SEDIMENTOLOGY the journal of the International Association of Sedimentologists IAS

Sedimentology (2021) **68**, 2707–2731 doi: 10.1111/sed.12870

Cryptic burrow traces in black shales – a petrographic Rorschach test or the real thing?

JUERGEN SCHIEBER, XINHE SHAO, ZALMAI YAWAR and BEI LIU
Indiana University Shale Research Lab, Indiana University, Bloomington, IN, 47405, USA (E-mail: jschiebe@indiana.edu)

ABSTRACT

In black shale studies, apparent lack of bioturbation is commonly taken as an indication of anoxic bottom waters. Yet, modern oxygen-stressed environments show that even at suboxic levels (0.0 to 0.2 ml l^{-1} oxygen), microscopic eukaryotic benthic organisms live in the uppermost millimetres to centimetres of the substrate. Known as meiofauna, these organisms disturb the primary fabric as they move through the sediment. These modern examples inspired students of the rock record to report sub-millimetre irregular–wiggly features in black shale thin sections as meiofaunal burrows. Preparation flaws in thin section manufacture can cause reduced light transmission that results in darkened regions when viewed in transmitted light, and one wonders whether micro-burrows reported in the literature are indeed burrows, or alternatively artifact-induced optical illusions. Examining shale thin sections of Archean to Tertiary age showed: (i) that burrow-like features are common regardless of age; and (ii) that burrow identification varies significantly between observers. When transposing locations of presumed traces onto scanning electron microscope images of the same field of view (diamond polished surface), no evidence of fabric modification at locations of presumed burrows was observed. Microfabric within and outside 'burrows' was the same, and larger fabric elements traversed 'burrows' uninterrupted. Once both sides of the rock slice were polished, presumed burrows could no longer be observed, indicating that damage to the underside of the thin section caused the mistaken identification of micro-burrows. Because burrows emplaced in water-rich muds must undergo substantial compaction-induced 'flattening' and deformation prior to lithification, geometries of presumed burrows that disagree with a plausible compaction regime provide an additional filter to separate potential burrows from artifact-induced features. Recognizing meiofaunal disruption is an important aspect for accurate palaeoenvironmental interpretation of black shales. Yet, initial assessment via optical microscopy needs to be verified through scanning electron microscope-based examination of shale fabrics.

Keywords Anoxia, artifact, black shale, micro-burrow, microscopy, palaeoenvironment.

INTRODUCTION

Shales and mudstones contain the lion's share of Earth history that is recorded in sedimentary rocks. Understanding their deposition is key to the reconstruction of past oceans, landscapes, climates and climatic cycles. Although largely neglected as a research focus by sedimentologists for the better part of a century (Schieber & Zimmerle, 1998), in the past 15 years the number of published shale studies has increased dramatically with the rise of horizontal well design and hydraulic fracturing as a way to extract commercial quantities of oil and gas from shale formations (Breyer, 2012; Camp *et al.,* 2013; Breyer, 2016). Because of the fine-grained nature of these rocks, many studies include the petrographic examination of thin sections for gaining information about sedimentary processes and post-depositional overprint, such as bioturbation, diagenetic cements and compaction (e.g. Lazar *et al.,* 2015). It is probably not too bold a statement to say that in the past 10 years alone, multiple times more shale thin sections were prepared and examined than in the entire century that preceded them; and, with so many more eyes looking, a growing body of new observations were and are being made that significantly raised our understanding of these long-ignored rocks. It is now possible to go to a geological convention, talk about shales, and even get good feedback and have some fun. Life is good.

In the study of black shales, the recognition of infaunal burrowers is a key element in the assessment of depositional setting and for deciding whether the shales in question accumulated under conditions that were fully anoxic or merely oxygen limited. Burrow traces can be exceedingly subtle (Schieber, 2003; and references therein) and their recognition subjective to the point where identical images can lead to starkly divergent assessments (cf. Egenhoff & Fishman, 2013; Schieber, 2014). The fact that meiofaunal fabric disruption is well-known from modern muds (Pike *et al.,* 2001; Bernhard *et al.,* 2003) certainly justifies giving this process due consideration in the study of ancient mudstones and shales. The open question is, however, how one might recognize meiofaunal burrowing once a mudstone has undergone diagenesis, organic matter degradation and burial compaction. The purported examples that have been published (e.g. Egenhoff & Fishman, 2013; Ma *et al.,* 2016; Borcovsky *et al.,* 2017; DeReuil & Birgenheier, 2019) are problematic because without the 'burrows' being marked and outlined by the authors, one wonders whether different sets of 'eyes' would see different burrows, or any burrows at all. For these reasons it probably should be standard practice to show original and annotated photomicrographs side by side when important features are traced or sketched on top of the original image in order to highlight them.

The purpose of this paper is to show how the confluence of innate aspects of thin section petrography and the inner workings of the human mind may be at the heart of a good many reports of cryptic bioturbation in black shales. Petrographic thin sections are the end result of mechanically cutting and grinding a piece of rock into a sliver that is about one-third the thickness of a sheet of paper. Anyone that has ever been engaged in their manufacture knows that the process is fraught with unforeseen complications and that 'bad' thin sections are a fact of life. Defects, such as scratches on glass carrier and rock slice, as well as air bubbles and schlieren of micro-bubbles in the glue between glass and rock slice, generally cause localized light scattering, and result in reduced light transmission and darkening on the microscope side of the thin section. When these defects are comparatively large, they are likely identified as such by experienced observers. Yet, when sufficiently small, say on the order of tens of microns wide, the associated optical effects are not as readily attributable to surface defects. What further complicates matters is a human willingness to see patterns in the most unlikely places, a propensity that once inspired Steven Jay Gould (1985) to state that: "The human mind delights in finding pattern – so much so that we often mistake coincidence or forced analogy for profound meaning. No other habit of thought lies so deeply within the soul of a small creature trying to make sense of a complex world not constructed for it." Both aspects, the thin section artifacts and the way the human brain works, will impact what an observer might 'see' in a thin section and how these observations will be processed and interpreted.

HUMANS AND PATTERN PERCEPTION

Humans recognize patterns in their environment by matching information from a stimulus with information held in memory (Eysenck & Keane, 2005). Pattern recognition is considered a crucial component of higher cognitive functions in humans and their evolutionary success (Mattson, 2014), and may very well be what makes us uniquely human. For geologists, the stimulus commonly comprises things seen directly or in previously captured images, and the ability to recognize relevant patterns is a critical skill. When well-honed, for example in a petroleum geologist, it can mean vast fortunes to be made, but when applied with an abundance of exuberance it can equally well spell disaster and financial ruin. Humans search for patterns to make sense of the world around them, and to know the dividing line between 'just right' and 'too much' is important enough to the human endeavour to have been studied and named (apophenia) by psychiatrists (Conrad, 1958). Pareidolia is a subcategory of apophenia and describes the human propensity to 'see' familiar shapes and patterns in visual stimuli, such as the shapes of clouds, tea leaves in a cup, seismic reflection profiles and stratal patterns. Not surprisingly, artists and writers have been intrigued by the phenomenon as well, as exemplified by the dialogue between Hamlet and Polonius in the third Act of Shakespeare's Hamlet (Shakespeare, 1603; the dialogue below is reproduced from the 1603 first edition).

Dialogue between Hamlet and Polonius/Corambis:

POLONIUS: My lord, the Queene would speake with you.
HAMLET: Do you see yonder clowd in the shape of a camell?
POLONIUS: T'is like a camell in deed.
HAMLET: Now me thinks it's like a weasel.
POLONIUS: T'is back't like a weasel.
HAMLET: Or like a whale.
POLONIUS: Very like a whale.

This all too human 'fluidity' of pattern recognition, is something to contend with in sciences as well, and scientists are constantly challenged to find ways to make sure that perceived patterns have a basis in reality. The realization that pareidolia even occurs in computer-based image processing (Rosen, 2012) underscores how deeply engrained it must be in the mental makeup of humans, and how important it is to be able to determine whether an observed pattern has meaning, or whether it is an artifact of sample processing and/or observation method. In this age of communicative abundance, how mouldable the human mind is with regard to what it perceives as truth is aptly illustrated by the contemporaneous proliferation of 'alternative facts' and 'post-truth'. Yet, as Aldous Huxley put it so succinctly: "Facts don't cease to exist because they are ignored.".

In the realm of petrography, what further confounds the problem is the widespread assumption that what we can see with our own eyes is the factual truth. This notion, epitomized as 'A Picture is a Fact' by Ludwig Wittgenstein (1922) in his philosophical musings on the nature of logic and reality, is the foundation on which the strength of petrographic reasoning rests. Yet, as shall be elaborated upon below, inserting a microscope between the object and the eye of the observer does change this fundamental assumption and necessitates that we consider optical effects that could alter our perception. This paper is about verification and reality checks with regard to petrographic observation of subtle bioturbation in carbonaceous (black) shales.

METHODS

The thin sections used as illustration for this paper are from the large collection in the Indiana University Shale Research Lab (IUSRL). The laboratory curates shale samples from the Archean to recent. All samples illustrated are glued with epoxy resin to a glass carrier slide (27×46 mm, 1.2 mm thick), and have a standard thickness of 30 μm (Fig. 1). For shale studies 'ultra-thin' thin sections (20 μm) have been used by a subset of investigators, but the one-third reduction in thickness still implies that many particles are substantially smaller than the section thickness.

Collected over a time span of 40 years, these thin sections were prepared by multiple in-house technicians, students and off-campus vendors. Most of the samples used in this contribution for illustration were single polished thin sections where the 'underside' has been processed like a standard thin section and ground flat with 1000 grit abrasive (*ca* 20 μm mean grain size) and the 'upperside' has been polished for scanning electron microscopy (SEM) and electron microprobe (0.5 μm abrasive). For four samples where the original sample was still available, double polished sections were prepared, with the 'underside' of the sample being polished to the same quality as the 'upperside'.

Petrographic examination and photomicrography were done on a Zeiss Photo III petrographic microscope (Carl Zeiss AG, Oberkochen, Germany) and SEM imaging was done on a FEI Quanta 400 field emission scanning electron microscope (FEI Company, Hillsboro, OR, USA). In order to avoid coating artifacts, SEM observations were made in low vacuum mode. Some

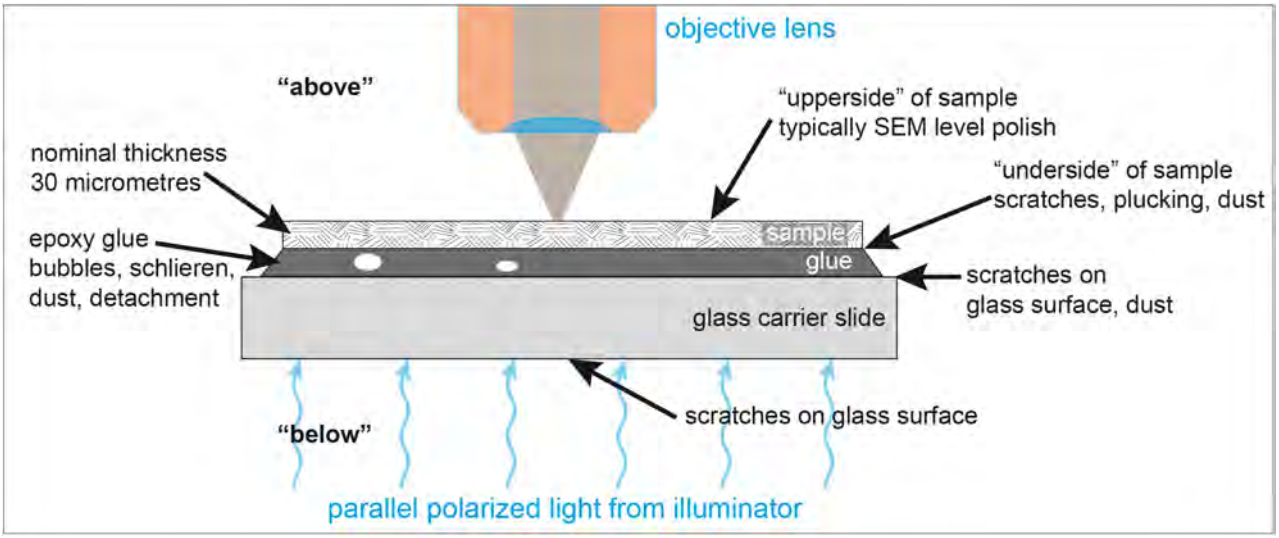


Fig. 1. Schematic cross-section of a thin section, marking its components and the location of various types of common artifacts that can interfere with the viewing of details under the petrographic microscope, as well as the typical light path for orthoscopic illumination. Because typically shale sections have a surface polish for scanning electron microscopy (SEM) viewing, no cover slide is shown.

image processing to balance colour and brightness/contrast was applied to the original images in Adobe Photoshop™.

Because the artifacts that are presumed to be at the root of the features discussed in this manuscript are found at the 'underside' of the sample, some photomicrographs were taken with the thin section turned upside down. In that case, in order to better see artifacts, sample surfaces were illuminated obliquely from above, using a fibre optics light source angled at 30°.

COMMON THIN SECTION ARTIFACTS

Being products of mechanical processing of rock samples, petrographic thin sections invariably are burdened with artifacts that reflect damage to the surface of the rock slice, the glass slide itself, air bubbles and dust and debris trapped in the epoxy glue between glass slide and sample, and schlieren (streaks of wavy optical inhomogeneities) formation in the glue (Fig. 1). In the following paragraphs examples of these and their impact on light transmission through the section are presented. These examples were chosen with a mind towards depicting artifacts that can serve as a sensible introduction to less experienced observers, with the full understanding that a seasoned petrographer might find them elementary. Acknowledging that petrographic training of geoscience students has not fared well in curricula revisions over the past decades probably justifies introduction of the problem with comparatively simple and even 'obvious' examples.

In petrographic microscopes, orthoscopic illumination mode is typically used when viewing thin sections, and that implies that parallel light rays arrive at the thin section and then pass through the sample. In addition, it is common knowledge that any roughness, unevenness and/or cracks on the underside of the sample cause refraction and reflection of light rays, a phenomenon known as 'chagrin' (Raith *et al.,* 2012). Chagrin-related reflection and scattering of light diminishes the amount of light that passes through the sample, darkening to some degree what is seen through the eyepiece of the microscope. Likewise, sample preparation artifacts that induce light scattering should be associated with localized darkened areas in thin sections.

The most common mechanical damage to thin sections are scratches on the 'underside' of the sample surface (Fig. 1), caused by abrasive and plucked out mineral grains when the sample surface is smoothed prior to gluing the sample to the carrier glass slide. Whereas the use of increasingly finer abrasives during surface preparation can significantly mitigate this problem, due to the general softness of mudstones and shales there will be always be at least a few thin sections in every box that exhibit that problem (Fig. 2).

Figure 2 illustrates that the scratches on the underside of the sample disrupt the sample surface and result in light scattering. Because of light scattering at scratch locations, less light passes through the thin section, and therefore the scratches appear darker in transmitted light.

A comparable phenomenon can be observed in relation to scratches on either side of the glass carrier slide, as illustrated in Fig. 3. Again, light scattering on a defect causes the defect to appear darker in transmitted light.

As seen in Figs 2 and 3, defects that induce light scattering below the sample result in corresponding darkened portions in the transmitted light image. As long as there is well-defined damage, such as a clearly visible scratch, the connection between damage and darkened portions of the thin section is readily made.

Air bubbles trapped in the epoxy seam between carrier slide and sample are another common cause of light scattering in thin sections. The light rays encounter a drastic change of refractive index (solid to gas), resulting in reflection and scattering, and significant reduction in light transmission (Fig. 4).

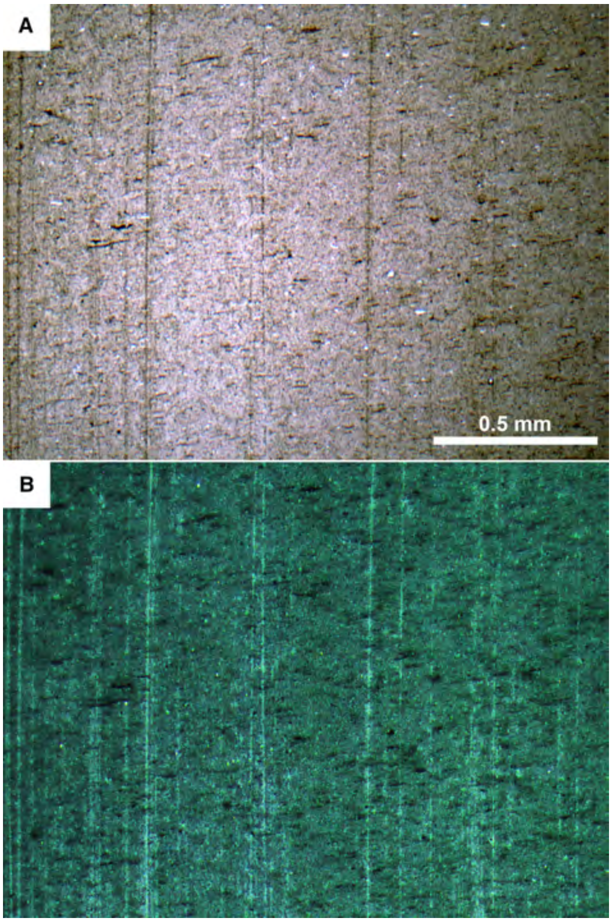


Fig. 2. Appearance of scratches on the rock slice. (A) As seen in transmitted light (from above), the scratches appear darker than the rest of the sample. (B) The view of the underside of the sample (thin section turned upside down), illuminated with a strong light at an angle of about 30°. The scratches are prominent (brighter) because of light scattering.

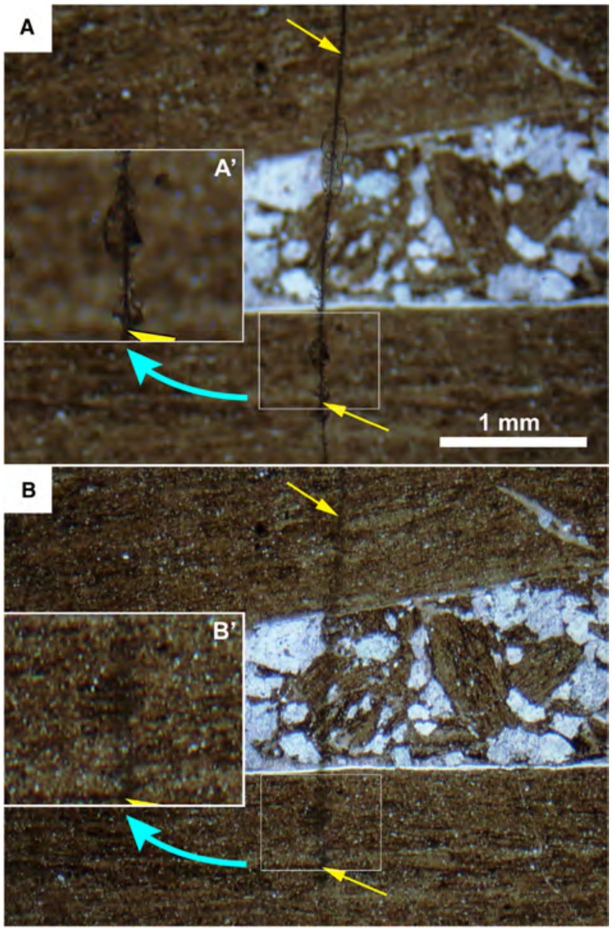


Fig. 3. Scratch on the underside of the glass carrier slide. (A) Thin section turned upside down, transmitted light. The scratch is in focus, the sample is out of focus. (B) Thin section in normal orientation, transmitted light. The sample is in focus, and the scratch (located below the sample) appears darker. Insets A′ and B′ show that when the sample is in focus, the scratch appears as a fuzzy darkened line.

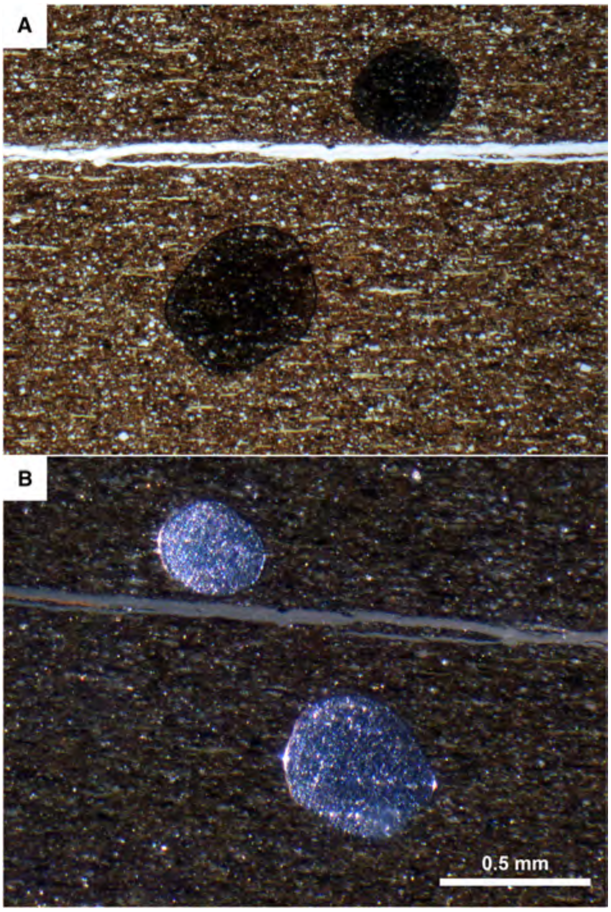


Fig. 4. The effect of air bubbles on light transmission. (A) Transmitted light view. The air bubble strongly reduces light transmission. (B) The view from below (thin section turned upside down), illuminated with a strong light at an angle of about 30°. The bubbles reflect and scatter light.

As long as the epoxy glue has not started to gel, an experienced thin section maker can remove bubbles by manipulating the sample. Once gelling has started, however, agitating the sample will merely smear out the bubble and produce patterns that superficially resemble burrow traces (Fig. 5), although careful examination of the sediment fabric (tracing of laminae) shows that the presumed 'traces' exist below the sample in the epoxy layer.

All of the above examples have in common that mechanical damage to the underside of the sample, as well as obstacles in the epoxy layer or damage to the glass carrier slide cause partial reflection and/or scattering of the parallel light rays that are directed at the thin section from the illuminator below. From an understanding of how a petrographic microscope works (Raith *et al.*, 2012), this implies that, relative to adjacent areas of the thin section that are not associated with such artifacts, light scattering will reduce the amount of light that passes through the thin section and affected areas will appear darker when viewed in transmitted light. In coarser-grained rocks with particles larger than the 30 μm thickness (or 20 μm for ultra-thin) of a thin section (Fig. 1) refractive index contrast is responsible for useful mineral identification properties like relief and the Becke Line (Raith *et al.*, 2012). In shales and mudstones, however, they cause further image degradation due to the fact that many of the constituent particles are smaller than the nominal 30 μm thickness of the sample. The scatter due to internal refraction and reflection causes backward extensions of light rays to not focus on a spot, and instead cause a blurry and defocused rendering of the margins of underlying artifacts.

Mechanical damage to mudstone surfaces is also a matter of composition. For example, whereas scratches tend to be quite visible in transparent thin sections (Fig. 2), they tend to not leave a clear 'trail' in more opaque, organic-rich dark mudstones (Fig. 6).

If one tries to focus on the marked (by red arrow) organic matter-rich interval in Fig. 6 from the underside, it is apparent that the underside of that layer is rougher and more irregular then the rest of the thin section. As one focuses up and down, variably shaped patches of shale come in and out of focus successively, suggesting a 'surface' that consists of low amplitude irregularly curved ridges and valleys. A general experience from multiple years of trying to smooth and polish mudstone samples is that carbonaceous mudstones tend to pluck comparatively easy, a property that probably can be attributed to their relative softness, as well as intermingling of mineral matter, organic particles, and interstitial bitumen that results in short-range mechanical heterogeneity.

APPLICATION TO PERCEIVED MICRO-BURROWS IN SHALES

In recent years there have been a number of publications (Fig. 7) that intended to show that irregular-curved darkened features in black shales are actually the burrows of small infaunal organisms (e.g. Egenhoff & Fishman, 2013; Ma *et al.*, 2016; Borcovsky *et al.*, 2017; DeReuil & Birgenheier, 2019; Biddle *et al.*, 2021). Yet,

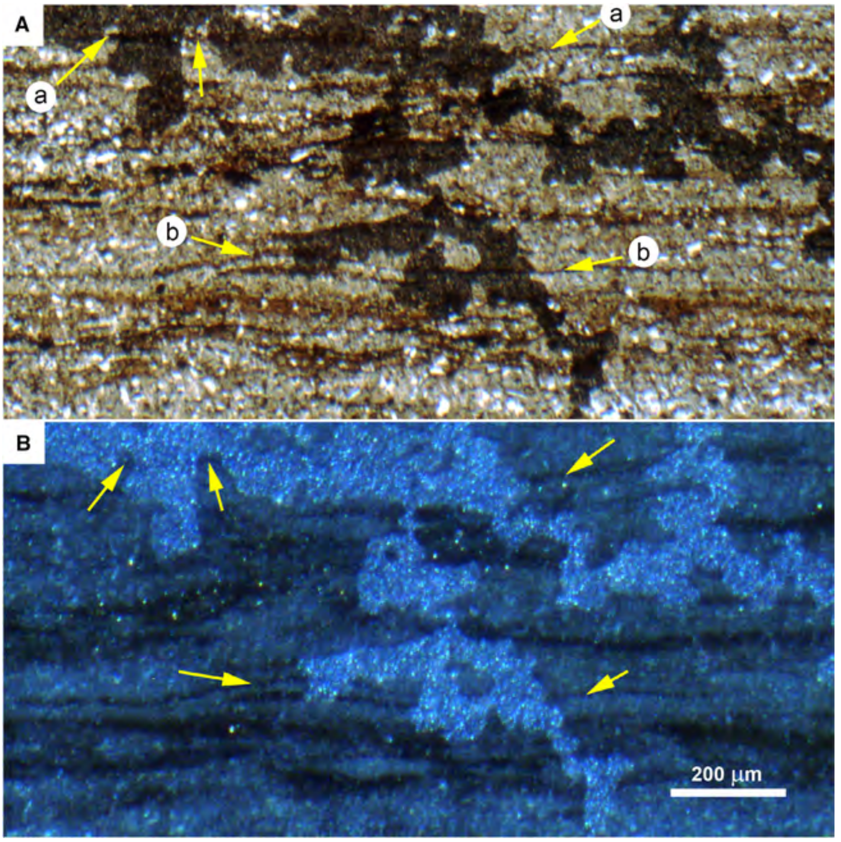


Fig. 5. Smeared out bubbles in epoxy layer. (A) Transmitted light view, bubble areas are darker. (B) View from below, illuminated with a strong light at an angle of about 30°. The bubbles reflect and scatter light. Matrix laminae (yellow arrows) that pass through the darkened areas and are hidden under reflective bubbles indicate that the burrow-like features are not part of the sample. The arrow pairs marked with 'a' and 'b' in white circles indicate two laminae that can clearly be followed through.

whereas probing and expanding the limits of benthic life into the realm of presumably 'forbidding' organic-rich muds is a much-needed endeavour, doubts have been raised previously about the validity of these claims via comparisons to potential modern equivalents and the impact of compaction on burrows made in water-rich sediments (Schieber, 2014).

An allied aspect of human pattern recognition is the desire to give names to things so as to manage effectively the complexity of the world around us, as exemplified by Hamlet seeing the cloud as a camel, a weasel, etc. Giving a name to something allows one to get connected to all the other information that has been accumulated on that thing already. A name, properly assigned, can be a very helpful shortcut to insight.

It is therefore not surprising that those that interpreted 'irregular-curved darkened features' as burrows, went a step further and associated them with traces described previously in the trace fossil literature. Following in the footsteps of Egenhoff & Fishman (2013), most of the above authors assigned them to the ichnospecies *Phycosiphon incertum*, presumed to be burrows of vermiform deposit feeders (e.g. Wetzel & Bromley, 1994). *Phycosiphon incertum* is a trace fossil whose morphology and appearance has been carefully described in multiple publications (e.g. Wetzel & Bromley, 1994; Naruse & Nifuku, 2008; Bednarz & McIlroy, 2009). In these publications *Phycosiphon incertum* is described as consisting of narrow and sinuous tubes that irregularly twist and form a series of closely packed loops that generally parallel bedding. Yet, whereas 'narrow and sinuous tubes' are observed by the above authors (Egenhoff & Fishman, 2013; Ma *et al.,* 2016; Borcovsky *et al.,* 2017; Biddle *et al.,* 2021) none of them has provided any observations that would confirm that these tubes have a tendency to be organized into bedding parallel loops. Although there is a superficial geometric similarity between the 'sinuous tubes' as pictured by these authors and bedding plane views of *Phycosiphon incertus* (Wetzel & Bromley, 1994), their thin sections are perpendicular to bedding, and in that view *Phycosiphon incertus* is highly compressed (Wetzel & Bromley, 1994) and does not look at all like the 'irregular-curved darkened features' that are shown in these publications (Egenhoff & Fishman, 2013; Ma *et al.,* 2016; Borcovsky *et al.,*

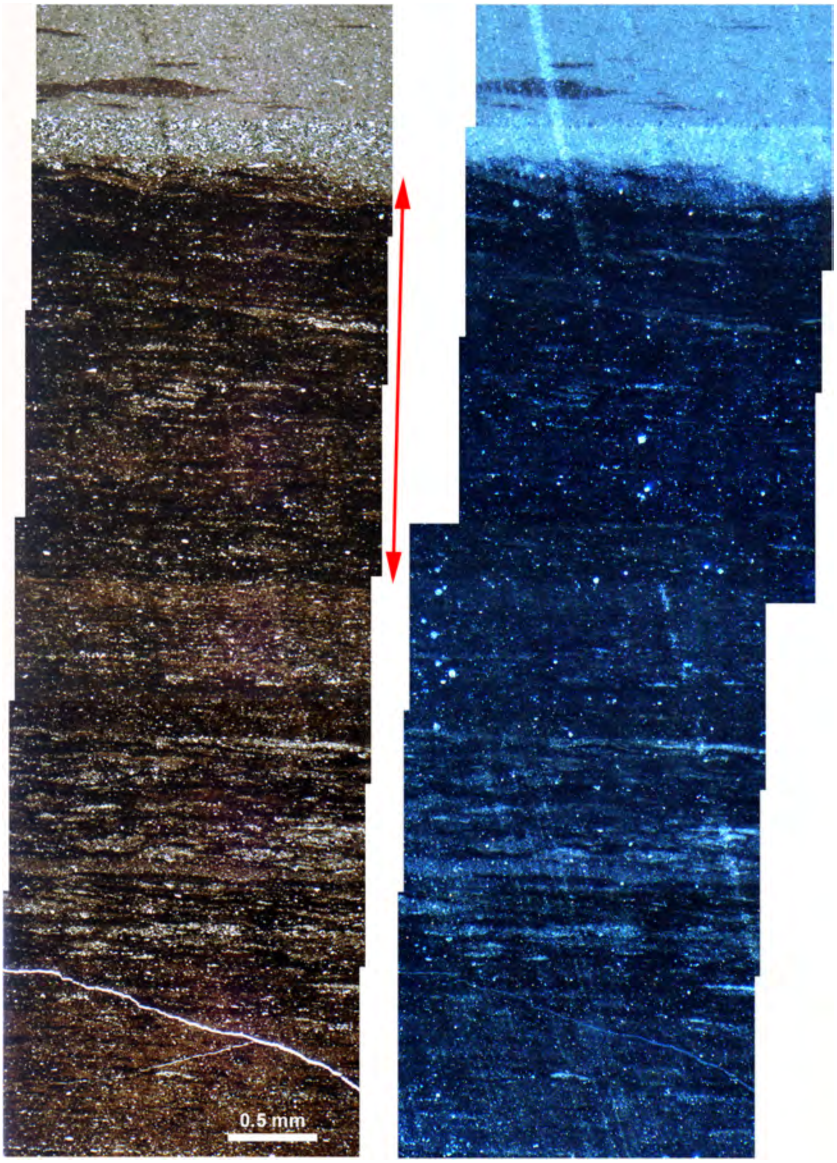


Fig. 6. Mechanical damage versus organic matter content. At left, transmitted light photomosaic with scratches visible in the light-coloured top portion. At right, reflected light view of the underside of the section. Scratches are visible in the top portion and in the moderate organic matter (OM) content lower half, but scratches 'fade' as they pass through the layer (marked with red double arrow) with the highest OM content.

2017; Biddle *et al.,* 2021). One is therefore left with an assertion, rather than a well-supported identification. From the perspective of the authors of this paper, if identification of specific trace fossils is used to support far-reaching re-interpretations of a given shale succession, documentation of diagnostic criteria is obligatory. In addition, to go through this exercise could be one way to differentiate true bioturbation features from resemblant features that are owed to artifacts.

The compaction perspective

Modern organic-rich surface muds are invariably water-rich (90 to 95 vol. % water; Migniot, 1968; Anderson & Dean, 1988; Bernhard *et al.,* 2003; Schieber, 2011) and small organisms (meiofauna) that colonize these surfaces (Pike *et al.,* 2001; Löhr & Kennedy, 2015) do disturb the fabric and even produce burrows that can be recognized in uncompacted epoxy-stabilized samples. How these tiny burrows from published modern examples might look once the sediment has undergone mechanical compaction is readily accomplished by shortening the vertical dimension by the appropriate amount (removing water content) in any image processing software (such as Adobe Photoshop™). Invariably, burrows that were recognizable in images of uncompacted muds became imperceptible

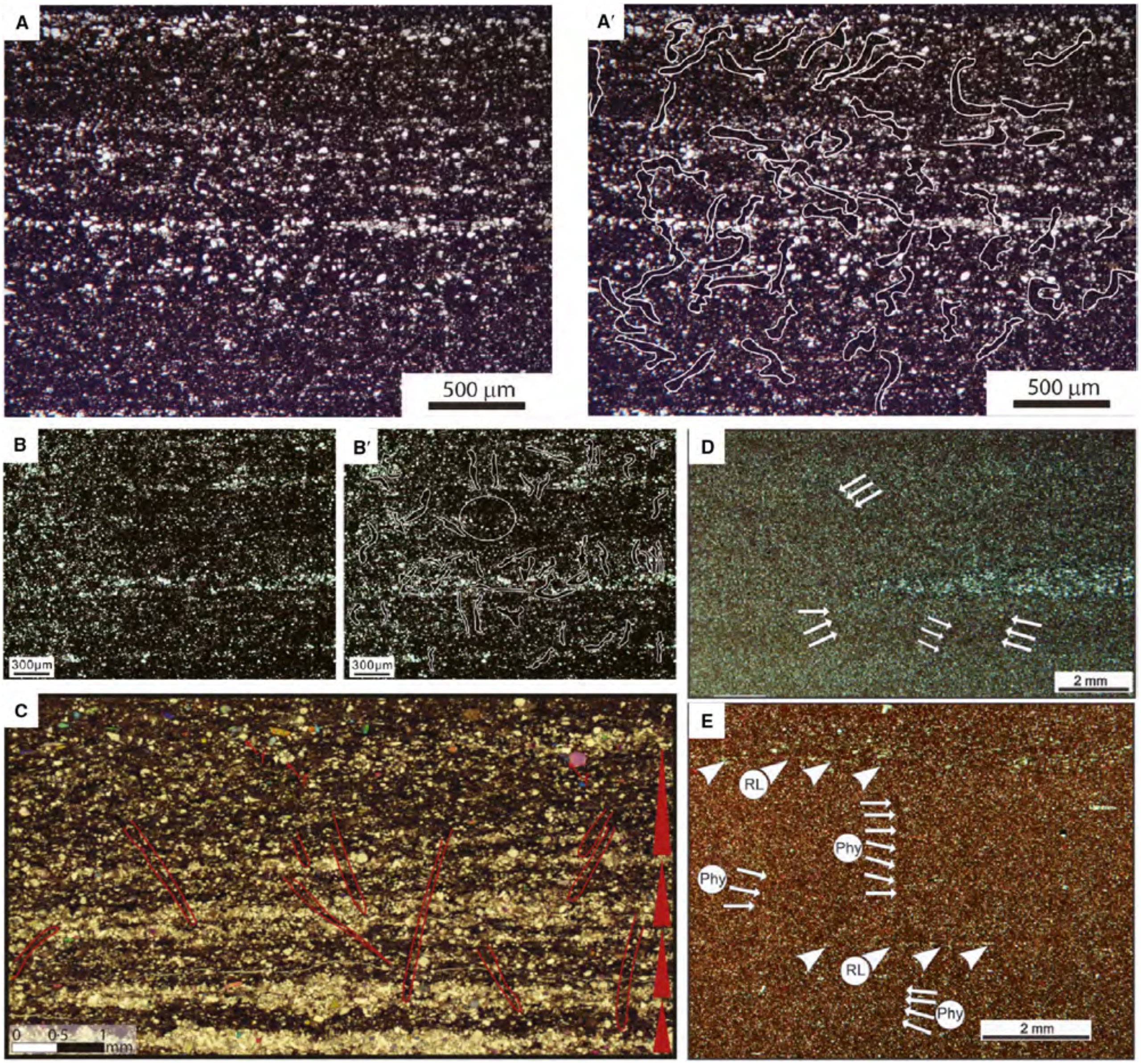


Fig. 7. Various attempts at identifying micro-burrows in ancient shale successions. (A) and (A′) By Egenhoff & Fishman (2013), with presumed traces (white lines) marked in A′. (B) and (B′) By Ma *et al.* (2016) (Silurian Longmaxi Formation, China), with presumed traces marked in (B′), (C) by DeReuil & Birgenheier (2019) (Cretaceous Mancos Shale, Utah), with presumed traces marked by red lines, and (D) and (E) by Borkovsky *et al.* (2017) (Devonian Bakken Shale, North Dakota). The clusters of arrows indicate presumed *Phycosiphon* (Phy) burrows, and triangles labelled RL mark presumed 'relict laminae'.

once the image had undergone 'virtual compaction' (e.g. Schieber, 2014). To explore the issue of compaction a bit further, an experimentally produced mud layer (kaolinite clay) of approximately 85 vol. % water content was inoculated with nematodes to get good images of burrow systems that might form in water-rich muds through meiofaunal activity (Fig. 8).

Figure 8 illustrates three things: (i) if colour contrast between burrow and matrix is small (Fig. 8C), it is likely that not much remains to be seen once compaction has taken place (Fig. 8E); (ii) that burrows that are subvertical approximately retain their original width and that foreshortening will impart an irregularly folded appearance (Fig. 8F); and (iii) that

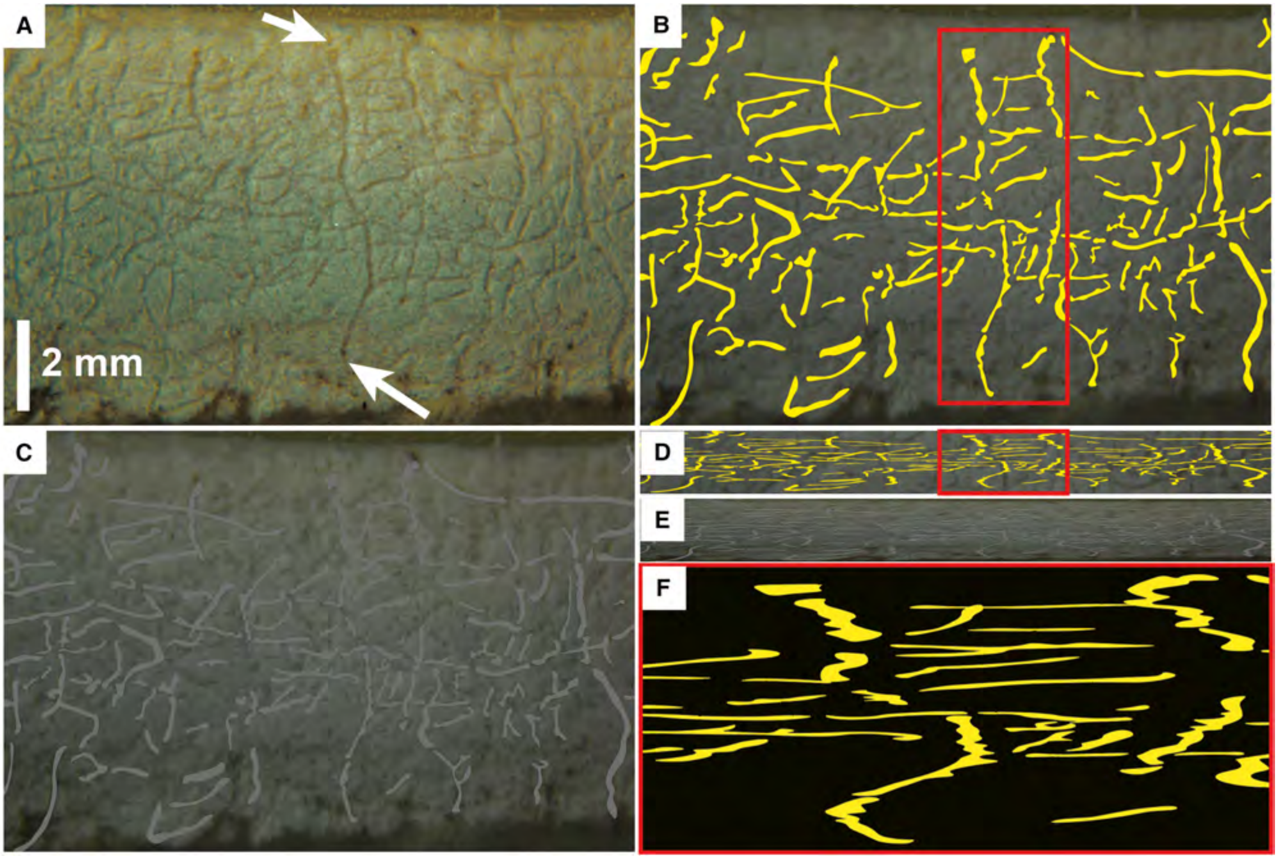


Fig. 8. (A) Experimental nematode burrows in a clay layer with 85 vol. % water content. (B) Tracing of these burrows as yellow outlines. The burrow tracing is intended to show the general burrow fabric, not every burrow visible. (C) The same as (B), but with the burrow outlines in grey. (D) and (E) Shows a version of (A) and (C) that has been vertically shortened in Adobe Photoshop™ to 15% of original thickness to simulate compaction. (F) Shows an enlarged version of the red outlined area from (D), which itself is a compacted version of the red outlined area in (B).

burrows that are subhorizontal become so flattened to be invisible in the absence of strong contrast to the surrounding matrix (Fig. 8E and F). It should also be noted that the burrows seen in Fig. 8A are those seen along the glass wall of the tank that contained the experiment. Due to ‘guidance’ by the glass wall the burrows are lined up in a plane, something that is highly unlikely in a sediment without such a ‘boundary’ condition. Therefore, to see burrows continuously in a section plane for more than 6 mm vertically (like the one marked by arrows in Fig. 8A) is highly improbable. Instead, because of the inevitable waviness of burrows, only short intercepts, probably at the millimetre-scale or shorter should be seen. If only millimetre long or shorter (pre-compaction) burrow sections were visible in a section plane, it seems highly unlikely that after compaction they should still be discernible in a contrast-poor substrate, such as a black shale.

Based on the above considerations, several visual criteria that suspected micro-burrows should meet in order to receive serious consideration can be specified. First, supposed burrows that extend for say 5 mm or more in a de-compacted image (vertically expanded to ‘bring back’ the initial water content of 80 vol. % or more), are highly unlikely in the case of actual burrows. Second, supposed burrow traces that are oriented at a high angle to bedding should have a wavy-compressed ptygmatic appearance (Fig. 8F). Third, is the width of subhorizontal burrow traces distinctly and systematically narrower than the width of burrows that are oriented at a high angle to bedding? Typical water contents of surface muds (80 vol. % or more) suggest that the width ratio between 'high-angle' and 'low-angle' burrows should be approximately 5 or higher. Fourth, do the burrow traces (like for example Fig. 7A') still resemble modern burrow systems (for example, Fig. 8) once they have been de-compacted (*sensu* Lobza & Schieber, 1999)? Of course, it would be too easy to cavalierly make light of the challenge to see traces in black shales in the first place. Could one for example argue that 'high-angle' burrows simply are easier to see because their width survives compaction (Fig. 8F), whereas 'low-angle' burrows become 'invisible' because they blend in with the secondary planar fabric that develops as a consequence of compaction? Yet, irrespective of these caveats, none of the perceived micro-burrow traces from the literature (Fig. 7), and none of the thin sections with visually analogous features that were examined for this study (see below) pass the 'compaction plausibility' filter defined above.

The compositional contrast perspective

To probe deeper with respect to shale fabrics, it is most helpful to examine polished surfaces of shales under the SEM for compositional as well as textural contrast between supposed burrows and the surrounding rock matrix. For example, in the case of the above-mentioned trace fossil *Phycosiphon incertus*, the burrow fill (faecal string) should be finer than the surrounding matrix (Wetzel & Bromley, 1994; Bednarz & McIlroy, 2009) and may show preferential pyritization of the burrow fill (Biddle *et al.,* 2021). Not having access to the specific thin sections shown in above publications (Fig. 7), thin sections in the collection of the IUSRL were examined for analogous features. From that search it appears that the features that Egenhoff & Fishman (2013) so eloquently described as 'Traces in the Dark' are rather ubiquitous in Phanerozoic (as well as older) black shales, and some examples are illustrated below.

The first example is a set of images (Fig. 9) from a black shale in the Middle Devonian Portwood Member of Kentucky. These shales were deposited in comparatively shallow water (Schieber & Lazar, 2004; Brett *et al.,* 2018) and thus to find bioturbation should not be considered implausible. It is indeed possible to convince oneself to see discontinuous 'wormy' features (Fig. 9A and B) in transmitted light, not unlike those shown by Egenhoff & Fishman (2013) and Ma *et al.* (2016). It should be noted in this context that all examples shown in this contribution were examined for 'traces' by multiple individuals, and that each person came up with a different set of 'traces' that only partially overlapped with that of other observers. In all but one example (Klein Naute Shale, Archean) only one set of traces is shown to avoid overcrowding the field of view.

If viewed under the SEM, the Portwood sample shows no apparent textural or compositional contrast between presumed burrows and surrounding matrix (Fig. 9C and D). High-contrast fabric elements, such as shreds of organic matter (black streaks in Fig. 9D) can be seen to pass through 'burrow' margins and entire 'burrows' (white arrows in Fig. 9D). Enlarged portions of Fig. 9D are shown in Fig. 9E and 9F and demonstrate clearly that presumed burrows are not associated with even the slightest change of texture and composition.

The second set of images (Fig. 10) is from the lower member of the Late Devonian Bakken Shale, a very organic-rich shale that occurs in the subsurface of North Dakota and Saskatchewan (Smith & Bustin, 1996). The third example is a set of images (Fig. 11) from the Jet Rock, a bituminous black shale of Toarcian age from the Yorkshire coast (Powell, 1984). A classical 'anoxic' black shale (Wignall, 1994), the Jet Rock nonetheless contains features that raise doubt about a complete absence of oxygen (Ghadeer & Macquaker, 2011; Trabucho-Alexandre, 2014).

As in Figs 9 and 10, once viewed under the SEM, there is no textural or compositional contrast between presumed burrows and surrounding matrix. High-contrast fabric elements, such as shreds of organic matter (black streaks in Fig. 11E and F) can be seen to pass through 'burrow' margins and entire 'burrows' (white arrows in Fig. 11D, and more closely viewable in enlarged frames E and F). To further document this characteristic, additional examples from the Ohio Shale (Late Devonian of Kentucky) and the lower Silurian Longmaxi Shale (lower Silurian of Sichuan, China) are shown in Figs 12 and 13, respectively, with the same results. At the locations of purported 'burrows' there is no indication of textural and compositional contrast between 'burrows' and shale matrix when polished surfaces are imaged by SEM.

Thus, although one may see in Figs 9 to 13 potential micro-burrows in black shales of an age where burrowing metazoans were known to colonize the seafloor, and where sedimentological studies suggest potential for shallow benthic

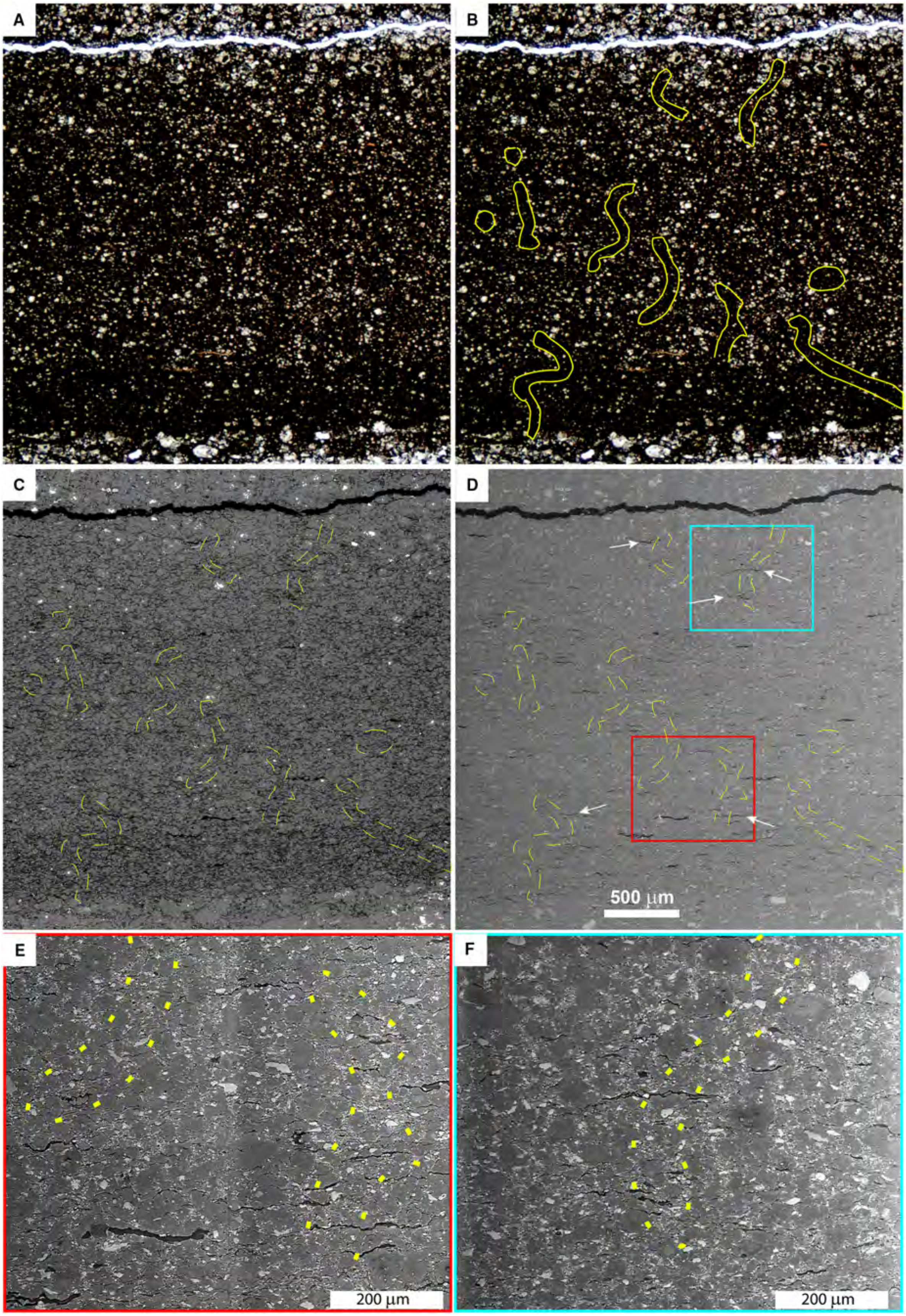

A
B
C
D
500 μm
E
200 μm
F
200 μm

Fig. 9. Potential micro-burrows in Portwood black shale. (A) Transmitted light image; (B) Same image with potential burrows marked with yellow outlines. (C) The exact same field of view under the scanning electron microscope (SEM) in backscatter electron (compositional) mode, and (D) the appearance in secondary electron (topographic) mode. Because the SEM was operated in low-vacuum mode there is additional textural information via charge contrast imaging. In (C) and (D) the location of presumed burrows from (B) has been transposed as dashed yellow lines. The scale bar in (D) also applies to images (A) to (C). The red and blue frames in (D) are enlarged in (E) and (F), respectively, in order to show more clearly that there is no textural or compositional contrast between the sites of purported burrows (yellow dotted outlines) and the surrounding shale matrix.

colonization, the 'burrows' are only seen in transmitted light. The 'burrows' cannot be recognized on polished surfaces from the exact same part of the sample.

The image comparison between what can be observed in transmitted light, and what is visible under the SEM (Figs 9 to 13) shows clearly that, whereas light microscopy is an indispensable tool of shale petrography, it also has its limitations. Although it is perfectly acceptable and indeed de rigueur to suspect the presence of burrowing organisms from features seen in thin sections, such suspicions need to be validated carefully and independently. Examination of shale and mudstone fabrics is the natural domain of electron microscopy, and observations of rock fabric via SEM readily shows details at such clarity (Figs 9 to 13) that it is the logical next step in such an investigation. Given that meiofaunal benthos consists of organisms that are of similar size to the sediment particles that surround them, their effect on the fabric of their rather fluid substrate may more typically be displacement and mixing of particles rather than outright development of burrows with limited preservation potential and likelihood of extreme compaction. Grain-scale fabric modification by meiofauna may well be the next level (beyond formation of micro-burrows) of subtlety in benthic colonization of muddy substrates and is a topic that needs future attention.

The evolutionary perspective

If one were to follow this logic a bit further, one might ask if micro-burrows should not at least be absent from thin sections of Precambrian shales because mobile eukaryotes are not known from rocks of such antiquity. Yet, a survey of thin sections from Proterozoic black shales illustrates (Figs 14 and 15) that features that resemble presumed micro-burrows as seen in younger rocks (Figs 7 and 9 to 13) are present, nonetheless. Whereas the examples in Fig. 14 are from thin sections with a cover glass, and thus could not be examined by SEM, a Proterozoic sample from the Velkerri Formation of Australia (Fig. 15) was polished and examined by SEM. Figure 15 shows 'traces' that can be outlined (Fig. 15B) and, just as in all other samples where polished surfaces were examined, the SEM images do not show compositional or textural contrasts that coincide with the location of purported traces. In fact, high-contrast fabric elements, such as shreds of organic matter (seen as black streaks in Fig. 15C and D) can be seen to pass through 'burrow' margins and entire 'burrows' (pointed out with white arrows in Fig. 15D).

To find textural analogues of presumed micro-burrows in black shales deposited long before the evolution of animals (Figs 14 and 15) is troubling. It definitely suggests that the 'traces' may have an origin that is not related to actual organisms disturbing the sediment fabric. Of course, a sensation might be indicated instead – that generations of geologists were oblivious to the presence of metazoan benthos in the Proterozoic. Given that eukaryotes evolved in the Proterozoic (Knoll *et al.,* 2006), might equivalents to protists that disturb modern muds (Pike *et al.,* 2001; Bernhard *et al.,* 2003; Löhr & Kennedy, 2015) already have inhabited the Proterozoic seabed?

Yet, even under above nonconformist assumption, trace makers of that type should surely be absent from shales as old as Archean, or so one would think. To follow up on that prospect, a shale sample from the Late Archean Klein Naute Formation of South Africa (Ostrander *et al.,* 2020) was examined (Fig. 16) for features that resembled those seen in Figs 7 to 13. The fact that features that appear analogous to perceived micro-burrows in younger rocks can be observed in that sample (Fig. 16) does give pause. That they appear texturally so similar to younger 'traces' (Fig. 16B) – even more so.

The tracings in Fig. 16D are what one can consider a blind test, because the individuals doing the tracing were simply given the task to outline shapes that in other studies had been considered cryptic bioturbation features. They did not know the age of the sample, and thus offered no 'resistance' to the idea that one might indeed expect to find micro-burrows in these rocks. Note in Fig. 16D that although some identified features overlap between individuals, there is considerable disagreement between the three sets of 'traces', suggesting a definite subjective component to their identification. Given the age of the shale in Fig. 16C, one might be inclined to end the quest at this point and simply attribute all aforementioned efforts at 'seeing' traces (Figs 7 and 9 to 13) to irrational exuberance. The issue at hand, however, is too important to be dismissed lightly.

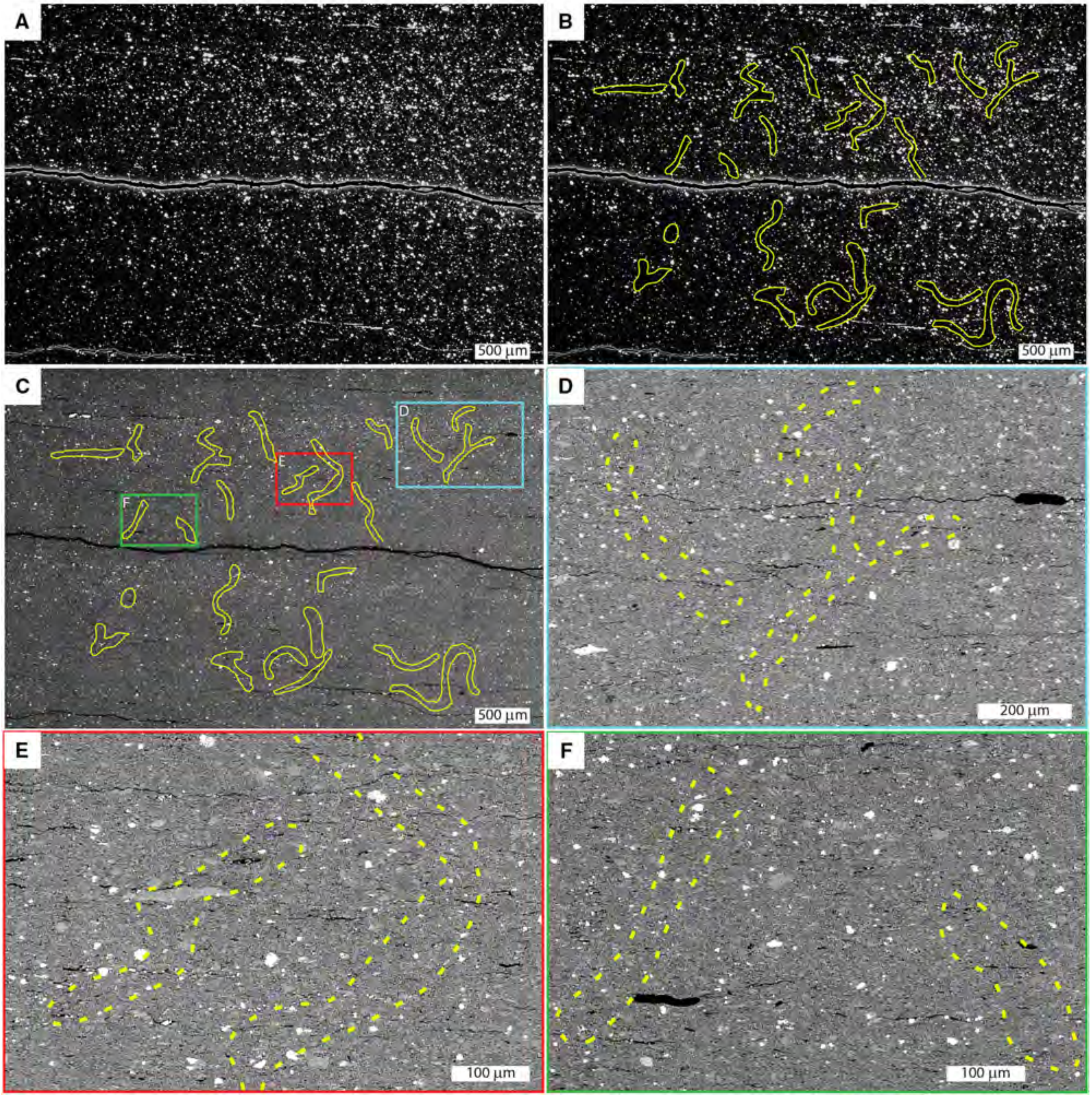


Fig. 10. Potential micro-burrows in the Late Devonian Bakken Shale. (A) Transmitted light image; (B) same image with potential burrows marked with yellow outlines. (C) The exact same field of view under the scanning electron microscope (SEM) in backscatter electron (compositional) mode with burrows marked with yellow outlines. The blue, red and green frames in (C) are shown enlarged in (D) to (F) and highlight the fact that the rock fabric and composition inside and outside the marked 'burrow' locations (yellow dotted outlines) is indistinguishable. Larger fabric elements, such as streaks of organic matter pass through the 'burrows' uninterrupted.

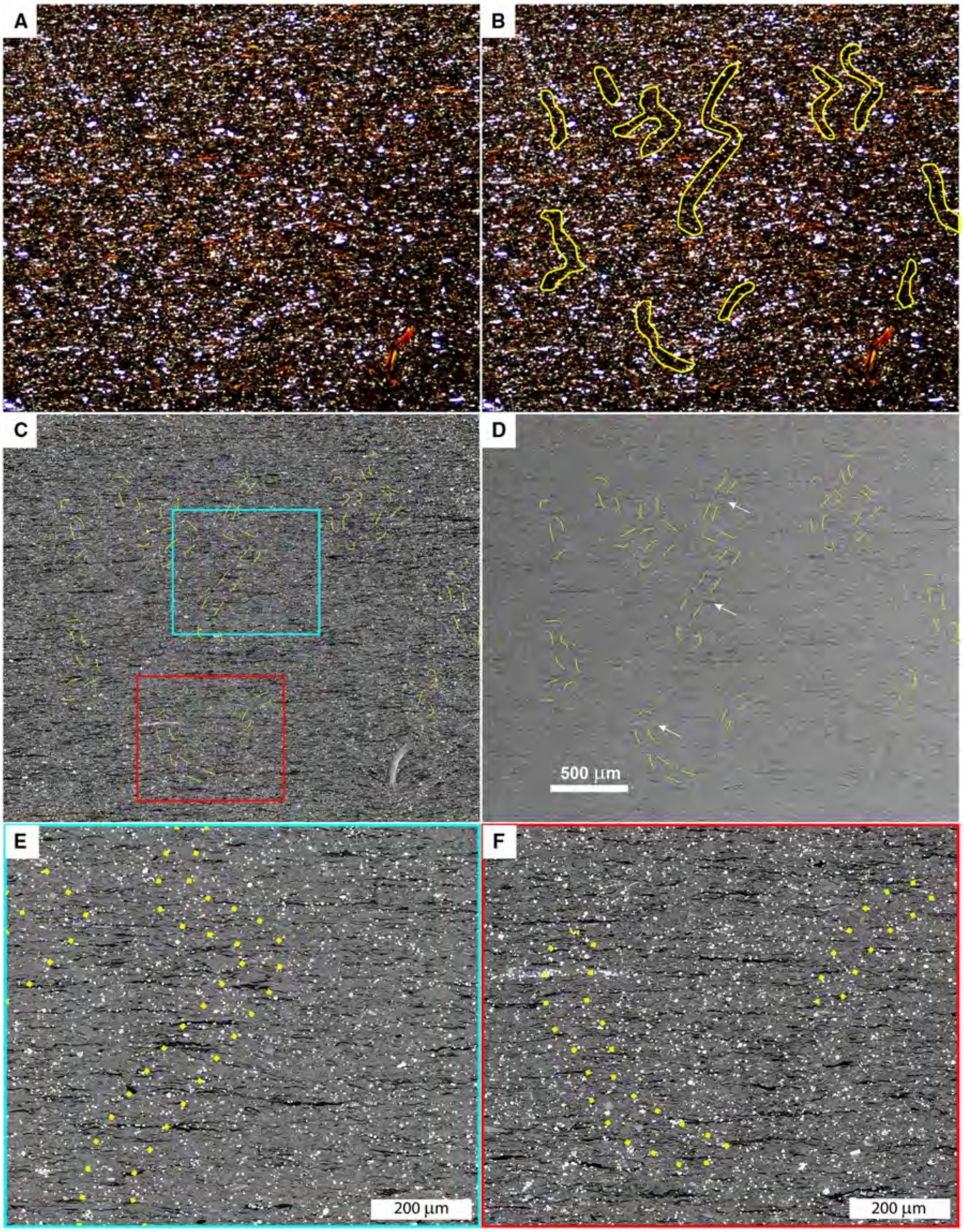


Fig. 11. Potential micro-burrows in the Toarcian Jet Rock. (A) Transmitted light image; (B) same image with potential burrows marked with yellow outlines. (C) The exact same field of view under the SEM in backscatter electron (compositional) mode, and (D) the appearance in secondary electron (topographic) mode. Fabric elements that pass through presumed burrows are marked with white arrows. Because the SEM was operated in low-vacuum mode there is additional textural information via charge contrast imaging. In (C) and (D) the location of presumed burrows from (B) has been transposed as dashed yellow lines. The scale bar in (D) also applies to images (A) to (C). The blue and red frames in (D) are enlarged as (E) and (F), respectively, in order to show more clearly that there is no textural or compositional contrast between the sites of purported burrows (yellow dotted outlines) and the surrounding shale matrix.

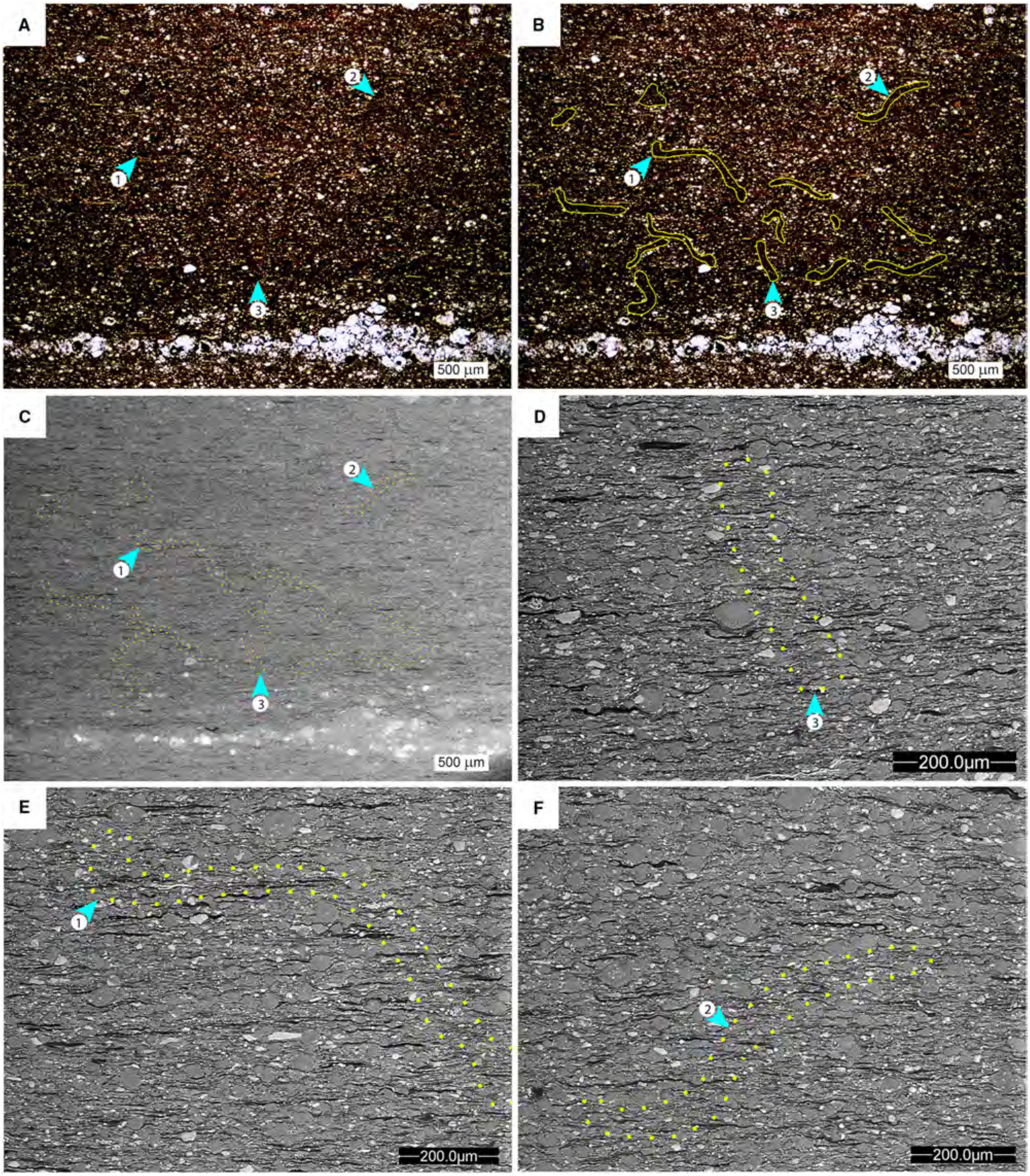


Fig. 12. Potential micro-burrows in a sample of Ohio Shale (Late Devonian of Kentucky). (A) Transmitted light image; (B) same image with potential burrows marked with yellow outlines. (C) The exact same field of view under the scanning electron microscope (SEM) in backscatter electron (compositional) mode, and (D) the appearance in secondary electron mode, with the location of presumed burrows from (B) transposed as dashed yellow lines. Three of these have been marked with blue arrows 1, 2 and 3 for closer inspection in (D) to (F). Because the SEM was operated in low-vacuum mode there is additional textural information via charge contrast imaging. (D) to (F) show enlarged versions of the 'burrows' marked with arrows 1 to 3 in (D). They show clearly that there is no textural or compositional contrast between the sites of purported burrows (yellow dotted outlines) and the surrounding shale matrix.

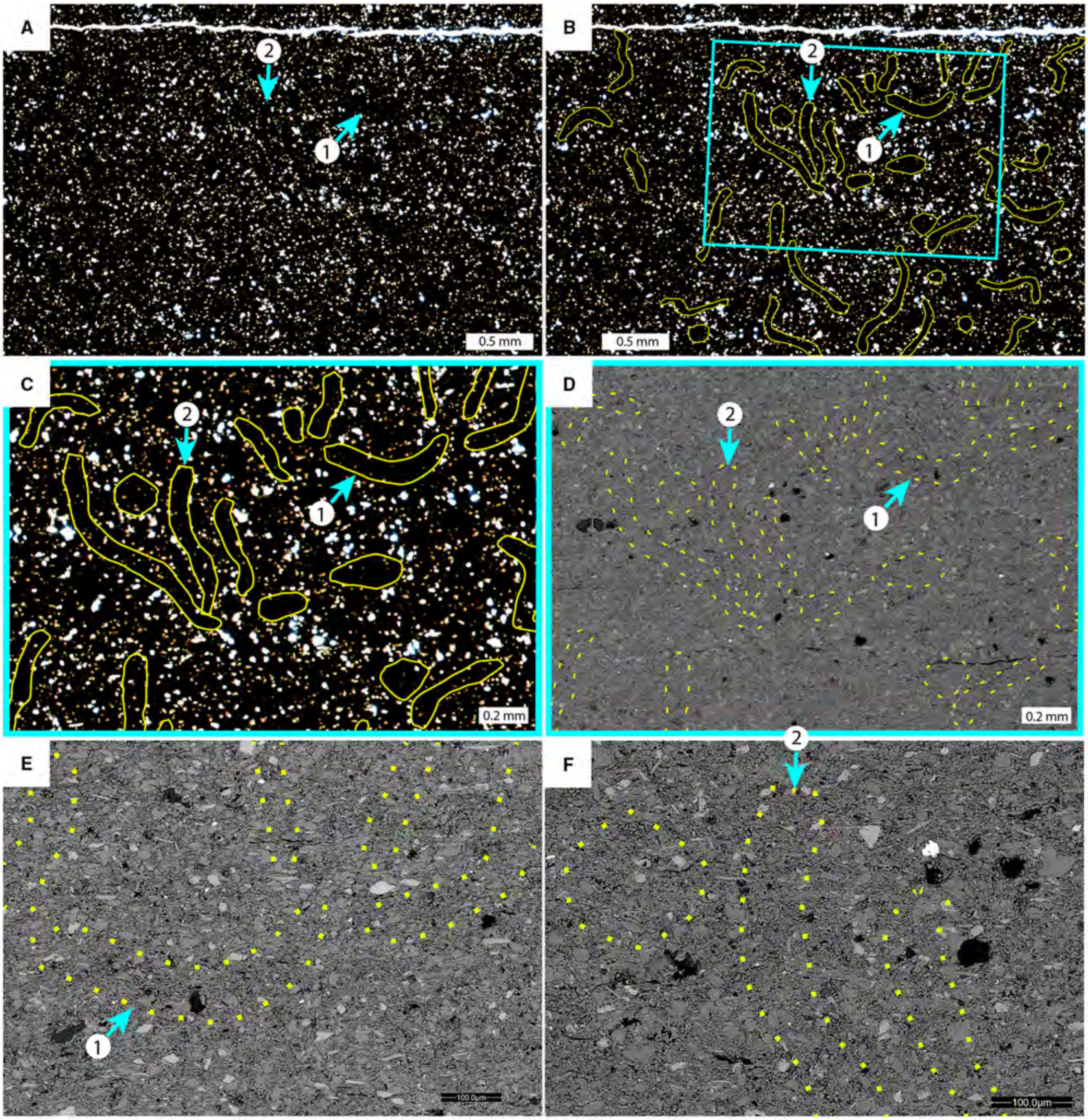


Fig. 13. Potential micro-burrows in a sample of carbonaceous Longmaxi Shale (lower Silurian, Sichuan, China). (A) Transmitted light image; (B) same image with potential burrows marked with yellow outlines. The blue frame marks the area of the thin section that was imaged at higher resolution with the scanning electron microscope (SEM). The numbered blue arrows mark 'burrows' that are shown in detail in (E) and (F). (C) The transmitted light view of the blue framed area in (B), with all markings transposed exactly. (D) The same field of view as in (C) but imaged by SEM in backscatter mode. The dark spots are areas of the surface that were plucked during polishing, on account of the rather soft nature of this sample. Presumed burrows marked with arrows 1 and 2 are shown at higher magnification in (E) and (F), respectively. As in other image sets, there is no textural or compositional contrast between the sites of purported burrows (yellow dotted outlines) and the surrounding shale matrix.

Another aspect that should be mentioned here is that, unlike soft-bodied organisms that are causing much of the macroscopic bioturbation (e.g. Bromley, 1996), a subset of meiofaunal trace makers does have preservable hard parts. Thus, an added criterion for the potential

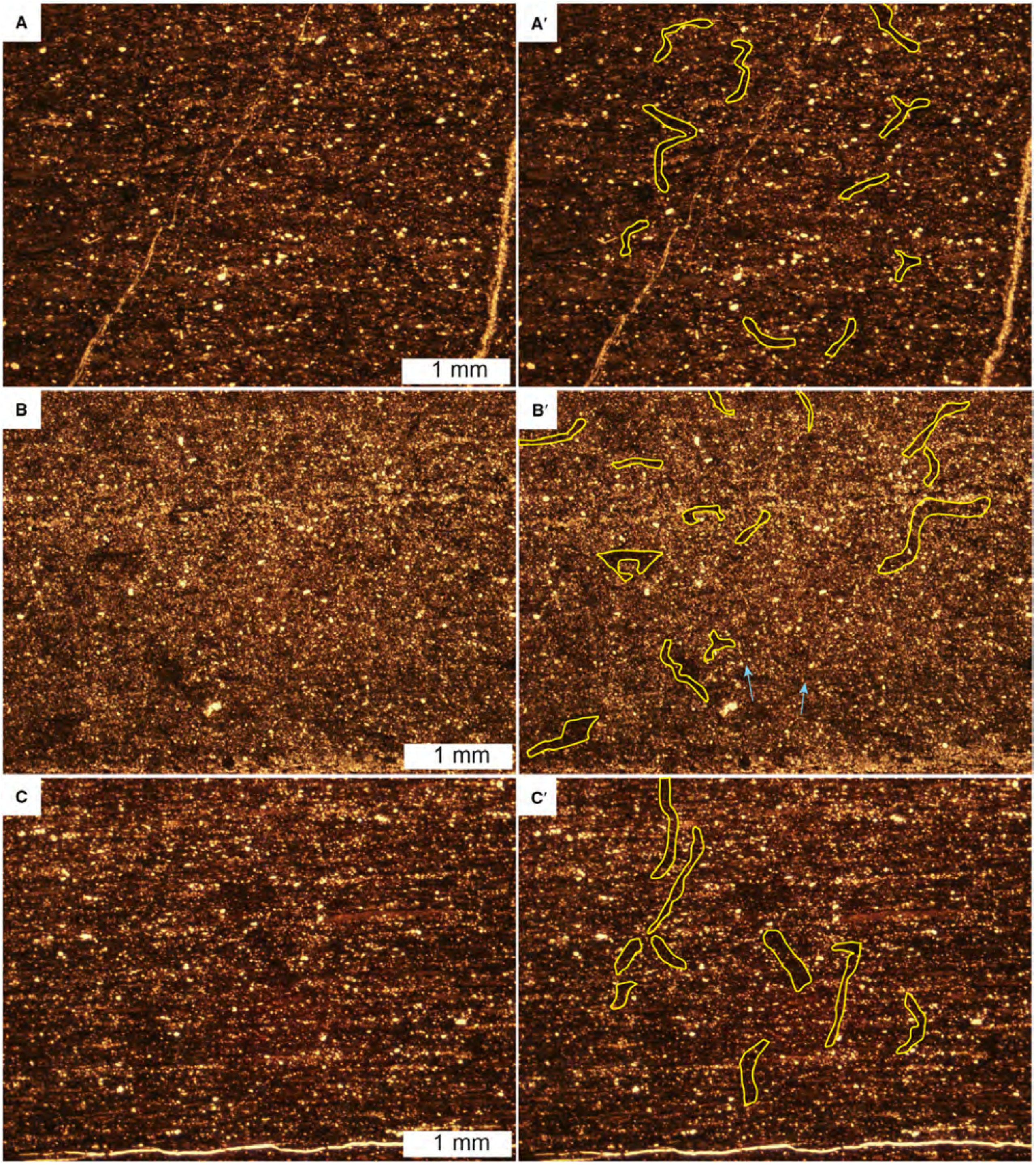


Fig. 14. A collection of transmitted light photomicrographs from Proterozoic black shales that show features (outlined in yellow at right) that resemble micro-burrows as shown in Figs 7 and 9 to 13. (A) and (A′) are from the Belt Series of the US; (B) and (B′) are from the Gunpowder Formation of Australia (blue arrows point to likely scratches); (C) and (C′) are from the Rampur Shale of India.

presence of microscopic benthic trace makers would be to look, for example, for tests of calcareous and agglutinated benthic foraminifera and scolecodonts (Hinde, 1880; Hints & Eriksson, 2007; Milliken *et al.,* 2007; Schieber, 2009; Dashtgard & MacEachern, 2016).

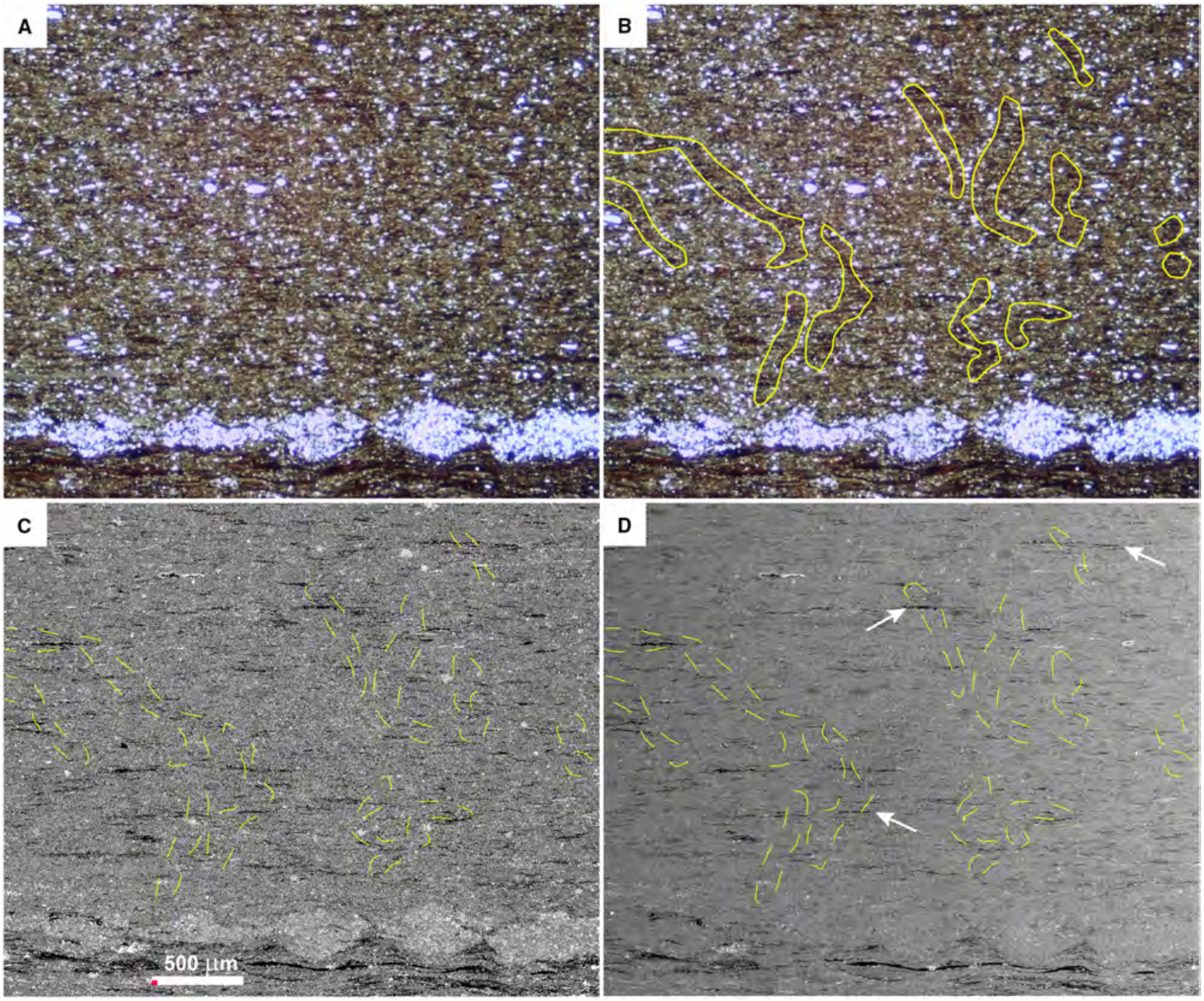


Fig. 15. Potential micro-burrows in Velkerri Formation black shale (Proterozoic, Australia). (A) Transmitted light image of polished thin section; (B) same image with potential burrows marked with yellow outlines. (C) The exact same field of view under the scanning electron microscope (SEM) in backscatter electron mode, and (D) the appearance in secondary electron (topographic) mode. Because the SEM was operated in low-vacuum mode there is additional textural information via charge contrast imaging. In (C) and (D) the location of presumed burrows from (B) has been transposed as dashed yellow lines. The scale bar in (C) also applies to the other images in this figure. As in other image sets, there is no textural or compositional contrast between the sites of purported burrows (yellow dotted outlines) and the surrounding shale matrix. Larger fabric elements, such as black streaks of organic matter – pointed out with white arrows in (D) – pass through the 'burrows'.

The double polish perspective

Given above elaborations on artifacts that cause darkening in transmitted light, and in view of the fact that the purported micro-burrows seem to occur in black shales of all ages, one has to wonder whether the 'traces' are actually a signal coming from the rock itself, or whether they are due to defects on the underside of the rock slice that cause darkening patterns that can be misinterpreted as burrows. Seeing that polished surfaces in Figs 9 to 15 do not show any textural and compositional anomalies that correlate to the location of purported burrows, with fabric elements passing right through presumed traces, suggests a possible test for the 'defect hypothesis', namely the preparation of double polished thin sections for comparison with standard polished thin sections from the same sample. This test was conducted for four

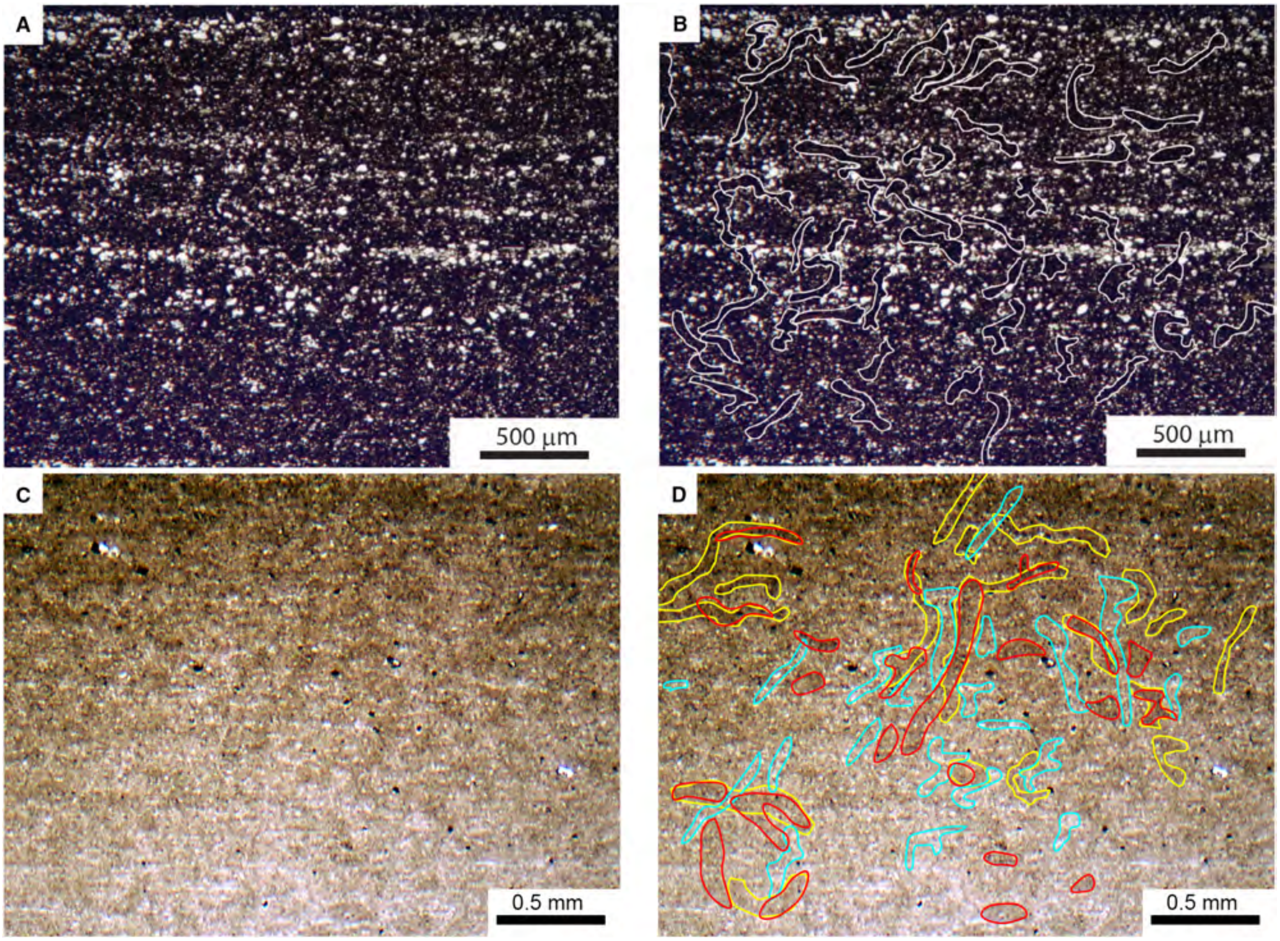
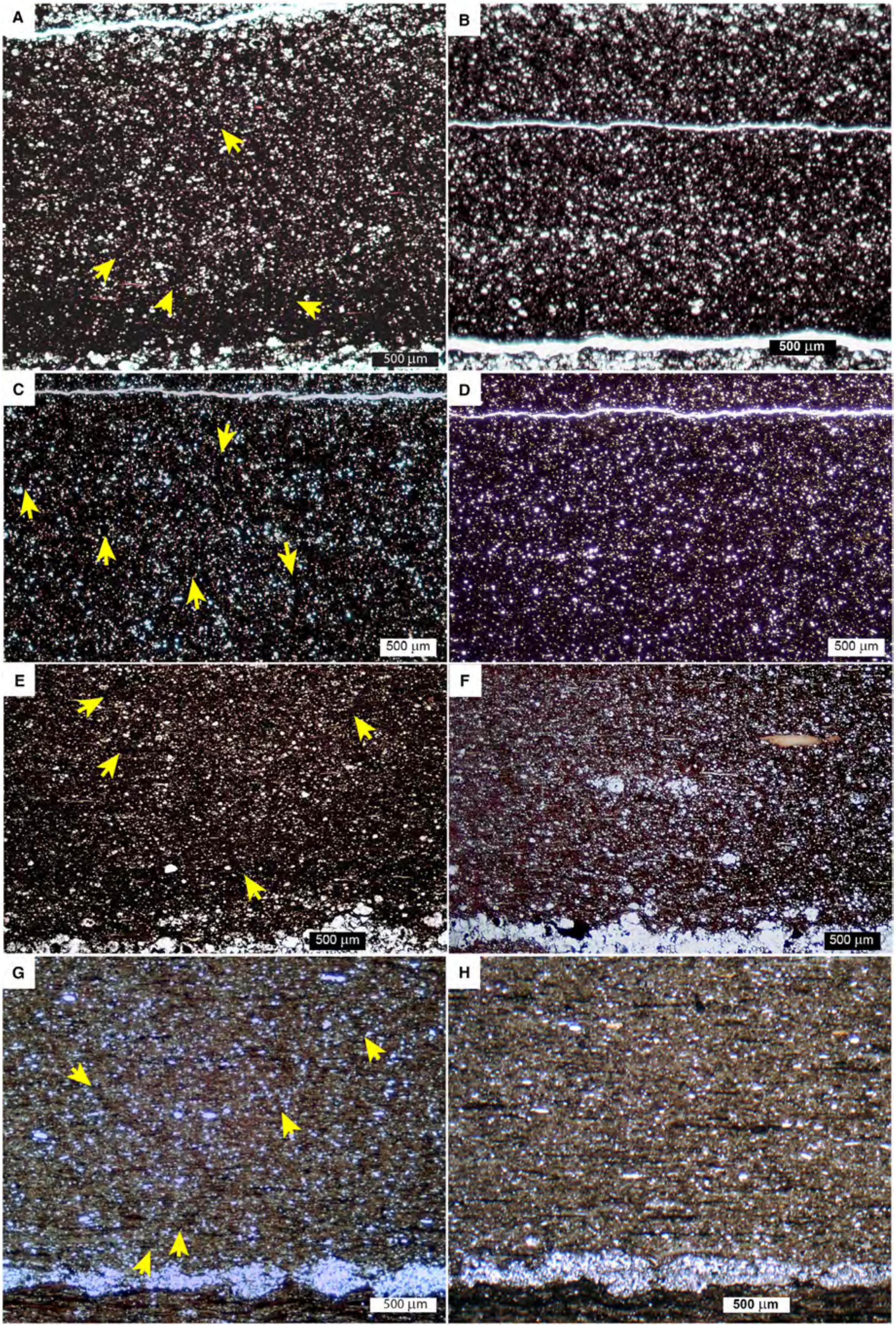


Fig. 16. Juxtaposing young versus very old traces. (A) Transmitted light image of Late Devonian Bakken black shale, with (B) showing 'traces' as envisioned by Egenhoff & Fishman (2013). (C) A textural analogue from the Late Archean Klein Naute Shale of South Africa with 'tracing' of comparable features (D). The different coloured (yellow, red, blue) sets of 'traces' in the Archean example were generated by three different individuals.

samples (Fig. 17). The sample from the Proterozoic Velkerri Formation of the McArthur Group in Australia (Fig. 15), the Devonian Portwood sample from Fig. 9, the Ohio Shale sample from Fig. 12 and the Longmaxi Shale sample from Fig. 13.

In three of the single versus double polished thin section pairs (Ohio Shale, Longmaxi Shale

Fig. 17. Four examples of the difference between single polished (left column) and double polished thin sections (right column). Top row shows photomicrographs from the sample of Portwood Shale introduced in Fig. 9. (A) Single polish image, some of the 'traces' are marked with yellow arrows. (B) A double polish photomicrograph for comparison. Second row, Longmaxi Shale introduced in Fig. 13. (C) Single polish image, some of the 'traces' are marked with yellow arrows. (D) A double polish photomicrograph for comparison. The third row shows photomicrographs from Ohio Shale sample introduced in Fig. 12. (E) Single polish image, some of the 'traces' are marked with yellow arrows. (F) A double polish photomicrograph for comparison. The bottom row shows photomicrographs from the Velkerri Shale sample introduced in Fig, 15. (G) Single polish image, some of the 'traces' are marked with yellow arrows. (H) A double polish photomicrograph for comparison. In all four cases, irregular-curved darkened features (interpreted as 'traces' in multiple publications) as shown in Figs 7 and 9 to 16, can be seen in the photomicrographs from single polished thin sections, and are no longer visible in photomicrographs of the same layer from double polished thin sections.


A
500 µm
B
500 µm
C
500 µm
D
500 µm
E
500 µm
F
500 µm
G
500 µm
H
500 µm

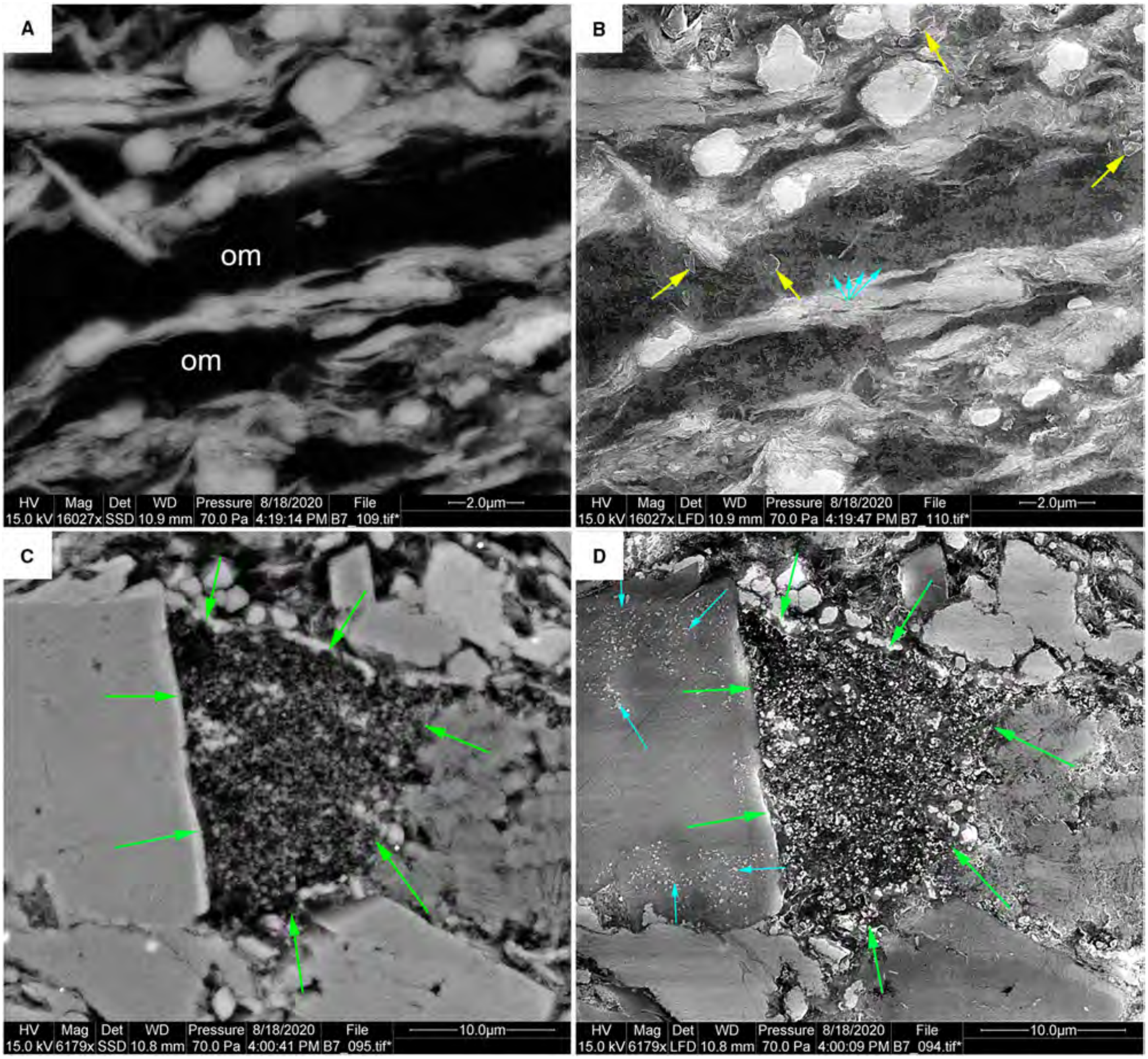


Fig. 18. Examples of sub-optimal polished shale samples. The image pair in the upper row shows (A) shale fabric in SEM backscatter mode, and (B) in secondary electron mode. In (A) the dark material is organic matter (OM) and looks solidly black when imaged with backscatter. In (B) a grey coating (blue arrows) is visible on the OM surfaces that consists of finely ground up rock and abrasive. Larger abrasive particles on the surface are marked with yellow arrows. These features do not show up in backscatter because most of the backscatter signal comes from below the surface. The image pair in the lower row also shows a backscatter image on the left and a secondary electron image on the right. (C) A plucked depression is filled with polishing debris (green arrows) that is texturally distinct from the sample at large. (D) The filled depression also looks texturally distinct in secondary electron mode. In secondary electron mode debris on mineral surfaces shows up readily (blue arrows) but is not visible in backscatter mode because the signal comes from below the surface.

and Velkerri Formation), the second, double polished thin section, is physically removed from the original single polished section by a mere 3 mm, and the photomicrographs show the same layer in the rock sample (Fig. 17). In the case of the double polish comparison for the Portwood sample, the original (single polish) and the second thin section (double polish) were also prepared from the same block of sample material but are separated by about 10 to 15 mm. Fractures at a low angle to bedding make the two sections (Fig. 17A and B) appear somewhat different, but Fig. 17A and B show the same layer of sediment.

Whereas the single polished sections in Fig. 17 (left column) all show the irregular-curved darkened features that are the focus of this paper, the double polished sections (Fig. 17, right column) no longer show them, confirming the above supposition that the presumed burrows must indeed relate to damage to the underside of the section.

Double polished images can also have other 'benefits', such as enhancing subtle internal layering (Fig. 17B), and making the sample look more 'silty' (Fig. 17F). The latter is a matter of better light transmission for coarse silt grains when both sides of the grain have a good polish. Nonetheless, because polishing a thin section still is a mechanical process, damage and plucking may still occur and produce artifacts, especially in soft and fragile samples. Having examined many polished thin sections by SEM over the years, the experience is that this damage is relatively easy to identify (Fig. 18), although it may not be very obvious topographically because it tends to get filled with caked-on debris (Fig. 18) during polishing. Making double polished sections definitely helps in the detection of artifacts that can give rise to pseudo-burrows when viewed with an optical microscope. Yet, for more definite assessment purported micro-burrows should whenever possible be examined by SEM on polished surfaces, so as to verify whether there are changes of fabric and composition that are consistent with micro-burrows. For samples where the definitive detection of burrows may be of paradigm-shifting importance, it may be necessary to avoid mechanical damage to the sample surface by using large format argon ion milling to produce polishes of exquisite clarity (e.g. Schieber, 2013; Schieber *et al.,* 2016; Li *et al.,* 2021).

CONCLUSIONS

This exposition of thin section artifacts as a plausible cause for perceived micro-burrows in black shales should not detract from the very real possibility that a given black shale in the rock record may have been bioturbated in subtle ways. There are enough studies to show this (Ekdale & Mason, 1988; Savrda & Bottjer, 1989; Kauffman & Sageman, 1990; Lobza & Schieber, 1999; Schieber, 2003; Lazar *et al.,* 2015; Löhr & Kennedy, 2015; Wilson & Schieber, 2015), as well as illustrating that recognition may require substantial effort and specialized techniques for visualization, such as micro-CT-scans (Spaw, 2012, 2013).

Because postulating bioturbation significantly changes the palaeoenvironmental interpretation of a given black shale stratum, it exhorts us to back up claims of bioturbation with observations that can support such claims. A potential protocol might be to first look at the back of the thin section to look for obvious damage, and air bubble-related features that could reduce light transmission. The next step should be to look for compaction effects (Fig. 8) and determine whether the observed burrow diameters are consistent with compaction of a very water-rich sediment (Fig. 8; 'compaction plausibility' filter). If uncertainty remains at this point, and assuming that the section is polished already, it should be examined by SEM, covering the same field of view as captured by photomicrographs in which potential micro-burrows were detected (Figs 9 to 15). If burrows are real, there should be some textural and compositional difference between purported burrows and their matrix. It should be standard operating procedure to verify fabric-scale speculations from optical microscopy with a follow-up SEM examination of rock fabrics. The presence of hard parts of benthic meiofauna in shales with potential micro-burrows can be considered a supporting argument for their identification; and, finally, if one wants to certify that damage to the underside of the thin section is the likely cause of darkened 'traces' that were initially interpreted as micro-burrows, a double sided polished thin section can be prepared to examine that issue (Fig. 17).

That micro-burrows in black shales are a possibility to be cognizant of is quite plausible if one considers observations from modern oxygen-stressed environments. However, due to the significance of such a finding with respect to palaeoenvironmental assessment, it is highly advisable to thoroughly scrutinize the samples (as summarized above) to avoid making claims that cannot be substantiated subsequently.

ACKNOWLEDGEMENTS

That thin sections can have exasperating artifacts has long been par for the course in the pursuit of shale petrography, and for many years the assumption was that everyone simply 'knew'. Though there never seemed to be an urgent need to put this into a publication, the time has come, and it seems now to be fitting (to paraphrase Yogi Berra) to thank everybody that made this paper necessary, and the many students that I berated over the years to be critical of the things they 'thought' they saw in thin sections. Their sufferings were not in vain after all. Being an impromptu project that simply mushroomed from meandering discussions on petrographic philosophy, there is no underlying grant proposal, but funding in the broadest sense was provided by the sponsors of the IU Shale Research Consortium (Anadarko, Chevron, ConocoPhillips, ExxonMobil, Shell, Statoil, Marathon, Whiting and Wintershall). A National Science Foundation equipment grant to J. Schieber (EAR-0318769) provided funds for the purchase of the analytical SEM that was used to acquire SEM images for this article. The paper also benefited from constructive suggestions by Joao Trabucho-Alexandre and two anonymous reviewers.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

Anderson, R.Y. and **Dean, W.E.** (1988) Lacustrine varve formation through time. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **62**, 215–235.

Bednarz, M. and **McIlroy, D.** (2009) Three-Dimensional reconstruction of "Phycosiphoniform" burrows: implications for identification of trace fossils in core. *Palaeontol. Electron.*, **12**, 12.3.13A.

Bernhard, J.M., **Visscher, P.T.** and **Bowser, S.S.** (2003) Submillimeter life positions of bacteria, protists, and metazoans in laminated sediments of the Santa Barbara Basin. *Limnol. Oceanogr.*, **48**, 813–828.

Biddle, S.K., **LaGrange, M.T.**, **Harris, B.S.**, **Fiess, K.**, **Terlaky, V.** and **Gingrass, M.** (2021) A fine detail physico-chemical depositional model for Devonian organic-rich mudstones: A petrographic study of the Hare Indian and Canol Formations, Central Mackenzie Valley. *Northwest Territories. Sed. Geol.*, **414**, 105838.

Borcovsky, D., **Egenhoff, S.**, **Fishman, N.**, **Maletz, J.**, **Boehlke, A.** and **Lowers, H.** (2017) Sedimentology, facies architecture, and sequence stratigraphy of a Mississippian black mudstone succession: The upper member of the Bakken Formation, North Dakota, United States. *AAPG Bull.*, **101**, 1625–1673.

Brett, C.E., **Zambito, J.J.**, **Baird, G.C.**, **Aboussalam, Z.S.**, **Becker, R.T.** and **Bartholomew, A.J.** (2018) Litho-, bio-, and sequence stratigraphy of the Boyle-Portwood Succession (Middle Devonian, Central Kentucky, USA). *Paleobiodivers. Paleoenviron.*, **98**, 331–368.

Breyer, J. (2012) *Shale Reservoirs: Giant Resources for the 21st Century. AAPG Memoir 97*, AAPG, Tulsa, OK, 519 pp,

Breyer, J. (2016) *The Eagle Ford Shale: A Renaissance in US Oil Production. AAPG Memoir 110*, AAPG, Tulsa, OK, 389 pp.

Bromley, R.G. (1996) *Trace Fossils: Biology, Taphonomy and Applications*. Chapman and Hall, London, 361 pp.

Camp, W., **Diaz, E.** and **Wawak, B.** (2013) *Electron Microscopy of Shale Hydrocarbon Reservoirs. AAPG Memoir 102*, AAPG, Tulsa, OK, 293 pp.

Conrad, K. (1958) *Die beginnende Schizophrenie. Versuch einer Gestaltanalyse des Wahns* [The commencing schizophrenia. Trial on a gestalt analysis of delusion]. Georg Thieme Verlag, Stuttgart, 165 pp.

Dashtgard, S.E. and **MacEachern, J.A.** (2016) Unburrowed mudstones may record only slightly lowered oxygen conditions in warm, shallow basins. *Geology*, **44**, 371–374.

DeReuil, A.A. and **Birgenheier, L.P.** (2019) Sediment dispersal and organic carbon preservation in a dynamic mudstone dominated system, Juana Lopez Member, Mancos Shale. *Sedimentology*, **66**, 1002–1041.

Egenhoff, S.O. and **Fishman, N.S.** (2013) Traces in the dark−Sedimentary processes and facies gradients in the upper shale member of the Upper Devonian-Lower Mississippian Bakken Formation, Williston Basin, North Dakota, USA. *J. Sed. Res.*, **83**, 803–824.

Ekdale, A.A. and **Mason, T.R.** (1988) Characteristic trace-fossil associations in oxygen-poor sedimentary environments. *Geology*, **16**, 720–723.

Eysenck, M.W. and **Keane, M.T.** (2005) *Cognitive Psychology: A Student's Handbook*. Psychology Press, Hove, 656 pp.

Ghadeer, S.G. and **Macquaker, J.H.** (2011) Sediment transport processes in an ancient mud-dominated succession: a comparison of processes operating in marine offshore settings and anoxic basinal environments. *J. Geol. Soc.*, **168**, 1121–1132.

Gould, S.J. (1985) *The Flamingo's Smile: Reflections in Natural History*. W.W. Norton & Co., New York, NY, 476 pp.

Hinde, G.J. (1880) On annelid jaws from the Wenlock and Ludlow formations of the west of England. *Q. J. Geol. Soc.*, **36**, 368–378.

Hints, O. and **Eriksson, M.E.** (2007) Diversification and biogeography of scolecodont-bearing polychaetes in the Ordovician. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **245**, 95–114.

Kauffman, E.G. and **Sageman, B.B.** (1990) Biological sensing of benthic environments in dark shales and related oxygen-restricted facies. In: *Cretaceous Resources, Events and Rhythms: Background and Plans for Research* (Eds Ginsburg, R.N. and Beaudoin, B.), pp. 121–138.Springer, Dordrecht.

Knoll, A.H., **Javaux, E.J.**, **Hewitt, D.** and **Cohen, P.** (2006) Eukaryotic organisms in Proterozoic oceans. *Philos. Trans. R. Soc. Lond., B. Biol. Sci.*, **361**, 1023–1038.

Lazar, O.R., **Bohacs, K.M.**, **Schieber, J.**, **Macquaker, J.H.S.** and **Demko, T.M.** (2015) *Mudstone Primer: Lithofacies Variations, Diagnostic Criteria, and Sedimentologic-stratigraphic Implications at Lamina to Bedset Scale. SEPM Concepts in Sedimentology and Paleontology*, **12**, SEPM, 205 pp.

Li, Z., **Schieber, J.** and **Pedersen, P.K.** (2021) On the origin and significance of composite particles in mudstones: examples from the Cenomanian Dunvegan Formation. *Sedimentology*, **68**, 737–754.

Lobza, V. and **Schieber, J.** (1999) Biogenic sedimentary structures produced by worms in soupy, soft muds; observations from the Chattanooga Shale (Upper Devonian) and experiments. *J. Sed. Res.*, **69**, 1041–1049.

Löhr, S.C. and **Kennedy, M.J.** (2015) Micro-trace fossils reveal pervasive reworking of Pliocene sapropels by low-oxygen-adapted benthic meiofauna. *Nat. Commun.*, **6**, 1–8.

Ma, Y., **Fan, M.**, **Lu, Y.**, **Guo, X.**, **Hu, H.**, **Chen, L.**, **Wang, C.** and **Liu, X.** (2016) Geochemistry and sedimentology of the Lower Silurian Longmaxi mudstone in southwestern China: implications for depositional controls on organic matter accumulation. *Mar. Petrol. Geol.*, **75**, 291–309.

Mattson, M.P. (2014) Superior pattern processing is the essence of the evolved human brain. *Front. Neurosci.*, **8**, 265.

Migniot, C. (1968) Etude des propriétés physiques de différents sédiments très fins et de leur comportement sous des actions hydrodynamiques. *La Houille Blanche*, **7**, 591–620.

Milliken, K., **Choh, S.J.**, **Papazis, P.** and **Schieber, J.** (2007) “Cherty” stringers in the Barnett Shale are agglutinated foraminifera. *Sed. Geol.*, **198**, 221–232.

Naruse, H. and **Nifuku, K.** (2008) Three-Dimensional morphology of the ichnofossil *Phycosiphon incertum* and its implication for paleoslope inclination. *Palaios*, **23**, 270–279.

Ostrander, C.M., **Kendall, B.**, **Olson, S.L.**, **Lyons, T.W.**, **Gordon, G.W.**, **Romaniello, S.J.**, **Zheng, W.**, **Reinhard, C.T.**, **Roy, M.** and **Anbar, A.D.** (2020) An expanded shale δ^{98}Mo record permits recurrent shallow marine oxygenation during the Neoarchean. *Chem. Geol.*, **532**, 119391.

Pike, J., **Bernhard, J.M.**, **Moreton, S.G.** and **Butler, I.B.** (2001) Microbioirrigation of marine sediments in dysoxic environments: implications for early sediment fabric formation and diagenetic processes. *Geology*, **29**, 923–926.

Powell, J.H. (1984) Lithostratigraphical nomenclature of the Lias Group in the Yorkshire Basin. *Proc. York. Geol. Soc.*, **45**, 51–57.

Raith, M.M., **Raase, P.** and **Reinhardt, J.** (2012) *Guide to Thin Section Microscopy*. Second edition, 127 pp. e-Book ISBN 978-3-00-037671-9.

Rosen, R. (2012) Pareidolia: A bizarre bug of the human mind emerges in computers. The Atlantic, August 7.

Savrda, C.E. and **Bottjer, D.J.** (1989) Anatomy and implications of bioturbated beds in “black shale” sequences: examples from the Jurassic Posidonienschiefer (southern Germany). *Palaios*, **4**, 330–342.

Schieber, J. (2003) Simple gifts and buried treasures implications of finding bioturbation and erosion surfaces in black shales. *Sed. Rec.*, **1**, 4–8.

Schieber, J. (2009) Discovery of agglutinated benthic foraminifera in Devonian black shales and their relevance for the redox state of ancient seas. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **271**, 292–300.

Schieber, J. (2011) Reverse engineering mother nature - Shale sedimentology from an experimental perspective. *Sed. Geol.*, **238**, 1–22.

Schieber, J. (2013) SEM observations on ion-milled samples of Devonian black shales from Indiana and New York: the petrographic context of multiple pore types. In: *Electron Microscopy of Shale Hydrocarbon Reservoirs* (Eds Camp, W., Diaz, E. and Wawak, B.), *AAPG Mem.*, **102**, 153−172.

Schieber, J. (2014) Traces in the dark−sedimentary processes and facies gradients in the Upper Devonian-Lower Mississippian upper shale member of the Bakken Formation, Williston Basin, North Dakota, U.S.A.--Discussion. *J. Sed. Res.*, **84**, 837–838.

Schieber, J. and **Lazar, R.O.** (2004) Devonian Black Shales of the Eastern U.S.: New Insights into Sedimentology and Stratigraphy from the Subsurface and Outcrops in the Illinois and Appalachian Basins. Field Guide for the 2004 Great Lakes Section SEPM Annual Field Conference. Indiana Geological Survey Open File Study 04-05, 90 pp.

Schieber, J., **Lazar, R.**, **Bohacs, K.**, **Klimentidis, B.**, **Ottmann, J.** and **Dumitrescu, M.** (2016) An SEM study of porosity in the Eagle Ford Shale of Texas – Pore Types and porosity distribution in a depositional and sequence-stratigraphic context. In: *The Eagle Ford Shale: A Renaissance in U.S. Oil Production* (Ed Breyer, J.A.), *AAPG Mem.*, **110**, 167−186.

Schieber, J. and **Zimmerle, W.** (1998) The history and promise of shale research. In: *Shales and Mudstones (vol. 1): Basin Studies, Sedimentology and Paleontology* (Eds Schieber, J., Zimmerle, W. and Sethi, P.), pp. 1−10.Schweizerbart’sche Verlagsbuchhandlung, Stuttgart.

Shakespeare, W. (1603) *The Tragedy of Hamlet*, 1st edn. N.L. and John Trundell, London. 71 pp.

Smith, M.G. and **Bustin, R.M.** (1996) Lithofacies and paleoenvironments of the Late Devonian and Early Mississippian Bakken Formation, Williston Basin. *Can. Soc. Petrol. Geol. Bull.*, **44**, 495–507.

Spaw, J.M. (2012) Identification, integration and upscaling of mudrock types-A pathway to unlocking shale plays. SPE/EAGE European Unconventional Resources Conference & Exhibition, Vienna, Austria, March 20–22, 2012. Paper Number SPE-153111-MS.

Spaw, J.M. (2013) Recognition of ichnofacies distributions and their contributions to matrix heterogeneity in mudstones. Unconventional Resources Technology Conference, Denver, Colorado, USA, August 12–14, 2013.

Trabucho-Alexandre, J. (2014) More gaps than shale: erosion of mud and its effect on preserved geochemical and palaeobiological signals. In: *Strata and Time: Probing the Gaps in Our Understanding* (Eds Smith, D.G., Bailey, R.J., Burgess, P.M. and Fraser, A.J.), *Geological Society, London, Special Publications*, **404**, 251−270.

Wetzel, A. and **Bromley, R.G.** (1994) Phycosiphon incertum revisited: Anconichnus horizontalis is its junior subjective synonym. *J. Paleontol.*, **68**, 1396–1402.

Wignall, P.B. (1994) *Black Shales. Oxford Monographs on Geology and Geophysics, 30.* Oxford University Press, Oxford, 127 pp.

Wilson, R.D. and **Schieber, J.** (2015) Sedimentary facies and depositional environment of the Middle Devonian Geneseo Formation of New York, USA. *J. Sed. Res.*, **85**, 1393–1415.

Wittgenstein, L. (1922) *Tractatus Logico-Philosophicus*. Harcourt, Brace & Co., New York, 75 pp.

Manuscript received 17 October 2020; revision accepted 14 March 2021