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STYLES OF AGGLUTINATION IN BENTHIC FORAMINIFERA FROM MODERN SANTA BARBARA BASIN SEDIMENTS AND THE IMPLICATIONS OF FINDING FOSSIL ANALOGS IN DEVONIAN AND MISSISSIPPIAN BLACK SHALES

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Abstract

Agglutinated foraminifera are benthic organisms that in modern sediments have been described from marginal marine to bathyal environments. A number of modern taxa have adapted well to oxygen deficient environments, but even those require at least some oxygen in order to persist at the seafloor. Agglutinated foraminifera in sediments from the central deep of the Santa Barbara basin are typically multi-chambered and have walls that incorporate a variety of silicate minerals. Some taxa are quite selective with regard to mineral type and size, whereas others seem to incorporate a wide range of minerals and grain sizes. With deeper burial these foraminifera tests collapse and give rise to mineral streaks that are distinct through comparatively narrow sorting and grain type variability.

Collapsed agglutinated foraminifera with mono-mineralic as well as mixed mineral walls have been observed in black shale samples of Devonian to Mississippian age, suggesting benthic assemblages comparable to those seen in modern and sub-recent Santa Barbara basin muds. The latter thrive in a largely suboxic setting, and suggest by analogy that extended bottom water anoxia, though frequently postulated, were not a requirement for the formation of Paleozoic black shales. Improved criteria for the recognition of benthic agglutinated foraminifera in the rock record should help to bring new perspectives to the ongoing debate about the origin of ancient black shale successions and accelerate the removal of simplistic models from the discussion.

1. Introduction

Oxygen deficient environments, such as the central portions of the Santa Barbara Basin, have long been studied for the particular role of benthic foraminifera in such settings (e.g Bernhard and Reimers, 1991; Pike et al., 2001; Bernhard et al., 2003). Benthic foraminiferal assemblages are sensitive to bottom water oxygen levels and have been used to estimate paleo-oxygen concentrations in such settings (Bernhard et al, 1997). Remains of benthic foraminifera have also been discovered in ancient black shale successions of Devonian and Mississippian age (Milliken et al., 2007; Schieber, 2009), but in both instances the only recovered foraminiferal remains were of agglutinated benthic foraminifera that consisted of well sorted fine detrital quartz and were cemented with diagenetic silica. These silica cemented foraminiferal remains are easily recognized in polished thin sections, and their detrital origin is confirmed by application of scanned cathodoluminescence (Schieber, 2009).

When looking at modern sediments, however, one realizes that acquisition of small quartz grains is not the only mode of chamber agglutination for benthic foraminifera. Looking at resin impregnated thin sections of Santa Barbara Basin sediments one quickly finds that foraminifera also use poorly sorted and poly-mineralic materials in the construction of their chamber walls, and they may also construct chamber walls almost exclusively from clay and mica flakes. The obvious question that arises is whether these other styles of chamber construction arose in more recent earth history, or whether they simply were missed because they are less obvious than silicified quartzose remains (Milliken et al., 2007; Schieber, 2009).

New observations from the Mississippian Barnett Shale (Milliken et al., 2007) and the Devonian Cleveland Shale (Schieber, 2009), show that other styles of foraminiferal chamber agglutination are indeed preserved in these ancient shales. By comparison with the Santa Barbara Basin this suggests that similarly diverse agglutinated benthic foraminiferal assemblages existed at the seabed of several Paleozoic black shale basins. By extension this suggests that in spite of claims to the contrary (e.g. Rimmer, 2004; Loucks and Ruppel, 2007), the bottom waters of these basins were not persistently anoxic, but instead may have been much more comparable to modern suboxic sea bottoms (oxygen content ~ 0.2-0.0 ml/liter; Tyson and Pearson, 1991).

Careful consideration of the many factors that control accumulation of organic matter in sediments show that organic matter preservation is not a black vs. white issue (i.e. productivity vs. preservation). A thoughtful appraisal of the issue by Bohacs et al. (2005) delineates multiple scenarios that can give rise to organic-rich sediments that fundamentally reflect the complex interactions between production, destruction, and dilution. Anoxic conditions alone, although they do imply relatively low rates of destruction, are not always sufficient to ensure the deposition of an organic-rich sediment.

Modern suboxic sea bottoms are accessible for study in various locations, and include the Santa Barbara Basin (Bernhard et al., 2003), the Cariaco Basin (Hughen et al., 1996), the Baltic (Bonsdorff et al., 1996), the Arabian Sea (Schulz et al., 1996), and the Saanich Inlet (Russel and Morford, 2001). Studying ancient black shales from a suboxic basin perspective may lead us to a much more realistic appraisal of the boundary conditions of Phanerozoic black shale accumulation.

2. Methods and Materials

The examined materials for this study were polished thin sections from the Late Devonian Cleveland Shale of Kentucky and from the Mississippian Barnett Shale of Texas. In addition, samples of Santa Barbara Basin (SBB) sediments, collected from the central portion of the basin, were provided by A. Schimmelmann. The latter were embedded in Spurr Resin and polished with diamond lapping film.

Polished thin sections 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 (4000x4000 pixels, 1000 μs beam dwell time) were run at 10 kV with a narrow lens aperture (aperture 4), and spot size 5. The thin sections were carbon coated and the observations were made under high vacuum. Working conditions for SEM backscatter imaging (BSE) were 15 kV, high vacuum, aperture 4, and spot size 3.

3. Observations

3.1. SANTA BARBARA BASIN

The SBB sediments contain a range of benthic foraminifera (e.g. Bernhard et al., 1997), but in this study the main effort was devoted to agglutinated foraminifera because those are not in danger of dissolution during diagenesis. No attempt was made to identify genera or species. The focus was on chamber wall composition and wall construction because those were considered features most readily recognized in ancient shales.

With regard to composition and wall structure, there appear to be three main types that occur side by side in SBB sediments (Fig. 1A). The first and apparently most common type in the examined SBB material has chamber walls that are lined with a thin layer of small silicate grains. The silicates are predominantly angular quartz grains that range in size from a few to ten microns and the wall is typically no thicker than two grains (Fig. 1B, E). Whereas in some foraminifera the chamber walls seem almost exclusively constructed of quartz grains, in others feldspar grains and mica flakes are also incorporated into the wall structure. The second type of wall structure is of the same general composition as the first type, but the size range of incorporated grains is broader (a few microns to several ten microns) and the walls typically are three or more grains in thickness (Fig. 1C, F). In the third type of wall structure (Fig. 1D) the chamber walls are covered predominantly with platy minerals (mica flakes, clay). The latter type of wall structure is thinnest and may be constructed from single layers of overlapping platelets (Fig. 1G), or may consist of several layers of overlapping platelets (Fig. 2D, E).

Whereas the outlines of agglutinated foraminifera are largely undistorted in samples that have only experienced shallow burial (Figs. 1A, 2A), once samples from greater depths (1-2 m core depth) are examined an increasing number shows partial chamber collapse (Fig. 2B) and flattening (Fig. 2C). Comparing for example the well preserved specimen in Fig. 1B with a collapsed counterpart in Fig. 2C, one can readily imagine that all that may be left after complete compaction is a streak of quartz grains in an otherwise more clay-rich heterogeneous matrix.

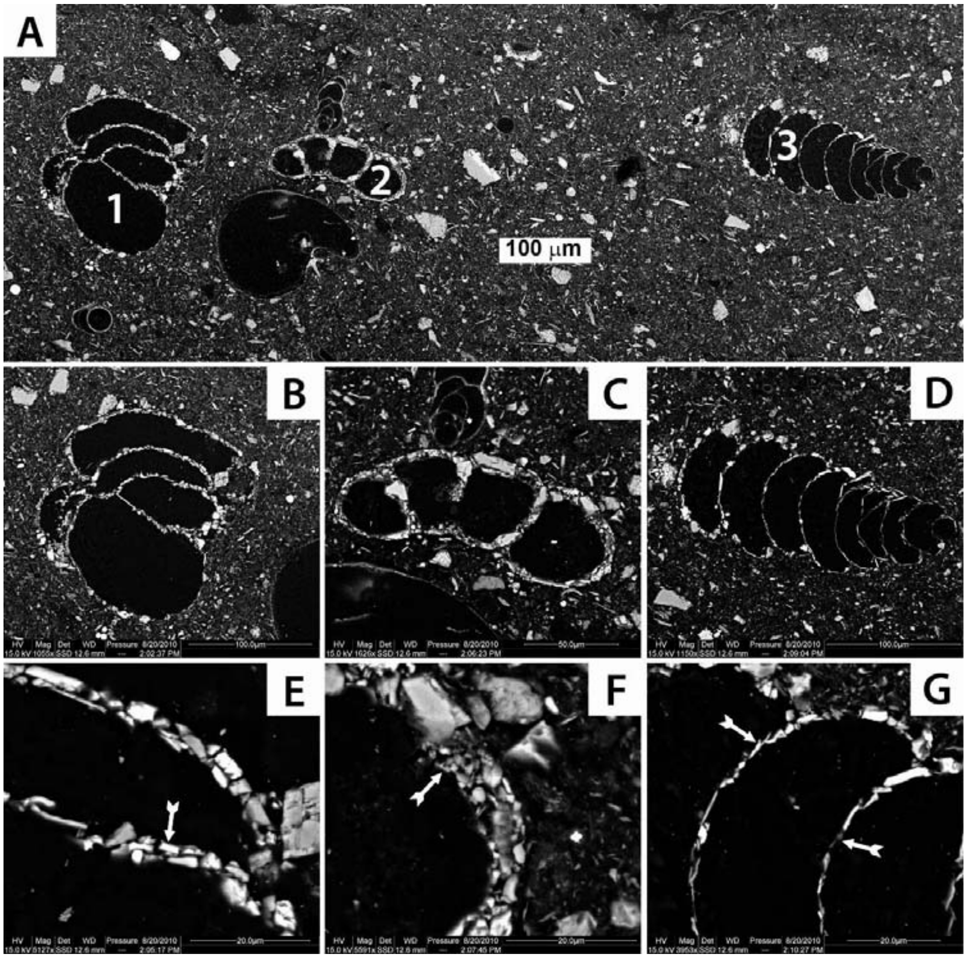

Figure 1: SEM images of common types of agglutinated foraminifera in sediments from the Santa Barbara Basin. **(A)** Image with several multi-chambered agglutinated foraminifera (marked 1 through 3) in a lamina. **(B)** Close-up of specimen 1, showing the agglutinated nature of chamber walls. The agglutinated material consists of silicate grains (mostly quartz) of a narrow size range (<10 microns). **(C)** Close-up of specimen 2. The chamber walls consist of a thicker layer (in comparison to specimen 1) of agglutinated silicate grains, and the grain size range of agglutinated grains is broader (up to 30 microns). **(D)** Close-up of specimen 3. In this foraminifera a large portion of the chamber walls is covered with platy minerals, mica flakes and clay, although other portions are also covered with quartz and some feldspar grains. The specimen is an example of mixed mineralogy wall construction. **(E)** Detail of chamber wall (arrow) of specimen 1. **(F)** Detail of chamber wall (arrow) of specimen 2. Note the poorer sorting and thicker agglutinate layer when compared to specimen 1. **(G)** Detail of chamber wall (arrows) of specimen 3. Note dominance of platy minerals.

Thus, what we can expect to find in fully compacted ancient muds is not the chambered structure of the original foraminifera, but rather whatever remains after the chambers have completely collapsed. There is a potential that in places a pre-compaction chamber fill forms a thin separation between chamber walls after compaction, something referred to as a medial suture (Schieber, 2009). Without such an infill the chamber walls can no longer be resolved and all we are left with is a thin lens of agglutinated material. Collapsed remains of agglutinated foraminifera are illustrated with the following examples from the rock record.

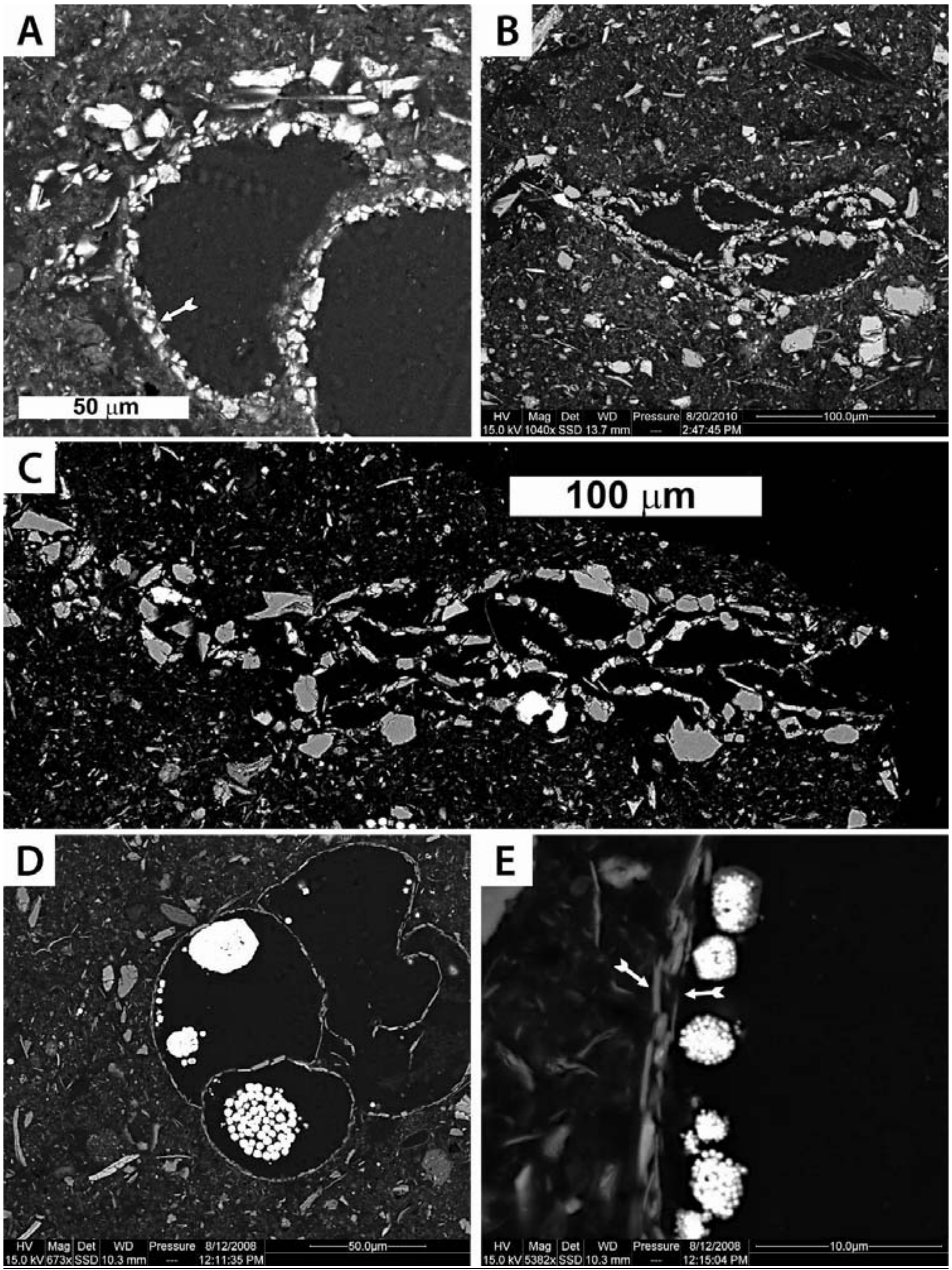

Figure 2: (A) through (C), collapse and compaction of agglutinated foraminifera in Santa Barbara Basin sediments (SEM images). **(A)** Close-up of undeformed chamber of thick-walled (arrow) agglutinated foraminifera (similar to specimen 2 in Fig. 1). **(B)** Partially collapsed foraminifera with deformation of chamber walls, but chambers still partially preserved. The image also highlights size selective behavior of foraminifera. The material (mostly quartz) that has been incorporated into the chamber walls is finer and much better sorted than quartz in the surrounding mud matrix. **(C)** Almost completely collapsed multi-chambered foraminifera. When compaction is complete the chamber interiors will no longer be visible and the foram will be a horizontal streak of quartz grains. **(D)** A thin-walled multi-chambered agglutinated foraminifera from the Santa Barbara Basin. The thinness of the wall reflects the fact that the agglutinate consists exclusively of platy minerals (clay and mica flakes). Bright grains in the interior of chambers are pyrite framboids and framboid clusters. **(E)** Close-up of the wall structure (between arrows) from (D). Shows that the wall consists of overlapping clay and mica platelets. Sorting of platy particles in the foram wall is significantly better than in the shale matrix to the left. Bright grains to the right of wall are pyrite framboids.

3.2. CLEVELAND SHALE, DEVONIAN

Lenticular bodies of fine-crystalline silica that have been interpreted as foraminiferal remains (Schieber, 2009) occur for example in numerous petrographic thin sections of Devonian black shales (Fig. 3A). They are up to 500 µm in length and up to 50 µm thick, have a fine-crystalline cherty appearance (Fig. 3A, B) and were initially considered silicified organic remains. Their granular appearance in SEM images also suggested that they might have originated as tiny ripples of fine silt that migrated over the muddy seafloor due to bottom currents (Schieber et al., 2007; Schieber, 2009).

Charge Contrast Imaging (CCI; Watt, Gruffin, and Kinny, 2000) and scanned color cathodoluminescence (CL) reveals that these features consist of discrete quartz grains set in a matrix of quartz cement (Fig. 3A'). Typically only a few microns in size, the quartz grains are well sorted, angular, and distinctly finer-grained than the quartz silt in the surrounding shale matrix (Figs. 3A, A').

Whereas a strong argument has already been made that above cherty streaks are foraminiferal remains (Schieber, 2009), new petrographic observations on the Late Devonian Cleveland Shale of Kentucky suggest that additional features in these rocks could be attributed to agglutinated foraminifera as well. For example, elongate lenticular features (Fig. 3B) that consist of variable mixtures of quartz silt, clay, and mica flakes with quartz cement (Fig. 3B'), and of a size and morphology comparable or identical to cherty streaks are common in these shales. They occur in the same sediment layers as cherty streaks and their morphology suggests a common origin. We also observe in these same layers bedding parallel streaks that consist almost exclusively of clays and mica flakes (Fig. 3C'), and are again morphologically very similar to cherty streaks (Fig. 3C).

3.3. BARNETT SHALE, MISSISSIPPIAN

Cherty streaks like those seen in the Cleveland Shale also occur abundantly in the Mississippian Barnett Shale of Texas (Fig. 4A, B), and have likewise been interpreted as foraminiferal remains (Milliken at al., 2007). A re-examination of Barnett Shale samples from that study has revealed additional features in these rocks that are close analogs to potential foraminiferal remains seen in the Cleveland Shale (Fig. 3) and Santa Barbara Basin sediments.

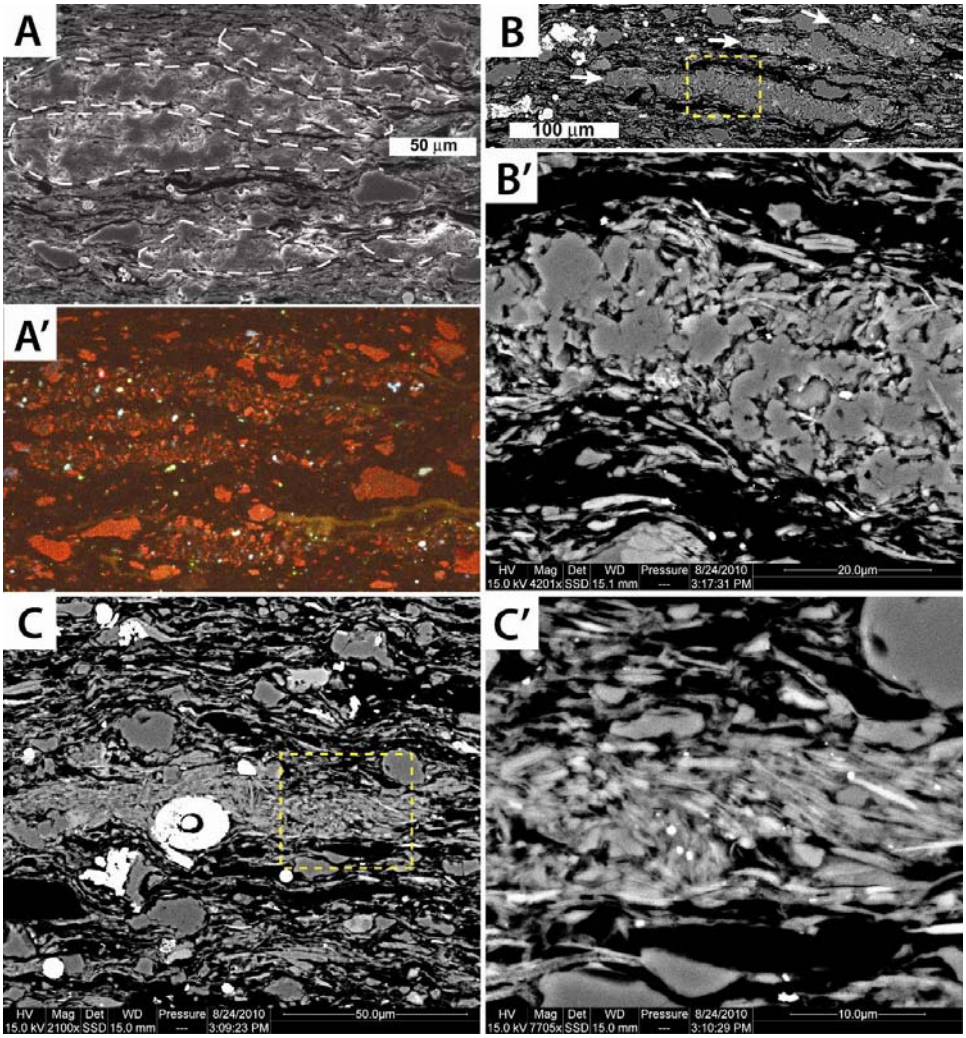

Figure 3: Petrographic features (SEM images) in the Devonian Cleveland Shale of Kentucky that are interpreted as remains of agglutinated benthic foraminifera (Schieber, 2009). **(A)** Multiple siliceous streaks in a shale sample, interpreted as agglutinated benthic foraminifera, are marked with dashed lines. **(A')** A cathodoluminescence scan of the same are as in (A). Detrital quartz appears as reddish to bluish angular particles. The areas occupied by foraminiferal remains are invariably much finer grained and better sorted than the surrounding shale matrix. **(B)** Another area in the same sample that shows morphological features (arrows) identical to the siliceous streaks seen in (A). These features differ in composition and consist of a mixture of quartz grains, clay and mica flakes. **(B')** A close-up (dashed box) of the features in (B). Shows the textural and compositional difference of this feature to the shale below and above. Shows that the feature consists of a mixture of quartz grains with platy clay and mica flakes. **(C)** Another area in the same sample that shows morphological features (arrows) identical to the siliceous streaks seen in (A). These features consist entirely of clay and mica flakes. **(C')** Enlargement of an area in (C) that is outlined by dashed box. The image shows clear textural contrast between feature and surrounding shale. The feature itself consists of aligned/shingled clay and mica flakes.

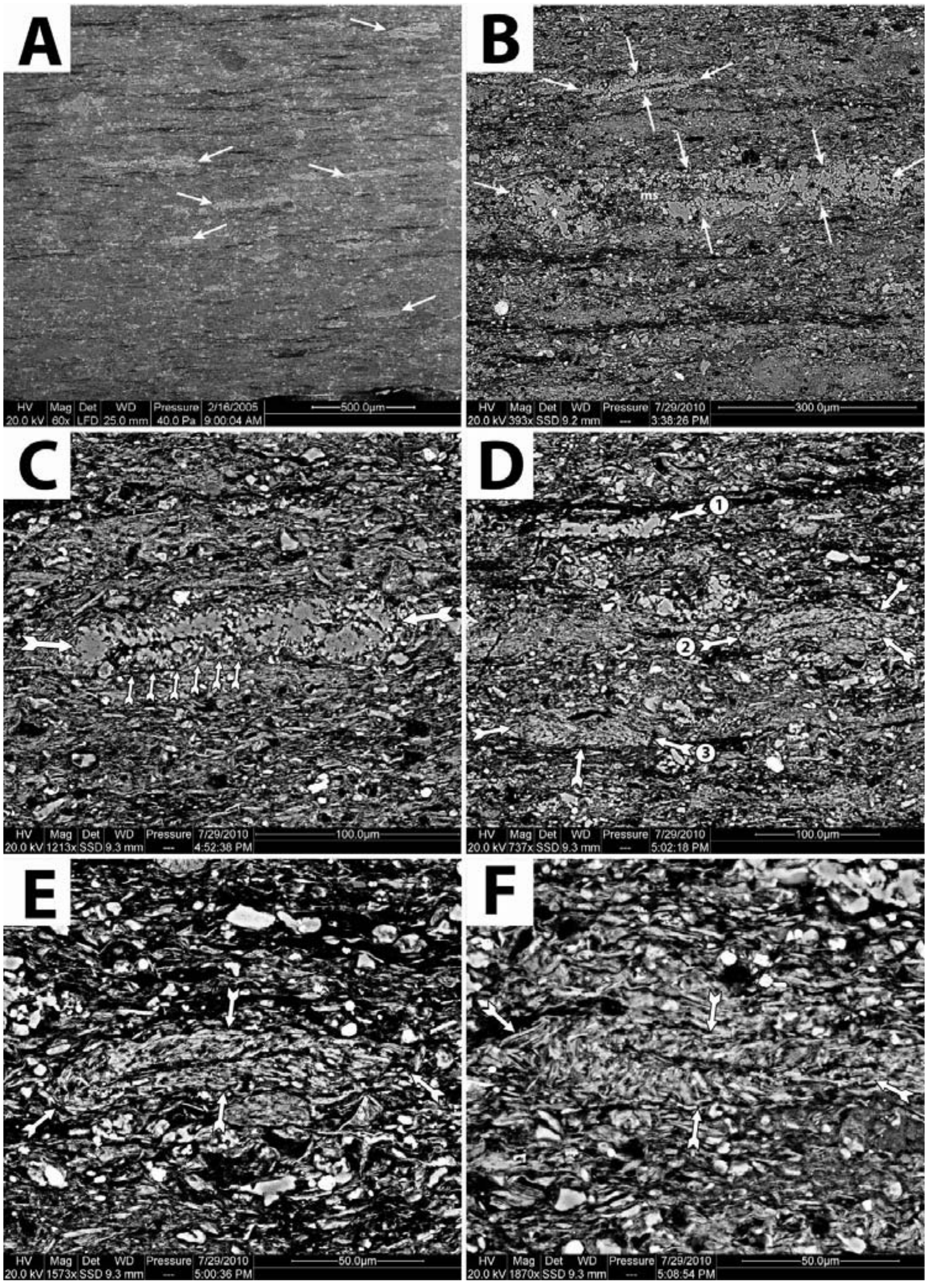

Figure 4: Petrographic features in the Mississippian Barnett Shale of Texas that are interpreted as remains of agglutinated benthic foraminifera. **(A)** Low magnification SEM image of Barnett Shale, bedding is close to horizontal. Dark streaks are rich in organic matter, light streaks (some marked with arrow) are silica-rich and

consist of fine detrital quartz with quartz cement. **(B)** A close-up of two of these siliceous streaks (marked with arrows). Both streaks show a medial clay-rich portion (marked ms, "medial suture" in lower specimen). These features are interpreted as collapsed agglutinated foraminifera that armored their chamber walls with small quartz grains. **(C)** A close-up of a siliceous streak/agglutinated foram (between large white arrows) with medial suture visible. In this case parts of the wall structure are dominated by clay minerals and mica flakes, the section pointed out with small white arrows. **(D)** Overview image that shows a siliceous streak (arrow 1) as seen in (B) and also two comparable features (arrows 2 and 3) that consist of mica and clay mineral flakes. **(E)** Close-up SEM image of feature marked by arrow 2 in (D). Shows a shingled structure of clays and micas and a medial suture. **(F)** Close-up SEM image of feature marked by arrow 3 in (D). Shows a shingled structure of clays and micas and a medial suture. The features shown in (E) and (F) are interpreted as collapsed benthic foraminifera that armored their chamber walls with clay and mica flakes.

For example, in the Barnett Shale not all siliceous streaks consist entirely of quartz. There is a portion of them where part of the wall consists of a mixture of quartz, clay, and mica flakes, (Fig. 4C). Other structures of comparable shape and size, and with medial suture, may consist entirely of clay minerals and mica flakes (Fig. 4 D, E, F).

4. Implications

In modern suboxic seafloor settings multiple species of benthic agglutinated foraminifera are able to persist (Bernhard et al., 1997), and thus finding several different strategies of chamber wall agglutination preserved in thin sections of SBB sediments (Fig. 1) is to be expected. Well developed grain selectivity has been documented for agglutinated benthic foraminifera in such settings (Pike and Kemp, 1996) and grain selectivity can therefore be considered a strong criterion for recognition in older sediments. In grain selection, foraminifera first accumulate random grains and then incorporate desired grain types and sizes into new chambers. The unused material is left behind as a "detritic heap" (Pike and Kemp, 1996). Agglutinated grains are held together by an organic cement, and in the samples studied by Pike and Kemp (1996) a preference for fine-grained quartz silt was noted. Pike and Kemp (1996) suggested that well sorted streaks of quartz grains in the rock record may be interpreted as remains of agglutinated benthic foraminifera, and that poorly sorted streaks represent "detrital heaps" of rejected material. Yet, as we can see from the multiple styles of agglutination in modern SBB sediments (Fig. 1), some types of benthic foraminifera are "sloppy" with regard to grain size selectivity (Fig. 1C). Thus, in the rock record poorly sorted streaks may at times also represent collapsed foraminiferal tests.

Fecal pellets of benthic organisms that ingest sediment and digest parts of the organic component, such as polychaete worms (Fauchald and Jumars, 1979), are in the same size range as mineral streaks produced by collapse of agglutinated foraminifera in the SBB (Cuomo and Rhoads, 1987; Cuomo and Bartholomew, 1991), and in cross section would have the same lenticular morphology as collapsed agglutinated foraminifera (Fig. 5). Fecal pellets, however, lack selectivity with regard to grain size and mineralogy and have a randomized interior texture (Fig. 5). Also, unlike collapsed foraminifera they would not show any evidence of medial sutures filled with a contrasting mineral matter (Fig. 4B, E, F).

In ancient shales, such as the Cleveland Shale and the Barnett Shale, lenticular bodies of fine-crystalline silica (Fig. 3, 4) have previously been identified as the likely remains of benthic agglutinated foraminifera in recent studies (Milliken et al., 2007;

Schieber, 2009). The identification was made using criteria developed by Pike and Kemp (1996), such as morphology, and selectivity with regard to mineralogy and grain size. That approach, however, because it restricted itself to agglutinated foraminifera that constructed their chambers of quartz grains, has its limitations.

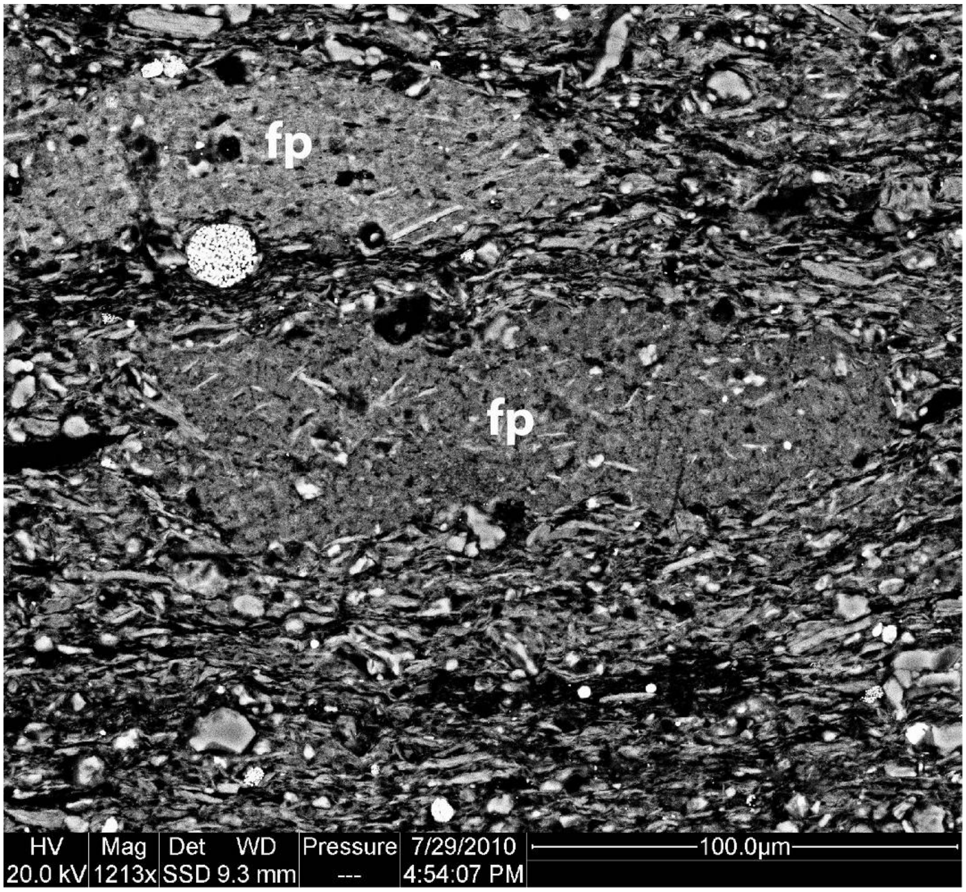

Figure 5: Petrographic features in the Mississippian Barnett Shale of Texas. For comparison with collapsed agglutinated foraminifera, two elongate lumps of material (marked fp) that are similar in morphology to siliceous streaks. Based on their random internal structure these are interpreted as fecal pellets of benthic organisms.

Obviously, agglutinated benthic foraminifera that coat their chamber walls with grains of mixed mineralogy do exist in modern sediments (e.g. Fig. 1D). In the rock record, as long as there is good morphological correspondence to the more readily identified remains of agglutinated foraminifera with well sorted monomineralic tests (Fig. 3A and 4A), one can have some confidence that mixed mineral streaks (e.g. Fig. 3B, B' and 4C) are foraminiferal remains as well.

Likewise, benthic agglutinated foraminifera that are selective towards clays and micas and incorporate platy grains of a narrow size range when compared with the size range available in the mud that surrounds them are evident in SBB sediments as well (e.g. Bernhard et al., 2006; and Fig. 1D, and 2D), and such forms have also been reported from other modern seafloor sediments (e.g. Gooday et al., 2008). Thin walled varieties like the one shown in Fig. 2D would of course yield a very thin mineral streak once compacted, but when high quality polishes (e.g. via argon ion milling) are used, the textural contrast and the better sorting may still alert the observer to the likely presence of a collapsed agglutinated foraminifera. The clay and mica dominated streaks from the Cleveland Shale (Fig. 3C, C') and the Barnett Shale (Fig. 4D, E, F) resemble the earlier described mineral streaks (quartz dominated and mixed mineralogy) in outward morphology, and that resemblance should probably be taken as a first hint that we may be dealing with yet another example of collapsed agglutinated foraminifera.

The other visual clue that indicates that these clay-mica streaks are unlikely to simply be squashed fecal pellets of benthic sediment ingesting organisms is the texture displayed by the platy minerals (Fig. 3C', 4E, F) and the medial sutures in some examples from the Barnett Shale (Fig. 4). Sediment ingestion would randomize the particles (Fig. 5), and there is no known alternative mechanism that could produce the observed particle arrangements and the medial sutures.

The suspected clay-mica agglutinated foraminifera from the Cleveland and Barnett Shales are unlike the clay-agglutinated examples from the SBB in two respects, the coating of platy minerals must have been quite thick when compared to the SBB example in Fig. 2D, and the minerals show an overlapping shingled arrangement (Fig. 3C' and 4E, F) that is unlike anything reported from modern equivalents. It may represent a style of wall agglutination that is no longer used by modern agglutinated foraminifera, or it is a style that has thus far escaped notice in modern settings.

That mixed mineralogy (Fig. 1D) and clay dominated (Fig. 2D) foraminiferal remains were not discussed by Pike and Kemp (1996) when they reported on agglutinated foraminifera from the SBB probably reflects the fact that these types tend to "blend" in more successfully with the shale matrix and thus probably escaped further scrutiny in these earlier studies. Another factor that matters in that regard is the quality of the polished surface that is examined under the SEM. Unless the polish is of high quality the critical textural details tend to be less obvious.

In the SBB bottom waters oxygen levels are too small to permit more than meiofaunal bioturbators (Pike et al., 2001). Because of the absence of macroscopic bioturbation the sediments retain a laminated appearance at the mm-scale (Pike and Kemp, 1996; Schimmelmann and Lange, 1996). Once these muds become part of the rock record they will be laminated carbonaceous shales that contain compacted tests of agglutinated benthic foraminifera. Given the observations reported here we should expect not only to find remains of agglutinated foraminifera constructed of quartz grains, but also collapsed grain assemblages that remain from mixed mineralogy foraminifera tests and those that are composed of clays and micas.

The SBB samples used in this study come from the deepest portions of the Santa Barbara Basin, where bottom waters are suboxic (oxygen content ~ 0.05 ml/liter) and, through intermittent influx of oxygenated bottom waters, experience 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), and the remains of agglutinated foraminifera that are found throughout the laminated deposits (Pike and Kemp, 1996; personal core observations). Brief interludes of anoxic bottom waters do not preclude seafloor colonization by benthic agglutinated foraminifera, because a number of modern agglutinated benthic foraminifera can endure brief (a few months) spells of bottom water anoxia. Some oxygen, however, is required so that they can persist on the seafloor (Bernhard and Reimers, 1991; Bernhard et al., 2003).

There have been recent reports of benthic foraminifera that can tolerate anoxic and even sulfidic conditions via foraminiferal denitrification (e.g. Risgaard-Petersen et al., 2006; Leiter and Altenbach, 2010; Piña-Ochoa et al., 2010). The latter authors found intracellular nitrate pools in a number of benthic foraminifera (including agglutinated forms) that are considered to be facultative anaerobes. Their oxygen respiration rates were considerably higher than their denitrification rates. In light of the higher energy yield from oxic respiration, this observation suggests that denitrification represents an auxiliary metabolic mode that supports the organism during temporary stays in oxygen-free environments, and that oxygen respiration may be required for growth and reproduction (Piña-Ochoa et al., 2010). In none of these studies has it been documented that any of the described species can survive anoxia through an entire life cycle, much less persist in such an environment for geologically relevant time spans (decades to millennia). Thus, although these observations indicate that certain agglutinated foraminifera are capable of intracellular denitrification, there is at present no evidence to suggest that this alternative metabolic pathway could have sustained them for multiple life cycles.

Identification of siliceous lenses (Fig. 2A, 3A), mixed-mineral lenses (Fig. 3B, 4C) and clay-mica lenses (Fig. 3C, 4D) in laminated Devonian and Mississippian black shales provides *prima facie* evidence that at the time of deposition an assemblage of agglutinated benthic foraminifera lived at the seafloor. By comparison with modern sediments of the SBB we may further presume that the respective bottom waters must have contained at least some oxygen (Pike and Kemp, 1996; Bernhard and Reimers, 1991; Bernhard et al., 2003). The preservation of laminae and the absence of macroscopic burrows on the other hand suggests that oxygen levels were too low to allow colonization by macrobenthos. As such, the situation with regard to bottom water oxygenation appears to be oxygen-depleted but not wholly anoxic. The observation of multiple types of relict agglutinated benthic foraminifera in laminated black shales of the Cleveland Shale and the Barnett Shale also indicates that in the Paleozoic suboxic sea-bottom environments were widespread in epicontinental seas. Analogous to what we observe in the SBB, brief anoxic interludes (a few months) probably occurred, 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).

Whereas 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), observation of siliceous streaks (Milliken at al., 2007; Schieber, 2009) served to indicate that other factors than persistent bottom water anoxia must have been at play to produce extensive black shales during the Late Devonian and the Mississippian. Finding a larger variety of agglutinated benthic foraminifera in these sediments further strengthens that argument, and gives more credence to an alternative scenario where short-lived anoxia were produced by seasonal thermoclines, in conjunction with seasonal mixing (Van Cappellen and Ingall, 1994). This "productivity-anoxia feedback" scenario allows high burial fluxes of organic carbon and is not in conflict with continued seafloor colonization by agglutinated benthic formanifera (Van Cappellen and Ingall, 1994; Sageman et al., 2003).

5. Conclusions

Through careful petrography and comparison to modern analogs, multiple types of agglutinated benthic foraminifera have been recognized in two ancient black shale successions. Given that the siliceous streak type of relict agglutinated foraminifera has already been observed in a wide variety of other black shales (Schieber, 2009), it is likely that evidence of ancient assemblages of benthic agglutinated foraminifera will be uncovered in many other black shale successions as well.

Expanding our knowledge of benthic agglutinated foraminifera in ancient black shale successions does on one hand force re-examination of current concepts of organic carbon preservation in the past. On the other hand, by looking at these rocks from the perspective of apparently quite comparable modern analogs, we no longer need to postulate specialized non-uniformitarian conditions (such as ocean-wide anoxia) to explain their existence. Combinations of variables that we can observe in modern oceans (such as in the SBB) may have sufficed to produce widespread deposition of carbonaceous sediments at certain times in the past.

The described approach for the detection of agglutinated benthic foraminifera in black shales can readily be expanded to other examples from the rock record.

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