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Review article

Current concepts in mudstone description and deposition: A synthesis for mudstone initiates

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Abstract | Conventionally, geologists have regarded mudstones as deposits formed through suspension settling in environments located at the terminus of sediment transport pathways, with the sediment sourced from a mix of detrital inputs into the basin and *in situ* production within the basin. However, mudstones are sedimentologically enigmatic as they are characterized by intricate small-scale features. Analysing mudstones with the typical techniques used for coarse grained siliciclastics does a disservice to the intricacies of these deposits. Grains, pores, and depositional fabrics within these rocks are not visible in hand sample, and often not even at the petrographic scale. Study of these features, at appropriate scales, can generate valuable insights into the physical and chemical conditions of their deposition. Along with analytical techniques, the conventionally held interpretations of these rocks are out of date. New insights into the origins and composition of grain components reveal significant variability, indicating these deposits are much more complex than traditionally understood. As a result, historical nomenclature and interpretation paradigms have undergone significant revision. However, there is still more research needed to fully address the challenges of mudstone description, classification and interpretation. This paper presents digestible discussions of changes in mudstone paradigms, the most effective practices consistent with modern understandings of mudstones, and considers areas that merit further consideration. Ideas presented herein are aimed at all those interested in mudstones, but is primarily meant for those new to the challenge of conducting mudstone analyses. Herein we recognize several preferred practices that have gained consensus in the literature, these include: (1) clearly defining common historical terms such as 'clay', 'silt', 'bed', and 'shale' depending on modern chosen usage; (2) outlining the transportational (i.e., functional) grain size of the deposit, as many constituents may be transported as amalgamated clasts; (3) clearly defining if reported mudstone composition is based on transported or apparent grain size (i.e., individual grain measurements); (4) thin section preparation methods and their integration with other complementary analytical techniques. As well, we discuss: (1) the use of both petrographic trace fossil analysis and microfacies analysis; (2) complex depositional mechanisms, beyond suspension settling, that lead to the accumulation of fine-grained deposits; and, (3) the interaction of several variables involved in accumulating organic-rich deposits. Ultimately, when embarking on mudstone analysis, one must first decide what question they are trying to answer. This will dictate the approach used, and if the focus is on the intricacies of grain size, composition, or depositional fabric.

Lay summary | Mudstones are enigmatic, being compositionally and depositionally complex. This makes their classification and interpretation in many cases challenging. Further, these deposits are often overlooked as being simple fine-grained deposits accumulating in low energy settings. This, however, is understood to be rarely the case. This paper provides an educational synopsis and digestible summary of the abundance of information that has come out of mudstone research over the past two decades. Herein we summarize the modern concepts in mudstone nomenclature, terminology, composition, analytical methodologies, depositional parameters, and mechanisms of organic matter enrichment.

Keywords: Mudstone; Black shale; Mudstone classification; Meiofauna bioturbation; Organic matter enrichment

1. Introduction

On volume alone, mudstones dominate the sedimentary record (Way, 1973; Potter et al., 1980; Schieber & Zimmerle, 1998). They record a wealth of information that aids our understanding of past Earth processes and are vital to the energy industry landscape (Schieber & Zimmerle, 1998). The apparent lateral continuity and wealth of settings in which they accumulate makes mudstones integral agents of correlation and broad-scale paleoenvironmental reconstruction (Schieber, 1998; Potter et al., 2005). Their porosity, permeability, and often organic-rich character makes them essential components of hydrocarbon systems as caprocks, seals, and unconventional reservoirs (Schieber & Zimmerle, 1998; Potter et al., 2005; Macquaker et al., 2010b); while their geochemical signatures have been used as proxies for past marine conditions (see Tribovillard et al., 2006, and LaGrange et al., 2020, for comprehensive overviews).

The sheer prevalence and economic importance of mudstones may naturally lead one to assume that they are well understood. This is, however, not the case. Only with the recent adoption of hydraulic fracturing to accompany horizontal drilling (early 2000s) did our understanding of mudstones really take off. Early investigations into the economic potential of unconventional source-rock reservoirs expressed a need for a better understanding of the processes leading to the accumulation of these fine-grained deposits, and the compositional intricacies encompassed within (e.g., Bohacs, 1998; Macquaker & Howell, 1999; Passey et al., 2010). Thus, the past two decades have seen an explosion of publications (Figure 1) related to new discoveries and views on mudstone composition and depositional processes. As our energy landscape continues to evolve, mudstones find additional economic potential as hosts for vital rare earth elements and critical minerals (e.g., Birdwell, 2012; Berna, 2019; Bern et al., 2021; Ardakani et al., 2022).

Beyond their economic potential, mudstone deposits hold essential information for understanding the drivers of Earth's past climatic changes (e.g., Wignall & Ruffell, 1990; Gosh et al., 2019; Iqbal et al., 2019; Milroy et al., 2019). Therefore, these deposits are invaluable not just for comprehending the mechanisms driving resource potential, but also for their role in decoding historical climate patterns.

The surge in mudstone research has led to a consensus that these seemingly simple, often organic-rich, fine-grained deposits are compositionally more complex than previously understood, and there is a wide expanse of depositional parameters beyond the classical assumption of suspension settling in poorly oxygenated quiescent settings (e.g., discussions in Schieber, 1998; Sageman et al., 2003). In fact, the traditional interpretation of mud delivered to the sea floor through suspension settling is, in actuality, very rarely the case. Individual mud constituents are more often transported to the sea floor as either amalgamated composite particles or remobilized in small rip-up-clast-like features following initial deposition (e.g., Plint, 2014; Schieber et al., 2010). Additionally, seemingly unbioturbated mudstone deposits at hand sample scale may be fully biogenically homogenized at the microscopic level (Schieber, 2003), sparking re-interpretations of depositional oxygenation.

Many of these revelations have been illuminated by high magnification or higher resolution imaging. Owing to the monotonous dark and fine-grained nature of mudstones, petrography has become the preferred 'first step' in mudstone analysis. Mudstone thin sections provide essential information on grain size, composition, pore characteristics, and sub-millimeter primary sedimentary and biogenic features not visible in hand sample. Compositional and textural elements illuminated through petrography have been paramount in the identification and confirmation of many mudstone breakthroughs. High-resolution imaging (e.g., scanning electron microscopy) complements and enhances interpretations derived from petrographic analysis. These two techniques together are fundamental to understanding a mudstone unit.

With these new understandings comes a need for the evolution of the associated nomenclature. For example, depositional grain size may now be described using either the apparent mineralogical diameters or the functional depositional grain size of composite particles; and commonplace terms such as 'bed' and 'shale' are contentious within the mudstone community, and their modern suggested usage can differ from conventional practice.

Keeping up with the new practices is challenging. Additionally, these concepts are spread over countless publications, in some cases presenting a barrier to access for those sedimentologists without institutional access privileges. Furthermore, many of the relatively new concepts are not yet integrated, at least not prevalently, into the undergraduate sedimentological education system. Thus, a succinct summary of varying topics within the ever-changing field of mudstones may prove most useful to those just entering the world of research on fine-grained sediment deposits. This paper is the culmination of insights gained during a mudstone novice and her collaborators' deep dive into the world of fine-detailed physicochemical depositional interpretations of organic-rich mudstones. This discussion focuses mainly on petrographic analyses and is intended to provide an overview of current terminological suggestions for mudstone assessment and classification. This review also explores the evolving ideas regarding mudstone deposition and sheds light on relevant topics for future discussions.

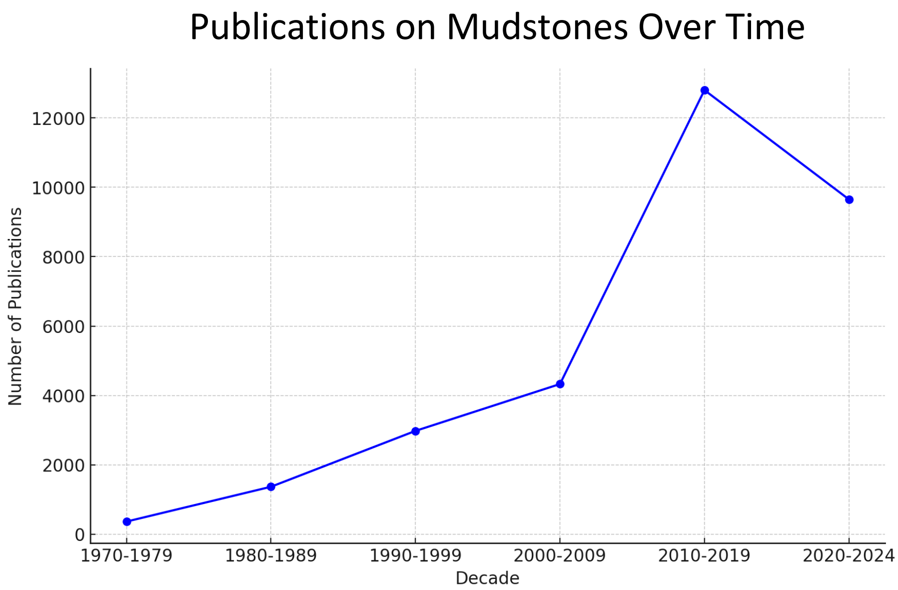

Figure 1 | Number of mudstone-related publications over the past six decades. Note the steep incline from 2000-2009 during the popular adoption of horizontal drilling and fracking. Data source: Web of Science, accessed: May 10th, 2024.

2. Nomenclature and terminology

2.1. Mudstone or Mudrock?

Siliciclastic fine-grained sedimentary rocks have many aliases but are most commonly referred to as 'mudrocks' or 'mudstones.' Some authors use the terms interchangeably, whereas others have used 'mudrock' to refer to fine-grained rocks in general reserving 'mudstone' for rocks composed of a mix of both clay-sized and silt-sized particles (e.g., 'claystone', 'mudstone', and 'siltstone' as a continuum) or more 'blocky' fine-grained deposits (i.e., non-fissile, see mudstone *versus* shale discussion below) (Potter et al., 2005). Recent consensuses propose that 'mudstone' be used as the general class term for fine-grained siliciclastic rocks, maintaining consistency with the other sedimentary blanket terms such as 'sandstone' and 'limestone' (e.g., Aplin et al., 1999; Macquaker & Adams, 2003; Potter et al., 2005; Lazar et al., 2015a, b). Following this, the term 'mudstone' is used herein as the default expression.

Historically, mudstones have been described on the basis of easily observable traits such as color and fissility (e.g., 'black shale'). They are often partitioned into siltstone, mudstone, and claystone categories based on grain-size distributions. Such generality in mudstone classification makes it difficult to directly compare units between individual studies. For example, the term 'claystone' is problematic. There is a difference between a *clay-mineral-dominated fine-grained rock* and a *clay-size-dominated fine-grained rock* (e.g., Lazar et al., 2015a). Indeed, such general descriptions do not facilitate the detailed interpretation of depositional processes (Milliken, 2014; Lazar et al., 2015a, b). Responding to the simplification of mudstone descriptions in literature, Macquaker and Adams (2003) proposed a simple and inclusive nomenclature where samples are defined based on composition and textural attributes. Specific terms were defined to represent compositional ranges. Samples containing >90% of a particular constituent are referred to as 'dominated' by that material, 50-90% represent a sample 'rich' with a material, and 10-50% represent a sample 'bearing' a material (Table 1). Macquaker and Adams (2003) cite examples such as: "clay-dominated mudstone (>90% clay) and silt- and sand-bearing clay-rich mudstone (50-90% clay, 10-50% sand and silt)". They suggested that textural terms be included as prefixes, such as 'bioturbated' or 'laminated'.

Lazar et al. (2015a) expanded on the refinement of mudstone nomenclature by developing terminology based on grain size, bedding, and composition (e.g., Table 1). This scheme aimed to integrate depositional, biogenic, and diagenetic processes over all scales (e.g., outcrop and thin section). They propose using a root term based on grain size (see discussion below), then modifying the rock name using prefixes that describe the bedding characteristics (character of the laminae or bedding contacts), mineralogic composition, origin of the constituents (e.g., diagenetic, detrital), and degree of biogenic reworking. The mineralogic composition can be further enhanced using the descriptive compositional terms outlined by Macquaker and Adams (2003) (e.g., 'rich' or 'bearing').

Readers are referred to Milliken (2014) for a comprehensive overview of historically proposed mudstone naming schemes. We, the authors, recommend that the nomenclature used for detailed mudstone studies should be that of Lazar et al.'s (2015a) fine, medium, and coarse mudstones or well-defined 'claystone', 'mudstone', 'siltstone' terms (Figure 2A); with Macquaker and Adams (2003) 'dominated', 'rich', and 'bearing' modifiers.

Term	Description	Use
Mudstone	Generic name for all fine-grained rocks (e.g., analogous to 'sandstone').	Historically utilized mudrock names
Claystone	Either a clay-mineral dominated rock or a rock composed dominantly of clay-sized grains (e.g., fine mudstone). If used, needs to be clearly defined as either a compositional or textural name.	
Shale	Textural rock description based on the presence of visible fissility, not a reliable rock name.	
Fine mud (fMs)	All particle constituents <8 µm.	Updated root mudstone naming terms, modified with prefixes
Medium mud (mMs)	All particle constituents 8-32 µm.	
Coarse mud (cMs)	All particle constituents 32-64 µm.	
Dominated	>90% of the sample is comprised of a particular constituent.	Used to enhance below compositional prefixes
Rich	50-90% of the sample is comprised of a particular constituent.	
Bearing	10-50% of the sample is comprised of a particular constituent.	
Calcareous	>50% carbonate (calcite, dolomite). Modifiers indicating constituent origin may be necessary (e.g., 'detrital carbonate rich'; 'foraminifera-rich', 'coccolith-rich'). Mudrock may be considered a 'chalk' if >80% calcareous microfossil tests.	Compositional prefixes
Argillaceous	>50% clay minerals (e.g., kaolinite, illite, smectite). Modifiers indicating constituent origin may be necessary (e.g., detrital-argillaceous or cemented-argillaceous).	
Siliceous	>50% quartz. Modifiers indicating constituent origin may be necessary (e.g., 'detrital quartz-rich'; 'radiolarian-rich'). May be considered a 'radiolarite' if >70% siliceous radiolarian tests.	
Other	Phosphatic (<20% phosphate), phosphorite (>20% phosphate), arkosic (>25% feldspar), subarkosic (5-25% feldspar).	
Cemented	Can be used to modify the above three compositional prefixes if the dominant composition exists in the form of diagenetic cement (e.g., calcite, microcrystalline quartz, kaolinite).	
Composite Particles	Particle comprised of clay and silt mineral grains, biogenic tests, and/or organic detritus and are functionally transported and deposited as a single amalgamated grain. Further broken down into four separate types: floccule, organomineralic aggregate, fecal pellet, intraclast (Table 2).	
Organic/ carbonaceous	A mudstone is considered enriched in organic matter if organic matter content is >2%.	
Microbioturbated	Biogenic reworking by benthic meiofaunal organisms. 'Biogenically homogenized' can be used to describe units showing complete reworking (i.e., lack of evidence for primary sedimentation mechanisms). Analogous to 'meioturbation' (c.f. Schieber and Wilson, 2021).	Textural prefixes

Table 1 | Common mudstone terminology and suggested usage.

2.2. Shale or Mudstone?

Similarly, the term 'shale' has its contentions in the mudstone community. Some sedimentologists have used 'shale' as a general catch-all class term (i.e., equivalent to 'sandstone' and 'limestone') for all fine-grained argillaceous sediments (Tourtelot, 1960; Potter et al., 1980), while others treat 'shale' and 'mudstone' interchangeably (e.g., Schieber and Zimmerle, 1998; Boggs, 2006; Ilgen et al., 2017). Most use 'shale' to classify those mudstones exhibiting parting spacing ('layering') (Folk, 1980), while the broader 'mudstone' is used to classify more blocky deposits (Potter et al., 1980, 2005). Finally, some reserve 'shale' strictly for a textural description of mudstones exhibiting fissility (Neuendorf et al., 2005; Milliken, 2014; Lazar et al., 2015b). In fact, the term 'shale' has been defined based on fissility by Neuendorf et al. (2005). Fissility represents the preferential splitting of a mudstone unit along approximately parallel surfaces due to the internal parallel arrangement of clay platelets (e.g., face-to-face contacts; *sensu* Reynolds & Gorsline, 1992) (Ingram, 1953). Parallel alignment of clay minerals occurs in response to conditions of deposition and early compaction. Suspension settling of loose particles or compaction of uncemented (pre-lithified) clay-mineral-dominated composite particles (further discussed in Section 2.4) can result in the preferential parallel alignment of clay-mineral platelets (Ingram, 1953). The ability of a rock to split along inherent planes of weakness is intimately tied to both the composition and ubiquity of the diagenetic cementing agent (Ingram, 1953). Some cementing agents will hinder breakage resulting in more massive 'blocky' mudstone deposits (Ingram, 1953). Fissility is a transient property, developing over time due to a combination of pressure alleviation, moisture release, and weathering (Ingram, 1953; Weaver, 1989; Milliken, 2014; Lazar et al., 2015b). Time-dependant physical properties are inappropriate as a classification basis, as the rock unit in question may start as one rock type (e.g., mudstone) and transition to another over time (e.g., 'shale' - based on the condition of inherent fissility) (*sensu* Milliken, 2014).

Additionally, fissility in mudstones is a feature commonly misascribed to the presence of macroscopically visible bedding or laminae, whether or not discernible beds and laminae are actually present (Macquaker & Adams, 2003; Lazar et al., 2015b). Mudstones exhibiting fissility can be laminated, but they may also be thinly bedded, or completely biogenically homogenized where burrows create the illusion of laminated fabric (e.g., the 'burrow-laminated' mudstones in Schieber, 2003), or where subsequent compaction results in the appearance of laminae (e.g., Douglas 1981; Cuomo & Rhoads, 1987; Cuomo & Bartholomew, 1991; Schieber, 2003; Schieber & Wilson, 2021). To reiterate a point often discussed in mudstone literature: the term 'fissility' should be used

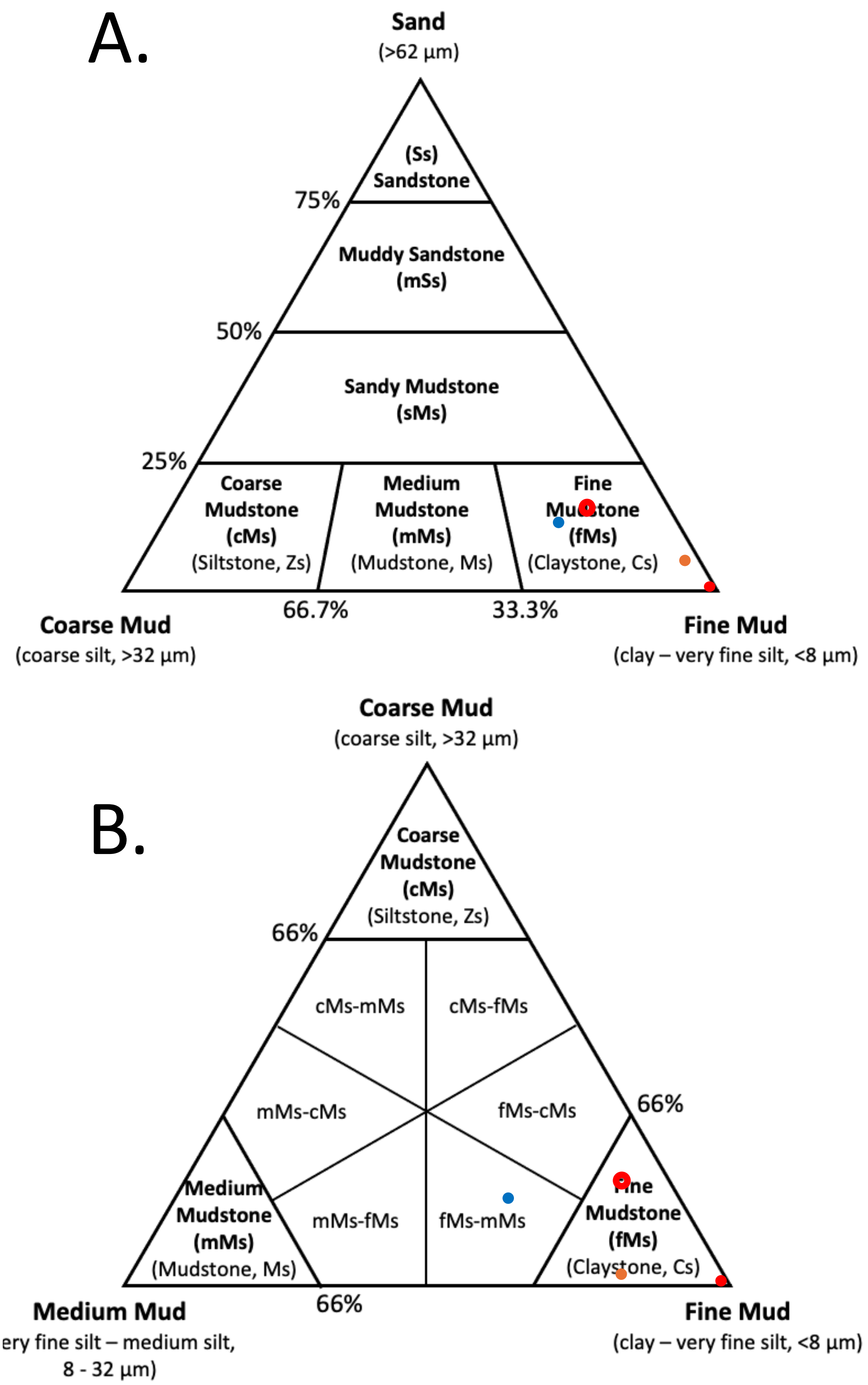

Figure 2 | (A) Ternary diagram designed by Lazar et al. (2015a). (B) Proposed ternary diagram for sand-poor units (focuses on the fine-grained fraction) with terminological divisions still at two-thirds compositional dominance (as defined in Lazar et al., 2015a). Plotted data represents examples from Figure 3. Fig. 3A - red dot, 3B - red circle, 3C - orange dot, 3D - blue dot.

strictly as descriptive terminology for mudstones showing evidence for parting or weathering along bed-parallel planes of weakness (Macquaker & Adams, 2003; Milliken, 2014; Lazar et al., 2015a). Thus, the term 'shale' should be considered only a textural weathering description and not used as a catch-all rock name (Macquaker & Adams, 2003; Milliken, 2014; Lazar et al., 2015a, Lazar et al., 2015b).

However, the term 'shale' as a reference to fine-grained siliciclastic deposits in general, and descriptive counterparts such as 'shale-oil' and 'shale-gas', are so embedded within the broader geosciences and energy industries that usage strictly for textural indication is unlikely to become the norm. Indeed, it is much simpler to say 'shale' than it is to say 'siliciclastic mudstone'. This is less of an issue in conversation, where the true character of the deposit under discussion is generally implicit. At the very least, when using 'shale' as a simple catch-all reference in publication, the true rock character should first be clearly defined (for example, using the nomenclature scheme put forth by Lazar et al., 2015a).

2.3. Grain size

By conventional definition 'mud' is a sediment composed of greater than 50% particles smaller than 62.5 µm (e.g., silt and clay) (Folk, 1980; Potter et al., 1980; Potter et al., 2005; Lazar et al., 2015a), and the 'clay-grain-size' cut off is variably designated as 1 µm, 2 µm, or 4 µm. However, individual clay mineral platelets can be silt-sized, and common framework silicate silt- and sand-forming minerals (e.g., quartz and feldspars) can fall below a researcher's selected clay-size designation (Figure 3A, using a clay cut-off of 2 µm) (Potter et al., 2005). These clay-sized framework silicates may also compositionally dominate mudstone deposits (e.g., Aplin & Macquaker, 2011). One must first determine where it is appropriate to use the terms 'silt' and 'clay' as defining grain size or mineralogical traits.

Lazar et al. (2015a) defined new grain size terms in place of the dual definition 'clay' and 'silt' endmembers and provided an updated ternary diagram (Figure 2A). These modernized grain size terms include 'fine mud' (grain sizes <8 µm; clay and fine silt), 'medium mud' (grain sizes between 8 µm and 32 µm; fine to medium silt), and 'coarse mud' (grains 32 µm to 62.5 µm; coarse silt) and encapsulate all particles that fall within a specified grain diameter designation regardless of mineralogy or origin. The grain diameter cut-offs in this new scheme were developed deliberately, incorporating various elements such as recent data on the variable transport behavior of sediment grains in these three size classes and the simplified ease of visually sorting grains with these larger diameter boundaries (in practice it can be exceedingly difficult to visually assess if grain diameters are at or below a 4 µm, 2 µm, or 1 µm cut off) (Figure 3) (Lazar et al., 2015a, b). Accordingly, rocks dominated by fine mud grain sizes (<8 µm) should be referred to as 'fine mudstones', and so on. They further suggest that if an author so chooses, they may substitute more commonly held terms into this new scheme, such as 'claystone' (fine mudstone), 'mudstone' (medium mudstone), and 'siltstone' (coarse mudstone) (e.g., Figure 2A), as long as these rock names are properly and clearly defined by an author.

Lazar and colleagues' (2015a) ternary diagram (Figure 2A) works well as an updated method for parsing out nuances of grain size within fine-grained deposits, as well as defining sizes of sub-sand-sized composite particles (discussed in the following section). However, the comprehensive nature of this ternary (covering fine mud through sand grain sizes) does not lend itself well to providing added understanding when specifically analyzing sand- and silt-poor units. For example, Lazar and colleagues' (2015a) ternary was used in a subsequent study when analyzing silt-mineral-poor units (e.g., Biddle et al., 2021). In the studied units, all samples from all formations were classified as 'fine mudstones', with grain-size measurements crowding specific areas of the ternary (e.g., colored dots in Figure 2A, representing the four examples in Figure 3). This result is not entirely useful when trying to parse out small-scale heterogeneities. Perhaps an alternate ternary diagram might be needed in such sand- and silt-poor cases, focusing solely on the sub-sand grain size components. Figure 2B provides a potential alternative. This updated ternary preserves the terminological divisions at two-thirds compositional dominance, as originally defined by Lazar et al. (2015a), while further providing an additional six grain size classifications defined on the varying composition of fine, medium, and coarse mudstone components. With this new ternary, the four examples from Figure 3 plot further away from each other, creating a better representation of the differences between them, while Figure 3D (blue dot in Figure 2) plots in a different grain size designation entirely (the fine-medium mudstone classification). This alternative ternary diagram may prove most useful in petrographic studies when outlining nuances in grain-size changes between individual beds or in otherwise homogeneous-seeming deposits.

As suggested by Lazar et al. (2015a) and practiced by Percy and Pedersen (2020), biased terms such as 'claystone' should be properly defined in each study (e.g., does 'clay' refer to the compositional dominance of clay minerals, or clay-sized grains?). Researchers are nevertheless encouraged to opt for more clear nomenclature such as 'clay mineral-rich' or 'fine-mudstone' (Lazar et al., 2015a, b; Percy & Pedersen, 2020).

If mudstone sedimentologists are to incorporate all compositional elements regardless of mineralogy into a particular grain size class, how should microfossils be treated? Dunham (1962) developed one of the most widely used carbonate classifications, wherein particles larger than 20 µm are considered 'grains', and particles smaller than 20 µm are considered 'mud'. In this scheme macrofossil and microfossil components are treated functionally as grain constituents. Adopting this methodology into Lazar and colleague's (2015a) mudstone grain size is difficult due to the differing definitions of mud (e.g., siliciclastic mud is defined as 50% of particles <62.5 µm). However, if microfossils are to be attributed to a particular clastic grain size class, it may be necessary to denote whether they are benthic, pelagic, or of transported origin (similar to describing if a sedimentological compositional component is diagenetic or detrital). For example, should the radiolarian-rich deposit in Figure 3D and plotted as the blue dots in Figure 2 (>70% radiolarian tests; 50% fMs, 25% mMs, 15% cMs, 10% fine sand) be called a 'siliceous radiolarian-rich fine to medium mudstone' accounting for the radiolarian tests, or a 'fine mudstone' with tests normalized out of the grain-size distribution calculation? Should the fact that the radiolarian tests are likely the product of suspension settling factor into the naming scheme? The answer is: it depends. If an investigator is interested in hydrodynamic conditions of deposition (e.g., carrying capacity), pelagic suspension-settled components may be negated. If the question is one of provenance (allochthonous *versus* autochthonous), they must

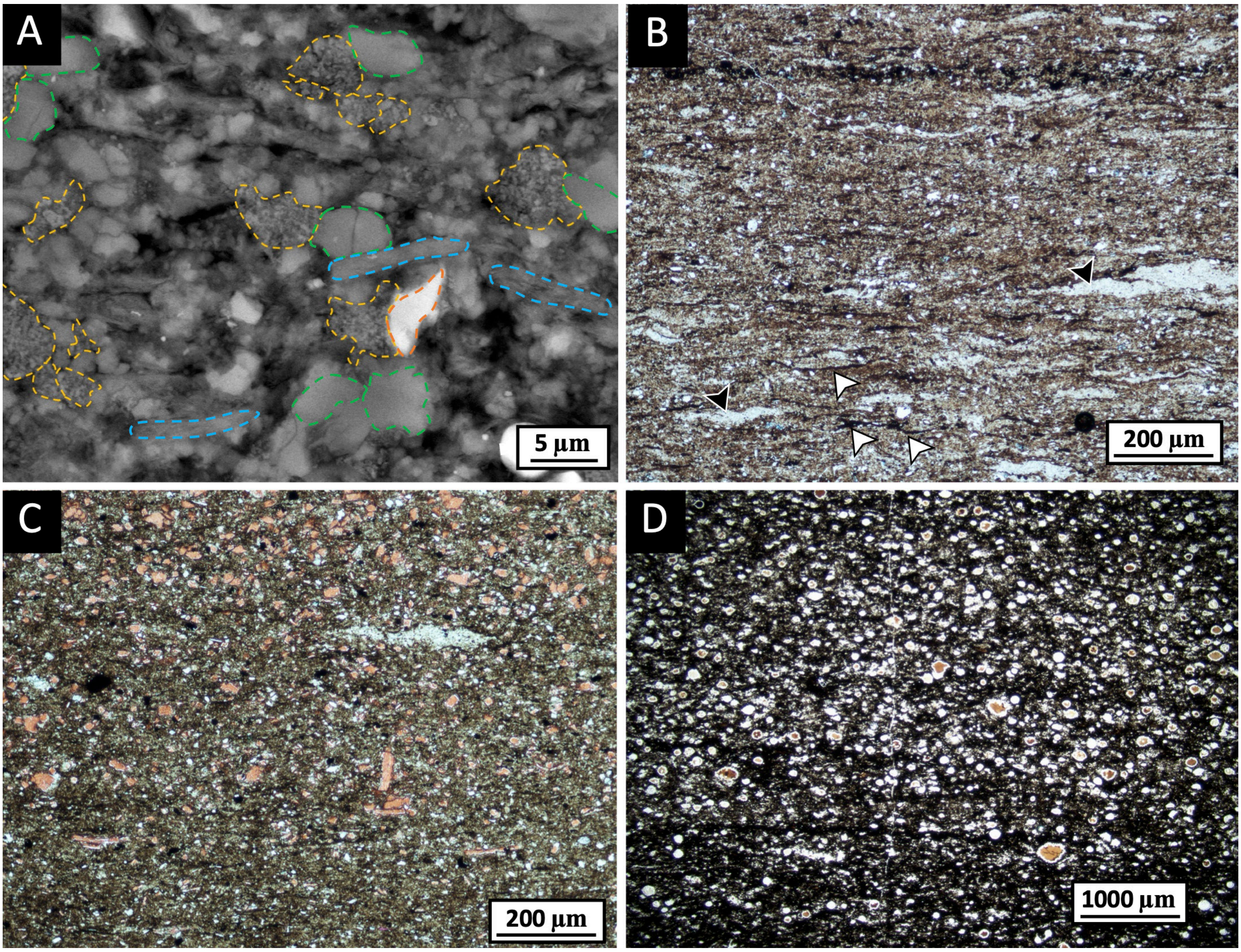

Figure 3 | Examples of variable grain size in mudstones. Photoplate illustrates the ease of use of the proposed fine, medium, and coarse mud diameter cut-offs in Lazar et al. (2015a) while also depicting how different grain size definitions (apparent versus functional) can change the rock name. Grain size distributions (colored dots) in Figure 2B have been normalized to eliminate sand-sized fraction. All photographs are from the Horn River Group, NWT Canada. (A) SEM BSE photograph of a mudstone matrix dominated by clay-sized particles. Dashed outlines highlight grains that quantitatively meet the definition of 'silt-sized' using a traditional 2 µm cut-off (clay-mineral composite particles - yellow, micas – blue, quartz – green, pyrite fragment - orange) (100% fMs). Silt-sized particles are the minority component of this sample. Sample plotted as the red filled-in circle on the Figure 2 ternary diagrams. Paramount Energy MGM Shell East MacKay I-78 core (1827.40 m). (B) Representative photomicrograph of the same elevation shown in A). White arrows indicate organomineralic aggregates, black arrows indicate clay-mineral rich intraclasts. The matrix is dominantly clay-sized (as seen in A). Sample plotted as the red open circle on the Figure 2 ternary diagrams, using functional depositional grain size as opposed to individual particle grain size (65% fMs, 7% mMs, 13% cMs, 15% sand). Husky Little Bear H-64 core (1174.25 m). (C) Photomicrograph showing a mudstone sample with a homogenized mixture of medium mud to sand-sized detrital calcite (pink stained), fine-to-medium mud detrital quartz (bright spots), and detrital clay (77% fMs, 16% mMs, 2% cMs, 5% sand). Sample plotted as the orange dot on the Figure 2 ternary diagrams. Husky Little Bear N-09 core (1796.05 m). (D) Photomicrograph of a recrystallized and partially dissolved radiolarian-rich mudstone (radiolarian tests are the bright/white circular features). Sample is plotted as the blue circle on the Figure 2 ternary diagrams. Grain size distribution was calculated including the radiolarian tests (>70% radiolarian tests, 30% detrital elements; grain size distribution: 50% fMs, 25% mMs, 15% cMs, 10% fine sand). If radiolarian tests are excluded, normalized grain size distribution is 100% fMs. Husky Little Bear H-64 core (1186.69 m).

be included. The universal integration of microfossils into a sedimentological grain size scheme still needs careful consideration and is yet forthcoming.

2.4. Composite particles

To further grain size confusion, the modern concept of composite particles (CPs) may also need consideration. Composite particles comprise clay and silt mineral grains, biogenic tests, and/or organic detritus and are functionally transported and deposited as a single amalgamated grain (sensu Li & Schieber, 2018; Figure 4). Composite particles behave hydrodynamically (i.e., functionally) as larger grain sizes (e.g., as silt or even sand-sized particles) (Schieber et al., 2007a; Plint, 2014; Li et al., 2021). Thus using 'silt' and 'clay' as a means to describe grain size, particularly when considering sediment transport and sedimentation, may not suit the research questions being posed. As such, it is best if research papers specify whether it is *functional depositional grain size* (i.e., the size at which the particle was transported) or *apparent grain size* (i.e., the size of the individual mineral and biogenic constituents) that is being used (Lazar et al., 2015b; Li & Schieber, 2018; Li et al., 2021).

Quantifying the original depositional size of composite particles with traditional grain-size proxies is difficult, owing to the fragility of these aggregates (Honjo et al., 1984; Alldredge & Silver, 1988). Sieving of sediments to determine grain size results in the disaggregation of composite particles and can only quantify apparent grain size at best or some value between depositional and apparent grain size at worst. The most reliable method to assess the volume and type of composite particles present is through petrographic and SEM analysis (visual analyses) (Honjo et al., 1984; Alldredge & Silver, 1988). However, there are still difficulties associated with confidently identifying composite particle margins from the surrounding matrix (e.g., Li et al., 2021), as well as post-depositional destruction of CPs through compaction and biogenic comminution. Occasionally, composite particles may be identifiable in zones of enhanced taphonomic preservation (e.g., zones of early cementation, enhanced lithologic contrast, or reduced compatibility). For example, Percy and Pedersen (2020) were able to identify small mudstone aggregates accumulated along ripple foresets in early diagenetic carbonate concretions, and Paz et al. (2023) were able to distinguish several different fecal pellet and pelagic aggregate morphologies in uncompacted ash beds. Ultimately, analyzing samples at appropriate scales is imperative to identify these features (e.g., high-resolution SEM analysis is needed as some composite particles may be <10 mm in diameter; e.g., Al-Mufti, 2022).

Ultimately, in many units it might not be possible to determine the functional depositional grain size. In such instances it is still worthwhile for future authors to mention they are referencing solely the apparent grain size, and that attempts at determining functional grain size were unsuccessful. Doing so will help to omit any potential confusion or redundant attempts at functional grain size determinations.

Composite particles have been referred to alternatively in the literature depending on their origin. Li and Schieber (2018) and Li et al. (2021) suggest that water column floccules themselves are a type of water-rich composite particle. Other similar pelagically-generated composite particles have been referred to in numerous ways, including: 'aggregate grains' (Plint, 2014; Percy & Pedersen, 2020), 'physico-chemical flocs' (Reynolds & Gorsline, 1992), and 'organomineralic aggregates' (Figure 4F), which are further parsed out into 'marine snow' (>500 µm) and 'phytodetritus' (<500 µm) (Macquaker et al., 2010b; Plint et al., 2012). Marine snow and phytodetritus are more commonly used to describe modern sediments and have been criticized in the past for their unclear nomenclature (e.g., Honjo et al., 1984). Pelagic fecal pellets have also been included in the composite particle designation (Lazar et al., 2015a; Li & Schieber, 2018). Milliken (2014) grouped all water-column generated composite particles into the designation of 'sediment aggregates' (Figure 4E). If the composite particle is the result of erosion and transportation of previously deposited semi-consolidated detrital mud sediment (Figures 3B, 4B-D, 11B, 11C, and 11E), the terms 'mud rip-up clasts' (Macquaker & Gawthorpe, 1993; Schieber et al., 2010; Li & Schieber, 2018) or 'intrabasinal rip-up clasts' (Biddle et al., 2021), 'intraclastic aggregates' (Plint, 2014), 'intraclasts' (Lazar et al., 2015a, b), and again 'aggregate grains' (Plint, 2014; Percy & Pedersen, 2020) have been used. Alternately, attempts have been made to classify composite particles separately based on their structure and size (Plint, 2014), and compositional and textural contrast with the surrounding matrix (Li et al., 2021). A size hierarchy of aggregate grains is described by Plint (2014), with the smallest unit being 'domains', constituting 0.5 to 1 µm parallel packages of a handful of clay platelets (Bennett et al., 1981), and larger 'face-to-face aggregates', 2 to 5 µm in diameter and composed of a collection of near-parallel clay 'domains' (O'Brien, 1987; Plint 2014). Face-to-face aggregates are subsequently the building blocks of Plint's (2014) storm-reworked intraclastic aggregates, 5 to 20 µm particles composed of multiple face-to-face aggregates and other components (e.g., quartz silt, organic matter). Li et al. (2021) described two general types of composite particles identified in the Dunvegan Formation: 1) 'soft' indented and flattened composite particles (argillaceous mud rip-up clasts and floccules), and 2) 'hard' compaction-resistant composite particles (volcanic rock fragments, chert fragments, shale lithic fragments, metamorphic rock fragments, and chlorite/siderite clasts). Conceivably, a standardization of composite particle terminology for variable origins would facilitate comparison across studies. Floccules, fecal pellets, organomineralic aggregates, and intraclasts (sensu Lazar et al., 2015b; defined in Table 2) are perhaps the simplest terms to define composite particle types going forward. Additionally, the definition of 'composite particle' should be updated to reference that these aggregates are unlithified upon deposition, and all rigid (lithified) allochthonous aggregates should be considered 'clasts' or 'fragments'. For example, the 'volcanic rock fragments', 'chert fragments', 'metamorphic rock fragments' and 'chlorite/siderite clasts' of Li et al. (2021) should be just that – fragments (and not a type of composite particle).

Other mudstone components that may be lumped into the composite particle designation include 'rafted silt aggregates' (Figure 5A, B) (Olsen et al., 1978; Schieber, 1999; Schieber, et al., 2007b) and 'microbial mat rip-up clasts' (Figure 5C, D) (Schieber, 1999; Schieber, 2007a; Schieber et al., 2007b). Rafted silt aggregates are postulated to form by entrapment of detrital silt within the extracellular polymeric substance (EPS) membranes of benthic microbial mats or cyanobacteria, which subsequently detach from the seafloor creating a buoyant silt raft (Olsen et al., 1978; Schieber, 1999; Schieber et al., 2007b). These features can look very similar to agglutinat-

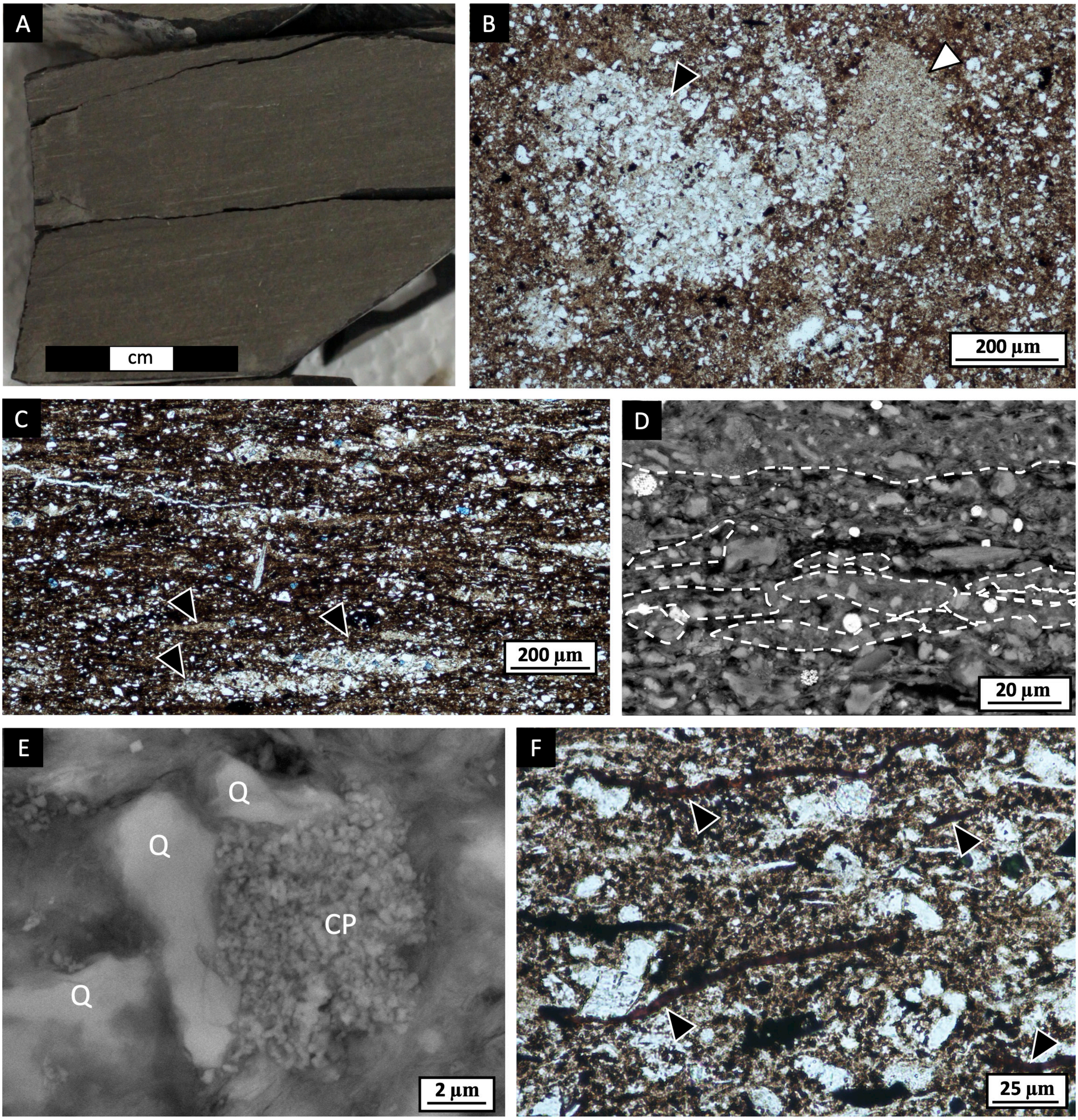

Figure 4 | Example photographs of different types of composite particles. All photographs are from the Horn River Group, NWT Canada. (A) Core photograph of an intraclast bearing mudstone. Paramount Energy MGM Shell East MacKay I-78 core (1829.25 m). (B) Bedding parallel photomicrograph showing a silt-mineral-rich intraclast (black arrow) and a clay-mineral intraclast or benthic fecal pellet (white arrow). Paramount Energy MGM Shell East MacKay I-78 core (1822.00 m). (C) Bedding perpendicular photomicrograph showing the lenticular character of intraclasts (arrows). Paramount Energy MGM Shell East MacKay I-78 core (1822.40 m). (D) Scanning Electron Microprobe Back Scatter Electron (SEM BSE) photographs of intraclasts (outline in dashed lines). Intraclasts show homogenized internal structure when compared to the clear horizontal structure of the surrounding matrix and OM. Matrix is made up of clay (intermediate interference colors - n), quartz silt (smooth intermediate n), organic matter (black) and pyrite framboids (bright n). Paramount Energy MGM Shell East MacKay I-78 core (1827.40 m). (E) SEM BSE photograph of a mudstone with a silt-sized clay mineral composite particle (CP; potential 'floccule') adjacent to detrital medium-mud (silt-sized) quartz (Q). Paramount Energy MGM Shell East MacKay I-78 core (1827.40 m). (F) Elongate organomineralic aggregate (arrows) (e.g., Macquaker et al., 2010b) in a clay and silt mineral matrix. Husky Little Bear N-09 core (1722.36 m).

ed foraminifera, however, they lack the definitive medial line that denotes agglutinated foraminifera (Milliken et al., 2007; Schieber, 2009; Macquaker et al., 2010b; Lazar et al., 2015a). By definition, these two composite particle types would meet the criteria for an 'intraclast' (e.g., the result of erosion and transportation of a previously deposited material). Thus, perhaps they should be considered 'rafted silt intraclasts' and 'microbial mat intraclasts'.

Term	Origin	Description	Examples
Floccules	Pelagic	Clumps of clay mineral platelets arranged randomly with edge-to-face contacts. Can be suspension settled or transported as bedload.	Schieber et al., 2007 (Figure 1); Schieber and Southard, 2009; Lazar et al., 2015b (Plate 4.7A, B); Li and Schieber, 2018
Organo-mineralic aggregates	Pelagic	Aggregates with diffuse edges, typically dark in color (dark brown) when compared to surrounding sediment. Wavy-crinkly appearance. Composed of a combination of amorphous organic matter, clay-sized grains, pyrite, and pelagic fecal pellets.	Honjo et al., 1984; Alldredge and Silver, 1988; Macquaker et al., 2010b (Figures 1, 2 and 3); Schieber et al., 2010; Plint et al., 2012 (Figure 9); Lazar et al., 2015b (Plate 4.7C, D)
Fecal pellets	Pelagic	Typically composed of organic debris, pelagic phytoplankton microfossil tests (e.g., coccolithophores), with minor amounts of sediment. Originally emplaced through suspension settling. Generally ovoid shape. Not as densely packed as benthic pellets.	Hattin, 1975; Cuomo and Bartholomew 1991; Macquaker et al., 2010b (Figure 1, 2B); Plint et al., 2012 (Figure 7B, C); Ulmer-Scholle et al., 2014 (pg. 204); Lazar et al., 2015a; Lazar et al., 2015b (Plate 4.7E, F); Löhr and Kennedy, 2015 (Figure 3C); Li and Schieber, 2018 (Figures 7 and 8); Percy and Pedersen, 2020 (Figure 4E)
	Benthic	Organic-matter and clay-mineral-rich, flattened elongate particles with tapering ends (ovoid shape). Typically depleted in pyrite when compared to the surrounding sediment matrix. Result from benthic deposit feeding and can be in-situ or transported.	Forbes 1984; Cuomo and Rhoads, 1987; Cuomo and Bartholomew, 1991; Macquaker et al., 2010b; Löhr and Kennedy, 2015 (Figures 3 and 4)
Intraclasts	Transported	Lenticular or ovoid features in cross section, ovoid with diffuse margins in bedding plane view. Generally lighter colored than the surrounding matrix. Form from rapid stabilization of intrabasinal sediment via biochemical processes and subsequent erosion and transportation through bottom water currents.	Macquaker and Gawthorpe, 1993; Schieber et al., 2007; Schieber et al., 2010 (Figure 2, 12, 13); Plint et al., 2012; Plint and Macquaker, 2013; Plint, 2014; Lazar et al., 2015a; Lazar et al., 2015b (Plate 4.8); Li and Schieber, 2018 (Figure 16); Percy and Pedersen, 2020; Biddle et al., 2021
	Microbial	Lenticular to elongate dark carbonaceous features, often having detrital silt grains incorporated within them.	Schieber, 1999 (Figures 2, 5 and 12); Schieber, 2007a (Figures 4 and 5); Schieber et al., 2010 (Figure 14); Lazar et al., 2015b (Plate 4.11); Aubineau et al., 2018 (Figure 7); Biddle et al., 2021 (Figures 7D and 9G)

Table 2 | Composite Particle types and descriptions.

No matter which classification an author chooses, contentious terms such as 'clay' and 'silt', or any alternative composite particle terminology, should be clearly defined.

2.5. 'Bedding' versus 'Laminae'

Organic-rich mudstones are often described as 'thin-bedded', 'laminated', or 'fissile'. The application of the term 'bed' in mudstones can be confusing. Much like the clay-mineral *versus* clay-size class dichotomy, there are dual definitions of 'bed' in the literature. The term 'bed' can be used to define a sedimentological unit >1 cm thick (Tucker, 1982). However, 'bed' can also be used to define a genetic unit representing a single or isolated depositional event (Campbell, 1967; Macquaker & Adams, 2003; Macquaker et al., 2010b; Lazar et al., 2015b; Ilgen et al., 2017). In coarse-grained siliciclastic rocks, beds by any definition are generally >1 cm, and so both definitions are practically applied. However, in fine-grained siliciclastic deposits, especially those that are clay-mineral-dominated, many depositional units are less than a centimeter in thickness. Lazar and colleagues (2015b) describe true genetically defined mudstone beds as typically ranging between 1-4 mm in thickness. Plint (2014) described mudstone prodelta deposits wherein all mudstone beds, using the genetic classification, were sub-centimetre scale. In a recent study of a 100-meter-long organic-rich mudstone drill core (*pers obs.* by S. Biddle), the thickest genetic beds averaged a thickness of 12 mm, with 42% of the thickest beds being <10 mm (Figure 6). In reality, the 'laminae' seen at hand sample scale is more often than not the product of stacked successions of individual sub-centimeter heterogeneous beds (Schieber, 1989; Macquaker & Taylor, 1997; Schieber, 1999; Rohl et al., 2001; Sageman et al., 2003; Macquaker et al., 2010a; Plint, 2014; Lazar et al., 2015b).

Regarding mudstones, the preferred application of 'bed' is to describe the deposits of a single event, while restricting 'laminae' to describing the internal partings of these units, regardless of thickness (e.g., Macquaker and Taylor's response in the discussion by Hesselbo et al., 1997; Macquaker et al., 2010b; Lazar et al., 2015b; Li et al., 2015). By doing so, 'beds' of all thicknesses can be compared genetically across individual units and studies. This is especially pertinent when evaluating clay-mineral dominated mudstones, as water-rich sediment beds that are depositionally thicker than 1 cm may compact substantially (up to 90% compaction; Schieber, 2011a). However, it may not always be clear which structures are the result of a single genetic event. In this case, an effort should be made to make clear whether the description of a unit as an individual 'bed', or as 'laminae', is based on genetic interpretation or conventional thickness measurements.

3. Methodology

Detailed investigation of mudstones requires more intricate analyses when compared to their coarser-grained siliciclastic counterparts (e.g., sandstones). Lazar et al. (2015b) provide an idealized workflow for petrographic analysis of these fine-grained units. Petrographic examination has become the standard for mudstone analyses. Microscopic investigation of fine-grained units is paramount in understanding subtle compositional textural dynamics. However, even petrographic analysis has its complications. Standard thin section preparation methods involve the production of 30 µm thick samples. Generally, the bulk of the components in these fine-grained units

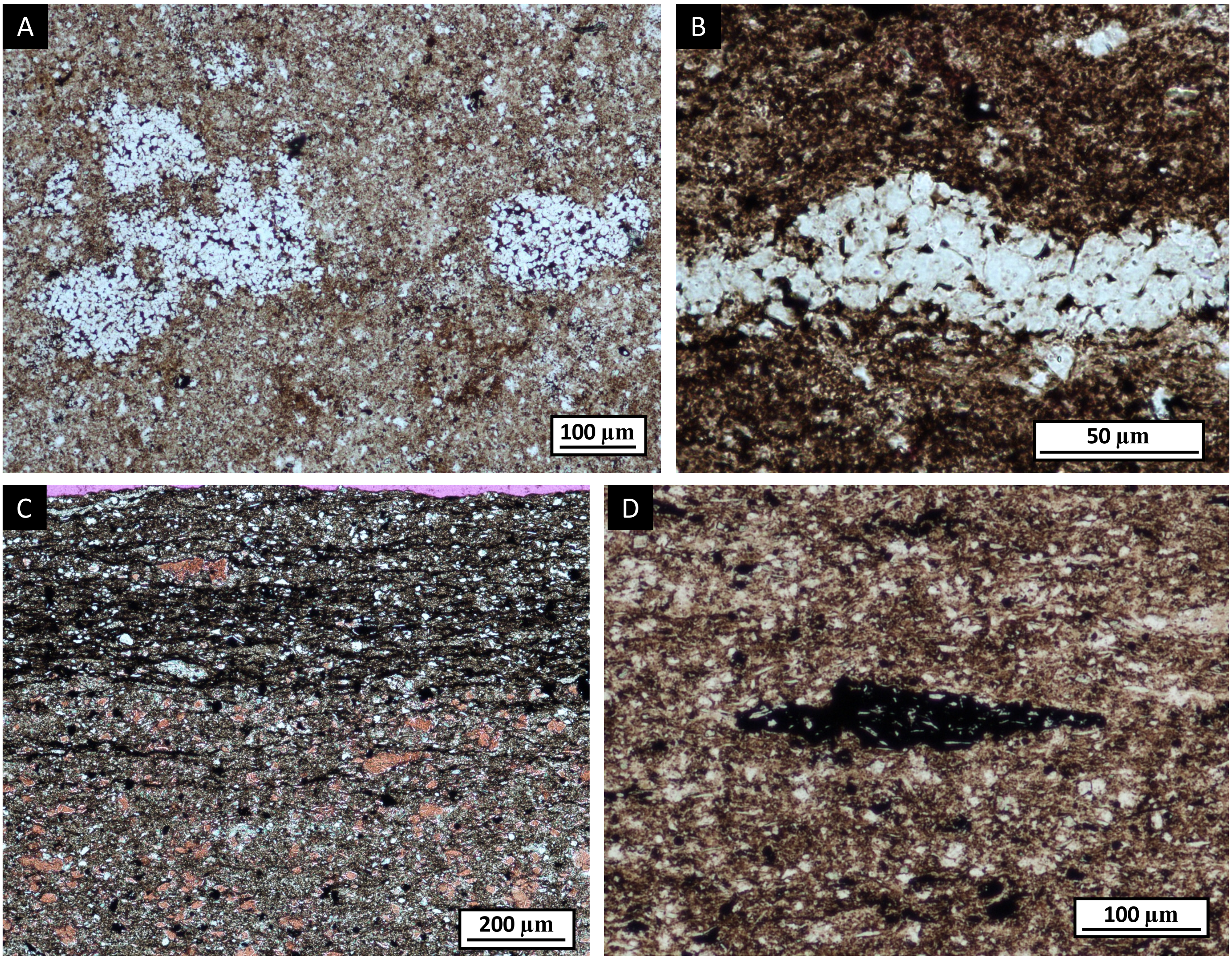

Figure 5 | Example photomicrographs of other potential composite particles. All examples are from the Horn River Group, NWT Canada. (A) Bedding plane view of several rafted silt aggregates. Paramount Energy MGM Shell East MacKay I-78 core (1835.00 m). (B) Cross section through a silt raft. Shows amalgamation of distinct individual quartz grains in an otherwise clay-rich matrix. Husky Little Bear N-09 core (1734.54 m). (C) Wispy accumulation of elongate organic matter. Represents possible sediment-rich microbial mat. Husky Little Bear N-09 core (1796.05 m). (D) Microbial mat rip-up fragment. Likely generated during erosive bottom currents, and encased in a thin clay-dominated storm bed. Husky Little Bear N-09 core (1710.08 m).

have maximum diameters smaller than 30 µm. Thus, when looking at standard thickness thin sections, individual grains cannot be identified (e.g., Milliken, 2014). The stacking of sub-30 µm particles in a single thin section inhibits the transmission of light. The result is thin sections that appear very dark, even when the light transmission settings are at their maximum. This has led to the standardization of 'ultra-thin' thin sections, with thicknesses of 20 µm for petrographic analyses of mudstones (Schieber, 1998; Macquaker & Adams, 2003; Macquaker et al., 2007; Macquaker et al., 2010b; Milliken, 2014; Lazar et al., 2015b; Percy & Pedersen, 2020; Biddle et al., 2021). Even so, ultra-thin thin sections can still appear dark, and isolating individual petrographic grain characteristics can be difficult (Milliken, 2014). Further, it is important to note that upon thinning of the thin sections, birefringence colors shift to higher-order colors.

For consistency in petrographic mudstone studies, it is suggested that all thin sections for a particular study are prepared in the same manner (e.g., ultra-thin, standard staining) at the same facility. This allows for the best comparison throughout a data set (single drill core/outcrop section or across multiple cores/outcrops). Preparing double-polished thin sections could help to eliminate mechanical defects (e.g., scratches, grain plucking) produced during the thin section preparation process, which may be mistaken for sedimentological and biogenic features (Schieber et al., 2021).

Furthermore, having both bedding perpendicular (elevation view) and bedding parallel thin sections from representative intervals is ideal for analyzing sedimentological and biogenic (e.g., ichnological) features in multiple orientations. For example, bedding parallel thin sections can help denote whether a lenticular feature in elevation view is a compacted intraclastic aggregate, or a cross section through a horizontal burrow trace (e.g., in bedding plane orientations burrows will be continuous laterally whereas composite particles are circular/ovoid). However, not all

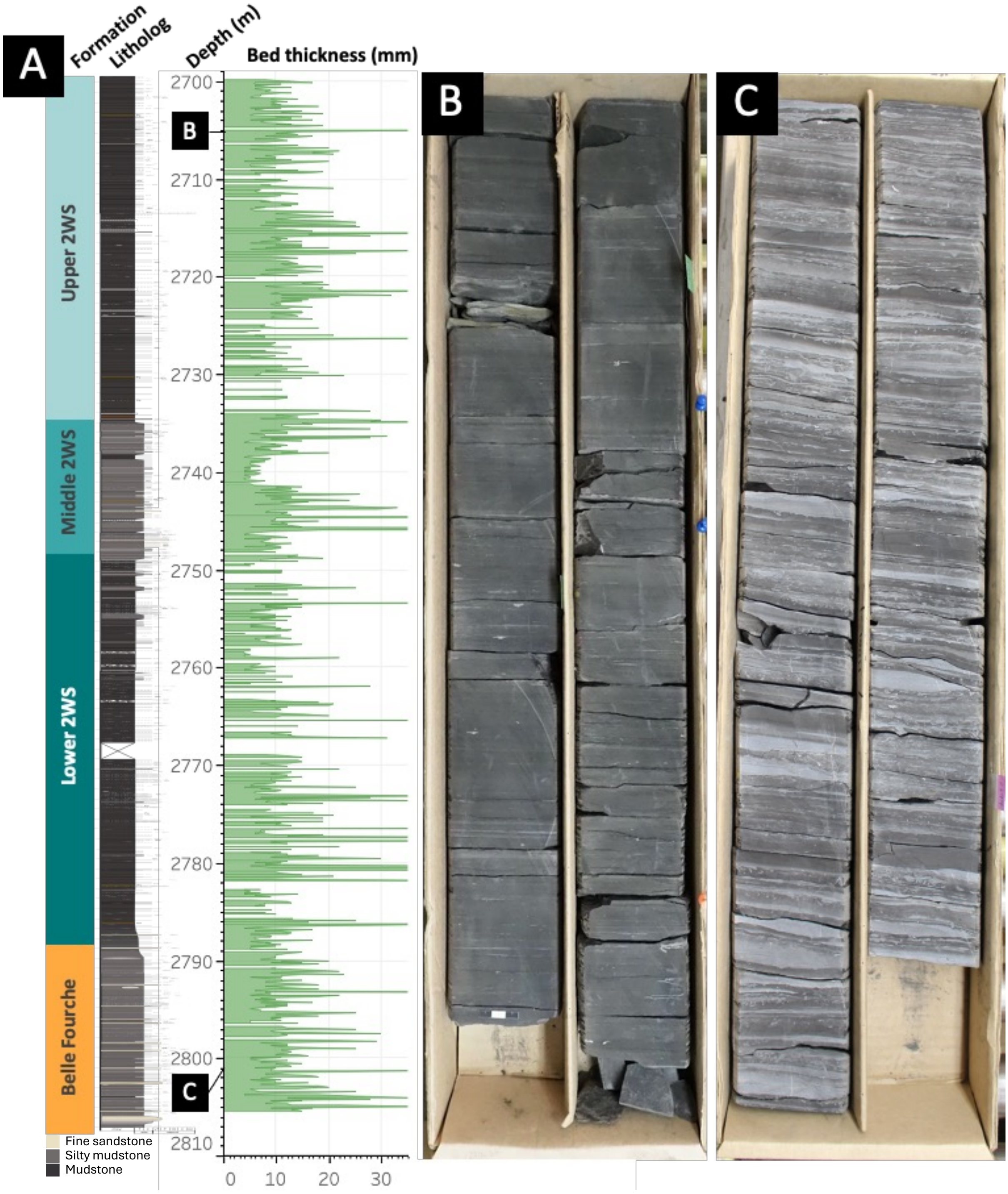

Figure 6 | (A) Litholog and maximum bed thicknesses (recorded in 10 cm bins) throughout the organic-rich mudstone Second White Specks Formation (2WS), Alberta (02.13-06-030-05W5/0). Bed thickness measurements were made through both homogeneous-appearing dark mudstone sections and silt-mineral-rich sections. (B) Representative box core photograph of homogeneous-appearing section. (C) Representative box core photograph of a macroscopically heterogeneous section.

features can be captured adequately or consistently by bedding parallel thin sections (e.g., ripples and microburrows), and thus bedding parallel thin sections work best in conjunction with elevation view thin sections.

High-resolution imaging, such as scanning electron microscopy (SEM) has become an increasingly popular analysis technique to assess compositional heterogeneity at scales smaller than deducible in ultra-thin thin sections. SEM analysis has been used to assess grain-to-grain relationships in part to determine depositional mechanisms. Reynolds and Gorsline (1992) for example used SEM analysis to determine if clay mineral grains were present as face-to-face stacks indicating suspension settling of individual particles, or present as edge-to-face aggregates indicating deposition and particle transport as composite grains. Li and Schieber (2018) used SEM imaging to identify distinct composite particle types, which aided in detailed interpretations of sediment depositional mechanics. High-resolution imaging has been used to assess the extent and products of diagenetic alteration (Milliken et al., 2007; Milliken et al., 2012; Dowey & Taylor, 2017). SEM imaging has also become standard practice in the identification of porosity types in organic-rich mudstones (e.g., Milner et al., 2010; Fishman et al., 2012; Han et al., 2016; Schieber et al., 2016; LaGrange et al., 2022). Milliken et al. (2007) used SEM imaging to identify benthic agglutinated foraminifera in the Barnett Shale, ultimately changing previous interpretations of depositional oxygenation. Microscopic bioturbation has also been investigated using SEM analysis (e.g., Egenhoff & Fishman, 2013; Löhr & Kennedy, 2015; Schieber & Wilson, 2021). The utility of SEM analysis in mudstone investigation is on par with that of petrographic analysis and can enhance interpretations deduced from thin section investigation. It is suggested that mudstone data should be documented and presented at both scales (e.g., both photomicrographs and SEM images of features should be available). Doing so will foster a universal better understanding of these features (e.g., the side-by-side petrographic and SEM images of the micro-burrow structures in Al-mufti et al., 2024).

With petrographic analysis and high-resolution imaging (SEM) being the two most omnipresent mudstone evaluation techniques, it may be useful to prepare ultra-thin thin sections with no coverslip or a removable coverslip, allowing samples to be analyzed both petrographically and under SEM. If geochemical datasets are integrated, it is recommended that analyses are performed on the actual rock samples taken for thin section and SEM analysis, otherwise direct comparisons may be difficult (e.g., bioturbation and diffusion of elements through pore waters can change chemical signatures over short distances; Scott & Lyons, 2012; Hülse et al., 2022; Löwemark & Singh, 2024).

3.1. Ichnology

Identification of bioturbation in mudstones has an appreciable impact on interpretations of the physicochemical stresses at play during the deposition of fine-grained sediments. Sediment-penetrating (infaunal) organisms require dissolved oxygen for respiration; therefore, their presence in sediments indicates some level of available dissolved oxygen at the time of burrow emplacement. Historically, organic-rich, seemingly laminated mudstones are interpreted to accumulate under anoxic bottom waters (e.g., Pedersen & Calvert, 1990), and thus the documentation of infaunal animal colonization is paramount in fine-tuning depositional oxygenation conditions.

Macroscopic bioturbation can be difficult to recognize in organic-rich mudstones due to a general lack of lithologic contrast between burrow fills and the surrounding matrix (e.g., Paz et al., 2023). Microscopic bioturbation is even more difficult to recognize and has only recently become an increased topic of study. The following discussion focuses on the methods of identification and quantification of microscopic biogenic reworking in mudstones.

Microscopic bioturbation is the result of sediment deformation by burrowing meiofauna, where meiofauna are variably defined as 42 µm – 500 µm (Fenchel, 1978; Giere, 1993, 2009); <300 µm (Pike et al., 2001); and 38 µm – 1 mm (Grego et al., 2014; Parry et al., 2017). The sub-millimeter diameters of meiofaunal burrows mean they cannot readily be recognized in hand sample, thus the influence of meiofauna is assessed most easily through petrographic analysis (Table 3, Figures 7 and 8).

Microbioturbation in thin section can be recognized by disturbances of the laminated or bedded sediment, including vertical interruptions in horizontal laminae (Figures 7, 8A and 9C) (e.g., the fragmentation and deformation described by and seen in Figure 2-P3 by Löhr & Kennedy, 2015; and experimentally achieved by Schieber & Wilson, 2021), discontinuous horizontal homogenization along bedding planes in bedding perpendicular thin sections (representing sinuosity or oblique cuts through horizontal trace fossils) (Figure 7C and 8C) (Macquaker et al., 2010b; Egenhoff & Fishman, 2013; Biddle et al., 2021), vertically or horizontally aligned outsized grains, paired parallel strings of grains interpreted as linings (Figures 7B and 8B) (Macquaker & Gawthorpe, 1993; Egenhoff & Fishman, 2013; Biddle et al., 2021), and general sediment homogenization (Figure 9A, B) (Macquaker & Gawthorpe, 1993; Macquaker et al., 2010b; Biddle et al., 2021; Schieber & Wilson, 2021). Micro-traces may also be recognized by focussed authigenic alteration, such as selective or preferential pyritization or calcification of burrow structures (Figures 7D and 8D) (Schieber, 2002, 2003; Egenhoff & Fishman, 2013; Parry et al., 2017; Biddle et al., 2021). In the absence of clearly identifiable meiofaunal burrows, benthic meiofaunal fecal pellets can be used as lines of evidence for microbioturbation; recognized as densely compacted organic-matter-rich oval to elongate pellets (<300 µm), occasionally incorporating the smallest material fraction from the surrounding sediment (Löhr & Kennedy, 2015). It may be worthwhile to note that the effects of microbioturbation as a whole may present macroscopically as homogeneous-appearing sediments in hand sample (as opposed to the well-laminated sediments typical of organic-rich mudstones) (Figure 9).

Previous studies have used Micro-CT (Zou et al., 2015; Parry et al., 2017) and petrography (e.g., Egenhoff & Fishman, 2013; Biddle et al., 2021) to analyze potential burrow networks in mudstones. Several types of meiofaunal burrows have been interpreted (Knaust, 2007; Egenhoff & Fishman, 2013; Parry et al., 2017; Biddle et al., 2021). At such fine scales it is difficult to employ known ichnotaxonomy, as micro-scale trace fossils often lack attributes necessary to fit them into particular classes or known ichnogenera. For example, one potential micro-trace fossil identified separately in four publications was described differently by each individual: 'irregularly-bended minute trails' (Knaust, 2007), '*Phycosiphon incertum* type B' (Egenhoff & Fishman, 2013), '*Multina minima*' (Parry et al., 2017), and 'sinuous trails' (Biddle et al., 2021). In this example, it is evident that the 'irregularly-bended minute trails' of Knaust et al. (2007) and the 'sinuous trails' in Biddle et al. (2021) are likely describing similar features. Further, these

Sedimentary Feature		Interpretation	Examples
A	Vertical or horizontal structures that disrupt or homogenize laminae	Unlined burrows that result in the shifting of sediment grains away from the migration path of the organism.	Egenhoff & Fishman, 2013 (Figures 6A, B and 8C); Biddle et al., 2021 (Figures 4, 9B and 10B); Schieber & Wilson, 2021
B	Vertical or horizontal paired parallel strings of aligned grains	Pseudo-linings created by grain-selective feeding or migration of coarse-grained fraction to burrow margins during burrow construction.	Egenhoff & Fishman, 2013 (Figure 6E)
C	Circular, sinuous, or punctuated often lighter-colored zones	Discontinuous horizontal homogenization along bedding planes, representing sinuosity or oblique cuts through horizontal trace fossils. Biogenic homogenization of ingested sediment and preferential removal of darker-colored organic matter, often showing selective ingestion of a particular sediment fraction.	Macquaker et al., 2010b (Figure 1B); Plint et al., 2012 (Figure 12a); Egenhoff & Fishman, 2013 (Figures 4 and 8E); Biddle et al., 2021 (Figure 3H)
D	Focused authigenic alteration	Selective or preferential pyritization or calcification of burrow linings or fill.	Schieber, 2003 (Figure 3); Egenhoff & Fishman, 2013 (Figure 5); Parry et al., 2017 (Figures 2 and 3)
E	Concentrically aligned grains	Tangential compression of sediment as an organism burrows via peristaltic waves (peristalsis).	Ulmer-Scholle et al., 2014 (Up. Cretaceous Monte Antola Fm., Liguria, Italy, pg. 190); Biddle et al., 2021 (Figure 3E)
F	Ovoid to round aggregates of densely packed material	Benthic fecal pellets composed of organic matter combined with material sourced from the surrounding matrix. May contain a discrete mix of material reflecting selective feeding strategies.	Löhr & Kennedy, 2015
G	Sediment homogenization (absence of primary sedimentary structures)	Complete sediment homogenization due to the pervasive burrowing and grain reorganization of meiofauna.	Egenhoff & Fishman, 2013 (Figure 6D); Biddle et al., 2021 (Figure 9C, D); Schieber & Wilson, 2021 (Figure 1E, F)

Table 3 | Petrographic sedimentary features attributed to burrowing activity of meiofaunal organisms. Left-side letter designations match the letters on Figures 7 and 8.

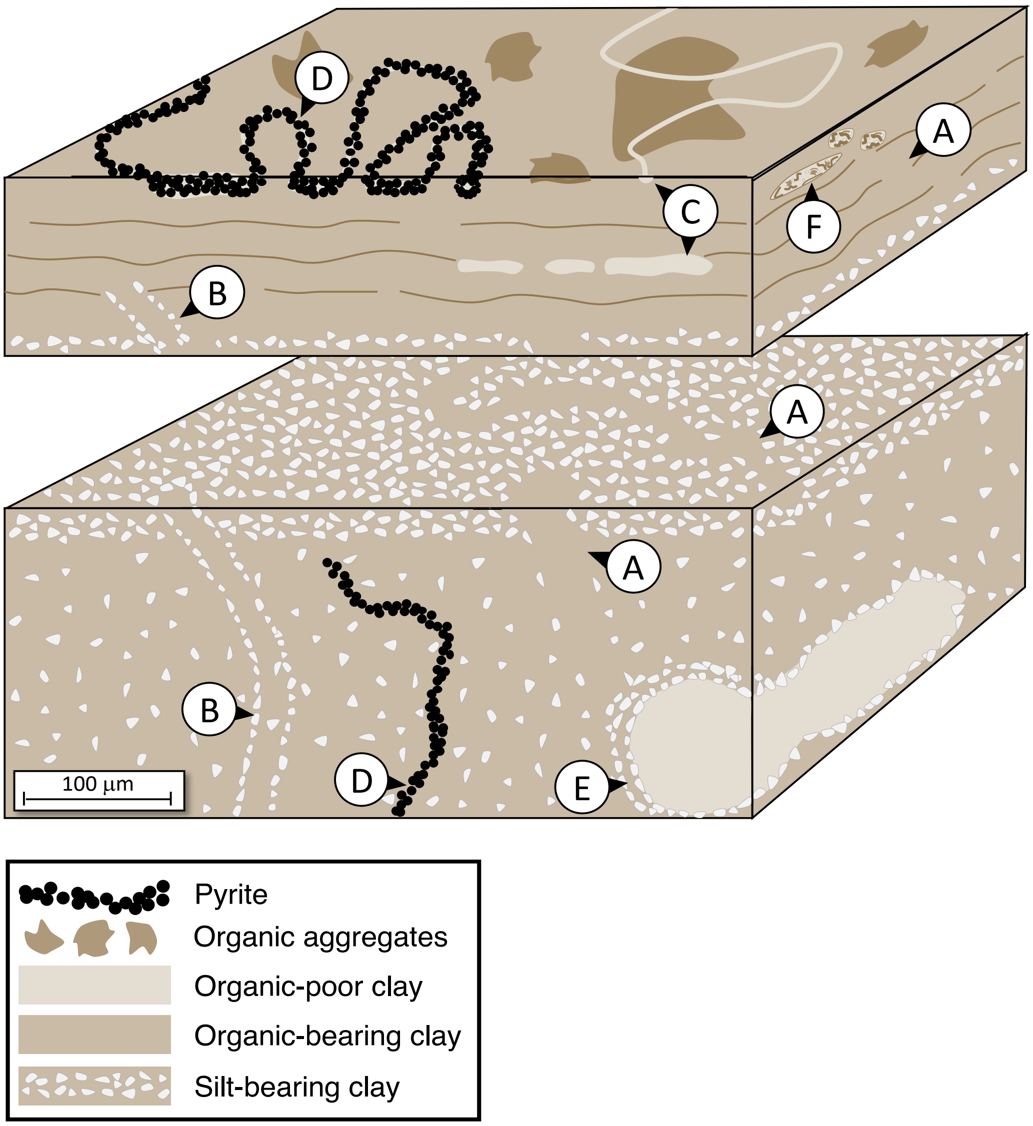

Figure 7 | Schematic diagram of the morphological characteristics of microbioturbation in thin section. Letter labels correspond to the features described in Table 3 and Figure 8. (A) vertical or horizontal structures that disrupt or homogenize laminae, (B) vertical or horizontal paired parallel strings of aligned grains, (C) circular, sinuous, or punctuated often lighter-colored zones, (D) focused authigenic alteration, (E) concentrically aligned grains, (F) ovoid to round aggregates of densely packed material.

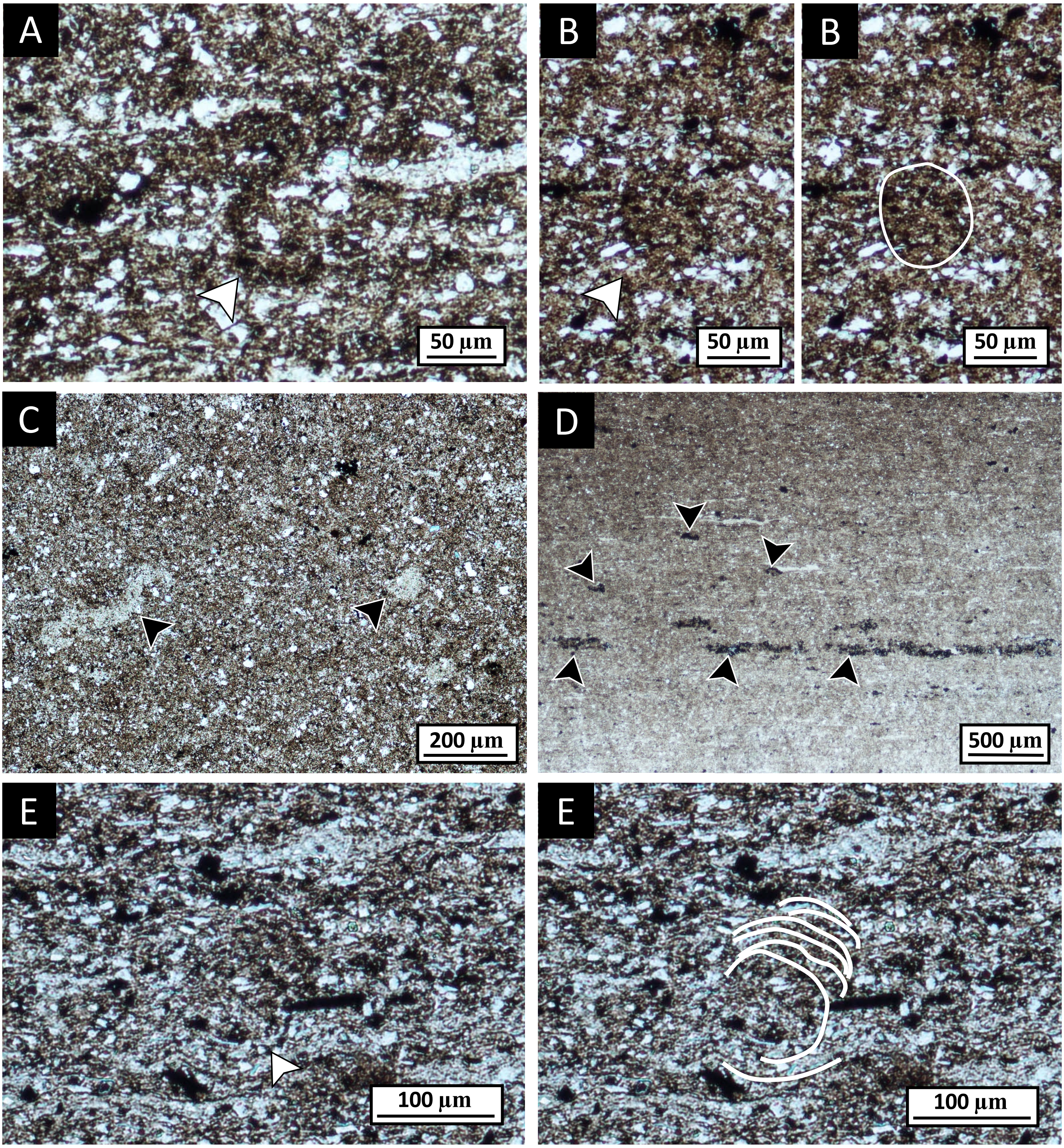

Figure 8 | Representative photomicrographs of morphologically distinct micro-traces. More examples of each can been found in (Biddle, 2020 Appendix C). All photomicrographs are from the Horn River Group, NWT, Canada. Letter labels match the features described in Table 3 and illustrated on Figure 7. (A) Vertical structure that disrupts surrounding matrix organization (white arrow). Husky Little bear N-09 core (1701.91 m). (B) Aligned grains around a burrow margin, illustrated by white arrow (left) and annotated burrow outline (right). Husky Little Bear N-09 core (1722.63 m). (C) Circular and sinuous punctuated lighter-colored zones (black arrows). Paramount Energy MGM Shell East MacKay I-78 core (1841.00 m). (D) Focused authigenic pyritization along punctuated horizontal burrow (black arrows). Husky Little Bear H-64 core (1180.27 m). (E) Concentrically aligned grains around a tangentially-compacted burrow, illustrated by the white arrow (left) and the annotated compacted burrow margin (right). Husky Little Bear N-09 core (1703.54 m).

features are markedly similar to the sinusoidal burrows and sinuous tubes produced by modern nematode meiofauna (e.g., Pike et al., 2001; Schieber & Wilson, 2021). Given the limitations of ichnotaxonomy, which include some dependence on sediment contrast and that holotypes are invariably macroscopic, morphological classification is perhaps the ideal way to characterize very small burrows and permits consistency between studies.

Additionally, microscopic bioturbation is difficult to quantify on the widely used 0-6 Bioturbation Index scale (BI) (Taylor & Goldring, 1993) and the 1-6 Ichnofabric Indices (II) (Droser & Bottjer, 1986). This is due to the

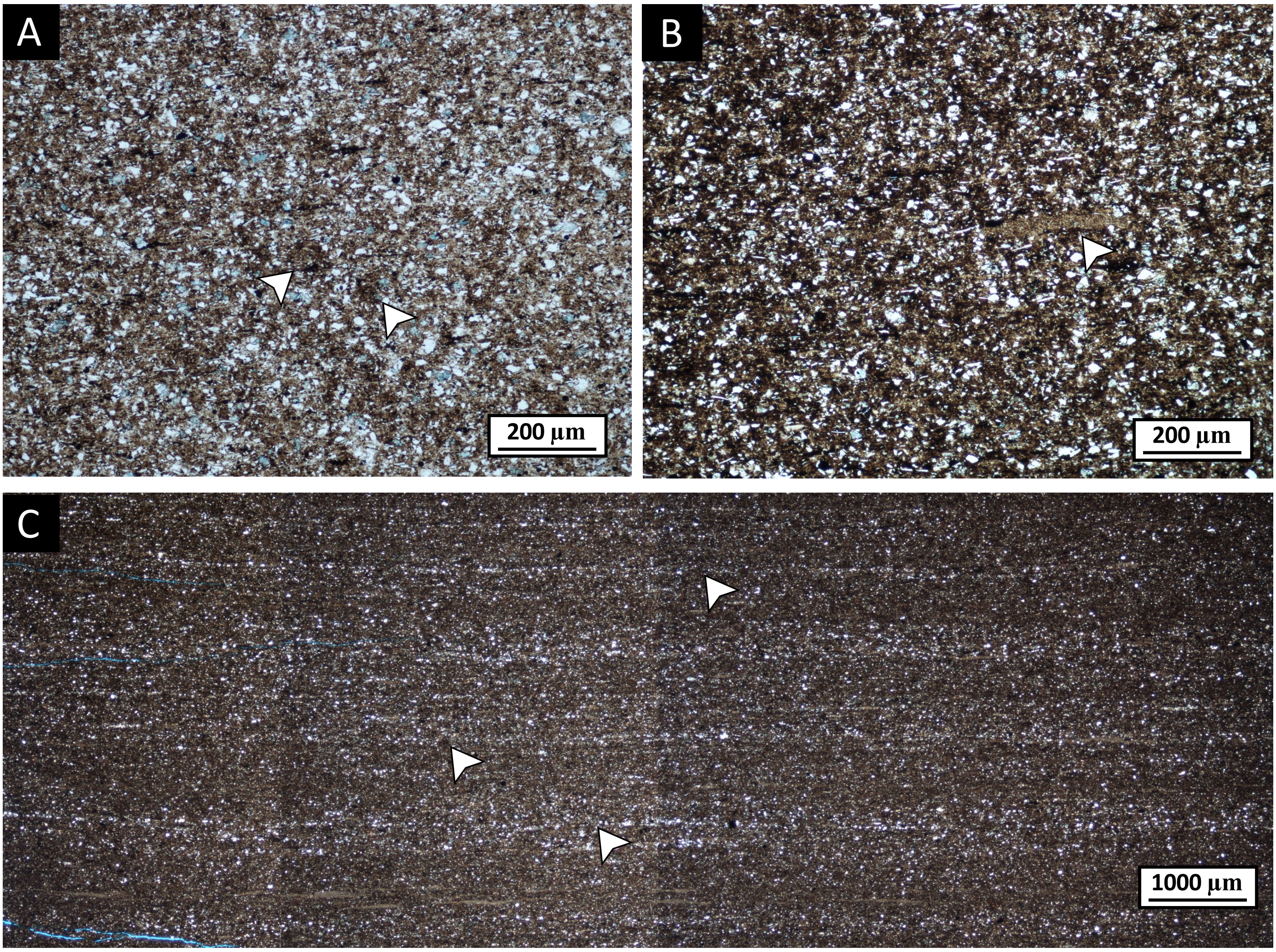

Figure 9 | General sediment character of microbioturbated mudstone beds. (A) Completely biogenically homogenized area. A few potential microburrows (white arrows) can be identified, likely owing to the prevalence of silt-minerals increasing burrow preservation potential. Horn River Group, NWT Canada, Husky Little Bear H-64 core (1214.64 m). (B) Complete biogenically reworked area with one obvious microburrow showing homogenized infill (arrow). Same thin section as (A). (C) Photomicrograph mosaic of discontinuous silt-mineral laminae resulting from partial bioturbation. Arrows indicate obvious areas of laminae interruption. Horn River Group, NWT Canada, ConocoPhillips Mirror Lake N-20 core (1910.44 m). In hand sample these beds would likely be misinterpreted as continuous plane parallel laminae.

difficulty associated with visually assessing deformation to primary sedimentary structures in thin section, where primary fabric destruction is the basis on which the BI and II are evaluated. Most often, thin sections are simply not large enough to show a representative example of the deformed primary structures, and the scale of lamination often exceeds the scale of the microscopic burrows (e.g., in cases of microscopic 'lam-scram' bioturbation, where only the tops of even the thinnest beds are reworked). Furthermore, the lack of lithologic contrast and the commonly dark appearance of mudstones in thin sections hinders the assessment of primary structure interruption. Instead, the extent of microbiogenic deformation may be quantified using the intensity of bioturbation (IB%), expressed as a percentage (0% - 100%) of sediment affected by biogenic reworking (e.g., Biddle et al., 2021).

Microbioturbation can be elusive when simply described from a photomicrograph. Even with indicating arrows these features may be difficult to see (e.g., Figure 8). For ease of presentation and reader understanding, it is strongly recommended to include dual images for presented photomicrographs with elusive microburrows: one original and one annotated (Figures 8B, 8E and 10) (e.g., Egenhoff & Fishman, 2013; Biddle et al., 2021; Schieber et al., 2021). If photoplate space is limited, a single photomicrograph with dashed outlines or half-annotated burrows (e.g., right-side outlined) may be sufficient (e.g., Schieber et al., 2021), bearing in mind that this may inadvertently guide the reader's eyes and obscure contacts.

Despite the use of petrographic microichnological analysis, analyzing bioturbation in organic-rich mudstones is inherently problematic. This is due to the difficulty associated with confidently identifying biogenic features from dewatering and other forms of soft sediment deformation, obscuring due to compaction, and a general lack of lithologic contrast (Schieber, 2003; Egenhoff & Fishman, 2013; Biddle et al., 2021). Thin section defects, such as scratches or bubbles in the epoxy can also potentially cause misinterpretations of biogenic influence (e.g., Schieber et al., 2021). However, these mechanical

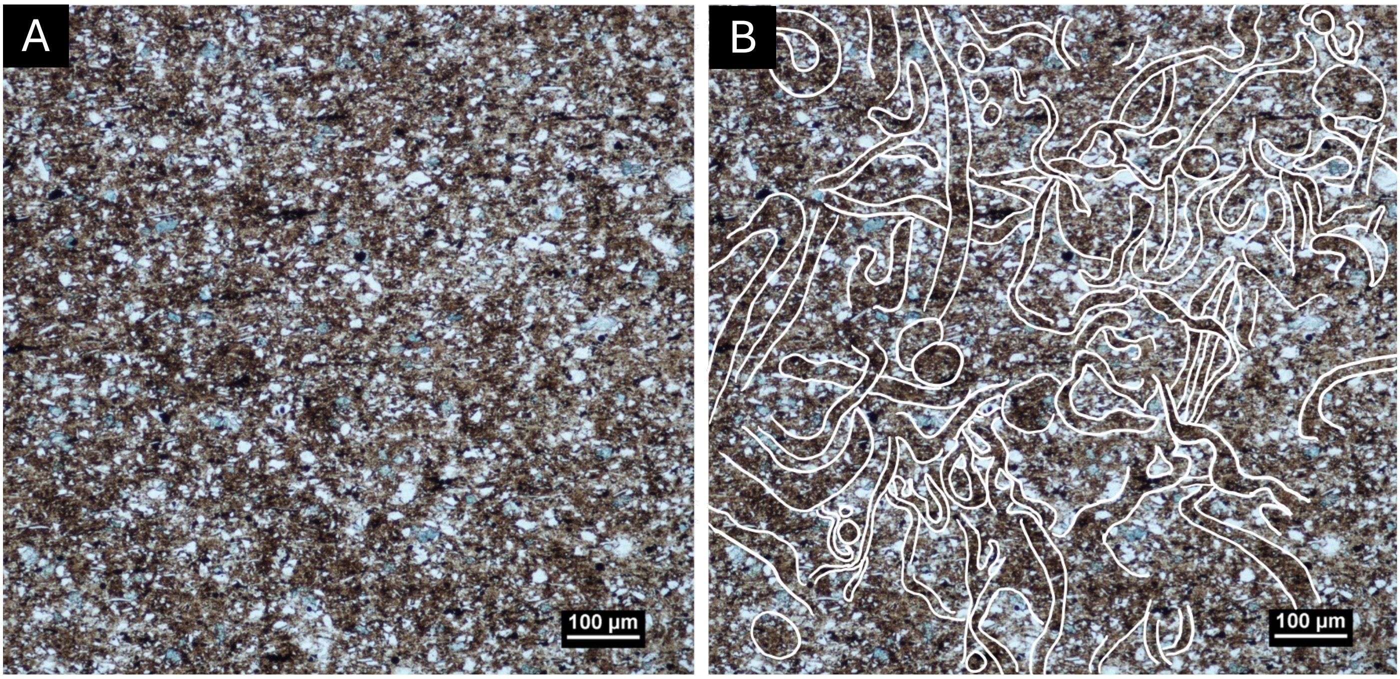

Figure 10 | Photomicrographs of an intensely micro-burrowed mudstone (IB% = >70; same thin section as Figure 7A and B) illustrating the utility of accompanying annotated photos. Traces are dominated by sinuous tunnels of Biddle et al. (2021). (A) Original photomicrograph. (B) Annotated photomicrograph with interpreted burrow outlines. Horn River Group, NWT Canada, Husky Little Bear H-64 core (1214.64 m).

artifacts are more easily identified than the previously discussed primary sedimentary features. Again, petrographic burrow traces should be interpreted based on disruption of primary fabric (e.g., lamination, aligned orientation of detrital or biogenic components). Artifacts such as bubbles in epoxy or scratches on either side of a thin section will not result in a disruption of primary fabric, but rather an overlay of features, often represented as darker areas. Finally, scratches are typically represented by continuous, fine straight features; something uncommon of biogenic features. Following the previously discussed thin section preparation methods and those discussed in Schieber et al. (2021) will help to eliminate many of these preparation artifacts. For example, double polishing will eliminate bubbles and scratches (Schieber et al., 2021), leaving only the intrinsic sedimentological and biogenic deformation features remaining (it is arguable that the double polished sections in Fig. 17 of Schieber et al. (2021), which they argue show no evidence of biogenic reworking, still show the sinuous features interpreted by others as microscopic traces).

Arguments have been made referencing the arbitrary nature of identifying individual microscopic burrows due to the common cross-cutting nature of the features, and the inherent difficulty of following one continuous burrow path (e.g., Schieber et al., 2021). The common cross-cutting nature of microscopic burrows indeed makes it difficult to follow the 'true' path of a particular trace. In some instances, the same individual may identify burrow systems differently upon a secondary inspection (e.g., Schieber et al., 2021). However, seeing individual burrows differently over time does not discount the fact that they are biogenic shafts or tunnels. Additionally, they indicate some form of sediment homogenization has occurred. It is also true that in some sediments, meiofaunal bioturbators may be of similar sizes to the sediment grains they are moving between. In such cases, where sediments behave granularly, migration of meiofaunal organisms results in small displacements of individual grains rather than the construction of well-formed burrows (Dorgan et al., 2006; Dorgan, 2015). In these instances, evidence for meiofaunal reworking may be reflected, again, as general unexpected sediment homogenization. Compaction experiments of meiofaunally bioturbated pure kaolinite clay mixtures (85% compaction) have shown that sub-horizontal burrows collapse readily under initial compaction to a point where identification of such features in ancient samples would be difficult, if not impossible (Schieber et al., 2021). However, sub-vertical burrows retain nearly original burrow diameters but show foreshortened lengths (Schieber et al. 2021). As should be expected with a pure kaolinite mixture lacking any lithologic contrast, identification of any sedimentary or biogenic feature post-lithification would be difficult. However, ancient microburrows identified in previous studies have been dominantly sub-vertical in elevation view, consistent with the compaction experiments (e.g., Egenhoff & Fishman, 2013; Ma et al., 2016; Borkovsky et al., 2017; DeReuil & Birgenheier, 2019; Biddle et al., 2021). Further, all published interpretations of ancient meiofaunal burrows have been noted from sediments that contained a significant silt-mineral proportion, which would limit total compaction while providing the necessary compositional contrast to be able to identify such features petrographically. An expanded discussion of the difficulties and criticisms associated with petrographic microburrow identification can be found in Biddle et al. (2021).

Organic-rich mudstones are historically considered the product of deposition under anoxic conditions and are thought to be devoid of evidence for benthic infaunal marine life. A lack of evidence for macroscopic biogenic reworking can contribute to misinterpretations of oxygen-deprived paleoenvironmental conditions. It is incomplete to assume all organic-rich mudstones lacking evidence for macroscopic burrowing will also be devoid of evidence for burrowing meiofauna (e.g., Egenhoff & Fishman, 2013; Löhr & Kennedy, 2015; Baucon et al., 2020; Biddle et al., 2021; Schieber & Wilson, 2021). There is research to suggest that seemingly unbioturbated organic-rich mudstone intervals at the macroscopic scale are in fact bioturbated at the microscopic level. Microichnological analysis has been used to redefine depositional oxygenation on units previously thought to represent anoxic settings (e.g., Egenhoff & Fishman, 2013; Löhr & Kennedy, 2015; Baucon et al., 2020; Biddle et al., 2021; Schieber & Wilson, 2021). Implementing microichnological analysis as standard practice in mudstone evaluation may trigger re-evaluations of depositional oxygenation in previously assessed units and will lead to a more complete understanding of physicochemical depositional conditions in future mudstone investigations. However, presently it is difficult to gain consensus on what is and is not relict microbioturbation, and thus the physicochemical interpretations that stem from such microichnological studies are not agreed upon. As with all studies, the best practice is to integrate findings of microichnological analysis with other data sets (e.g., geochemical proxies).

3.2. Microfacies

Microfacies analysis is a technique used in petrographic mudstone studies to complement and enhance traditional lithologic facies descriptions, which may be difficult to denote in organic-rich fine-grained rocks (Bohacs, 1998; Potter et al., 2005; Macquaker et al., 2007), and whole-rock geochemical techniques, which may homogenize data over several heterogeneous thin beds (Macquaker et al., 2007). Microfacies analysis involves the petrographic categorization of compositional, textural, and ichnological attributes (including the microichnological features described previously) of sedimentary units that may not be visible with the naked eye. Microfacies are most useful in reconstructing fine-scale physicochemical fluctuations during deposition, at and just below the sediment-water interface.

With the aim of this paper being universal best practice, it is relevant to discuss microfacies terminology. The term 'microfacies' itself does not have a well-defined scale. Originally defined as petrographic and palaeontologic criteria recognized in thin sections (Brown, 1943); more recently, microfacies are considered to represent "the total of all sedimentological and paleontological data which can be described and classified from thin sections, peels, polished slabs or rock samples" (Flügel, 2004; page 1). Most descriptions of microfacies from mudstone studies do however reserve the term strictly for petrographic observations (e.g., Schieber & Zimmerle, 1998; Dawson, 2000; Macquaker et al., 2010b; Jennings & Anita, 2013; Plint, 2014; Zou et al., 2015; Dowey & Taylor, 2017; Newport et al., 2018; Biddle et al., 2021). Yet, some studies assign a quantitative value to their definition. For example, Percy and Pedersen (2020) define their microfacies based on what they refer to as "the laminae scale (<1 cm)". A problem with this is the strict definition of laminae, which for mudstones should be scale-independent and defined on genetic interpretation (e.g., Campbell, 1967; Macquaker et al., 2010b; Lazar et al., 2015b; Ilgen et al., 2017). To some degree, all facies analyses (no matter the scale) are based on the details of the beds. However, it is difficult, if not impossible, in many mudstone intervals to identify bed-scale features in hand sample (the typically applied scale of 'lithofacies', e.g., Figure 11). In simple terms, the 'lithofacies scale' used in mudstones may describe general characteristics (e.g., color, diagenetic features, biologic components, fissility, and bed scale features *if visible*) over an interval. In contrast, the microfacies describe the true bedding character at a particular point.

Preferred methods of microfacies investigation can differ between individual investigators and separate studies. Samples selected for thin section preparation are often chosen at intervals of macroscopic lithologic interest, as opposed to sampling at standard pre-selected depth intervals. The reason for this is twofold: 1) petrographic microfacies are generally used to complement mudstone studies and are not the primary focus, and 2) thin section preparation can be costly and time-consuming. Petrographic samples taken from random lithologic intervals of interest will not be representative of continuous changes throughout a core or outcrop section.

Non-depth-standardized petrographic microfacies analysis is still highly useful for evaluating a mudstone unit's true compositional and textural characteristics. However, it does not offer constraints on temporal microfacies changes. To address this, some mudstone studies have incorporated standardized depth-selected microfacies sampling into their analyses (e.g., Percy & Pedersen, 2020). However, both approaches (standardized and non-standardized depths) are inherently point-sampling analytical methods. In the pursuit of best practice, it is encouraged to implement depth-standardized thin section analysis when possible. Further, standardizing depths at which both bedding parallel and bedding perpendicular thin sections are prepared may help to denote individual microfacies. Alternatively, bedding parallel thin sections may be created after microfacies have been interpreted from bedding perpendicular thin sections. This will help with a complete understanding of individual microfacies (e.g., can help to further understand any primary sedimentological features, or the intensity of microbioturbation and the morphology of any micro-trace fossils present).

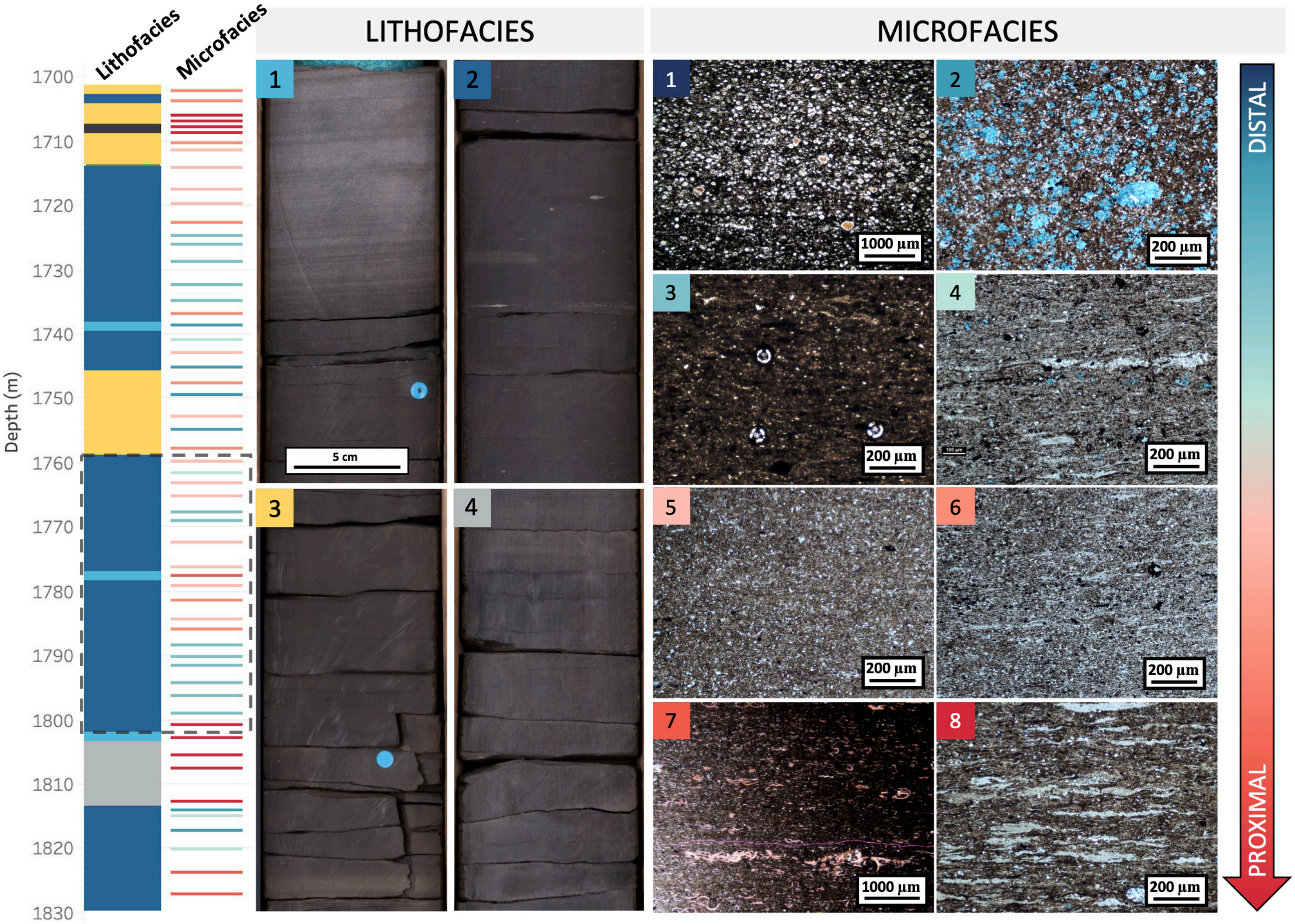

Figure 11 | Visual comparison of lithofacies and microfacies distributions throughout the Horn River Group organic-rich mudstone (Husky Little Bear N-09 core). Left: lithofacies and microfacies distributions over a single drill core. Middle: representative photographs of the four lithofacies identified. Right: representative photomicrographs of the eight microfacies identified in thin sections from this core. Microfacies analysis shows refined insight into thick continuous sections of a single macroscopic lithofacies (e.g., outlined section on the data log to the left shows six different microfacies within a single lithofacies) (Biddle et al., 2021; LaGrange et al., 2022). This figure illustrates the utility of microfacies analysis, for detailed facies descriptions and interpretations see Biddle et al. (2021) and LaGrange et al. (2022).

One current debate entwined with microfacies analysis is whether this point sampling method is representative of continuous temporal changes in fine-scale physicochemical depositional conditions (e.g., representative of an entire core or outcrop section). Percy and Pedersen (2020) assessed this sampling bias in an organic-rich mudstone by comparing continuous visual facies logged at a 5 mm scale to point-sampled locations at 50 cm increments over the length of a 100 m drill core. They found that the relative abundance of each facies quantified using continuous *versus* point-sampling was similar, suggesting that the point-sampling method inherent to microfacies analysis is not as misrepresentative as previously thought. However, the point sampling became progressively less representative in units with an increasing number of unique facies. One major discrepancy was that the point sampling method was not able to capture an upward increase in occurrences of certain facies if the point-sampling depth continuously misaligned with thin facies occurrences. This underrepresentation of particular facies is easy to correct if elements of these petrographic facies are macroscopically identifiable and quantifiable during traditional litho-logging (e.g., in the case of Percy & Pedersen, 2020). Nonetheless, if an organic-rich mudstone drill core lacks macroscopically identifiable indications of heterogeneity, point sampling microfacies provides the most insight into detailed physicochemical depositional conditions. One example of this is the Horn River Group mudstones in the Northwest Territories of Canada, where traditional lithofacies identification does not provide significant insight into the inherent heterogeneity of a macroscopically homogeneous mudstone (Figure 11) (Harris, 2020; Biddle et al., 2021; LaGrange et al., 2022).

A second inherent problem with microfacies analysis is the correlation of facies at these sub-centimeter scales. Correlating microfacies between thin sections from separate cores or outcrops is exceedingly difficult, if not impossible. This was demonstrated by Plint (2014), when correlating such millimetre-scale beds between two points on the same rock sample, spaced only 20 mm apart was unmanageable due to localized scour and fill and millimetre-scale lateral facies changes.

Despite these pitfalls, it has been shown that microfacies analysis greatly contributes to the understanding of paleodepositional conditions and depositional processes responsible for mudstone accumulation (e.g., Egenhoff & Fishman, 2013; Lazar et al., 2015b; Percy & Pederson 2020; Harris, 2020; Biddle et al., 2021; LaGrange et al., 2022).

4. Depositional processes

The conditions leading to the accumulation of fine-grained sediments are conventionally understood to be deposition in low-oxygen, low-energy settings. The seemingly parallel laminated nature of organic-rich mudstones confirms such interpretations. However, advancements in analytical techniques (e.g., high-powered slow-motion cameras used to capture results of flume experiments, scanning electron microscopy imaging for analysis of matrix compositions) have sparked a re-thinking of the depositional processes responsible for such deposits. Flume experiments have led to the identification of unidirectional ripples forming from homogeneous kaolinite clay suspensions (Schieber et al., 2007a), micro-scale rip-up clasts (e.g., composite particle intraclastic aggregates) forming from semi-consolidated kaolinite (Schieber et al., 2010), and several types of fine-grained low-density sediment gravity flows resulting in thin beds (<1 cm thick) (Baas et al., 2009; Sumner et al., 2009). Mud ripples in modern marginal marine settings have since been observed (Shchepetkina et al., 2018). Notably, petrographic analyses of various mudstones have confirmed that these features do appear in ancient natural deposits (e.g., lenticular fabrics identical to the rip-up clasts described in flume experiments; Schieber et al., 2010; Plint et al., 2012; Ulmer-Scholle et al., 2014; Biddle et al., 2021). Petrographic analyses have also revealed several sedimentary structures interpreted as the result of relatively high-energy deposition (Figures 12 and 13). For example: the presence of seemingly plane parallel laminae that thin and swell, interpreted as the result of variable bed load deposition under bottom currents (Schieber & Southard, 2009); scour surfaces and normally graded beds indicating increased bottom current energies and waning flow deposition (Figure 12C, D) (e.g., Ulmer-Scholle et al., 2014, Biddle et al., 2021); micro-scale lag deposits (Figure 12B) (Schieber, 1994; Schieber, 1998; Egenhoff & Fishman, 2013); wave-enhanced sediment gravity flows (WESGFs) (Figure 12A) (Macquaker et al., 2010a); and tempestites or low-density flows (Figure 12E) (Abbott, 2000). Additionally, Bhattacharya and MacEachern (2009) used macroscopic techniques to show that previously studied ancient mud belts may represent rapid and high-energy accumulation of prodeltaic muds through hyperpycnal flows. It is now broadly accepted that all of these features contradict previous notions of mudstones forming solely from quiescent suspension settling in distal settings. Many of these structures indicate direct sediment reworking by wave energy (commonly storm-generated). Accordingly, numerous mudstones previously interpreted to represent deep water quiescent deposition may be the result of relatively high energy and/or shallow water deposition (depositional energies high enough to transport mudstone constituents through bedload (e.g., 10 to 26 cm/s in Schieber & Southard, 2009).

5. Organic matter enrichment

A large, and probably the most popular, sub-type of mudstones are those that are 'organic-rich'. It is important to note that organic-rich mudstones are no different from 'regular' mudstones, beyond their carbon-rich character. All concepts discussed thus far apply to both organic-rich mudstones and mudstones in general.

Mudstones which have total organic carbon (TOC; a measure of organic matter enrichment) contents ranging between 2-25% are generally considered enriched and can be referred to as organic-rich or carbonaceous (Lazar et al., 2015a, b). It is commonly accepted that the elevated organic matter content in organic-rich mudstones is the result of slow hemipelagic suspension settling, paired with persistently anoxic/euxinic bottom waters (Figure 14A) (e.g., Demaison & Moore, 1980; Pratt, 1984; Canfield, 1989; Pedersen & Calvert, 1990). This is owing to the understanding that under an absence of available dissolved oxygen, less efficient anaerobic organic matter degradation prevails, resulting in a build-up of refractory material (e.g., Canfield, 1994). However, mudstones are compositionally more heterogeneous and depositionally more dynamic than previously understood. It therefore stands that the mechanisms leading to organic enrichment are more complex than formerly thought. Bottom water anoxia as the sole mechanism for organic matter preservation within organic-rich rocks has been countered by Pedersen and Calvert (1990), Schieber (1998), Sageman et al. (2003), Ghadeer and Macquaker (2012), Egenhoff and Fishman (2013), Borcovsky et al. (2017), Percy and Pedersen (2020), Biddle et al. (2021), and many more. Bohacs et al. (2005) summarize three mechanisms contributing to organic matter enrichment in mudstone units: production, destruction, and dilution (e.g., Figure 14). All mudstones have the potential to become organic-rich, and it is the interplay of the three that determines if they do. The simple tripartite production-destruction-dilution model can be further broken down into several individual factors (Table 4). Many of these factors are well summarized in Arndt et al. (2013). Using the mechanisms put forth by Bohacs et al. (2005) organic enrichment in mudstones can be the result of any combination of production, destruction, and dilution; and the relative contribution of each factor may fluctuate over the depositional lifetime of a unit.

5.1. Production

Production is an all-encompassing topic, including all biogenic silica, carbonate, and organic matter produced within a basin. Specifically, organic matter production can be thought of in two facets: 1) quantity and 2) quality. Quantity simply refers to the total amount of photosynthetic organic matter formed by organisms in surface waters (Bohacs et al., 2005). We have elected to include

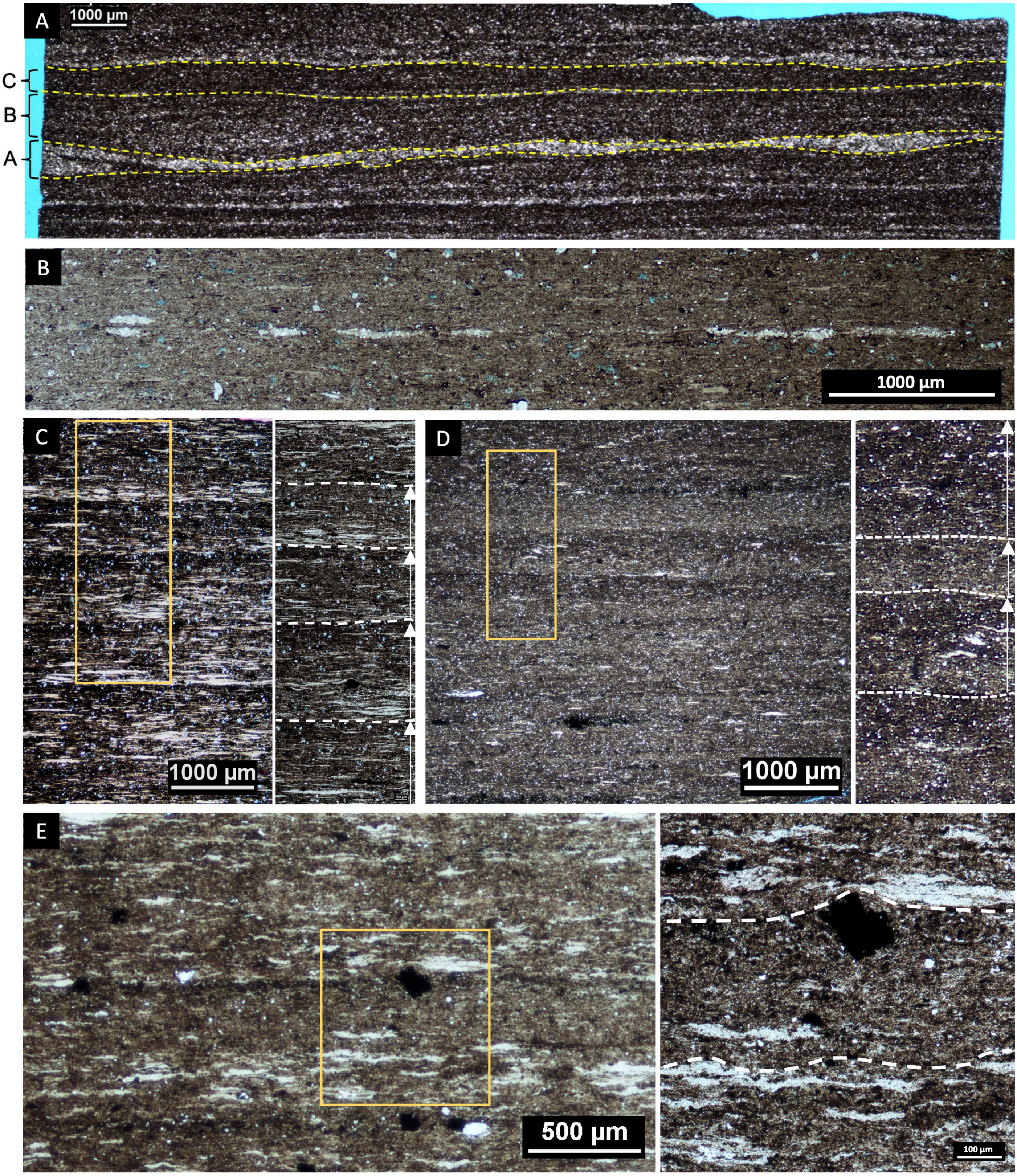

Figure 12 | Example photomicrographs of relatively high energy depositional features seen in organic-rich mudstones. All photomicrographs are from the Horn River Group, NWT Canada. (A) Photomicrograph of a wave enhanced sediment gravity flow (WESGF). Depositional surfaces have been outlined to show three-part layering (A, B, C) from Macquaker et al. (2010a). The base of 'A' represents a scoured surface. ConocoPhillips Mirror Lake N-20 core (1910.44 m). (B) Discontinuous intraclastic lag. Lag dictates an otherwise unidentifiable bed contact. Husky Little Bear N-09 core (1699.77 m). (C) Stacked normally graded beds, fining upwards from intraclastic aggregate-rich bases to clay-rich tops. An annotated photo of the yellow highlighted area is shown to the right. Husky Little Bear N-09 core (1807.35 m). (D) Stacked normally graded beds, fining upwards from phytodetritus and silt-rich bases to clay-rich tops. An annotated photo of the yellow highlighted area is shown to the right. ConocoPhillips Mirror Lake N-20 core (1710.08 m). (E) Massive-appearing sediment gravity flow deposit bound by intraclast-rich beds. The relatively large black feature is a pyrite fragment. The image to the right represents the yellow boxed area. Husky Little Bear N-09 core (1706.58 m).

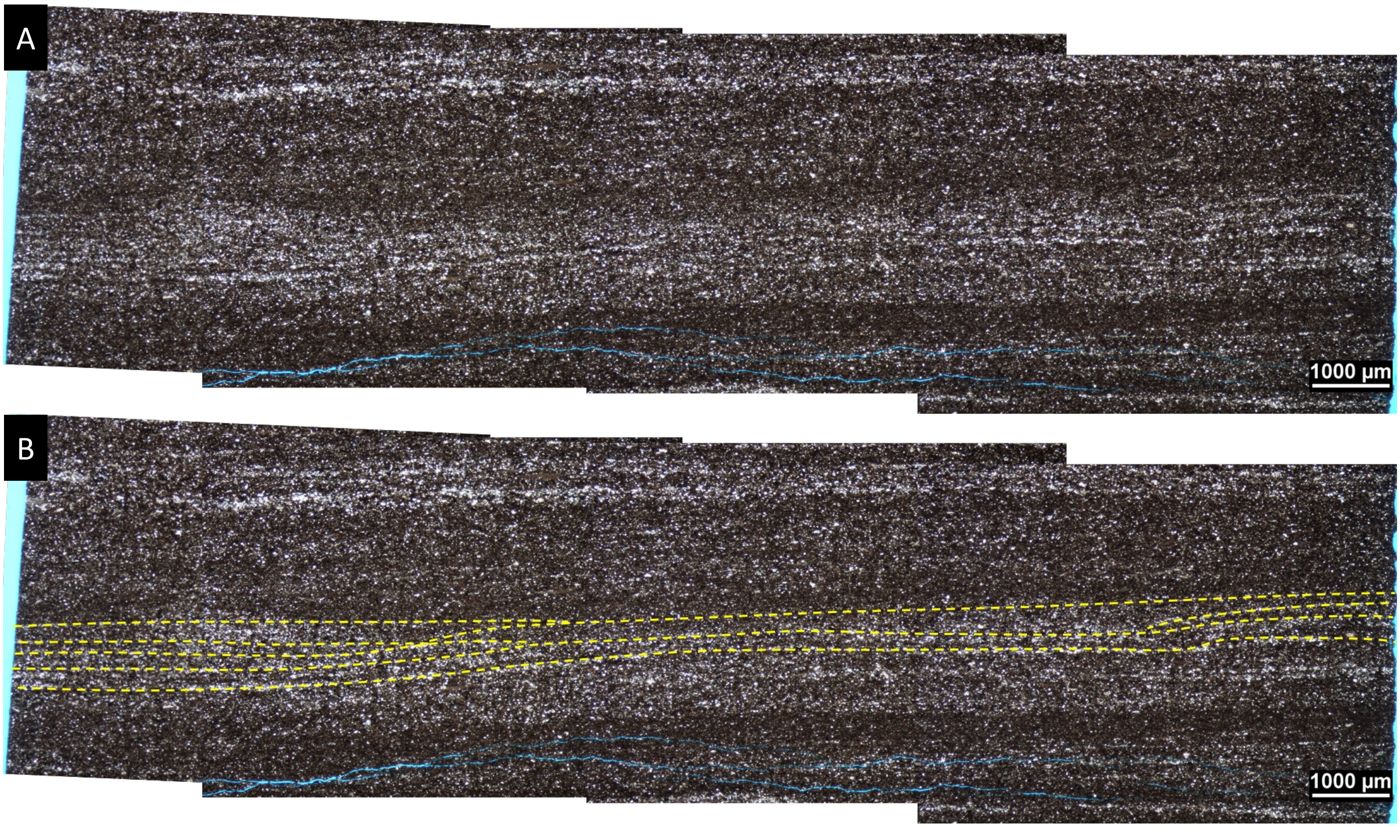

Figure 13 | (A) Photomicrograph mosaic showing a cross-section of a unidirectional current ripple (flow is from right to left). (B) Same photo as A), with foresets illustrated by dashed yellow lines. Horn River Group, NWT Canada, ConocoPhillips Mirror Lake N-20 core (1910.44 m).

the amount of incoming terrestrially generated organic matter as part of production (Schlesinger & Melack, 1981; Ittekkot, 1988; Meybec, 1993; Hedges & Keil, 1995; Keil, 2011), even though its allochthonous origin excludes it from true intrabasinal production. In this way, production acts as a limiting factor (e.g., Ardnt et al., 2013). Without initial photosynthetic generation of organic matter, no organic-rich deposits can accumulate. In reality, only a small fraction of the organic matter produced will make it to the sea floor intact (e.g., Hedges & Keil, 1995).

Quality encompasses the inherent reactivity (i.e., composition) of the produced organic matter. Marine-generated organic matter is more easily degraded than terrestrially-derived organic matter. This is owing to the structural simplicity of single-celled marine biomass, composed dominantly of easily degradable lipids and nitrogenous compounds (Burdige, 2007); while terrestrial organic matter contains difficult-to-degrade structural supporting cellulose and lignin (e.g., Hedges et al., 1988; de Leeuw & Largeau, 1993; Arndt et al., 2013). Further, marine organic matter experiences the total of its degradation within the water column and associated sediments; while terrestrial matter enters the marine realm already partially refractory, as it experiences degradation on land and in the soil before delivery to the ocean waters (e.g., Zonneveld et al., 2010).

5.2. Destruction

Destruction was originally outlined by Bohacs et al. (2005) as being 'threshold governed' (i.e., some destructive processes cannot occur below certain limitations or outside of specific environmental conditions). For example, a paucity of organic matter consumption by metazoan infauna (e.g., bioturbating organisms) occurs in oxygen concentrations too low to support such infauna. Here, destruction has been further expanded to include factors such as: 1) all aerobic and anaerobic degradation by organisms; 2) the amount of dissolved oxygen available in the water column; 3) the availability of oxidants in pore waters; 4) the depth of the water column; 5) the packaging and associated protection of the organic matter; and, 6) the amount of post-depositional sediment reworking.

Aerobic degradation of organic matter may be completed by both pelagic and benthic bacterial and metazoan organisms. Using highly reactive oxygen and specialized enzymes, these organisms efficiently break down (i.e., oxidize) organic carbon compounds (e.g., Canfield, 1994), including terrestrial lignin (Senior & Balba, 1990; Canfield, 1994), ultimately to carbon dioxide. The process of aerobic degradation leads to the consumption of nearby oxygen. Thus, oxygen supply and oxygen consumption exemplify a delicate balance in the water column and in the surficial sediment layers. The amount of dissolved oxygen in the water column can control the depositional flux of intact (i.e., undegraded) organic matter. The longer an organic particle is exposed to oxygen, the less likely it is to make

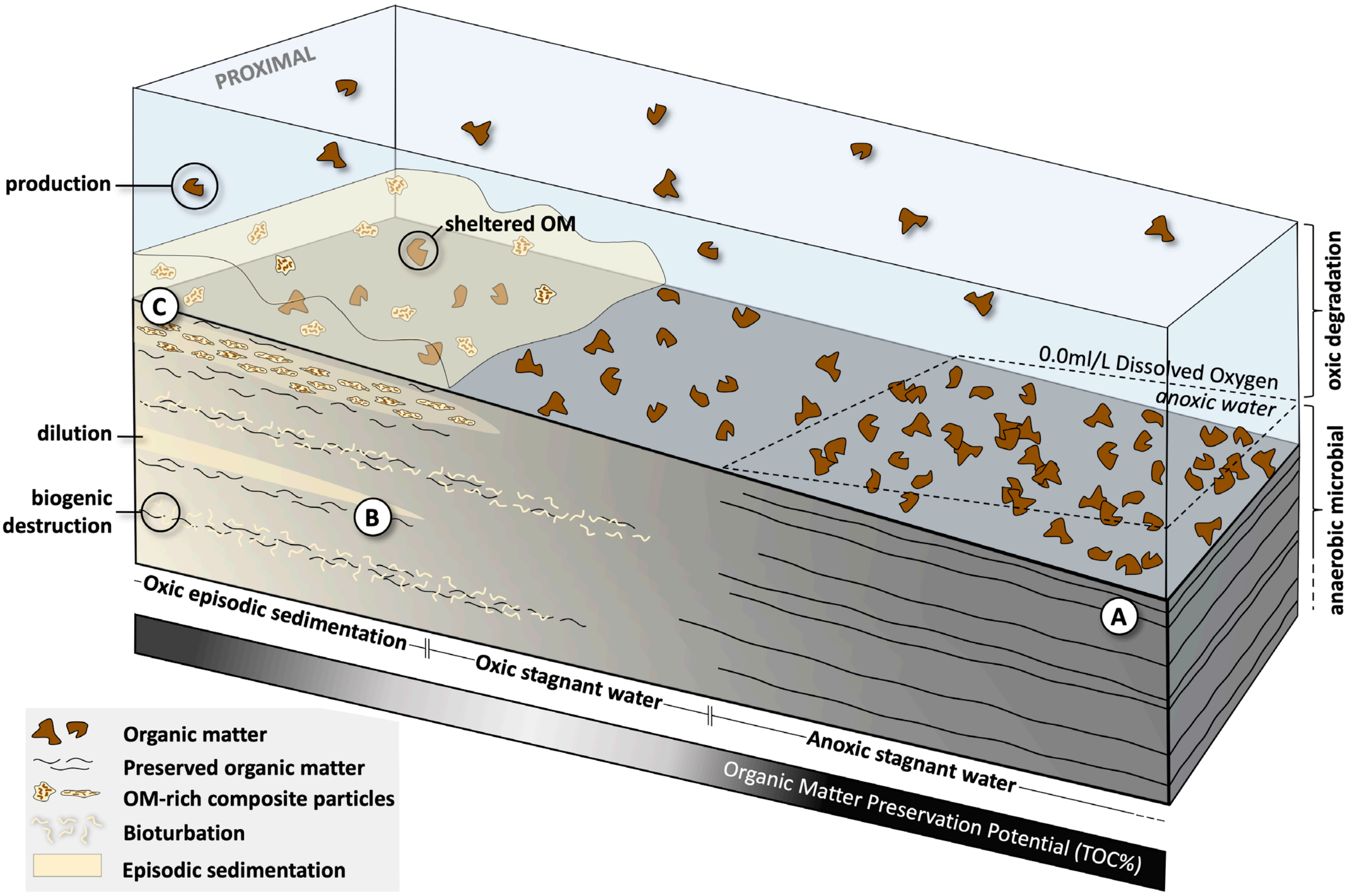

Figure 14 | Ilustrated organic matter enrichment mechanisms under three varying bottom water physicochemical conditions: i) Oxic with episodic sedimentation, ii) oxic with low energy bottom waters, and iii) anoxic stagnant water. (A) Conventional interpretation of organic matter enrichment. (B) Interpreted enrichment scenario in Borcovsky et al. (2017) and Biddle et al. (2021). (C) Interpreted enrichment scenario in Percy and Pedersen (2020).

it to the sea floor. In contrast, the more organic matter a water column is subject to, the less likely it is to remain oxygenated. For example, high rates of production above an oxygenated water column can lead to oxygen-depleted waters upon total consumption of available oxygen by degradative processes (Bohacs et al., 2005; Capone & Hutchins, 2013; Tutasi & Escibano, 2020; Canfield & Kraft, 2022). Naturally, the depth of the oxygenated water column plays a role in the delivery of organic material, and its resulting depositional quality. The deeper the water, the more likely the original labile organic matter is to be partially or completely aerobically degraded or mineralized into undesirable refractory material (e.g., Wakeham et al., 1997a, b; Dauwe et al., 1999; Arndt et al., 2013). This prevents the sediment from becoming organic-rich.

Gravity primarily drives the settling flux of organic matter. As a result, larger particles reach the seafloor faster and are thereby exposed to less oxic degradation in the water column. Likewise, some pelagic organic matter is naturally heavy, being encased within the mineralized tests of sinking primary producers, such as diatoms. Additionally, free or dissolved organic matter can become incorporated into heavy composite particles, such as organomineralic aggregates and fecal pellets (Macquaker et al., 2010b), during its journey to the seafloor (e.g., Alldredge & Jackson, 1995; Francois et al., 2002; Klaas & Archer, 2002; Passow, 2004; Arndt et al., 2013). Thus, the 'packaging' of organic matter within larger, heavier structures is an important mechanism in potential organic enrichment (e.g., Thiel, 1995; Simon et al., 2002; Macquaker et al., 2010b). Beyond increased settling flux, packaging acts as a protective barrier, sheltering the organic matter from oxygen and degradative enzymes in the water column (Keil et al., 1994; Mayer, 1999; Henrichs, 2005; Arndt et al., 2013). Consequently, dichotomous microenvironments develop within and around the packaged material (Macquaker et al., 2010b). This sheltering effect is further prevalent in organic-matter-rich intraclastic aggregates, where the re-transported material is protected from degradation at the seafloor (e.g., Huguet et al., 2008; Percy & Pedersen, 2020).

Upon accumulation on the sea floor, organic matter is subject to a new suite of aerobic degradation mechanisms via the direct and passive influence of infaunal bioturbators. Direct ingestion of organic matter by burrowing organisms acts to reduce the organic carbon content of the sediments. Subsequent egestion of excess comminuted particulate organic matter results in refractory organic material with larger surface area to volume ratios, providing a more active area for degradative enzymes (e.g., Rice, 1986; Kemp, 1987; Middelburg & Meysman, 2007). This ultimately leads to quicker bacterial breakdown. Bioturba-

Mechanisms of Organic Matter Enrichment		References
Production	*Quantity* • Rate of primary production	Schlesinger and Melack, 1981; Ittekkot, 1988; Meybec, 1993; Hedges & Keil, 1995; Berner, 2003; Bohacs et al., 2005; Keil, 2011; Arndt et al., 2013
	Quality • Reactivity of OM (how desirable it is, e.g., labile vs refractory) • Marine: easily degradable cellulose and lipids • Terrestrial: hard to degrade lignans	Westrich & Berner, 1984; Colberg, 1988; Hedges et al., 1988; Cowie et al., 1992; De Leeuw & Largeau, 1993; Dauwe et al., 2001
Destruction	*Aerobic degradation* • Bacterial and metazoan degradation • Amount of dissolved oxygen in the water column • Depth of the water column	Colberg, 1988; Senior & Balba, 1990; Canfield, 1994; Wakeham et al., 1997a, b; Dauwe et al., 1999; Bohacs et al., 2005; Arndt et al., 2013
	Packaging and protection • Increased settling flux of heavy composite-particle-hosted or test-ballast OM • Sheltering of OM in degradative enzyme-inaccessible aggregates	Keil et al., 1994; Mayer, 1994; Alldredge & Jackson, 1995; Mayer, 1999; Francois et al., 2002; Kennedy et al., 2002; Klaas & Archer 2002; Passow, 2004; Henrichs, 2005; Huguet et al., 2008; Macquaker et al., 2010b; Arndt et al., 2013; Percy & Pedersen, 2020
	Bioturbating infauna • Ingestion (removal of OM) • Egestion (increase in OM surface area:volume, production of refractory OM) • Sheltering of OM in expelled fecal pellets and compacted burrow linings • Enhanced OM degradation through bioirrigation and redox oscillation • Disruption of degradation tiers through sediment churning • Redistribution of labile and refractory OM ('priming') • Reduction of degradative bacterial communities by metazoan grazing	Rice, 1986; Kemp, 1987; Canfield, 1994; Kristensen, 2001; Aller & Aller, 1998; Aller & Blair, 2006; Middleberg & Meysman, 2007; van Nugteren et al., 2009; Zonneveld et al., 2010; Arnosti, 2011
	Anerobic degradation • Bacterial degradation • Less efficient than aerobic degradation • Controlled by the availability of terminal electron acceptors and sediment mixing	Claypool & Kaplan, 1974; Froelich et al., 1979; Demaison & Moore, 1980; Emerson, 1985; Canfield, 1994;
	Chemical changes in redox pathways • Reoxidation of anoxic bottom waters • Missing redox tiers (e.g., lack of detritally-derived iron to uptake sulfur results in sulfur-bearing ('sour') hydrocarbons, reduced biogenic influence, and increased OM)	Aller, 1982; Schieber, 2007b; Schieber, 2011b; Taylor & Macquaker, 2011; Macquaker et al., 2014;
	Physical post-depositional reworking • Disruption of degradation tiers through sediment churning • Redistribution of labile and refractory OM ('priming') • Release of OM through destruction of aggregates	Kristensen, 1985; Aller, 1994; Aller & Aller, 1998; van Nugteren et al., 2009; Guenet et al., 2010; Michaud et al., 2010
Dilution	*Sedimentation rate* • Enhanced OM burial through high sedimentation rates	Heath et al., 1977; Toth & Lerman, 1977; Berner, 1978; Coleman et al., 1979; Muller & Suess, 1979; Ibach, 1982; Bralower & Thierstein, 1984; Stein, 1990; Henrichs & Reeburgh, 1987; Betts & Holland, 1991; Calvert & Pedersen, 1992; Canfield, 1994; Bohacs et al., 2005; Ghadeer & Macquaker, 2012; Egenhoff & Fishman, 2013; Borcovsky et al., 2017; Percy & Pedersen, 2020; Biddle et al., 2021
	Type of sediment • Sorption ability (clay platelets > framework silicate grains) • Swelling potential (e.g., smectite) • Compaction potential	Hedges et al., 1988; Keil & Hedges, 1993; Keil & Kirchman, 1994; Mayer, 1994; Hedges & Keil, 1995; Taylor, 1995; Mayer & Xing, 2001; Kennedy et al., 2002; Henrichs, 2005; Kennedy & Wagner, 2011; Arndt et al., 2013

Table 4 | Mechanisms of organic matter enrichment.

tion may also act to release previously sheltered organic material by destroying pelagically-generated composite particles. In contrast, bioturbation may act to increase the preservation of organic material in sediments through: 1) the construction of burrow wall linings, where tight packing acts to shelter organic matter (e.g., Kristensen, 2001; Zonneveld et al., 2010); 2) resultant sheltering organic matter in benthic fecal pellets; and, 3) grazing on bacterial populations that act to degrade organic material (e.g., reducing biomass of degradative organisms) (van Nugteren et al., 2009).

Once settled and out of the diffusive influence of oxygen and bioturbating infauna, buried often by only millimeters or centimeters of sediment, organic material is subjected to anaerobic degradation processes (i.e., processes occurring in an absence of available oxygen). Anaerobic degradation of organic matter by bacteria uses a series of sequentially less efficient pathways (i.e., substances with less reactive terminal electron acceptors; or simply, substances worse at oxidizing organic matter – commonly described as 'the redox ladder'), often incorporating numerous vertically stacked bacterial tiers. In simplistic terms, organic matter degradation will successively exhaust (in order of most oxidizing to least oxidizing) O_2, NO_3^-, Mn (IV), Fe (III), and SO_4^{2-} as terminal electron acceptors, ultimately ending with methanogenesis (e.g., Claypool & Kaplan, 1974; Froelich et al., 1979; Coleman, 1985 Arndt et al., 2013). Of course, degradation within a specific tier depends on the electron acceptor availability within the sediments at a particular location (e.g., Demaison & Moore, 1980; Emerson, 1985; Canfield, 1994). This loss of degradability with depth may also be a function of increasingly more refractory material passing through the degradative tiers (e.g., Arndt et al., 2013). Thus, the deeper you get within the sediment the less organic matter degradation you can expect. Further, with all else being equal, anoxic water columns and underlying sediments are more likely to become organic-rich as the degradative pathway is lacking its most efficient component - oxygen (e.g., Demaison & Moore, 1980; Emerson, 1985; Canfield, 1994). However, this too has been debated, as in some studies there appeared to be nearly equal preservation in anoxic and oxic settings (e.g., Henrichs & Reeburgh, 1987; Lee, 1992; Kristensen & Holmer, 2001).

Disruption of the vertically zoned sedimentary degradation pathway, by chemical (e.g., changing bottom water chemistries), physical (e.g., erosion and resuspension), or biogenic (e.g., burrowing) processes, acts as a catalyst to restart degradation or mineralize organic matter. Chemically induced changes in locally established redox pathways, such as intermittent or temporary oxygenation of anoxic bottom waters will result in dissolution and alternative mineralization of diagenetic precipitates and organic matter (e.g., Schieber, 2007b; Schieber, 2011b). Reduction of ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}) plays an important role in organic matter enrichment. In sediments with abundant Fe^{3+}, iron reduction dominates over sulphate (SO_2^{4-}) reduction (e.g., Taylor & Macquaker, 2011). Iron reduction is the more efficient process, resulting increased organic matter degradation. In iron-rich sediments, Fe^{2+} from iron reduction binds with H_2S from sulphate reduction to produce insoluble iron sulphides (e.g., pyrite). This process regulates H_2S concentrations, buffering pore-water pH (Schieber, 2011b). An absence of detritally-derived iron alters the ideal redox ladder and puts H_2S in direct contact with diffusive O_2, producing excess H^+ and decreasing pH (e.g., Taylor & Macquaker, 2011). Acidic pore waters further limit infaunal populations (e.g., Schieber, 2011b), and in turn, biogenic degradation of organic matter is reduced (e.g., Schieber, 2011b). Limited or absent iron reduction further leads to the 'sulfurization' of organic matter (e.g., the mineralization of kerogen to contain sulphur, producing 'sour' fluids) instead of producing iron-sulphide diagenetic precipitates (e.g., Macquaker et al., 2014).

Biogenic churning of the sediments by infaunal sediment mixers may introduce fresh labile organic matter into deeper regions and resurface previously degraded refractory organic material into the upper more efficient degradation tiers. The introduction of more reactive material into deeper tiers can stimulate the further degradation of stable refractory material in a process known as 'priming' (e.g., Aller, 1994; van Nugteren et al., 2009). Priming acts to revive the destruction of deep stable refractory organic matter through the production of enzymes that break down both the new and old material simultaneously (e.g., Guenet et al., 2010). The continuous mixing and ingestion of organic-bearing sediments by infaunal bioturbators acts to intermittently oxidize the upper portion of the sediment, preventing the stabilization of bacterial tiers. This leads to sustained effective degradation by regeneration of terminal electron acceptors and the redistribution of metabolic waste products, while preventing organic material from entering deeper tiers (e.g., Kristensen, 1985; Aller, 1994; Aller & Aller, 1998; Kristensen et al., 2011). Bioirrigation by tube-building infauna (i.e., the ventilation of open burrows via animal-induced pumping of oxygenated bottom water) disturbs the redox ladder and acts to passively enhance the degradation of surrounding sediment-contained organic matter. The influx of oxygenated waters at typically oxygen-free depths generates a redox oscillation, combining the alternating effects of aerobic and anaerobic degradation (Canfield, 1994; Aller, 2001; Aller & Blair, 2006; Zonneveld et al., 2010).

Finally, physical sediment erosion by bottom water currents acts to revitalize organic degradation in previously anerobic sediments by restimulating more efficient redox tiers.

5.3. Dilution

Dilution refers to the organic carbon-free sedimentation rate (e.g., detrital sedimentation). Many studies have suggested that increased sedimentation rate (e.g., increased dilution) is one of the key mechanisms in organic matter preservation, as it shelters organic carbon from oxidants within the water column and pore waters, as well as from metazoan and bacterial degradation (e.g., Toth & Lerman, 1977; Berner, 1978; Ibach, 1982; Bralower & Thierstein, 1984; Henrichs & Reeburgh, 1987; Betts & Holland, 1991; Canfield, 1994; Bohacs et al., 2005; Ghadeer & Macquaker, 2012; Egenhoff & Fishman, 2013; Borcovsky et al., 2017; Percy & Pedersen, 2020, Biddle et al., 2021). Indeed, frequent episodic sedimentation 'halts' degradation in the previously emplaced, now buried sediments (e.g., basal parts of frequently emplaced storm beds contain more organic material than upper parts; Ghadeer and Macquaker, 2012). However, increased organic matter preservation in high recurrence interval deposits does not always lead to 'enriched' deposits as a whole. Too much sedimentation leads to a negative correlation with preserved concentrations of organic matter (e.g., Bohacs et al., 2005).

Contrary to expectation, Borcovsky et al. (2017) identified a proximal increase in TOC in the organic-rich mudstone Bakken Formation in the Williston Basin of North Dakota. This relationship was attributed to episodic sediment deposition enhancing organic matter preservation in more landward positions (Figure 14B). Similarly, Horn River Group deposits in the Northwest Territories of Canada reveal that the highest TOC values occur in what is interpreted as the most proximal, highly bioturbated, depositionally energetic, and coarsest-grained sediments, and that these values steadily decline basinward (Biddle et al., 2021). Here it was determined that persistent anoxia was not the sole factor in TOC preservation, but rather a combination of heightened sedimentation, rapid burial, and possible elevated rates of primary production were at play (Figure 14B). Percy and Pedersen (2020) studied the organic-rich Cretaceous Second White Specks and Belle Fourche Formations in Western Canada. They reported the highest TOC contents in proximal sediments dominated by organic-rich composite particles. The composite particles comprising these high TOC beds were interpreted to be reworked and deposited through relatively high-energy bedload transport (e.g., mud rip-up clasts or intraclastic aggregates). Organic matter preservation was determined to be the result of a combination of shorter settling times for organic-rich composite particles when compared to their individual constituents, and fluctuations between increased surface water productivity and low detrital input alternating with episodic sedimentation events burying and preserving organic-rich beds (Figure 14C).

Mineral-associated organic matter (e.g., bound dissolved organic matter) makes up the bulk of the organic carbon contributing to the development of carbonaceous deposits (e.g., Mayer, 1994; Hedges & Keil, 1995; Kennedy et al., 2002). Thus, the composition of sediment contributing to dilution further plays a role in organic matter preservation. This is with specific regard for the properties of clay minerals. Sorption of organic matter to mineral surfaces has been shown to shelter the grain-coating organic matter through steric prevention of enzymatic breakdown (Keil & Hedges, 1993; Keil et al., 1994; Mayer & Xing, 2001; Kennedy et al., 2002). The larger surface area of clay platelet grains inherently provides more sorptive sheltering. However, this idea rests on several caveats including the thickness of the organic coating (e.g., Taylor, 1995; Arndt et al., 2013), the potential ignition of condensation reactions (e.g., Hedges et al., 1988; Keil & Kirchman, 1994), and the long-term exposure to oxygenated pore waters (Hedges & Keil, 1995). The specific mineralogy of the clay also plays a role in increased preservation, where swelling smectite clays have been identified as providing additional sheltering within large, protected interlayer sites (Kennedy & Wagner, 2011). The high compaction potential of clay-dominated sediments further acts to shelter deposited organic matter by limiting access of destructive enzymes via porosity and permeability reduction (e.g., Henrichs, 2005). The contribution of auto-dilution (i.e., dilution through accumulation of non-organic biogenic test components) is also significant. Sedimentation dominated by production-derived components results in deposits less likely to become diluted, as the organic component is tied directly to the sediment component (Tyson, 1995).

6. Relativity

Many terms become relative depending on the composition or the scale at which you are evaluating a unit. For example, the term 'matrix' may be subjective if you are looking at a conglomerate, sandstone, or mudstone. As Kitty Milliken (2015) said, "Everything in a mudrock could be matrix in a sandstone".

Relativity comes into play when considering terms such as 'grain size', 'bed', and 'energy'. It has been found that the depositional grain size of a sedimentary unit may contradict classical apparent grain size definitions (Schieber et al., 2007a; Li & Schieber, 2018; Percy & Pedersen, 2020; Li et al., 2021), bringing to light the concept of 'relative grain-size'. Namely, does the grain size represent common mineralogical grain sizes (e.g., silt referring to framework silicate quartz and feldspar minerals), apparent grain size (e.g., clay-sized quartz grains), or functional depositional grain size (e.g., sand- and silt-sized composite particles). Here, the answer depends on the question. When considering composition and provenance, the mineralogy needs consideration. When discussing hydrodynamic regimes, the depositional (functional) grain-size matters. No matter which definition is ultimately chosen, the functional grain size of the deposit should be reported. It is important to recognize that subsequent winnowing of sediments can result in accumulations of silt- and sand-sized composite particles, which no longer reflect the original depositional energies, but instead reworking energies. Similarly, the incorporation of microfossils as grain-size components is relative to the question being asked. Are you interested in: 1) depositional energies, in which case pelagic test should be excluded but transported ones included; or 2) provenance, in which case all components must be considered. The term 'bed' becomes relative depending on the definition an author adopts (e.g., quantitative *versus* genetic). Discussions of depositional energy are also relative depending on the unit being evaluated. The phrase 'high energy' has been used to describe the depositional conditions at the sediment-water interface for many mudstone studies (e.g., Schieber, 1994; Macquaker et al., 2010a; Egenhoff & Fishman, 2013; Borcovsky et al., 2017; Shchepetkina et al., 2018; Percy & Pedersen, 2020; Biddle et al., 2021). Commonly, this use of 'high energy' refers to bottom water currents with the competence to transport mudstone-forming constituents through bedload, as opposed to stagnant bottom waters (Schieber et al., 2007a; Schieber & Southard, 2009). Descriptions of high energy in mudstone studies are vastly different than the high energies used to describe coarser-grained sedimentary units.

The compositional breakdown of a mudstone may be subjective relative to the methodology or scale at which it is evaluated. Using macroscopic outcrop and core-scale classification, a unit might be traditionally classified as a 'mudstone' or 'claystone'. Looking at the same unit petrographically it might be found that it is dominated by silt- and sand-sized composite particles. The same unit may further appear to be dominated by products of diagenesis when evaluated using high-resolution imaging techniques (e.g., SEM; Milliken, 2014). The new wave of information regarding the components and depositional processes associated with mudstones sparks a necessary revamping of terminological ideologies (Macquaker & Adams, 2003; Milliken, 2014; Lazar et al., 2015a, b). For example, should the mudstones composed of silt-sized composite particles in Li et al. (2021) be classified as a 'claystone' based on dominant mineralogy, 'mudstone' based on texture, or 'siltstone' (or 'coarse mudstone' via Lazar et al., 2015a) based on functional depositional grain size and hydrodynamic properties? Should the nomenclature introduced by Macquaker and Adams (2003) and Lazar et al. (2015a) be expanded further to include modifiers such as 'silt-sized composite-particle-dominated coarse mudstone' (e.g., Schieber, 2015)? Perhaps it is all dependent on the scale and level of detail needed to achieve a result or answer a question, or the amount and quality of the collectible data (e.g., can functional depositional grain size even be determined?).

Petrographic analyses and high-resolution imaging shed light on compositional, textural, and fabric characteristics that are highly likely to go unidentified during macro-scale assessment techniques, such as lithofacies analysis. Petrographic microfacies and microichnological analyses are becoming more standard practice in modern mudstone analysis. Ultimately, to comprehensively understand the depositional conditions of a fine-grained sedimentary unit one should have an understanding of the individual rock components. This requires a detailed knowledge of the mineralogy, grain size, functional depositional grain size, macro- and microscopic primary sedimentary structures, and ichnology.

7. Future work

This review opens further questions regarding the importance of petrographic microfacies analysis. Subsequent work may involve continued comprehensive integration of microfacies interpretations with known sequence stratigraphic interpretations and geochemical trends for mudstone units (e.g., to build on the models of Bohacs, 1998; Macquaker et al., 2007; Borcovsky et al., 2017). This may also help to assess the legitimacy of potential proximal to distal microfacies relationships (e.g., microfacies-generated proximal to distal trends in Borcovsky et al., 2017 and Biddle et al., 2021). Future work may also entail comparisons of microfacies identified within a variety of mudstone units (both geographically and temporally) to see if there is a standard set of predictable mudstone microfacies. If there exists a set of standard mudstone microfacies, if their proximal to distal interpretations can be validated by integration with other methods (e.g., micropaleontological, palynological, sequence stratigraphic, and geochemical analyses), and if there is a recurring trend between increasing proximity and increasing TOC, such microfacies analysis may have merit in identifying potential "sweet spots'' in fine-grained source-rock reservoirs and sealing units for carbon and hydrogen sequestration (e.g., Jonk et al., 2022). Additional future directions in the field of mudstone microfacies analysis may include the development of agreed upon microfacies standards and possible petrographic facies models, similar to those for carbonates and coarse-grained clastic deposits (an idea that was even postulated more than 25 years ago by Schieber & Zimmerle, 1998).

Neoichnological studies of microbioturbation in various fine-grained sediments with variable pore water dissolved oxygen contents would be a valuable way to comprehensively assess the potential of microbioturbation as a paleo-redox proxy in mudstones. Neoichnological studies on the physicochemical controlling factors of well-known ichnofauna have led to the solidification of ichnology as a standard line of evidence for paleodepositional interpretations, with perhaps the most famous being the development of the Seilacherian Ichnofacies (Seilacher, 1967). Expanding these studies into the microscopic realm would lead to a better understanding of: 1) the distribution of various meiofaunal organisms in relation to redox boundaries; 2) how burrowing strategies change with pore water chemistry and sediment mechanics (e.g., Dorgan et al., 2005, 2007, 2013, 2016; Dorgan, 2015); and 3) the preservation potential of these structures (e.g., Schieber et al., 2021). Concerning reservoir analysis, future investigations of microbioturbation within organic-rich mudstones may evaluate how microscopic burrows alter the reservoir properties of unconventional reservoirs. Potential studies may attempt answering such questions as: 1) can microburrows act as fluid conduits or migration pathways within fine-grained reservoirs, 2) how (if at all) does microbioturbation affect fracture propagation within reservoirs, and how does this change with varying bioturbation intensities (unbioturbated vs. biogenically homogenized), and 3) does the positive relationship between higher depositional energies, bioturbation intensity and TOC preservation hold true in other organic-rich mudstone formations?

8. Summary

Several topics have been discussed herein, and the following conclusions are an amalgamation of recent ideologies and consensus within the mudstone community:

1. Suggested mudstone nomenclature is Lazar et al.'s (2015a) fine, medium, and coarse mudstones or well-defined 'claystone', 'mudstone', and 'siltstone' terms (Figure 2); with modifiers such as 'dominated', 'rich', and 'bearing' presented by Macquaker and Adams (2003).

2. One should define the terms 'clay' and 'silt' as either a textural or mineralogical description.

3. One should define if they are using apparent grain size (e.g., individual mineral grain diameters) or functional depositional grain size (e.g., including composite particles as a single grain) when referring to constituents.

4. Composite particles should be named according to the four main types presented in Table 1, or clearly defined by the author.

5. The basis for naming fine-grained deposits should be explicitly defined. Are the analyzed rocks classified based on their mineralogical composition, apparent grain size, or functional depositional grain size?

6. Regardless of rock naming scheme used, consideration should be paid to the hydrodynamic conditions necessary for accumulation (e.g., composite particle deposits that accumulate under the same hydrodynamic conditions as fine-grained sandstones).

7. The term 'bed' should be strictly reserved for the description of a single genetic event, regardless of bed thickness.

8. The term 'shale', which is inherently linked to the presence of well-developed fissility, should be reserved as a naming modifier for weathered mudstones and avoided as an all-encompassing rock name.

9. When conducting petrographic analysis, thin sections should be prepared ultra-thin (20 μm). If SEM analysis is to also be done, thin sections may be prepared without a cover slip or with a removable cover slip.

10. Double-polished thin sections are ideal to eliminate the majority of mechanical defects produced during the thin section preparation process.

11. If geochemical analysis is being run along with petrographic analysis, geochemical data should be taken from the same rock sample used for thin section preparation.

12. When analyzing mudstones for evidence of microbioturbation, potential trace fossils should be described morphologically and attribution to a particular ichnospecies should be avoided.

13. If characterization of the extent of bioturbation is difficult using the standard Bioturbation Index (BI) or Ichnofabric Indices (II), Intensity of Bioturbation (IB%) may be used.

14. Photomicrographs showing evidence for microbioturbation should be accompanied by an annotated version for ease of understanding.

15. Microfacies are commonly restricted to petrographically identified features.

16. Microfacies should be described from both bedding parallel and bedding perpendicular thin sections where possible.

17. Depositional conditions of fine-grained sediments are more complex than traditionally understood, and petrographic examination can help to identify elusive features that may indicate particular physical depositional conditions.

18. Organic-rich mudstones are a subset of all mudstones. The only difference – organic enrichment, is dictated by complex interactions between the numerous intricacies within the 'production, destruction, and dilution' model.

19. Some organic-rich mudstones may have the highest organic enrichment values in the most proximal depositionally energetic settings.

Despite the extensive research to date on organic-rich mudstones, there remains a wealth of information to glean from these elusive rocks; this paper only scratches the surface of the topics discussed here.

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Author contribution

Literature review, initial writing, drafting: S.K. Biddle. Additional insights and revision: M.T. LaGrange, B.S. Harris, S. Egenhoff, M.K. Gingras

Data availability

This article is a review of previously conducted studies, and thus no independent data analysis was performed.

Conflict of interest

The authors declare no conflict of interest.

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