Simple Gifts and Buried Treasures – Implications of Finding Bioturbation and Erosion Surfaces in Black Shales

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ABSTRACT: Detailed sedimentological study of Devonian black shales from the eastern USA shows that these rocks contain valuable textural clues to their depositional history, clues that hitherto have gone mostly unrecognized. Cryptic bioturbation and subtle erosional features suggest the presence, originally, of much more benthic life and bottom current activity than is commonly assumed for these deposits. Sedimentary features observed in black shales can provide prima facie evidence of depositional processes at a resolution that is hard to match with geochemical approaches. No geochemical study of black shales should be conducted without careful sedimentological evaluation because subtle sedimentary features may have a direct bearing on the applicability of proposed genetic models. Knowledge of sedimentary features is required to guide geochemical sampling so as to avoid averaging intervals of dissimilar origins, and to provide critical constraints for the interpretation of geochemical data sets.

INTRODUCTION

Fine-grained terrigenous clastics, also known as mudstones and shales, are in general a still poorly understood and understudied group of sedimentary rocks. Nonetheless, they dominate the sedimentary record in terms of rock volume and recorded time. The one exception within this category is those fine-grained siliciclastics that contain appreciable quantities of organic carbon, the so-called black shales. Although black shales constitute only a small proportion of the total volume of fine-grained siliciclastics, they have received more study than all other mudstones and shales combined. For a long time the reasons for this have been economic in nature, owing to the fact that probably more than 90 percent of the world's recoverable oil and gas reserves were sourced from black shales (Klemme and Ulmishek, 1991).

Because organic carbon results mostly from photosynthesis by plants and algae, an atom of carbon buried in sediments implies a molecule of oxygen added to the atmosphere. Carbon burial is linked to other global biogeochemical cycles (O, S, N, P, etc.) and is a critical variable in our attempts to understand the history and evolution of the oceans and atmosphere, as well as global climate change. Over geologic time, carbon burial probably was responsible for a gradual rise in atmospheric oxygen levels. Also, by reducing the greenhouse effect it can lead to lower global temperatures and even ice ages (Berner, 1997). In that context, considering that the geological record is punctuated by global episodes of widespread black shale formation (Klemme and Ulmishek, 1991), understanding what variables are required to produce a "black shale world" is of considerable significance.

Early comparisons with black muds from the bottom of the Black Sea have long led geologists to think that ancient black shales required anoxic bottom waters for their formation, and that they typically formed in the distal and deepest portions of sedimentary basins. Recent research into black shales (e.g., Schieber, 1998; Sageman et al., 2003), however, has shown this to be a highly simplistic, though widely held, notion. Much progress has been made towards appreciating the often subtle differences between black shale formations and arriving at sophisticated appraisals of to their depositional histories. Wignall (1994) provided a good overview of progress that has been made and controversies that still remain.

A central theme in black shale studies has been the detection of bottom water anoxia at the time of deposition. A variety of approaches have been tried to that end, including geochemical proxies (e.g., Raiswell and Berner, 1985; Jones and Manning, 1994), paleoecological measures (e.g., Richter, 1931; Rhoads and Morse, 1971; Kauffman and Sageman, 1988), ichnological criteria (e.g., Savrda and Bottjer, 1986; Ekdale and Mason, 1988; Wignall, 1994), sedimentological assessments (e.g., Rich, 1951; Conant and Swanson, 1961; Schieber, 1994), or combinations of approaches (e.g., Seilacher and Meischner, 1964; Heckel, 1977; Baird and Brett, 1991; Sageman et al., 2003).

In this paper, I will focus on the benefits of inferences derived from careful visual examination of black shales. I will also point out cases where geochemical proxies for the state of oxygenation clearly disagree with what the rocks themselves are telling us, and what the implications are for geochemical approaches to black shale origins. All examples are from Devonian black shales of the eastern USA. A still widespread perception of these sediments is that they were largely devoid of benthic life because of prevailing anoxic conditions (Ettensohn, 1985; Cluff, 1980). Based on the observations in the following examples, a case can be made that benthic occupation and bottom current activity was probably the norm rather than the exception during the time of deposition these black shales.

Example 1: Burrows that aren't – the importance of recognizing the traces of "sediment swimmers"

We commonly recognize burrows in sediments when they contrast visibly with the matrix (difference in color, texture, composition), and take it for granted that an excavated tunnel is filled with sediment to produce what we see. This assumption, however, is flawed. It does not take into account that very similar looking features are also produced when worms swim through liquid mud. Being able to differentiate traces of "sediment swimmers" from those of "tunnel builders" can result in a completely different interpretation of the depositional setting of a shale.

Figure 1A shows alternating beds of black and greenish-gray shale from the Dowelltown Member (Conant and Swanson, 1961) of the Chattanooga Shale (Devonian) in central Tennessee. Visible bioturbation (traces filled with gray shale) diminishes in intensity downwards into the black bed, suggesting at first glance that the seafloor was only hospitable to benthos at times of gray shale deposition. By default this implies anaerobic/anoxic conditions for the black shale beds, an interpretation that characterizes other studies of comparable black shale/gray shale alternations (e.g., Cluff, 1980; Beier and Hayes, 1989; Hasenmueller, 1993; Calvert et al., 1996). However, the fact that there is also bioturbation (though not immediately obvious) in the lower portions of black shale beds (Fig. 2) complicates matters. Because the traces in Fig. 2 are filled with black mud, they are practically "invisible" without image enhancement.

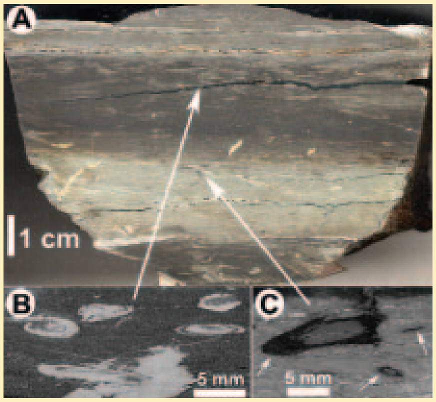

Figure 1: (A) Cut and ground (1000 grit) surface of shale that consists of alternating black and greenish-gray beds. Note the downward-diminishing abundance of gray burrow fills in the central black bed. (B) Close-up of "mantle and swirl" traces in the upper portion of the black bed. These traces are produced when worms move/swim through the soft watery substrate (~70% water content) and drag gray mud downwards into black muds. (C) Close-up of equivalent traces (white arrows) that were produced when worms moved into the underlying gray layer and dragged black mud behind them.

Lobza and Schieber (1999) demonstrated through a combination of experiments and textural studies how some traces in black shales (Figs. 1, 2) were formed. Many of the "burrows" illustrated in Figure 1A formed when worms "swam" or "wiggled" through a soft-soupy substrate with high water content (~70-75%). Rather than being sediment-filled tunnels, these "burrows" represent instead mixing structures produced by worms that dragged mud of one color into adjacent mud layers of different color (Figs. 1B, 1C). From a process perspective, they are biodeformational structures (e.g., Wetzel, 1991a; Wetzel and Uchman, 1998) and, for lack of a better name, we called them "mantle and swirl" traces (Lobza and Schieber, 1999). Now, as long as mud of contrasting color is dragged along by moving worms, these traces show up nicely (Fig. 1). Yet, if a worm moves only in one layer, its trace will be filled with similar material and there will be no color contrast (Fig. 2). This kind of "black on black" trace will be essentially "invisible" (Fig. 2). Likewise, after some distance from crossing the color boundary (e.g., gray to black), the gray mud that the worms dragged behind will run out and there will be no more color contrast.

Proper identification of "sediment swimmer" traces matters. It tells us that the erstwhile black muds contained benthic life at the time of deposition, and not at some unspecified later time. Experiments on self-compaction of freshly deposited muds (Barrett and Schieber, 1999) indicate that it will take from a few days to weeks of consolidation to arrive at a water content of around 70%. Therefore, the organisms that produced the traces in Figures 1 and 2 must have done so shortly after deposition of these muds. They actually lived in carbonaceous surface muds, and that makes it highly unlikely that anoxic conditions were the norm when the black shale layers were deposited. Thus, recognizing "sediment swimmer" traces in these black shales mitigates against the prevalent assumption of anaerobic conditions.

Example 2: Counterintuitive lessons from pyrite – not so anoxic after all

Round to elliptical pyritic features (Fig. 3A) are common on broken or cut surfaces of black shales, and are commonly interpreted as concretionary in origin. Pyrite concretions are not only common in black shales, but they also evoke images of anoxic conditions, especially when associated with a laminated appearance. In combination, these features of black shales (pyritic, laminated) are often thought to indicate anoxic conditions and an absence of benthos.

In our example, however, X-radiographs reveal a more interesting story. What looked like concretions in cross section turns out to be pyritic trails in plan view (Fig. 3C). These trails may follow chaotic loops, turn sharply through 360 degrees, and rise and fall through the sediment (Fig. 3B). The traces, which resemble *Spirophycos* or *Nereites*, were evidently produced by small organisms that zigzagged their way through the mud in search of food. This forces us to rethink our initial assumptions of anoxic conditions for certain black shale deposits. Such pyritic trails may be much more common in black shales than we currently appreciate.

While deducing oxygenated bottom waters from pyritic trails (Fig. 3) does not require a great leap of faith, proposing that pyrite concretions in black shales may actually be indicators of oxygenated bottom waters probably would meet considerable resistance. Yet, from a geochemical perspective, oxygenated waters above the seabed seem to be a prerequisite for forming localized pyrite concentrations in the bottom sediments. This is so because under fully anoxic conditions, with an excess of H_2S in the sediment, all the iron that was released from terrigenous grains would be precipitated immediately in the form of disseminated and tiny iron sulfide grains. Under oxic bottom waters, however, anoxic, organic-rich sediments are typically non-sulfidic in the surface layer (Berner, 1981), and thus allow for localized accumulation of pyrite. In such settings,

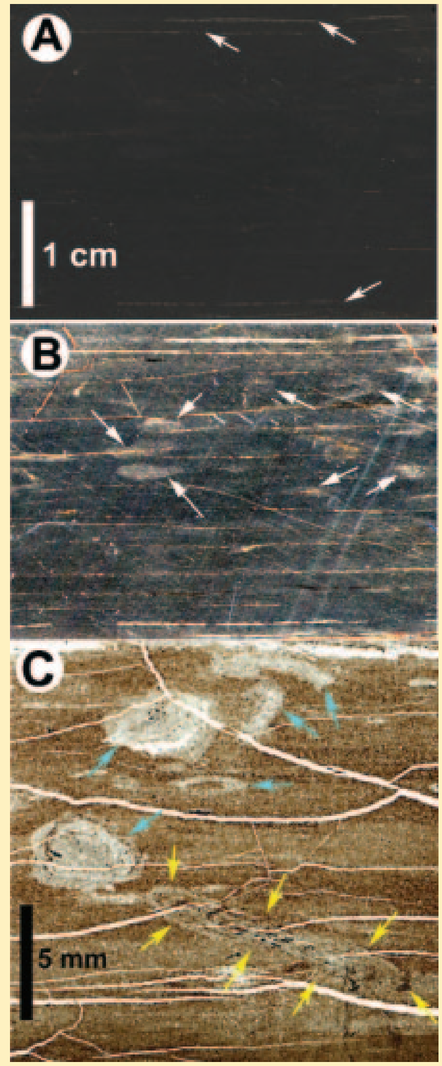

Figure 2: (A) Seemingly undisturbed black mud with some silt laminae (white arrows). (B) the same image with serious image enhancement applied (contrast enhancement with Adobe PhotoshopTM). With contrast enhancement, lighter colored oval-shaped features (white arrows) turn out to be compressed "mantle and swirl" traces. Under normal conditions they are "invisible" because they are filled with black mud. (C) Thin-section photomicrograph illustrating the subtle nature of black shale filled traces. Gray shale-filled traces (blue arrows) are easily be observed on ground surfaces (Fig. 1); yellow arrows outline a black shale filled trace that has little color contrast with the surrounding black shale.

iron oxyhydroxide coatings on terrigenous grains of the surface sediment would be a ready source of easily solubilized iron that would keep pore waters free of H_2S via pyrite formation (Canfield and Raiswell, 1991; Canfield et al., 1992). Simultaneously, bacterial decay of organic matter would remove downwardly diffusing oxygen from the pore waters. Under the ensuing combination of anoxic and non-sulfidic conditions, iron should be able to migrate through the sediment, making possible the localized accumula-

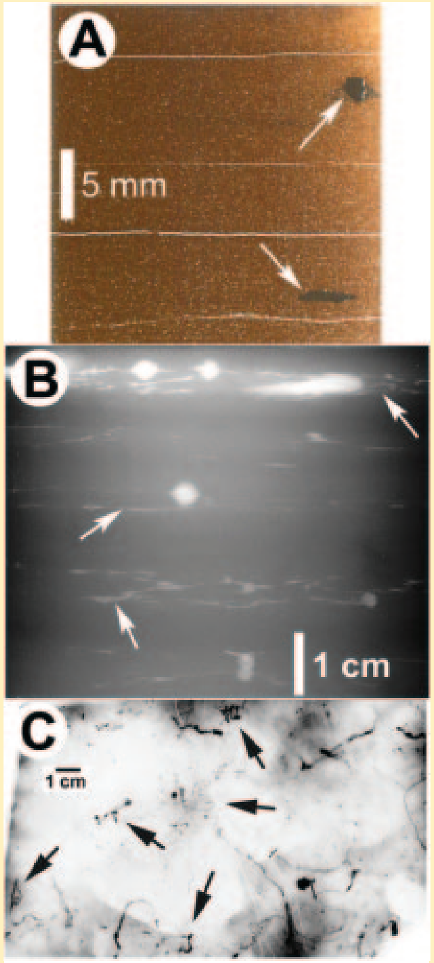

Figure 3: (A) Thin section of faintly laminated black shale with mm-scale, round-elliptical pyrite concretions (arrows). Sample is from the New Albany Shale, Indiana. (B) X-radiograph from same sample (note change in scale, view perpendicular to bedding). Laminae do not have enough contrast to show up, only pyritic structures produce sufficient contrast. Irregular pyritic trails occur obliquely through the sediment (arrows). Bright spots are localized pyrite accumulations that nucleated on the trails. (C) X-radiograph from a slab of comparable lithology (Chattanooga Shale from Tennessee; view perpendicular to bedding). Pyritic trails with erratic and sharp turns are present. Intensity varies because pyritization is not uniform along trail.

tion of pyrite. Thus, various kinds of pyrite aggregates present in black shales (pyrite nodules, pyritized burrows, pyritized fossils, etc.) actually carry a counterintuitive message – oxygenated waters were present above the seabed.

Example 3: More counterintuitive stuff – Burrowing produces laminated black shales

Most black shale researchers consider laminated black shales that lack evidence of disturbance of bedding as reliable indicators of anaerobic or anoxic conditions (e.g., Wignall, 1994). A safe assumption supposedly, but what if one were to introduce a way by which burrowing could result in a laminated black shale fabric? Work on the New Albany Shale (Devonian of Indiana) has uncovered evidence for just such a mechanism at work.

Figure 4 shows a fairly typical specimen of New Albany black shale. Horizontal streaks of silt (Fig. 4A) extend in many instances across the width of a thin section, giving it a laminated character that compares well to many other laminated black shales (O'Brien and Slatt, 1990). On initial inspection, this specimen appears to represent a laminated black shale from an anoxic setting. However, silt streaks and laminae that were slightly non-parallel and showed variable orientation across the specimen surface cast doubt on this interpretation. Enhancing Fig. 4A with Adobe Photoshop™ highlighted the silt streaks and laminae (Fig. 4B), and furthermore revealed subtle discontinuities and disruptions of laminae (Fig. 4C). Were these features due to scouring by bottom currents, or were they due to bioturbation? Lateral tracing of these features would have been helpful, but large study specimens are rarely available. Drill core material is too narrow, and in outcrop specimens, even the slightest weathering completely obscures the features in question. Persistence, however, uncovered several specimens that established that the type of black shale shown in Figure 4 ("black shale with silty streaks") was actually a product of bioturbation (Fig. 5).

Figure 5 shows "black shale with silty streaks" penetrating and crosscutting a preexisting black shale with homogenous appearance (Fig. 5D). The burrowers seem to have moved through the sediment more or less horizontally, producing "sheets" of reworked material that usually extend beyond the diameter of the core (~10 cm). In so doing, the burrowers produced what one might call a "burrow-laminated" fabric, causing grain segregation (silty streaks). Lamina disruptions (Figs. 4, 5D) suggest that burrowers reworked the sediment more than once, possibly a reflection of the high organic matter content.

In the New Albany Shale, black shale intervals ranging up to four meters in thickness may show pervasive "burrow-laminated" fabric (Fig. 4), indicating almost complete reworking (Fig. 5) of an organic-rich mud. In places where gray shale beds are intercalated, other burrows, most commonly *Zoophycos*, penetrate downwards into "burrow-laminated" black shale. Apparently, the bioturbation that gave rise to "burrow-laminated" fabric occurs early in the depositional history when the sediment still has a high water content. The horizontal mining habit of the burrowers, combined with substantial subsequent compaction (down to 30-40% of original thickness), produced a horizontally laminated fabric.

The *Zoophycos* traces observed in "burrow-laminated" black shales consist of closely spaced horizontal sheets. One may speculate whether the organisms that produced the "burrow-laminated" fabric also produced the subsequent *Zoophycos* burrows, and whether the difference in appearance reflects a lower water content of the sediment at the time of *Zoophycos* emplacement. Bioturbaters produce different burrows depending on substrate consistency (e.g., Bromley, 1996). The notion that "burrow-laminators" may be related to the organisms that produce *Zoophycos* style traces also receives support from a study of Devonian shales in the Catskill Delta of New York. There, gray mudstones are completely reworked by *Zoophycos*, yet the *Zoophycos* morphology is largely subsumed by the now "burrow-laminated" character of the sediment (Schieber, 1999).

Example 4: Erosive features in black shales suggest bottom currents, water column mixing, and a stratigraphic record littered by gaps

Erosive features in black shales are recognizable from the outcrop scale down to the microscopic scale (e.g., Baird, 1976; Baird and

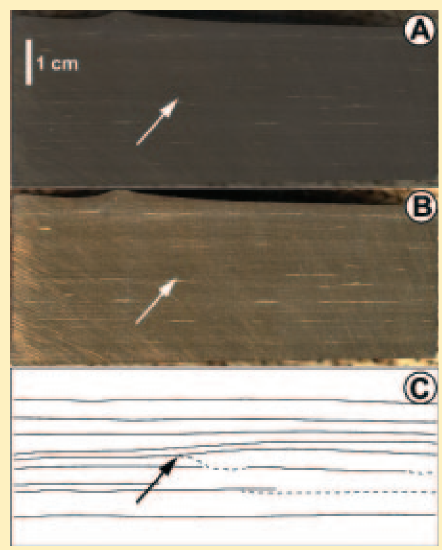

Figure 4: Laminated black shale from the New Albany Shale, Indiana. (A) Black shale sample as it would appear to the unaided eye. (B) Same sample after contrast enhancement with Adobe Photoshop™: silty streaks are more clearly visible, and laminae are non-parallel, undulose, and terminated in places. (C) Tracing of some laminae to highlight lamina characteristics. Black arrow indicates where one lamina (from right) terminates against an overlying lamina. Lamina directly to the left has been cut by whatever produced the lamina coming from the right. Black arrow is reproduced in the same position in (A) and (B).

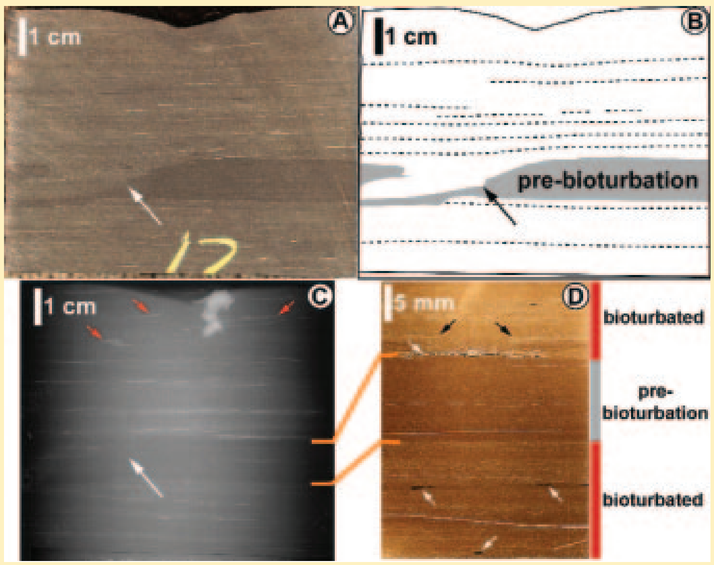

Figure 5: Image-enhanced, laminated black shale from the New Albany Shale, Indiana. (A) The black shale with silty streaks cuts across (white arrow) an earlier black shale that appears more homogenous and darker. (B) Line drawing to highlight lamina characteristics and crosscutting relationship in A. Penetration of the laminae is "burrow style" (black arrow). (C) X-radiograph of same sample. The arrows in A, B, and C all point to the crosscutting bioturbation. (D) Photomicrograph of thin section from same interval (note scale change) showing that the pre-bioturbation black shale is homogeneous, and that silty laminae and streaks are typical for the bioturbated portions. More abundant pyrite in silty streaks (white arrows) makes them show up better in X-radiographs (C). We also see lamina disruptions in the bioturbated portions (black arrows).

Brett, 1991; Schieber, 1998). Yet while larger scale features, such as macroscopic scours and truncation surfaces, are gradually accepted as indicators of strong bottom currents with attendant implications for water column mixing and oxygenation, small scale erosion features still go largely unrecognized.

Figure 6 illustrates how we can decipher depositional history from the context of burrows, burrow fills, and erosion surface morphology. At first, Figure 6 seems to show just another black shale-gray shale couplet like the one illustrated in Figure 1, except that *Chondrites* burrows, in addition to "mantle and swirl" traces, are present. Things change when the image is contrast enhanced: what appeared initially to be a single black shale layer is actually a succession of two layers (Fig. 6A). The lower black layer (#1) is cut by an irregular erosion surface (Fig. 6B) that reflects a cm-scale pre-compaction relief, and the gray-shale-filled *Chondrites* burrows within that layer are truncated at the erosion surface (Fig. 6B). The gray fill of the *Chondrites* burrows thus predates erosion (ES1) and subsequent deposition of the black layer (#3) that overlies erosion surface ES1. This relationship requires that the lower black shale layer (#1) was once overlain by a gray shale layer (#2) that supplied the fill for the *Chondrites* burrows. Erosion of this gray layer preceded deposition of the next black layer (#3).

The burrows in the second black layer (#3) reveal a comparable story (Fig. 6C). They are cut by erosion (ES2) and have a gray fill that differs in composition from the gray shale above. As above, this indicates yet another gray shale layer (#4) that was eroded prior to deposition of the gray shale layer that we see now (#5). Basically, although we can recognize only three layers of shale, we have to conclude that there were at least five (or more) layers originally. Erosive interludes as revealed in Figure 6 suggest that powerful bottom currents may have been much more common in black shale settings than commonly assumed. This reinforces the conclusions drawn from prior examples: namely that water column mixing and oxygenation of bottom waters was the norm rather than the exception.

The surface relief of these erosion surfaces (ES1 and ES2) indicates that what was eroded were semiconsolidated muds, "stiff" enough to resist eroding currents. The degree of compaction observed in *Chondrites* burrows, suggesting a water content of about 45% (cover art), confirms this assessment. Because the *Chondrites* burrows occur next to "mantle and swirl" traces that were emplaced at water contents of around 75% (cover art), they were obviously emplaced later in the depositional history and probably at a greater depth in the sediment. Judging from studies of deep sea muds (Ekdale et al., 1984; Wetzel, 1991a), the organisms that produce *Chondrites* may penetrate to depths of about 35 cm. In our example, the mud had a water content of about 45% at the time *Chondrites* was emplaced; thus those 35 cm would be reduced to a 20 cm layer of consolidated shale. In Figure 6, all that remains of two such mud layers are the bottom portions with *Chondrites* burrows. If these two layers are essentially what is missing from the specimens in Figure 6, then our 5-cm-thick sample (Fig. 6) may be all that is left of nearly 50 cm of potential rock record. In the context of other examples of intermittent erosion in black shales and marine mudstones (e.g., Baird, 1976; Baird and Brett, 1991; Schieber, 1998, 1999) it may well be that, just like it is true for sandstones and carbonates, the shale portion of the sedimentary record is dominated by gaps rather than by record.

IMPLICATIONS

Because it is commonly assumed that oxygen content or organic productivity of marine waters exerts the main control on black shale formation, discussion of their origin has largely been dominated by geochemical arguments (e.g., Beier and Hayes, 1989; Calvert et al., 1996). Geochemists have devised geochemical proxies that may provide insight into the formative conditions of black shales (notably, indices that allow us to determine the oxygenation state of the water column and the presence of anoxia; Jones and Manning, 1994). Although I have no problem with geochemistry (indeed, it is an integral part of my studies of Devonian black shales), it is clear from information summarized here that there are many conflicts between what sedimentary features tell us and what geochemical proxies would suggest. For example, the most widely employed anoxia proxy, degree of pyritization (DOP; Raiswell et al., 1988), indicates anoxic conditions for most of the samples that we analyzed. This interpretation is not supported by the erosive features and various intensities of bioturbation that these same samples contain. Sedimentological and petrographical study of the samples reveals that intermittent erosion and reworking caused hydraulic pyrite enrichment in silty laminae and lag deposits, causing artificially high DOP values (Schieber, 2001). Comparable problems exist with regard to other proxies.

As the DOP example illustrates, uncritical reliance on geochemical data and proxies is risky. Sedimentological aspects of shale deposition need to be considered in the formulation of realistic geochemical models. Another inherent problem is that geochemical models for black shale formation are typically based on bulk analyses of homogenized samples representing stratigraphic intervals ranging from centimenters to tens of centimeters in thickness. In distal Devonian black shales a 10 cm interval of shale may represent a time span of as much as 100,000 years (Schieber, 1998), and much can happen to an original deposit over such a long time span. Sedimentological evaluation is a necessary prerequisite for successful geochemical studies because prima

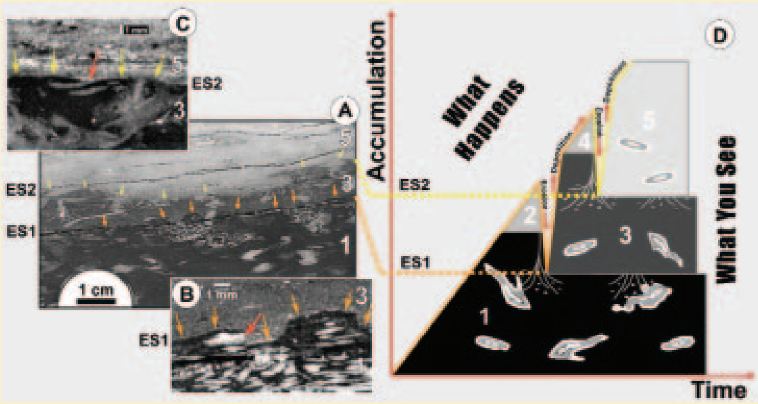

Figure 6: Multiple erosion surfaces and missing layers in a black shale (layers numbered 1 through 5 in ascending order). (A) Strongly contrast enhanced image of black shale-gray shale couplet. Two dark layers are actually present. The lower one is truncated by erosion surface ES1 (orange arrows). The second dark layer is truncated by erosion surface ES2 (yellow arrows). (B) shows detail of ES1 (orange arrows) with irregular surface topography. The burrow fill in layer 1 is lighter in color than the material from the layers that cover the erosion surface (red arrow), indicating that the gray layer (layer 2) that supplied the fill has been eroded. (C) Detail of ES2 (yellow arrows), illustrating that burrow fill of the second dark layer (layer 3) differs compositionally from the material of the overlaying gray layer (red arrow). (D) Sediment accumulation vs. time diagram illustrating the succession of events that lead to the observed rock record.

facie knowledge of depositional processes places critical constraints on the interpretation of geochemical data sets, and is a requirement for sensible geochemical sampling (e.g., in order to avoid averaging intervals of dissimilar origins).

CONCLUSIONS

Black shales may seem to be largely featureless initially, but careful study can reveal a wealth of sedimentological detail that has a direct bearing on which genetic models are permissible, and which ones are unacceptable. As illustrated in the four examples above, careful examination of black shales can help to: (1)establish whether bioturbation features are syngenetic with a black shale horizon (example 1); (2)extract information about paleo-oxygenation from pyrite aggregates (example 2); (3) resolve whether laminated fabric is a primary depositional feature or a secondary feature due to bioturbation (example 3); (4) reveal erosive features that provide information about bottom currents, water-column mixing, and oxygenation, as well as information about the completeness (or lack thereof) of the stratigraphic record in shales (example 4).

Although this list is necessarily incomplete, it serves to make my main point – it pays to look at your shales. A sedimentological inventory of a black shale succession, developed through study of outcrops, hand specimens, core samples, and thin sections, can greatly advance our understanding of these rocks. Such an inventory should be conducted before the decision is made to engage in costly and time-consuming geochemical studies.

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