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Discovery of agglutinated benthic foraminifera in Devonian black shales and their relevance for the redox state of ancient seas

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ABSTRACT

Agglutinated foraminifera are benthic organisms that occur in marginal marine to bathyal environments. Though some taxa can live in oxygen deficient environments, they require at least some oxygen in order to persist at the seafloor. The discovery that they occur widely in Late Devonian black shales has a bearing on the boundary conditions required for episodes of extensive carbon sequestration in marine sediments and their connection to atmospheric composition and global climate. Devonian black shales of the eastern US have been studied extensively to determine the fundamental controls on carbon burial, and a range of mechanisms has been proposed. Finding agglutinated benthic foraminifera in these black shales refocuses the debate about their origin and points to limitations of earlier models.

1. Introduction

The Late Devonian is notable in Earth history because of a mass extinction event (Hallam and Wignall, 1997) and globally extensive formation of black shales (Klemme and Ulmishek, 1991). The latter marks the onset of a substantial rise in atmospheric oxygen that culminated approximately 290 m.y. ago and is linked to the Gondwana Glaciation (Berner, 2001). In an effort to uncover the factors that contributed to widespread black shale deposition, Late Devonian black shales of the eastern US have undergone extensive study from multiple perspectives, and the state of water column oxygenation has been an issue of ongoing debate (e.g. Sageman et al., 2003; Schieber, 1998, 2003; Rimmer, 2004; Algeo, 2004). For given intervals of this black shale succession, interpretations can range from dysoxic to stratified anoxic or even euxinic (anoxic–sulfidic) bottom waters (e.g. Sageman et al., 2003; Kepferle, 1993; Werne et al., 2002). Because benthic foraminifera require at least some oxygen in order to persist at the seafloor (Bernhard and Reimers, 1991; Bernhard et al., 2003), finding them to be widespread in Late Devonian black shales of the eastern US indicates that extended time periods of stratified anoxic or euxinic bottom waters can be eliminated as factors that contributed to massive carbon burial in these strata. Examination of samples from other geologically significant black shale intervals has revealed remains of agglutinated benthic foraminifera as well, and indicates a need for re-examining the global black shale record.

2. Methods and materials

More than one thousand thin sections from the Appalachian and Illinois Basins of the eastern US (Fig. 1 and Table 1) were examined. This comprehensive data set spans the entire Late Devonian (Frasnian and Famennian) time interval and include all of the regionally extensive black shale units. The slightly older Oatka Creek Shale (Givetian, New York) is included because it is cited as an example of a "euxinic" black shale (Sageman et al., 2003; Werne et al., 2002).

Polished thin sections for this study were prepared by a commercial lab, Petrographic International, in Choiceland, Saskatchewan. Initial screening of thin sections was done with a petrographic microscope (Zeiss Photo III) in transmitted and reflected light. Petrographic microscope images shown here were acquired with a Pixera Pro 600ES digital camera with 5.8 megapixel resolution. A subset of these samples was then examined by scanned color cathodoluminescence in order to confirm the agglutinated character of features identified as agglutinated foraminifera. The used instrumentation was a FEI Quanta FEG 400 ESEM equipped with an energy dispersive X-ray microanalysis (EDS) system and a GATAN Chroma CL cathodoluminescence (CL) detector. High resolution CL scans (4000×4000 pixels, 1000 µs beam dwell time) were run at 10 kV with a narrow lens aperture (aperture 4), and spot size 5. The thin

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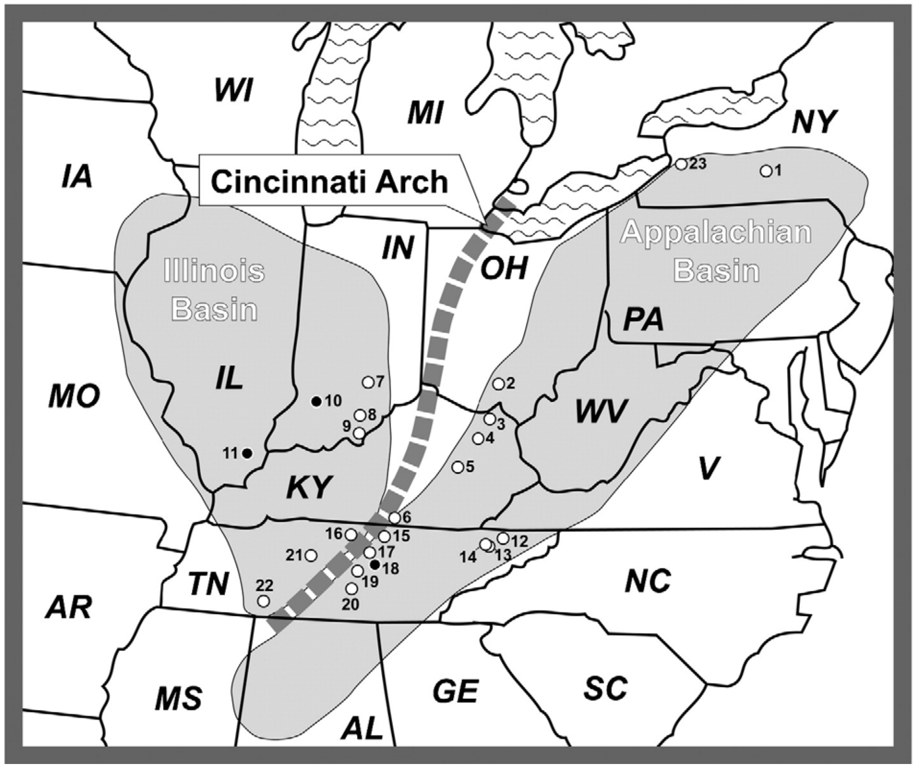


Fig. 1. Overview map of study area in the eastern U.S. States are marked by their outlines and the postal state identifier. The numbers next to sample localities (circles) refer to the location list in Table 1. Full circles (black with white rim) indicate localities where closely spaced samples were examined over the entire stratigraphic thickness. The Illinois and Appalachian Basins are outlined with shading. The dashed line marks the Cincinnati Arch, a positive element that was intermittently flooded during the Late Devonian.

sections were carbon coated and the observations were made under high vacuum. Working conditions for SEM backscatter imaging (BSE) were 10 kV, high vacuum, aperture 4, and spot size 3.

3. Identifying agglutinated foraminifera

Modern muds from the Santa Barbara Basin (offshore California) and the Guaymas Basin (Gulf of California) contain agglutinated benthic foraminifera with well developed grain selectivity (Fig. 2). These foraminifera first accumulate random grains, then incorporate desired grains into new chambers, and finally leave behind the rejects as a “detritic heap” (Pike and Kemp, 1996). Grains are bound by an organic cement, and there is clear preference for fine-grained quartz silt. During burial and compaction their tests collapse, resulting in lenticular bodies of fine quartz grains (some hundred microns long, some tens of microns thick). Internal sutures may be preserved as a

Table 1
Sampled localities

#	Location	Unit	Age	Type
1	South Crosby, Yates Cty., NY	Sonyea Group	Lower Frasnian	Outcrop
2	Tener Mountain, Adams Cty., OH	Ohio Shale and Cleveland Shale	Famennian	Outcrop
3	KEP-3, Adams Cty., KY	Ohio Shale and Cleveland Shale	Famennian	KGS drill core
4	Morehead, Rowan Cty., KY	Ohio Shale and Cleveland Shale	Famennian	Outcrop
5	Irvine, Estill Cty., KY	Ohio Shale and Cleveland Shale	Famennian	Outcrop
6	Burkesville, Cumberland Cty., KY	Chattanooga Shale, Gassaway Member	Famennian	Outcrop
7	Core 763, Bartholomew Cty., IN	New Albany Shale	Frasnian and Famennian	IGS drill core
8	Humphrey #1, Lawrence Cty., IN	New Albany Shale	Frasnian and Famennian	UPR drill core
9	Wiseman #1, Harrison Cty., IN	New Albany Shale	Frasnian and Famennian	UPR drill core
10	Core 873, Daviess Cty., IN	New Albany Shale	Frasnian and Famennian	IGS drill core
11	Core 26376, Saline Cty., IL	New Albany Shale	Frasnian and Famennian	ILGS drill core
12	Eidson, Hawkins Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
13	Rock Haven, Grainger Cty., TN	Brallier Formation	Frasnian and Famennian	Outcrop
14	Thorn Hill, Grainger Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
15	Celina, Clay Cty., TN	Chattanooga Shale, Gassaway Member	Famennian	Outcrop
16	Westmoreland, Sumner Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
17	Chestnut Mound, Smith Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
18	Hurricane Bridge, DeKalb Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
19	Woodbury, Cannon Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
20	Noah, Coffee Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
21	Pegram, Cheatham Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
22	Olive Hill, Hardin Cty., TN	Chattanooga Shale	Frasnian and Famennian	Outcrop
23	Lancaster, Erie Cty., NY	Oatka Creek Shale	Givetian	Outcrop

KGS = Kentucky Geol. Surv.; IGS = Indiana Geol. Surv.; ILGS = Illinois Geol. Surv.; UPR = Union Pacific Resources; NY = New York; OH = Ohio; KY = Kentucky, IL = Illinois; IN = Indiana; TN = Tennessee.

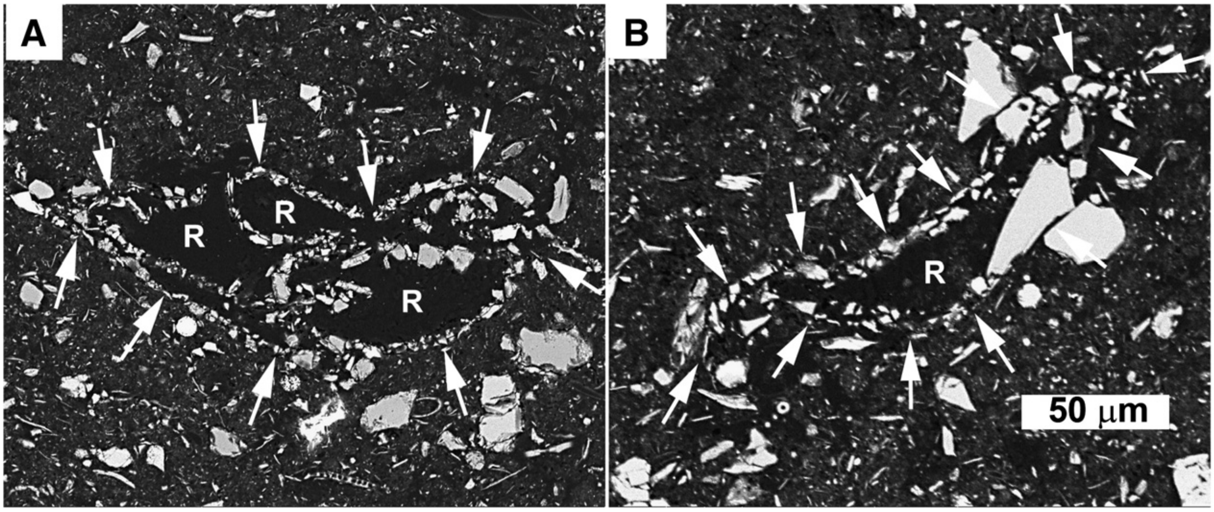


Fig. 2. Backscatter electron images of partially collapsed agglutinated foraminifera in sediments from the Santa Barbara Basin. Sample has been embedded with Spurr Resin. White arrows mark outer edge of foraminiferal tests, R indicates resin filled chambers. (A) shows a collapsing multi-chambered specimen, and (B) shows collapse of single chamber specimen. Note the finer grain size and better sorting of quartz grains in the foraminiferal tests, relative to surrounding mudstone matrix. Once fully collapsed, specimen (B) would look very similar to agglutinated benthic foraminifera from the Late Devonian.

relic feature of former chambers (Fig. 2). It has been proposed that lenses of well sorted fine-grained silt in ancient mudstones are remains of agglutinated benthic foraminifera, and that isolated lenses of coarser and poorly sorted silt may represent “detritic heaps” (Pike and Kemp, 1996).

Lenticular bodies of fine-crystalline silica, up to 500 µm in length and up to 50 µm thick, occur in numerous petrographic thin sections of Devonian black shales (Figs. 3 and 4). They appear fine-crystalline cherty (Fig. 4B, C) and resemble the flattened cysts of marine algae (Fig. 3), such as *Tasmanites* (Tappan, 1980). Therefore they were initially considered silicified organic remains. Their granular appearance in SEM images (Fig. 5C) suggested as an alternative hypothesis that they originated as tiny ripples of fine silt that migrated over the muddy seafloor due to bottom currents.

Charge Contrast Imaging (CCI; Watt et al., 2000) and EDS analysis with an environmental scanning electron microscope (ESEM) shows that these features consist of discrete quartz grains set in a matrix of quartz cement (Fig. 5A). Scanned color cathodoluminescence (CL) reveals an orange-reddish CL color for the quartz grains and an essentially non-luminescent cement (Fig. 5B). Typically only a few microns in size (Fig. 5), the quartz grains are well sorted, angular (Fig. 5A, B, D), and distinctly finer-grained than the quartz silt in the surrounding shale matrix (Fig. 5D, E).

Their angular shape (Fig. 5A, B) indicates that the quartz grains are detrital (Blatt, 1992; Schieber et al., 2000), and the orange-reddish CL color (Fig. 5) suggests derivation from low grade metamorphic rocks (Zinkernagel, 1978; Schieber and Wintsch, 2005). The non-luminescent cement is of diagenetic origin (Schieber et al., 2000;

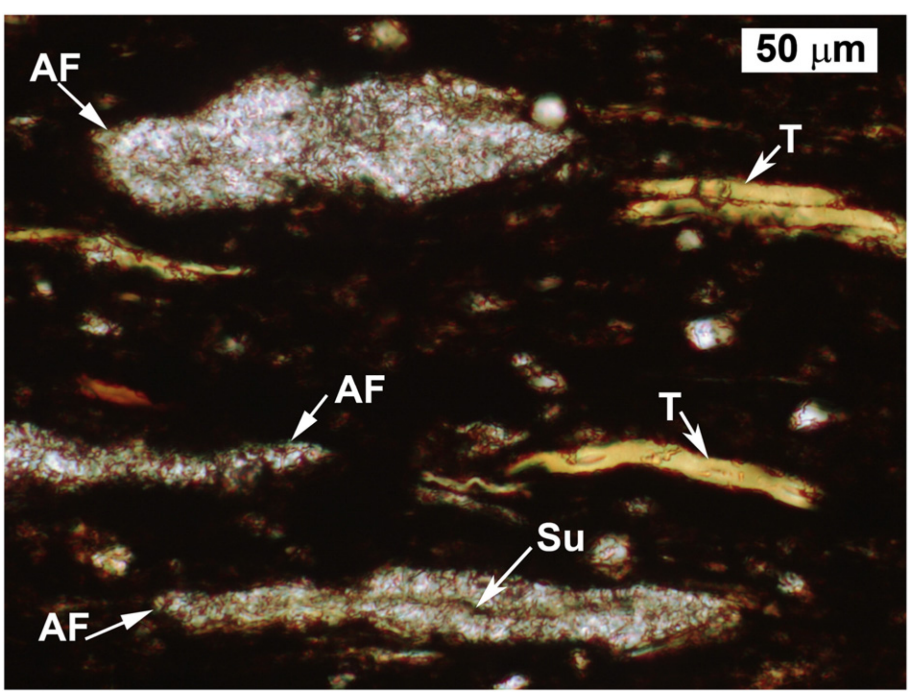


Fig. 3. Photomicrograph of lenticular siliceous features interpreted as agglutinated foraminifera (arrows AF) in continuously laminated black shale (Cleveland Shale, NE Kentucky). Arrow Su points to medial suture that suggests that these features are collapsed foraminiferal tests. Arrows T point out collapsed cysts of the marine alga *Tasmanites*.

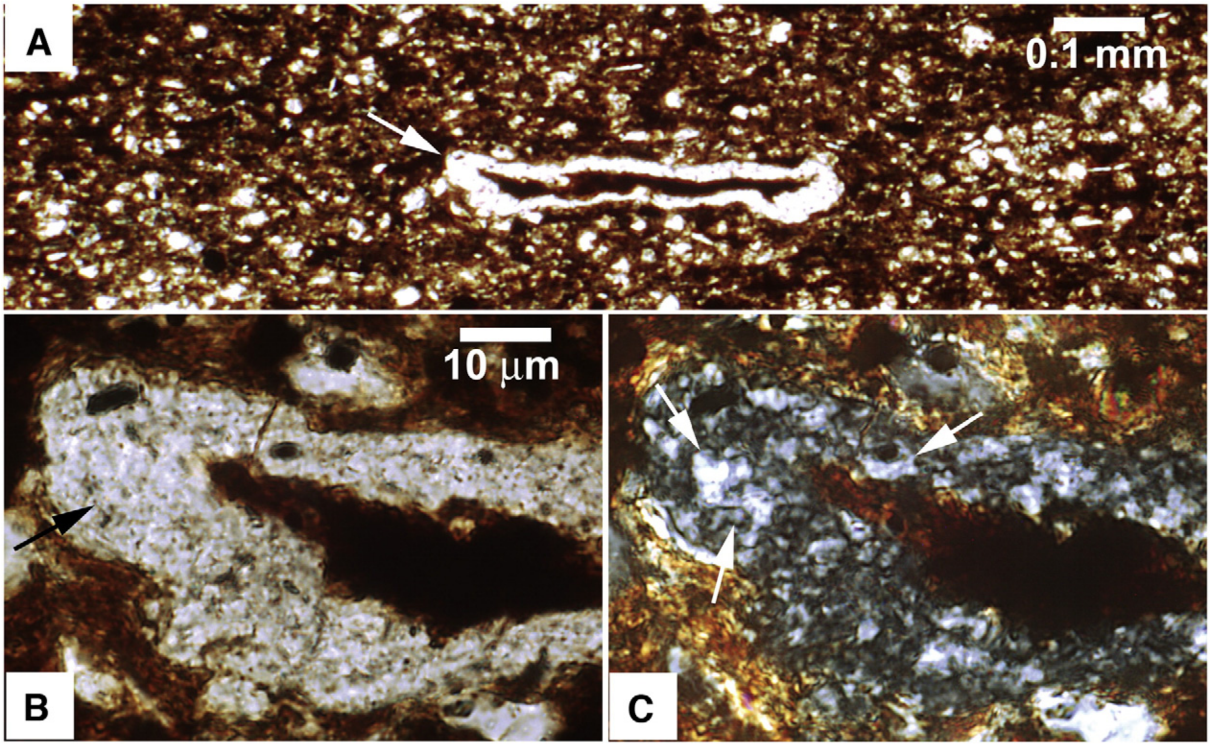


Fig. 4. (A) Photomicrograph of agglutinated benthic foraminifera (white arrow) with a partial internal fill that prevented complete collapse (Chattanooga Shale, Central Tennessee). (B) Close-up that shows granular nature (black arrow) and deformation of wall. (C) Same view as in (B), but with polarizers crossed. The cherty polycrystalline nature of the siliceous walls is clearly visible. White arrows point to individual quartz grains.

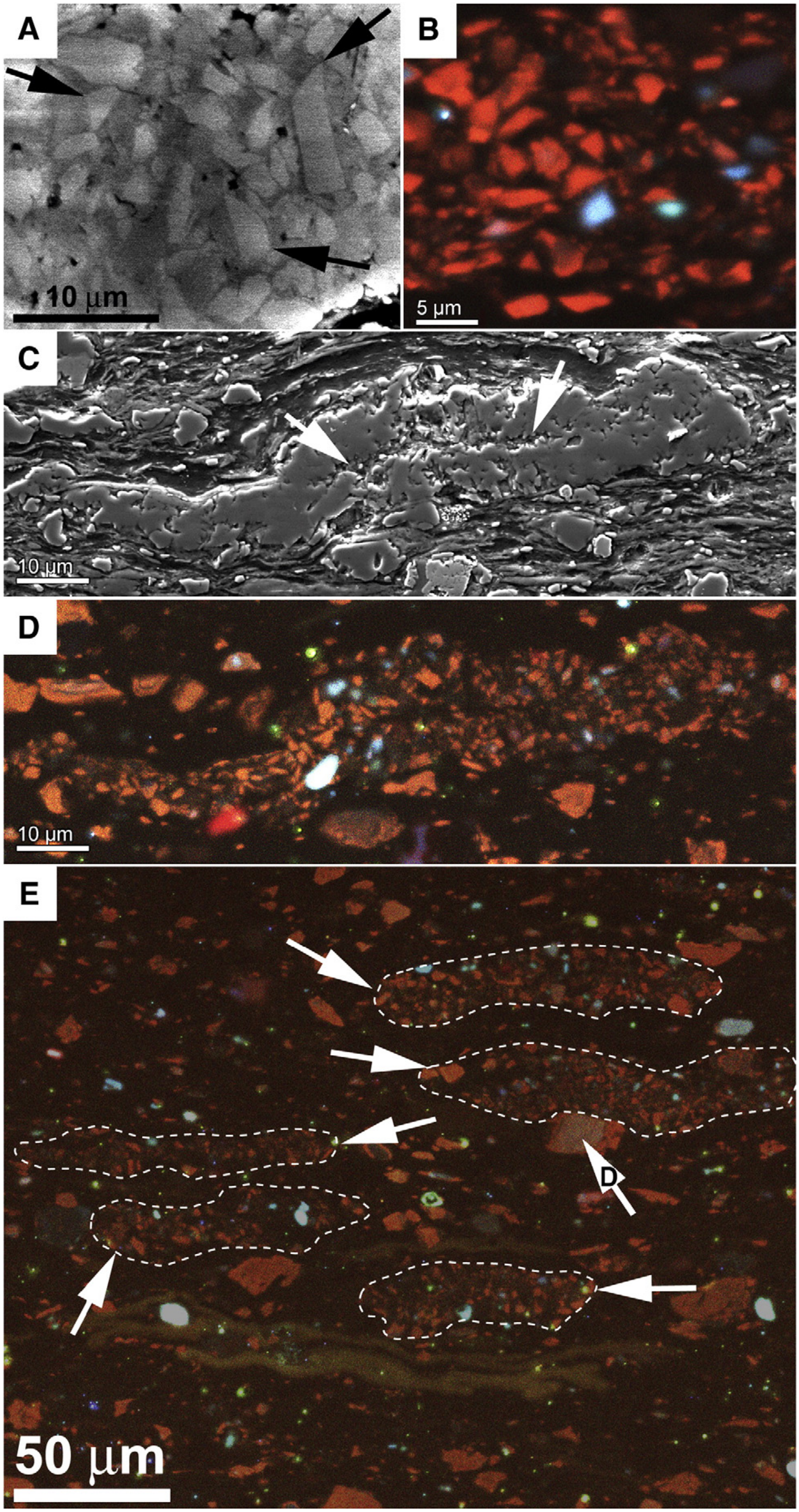
Zinkernagel, 1978). The small grain size (Fig. 5) of the quartz grains argues against interpreting these features as tiny migrating ripples. Micron-size quartz grains travel in suspension under even the slightest of currents (Potter et al., 2005) and thus should not form ripples. Nonetheless, recent flume studies have shown that flocculated mud can form ripples that travel over the sediment surface, and muddy ripples of this type have indeed been identified in Late Devonian black shales (Schieber et al., 2007). These muddy ripples do in fact contain thin lenses and laminae of quartz silt (Schieber et al., 2007), but these are much coarser grained than the quartz observed in agglutinated foraminifera (Fig. 6). Furthermore, interpreting these features as flocculated quartz grains is implausible because flocculation typically produces poorly sorted aggregates dominated by clay minerals and silt grains (Potter et al., 2005). As mixtures of detrital quartz and diagenetic silica cement, these features also cannot be explained as silica replacements of algal cysts or similar appearing organic particles.

By comparison with Santa Barbara Basin and Guaymas Basin muds, the observation that detrital quartz grains from siliceous lenses in Devonian black shales are well sorted and much finer than the quartz grains in the surrounding shale matrix (Fig. 5) strongly suggests that they are the remains of benthic agglutinated foraminifera (Pike and Kemp, 1996). Residual infills (Fig. 4A) and medial sutures (Figs. 3, 5C) indicate compactional collapse of originally hollow features, consistent with the idea that they are the remains of agglutinated foraminifera. Milliken et al. (2007) described very similar features from silica accumulations in the Mississippian Barnett Shale of Texas that were termed “cherty” stringers and closely resemble the lenticular bodies of fine crystalline silica in Devonian black shales. They interpreted these features as collapsed and silicified benthic agglutinated foraminifera.

Deformation during compaction, as well as soft sediment deformation around “hard” grains (Fig. 5E), indicates binding of quartz grains with a deformable substance prior to cementation with silica, such as the organic cement found in modern agglutinated foraminifera (Pike and Kemp, 1996). Thus, any Devonian black shale unit that contains these siliceous lenses carries *prima facie* evidence that at the time of its deposition, agglutinated benthic foraminifera lived at the seafloor. By extension, this means that the bottom waters contained at least some oxygen (Pike and Kemp, 1996; Bernhard and Reimers, 1991; Bernhard et al., 2003).

4. Distribution of agglutinated foraminifera

Search of over one thousand thin sections from multiple locations in the Appalachian and Illinois Basins (Fig. 1 and Table 1), and covering the entire stratigraphic range of these black shales (Table 1), showed agglutinated benthic foraminifera in many samples. In three locations the entire stratigraphic interval (Frasnian–Famennian) was closely sampled. In location 18 (Hurricane Bridge Section, DeKalb County, Tennessee, Appalachian Basin) 56 thin sections were spaced over 9.5 m of a highly condensed section, and 43 of them (77%) contained remains of agglutinated foraminifera. In locations 10 (Daviess County, Indiana) and 11 (Saline County, Illinois), both located in the Illinois Basin (Fig. 1), 48 and 49 thin sections were spaced over 39 and 49 m of section respectively. In both locations 50% of the thin sections contain remains of agglutinated foraminifera. Agglutinated foraminifera were absent in strongly bioturbated gray shales, generally of low abundance in bioturbated black shales (Schieber, 2003), and a common component in black shales that appeared laminated and did not show recognizable bioturbation features (Schieber, 2003). The densely sampled sections mentioned above (#'s 10, 11, 18, Fig. 1) contain representatives of all regionally significant black shale intervals. Stratigraphic intervals missing due to local erosion (Schieber and Lazar, 2004) were supplemented with samples from other exposures and drill cores. For other localities (Fig. 1) sample coverage was not as dense, but thin sections were available for each stratigraphic unit and for black shale intervals.


A
10 μm
B
5 μm
C
10 μm
D
10 μm
E
D
50 μm

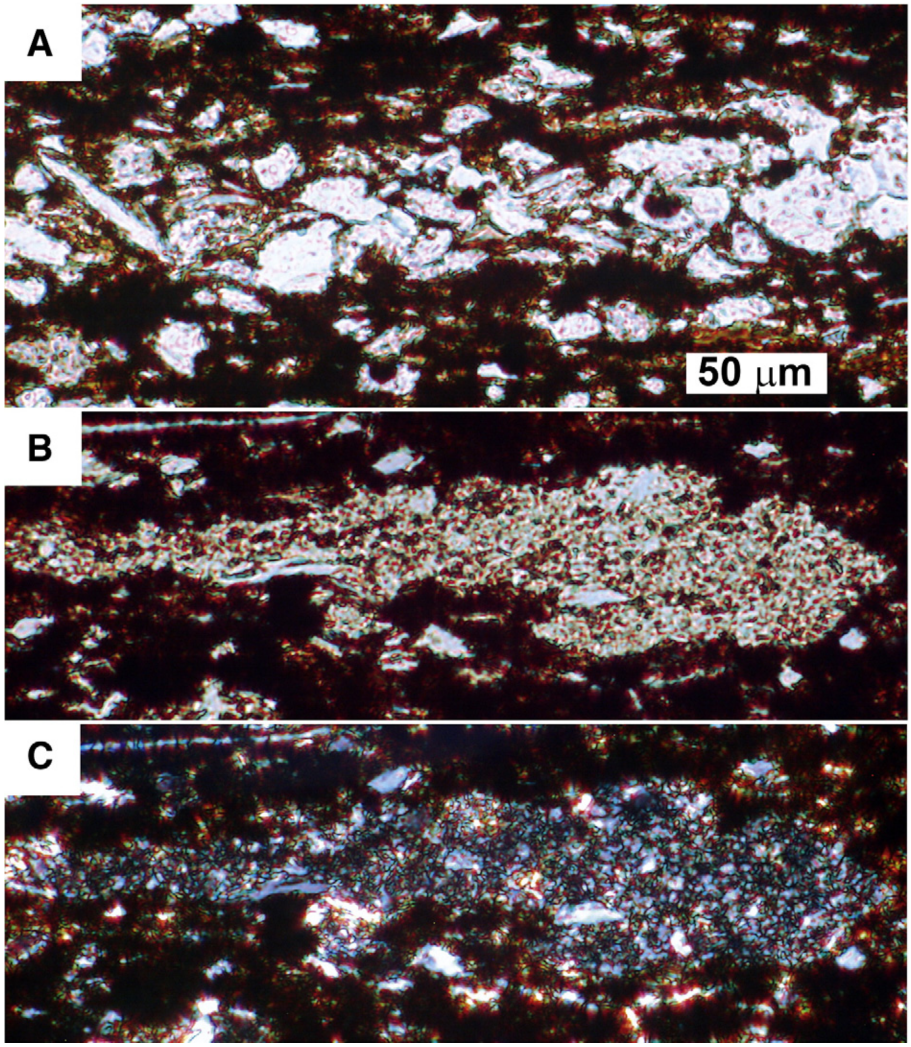


Fig. 6. Contrast between thin lenses and laminae of current deposited quartz silt and collapsed and silica cemented agglutinated foraminifera from the Late Devonian Chattanooga Shale of Tennessee. (A) Photomicrograph of thin lamina of detrital quartz silt (center of image). The individual quartz grains are typically several ten microns across. (B) Photomicrograph of a collapsed agglutinated foraminifera from the same sample, photographed at the same scale. Note fine-grained nature of quartz. (C) Same field of view as in B, but with crossed polarizers. Note the fine-grained nature of the quartz, in contrast to grain size of detrital quartz seen in A.

All black shale bearing intervals (Table 1) contain foraminiferal remains, but overall abundance depends on the shale type. Continuously laminated black shale shows well developed lamination, lacks signs of bioturbation, and consistently contains agglutinated benthic foraminifera (Fig. 3). Discontinuously laminated black shale lacks well developed lamination, shows subtle signs of bioturbation (Schieber, 2003), and also contains foraminiferal remains. However, as the intensity of bioturbation increases, foraminiferal remains become increasingly rare in discontinuously laminated black shales. Destruction of foraminiferal tests by bioturbating organisms is probably the cause for their lower abundance in discontinuously laminated black shales and their absence in strongly bioturbated gray shales.

5. Prior work on Devonian black shale deposition

Prior studies of Devonian black shales largely relied for water column characterization on geochemical proxies, such as the distribution of redox sensitive metals, in particular Mo and Fe, but also carbon/sulfur relationships and degree of pyritization (DOP) (e.g. Sageman et al., 2003; Rimmer, 2004; Algeo, 2004; Werne et al., 2002; Beier and Hayes, 1989). These studies target specific stratigraphic intervals because of the considerable effort involved. Stratigraphic intervals considered as deposited beneath persistently anoxic bottom waters include the Clegg Creek Member of the New Albany Shale in Indiana and Kentucky (Beier and Hayes, 1989), the Oatka Creek Shale in New York (Sageman et al., 2003; Werne et al., 2002), and the Cleveland Shale of Kentucky and

Fig. 5. (A) ESEM charge contrast image (CCI) of siliceous features (New Albany Shale, Southern Indiana). Clearly shows detrital angular quartz grains (brighter, black arrows) with interstitial quartz cement (darker). (B) Scanned color cathodoluminescence image shows mostly angular orange-reddish and dull blue quartz grains derived from slates and schists (Schieber and Wintsch, 2005). The few bluish grains are probably derived from gneisses or granites. The intervening diagenetic cement is essentially non-luminescent. (C) SEM image of siliceous feature with preserved medial suture (white arrows). (D) Scanned color cathodoluminescence image of the same area. Shows abundant fine quartz grains of mostly metamorphic derivation. Quartz grains are fine-grained and well sorted, and contrast with the coarser and poorly sorted quartz grains in the surrounding shale. (E) Scanned color cathodoluminescence image from a sample of Cleveland Shale (NE Kentucky). Shows multiple collapsed tests of agglutinated benthic foraminifera (white arrows, enclosed by thin white dashed lines). Note contrast in grain size and sorting between foraminifera tests and the shale matrix. Arrow marked D points out a spot where a collapsed foraminifera was deformed around a larger silt grain due to compaction.

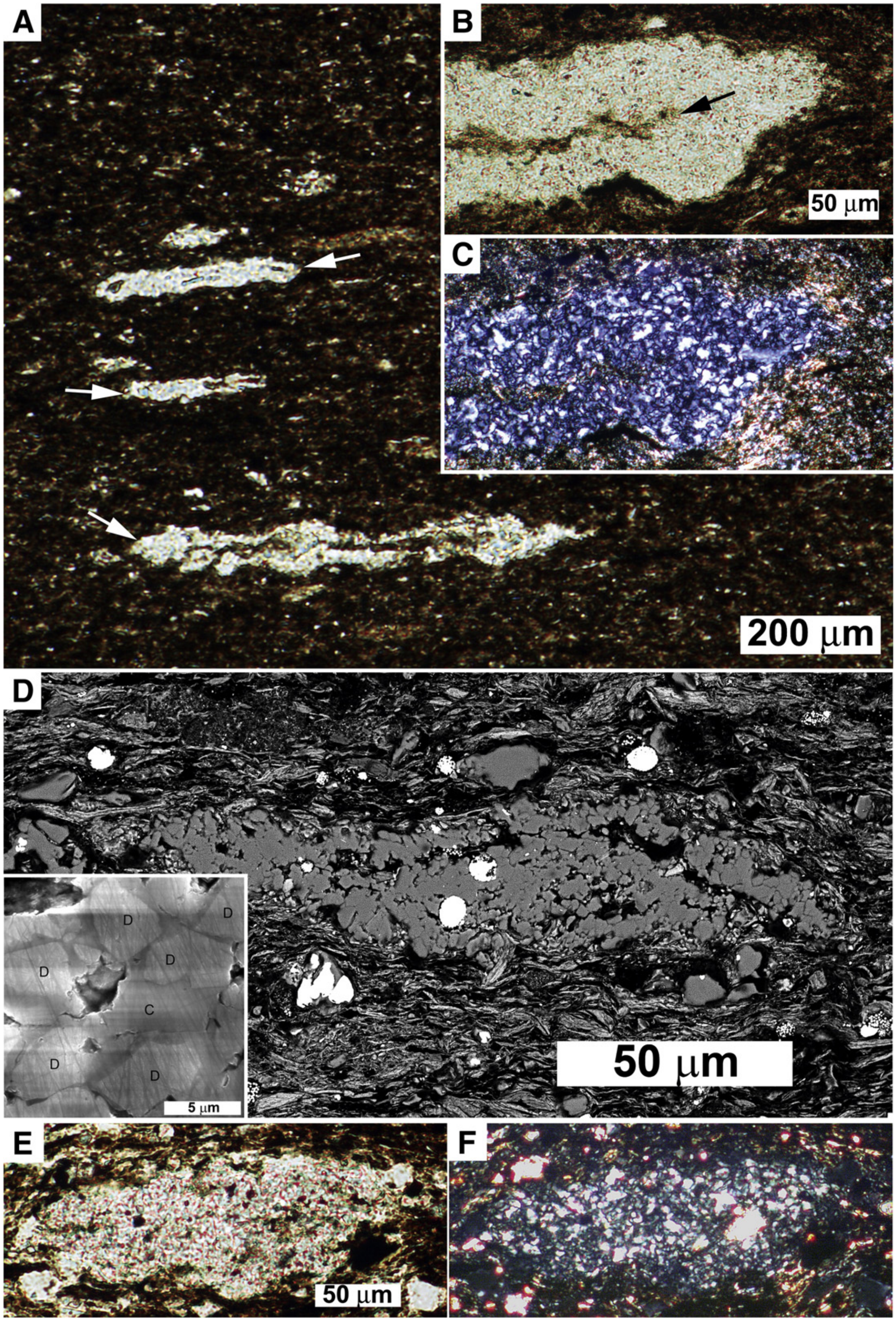


Fig. 7. Agglutinated foraminifera in other black shale units from the rock record. (A) Photomicrograph of collapsed agglutinated foraminifera (arrows) in the Pennsylvanian Finis Shale of North Texas. (B) Close-up of foraminifera from same sample. (C) Same field of view as in (B) with crossed polarizers. Note gray birefringence of fine crystalline quartz. (D) SEM photomicrograph (backscatter image) of collapsed foraminifera in the Mississippian Barnett Shale of Texas (see also Milliken et al., 2007). Inset in lower left corner shows "charge contrast imaging" (CCI) of portion of foraminifera. Angular detrital quartz grains (the type of grains marked D) appear brighter than the intervening silica cement (marked C). The criss-crossing straight lines are scratches from thin section preparation. (E) Photomicrograph of collapsed agglutinated foraminifera in the Late Devonian Bakken Shale of Saskatchewan. (F) Same field of view as in E, but with crossed polarizers. Note fine crystalline quartz with gray birefringence.

Ohio (Rimmer, 2004; Algeo, 2004). All of these are dominated by continuously laminated black shale (Schieber, 2003; Schieber and Lazar, 2004) as defined above. Black shale intervals considered as deposited under dysoxic and variably oxygenated conditions include the Morgan Trail and Camp Run members of the New Albany Shale in Indiana and Kentucky (Beier and Hayes, 1989), the Huron Shale of Kentucky and Ohio

(Rimmer, 2004), and the Geneseo, Middlesex, Rhinestreet, Pipe Creek, and Dunkirk Shale intervals in New York (Sageman et al., 2003). These stratigraphic intervals are dominated by discontinuously laminated black shales as defined above. The Late Devonian Chattanooga Shale of Tennessee (Fig. 1) has primarily been studied from a sedimentological perspective (Schieber, 1994, 1998) and contains the same types of black shales as observed in other areas of the Illinois and Appalachian Basins. In central Tennessee it was deposited within reach of storm wave base, an unlikely scenario for a stratified water column. In eastern Tennessee, in contrast, the Chattanooga Shale and related units were deposited in deeper water in association with turbidites (Schieber, 1994).

6. Implications

Modern muds of the Santa Barbara Basin are laminated, carbonaceous, and undisturbed by bioturbation (Pike and Kemp, 1996; Schimmelmann and Lange, 1996). Upon full compaction they will appear as laminated carbonaceous shales that contain compacted tests of agglutinated benthic foraminifera, comparable to continuously laminated black shales in the Devonian of the eastern US. The discovery of agglutinated benthic foraminifera in the latter fundamentally constrains their depositional environment.

Certain modern agglutinated benthic foraminifera can thrive in environments with low dissolved oxygen and can even endure brief (a few months) spells of anoxia. Yet, they do require some oxygen in order to persist (Bernhard and Reimers, 1991; Bernhard et al., 2003). The deepest portions of the Santa Barbara Basin have suboxic bottom waters (oxygen content ~ 0.05 ml/L) and experience bottom water renewal events every few years (Bograd et al., 2002). The redox interface is located just beneath or at the sediment–water interface and marked by a mat of sulfide oxidizing *Beggiatoa* (Reimers et al., 1996). Intermittently the redox interface may creep upwards into the bottom mm's to cm's of the water column (Reimers et al., 1996). Other than that, the water column is never entirely devoid of oxygen. That this was the likely state of affairs for most of the recent as well as the more distant geological past is indicated by long-term monitoring (Bograd et al., 2002; Reimers et al., 1996), as well as by the remains of agglutinated foraminifera that are found throughout the laminated deposits (Pike and Kemp, 1996; personal core observations).

By analogy with the Santa Barbara Basin, the common presence of agglutinated benthic foraminifera in Devonian black shales of eastern North America indicates that the bottom waters may have been oxygen depleted, but were not wholly anoxic. Brief anoxic interludes (a few months) were possible, because we know that benthic foraminifera from the Santa Barbara Basin can survive brief anoxia (Pike and Kemp, 1996; Bernhard and Reimers, 1991; Bernhard et al., 2003). It is unlikely, however, that they could have endured prolonged periods of anoxia.

Continuously laminated black shales in the Illinois and Appalachian Basins have been interpreted as deposited beneath persistently anoxic and even euxinic bottom waters on the basis of geochemical proxies (Sageman et al., 2003; Rimmer, 2004; Algeo, 2004; Werne et al., 2002). The observations reported here indicate, however, that other factors than persistent bottom water anoxia must have been at play to produce extensive black shale formation at the generally small sedimentation rates of the Late Devonian inland sea of North America (Schieber, 1998). An alternative scenario, involving short-lived anoxia produced by seasonal thermoclines, may, in conjunction with seasonal mixing, have enabled "productivity-anoxia feedback" (Van Cappellen and Ingall, 1994) to maintain high burial fluxes of organic carbon (Sageman et al., 2003). Such a scenario would allow for persistence of agglutinated foraminifera at the seabed. A eutrophication model that incorporates these aspects has been suggested as a general mechanism for Devonian black shales in the eastern US (Sageman et al., 2003). That model, however, has only been tested for black shales in the northernmost portion of the Appalachian Basin (Sageman et al., 2003). Finding agglutinated benthic foraminifera as *prima facie* evidence for the absence of extended anoxia over such a wide area of black shale deposition (Fig. 1) suggests that the eutrophication model (Sageman et al., 2003) may have general validity.

Geochemists have devised various proxies that may provide insight into the formative conditions of black shales, in particular indices that allow us to determine the oxygenation state of the water column and the presence of anoxia (e.g. Beier and Hayes, 1989; Jones and Manning, 1994; Calvert et al., 1996). On close inspection, however, there are frequently conflicts between information derived from looking at the rocks (sedimentary structures, biota, ichnofossils), and the state of oxygenation suggested by geochemical indicators. For example, a widely employed anoxia proxy, the degree of pyritization (DOP; Raiswell et al., 1988), indicates anoxic conditions for many of our Devonian black shale samples. Yet erosive features at various scales (Schieber, 1998), subtle bioturbation features (Schieber, 2003), and the agglutinated foraminifera reported here, are at odds with this proxy. Sedimentological and petrographical study shows that intermittent erosion and reworking caused hydraulic pyrite enrichment in silty laminae and lag deposits, causing artificially high DOP values (Schieber, 2001). In addition, the exact processes that lead to the enrichment of redox sensitive trace metals may not be known to the extent needed to use them as reliable paleoredox proxies. Molybdenum, for example, has for some time now been considered a reliable proxy for detection of euxinic bottom waters (Meyers et al., 2005). Yet, we also know from observations of modern environments that Mo enrichment occurs in sediments overlain by oxygenated waters in cases where the redox interface is just a few millimeters below the sediment water interface (Elbaz-Poulichet et al., 2005; Morford et al., 2005). Finally, the scale of observations matters as well. 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 and petrographic evaluation is a necessary prerequisite for successful geochemical studies because prima 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).

For a general evaluation of how widespread agglutinated foraminifera might be in black shales, additional thin sections from my collection were examined for the features described above (Fig. 7). The search showed that agglutinated foraminifera also occur in laminated black shales from the Bakken Shale (Late Devonian of Saskatchewan, Canada), the Sunbury Shale (Mississippian of Ohio), the Barnett Shale (Mississippian of Texas) (see also Milliken et al., 2007), and the Pennsylvanian Finis Shale of Texas (Lobza et al., 1994). In addition, pictures of agglutinated foraminifera from the Kimmeridge Clay (Jurassic of Britain) were shown to me some time ago by Dr. Joe Macquaker of Memorial University of Newfoundland.

Thus, systematic re-examination of other geologically significant black shale intervals may show that agglutinated benthic foraminifera are much more common in black shales than previously appreciated. Such a finding would require a general reassessment of the underlying causes for times of extensive black shale accumulation in the geologic past. Rather than postulating specialized non-uniformitarian conditions that supposedly rendered large portions of the oceans anoxic, it seems perfectly possible that combinations of variables that we observe in modern oceans (for example the Santa Barbara Basin) can result in widespread production of highly carbonaceous sediments.

The described methodology for the detection of agglutinated benthic foraminifera in black shales has also been utilized successfully by Milliken et al. (2007) for the Mississippian Barnett Shale of Texas, and appears readily applicable to other examples from the rock record. In most instances collections of thin sections are probably already available, and should allow researchers to quickly assess whether agglutinated benthic foraminifera were once present.

Acknowledgements

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