SEDIMENTOLOGY the journal of the International Association of Sedimentologists IAS

Sedimentology (2022) **69**, 2682–2688 doi: 10.1111/sed.13021

Reply to the Discussion by Al-Mufti on "On the origin and significance of composite particles in mudstones: Examples from the Cenomanian Dunvegan Formation" by Li *et al.* (2021), *Sedimentology*, 68, 737–754

ZHIYANG LI*,†, JUERGEN SCHIEBER* and PER KENT PEDERSEN‡
**Department of Earth and Atmospheric Sciences, Indiana University, Bloomington, IN 47405, USA (E-mail: zli@coloradocollege.edu; lizhiyanglee@gmail.com)*
†Department of Geology, Colorado College, Colorado Springs, CO 80903, USA
‡Department of Geoscience, University of Calgary, Calgary, AB T2N 1N4, Canada

We thank Dr Al-Mufti for the interest he has taken in our paper (Li *et al.*, 2021) concerning the types of mud-dominated composite particles (MCPs) or clay-particle aggregates (*sensu* Al-Mufti, 2022) in the prodelta mudstones of the Cenomanian Dunvegan Formation. It is our hope to contribute to advancing the field of mudstone sedimentology by taking this opportunity to reiterate some of our key points. Below, we comment on the two points raised in Al-Mufti's discussion from multiple perspectives.

FLOCCULES, INTRACLASTS OR ARTEFACTS (REPLY TO COMMENT 1)

Although Dr Al-Mufti does not agree with our notion that "floccules are too challenging to identify due to their homogenous appearance in the fine-grained matrix", he did not present any convincing evidence that floccules can indeed be identified in compacted Dunvegan prodelta mudstones. The so-called face-to-face (FF), edge-to-edge (EE) and edge-to-face (EF) aggregates that are interpreted as 'intraclastic aggregates' by Al-Mufti (2022) differ fundamentally from floccules. Floccules are irregular shaped aggregates formed from suspended fine-grained particles under the influence of van der Waals electrostatic forces (Kranck, 1973; Mehta *et al.*, 1989; Syvitski *et al.*, 1995). Intraclasts, in contrast, originate from intra-basinal erosion/reworking of surficial or shallowly buried muds that had become sufficiently cohesive to resist disaggregation during subsequent erosion and transport (Macquaker & Gawthorpe, 1993; Schieber *et al.*, 2010).

No specific criteria are provided to support the designation of the face-to-face (FF) aggregates outlined in fig. 1 (Al-Mufti, 2022) as intraclastic aggregates. Different types of allochthonous MCPs identified in the Dunvegan Formation are characterized by distinct suites of characteristics (for example, grain size, mineral composition, texture; Li *et al.*, 2021), which allows them to be distinguished from their surroundings. The inherent reason that makes differentiating floccules from intraclasts (specifically type F1 argillaceous rip-up clasts in Li *et al.*, 2021) so challenging is that both are autochthonous MCPs and have rather similar (if not the same) composition and texture. Moreover, both floccules and argillaceous rip-up clasts were at the time of deposition very water-rich and thus during burial subject to high levels of compaction and deformation around 'hard' particles, such as discrete mineral grains (quartz, feldspar, etc.) or allochthonous MCPs (rock fragments). During compaction, the original outlines of floccules or argillaceous rip-up clasts will be distorted/deformed, with collapse of their internal highly porous fabric, and in the absence of compositional contrast adjacent floccules or argillaceous rip-up clasts can no longer be differentiated. All of the aggregates outlined in fig. 1 (Al-Mufti, 2022) are argillaceous in composition and show essentially the same texture. Although nicely drawn, the outlines of particles and markings of presumed clay fabrics are merely an interpretation by the author. If raw images were given to, say, ten individuals with a set of instructions on how to mark particles, we are confident that there would be ten different versions of particle arrangements. When in search for patterns, humans invariably 'find a way' (Schieber *et al.*, 2021), but whether such perceived patterns have a basis in reality begs serious scrutiny. As detailed below, from our understanding of mud-aggregate generation, transport, deposition and burial, the particles as marked by Al-Mufti (2022) cannot be considered intraclastic aggregates.

Let us assume for an instant that the aggregates in fig. 1 (Al-Mufti, 2022) are outlined correctly. Do they then make sense as intraclasts (i.e. argillaceous rip-up clasts)? Consider that, at the beginning of their journey, muddy intraclasts are water-rich (upward of 70% by volume; Schieber, 2011) and fragile, and that upon compaction the water is lost, and the particles should yield to gravity and get flattened in bedding-normal view. In contrast to that expectation, most aggregates outlined by Al-Mufti (2022) are equidimensional in the bedding-normal view. There is no evidence of particles flattened by compaction, implying that they were hard-enough (solid particles) to resist compaction.

Compaction-resistant (water-poor) intraclasts can be produced through the erosion or reworking of shallowly buried muds that have been strengthened through the precipitation of early diagenetic minerals. Indeed, the sideritic and siliceous rip-up clasts (type F2 and F3 MCPs, *sensu* Li *et al.*, 2021) in the Dunvegan system do show more resistance to compaction with increasing siderite or quartz cement content. Yet, none of the aggregates outlined in fig. 1 (Al-Mufti, 2022) contain discernible early diagenetic minerals. Because, in the absence of early cementation, argillaceous intraclasts are destined to suffer significant compaction, the equidimensional shape of most aggregates outlined in fig. 1 (Al-Mufti, 2022) makes their identification as intraclasts untenable.

We further contend that the presumed aggregates in fig. 1 (Al-Mufti, 2022) are mostly artefacts. The scanning electron microscope (SEM) images were made on a mechanically polished thin section, and fig. 1D and E (Al-Mufti, 2022) clearly show common grooves or scratches indicating that the surface has been plucked during polishing. The outlined aggregate in fig. 1F (Al-Mufti, 2022) seems to be bounded by cracks, across which the texture persists. These kinds of cracks are common artefacts of thin sections prepared from weathered outcrop samples of mudstones, such as the samples used by Al-Mufti, 2022 (fig. 2B and C) from the Dunvegan Formation. Recognizing these artefacts on polished thin sections when using backscatter electron SEM imaging requires experience, whereas in secondary electron mode (which emphasizes topography) such surface flaws would be glaringly obvious. Unfortunately, all presented images in fig. 1 (Al-Mufti, 2022) were taken in backscatter electron mode. Because the width (and likely the depth) of grooves or scratches in his observed areas is comparable to the size of outlined aggregates, it does not allow confident identification of individual aggregates, especially at such high magnification. The best way to avoid textural ambiguity in mudstone studies is the study of ion milled surfaces instead of mechanical polishes. We do this routinely and employed this methodology in the Li *et al.* (2021) study that is being critiqued by Al-Mufti (2022).

Also, focusing on such small areas (at such high magnification) as in fig. 1 (Al-Mufti, 2022) is meaningful only when starting the exploration of mudstone fabrics at low magnification in order to establish the overall context of fabric elements. We too examined our Dunvegan samples at high magnification, but we zoomed into smaller regions step by step, always keeping the broader context in mind (Fig. 1). Taking a prodelta 'mudstone' sample from the allomember E1 of the Dunvegan Formation as an example, our observations were made at multiple scales – starting from centimetre-scale/millimetre-scale sedimentary features in the core and on polished slabs (Fig. 1A) to micrometre-scale petrographic characteristics (Fig. 1B to E) through integrated optical and scanning electron microscopy analysis – within the well-developed depositional and stratigraphic framework (figs 1 and 2 in Li *et al.*, 2021). In the fine-grained matrix of Dunvegan prodelta mudstones, there are no effective identification criteria to allow the identification of individual floccules or intraclasts because, except for some fortunate conditions, the fine-grained matrix shows an overall uniform composition and texture (Fig. 1). Figure 1A and B represent such a rare case where the lens-shaped particles can be identified as argillaceous rip-up clasts. Note that their degree of compaction (flattening) indicates an original water content of 85 vol.% or more. The criteria for their recognition as rip-up clasts have been discussed extensively in the original manuscript and will not be duplicated here. Figure 1C to E are closer views of different areas in Fig. 1B taken at relatively high magnification. The lens-shaped particles in Fig. 1A and B can be identified as MCPs on the basis of the distinct contrast in grain size, composition and texture when compared with the surrounding relatively coarser matrix. Without distinct lithological contrast, there is no effective criterion to identify

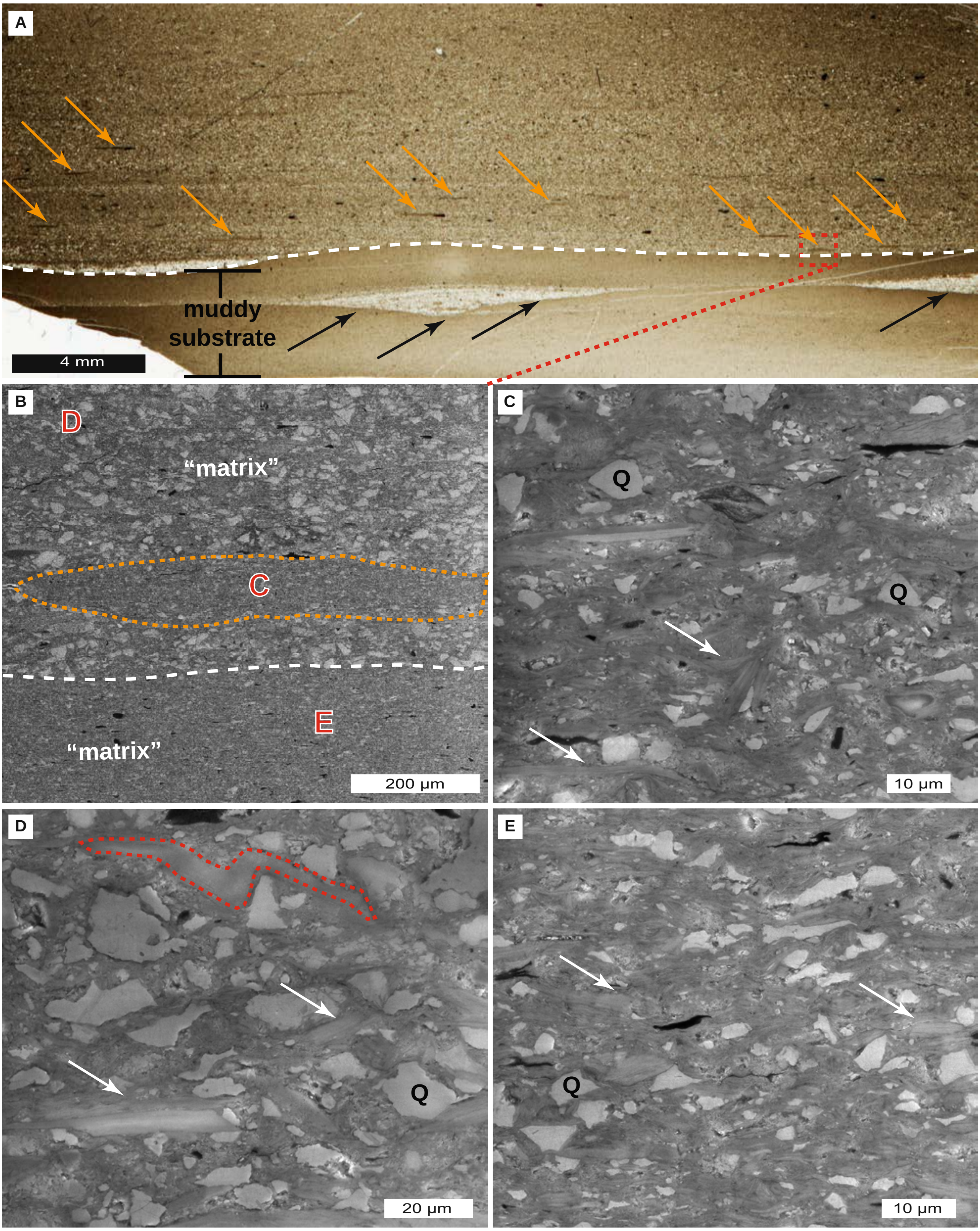
A
muddy
substrate
4 mm
B
D
"matrix"
C
E
"matrix"
200 μm
C
Q
Q
10 μm
D
Q
20 μm
E
Q
10 μm

Fig. 1. The identification of mud-dominated composite particles (MCPs) should be done systematically and always with a well-established context. (A) Scanned thin section image of a prodelta 'mudstone'. This sample is from the allomember E1 of the Dunvegan Formation (from core 3 in Li *et al.*, 2021). The presence of common argillaceous rip-up clasts (orange arrows) right above an erosional surface (white dashed line) indicates that the rip-up clasts were probably derived from erosion of the muddy substrate. The muddy substrate shows traction-generated structures including erosional base and starved silt ripples (black arrows). (B) Closer view of the dashed area in (A) under a scanning electron microscope (SEM) showing characteristics of the muddy substrate below the erosional surface (white dashed line) and an argillaceous rip-up clast (outlined in orange) within a sightly coarser, but still overall fine-grained matrix. (C) Closer view of the area labelled 'C' within the argillaceous rip-up clasts in (B). (D) Closer view of the area labelled 'D' in (B) showing characteristics of the fine-grained matrix above the erosional surface. The fine-grained matrix was likely deposited as floccules comparable in size with the coarse sand-sized to even very coarse sand-sized argillaceous rip-up clasts. Note the deformation of one mica flake (red dashed outlines) around a hard quartz grain. Water-rich argillaceous rip-up clasts and floccules would even more severely deformed and collapse around harder particles after compaction. (E) Closer view of the area labelled 'D' in (B) showing characteristics of the fine-grained matrix below the erosional surface. On the basis of the traction-generated structures [black arrows in (A)], the apparently fine-grained interval below the erosional surface was likely deposited from bedload transport of mud floccules, although their original outlines cannot be recognized. Note the preferred horizontally aligned mica flakes (white arrows) resulting from compaction in (C) to (E). (B) to (E) are all secondary electron images. The surfaces captured in (C) to (E) are fairly smooth but not perfectly smooth. The slight variations in brightness in (C) to (E) are to some degree related to the differential relief of the polished surface. Q, quartz.

individual argillaceous intraclasts or floccules in the two fine-grained matrix areas in Fig. 1D and E).

Al-Mufti (2022) also did not propose a plausible mechanism to explain the formation of these 5 to 15 μm intraclastic aggregates in prodelta mudstones. He suggested that these relatively small intraclastic aggregates are in fact most common in the fine-grained matrix (*sensu* Li *et al.*, 2021). His first proposed formation process for these aggregates is clay particle floccules formed in highly concentrated fluid muds. Note, however, that a mud in that concentration range, say 100 g solids per litre, has a water content in excess of 95 vol.%. If these presumed 5 to 15 μm intraclastic aggregates had indeed originated in a liquid mud they should show severe compaction, which they clearly do not. The size of these 5 to 15 μm intraclastic aggregates is another puzzle. If they indeed formed within highly concentrated fluid mud, they would likely merge to form larger aggregates or floccules (McCool & Parsons, 2004). Even without the presumption of a fluid mud origin, bedload floccules forming in moving suspensions (Schieber *et al.*, 2007; Schieber, 2011) range in size from very fine to coarse sand size (63 to 1000 μm), and the size of floccules measured in various continental and offshore environments can vary from a few to even thousands of micrometres (Droppo & Ongley, 1994; Syvitski *et al.*, 1995; Sternberg *et al.*, 1999; Hill *et al.*, 2001). Thus, the size of these presumed aggregates does not match floccule sizes directly observed in either experimental studies or modern environments. Given this known reality of actual floccule sizes, it is very likely (if not inescapable) that by observing at such high magnification Al-Mufti (2022) would have been looking at the interior of floccules, and not the floccules themselves.

His second proposed formation process of presumed intraclastic aggregates is clay particle reorientation during compaction. This, however, is not consistent with his very own annotated rendering (fig. 1A; Al-Mufti, 2022), which shows different preferred orientations of clay flakes, ranging from subhorizontal to subvertical. Different aggregates would have had to be compacted from different directions, a physically insupportable supposition. We posit that this demonstrates over-interpretation (i.e. looking at only a subarea within a much larger floccule), because when all of the white dashed lines were removed from fig. 1A (Al-Mufti, 2022), the orientation of clay flakes (black lines) is indeed more or less horizontal, consistent with vertical compaction. Note in this context the overall preferred horizontal alignment of mica flakes in Fig. 1C to E. The alignment of mica flakes in Fig. 1C indicates vertical compaction and is consistent with the compacted and 'flattened' argillaceous rip-up clast. The overall horizontal alignment of mica flakes in Fig. 1D and E, again, reflects the compaction of the two fine-grained matrix areas in Fig. 1B. The fine-grained matrix most likely was deposited from moving suspensions that transported flocculated mud in bedload (Schieber *et al.*, 2007; Schieber, 2011), with floccules up to several hundreds of micrometres in size, comparable to the argillaceous rip-up clasts in Fig. 1A and B. Unfortunately, individual floccules or argillaceous rip-up clasts can no longer be differentiated after compaction and thus give the appearance of a fine-grained matrix.

Finally, Al-Mufti (2022) agrees with our documentation of coarse silt-sized to sand-sized allochthonous MCPs in the Dunvegan prodelta mudstones. His only argument is that the fine-grained matrix, a term that we used to refer to the material that surrounds areas occupied by distinct mineral grains and allochthonous MCPs, consists of abundant 5 to 15 μm (presumed) intraclastic aggregates. The coarse silt-sized to sand-sized allochthonous MCPs, being the clasts of volcanic rocks, metamorphic rocks and fully compacted sedimentary rocks, can be considered to have an average density of 2.65 g/cm^3, similar to quartz, the most common mineral in the coarse silt size category in the Dunvegan prodelta mudstones (fig. 9 in Li *et al.*, 2021). Therefore, these allochthonous MCPs have a settling velocity comparable to common quartz silt because of their comparable size and density. If the fine-grained matrix had indeed consisted of abundant 5 to 15 μm intraclastic aggregates, they would have had an initial density of *ca* 1.33 g/cm^3 (assuming an 80 vol.% water content). Using 50 μm as a representative size for these coarse silt-sized allochthonous MCPs and quartz grains, intraclastic aggregates of 10 μm size with 80 vol.% water content would have 0.008 of the settling velocity of solid MCPs and quartz grains on the basis of Stoke's Law. It would be impossible under these conditions to simultaneously deposit the 5 to 15 μm intraclastic aggregates and the observed coarse silt-sized to even sand-sized allochthonous MCPs and quartz grains. Argillaceous rip-up clasts in our samples range from coarse silt (several tens of μm) to coarse (and even very coarse) sand size (rip-up clasts in Fig. 1A and B are up to 1000 μm along their longest axis). Whereas we have no direct observations on which to base the original size of floccules (low preservation potential), floccules in the Dunvegan prodelta mudstones should be comparable in size or slightly larger than the argillaceous rip-up clasts because floccules have higher water content and thus are less dense. Our deduced size of argillaceous intraclasts and floccules are consistent with those observed in flume experiments and on modern continental shelves (Sternberg *et al.*, 1999; Hill *et al.*, 2001; Schieber *et al.*, 2010; Manning *et al.*, 2013). The fine-grained matrix was most likely formed by deposition of sand-sized floccules and intraclasts that can no longer be differentiated in the compacted rock. Under most circumstances, their presence and abundance can only be inferred on the basis of careful SEM analysis on well-polished surfaces, integrated with detailed analysis of small-scale sedimentary features (for example, bedload structures).

THE TERM MUDSTONE ENTAILS A LOT MORE THAN CONVENTIONALLY CONSIDERED (REPLY TO COMMENT 2)

Although we think Al-Mufti (2022) completely missed our main point, we appreciate this opportunity to reiterate the key take-away point of this study. Although Al-Mufti (2022) states that we question the use of the term 'mudstone' for Dunvegan prodelta strata, this is a complete misreading of what we tried to convey. In no place did we imply in Li *et al.* (2021) that it is wrong to use the term mudstone, nor did we imply that the term sandstone would be a more appropriate name for these prodelta 'mudstones'. The main point we were making is: one needs to be cognizant of what the term mudstone really means. According to the definition by Lazar *et al.* (2015), it is perfectly correct to classify the Dunvegan prodelta deposits as mudstones because more than 50% of the discernible GRAINS in these deposits are in the mud size range (<62.5 μm). However, no sedimentary rock should simply be defined by the grain size of component mineral grains, because by their very nature, sedimentary rocks have a FLUID DYNAMIC DIMENSION. They are the end result of the interaction between actual particles and currents of water or air. It is for that reason that, for example, carbonate classifications have an aspect that reflects depositional energy (textural maturity, Folk, 1959; amount of mud, Dunham, 1962), and why there are mudstones that by way of fluid dynamics started out as an accumulation of sand-sized particles (Rust & Nanson, 1989; Sternberg *et al.*, 1999; Schieber *et al.*, 2010; Schieber, 2016; Laycock *et al.*, 2017; Li & Schieber, 2018; Schieber *et al.*, 2019; Li *et al.*, 2020, 2021). If that circumstance goes unrecognized when a seemingly simple mudstone is investigated, erroneous interpretations of depositional processes and ambient energy conditions of these rocks are likely to follow. For the Dunvegan Formation we made a convincing case that the clays in its prodelta mudstones were largely transported and deposited as constituents of coarse silt-sized to sand-sized MCPs (Li *et al.*, 2021). Whereas it may be safe to ignore the small amount of easily visible sand-sized MCPs (and mineral grains) when designating these prodelta deposits as mudstones, it would not at all serve the deeper understanding of these rocks if we were to ignore the presence of sand-sized MCPs. In combination with the presence of bedload structures, these sand-sized particles were likely transported together with other sand-sized floccules and intraclasts, which then coalesced into the fine-grained matrix after compaction and became 'invisible'. The Dunvegan prodelta 'mudstones', as well as many other marine mudstones, are probably only 'fine-grained' in terms of their mineral constituents. One should resist the notion to assume that all mudstones were deposited under overall quiet and low energy conditions just because the constituent minerals are of fine grain size. Instead, one should interpret their depositional processes and conditions on the basis of the size of recognizable transported particles (Fig. 1A and B), and inferences accrued from careful examination of their petrographic and sedimentological characteristics. Doing so will transform dull mudstones into the most intriguing sediments on Earth and other planetary bodies.

CONFLICT OF INTEREST

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

DATA AVAILABILITY STATEMENT

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

REFERENCES

Al-Mufti, O.N. (2022) Discussion of Li et al. (2021) – on the origin and significance of composite particles in mudstones: examples from the Cenomanian Dunvegan formation. *Sedimentology*, **68**, 737–754.

Droppo, I.G. and **Ongley, E.D.** (1994) Flocculation of suspended sediment in rivers of southeastern Canada. *Water Res.*, **28**, 1799–1809.

Dunham, R.J. (1962) Classification of carbonate rocks according to depositional textures. In: *Classifications of Carbonate Rocks—A Symposium* (Ed Ham, W.E.), pp. 108–121. The American Association of Petroleum Geologists, Tulsa, OK.

Folk, R.L. (1959) Practical petrographic classification of limestones. *AAPG Bulletin*, **43**, 1–38.

Hill, P.S., **Voulgaris, G.** and **Trowbridge, J.H.** (2001) Controls on floc size in a continental shelf bottom boundary layer. *J. Geophys. Res. Oceans*, **106**, 9543–9549.

Kranck, K. (1973) Flocculation of suspended sediment in the sea. *Nature*, **246**, 348–350.

Laycock, D.P., **Pedersen, P.K.**, **Montgomery, B.C.** and **Spencer, R.J.** (2017) Identification, characterization, and statistical analysis of mudstone aggregate clasts, cretaceous Carlile formation, Central Alberta, Canada. *Mar. Petrol. Geol.*, **84**, 49–63.

Lazar, O.R., **Bohacs, K.M.**, **Macquaker, J.H.S.**, **Schieber, J.** and **Demko, T.M.** (2015) Capturing key attributes of fine-grained sedimentary rocks in outcrops, cores, and thin sections: nomenclature and description guidelines. *Journal of Sedimentary Research*, **85**, 230–246.

Li, Z. and **Schieber, J.** (2018) Composite particles in mudstones: examples from the late cretaceous Tununk shale member of the Mancos shale formation. *J. Sediment. Res.*, **88**, 1319–1344.

Li, Z., **Schieber, J.** and **Bish, D.** (2020) Decoding the origins and sources of clay minerals in the upper cretaceous Tununk shale of south-Central Utah: implications for the pursuit of climate and burial histories. *Depos. Rec.*, **6**, 172–191.

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

Macquaker, J.H.S. and **Gawthorpe, R.L.** (1993) Mudstone lithofacies in the Kimmeridge clay formation, Wessex Basin, southern England; implications for the origin and controls of the distribution of mudstones. *J. Sediment. Res.*, **63**, 1129–1143.

Manning, A.J., **Spearman, J.R.**, **Whitehouse, R.J.**, **Pidduck, E.L.**, **Baugh, J.V.** and **Spencer, K.L.** (2013) Flocculation Dynamicsof mud: sand mixed suspensions. In: *Sediment Transport: Processes and their Modelling Applications* (Ed. Manning, A.J.), pp. 119–163. InTech, London.

McCool, W.W. and **Parsons, J.D.** (2004) Sedimentation from buoyant fine-grained suspensions. *Cont. Shelf Res.*, **24**, 1129–1142.

Mehta, A.J., **Hayter, E.J.**, **Parker, W.R.**, **Krone, R.B.** and **Teeter, A.M.** (1989) Cohesive sediment transport. I: process description. *J. Hydraul. Eng.*, **115**, 1076–1093.

Rust, B.R. and **Nanson, G.C.** (1989) Bedload transport of mud as pedogenic aggregates in modern and ancient rivers. *Sedimentology*, **36**, 291–306.

Schieber, J. (2011) Reverse engineering mother nature — shale sedimentology from an experimental perspective. *Sediment. Geol.*, **238**, 1–22.

Schieber, J. (2016) Experimental testing of the transport-durability of shale lithics and its implications for interpreting the rock record. *Sediment. Geol.*, **331**, 162–169.

Schieber, J., **Miclăuş, C.**, **Seserman, A.**, **Liu, B.** and **Teng, J.** (2019) When a mudstone was actually a "sand": results of a sedimentological investigation of the bituminous marl formation (Oligocene), eastern Carpathians of Romania. *Sediment. Geol.*, **384**, 12–28.

Schieber, J., **Shao, X.**, **Yawar, Z.** and **Liu, B.** (2021) Cryptic burrow traces in black shales – a petrographic Rorschach test or the real thing? *Sedimentology*, **68**, 2707–2731.

Schieber, J., **Southard, J.B.** and **Schimmelmann, A.** (2010) Lenticular shale fabrics resulting from intermittent erosion of water-rich muds—interpreting the rock record in the light of recent flume experiments. *J. Sediment. Res.*, **80**, 119–128.

Schieber, J., **Southard, J.** and **Thaisen, K.** (2007) Accretion of mudstone beds from migrating floccule ripples. *Science*, **318**, 1760–1763.

Sternberg, R.W., **Berhane, I.** and **Ogston, A.S.** (1999) Measurement of size and settling velocity of suspended aggregates on the northern California continental shelf. *Mar. Geol.*, **154**, 43–53.

Syvitski, J.P.M., **Asprey, K.W.** and **Leblanc, K.W.G.** (1995) In-situ characteristics of particles settling within a deep-water estuary. *Deep-Sea Res. II Top. Stud. Oceanogr.*, **42**, 223–256.

Manuscript received 31 May 2022; revision accepted 15 June 2022