980; Jaminski et al., 1998; and own observations) can be considered a reflection of this situation in the rock record. With detailed studies, however, different types of "amorphous" organic matter may be identified on the basis of texture and color (Boussafir et al., 1995), and may even be further characterized as to their source with techniques that go beyond standard organic petrology (e.g., TEM and kerogen

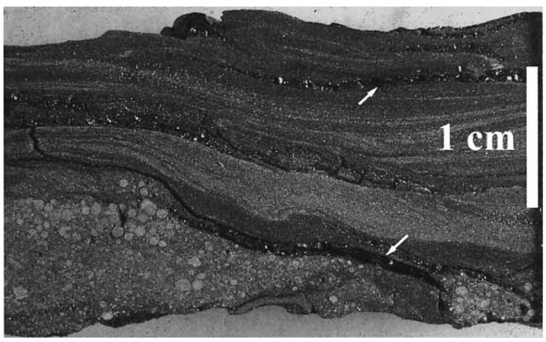

Fig. 9. Coaly streaks (arrows) in a sandy lag deposit. The rounded particles in the base of the lag are actually reworked pyrite grains. If the coaly streaks had originally been pieces of woody branches, one should expect deformation and sagging of overlying material into the developing concavity. The absence of this feature suggests that they were instead layers and lenses (in swales?) of organic muck that were compacted by subsequently deposited sand and silt layers.

pyrolysis; Boussafir et al., 1995). Thus, it is possible to derive important information even from seemingly structureless organic matter if the necessary efforts are made.

4. What information is of interest to sedimentologists?

When studying black shales, the basic questions that sedimentologists would like to answer are pretty much the same as would be asked in the study of any other sedimentary rock. In particular we would like to know about depositional processes and environments, the water depth, and the oxygen levels in the overlying water column. Whereas we can learn about depositional processes and environments from the careful observation of sedimentary structures and shale fabrics (Schieber, 1998c, 1999), the assessment of oxygen levels has posed quite a problem and is at the heart of the anoxia vs. productivity debate (Macquaker and Gawthorpe, 1993; Oschmann, 1988, 1991; Demaison and Moore, 1980; Heckel, 1991; Demaison, 1991; Byers, 1977; Pedersen and Calvert, 1990; Calvert, 1987; Calvert and Pedersen, 1992; Calvert et al., 1996; Wetzel, 1991; Wignall and Hallam, 1991; Prauss et al., 1991; Jones and Manning, 1994; Arthur and Sageman, 1994; Tyson, 2001).

Because a lack of oxygen in bottom waters prevents the colonization of the seafloor by benthic organisms, it has long been assumed that an absence of bioturbation and the presence of a laminated sediment fabric signifies anoxic conditions without postdepositional disturbance of the sediment (e.g., Byers, 1977). Yet, it can be demonstrated with two examples, one from the Chattanooga Shale of Tennessee, and one from the New Albany Shale of Indiana, that this determination is not as easy as it may initially appear.

In the lower portion of the Chattanooga Shale occurs the Dowelltown member (Conant and Swanson, 1961), which in part consists of alternating beds of laminated black shale and bioturbated gray mudstone, and a comparable situation exists in the Camp Run Member of the New Albany Shale (Hasenmueller, 1993). These alternating beds of laminated black and bioturbated gray shale are thought by many to reflect alternating anoxic and dysoxic conditions (Cluff, 1980; Hasenmueller, 1993; Leventhal, 1998; Ingall et al., 1993). In both cases, bioturbation is seen to penetrate from the gray mudstones downward into the black shale beds, and has been explained as a postdepositional modification (post black shale) that is not in conflict with a presumed anoxic origin of the black shales.

Careful study of bioturbation in the Dowelltown member shows that the first recognizable bioturbation of black shale beds (TOC content ranging from 5% to 15%) was produced very early in depositional history, when the organic bottom muds had a water content of 75% or more and behaved essentially like a viscose fluid (Lobza and Schieber, 1999a). Continued bioturbation can be documented down to a water content of 45%, at which point the mud was sufficiently stiff to support open burrow tubes (Lobza and Schieber, 1999b). Although the black shales show silt laminae, these laminae also show disruption by first-generation burrowers (Schieber, 1998a). In addition, we also find benthic fecal pellets scattered through the black shale matrix (Schieber, 1998a). Thus, although the bottom muds were probably not exceedingly hospitable, the bioturbation nonetheless reflects syndepositional benthic life.

Fig. 10A and B shows the laminated nature of black shale beds in the Camp Run member of the New Albany Shale. Fig. 10C, however, demonstrates that what at first glance looks like primary lamination, is instead a compacted bioturbation fabric produced by horizontal moving sediment feeders. Thus, the presence of lamination does not guarantee absence of bioturbation.

4.1. The limitations of geochemical proxies

Because the oxygenation of bottom waters is potentially reflected in the interrelationships of iron, sulfur, and organic matter, geochemists have proposed various schemes to differentiate anoxic and oxygenated settings (e.g., Raiswell et al., 1988; Leventhal, 1998). For example, the distribution of data points in a C/S plot has been widely used for that purpose (e.g., Berner, 1970; Leventhal, 1987). If applied to a data set from the Chattanooga Shale (Fig. 11), the suggestion is that of a largely normal marine (meaning oxygenated) setting. More recently, the degree of pyritization (DOP), has received much

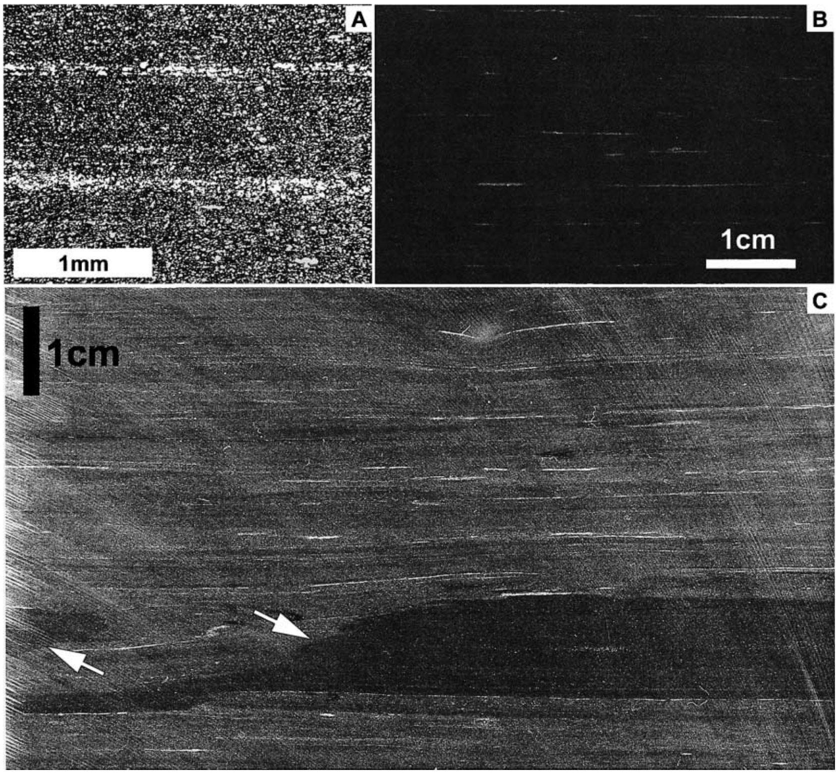

Fig. 10. Views of a black shale bed in the Camp Run Member of the New Albany Shale in Indiana. (A) Photomicrograph, showing parallel silt laminae (lighter color); (B) hand specimen showing macroscopic laminated black shale fabric; (C) strongly contrast-enhanced photo that shows that the visibly laminated black shale actually cuts across an earlier (somewhat darker) black shale bed. The latter appears to be a remnant of the originally deposited material, whereas the latter was reworked by bioturbating organisms. Only because of the strong compaction that these shales experienced do the bioturbated portions look laminated.

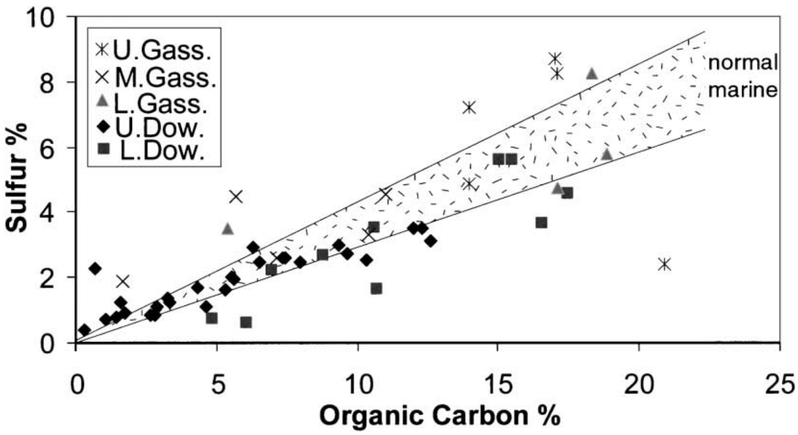

Fig. 11. Carbon–sulfur plot for 50 samples taken through the 9.5-m thickness of the Chattanooga Shale. The great majority of sample plots within or below the field that Leventhal (1998) considers normal marine. Only a small number of samples (seven) plot significantly above the ''normal marine'' field. Yet even these still show some evidence of benthic life, such as lamina disruptions and benthic fecal pellets (Schieber, 1999).

attention as an indicator of anoxic conditions. The DOP is defined as the ratio between iron actually in pyrite and the iron that can potentially be converted to pyrite, and a value of 0.75 or larger is considered indicative of anoxic conditions (Raiswell et al., 1988). When applied to the data set shown in Fig. 11, the implications from DOP are that all the black shale beds in the Chattanooga Shale reflect anoxic conditions (Fig. 12). Even some of the bioturbated gray shale beds return a DOP in excess of 0.75. Thus, two widely used geochemical proxies for anoxia, both based on the characteristics of the C/S/Fe system, yield conflicting results for the same sample set. The sad truth is, that depending on what type of criterion we use (sedimentological, biological, geochemical, etc.), we are likely to receive a different answer to the question whether a black shale was deposited under anoxic conditions or not. But perhaps all answers have merit. We might for example have had rapidly fluctuating oxygen levels, may be even seasonal anoxia (Tyson and Pearson, 1991; Oschmann, 1991). Because of the time averaging that is typical for slowly deposited sediments, evidence for the existence of such short-term variations would be difficult to extract from the sediments in question. In the case of the Chattanooga Shale, the most likely explanation for the high DOP values is the fact that erosional features and evidence of sediment reworking can be found throughout, with erosional features ranging in size/depth from millimeter- to meter-scale (Schieber, 1998a). The more conspicuous pyritic lags may reach 5 cm in thickness and consist of small concretions and framboids, as well as of mineralized algal cysts and fecal pellets. Small-scale pyritic lags, usually less than a millimeter thick, are very common. This type of mechanical pyrite enrichment inevitably raises the DOP calculated from whole rock analyses and leads to an erroneous assessment of seafloor oxygenation. In the overall context of conflicting answers from various anoxia proxies, tight integration of geochemical data with sedimentological and paleontological observations should help greatly to properly evaluate the presence or absence of anoxia for a specific black shale unit.

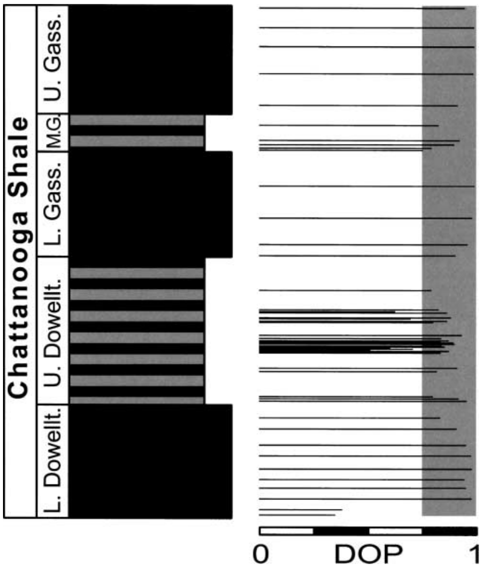

Fig. 12. Degree of pyritization (DOP) for the set of samples shown in Fig. 11. The stratigraphic section at left shows massive black shale units (black) and units that consist of interbedded gray and black shales (gray/black stripes). Only seven samples plot below a DOP of 0.75, the presumed boundary between dysoxic and anoxic black shales (Raiswell et al., 1988). Most of the samples from black/gray interbedded units are above DOP 0.75. Even some of the obviously bioturbated gray shales have DOPs above 0.75. The black shales in the black/gray units show very early bioturbation (Lobza and Schieber, 1999a), but consistently have DOPs above 0.75.

The role that organic petrology could play in this context relates to the recognition of aerobic vs. anaerobic degradation of organic matter. Is there a chance to differentiate between these two styles of degradation by way of organic petrology? A common maceral in black shales, bituminite, is thought to represent bacterially degraded organic matter (Taylor et al., 1998). In addition, several subtypes of bituminite (or amorphous organic matter) have been recognized on the basis of fluorescence color (Teichmüller and Ottenjahn, 1977) as well as through combinations of texture and transmitted light color (Boussafir et al., 1995). Further characterization of these subtypes as to their source through additional techniques, such as TEM and kerogen pyrolysis (Boussafir et al., 1995), shows promise for future investigations. It might also be quite rewarding to examine the composition of bituminite subtypes by electron microprobe (e.g., Bustin et al., 1996) and to compare the results to organic matter found in modern black muds that were deposited under anoxic vs. oxic conditions. A study of the Bakken Shale by Stasiuk (1993) gives some idea of what kinds of things we might want to look for at the petrographic level, such as bacterial and algal remains and indications of degradational relationships between structured precursor macerals (e.g., alginite) and bituminite.

4.2. Possible uses of organic petrology in sequence stratigraphy

Sequence stratigraphy has over the past two decades proven to be a powerful paradigm that has invigorated stratigraphic research (e.g., Vail et al., 1991). While well established in the study of sandstone and carbonate-rich successions, it also made recent inroads in the study of shale successions (Bohacs, 1998; Schutter, 1998). Even distal condensed black shale successions can be examined from a sequence stratigraphic perspective (Schieber, 1998b; Wignall and Maynard, 1993; Hallam, 1985).

In the Chattanooga and New Albany Shale laterally extensive erosion surfaces that can be considered sequence boundaries (Schieber, 1998b) can be observed in outcrop (Fig. 2), as well as in drill core (Fig. 13). These sequence boundaries can be recognized in areas shallow enough to undergo erosion (either subaerial or subaqueous) during sea level drops, but to do so requires careful examination (Schieber, 1998a,b). In deeper portions of basins, where these sequence boundaries turn into their "correlative conformities," detection poses a formidable challenge. The obvious problem is that in deeper settings successive black shale sequences are simply packages of black rocks that are not separated from each other by a physical bounding surface. In the New Albany Shale, we had some success in tracing erosion surfaces downdip by using gamma

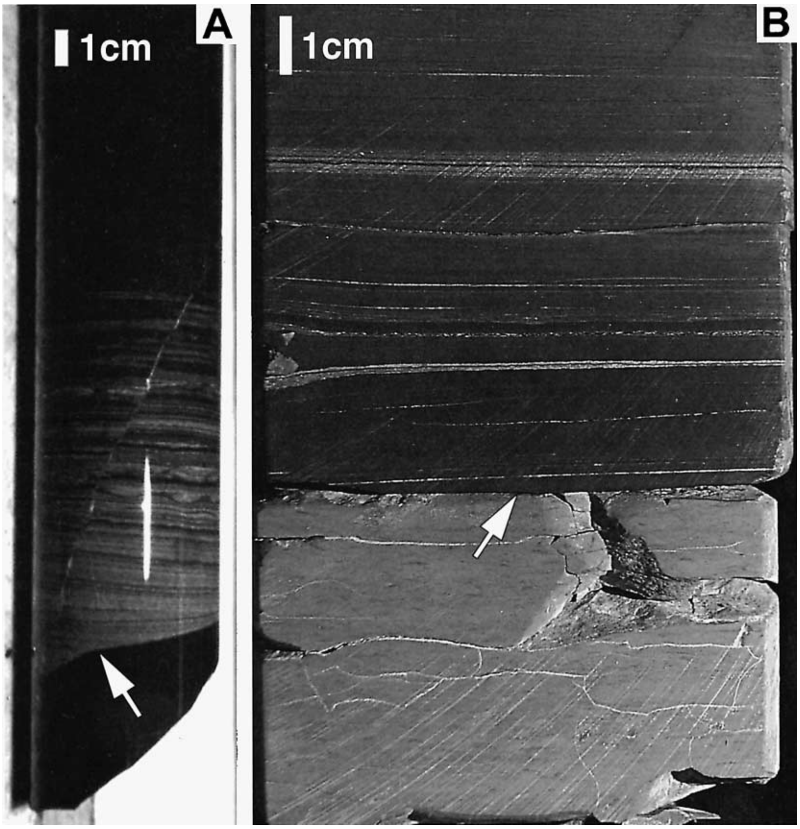

Fig. 13. Photos of cores with visible erosion surfaces. (A) From Chattanooga Shale in Tennessee. Arrow points out scoured erosional surface, overlain by laminated silt lag. (B) From New Albany Shale. Knife-sharp contact (arrow) between gray shales below and laminated black shales above marks an erosion surface at the Frasnian/Fammenian boundary (Fig. 5).

ray log motifs (Johri and Schieber, 1999), but it is still desirable to back up such interpretations by finding tangible indications of the boundary in the rock itself.

These rocks contain a range of organic macerals, specifically vitrinite, inertinite, bituminite, and alginite, but the latter two strongly dominate. While examining polished thin sections from the Chattanooga Shale and the New Albany Shale, I noticed some patterns in the distribution and characteristics of alginite and bituminite that could be useful for the delineation of black shale sequences in the absence of erosion surfaces. I will illustrate this with petrographic observations that were made at the base, the top, and also in the mid-portions of black shale intervals that were separated from each other by erosion surfaces.

At the base of black shale packages it appears that both alginite (mostly compressed *Tasmanites* cysts) and bituminite are common, but that alginite is more abundant than bituminite (Fig. 14A, B, C). In the lower third to mid-portions of black shale sequences, essentially where we perceive the maximum flooding surface (MFS) and condensed zone shales to be, we observe a very large abundance of alginite, and the shale matrix contains little bituminite (Fig. 14D, E, F). Finally, in the upper portions of sequences we observe that there is less visible alginite than in the other two intervals, and that bituminite is more conspicuous and occurs in greater abundance than before (Fig. 14G, H, I).

These changes may reflect the combined influences of changing sedimentation rates and frequency of reworking on organic matter accumulation and preservation. At the onset of sea level rise, clastic sediment input is diminished because of flooding of river valleys, and nearshore and coastline erosion is the main source of clastic material. Thus, the organic matter fraction of the freshly deposited sediment is comparatively large (Fig. 14A, B, C). Because of the shallow water conditions (Schieber, 1994a, 1998a), however, the water column is oxygenated and storms cause resuspension of previously deposited organic matter. The consequence of this should be that the more resistant particles (in particular the algal cysts that we refer to as *Tasmanites*; Tappan, 1980) are enriched in the ensuing deposit, whereas aerobic decomposition should reduce the proportion of the more labile organic matter. Because the latter would most likely turn into bituminite in the course of organic matter diagenesis (Taylor et al., 1998), resuspension would thus lead to a lower bituminite content in the resulting black shale. When flooding is at a maximum, clastic sedimentation will be at a minimum and highly carbonaceous condensed zone shales will accumulate. Although the water depth has increased, because sedimentation rates are so small, intermittent resuspension allows for almost complete bacterial breakdown of more labile organic particles, and produces a deposit that is strongly dominated by particles with the highest potential for survival. In our particular case this means shales that contain abundant large *Tasmanites* (alginite), and only very small amounts of bituminite (Fig. 14D, E, F). Because nearshore and coastal erosion during transgression provides for higher sediment accumulation rates than found in condensed zone shales, we should expect better burial and preservation of labile organic matter and a comparatively larger bituminite content in transgressive black shales. Regressive black shales (Fig. 14G, H, I) signal a gradual increase in clastic sediment supply. The increase in sedimentation rates implies not only a relative decrease in organic matter content, but also less frequent reworking and thus improved burial and preservation of organic matter. As a consequence, bituminite in regressive black shales is proportionally more abundant than in transgressive and condensed zone black shales. Because of clastic dilution of organic matter, the alginite content is visibly lower as well (Fig. 14H).

To summarize, as a black shale sequence develops there are systematic changes in the amount of sediment reworking, the proportion of biogenic sedimentation, and the supply of terrigenous sediment. The perceived changes are consistent with sequence stratigraphic concepts (Vail et al., 1991), and are reflected in organic petrographic characteristics that change systematically from the bottom to the top of a sequence (Fig. 15). Whereas the succession of features shown in Fig. 15 is necessarily more variable in shallower portions of the basins where onlap or erosion leads to missing parts, in deeper water we should expect it to be quite uniform and predictable. The model shown in Fig. 15 still requires further detail work and verification, and work is in progress to examine the perceived relationships in deeper water

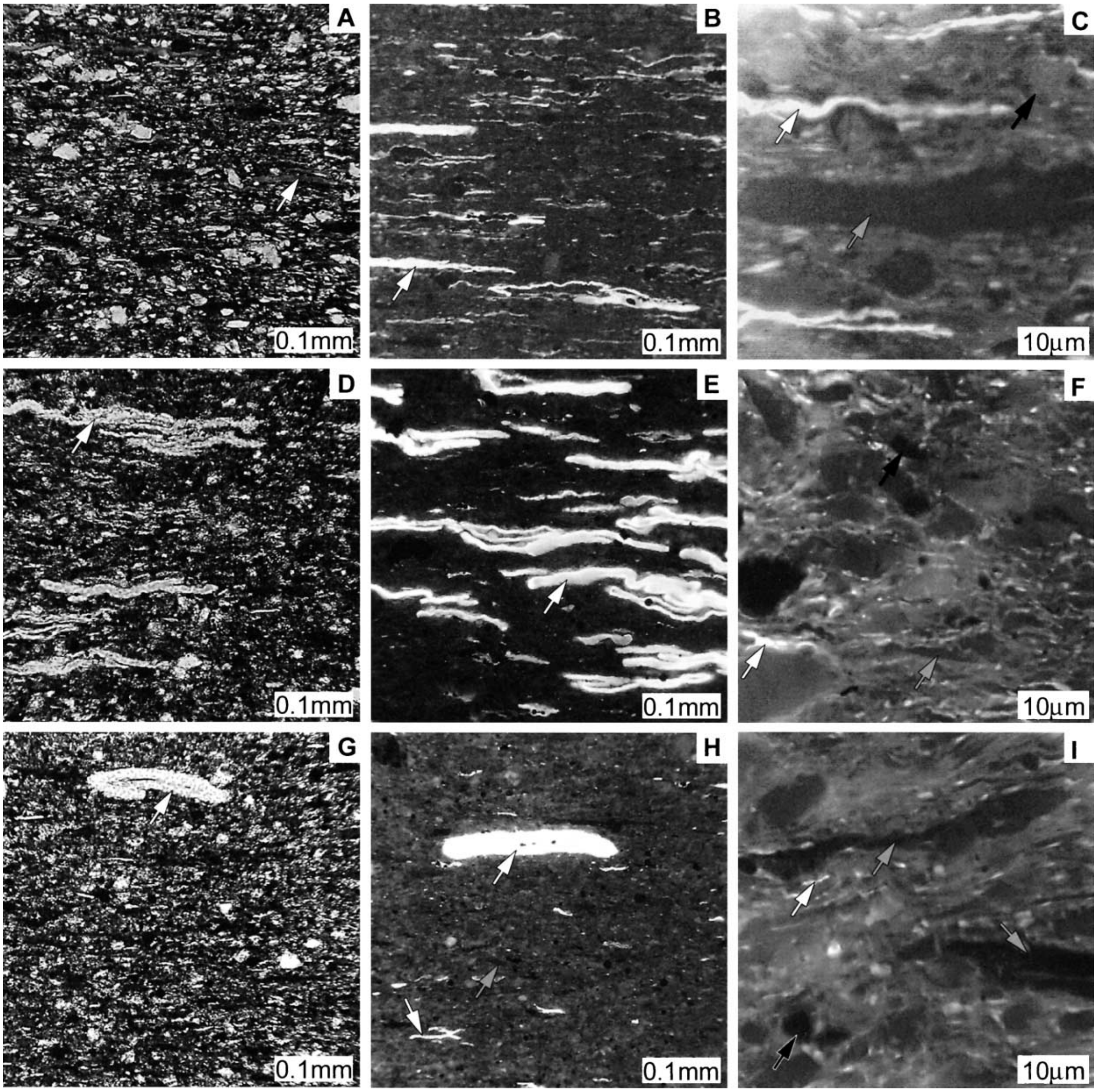

Fig. 14. Photomicrographs from base of sequence (A, B, C), condensed zone or "maximum flooding surface" (D, E, F), and top portion of sequence (G, H, I). The photomicrographs on the left were made with transmitted light, those in the center and on the right record blue light fluorescence images. Base of sequence (A, B, C): compressed *Tasmanites* cysts, (alginite, white arrows) are the prominent organic maceral, although there are also streaks of dark/brownish fluorescing bituminite (gray arrow in C). Overall there seems to be more alginite than bituminite. The black arrow in C points to a pyrite framboid. Condensed zone shales (D, E, F): Compressed *Tasmanites* cysts (alginite, white arrows) are very abundant and strongly dominate. Bituminite, although present (gray arrow in F) is small and in low abundance. The rock matrix (F) consists largely of mineral matter, shreds of alginite (white arrow in F), and some pyritic particles (black arrow in F). Top portion of sequence (G, H, I): Alginite (white arrows) is less abundant, and darker streaks and lumps of bituminite (gray arrows in H, and I) are more conspicuous than previously. The rock matrix has abundant bituminite (gray arrows in I) and only small shreds of alginite (white arrow in I). Black arrow in I points to a pyrite framboid.

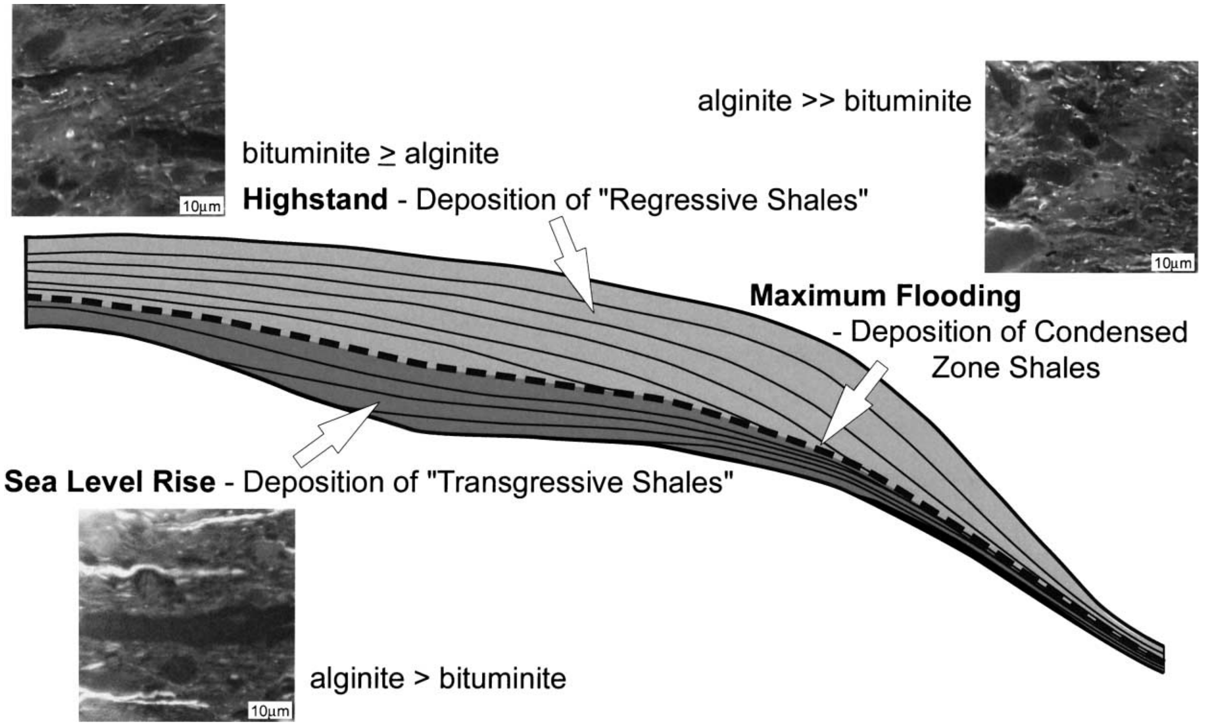

Fig. 15. Conceptual model and summary of organic petrology and maceral characteristics within a black shale sequence in a sequence stratigraphic context.

portions of the New Albany Shale. Obviously, application of this model works best when average productivity does not change too much through the extent of a black shale sequence. Caplan and Bustin (1998) give an example how significant productivity fluctuations in black shale successions can be detected through the examination of geochemical characteristics.

5. Conclusions

Observations of modern organic-rich muds illustrate the rapid decay of organic particles and the problems we face if we try to evaluate the source of organic macerals on the basis of organic petrology alone. Targeted electron microscopy and organic geochemistry are necessary adjuncts. Properties of modern organic-rich muds also suggest that the precursor sediment of high-TOC black shales may have had a jelly-like consistency and may have behaved in a more cohesive manner than commonly assumed. Coal-like bituminite streaks in Devonian and other black shales may actually represent compressed layers of essentially pure organic debris, rather than the fossil remains of pieces of wood.

Sedimentologic examination of Late Devonian black shales in the eastern US, such as the Chattanooga and New Albany Shale, suggests that a deep water setting is not a necessary requirement for black shale formation. Seemingly continuous black shale successions may show internal erosion surfaces that were produced during emergence and low stands of sea level, and allow sequence stratigraphic subdivision.

Detailed examination of Late Devonian shales for primary (e.g., lamination) and secondary (bioturbation) sedimentary features shows that subtle evidence of bioturbation is widespread. Even laminated black shales, supposedly a product of anoxic sedimentary settings, may display pervasive bioturbation upon close inspection. Likewise, geochemical proxies that have been employed to differentiate anoxic from dysoxic and aerobic settings, may lead to different and conflicting results. If petrographic criteria could be developed that would allow the distinction of aerobic vs. anoxic decay for organic particles, it would be a valuable criterion for the differentiation of dysoxic from anoxic black shale facies.

During sequence development, there are systematic changes in the degree of sediment reworking, the amount of biogenic sedimentation, and the organic/clastic ratio. When applied to black shale sequences, this can lead to systematic changes in maceral content from bottom to top of a sequence, and allow distinction of transgressive, condensed zone, and regressive black shales. Whereas black shale sequences can be differentiated by erosion surfaces in shallow portions of sedimentary basins, the observed changes in maceral content may allow the identification of sequences in deeper portions of basins, where erosion surfaces are replaced by their "correlative conformities."

There is no simple petrographic way for determining the source of organic particles in black shales in detail. Once calibrated with insights and data from other methodologies (e.g., electron microscopy, geochemistry), however, organic petrology can provide new clues and insights for the sedimentologist. A tight integration of sedimentology, organic petrology, and geochemistry should help us to arrive at an understanding of the origin of black shales that is consistent with the available data, and addresses the underlying mechanisms.

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