SEDIMENTOLOGY the journal of the International Association of Sedimentologists

Sedimentology (2015) **62**, 389–393 doi: 10.1111/sed.12150

Discussion: "Mud dispersal across a Cretaceous prodelta: Storm-generated, wave-enhanced sediment gravity flows inferred from mudstone microtexture and microfacies" by Plint (2014), Sedimentology 61, 609–647

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This discussion aims to comment on aspects in a recent paper by Plint (2014) where mud transport during deposition of prodeltaic strata of the Cretaceous Dunvegan Formation is examined. The author has made considerable effort to look at the grain scale fabric of these rocks, and by adding data from drill core also made a good argument that the fabrics of outcrop samples were not fundamentally altered by weathering processes. The author concludes that a considerable portion of the clays in these mudstones did not arrive in discrete flakes or in a flocculated state, but as aggregates that were at least in part transported in bedload. The presumed aggregates are similar in size to the quartz silt grains that they are associated with, and are in essence their hydraulic equivalents.

There are, however, issues with the proposed origins of the various types of mud aggregates that are described. Although these concerns may seem subtle to those that are not engaged in mudstone studies, they are nonetheless vital beyond this particular field of inquiry. Because mudstones and shales comprise at least two-thirds of the sedimentary rock record (Schieber, 1998), any misunderstanding about the processes that control their deposition have an adverse impact on our understanding of the rock record overall. A good grasp of depositional processes is also of economic importance, because properties like porosity and permeability can be tied back to original depositional fabrics (Schieber, 2011a, 2013). The author specifically proposes: (i) that randomly oriented face–face clay aggregates (2 to 5 μm diameter in size) formed through flocculation in fluid mud; and (ii) that small (5 to 20 μm diameter in size) intraclastic aggregates (termed 'IAs' for the remainder of this discussion) were eroded by storms from the seabed.

With regard to the first point, the author refers to a paper by Nishida *et al.* (2013) for support. In that paper, the hypothesis is advanced, on the basis of experiments, that an abundance of dense face–face aggregates (<10 μm in size) is indicative of sea water based fluid muds (10 to 30 g/l clay suspension). However, Nishida *et al.* (2013) used commercially available ground clays, and face–face aggregates are common in commercial clay products that are mined from compacted or lithified deposits because of face–face relations inherited from compaction. Also, Nishida *et al.* (2013) oven-dried their samples prior to scanning electron microscope (SEM) examination. Given that modern surface muds have high water contents and porosities (70 to 90 wt% is common, e.g. Schimmelmann *et al.*, 1990) the methodology for sample preparation is critical for making observations that realistically reflect original fabrics (e.g. Bennett *et al.*, 1991). Because surface tension forces enormously distort clay fabrics during sample dehydration, critical point drying has for many years been considered the best method to faithfully maintain particle to particle integrity of wet clay samples for electron microscopic fabric investigations (Bennett *et al.*, 1977; Tovey & Wong, 1978). It is therefore exceedingly unlikely that the samples prepared by Nishida *et al.* (2013) reflected original depositional fabrics. By extension, from the broader perspective of clay fabric literature, the Nishida *et al.* (2013) reference does not provide support for the hypothesis that the face–face aggregates observed in the Dunvegan Formation are indicative of deposition from fluid muds.

Staying with the issue of fluid muds, it is also doubtful whether aggregates formed in fluid muds would be a mere 2 to 5 μm in size. In multiple settling tube experiments (Schieber, 2011b) that covered the concentration range from highly diluted (<1 g/l) to advanced liquid mud (40 g/l), floccules formed as soon as agitation stopped, and floccules were hundreds of microns and larger (Fig. 1). Overall it is probably premature, and not supported by what is known about clay fabrics, to hypothesize that micron-size face–face aggregates in the prodelta mudstones from the Dunvegan Formation are indicative of deposition from fluid muds.

The nature of clay fabrics figures prominently in this paper and, due to the small size of mudstone components, electron microscopic evaluation of particle relations is critically dependent on the flatness of the surface that is being examined. Surface roughness in general is a serious detriment. Examining mudstone fabrics on broken surfaces was described by O'Brien & Slatt (1990) and, at the time, this methodology was probably the best available to look at microfabrics of mudstones. However, what is visible on broken surfaces is the fabric of a torn-apart rock, and the surface roughness due to grain plucking is considerable. In standard polished thin sections, surface quality is better, but still generally poor when the rock fabric is clay dominated. Clay-rich rocks are so soft that surface smear during polishing is very difficult to avoid and that circumstance limits the ability to see grain relations in detail. In the paper in question, mudstone fabrics are imaged on broken surfaces as well as in polished thin sections (Plint, 2014, figs 9, 11 and 12) and, in both, the author sketches out and labels the aggregates and aggregate types that he discusses in the text. Although such an approach is widely used in scientific illustration, given the above-mentioned limitations on surface quality it is fair to argue that the aggregates shown by the author are very much in the eye of the beholder. For example, when the polish in fig. 9 of Plint (2014) is evaluated, the surface roughness seen in secondary electron mode (fig. 9A) is considerable and caution should prevail when interpreting fabrics. Probably, the best currently available technology to make distortion free surfaces for examination of clay fabrics is the application of argon ion-milling prior to SEM imaging (Schieber *et al.*, 2010; Schieber, 2013), and it is to be hoped that future investigations of clay fabrics in sedimentary rocks are based on samples that have been prepared with that method. In order to avoid confusion between the figures in this discussion and those used in the paper by Plint, the former are denoted as 'Fig. 1' etc., whereas the latter are denoted as 'fig. 1' etc.

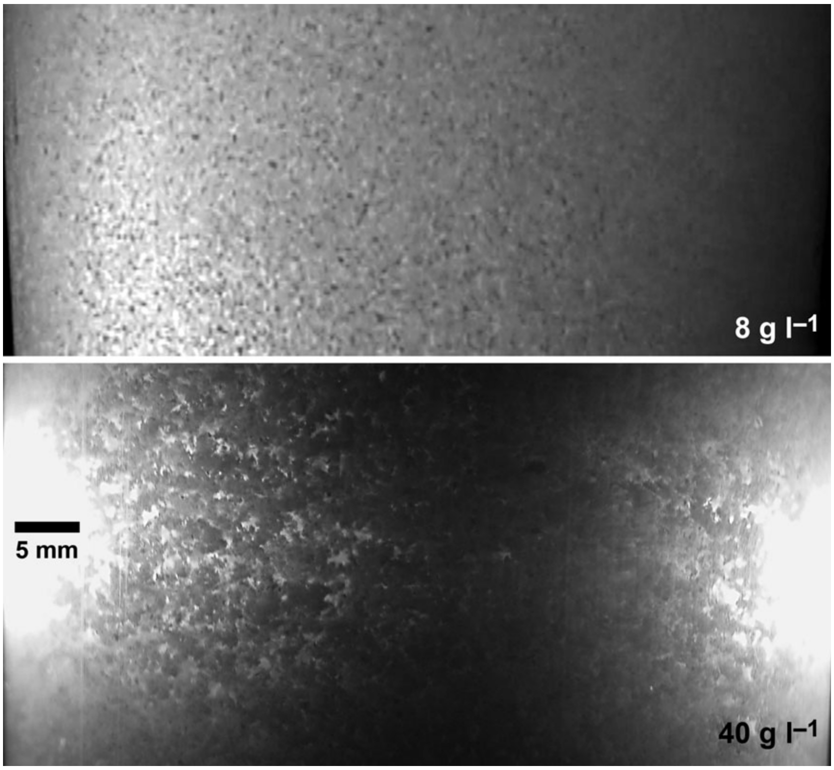

Fig. 1. Floccule formation in clay suspensions of 8 g/l (top) and 40 g/l (bottom). The bright, overexposed areas are due to intense light from fibre optic lights. In both cases aggregates are visible that range in size from hundreds of microns to millimetres in size. The formation of large floccules in the millimetre-size range is much more pronounced in the liquid mud sample (40 g/l) at the bottom.

Yet, whereas there may be disagreement about the best way to study microfabrics and whether or not fluid muds lead to certain types and sizes of aggregates, a fundamental problem with this paper is the contention that small (5 to 20 μm diameter in size) intraclastic aggregates (IAs) originated by storm erosion of the sea bed. That storms erode the sea bed and produce mud clasts as a consequence is in itself not a problem. It can be shown in experiments that surficial muds with as much as 85 vol% water can form aggregates up to millimetre-size upon erosion, and that such aggregates travel large distances (Schieber *et al.*, 2010). The IAs described by Plint are well-illustrated with photomicrographs and SEM images, are most probably real and have also been observed in other shale successions (Fig. 2).

A matter of concern is the fact that although Plint's IAs may in places show deformation due to compaction, his figs 6A, 6B, 8B, 8C and 9C show a substantial portion of them to be remarkably rounded and even near spherical. Just like the clasts in Fig. 2 of this contribution, the IAs illustrated by Plint seem to have experienced little physical compaction and may not be intraclasts at all. In Plint (2014), height to length ratios for deformed IAs suggest up to 50% vertical shortening, whereas those of rounded IAs indicate between 0% and 20% vertical shortening. This phenomenon suggests that the Dunvegan IAs had already seen substantial compaction prior to being buried in their present sedimentary context, comparable to what is seen in Fig. 2 of this contribution.

Plint (2014) states (p. 622) that:

> *"the cohesion and adhesion of clay particles increase on a time scale of days to decades as a result of a variety of mechanisms that include compaction, electro-chemical bonding and the production of extracellular polysaccharide coatings by bacteria and diatoms and attributes the apparent cohesiveness of IAs to above amalgam of processes. Whereas all of the mentioned processes can and do provide increased cohesion to surficial sediments, the lack of vertical shortening seen in these IAs nonetheless speaks to a degree of pre-erosion compaction and lithification that is hard to reconcile with a depositional model where they are eroded from the contemporaneous sea bed"* (Plint, 2014, fig. 26).

The literature on the compaction of surficial sediments has been well-summarized in a recent paper by Kominz *et al.* (2011). Muddy ocean sediments from shelf, slope and deep-sea settings, collected on coring expeditions, as well as experimental work (Schieber, 2011a,b), suggest

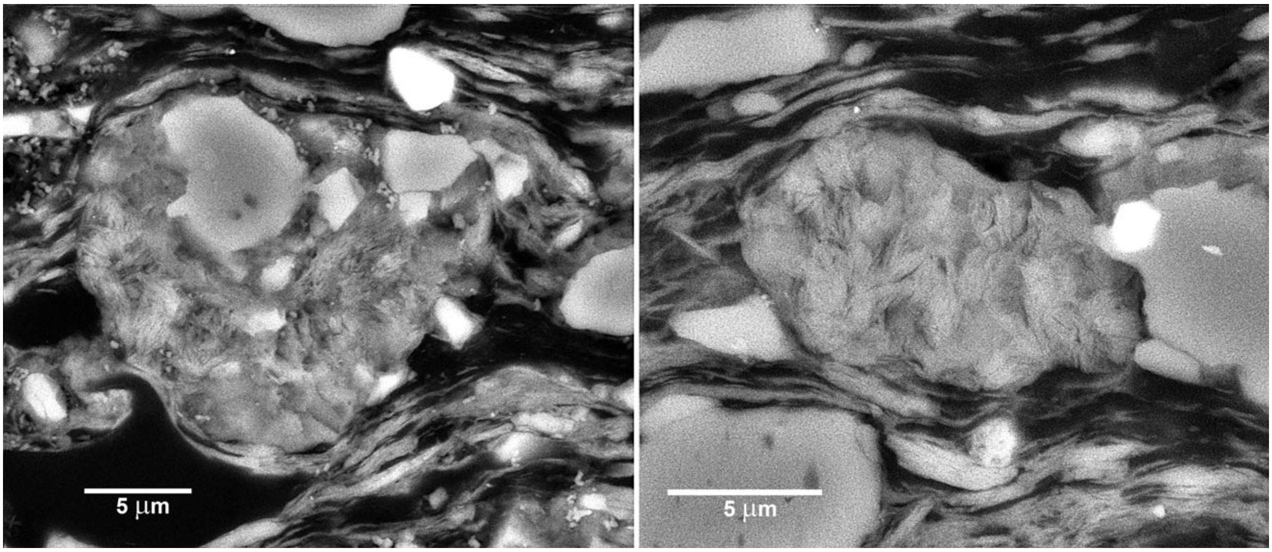

Fig. 2. Rounded mudstone clasts (SEM backscatter images) in the Chattanooga Shale of Tennessee. Left image: differential compaction of laminae around the clast indicates deposition in water-rich surficial muds. Whereas the clast has a randomized fabric, it is buried in mud with a well-developed planar fabric. This phenomenon suggests that the clast originated elsewhere and is not an intraclast. Right image: also shows differential compaction of the shale matrix surrounding the clast, as well as a randomized internal fabric of the clast. Although the clast looks somewhat flattened, the internal fabric does not suggest vertical shortening. Both clasts appear to have been 'hard' particles that hydraulically behaved like other silt grains in this rock. They are in essence rock fragments.

that as a rule surficial muds start out with 80 to 90% porosity (or water content) and that it takes considerable burial before these muds compact to even 50% porosity (e.g. Bennett *et al.*, 1991). According to Kominz *et al.* (2011), between 200 to 300 m of burial, should be expected for such a degree of compaction/dewatering. It can of course be argued that under certain circumstances, such as very slow rates of deposition, surficial muds might attain higher levels of compaction closer to the sediment water interface, or that early diagenetic cementation caused them to 'harden' at shallow burial. There is, however, no supporting evidence for this in Dunvegan mudstones. Concerning IAs that show only minor (0 to 20%) vertical shortening, there are no documented occurrences of modern near surface (a few metres of burial) sediments that have been compacted to that level (0 to 20%) of porosity, and no compelling case been made for ancient mudstones.

It appears therefore that the near spherical IAs in the Dunvegan Formation had to come from substantial burial depth. On the conservative side this depth probably measured in the tens of metres, and it was most probably closer to 100 m or more.

Consolidation levels as seen in the Dunvegan IAs also occur in mud aggregate sandstones of desert streams (e.g. Rust & Nanson, 1989). Whereas a pedogenic origin (Nanson *et al.*, 1986) or burial compaction and subsequent erosion are both reasonable scenarios for producing such consolidated clasts, producing them via storm erosion of the sea bed seems to be the least plausible scenario. The latter should have been severely flattened by burial (e.g. Schieber *et al.*, 2010; Schieber, 2011a,b) and should appear as thin streaks and show compactional deformation and bending around harder grains (Schieber *et al.*, 2010). This observation then poses the rather interesting question of whether there is any evidence on the Dunvegan shelf of incisions (related to sea-level drop) that might have caused deep (tens of metres) erosion into previously deposited muds, or whether detailed petrography of the clasts (on ion milled surfaces) might help to trace them back to mudstones that were exposed in the hinterland or coastal plain. In the latter case, the IAs would clearly be lithoclasts (sedimentary rock fragments) rather than intraclasts.

Thus, whereas initially the Dunvegan Formation seems to be dominated by clay-rich mudstones, the study by Plint (2014) suggests that sedimentologically at least, a good portion of these strata are siltstones (dominated by mudstone lithics) and that bedload transport played a much bigger role than originally assumed. Because it is quite likely that mudstone lithoclasts are also much more common in the sedimentary rock record elsewhere, sedimentologists would be well-advised to examine other shelf mud successions for recycled mud aggregates in order to arrive at realistic assessments of the depositional environments.

The study by Plint (2014) has multiple aspects that should be emulated in other mudstone studies, such as the detailed measured sections and the careful description of macroscopic sedimentary features and vertical successions. It definitely reinforces the notion that careful petrographic examination of the mudstone rock record is long overdue, and when applied systematically is likely to radically change the way we think about the origin and deposition of these rocks that constitute two-thirds of the sedimentary rock record (Schieber, 1998, 1999).

REFERENCES

Bennett, R.H., **Bryant, W.R.** and **Keller, G.H.** (1977) *Clay Fabric and Geotechnical Properties of Selected Submarine Sediment Cores from the Mississippi Delta*, vol. 9. NOAA Professional Paper. U.S. Department of Commerce, Washington, D.C., pp. 1–86.

Bennett, R.H., **Obrien, N.R.** and **Hulbert, M.H.** (1991) Determinants of clay and shale microfabric signatures: processes and mechanisms. In: *Microstructure of Fine-Grained Sediments: From Mud to Shale* (Eds R.H. Bennett, W.R. Bryant and M.H. Hulbert), pp.5–32(582 pp). Springer-Verlag, New York.

Kominz, M.A., **Patterson, K.** and **Odette, D.** (2011) Lithology dependence of porosity in slope and deep marine sediments. *J. Sed. Res.*, **81**, 730–742.

Nanson, G.C., **Rust, B.R.** and **Taylor, G.** (1986) Coexistent mud braids and anastomosing channels in an arid-zone river: Cooper creek, central Australia. *Geology*, **14**, 175–178.

Nishida, N., **Ito, M.**, **Inoue, A.** and **Takizawa, S.** (2013) Clay fabric of fluid mud deposits from laboratory and field observations: potential application to the stratigraphic record. *Mar. Geol.*, **337**, 1–8.

O'Brien, N.R. and **Slatt, R.M.** (1990) Argillaceous Rock Atlas. Springer Verlag, New York, 141 pp.

Plint, A.G. (2014) Mud dispersal across a Cretaceous prodelta: storm-generated, wave-enhanced sediment gravity flows inferred from mudstone microtexture and microfacies. *Sedimentology*, **61**, 609–647.

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. (1998) Deposition of mudstones and shales: overview, problems, and challenges. In: *Shales and*

Mudstones: Basin Studies, Sedimentology and Paleontology (Eds J. Schieber, W. Zimmerle and P. Sethi), vol. 1, pp. 131–146. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

Schieber, J. (1999) Distribution and deposition of mudstone facies in the Upper Devonian Sonyea Group of New York. *J. Sed. Res.*, **69**, 909–925.

Schieber, J. (2011a) Shale microfabrics and pore development – an overview with emphasis on the importance of depositional processes. In: *Gas Shale of the Horn River Basin* (Eds D.A. Leckie and J.E. Barclay), pp. 115–119. Canadian Society of Petroleum Geologists, Calgary.

Schieber, J. (2011b) Reverse engineering Mother Nature – shale sedimentology from an experimental perspective. *Sed. Geol.*, **238**, 1–22.

Schieber, J. (2013) SEM Observations on ion-milled samples of Devonian Black Shales from Indiana and New York: the petrographic context of multiple pore types. *AAPG Mem.*, **102**, 153–172.

Schieber, J., **Southard, J.B.** and **Schimmelmann, A.** (2010) Lenticular shale fabrics resulting from intermittent erosion of muddy sediments – comparing observations from flume experiments to the rock record. *J. Sed. Res.*, **80**, 119–128.

Schimmelmann, A., **Lange, C.B.** and **Berger, W.H.** (1990) Climatically controlled marker layers in Santa Barbara Basin sediments and fine-scale core-to-core correlation. *Limnol. Oceanogr.*, **35**, 165–173.

Tovey, N.K. and **Wong, K.Y**. (1978) Preparation, selection, and interpretation problems in scanning electron microscope studies of sediments. In: *Scanning Electron Microscopy in the Study of Sediments* (Ed. W.B. Whalley), pp. 181–199. Geo-Abstracts, Norwich, England.

Manuscript received 17 March 2014; revision accepted 18 July 2014