

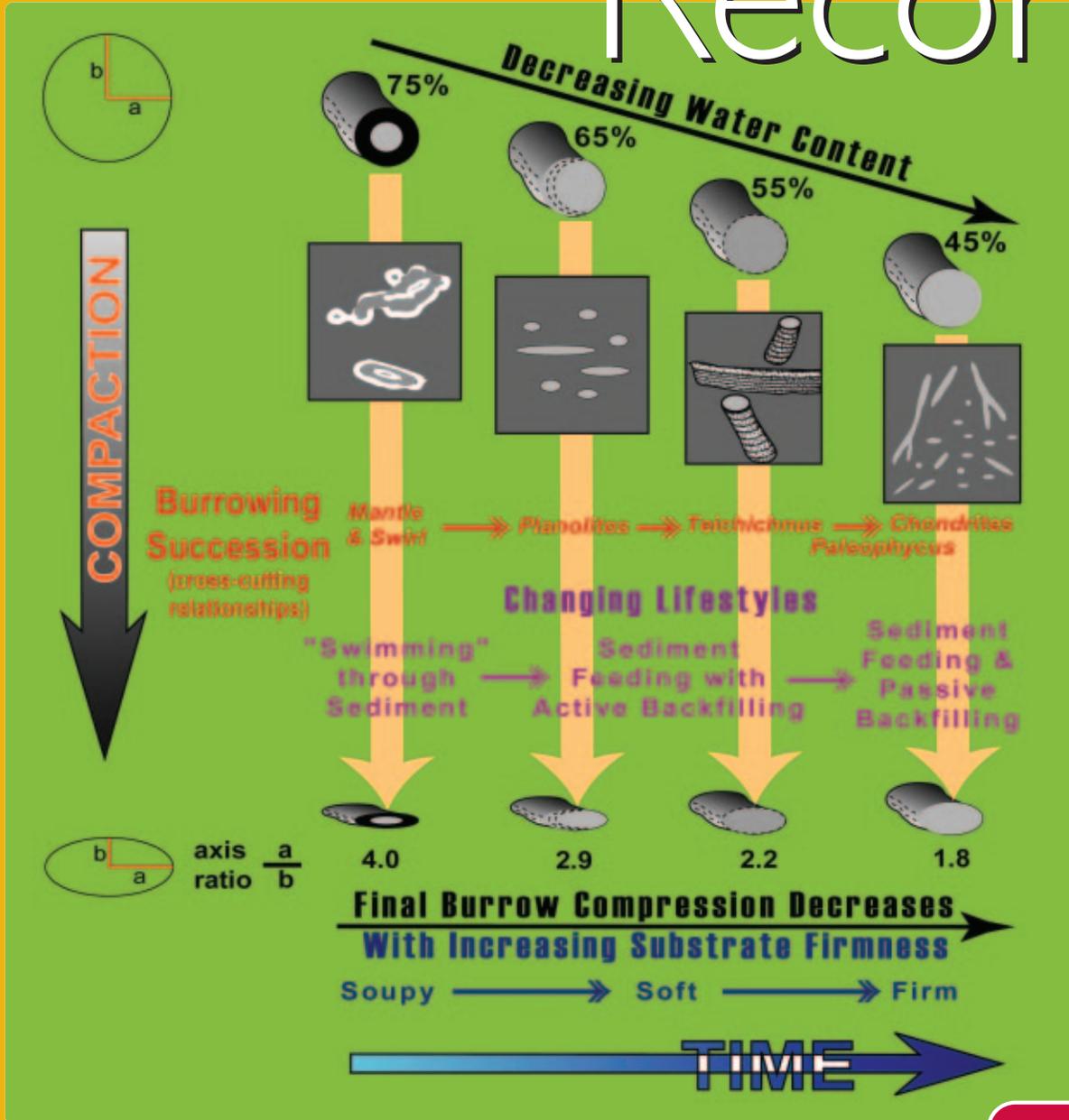
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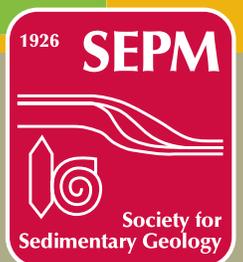
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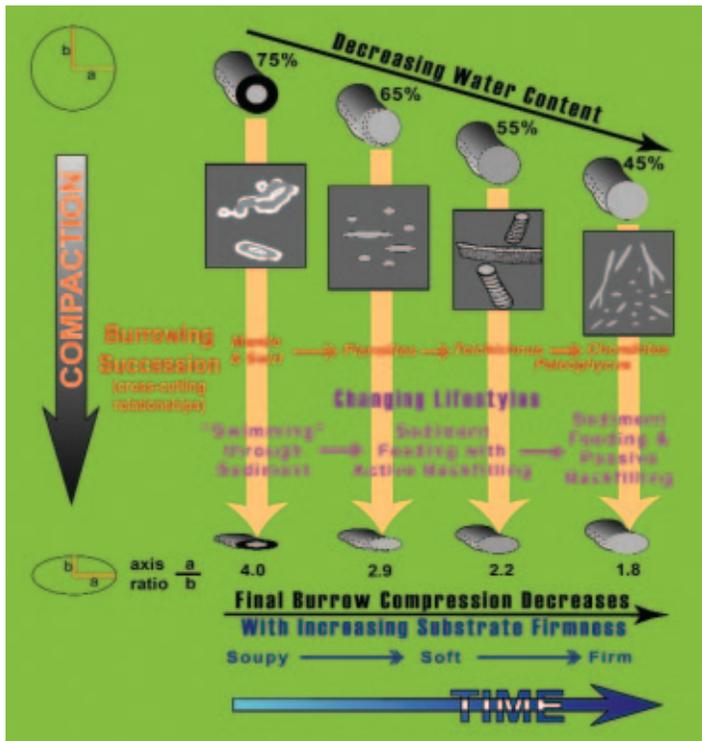
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Cover art: Progressive burrowing of self-compacting muds: summary of observations from trace fossils in black shale-gray shale couplets (Fig. 1, Schieber, this issue). Cross-cutting relationships show that burrows are emplaced in the following succession: "Mantle and Swirl," Planolites, Teichichnus, Palaeophycus, and Chondrites. The axis ratio of burrow tubes shows that early burrows were emplaced in a watery and soupy substrate, whereas late burrows were emplaced into a substrate of firm consistency (see Schieber, this issue).

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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 (Bernier, 1997). In that context, consider-

ing 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 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.

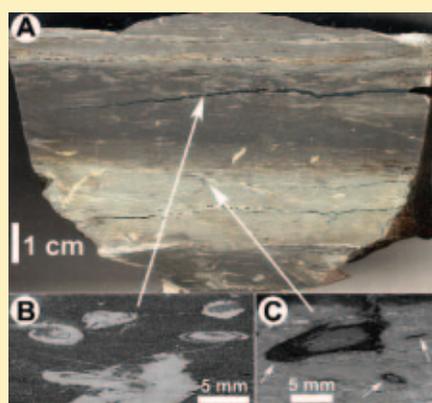


Figure 1: (A) Cut and ground (1000 grit) surface of shale that consists of alternating black and greenish-gray beds. Note the downward-diminishing abundance of gray burrow fills in the central black bed. (B) Close-up of “mantle and swirl” traces in the upper portion of the black bed. These traces are 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,

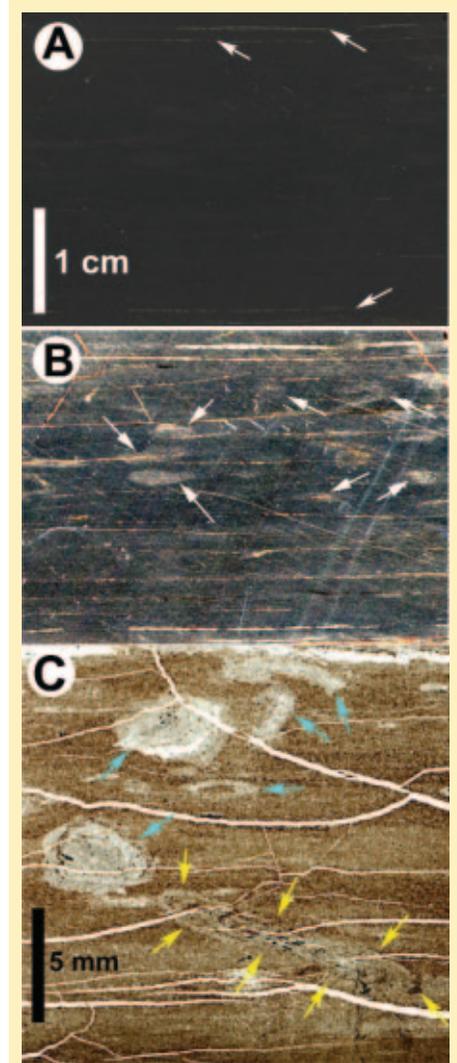


Figure 2: (A) Seemingly undisturbed black mud with some silt laminae (white arrows). (B) the same image with serious image enhancement applied (contrast enhancement with Adobe Photoshop™). With contrast enhancement, lighter colored oval-shaped features (white arrows) turn out to be compressed “mantle 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 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-

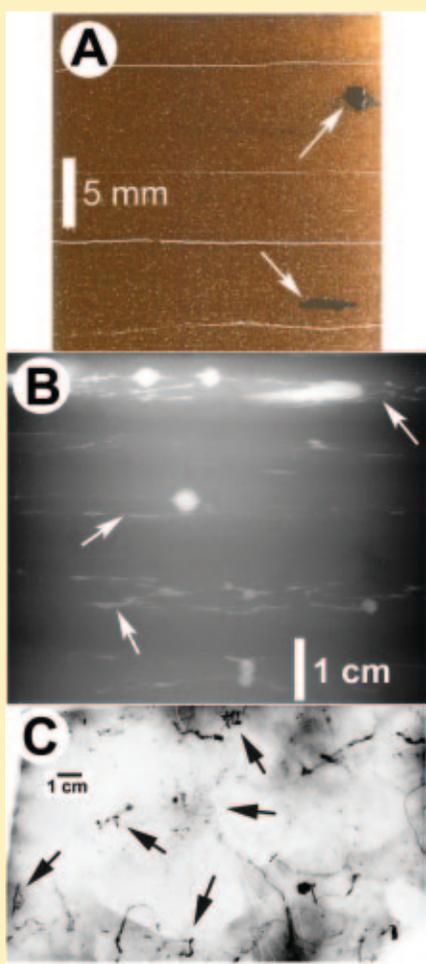


Figure 3: (A) Thin section of faintly laminated black shale with mm-scale, round-elliptical pyrite concretions (arrows). Sample is from the New Albany Shale, Indiana. (B) X-radiograph from same sample (note change in scale, view perpendicular to bedding). Laminae do not have enough contrast to show up, 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. Bioturbators 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

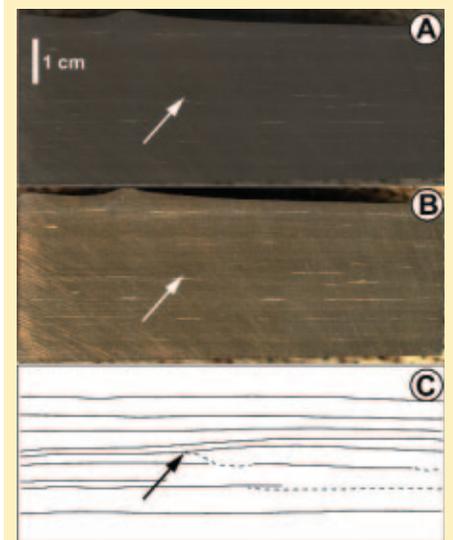


Figure 4: Laminated black shale from the New Albany Shale, Indiana. (A) Black shale sample as it would appear to the unaided eye. (B) Same sample after contrast enhancement with Adobe Photoshop™: silty streaks are more clearly visible, and laminae are non-parallel, undulose, and terminated in places. (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).

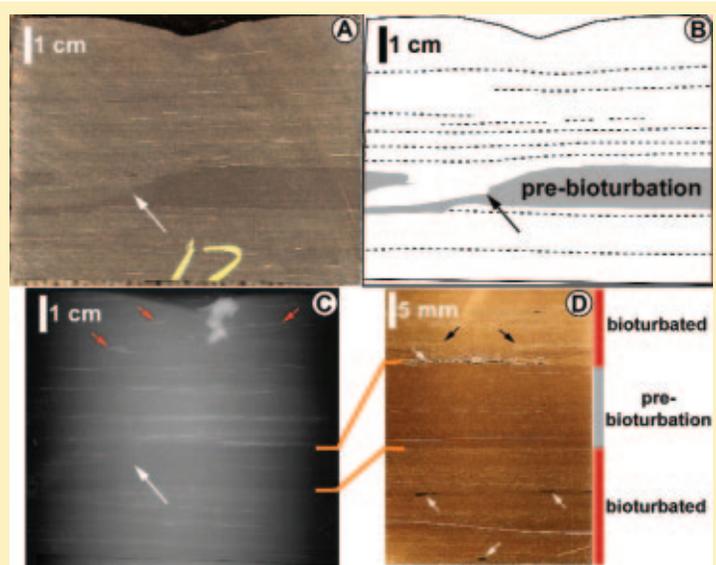


Figure 5: Image-enhanced, laminated black shale from the New Albany Shale, Indiana. (A) The black shale with silty streaks cuts across (white arrow) an earlier black shale that appears more homogenous and darker. (B) Line drawing to highlight lamina characteristics and crosscutting relationship in A. 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).

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-

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.

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 centimeters 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

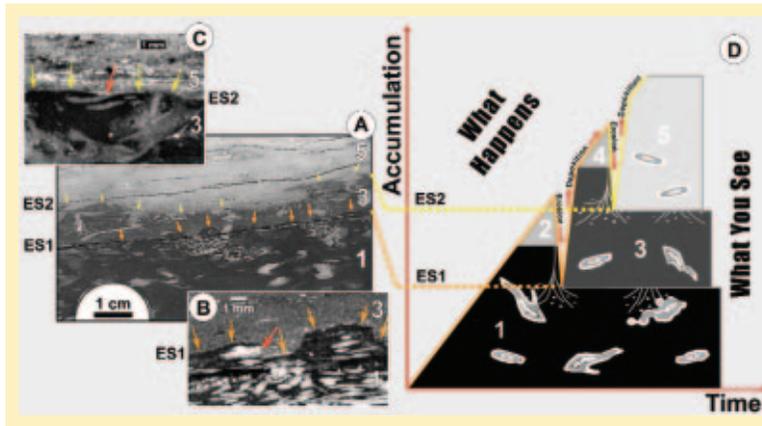


Figure 6: Multiple erosion surfaces and missing layers in a black shale (layers numbered 1 through 5 in ascending order). (A) Strongly contrast enhanced image of black shale-gray shale couplet. Two dark layers are actually present. The lower one is truncated by erosion surface ES1 (orange arrows). The 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 overlying gray layer (red arrow). (D) Sediment accumulation vs. time diagram illustrating the succession of events that lead to the observed rock record.

facies 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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The Hand Lens—a student forum

A Muddied Perspective on the Future of Sedimentary Research

Shales, claystones, and mudrocks: these words may make many of us uncomfortable... but why? Early in my studies I was impressed by the diverse array of environments represented in the record by "shale". Subsequent experience, however, left me perplexed about how anything could ever be resolved meaningfully by looking at the stuff. Although their charms may be subtle, mudstones refuse to be ignored. Mudstones are the source rocks for the bulk of the natural fuels. Many mudstone deposits record relatively continuous sedimentation with minimal influence of reworking, erosion, or winnowing. Fossils in mudstones are often found in situ, unsorted, and well preserved. The ubiquitous actions of microbes leave diagnostic suites of early diagenetic minerals and associated chemical signals that can help refine conditions of the depositional or early diagenetic environment. Perhaps most importantly, mudstones represent a more disparate spectrum of depositional environments than any other lithofacies. Nevertheless, fine-grained sediments remain grossly under-appreciated by geoscientists. The reasons for this are not altogether mysterious: sedimentary geologists tend to enjoy interpreting rocks in the field.

Upon first glance, mudstones can be a bit baffling. Typically, fine-grained sediments suffer the effects of weathering more drastically than coarser lithofacies and they are the first rocks to fail when tectonic stresses are applied. Thus, mudstone outcrops are rare, and are often of poor quality. Even upon close outcrop inspection, sedimentary structures generally remain elusive. Pioneering studies of mudstones in a stratigraphic context (summarized in Potter, et al., 1980) recognized many key features that allowed a broad-scale subdivision of mudstones based key attributes such as color, associated lithologies, and macroscopic diagenetic features. These studies have proven vital for interpreting relative depositional settings, depositional dynamics within a facies, or bed-to-bed scale environmental changes that have proven so important in rigorous study of other lithofacies. Indeed, the information locked in mudstones is not easily extracted.

I find that mudstones are best understood through a combined approach, using the benefits of laboratory analysis in combination with the indispensable information gained from studying rocks in their field context. Below, I review some exciting recent develop-

ments, with far-reaching implications, derived from new field-lab integrative approaches to muds. Breakthroughs like these have enhanced my appreciation of fine-grained rocks that comprise the bulk (>60%) of the sedimentary record (Potter et al., 1980), but comparatively few pages of sedimentology textbooks.

An enormous amount of time, energy, and money has been poured into research seeking the causes of, and controls on, organic carbon preservation, leading ultimately to oil formation. In recent decades, debate has focused on two primary factors: 1. effects of anoxia, and 2. rates of productivity, sedimentation and burial. A new model (Kennedy et al., 2002) suggests that there is a relationship between preservation of organic carbon and surface area of the reactive interlayers of clay minerals. Clay minerals, especially smectites, apparently adsorb amorphous organic matter from the water column, storing it safely from the action of microbes. The study showed that much of the organic matter in the Cretaceous Pierre Shale is bound within smectite interlayers, and that this amorphous organic matter is far more abundant than the particulate organic matter retained in the rock. While other factors are clearly important in the genesis of organic-rich mudstones, this model proposes that trends in detrital clay mineralogy exert a first-order control on storage of organic carbon in marine rocks.

Driven in no small part by the fact that they are the most important petroleum source rocks, black shales have been the focus of a disproportionate amount of attention. Traditionally they have been regarded as representative of deposition under sustained anoxic conditions. Abundant black shales are characteristic of certain intervals of time (e.g., Late Devonian, Cretaceous), and have been suggested to signify "oceanic anoxic events," a concept which would, if correct, have radical implications for the biosphere-ocean system during these times. Schieber (1994) threatened the anoxic paradigm by demonstrating that macroscopic bioturbation, representing the activities of aerobically metabolizing metazoans, is common in some black shales. This straightforward finding indicates that these deposits do not necessarily represent episodes of basin-wide stagnation. Furthermore, macroscopic bioturbation has been documented in black shale horizons bearing preservation of originally nonmineralized fossil tissues (by pyrite replacement; Sutcliffe et al., 1999). Preservation of nonmineralized tissues in black shales has long been considered to require anoxia. Thus, this finding has important pale-

oecological implications, most importantly, that such fossils may be preserved in situ under habitable (oxic) benthic conditions, and do not require transport.

In recent years, basinal mudstones have been the focus of an increasing body of paleoceanographic research that has tapped into the high-resolution record they provide. Throughout the last decade, increasing analytical precision has allowed isotopic analysis of ever-smaller samples. One of the most startling ramifications of such study has been the recognition that profound climate change is not necessarily a slow, steady process, but can operate on timescales ranging down to the decadal scale. Such rapid change may involve multiple feedback mechanisms. One such mechanism is the destabilization of methane hydrates, which are stored in solid form in organic-rich sediments under cool conditions, but which release (greenhouse) methane gas when oceanic warming occurs (Kennett et al., 2003).

Importantly, some mudstones may now be dated directly. Until recently, siliciclastic rocks were dated using either detrital zircons, which come with their own set of problematic assumptions, or using rare intercalated ash beds or lava flows and various means of stratigraphic correlation. Recent work by Creaser et al. (2002) has demonstrated that some organic-rich mudstones may be dated using the rhenium-osmium trace element isotope system as a geochronometer.

These are only a few examples of recent breakthroughs from the mudstone record that serve to remind me of the wealth of information locked in mudrocks. Although wading into thixotropic paleoenvironments can seem daunting, the effort can clearly be rewarding, and I think it's safe to assume that we will be hearing a great deal from this part of the sedimentary record in coming years.

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NSF-Sponsored Workshop on Deep-Time Paleoclimatology

Twenty-two geoscientists, including a healthy contingent of sedimentologists, sedimentary geochemists and paleontologists in addition to climate modelers, converged on Arlington, VA in May (2003) to discuss the status and future of research on Earth's "deep-time" (pre-Quaternary) climate record.

Earth's deep-time geologic record preserves the results of multiple large-scale experiments in environmental change. Although studies of recent climate states can capture a resolution commonly lacking in deep-time studies, they fail to capture the full range of climate-system

that can be studied in deep time may exceed human time scales, through feedbacks and thresholds, they can affect those climate processes that do operate on human time scales. Until we can understand these processes, gaps in our ability to understand climate on shorter time scales will remain, contributing to climate-prediction uncertainty.

Workshop discussions highlighted the following key points:

- Study of the Earth's climate record at all spatial and temporal scales is needed in order to comprehend the full range of variability rep-

resented in the climate system. In contrast, deep-time studies showcase environmental disturbances unknown from the recent, as well as feedbacks that occur on longer time scales and in response to perturbations that are different from those observable in the recent. Although some of the processes

represented in the climate system. The deep-time geologic record preserves numerous examples of past climate transitions between states more extreme than those represented in instrumental data, in historical records, or even by Quaternary standards. Critically, some of these transitions show evidence of having occurred abruptly, a major societal concern in light of the large changes that are now occurring in our current climate system. Understanding the details of large-scale climate transitions and, more importantly, the processes involved could very well be critical to an informed assessment of future climate change.

- Major science themes and issues that require attention in order to achieve a holistic understanding of Earth's climate system include the following:
 - ♦ Time issues, especially greenhouse-icehouse-hothouse transitions, interaction of climate components at different time scales, and prediction of climate thresholds
 - ♦ The various forcings and feedbacks that link greenhouse gases, particularly carbon dioxide and methane, as well as water vapor, to climate change

Continued on next page

COMMENTS FROM THE COUNCIL

SEPM International Activities

SEPM has been a global organization for many years. Currently there are more than 1100 international members in over 70 countries around the world. Despite this large international membership, many of SEPM's activities are concentrated in North America. The Society has a goal to increase its global activities to benefit its members and to increase its global membership. There are several ways in which this can be done, but it demands engagement from our members everywhere. Therefore, both international members and US members are encouraged to propose ideas to increase SEPM activities in the global scene. Such activities could include:

- Research conferences, organized by SEPM alone or jointly with other organizations. Cooperation with local geological organizations is strongly encouraged.
- Sessions sponsored or cosponsored by SEPM at international conferences. Thematic sessions on subjects in sedimentary geology are organized at most geology meetings and SEPM, through its interna-

tional membership, should be a key player in organizing such sessions.

- Production of SEPM Special Publications. SEPM has a great record of publishing thematic publications on important topics. A Special Publication should be the end goal of a thematic session at a conference or a Research Conference. Field trips are perhaps the best way of creating enthusiasm among geologists. There is nothing like the varied discussions on a challenging outcrop. Field trips are often combined with Research Conferences and conventions.
- Student activities, which can be field trips, student sessions at conferences or workshops. The SEPM Foundation has made it a special issue to help students attend SEPM events.
- Contribution of papers to *Journal of Sedimentary Research*, *PALAIOS* and Special Publications on topics from international localities.
- More international sections. SEPM has two international sections, one in Venezuela (Latin America section) and one in

Germany (Central European section). Another section is currently being organized in the Asia area. The aim of an international section is to organize and increase sedimentary geology activities within their region, with the help of the overall society's name recognition, headquarters staff and financial support. However, it is also important that the international sections partner with other organizations to benefit sedimentary geology in the most appropriate way in that specific region. SEPM's aim is to have more international sections with time, which will work to increase international sedimentary geology activities such as those listed above.

Therefore, do not hesitate to contact me or any other member of the SEPM council or Headquarters staff if you have ideas for SEPM international activities!

Ole J. Martinsen
International Councilor
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PRESIDENT'S OBSERVATIONS

Charting a Course

- ◆ The ecosystem-climate relationship, e.g., co-evolution of the biosphere and atmosphere
- ◆ Tectonic-climatic and climatic-eustatic interactions
- ◆ Multi-component coupling in climate models
- ◆ The effects of solar and orbital controls on climate at all scales

- The use of climate models to study paleoclimate is critical because models allow us to test hypotheses, particularly regarding interactions and feedbacks among Earth's climate system components. Unfortunately, most models have been constructed based on the very different constraints of modern instrumental data and are, therefore, difficult to set up for paleoclimate simulations. Model output, geared towards atmospheric diagnostics, is also difficult to compare to geologic records.

- High-quality proxy data on past climate states are equally critical, for accurate reconstructions, as input to climate models, and for independently testing model-derived interpretations. However, the community needs decreased ambiguity in existing proxies, and continued development of new and more accurate proxies for past climatic parameters, especially for deep-time slices.

- The paleoclimate research community needs new and better means to facilitate communication and collaboration, and to develop synergy between those who model paleoclimate and those who collect and analyze deep-time paleoclimate data. Closing the current gap between these two subdisciplines will catalyze rapid progress in the study of Earth's deep-time climate record.

Critical to progress in deep-time paleoclimatology is community feedback to help chart future directions, and approaches to the impasses listed above. To this end, please visit <http://geoclimate.ou.edu> to register feedback useful for guiding future research efforts and initiatives. The full workshop report is available on the geoclimate website.

Funding was provided by the National Science Foundation (grant #0323841) through the Geology and Paleontology Program (Earth Sciences Division), the Paleoclimate Program (Atmospheric Sciences Division), and the Division of Polar Programs.

Organizers: G.S. (Lynn) Soreghan, University of Oklahoma; Judith T. Parrish, University of Arizona; Christopher G. Maples, Indiana University

It has been just a few months since I assumed office as your President. Fortunately for me, I follow on the heels of Peter McCabe, who put our society on a solid course during his term. My biggest job will be to keep the ship on a steady course. Perhaps the greatest accomplishment of Peter's administration was the creation of *The Sedimentary Record*. This new publication will hopefully establish a stronger link between our members and the society.

One of the biggest challenges currently facing us is that of declining membership. This decline is, in large part, due to the demographics of the geoscience profession. Many of us are getting older. To offset the decline we must encourage student membership and become a truly global society.

Council has spent many hours discussing student involvement in SEPM and has done a number of things to encourage student membership. We now have a \$25 student membership that includes online access to both of our journals, as well as, our regular member discounts on publications and the semi-annual free books to students events. With all of these efforts, I must confess that I am still puzzled by the relatively low numbers of student members in the society, given the fact that sedimentary geology is still very much a principle component of the Earth Sciences. I was encouraged by my advisors to join professional societies and did so as a student. From that time on I began to feel more connected with the profession. I continue this important effort with my own students and even go so far as to purchase their first year's membership for them (at \$25 it is a real bargain for me). Today, with low membership costs and high benefits for students, I can't see why more students are not taking advantage of society membership. Maintaining a strong, dynamic and young membership is vital to our society and to the science. We must all work harder at increasing membership. Let me know if you have suggestions in this area.

This past year one of my graduate students and I attended the SEPM Incised Valley Research Conference in Casper, Wyoming. This was an excellent conference, well attended, packed with high quality talks, wonderful field trips and opportunities to interact with colleagues and friends. We both came away with new ideas and were ener-

gized for addressing our own research projects. In my opinion, research conferences are one of the greatest services our society offers. I have attended several over the years and have, without exception, had experiences similar to those of the Casper meeting. I would like to see us doing more conferences on a greater range of themes.

Did you know that there are SEPM staff who are dedicated to helping with the organization and running of research and field conferences? Have you ever thought about running such a conference? It is probably easier than you think and the rewards are great. Check out the SEPM web site to find out how you can propose a conference, or contact Judy Tarpley at SEPM headquarters and get one started.

One of the other great benefits of our society is the Special Publications program. The Society is always looking into ways to expand and hasten the turn-around time for special publications. Our web site now provides information to authors of special publication articles that allow them to track their papers through the system (<http://www.sepm.org/publishing/upcoming.htm>). We are working hard to speed up the review, editing and printing process. We are currently investigating using online submission and review. Our goal is to reduce the turn around time to as little as possible. Ranging from the traditional print to electronic media, advanced level compendium to college level course material, I would encourage anyone to think about publishing with SEPM. If you are interested in proposing a special publication, contact Laura Crossey (lcrossey@unm.edu) at the University of New Mexico, who is SEPM's Special Publications Editor.

The sedimentary geology community will play a key role in the future of the Earth Sciences and our society must remain strong or the science will suffer. I encourage you all to take a more active role in the society. Join a committee, attend annual meetings and research conferences and encourage new members. This is a great society of fascinating people with a common interest in the sedimentary record of Earth's history.

John Anderson
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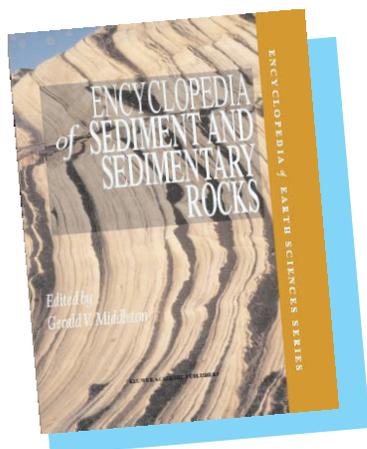
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