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Review

Reverse engineering mother nature — Shale sedimentology from an experimental perspective

Juergen Schieber

Department of Geological Sciences, Indiana University, Bloomington, IN 47405, United States

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ABSTRACT

Experimental study of the sedimentology of shales can take a variety of forms. At its simplest one can experiment with suspensions in a glass jar and try to understand their settling behavior, or one can manipulate mud in a tank or bucket to gain insights into its rheology. This approach was championed over a century ago by Sorby, and the insights gained can be quite profound. More recently, tank and settling tube experiments of animal-sediment interactions, compaction behavior, and sediment unmixing via re-suspension have proven to be highly informative in spite of their simplicity. Flumes can be used to obtain quantitative information about depositional and erosional parameters and to generate fundamental bedforms. In flume experiments, however, it is of critical importance that the flume be designed in a way that flocculated materials move under shear stress conditions that would be reasonable in natural environments. Although much flume work on muds has been conducted by hydraulic engineers, the transfer of that knowledge to sedimentology is hampered by the fact that engineers and sedimentologists are interested in different (though not mutually exclusive) products from such experiments. Engineers and hydrologists are commonly concerned with quantifying fluid flow properties, whereas sedimentogists are particularly interested in the sedimentary products that result from a variety of flow conditions. Recent sedimentologically oriented flume studies have shown that muds can form deposits at flow velocities and shear stresses that would suffice to transport and deposit medium grained sand. Mud suspensions are prone to flocculation and the resulting floccules travel in bedload and form ripples that accrete into beds. The latter finding suggests that many laminated shales were deposited from currents rather than by settling from slow moving or still water. There are many other sedimentary features in shales that can potentially be reproduced in flume studies and in the future serve to provide a quantitative basis for shale sedimentology.

1. Introduction

> *"In the case of nearly all branches of science a great advance was made when accurate quantitative methods were used instead of merely qualitative."* (Sorby, 1908)

The above quote introduces a seminal paper, "On the application of quantitative methods to the study of the structure and history of rocks", by the grandfather of sedimentary geology, Henry Clifton Sorby. The paper was read to the London Geological Society on January 8th 1908, when Sorby was already bedridden and unable to attend himself. He died two months later on March 9th 1908. The paper was published posthumously (Sorby, 1908).

Simply reading the section of the paper that deals with the deposition of mud makes one realize that Sorby had arrived at an understanding of mud deposition and the study thereof that makes him seem outright "modern". For example, he writes about how he collected clay from his garden, and then conducted settling experiments that informed him about the difference in behavior between low and high density clay suspensions, and gave him insights on flocculation, and the origin of grading vs. homogenous texture in accumulating mud deposits. Although Sorby did not have access to a flume, he was an ardent observer of nature and concluded from observations in tidal channels that muds can indeed be deposited from currents and that current fluctuations should give rise to very thin laminae. He even suggested that the laminar structure in shales from the Kimmeridge Clay and the Lias of Whitby was the result of deposition from currents. Ironically, in ongoing debates about the sedimentology of muds this latter observation is considered a novel idea.

In this same paper Sorby also introduces the use of Canada Balsam to impregnate unlithified muds for thin sectioning and microscopic study, another illustration of his innovative approach to sedimentology. In the same paragraph where he explains the use of Canada Balsam, he also states that "examination in a natural condition is enough to show that the structure of clays differs enormously, and indicates formation under very different conditions; but there is

E-mail address: jschiebe@indiana.edu.

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always some doubt as to their true structure, when not made into thin sections". A century later the making of thin sections of modern muds has been made easier by introduction of low viscosity resins, such as Spurr (1969), but it still is not a simple matter and requires experimentation and considerable skill. Today, as it was a century ago, the study of petrographic thin sections remains a most powerful and highly valuable tool in the arsenal of the shale geologist.

Sorby may have lacked modern tools for the study of muds and shales, but this did not stop him from using his well-honed observational skills and his knack at experimentation to arrive at a prescient understanding of the challenges ahead in the study of shale sedimentology. He passed into history just a few short years before the onset of a century's worth of flume studies in sedimentary geology (Gilbert, 1914), a period of research that greatly advanced our understanding of sedimentary processes.

There are multiple reasons why understanding the processes that affect the transport and deposition of mud in natural environments is an important subject. Among these is the reality that muddy substances cover much of the earth's surface, the fact that the sedimentary rock record consists to at least two thirds of shales (e.g. Schieber, 1998), the role of shales in the sequestration of fossil organic carbon, the economic importance of shales as source rocks, seals, and reservoirs of hydrocarbons, and the importance of mud management in harbors, shipping lanes and water reservoirs. Shale and mudstone are both widely used terms for fine grained terrigenous clastic rocks, but there is at present no broadly agreed upon terminology for naming and classifying these rocks (e.g. Potter et al., 2005). In discussions within this paper, where experiments are related to the rock record, I will therefore primarily use the term shale, but with the understanding that it includes what some prefer to identify as mudstones.

In the century that followed Sorby's exhortation to apply experimental methods to the understanding of the geologic rock record, much has been accomplished in that regard. Experimental methods are now an essential part of research in geochemistry (Holloway and Wood, 1988) and igneous and metamorphic rocks (Philpotts and Ague, 2009). In the sedimentary geology field as well, experimental work has been essential for progress (e.g. Middleton and Southard, 1977). With regard to the deposition and erosion of sandy sediments, hydraulic engineers and quantitatively oriented sedimentologists have been able to establish the physical basis for many of the sedimentary features observed in natural deposits (Middleton and Southard, 1977; Allen, 1985). More recently, large sedimentation tanks have been constructed that allow us to directly observe complex histories of erosion, transport, and deposition of sand, and then to dissect and analyze the resulting deposits and relate them to what we observe in natural scale systems (Paola et al., 2001).

Thus, whereas we are now in a position to make fact-based predictions with regard to the behavior of sandy and gravelly sediments, there is no comparable legacy of experimental work on muddy sediments. There is still a tremendous amount of work ahead before we can claim to have an in depth understanding of the processes that govern the erosion and deposition of muddy sediments, and by extension the ability to predict the distribution of depositional fabrics and derived physical properties in ancient shale successions.

Much of the existing work on muddy sediments was conducted by engineers in an effort to understand controls on channel erosion, harbor silting, and coastal management, but productive feedback between sedimentologists and the engineering community has been limited (e.g. Middleton and Southard, 1977). The reasons for this state of affairs become abundantly clear when one ventures from the sedimentology side into the engineering literature. It is a matter of language, a story of parallel universes. Engineers converse via equations and diagrams, whereas sedimentologist are used to look at sedimentation processes in terms of sedimentary structures and stratification. Just searching through several recent books on fine sediment hydraulics and engineering (e.g. McAnally and Mehta, 2001; Winterwerp and Kranenburg, 2002; Winterwerp and van Kesteren, 2004), one is hard pressed to find either a single photograph or discussion of sedimentary structures produced by the processes that are documented with much detail and mathematical formulation. Thus, even though physical experimental data about the deposition and erosion of muds were in principle available, the type and presentation of data did not lend themselves to utilization by sedimentologists.

What we do know today is that unlike sands, the erosion and deposition of mud is at least as much governed by cohesion between particles and the degree of consolidation as it is by flow velocity and particle size distribution. There is also a growing appreciation that muddy sediments are highly complex systems that may require as many as 32 variables and parameters for satisfactory physicochemical characterization (Berlamont et al., 1993). The classical studies by Hjulström (1955) and Sundborg (1956) showed that muds require larger current velocities for erosion than sands due to cohesive forces, and that, depending on the degree of consolidation, mud erosion may require current velocities of the same order of magnitude as those needed for the erosion and transport of gravel. Subsequent work by for example Parthenaides (1965), Southard et al. (1971), and Lonsdale and Southard (1974) confirmed these general relationships, and also showed that the subject of mud erosion is much more complex than what originally could have been expected (Migniot, 1968; Einsele et al., 1974).

Ongoing research (e.g. Schieber et al., 2007a), as well as careful observations of the rock record (e.g. Macquaker and Gawthorpe, 1993; Schieber, 1999), clearly show that shales and mudstones were by no means all deposited by low energy processes and that they most likely record a much wider array of depositional parameters than currently appreciated. Visits to recent research conferences on shale gas systems (e.g. 2010 AAPG Hedberg Conference in Austin, Texas; 2011 Houston Geological Society Applied Geoscience Conference, Woodlands, Texas) served to underscore how poorly known these rocks are relative to other sediment types.

2. Experimental study of muds

Though today flume studies are the mainstay of experimental sedimentology, Sorby also showed very elegantly that flume studies need not be the only means at our disposal to understand the nature of shales and mudstones (or any other sediment type for that matter). I have adopted this philosophy as well, and consider these so called "simple" experiments an extremely useful method to focus the mind on actually observable variables. I will therefore precede my discussion of flume studies in shale sedimentology with some examples on how simple "trial and error experimentation", using tank and settling tube experiments, can provide crucial new insights into the language that "so much of the history of our rocks appears to be written in" (Sorby, 1908). In that section we will examine the potential role that sediment dwelling organisms, in particular worms, can play in the post-depositional modification of muddy sediments, and how their activities might manifest themselves in the rock record. In addition, we will look at experiments that test the load-bearing capacity of muds, and the potential consequences of re-suspension and re-settling of surficial muds.

2.1. Trial and error experimentation

2.1.1. "Thinking like a worm"

In modern mud bioturbation by worms and worm-like organisms has a significant impact on preservation of primary sedimentary structures and the overall texture of the shale matrix (e.g. Bromley, 1996). Although bioturbation is destructive with regard to primary sedimentary structures, the way in which it disturbs and reorganizes the sediment still informs about a variety of other parameters, such as sediment consistency, relative sedimentation rates, and oxygen availability (Seilacher, 2009). In shales, only a subset of bioturbation features falls into formally named categories of burrow types, such as *Chondrites, Teichichnus,* and *Zoophycus* (Wetzel and Uchmann, 1998), burrows that are emplaced into partially consolidated muds. Much of bioturbation in muds, however, occurs early in depositional history when water content is on the order of 70 to 90 wt.% and the sediment is of liquid consistency. Instead of tunneling, bioturbating organisms swim through the sediment and disturb its fabric. This type of bioturbation is chaotic and messy and is an understudied area of ichnology.

2.1.2. Biodeformational structures — muddy marble cake

A number of years ago I collected samples of bioturbated Devonian black shales in the Eastern US that showed a variety of burrow-like morphologies (Fig. 1) that did not seem to not fit into established categories commonly cited in the literature. At first glance these traces looked like what has been described as "halo" or "rind" burrows in the literature, attributed to chemical precipitates along the burrow margin (Donahue, 1971; Piper et al., 1987; Bromley, 1996). When a student (Vadec Lobza) and I took the time to look more closely at these features, we realized that they were decidedly more complex than simple diagenetic haloes. The closest structural analog that occurred to us was that of marble cake, produced when one stirs together light and dark cake batter (Fig. 1D). We had in these rocks alternating layers of gray shale and black shale, and we reasoned that if both layer types were in a state of liquidity, an organism that moved through them should produce the mixing structures we observed (Fig. 1B and C). We felt, however, that to demonstrate this experimentally would make a much stronger argument.

After some tinkering, Vadec decided to try to mimic our postulated Devonian situation by dragging plastic baitworms through superimposed and differently colored layers of still liquid Plaster of Paris (Fig. 2). The advantage of this method was that we could do the experiment in one day, let the plaster harden over night, and serial section the plaster blocks the next day to see what structures we had produced. We succeeded to produce direct analogs of our suspected Devonian mixing traces (Fig. 3), and were able to make a convincing argument that the structures observed in Devonian shales were produced by worm-like organisms that moved through a substrate that was in essence a liquid mud with the consistency of well stirred yogurt (Lobza and Schieber, 1999). Following a suggestion by Andreas Wetzel we named these biodeformational features (Wetzel, 1991) "mantle and swirl" structures, and since we published on their origin (Lobza and Schieber, 1999) they have been reported from a variety of other shale successions (e.g. Hickey and Henk, 2007; Hall and Savrda, 2008; Bhattacharya and MacEachern, 2009).

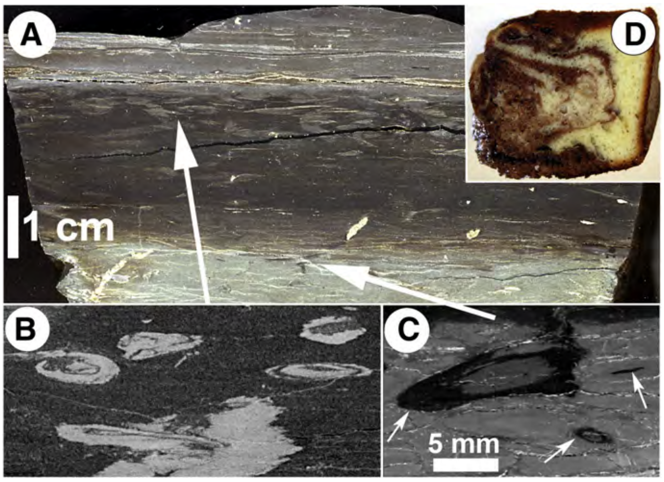

Fig. 1. Mantle and swirl traces from Chattanooga Shale (Lobza and Schieber, 1999). (A) Alternating beds of dark (carbonaceous) and light gray shale with mixing traces produced by sediment swimmers. (B) Close-up of mantle and swirl traces in a dark matrix (digitally enhanced and lighter than original material). Note haloes of light material and mixed in darker material (marble cake texture). (C) Analogous structure in a light gray matrix. Now the haloes consist of dark material. (D) Actual picture of marble cake. Note the similarity of the swirl pattern to those in (B) and (C).

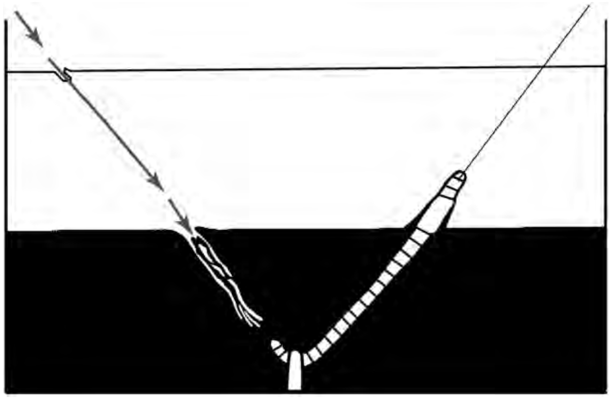

Fig. 2. A plastic bait worm is being pulled across two layers of liquid plaster of Paris that contrast in color (black vs. white). Note the mixing trace that the worm leaves behind (Lobza and Schieber, 1999).

2.1.3. The poop conveyor — layer inversion by worms

In another experiment that involved worms, a layer of organic-rich mud was deposited in a glass cylinder, and after allowing for settling of the mud, a layer of sand was carefully deposited on top (Fig. 4). The mud had sludge worms (*Tubifex tubifex*) living in it, and these worms quickly penetrated the sand layer and extended their tail end above it to access oxygen, while the head end probed the mud layer for food. After ingestion, the waste products moved through the worm, were excreted at the tail end, and build up on top of the sand layer. Over the course of a mere nine months the sand layer was buried under nearly 4 cm's of fecal matter (Fig. 4). In essence, older sediment that once was buried beneath the sand layer was now on top of it, and the order of layering had been reversed. In nature, of course, it is likely that the worms would not be equally effective at every location, and the sand layer migration would likely be quite uneven and still recognizable as such. In a drill core, however, similar in dimension to our experiment, such inversions would easily be missed and could potentially lead to misinterpretation of sedimentary processes. Although the experiment was initially set up to get some idea of the rate of sediment mixing by burrowers, the result was unexpected yet instructive. The sand layer, because it did not contain food for the worms, was not ingested and merely disturbed by a few grain lengths as the worms passed through. Thus the sand layer stayed largely intact. The lower boundary was disturbed by rising methane bubbles, but in deeper water these bubbles would not have formed and the lower boundary would most likely have remained quite sharp.

Deposit feeder "conveyors" have been described previously from marine muds by Schäfer (1962), Rhoads (1974), and Thayer (1983), documenting sediment mixing, grain size segregation, biologically induced grading, and modification of sea floor topography. Unlike in the above described experiment, however, these authors did not observe downward "migration" of a discrete sediment layer and reversal of stratigraphic order.

2.2. Experiments with settling tanks

A common feature of many shales are thin layers and discrete laminae of silt and fine sand (Fig. 5), and although these may reflect as diverse processes as distal turbidites and tempestites, bottom currents,

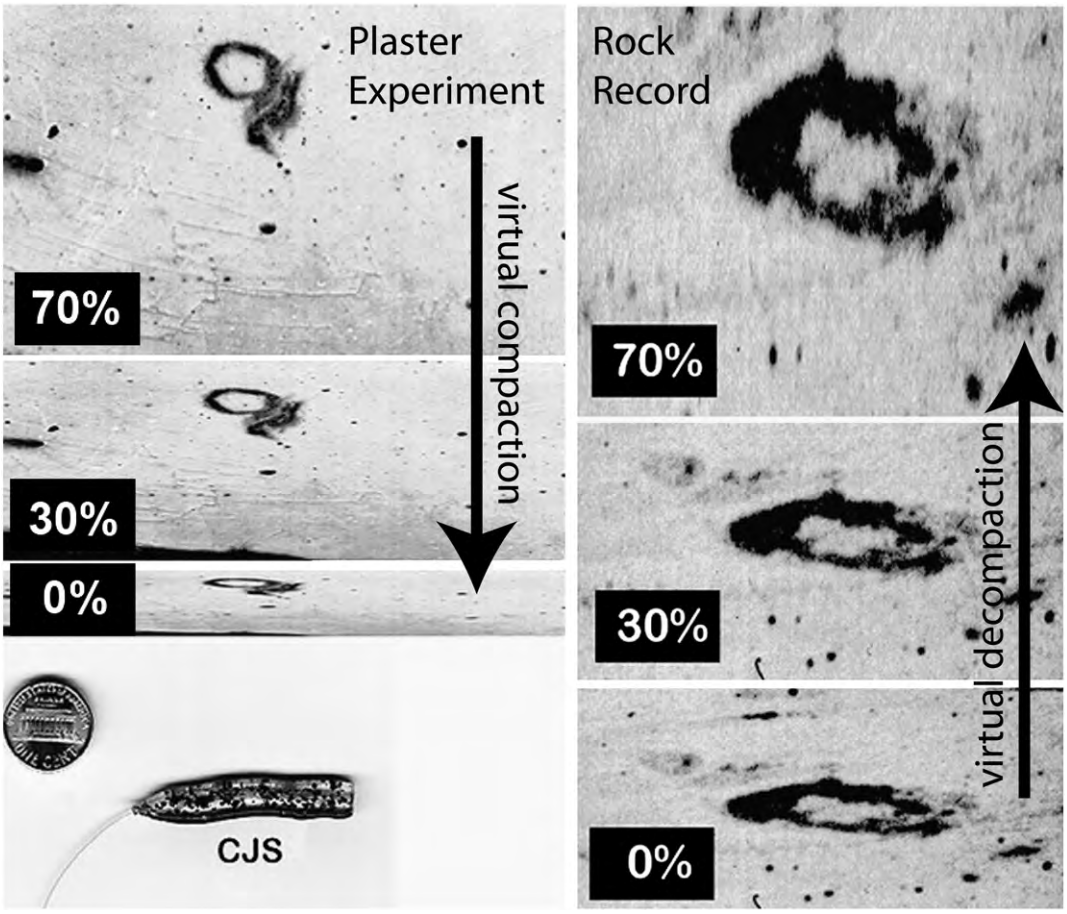

Fig. 3. A comparison between plaster experiment (left half) and rock record equivalent (right half, Chattanooga Shale). The left hand traces were produced when a worm was dragged through black/gray plaster layers. An example of the produced trace is the top left image. Had this trace been produced in mud with 70% water content, compacting the mud to 30% and 0% water content would have produced the traces shown below. The right hand traces are ancient equivalents from the Chattanooga Shale. The original trace is at the right half bottom (water content 0%). Virtual decompaction to 30% and 70% water content produced the images above. The match between experimental and actual trace is very close (Lobza and Schieber, 1999).

and even fall-out from dust storms (e.g. Schieber, 1990), a fundamental question one may want to ask concerns the water content of the mud that underlies such layers. Because freshly deposited muds tend to have water contents in excess of 90% (e.g. Migniot, 1968; Terwindt and Breusers, 1972) they are so fluid that one can barely feel their presence when sticking in a finger. How could something that fluid support for example a thin layer of sand or silt? Would the denser layer not simply force gravitational collapse of the underlying mud (Fig. 6) and sink into the underlying layer in irregular lumps? Settling tube experiments concerning that question were reported by Terwindt and Breusers (1972), and suggested that once freshly deposited mud has compacted for about 4 to 6 h (water content ~90 vol.%) it can already support a sand layer of up to 5 mm thickness.

Because the cross section area of a standard settling tube is rather small (~20 cm^2), friction on the tube wall in the Terwindt and Breusers (1972) experiments may have provided stabilization to the sediment that is not afforded a natural and laterally extensive deposit. We therefore tried to duplicate these experiments in partitioned settling tanks where rectangular areas of 200 cm^2 were loaded with sand. In these experiments (Barrett and Schieber, 1999) we used mud from weathered outcrops of Eagleford Shale (Cretaceous, North Texas) that was passed through a 63 µm sieve to screen out sand grains and fossil debris. Weighed quantities of this mud were suspended in water-filled fish tanks by stirring, and regularly spaced vertical partitions were inserted in these tanks immediately after stirring had stopped. In that way we produced a larger number of mud aliquots to experiment with (Fig. 7).

The settling curve of the mud (Fig. 8) was determined by observing the mud-water interface and measuring its downward progression at successive time intervals. The water content was calculated by subtracting the volume of the mineral matter from the measured mud volume (Fig. 6). A thin layer of sand (1 mm thick) was added to individual tank partitions at half hour intervals to test the loading capacity of the mud. Whereas early in the experiment the sand layers completely sank in and disappeared wholly or partially in the mud (Fig. 9), once the mud had been allowed to settle for 6 h (water content ~85 vol.%) the thin sand layer remained stable at the surface (Fig. 9). The experiments were performed in freshwater as well as salt water (3% NaCl), and the results with regard to settling time needed for a stable sand layer were the same in both cases.

When compared to the experiments by Terwindt and Breusers (1972), in our experiments we placed a thinner sand layer (1 mm) on the settled mud, and it took 2 h longer for the mud to be able to sustain the weight of this thinner sand layer. Because our experiments had a larger “free” area for potential foundering of the sand layer, this suggests that the experiments by Terwindt and Breusers (1972) overestimated the load bearing capacity of freshly deposited muds because of frictional effects at the settling tube walls. In addition, the difference in load bearing capacity vs. settling time probably also reflects differences in the composition of the respective muds. From these observations we can make the general conclusion that, depending on composition, freshly deposited muds should require at least several hours of settling in order to support a thin sand layer (≥1 mm), and correspondingly more for thicker sand layers. The

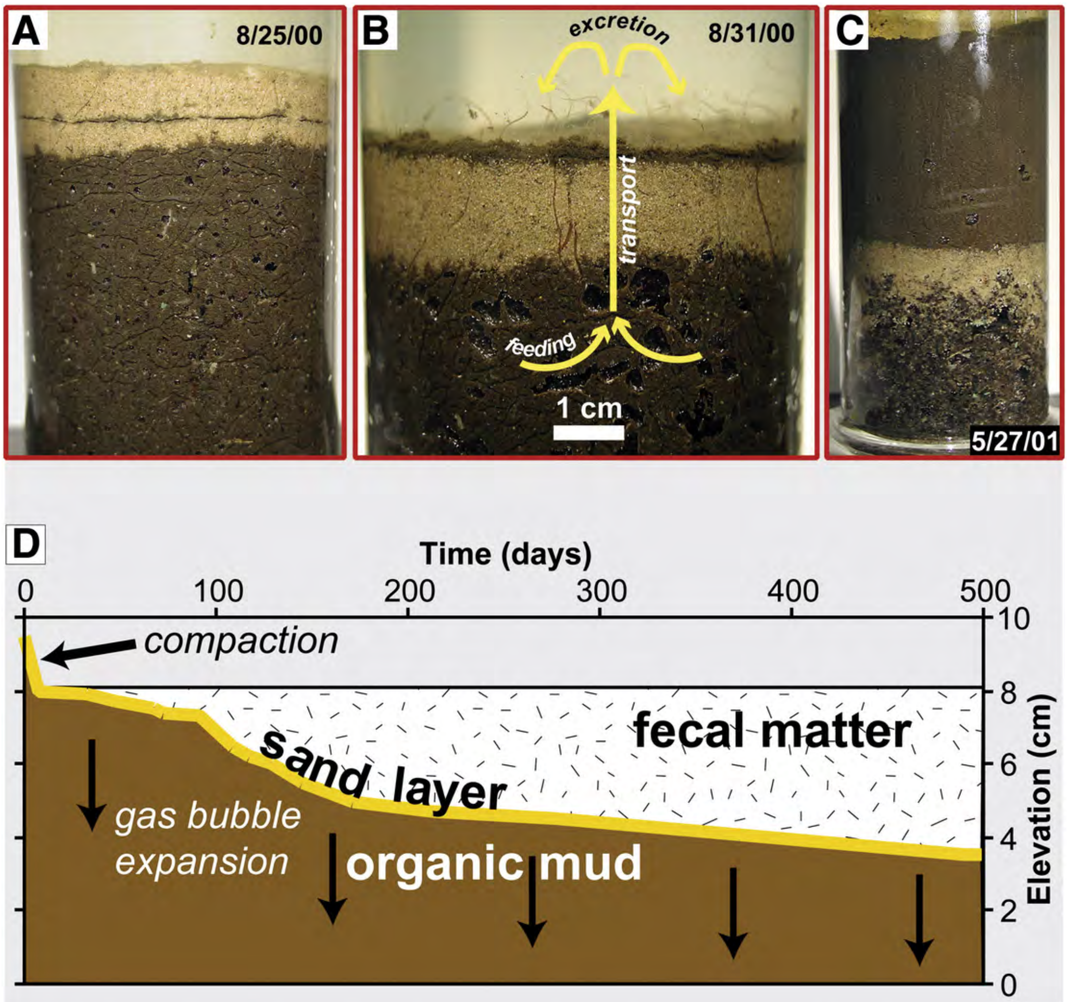

Fig. 4. Worms moving a sand layer. Top panels (A, B, and C) show the change in the position of the sand layer from the beginning and up to a point 275 days into the experiment. Shows that more and more fecal matter is being piled on top. The bottom chart (D) shows the proportions of organic mud and fecal matter layer through the entire course of the experiment.

muds in question have water contents in the 85–90 vol.% range, and the support for the superimposed sand layer reflects the strength of a three dimensional framework (cardhouse structure) of clay flakes and other grains that adhere to each other via weak van der Waals forces (Maxwell, 1874). These muds behave as fluids when disturbed and offer so little resistance to manipulation that one may wonder whether they could still provide that support if the sand, instead of simply "raining" out of the water column, was deposited by currents that exerted a shear force on the surface. It is a question we will revisit once we discuss flume experiments.

2.3. Experiments with settling tubes

Suspending mud in glass cylinders and watching how the mud settles out is a time honored way to teach students some basic properties of muddy suspensions. From observations made with this method, Sorby (1908) was able to conclude that the behavior of muddy suspensions is dependent on the concentration of suspended materials, and it can still be employed today to provide novel insights. Although the equipment may appear simple, the discoveries to be made are only limited by the imagination of the experimenter.

Some years ago, while studying Devonian shale successions, my students and I were trying to understand the origin of interbedded black and gray shales (Fig. 1). Black–gray cycles in shales have been explained by various mechanisms (de Graciansky et al., 1979; Wetzel, 1991), such as fine grained turbidites that interrupt accumulation of organic-rich distal muds, organic matter turbidites that periodically enrich basinal sediments with organic matter, pulsing input of organic matter controlled by surface productivity, and intermittent anoxia due to pycnocline migration (Byers, 1977). This latter explanation had been widely advocated by geologists for Devonian successions in the eastern US (e.g. Ettensohn, 1985; Kepferle, 1993). Yet, when examining the sedimentary features of certain intervals of these rocks more closely, we made observations that suggested a significantly different alternative mode of origin.

In the intervals in question, the pertinent sedimentary features of these depositional cycles are they overlie sharp erosional truncations (Fig. 10), show basal silt lenses and generally more silt in the lower black portion, contain mantle and swirl traces of sediment swimmers that moved between black and gray layers (Fig. 1), and show a gradational boundary between basal black and overlying gray intervals (Fig. 10). What these observations suggest is that deposition of black–gray cycles was preceded by high energy events that were accompanied by erosion (sharp base), and that both the black and gray portion were in a liquid mud state at the same time (mantle and swirl traces). A greater abundance of silt in the lower black portion implies grading and fining upwards. Given these features, one could propose that erosion, for example as a consequence of exceptionally strong

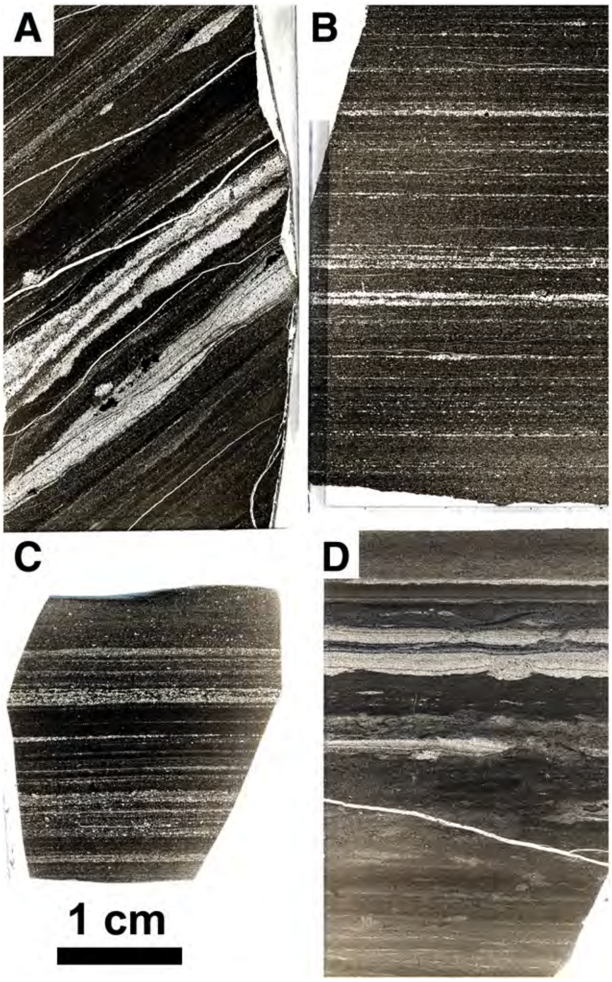

Fig. 5. Images of thin silt and sand layers in the rock record. (A) Chattanooga Shale, Devonian of Kentucky, (B) Bakken Shale, Devonian of Saskatchewan, Canada, (C) Eagleford Shale, Cretaceous of Texas, and (D) Mancos Shale, Cretaceous of Utah. All thin sections displayed at the same scale.

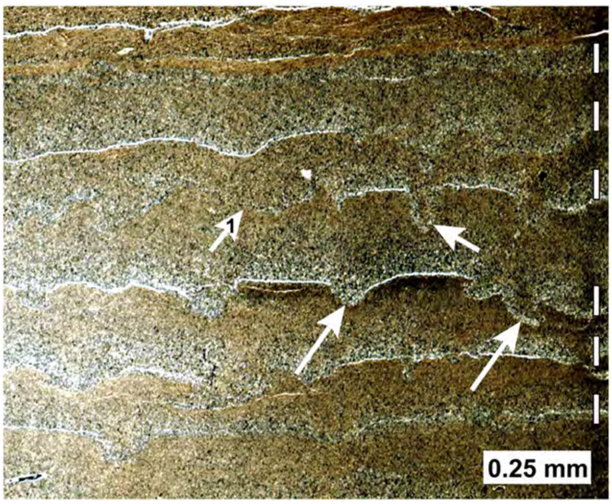

Fig. 6. Thin section photomicrograph of modern epoxy impregnated mud from the Guiana/Amapa coast (northeastern South America). These muds were deposited very rapidly, and as a consequence the surficial muds have high water contents (Rine and Ginsburg, 1985; Allison et al., 2000). The image shows alternating clay-rich and silt-rich (marked with vertical white bars) laminae. The latter show lobes of silt (white arrows), so called load structures. The load structures formed because the underlying clay-rich layers were very watery and less dense than the overlying silt layers. In places silt layers appear to have sunk through the mud completely to merge with the next silt layer underneath (arrow 1). Thin section made available courtesy of Meade Allison.

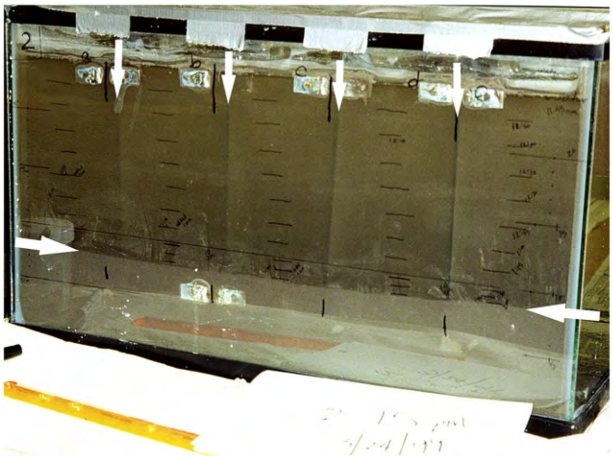

Fig. 7. Picture of fish tanks with dividers. Position of dividers marked with vertical white arrows. The horizontal white arrows mark the position of the boundary between settled mud and suspension.

storms, resuspended the more readily erodible part of the seabed, and that the observed cycle resulted from settling of this material after the storm had abated.

Such an interpretation does, of course, contradict conventional wisdom which stipulates that the observed cycles indicate oscillations between dysoxic and anoxic conditions through time, and imply a stratified water column with a lower layer of anoxic water for the black intervals (e.g. Byers, 1977; Cuff, 1980; Ettensohn, 1985; Kepferle, 1993). One problem with our supposition was that mineral matter (clays and silt) is much denser than organic matter. Thus, even if erosion and resettling had occurred, one would presume that the organic matter should have ended up in the top portion of the resettled sediment instead of at the bottom. We decided to test this assumption by comparing the settling of a clay suspension with that of a suspension of finely blended organic debris from a pond bottom. It turned out that in spite of the differences in density, the organic debris formed such large floccules that it still settled out considerable faster than the clay (Fig. 11).

After that rather interesting result, we wanted to experiment with a mixture of organic debris and clay, and produce a deposit thick

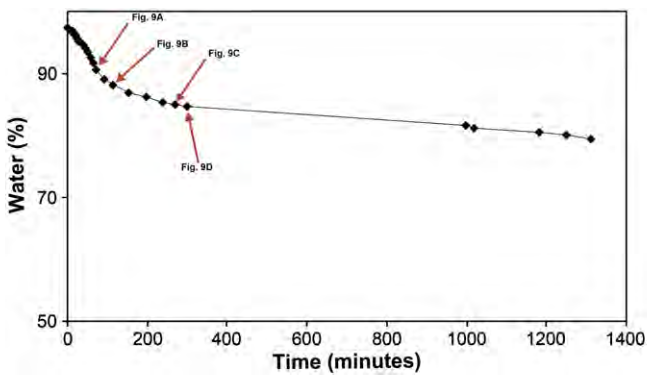

Fig. 8. Settling curve for mud in tanks. Initially, the percentage of water in the mud decreases rapidly. After about 70 min of settling (arrow Fig. 9A) the water escape slows due to beginning of fabric development (water flow begins to be constrained by mud pore spaces) and the water content of the settled mud is 91%. At the point marked with the next arrow (arrow Fig. 9B) the water content of the settled mud has dropped to 88%. At the point when a fully self-supporting mud fabric has formed (arrow Fig. 9C; 85% water content), the established pore diameters and the weight of the mud determine the rate of water escape and cause a linear lowering of the mud/water interface and of the water content. The point marked by arrow 9D indicates the formation of the first stable sand layer at 84.5% water content, approximately 5 h after the start of settling.

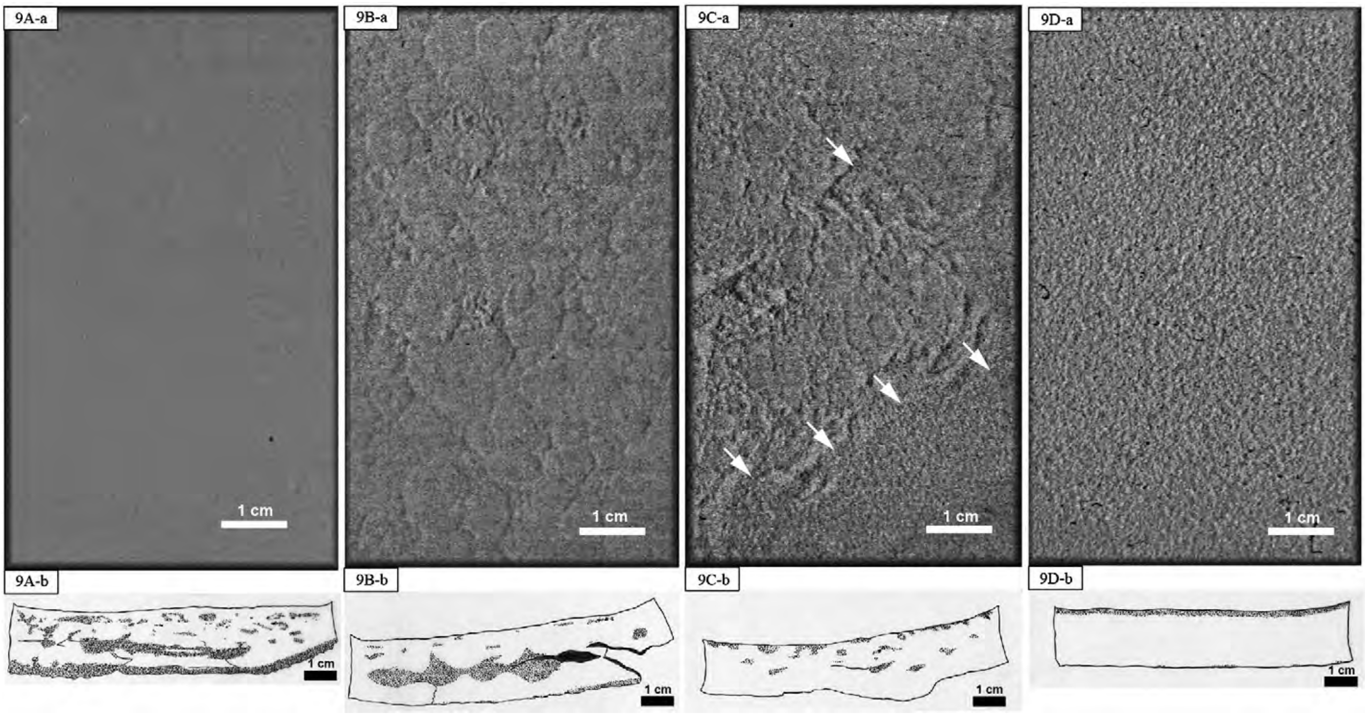

Fig. 9. Surface of mud layer with sand addition across a range of water contents and cross section drawings of the final deposits (after drying). (A) At 91% water content. (A-a) Plan view of the first section to receive sand. (A-b) A cross sectional drawing of the final deposit. The sand sunk completely through the mud surface, leaving no visible trace on the surface. (B) At 88% water content. (B-a) Plan view of third section that shows increasing surface texture due to turbulence produced by the sinking sand layer. (B-b) The cross section shows less sand reaching the bottom of the tank and more segregation of sand into clumps (ball and pillow structure). (C) At 85% water content. (C-a) Section 7, patches of sand are seen to remain stable on the surface (white arrows, note granular surface texture). (C-b) The cross section shows abundant sand at or close to the surface, and also smaller and more shallow placed sand lumps. (D) At 84.5% water content. (D-a) Section 8, sand remains stable on the surface. The sand surface differs from mud surfaces by its granular texture. (D-b) The cross section shows an even sand layer at the surface.

enough to provide samples for chemical analysis of organic carbon distribution. Because we needed larger amounts of material we conducted these experiments with large settling tubes that were 3 m long and 6.35 cm wide (Fig. 12A), providing a settling thickness that was at least of the same order of magnitude as an envisioned layer of storm suspended shelf mud. We repeated the precursor experiment where clay and organic debris settling was tested separately, and again the organic matter floccules were considerably larger than clay floccules and settled out much faster than the clays under otherwise identical conditions (Fig. 12B and C). Microscopic examination showed that

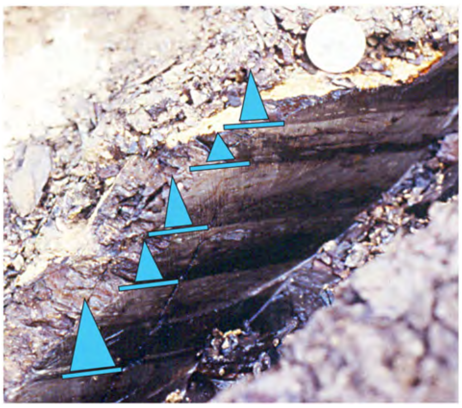

Fig. 10. Thin depositional cycles of alternating black and gray shales in the Chattanooga Shale of Tennessee. Each cycle (marked by blue triangle) starts with a sharp basal surface (blue line) and may show scouring and silt lenses at the base. The lower portion of each cycle is black due to abundant organic matter, and visibly bioturbated from the top. The upper gray portion of each cycle is more intensely bioturbated. Coin for scale is 25 mm in diameter.

the organic particles were covered with microbial biofilms, and we attributed the rapid formation of large flocs to the sticky nature of the biofilms (Schieber, 2001).

We then prepared a mixture of blended organic debris and clay, added it to the tube filled with seawater, vigorously stirred the ingredients, and then allowed the solids to settle. After settling was complete we let the sediment consolidate for several more days, and then slowly drained the water, partially dried the sediment plug by circulating air through the tube, and finally removed the sediment plug for analysis (Fig. 13A). The dried plugs were cut into equal sections and analyzed for organic carbon. The data showed that, dependent on the original sediment loading, the faster settling organic matter could indeed be enriched in the bottom portion of the plug. At high sediment loadings of several 10 g/l there was no clear segregation of organics and clays (Fig. 13B). The downpour of particles produced strong water displacement and turbulence in the bottom portion of the tube and led to continued mixing for most of the time of active sediment deposition. At sediment loadings below 10 g/l, however, basal turbulence was much reduced and there was a clear upwards decline of TOC in the accumulating deposit (Fig. 13C). Applied to the rock record, this counter-intuitive result suggests that black–gray cycles could indeed have formed via suspension-resettling driven segregation of clays and organics (Schieber, 2003).

One should of course exercise caution when applying this concept to the rock record. How thick, one might ask, could a layer of said origin be in the rock record under realistic assumptions? Let us assume, for example, an area in an epeiric sea that is on average 50 m deep, and assume further that the entire water column is stirred up, and that the suspended sediment concentration is 1 g/l. In that case a fully compacted deposit (assumed density 2.5 g/cm^3) would be a mere 2 cm's thick. Thus, whereas thin (some cm's thick) black–gray cycles with above described attributes may indeed have formed via

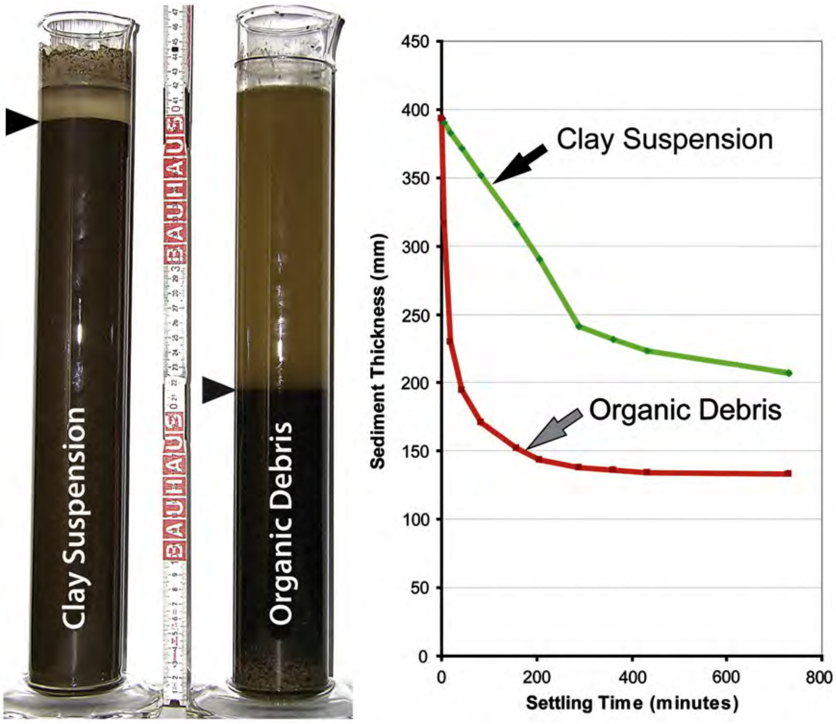

Fig. 11. The difference in settling behavior of suspensions of clay and of finely blended organic debris. Black triangles show the top of the two suspensions after 41 min of settling (scale in centimeters). At right, the recorded settling curves for the two cylinders, showing that the organic debris settled much faster than the clay suspension. Settling of the organic debris was largely complete after approximately 1 h, whereas clay settling required approximately 5 h.

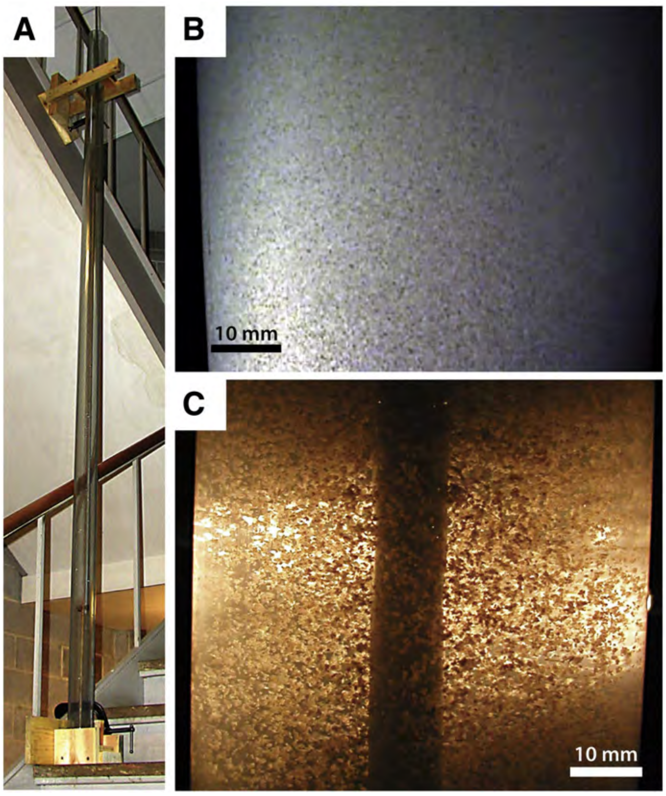

Fig. 12. Large settling tube experiment. (A) The settling tube was placed in the center of the stairwell and filled with seawater and sediment. The suspension was stirred vigorously with a long stirring rod from the next level up, and then allowed to settle. (B) Experiment with pure kaolinite that illustrates the size of floccules that form during settling. (C) Experiment with pure organic debris that was collected from the bottom of a pond and run through a blender before the experiment. Note that the organic matter floccules are significantly larger than the kaolinite floccules.

the suggested suspension-resettling mechanism, thicker black–gray cycles (some dm's thick) more likely represent fine grained distal parasequences or fluctuations in oxygen levels (VID-1).

2.4. Experimentation with flumes

With mud being by definition any sediment containing more than 50% grains smaller than 63 μm (e.g. Potter et al., 2005), the section below summarizes results from flume studies that were done with natural muds, as well as with carefully prepared slurries of silts and clays. This research was conducted across a range of disciplines, such as sedimentology, oceanography, civil engineering, hydraulic engineering, and environmental engineering. Due to differing objectives, methodology and measured parameters vary greatly between disciplines. As a result, the comparison of experimental outcomes poses a considerable challenge.

2.4.1. Flume work with muds from a historical perspective

Flume experiments on mud deposition and erosion have for the most part been conducted by engineers (e.g. Krone, 1962), and the majority of them was performed with annular flumes or designs inspired by them (e.g. Partheniades et al., 1966; Mehta and Partheniades, 1973; Krishnappan, 1993; Stone and Krishnappan, 2005; Stone et al., 2008). Annular flumes consist of a rotating channel and a counter-rotating ring (lid) that touches the top of the fluid, a design that allows the minimization of secondary flow and simplifies shear stress measurements. Mehta and Partheniades (1973) and Hayter et al. (1999) found that the critical controls on deposition were bed shear stress, flow depth, concentration of suspended sediment, and the character of the suspending fluid (e.g. fresh water vs. salt water). The most commonly measured variables are the critical thresholds of deposition and erosion because of their importance for engineering studies of shoaling and erosion in channels, navigable waterways, canals, and harbors. Specialized annular flumes that are able to make shear stress measurements in situ have also been designed and deployed (e.g. Maa,

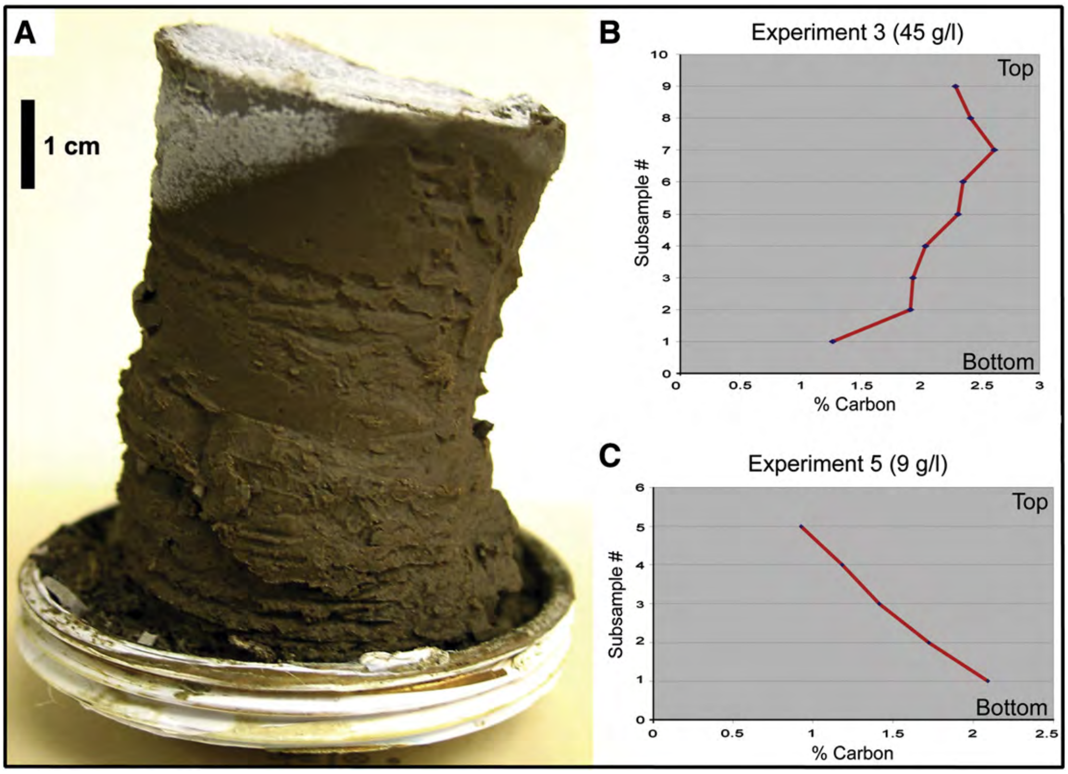

Fig. 13. Samples and sample analyses from long tube experiments. (A) A partially dried sediment plug that has reached the consistency of soft butter and has been removed from the tube (it sits on the screw cap from the bottom of the tube). (B) Carbon distribution in a plug from an experiment with high sediment concentration (45 g/l). (C) Carbon distribution in a plug from an experiment with lower sediment concentration (9 g/l).

1989). From a sedimentologist's perspective, one drawback of engineering studies is that they are often empirical and site specific, and that physically based empirical relationships are described via compounded parameters (Delo, 1988; Mehta, 1989; Teisson et al., 1993). Nonetheless, the engineering literature on mud erosion and deposition is extensive, and above references are only examples to facilitate access to a much broader body of work.

An interesting study that has relevance for shale sedimentology was published by Rees (1966), reporting on a series of experiments with fine quartz silt of 10 μm median diameter in a linear recirculating flume. In that flume, water and sediment traveled down the length of a straight flume channel, were piped to a pump, and then pumped back to the beginning of the flume channel. The pump was of the centrifugal type, where a rotating impeller raises the fluid pressure and effects flow (Rees, 1966). At mean flow velocities that ranged from 8 to 14 cm/s and 5 cm flow depth he observed formation of rippled surfaces and internal cross-stratification within accreting beds. Rees assumed that he had observed the behavior of discrete silt particles instead of floccules because he had removed the clay fraction through prior washing of the sediment. In natural settings, of course fine silt always is mixed with clay minerals, and it is probably because of this that his study did not receive much attention among mainstream sedimentologists. In hindsight one may wonder whether the silt did indeed not form floccules, and whether this critical aspect warrants verification through new experiments. A thematically related linear flume experiment was conducted by Mantz (1973) with muscovite and biotite flakes of medium silt (30 μm) to fine sand size (120 μm). Once the threshold of motion had been exceeded, elongate ridges parallel to flow direction formed on the bed surface. No cohesion between particles was observed and the ridges were interpreted to be equivalent to parting lineations that we find in the rock record.

Flume experiments on the durability of mud clasts were conducted by Smith (1972), using precast tiles of muddy sediments of variable composition and water content. The tiles were placed in a racetrack flume with a sandy bottom, transported in bedload, and their abrasion over time recorded. Clay-rich and initially moist mud tiles were the most erosion resistant, but all mud tiles wore down and rounded quickly. The main conclusion was that most mud intraclasts in sedimentary deposits probably underwent little transportation from their site of origin. Although these experiments do not directly relate to the deposition and erosion of mud, they are included here because they do touch on the broader topic of shale sedimentology.

The fate of mud in tidal environments has attracted interest because tidal deposits are subjected to a wide range of flow velocities including slack water conditions, and contain facies where sand and mud layers are intimately associated (Reineck and Wunderlich, 1968). Rapid mud deposition in the slack water interval between the in- and outgoing tide is typically considered crucial for mud accumulation in tidal settings. Reineck and Wunderlich (1969) showed through careful monitoring of modern tidal flats that 3 mm thick water-rich mud layers can be formed in a single slack-water period.

Terwindt and Breusers (1972) investigated whether centimeter-thick clay layers that are seen in older tidal deposits could possibly be deposited during a single slack water period, and how they could possibly escape erosion during the following tidal cycle. They concluded from a combination of erosion experiments in a recirculating flume and observations on natural deposits that thin, mm-tick, mud beds may be generated during a single tidal cycle, and that thicker mud beds may require multiple tidal cycles where a given mud layer is only partially eroded.

Einsele et al. (1974) explored the influence of clay type, void ratio, and shear strength on threshold of erosion velocities, and found that the “geologic history” of a mud plays a significant role in determining that variable. Under "geologic history", Einsele et al. (1974) include whether a mud was deposited from dilute or dense suspensions (slurries), the fabric that developed during settling and consolidation, and the distribution of inhomogeneities.

Young and Southard (1978) studied erosion of marine muds with a recirculating flume in the laboratory and on a shallow shelf with in-situ measurements by a sea-floor flume, and demonstrated that the threshold of erosion velocity decreases with an increase in the degree of bioturbation, and that there is a systematic increase in threshold of erosion velocity with organic content in non-bioturbated sediments. They also found that the bioturbated marine sediments in their study required lower threshold of erosion velocities than one would expect from predictions made in the works of Hjulström (1955) and Sundborg (1956). The latter authors predicted that muds should be more difficult to erode than fine sand, whereas Young and Southard (1978) found that the opposite was the case for the muds in their study. They explained the discrepancy with the lower bulk density of biologically aggregated sediments. Young and Southard (1978) also noted significant lateral variability in threshold of erosion velocity in their seafloor study. Because bulk physical properties of the sediments varied very little, they suggested that the differences in threshold of erosion velocity were related to more subtle and at the time unmeasured physical and biochemical parameters.

Hawley (1981) studied the same complex of questions as initially investigated by Terwindt and Breusers (1972), namely whether or not mud beds could be formed in nearshore subtidal areas purely as a result of tidal activity. His experiments differed from those of Terwindt and Breusers (1972), in that his flume-simulated deposition as well as erosion of mud layers. In his experiments he used a linear recirculating flume that simulated 12.5 h tidal cycles and he examined the effects of clay type, bed thickness, and current velocity on the preservation potential of deposited mud beds. His experiments suggested that pure tidal action was unlikely to produce persistent mud interbeds because the slack water mud blankets were not sufficiently erosion resistant to withstand the shear stress during subsequent tidal flow. He suggested that mechanisms that permit deposition of thicker mud beds and allow for longer consolidation times, such as storm action, would be more likely to generate preservable mud beds.

Many ancient muds show lamination, and the potential origin of lamination was the subject of a flume study by Pasierbiewicz and Kotlarczyk (1997). They used a recirculating linear flume, mean flow velocity was 15 cm/s, flow depth was approximately 5 cm, and sediment concentrations varied between 1.4 and 3.3 g/l. In a given run pulses of different clay types were added successively to the flume, and a "resting period" of one or two days allowed the sediment to compact between runs. The resulting deposit showed visible laminae. The lamination largely reflected the episodic sediment input and the resting periods between runs. Laminae formed during continuous deposition within a given run showed gradual contacts, whereas the breaks in deposition between runs (resting periods) produced sharp contacts.

The influence of suspended clays on the velocity and turbulence structure of muddy flows was the subject of flume research by Baas and Best (2002). Their study was conducted with a linear recirculating flume, and suggests that muddy flows with high suspended sediment concentrations (in excess of 10 g/l) diverge in their fluid-dynamic characteristics from their clear-water counterparts. As clay concentration increases in these flows, a lower region of reduced velocity develops that is separated from the overlying flow by a distinct shear layer. They propose that large-scale Kelvin–Helmholtz instabilities arise along this shear layer and influence turbulence generation and fluid mixing. The formation of parallel laminae in turbiditic muds and sediment sorting in a variety of clay-rich flows is attributed by the authors to these instabilities. The ideas set out in this paper were further developed in successor papers (Baas and Best, 2008; Baas et al., 2009).

Shales and mudstones comprise more than two thirds of the known sedimentary rock record (e.g. Schieber, 1998), and from that vantage point one may wonder why sedimentologists have done comparatively little to avail themselves of the results of the flume studies mentioned above in order to improve their reading of the rock record. In part this may have been because of the prevailing notion that shales only accumulate in low energy settings, and in part it may have been a matter of utility. Although above mentioned flume studies do shed some light on a range of issues related to the deposition and erosion of muds, once one thinks about it a bit more carefully one realizes that these studies have a variety of shortcomings and problems that make them of limited use to sedimentologists that are interested in the interpretation of actual rocks.

For one thing, and probably most importantly, with the exception of the study by Pasierbiewicz and Kotlarczyk (1997), none of these studies reports on sedimentary features that might have been observed in the muds that accumulated during flume experiments. It is exactly such features, however, that allow the practicing sedimentologist to relate what he sees in ancient rocks to conditions and processes observed in modern sedimentary environments. Also, whereas in flume experiments with sand there is enough visibility to see bedforms migrating through the flume channel, no such luxury is afforded to those that conduct comparable experiments with mud. For example, in experiments with kaolinite, a mere 50 mg/l of sediment will render the flow opaque and we are thus reduced to study the "sedimentology of milk" (Schieber et al., 2007b). It is not surprising therefore that none of the above experiments reports on any features or bedforms that might have been active during mud deposition.

Because muds have a tendency to flocculate in seawater as well as freshwater (Bennett et al., 1991; Stone and Krishnappan, 2003; Schieber et al., 2007a), they will in most situations behave as aggregates rather than individual particles. Thus, flocculation is a major factor in the rapid settling of muds in a large variety of environments. Kranck (1991) presents experimental data that relate shale microfabric features to the mechanics of flocculation, and gives references to other studies of flocculation. Therefore, in experimental work with mud it is essential that floccules are allowed to form and to have flow conditions that give them survival chances comparable to natural settings. The lack of floccule survival is the weak point in above experiments that were conducted with recirculating flumes. The centrifugal pumps that are typically used in this design exert very high shear forces on the fluid and effectively shred any floccules that may have formed. Thus, in these flumes, flocculation is impeded and the floccules are not as well developed (and as large) as one could expect in the absence of this continuous destruction. Mud experiments run in these flumes may well be of very high experimental rigor with regard to reproducibility of results, but whatever is observed or measured may not necessarily be reflective of natural conditions. This limitation does not apply to annular flume experiments, but the latter still suffer from lacking visualization of potential bedforms, and the lack of interest in the structures of final deposits on part of the investigators.

2.4.2. Recent racetrack flume experiments

Coming from a sedimentological background, the need for experimental work in shale sedimentology grew from the realization that many of these fine-grained rocks contain small-scale sedimentary structures that can potentially provide information about their depositional conditions and history (O'Brien and Slatt, 1990; Schieber, 1986, 1989, 1990, 1991, 1998, 1999). At the same time, however, it was quite obvious that there simply was not much information available that enabled us to link features observed in the rock record to sets of physical variables measurable in modern environments.

Although one might hope to glean the required information from studies of modern mud accumulating environments (e.g. Kuehl et al., 1986; Nittrouer et al., 1986; Kuehl et al., 1988, 1991; Segall and Kuehl, 1994), the heterogeneity of modern sediments makes it quite difficult to connect observed sedimentary features and measured process variables. Our knowledge of modern mud deposition is two-dimensional and spotty, but interpretation of the ancient record requires a three-dimensional solution. Improved studies of modern environments might alleviate some of these problems, but it seemed clear that true improvement would require experimental studies of mud deposition.

With this objective in mind, and knowing about the limitations of earlier experiments, my students and I built a simple flume with an alternative drive system as a class project. Because we wanted to avoid shredding the fluid, we built an Archimedes screw to lift the mud suspension to an elevated reservoir, and then fed it back into the flume from there. The system worked, and large floccules traveled through the flume channel. A major limitation of that setup was that an Archimedes screw cannot simply turn faster to transport more fluid due to counteracting centrifugal forces. Thus, we could not work with high flow velocities or high flow volumes.

Some years later, the observations from that intriguing experiment spurred work on a new flume design that overcame the velocity and flow volume limitations of the Archimedes screw experiment. This flume (Fig. 14), built with suggestions on design issues from John Southard, is a racetrack type flume with straight sections that are 7.2 m long, 25 cm wide, and with turning sections of 1.5 m radius. The water is propelled in one of the straight sections with a motor driven paddle belt that engages the flow over a 6 m distance. The paddle belt allows us to move the water without inflicting unnaturally high shear forces on the flow and thus preserves the floccules that are present. In order to maintain uniform flow a flow lid is placed on the flow in the turning sections and the observation stretch. The flow lid is placed at 10 cm above the bed (5 cm effective flow depth), and in that configuration flow velocities from zero to 65 cm/s can be achieved. This velocity range allows us to explore a wide range of flow conditions relevant for shale sedimentology, and is also quite adequate to transport very coarse sand in bedload. We currently have two flumes with identical geometries in operation, and are constructing a third flume with the ability to cool to 4 °C and control of oxygenation levels. For both flumes the speed of the drive motor has been calibrated to flow velocities measured with a Marsh-McBirney flow meter and a Sontek ADV flow meter. Suspended sediment concentration is recorded with optical sensors, and other water quality parameters (pH, Eh, O_2, conductivity, salinity, and temperature) can be recorded as well.

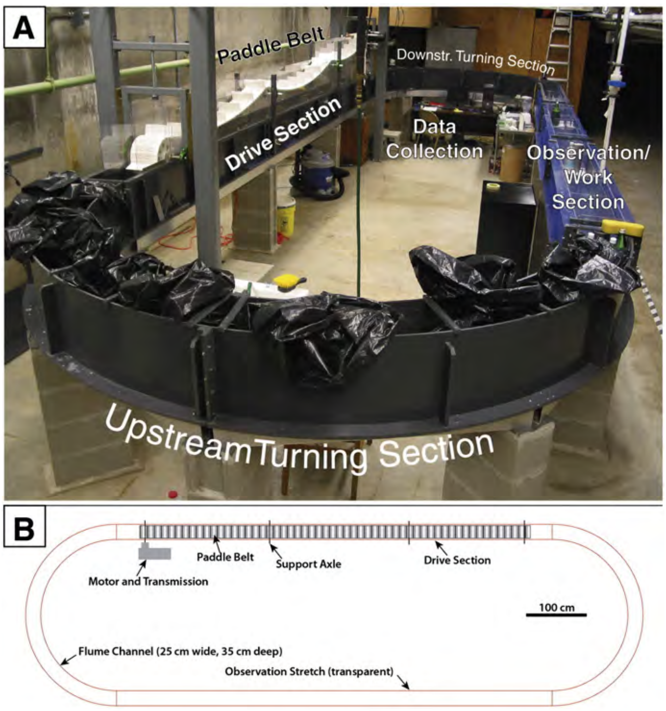

Fig. 14. (A) Our first flume with an open channel design and the ability to add a flow lid as needed. Only the observation stretch is made of transparent material. The various elements are labeled in the photo. The drive belt is fully adjustable in height. (B) A plan view of the flume with design elements labeled.

Because even dilute mud suspensions are murky enough to prohibit observation of what goes on inside the flume, we had to find alternative ways to observe sediment movement and potential bedload transport. One solution that has worked well for us is to place strong lights above the flow, and then observe whatever is moving through the transparent flume bottom. Doing this we are able to not only observe, film, and photograph bedforms such as ripples (Fig. 15), but also individual floccules via macro-lens and HD-video.

Over the course of the past five years, our flume work with muddy suspensions has produced several critical results that are changing the way we view deposition and sedimentology of shales (Schieber et al., 2007a; Schieber and Southard, 2009). The most important of these results is that muds as well as pure clays can be deposited from swift flows in the 15 to 30 cm/s range (5 cm flow depth). Quiescent conditions are not a requirement for mud accumulation. The second result is that muds and clays will flocculate even in distilled and freshwater to a degree that enhances their deposition from currents. Depending on clay type, seawater typically improves flocculation efficiency, but is not a prerequisite for flocculation. Finally, a portion of the floccules that form in muddy suspensions are large enough and strong enough to travel in bedload and form floccule ripples that migrate over the flume bottom (measurement of floccule size is discussed in Section 2.4.2.2.). Over time over-riding floccule ripples will lead to the accretion of mud beds. Thus, although conventional wisdom held that muds need a quiescent environment to settle and form beds, they can also form from lateral advection of muds in energetic environments.

2.4.2.1. Depositional parameters. In our current work we follow two experimental approaches. The first approach (Schieber et al., 2007a) consists of starting an experiment at full suspension velocity (e.g. 50 cm/s at 5 cm flow depth), and then reducing velocity in equal-sized steps until we arrive at the critical velocity of sedimentation (Fig. 16). At this velocity suspended sediment concentration steadily drops until the bulk of the sediment load has been deposited. The critical velocity of sedimentation is bracketed between the last flow velocity where the flow equilibrated and the velocity where a steady drop of suspended sediment concentration occurs (Fig. 16). Because with this approach we start each velocity reduction at a different suspended sediment concentration, we wanted to have a second approach that could not be influenced by initial suspended sediment concentration. This second approach also involves velocity reductions, but now we resuspend all sediment after equilibrium is reached, and then do a larger velocity step from full suspension (Fig. 17). Within the 5 cm/s velocity brackets that we currently use in our experiments, both methods give us the same result with regard to critical velocity of sedimentation. Additional experimentation involves increasing the size of the velocity step after the critical velocity of sedimentation has been reached (Fig. 18). Doing so produces increasingly steeper decline curves and faster bed accretion. In our flumes, the critical velocities determined in these experiments can be correlated with bottom shear stress values derived from velocity profiles established for the various flow velocity settings.

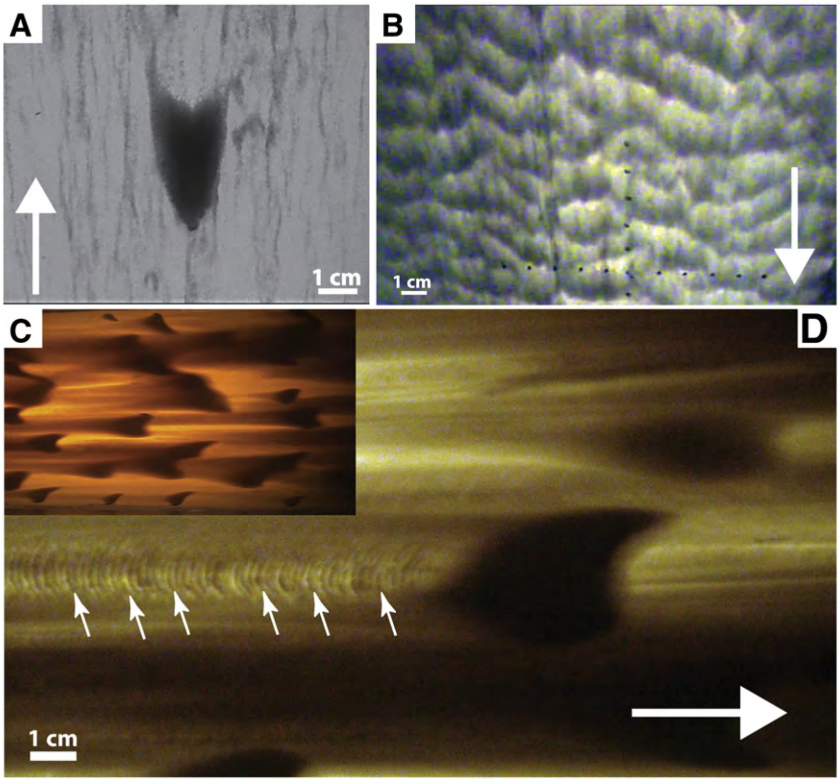

Fig. 15. Floccule ripples observed from beneath the flume via backlighting. (A) Single barchanoid ripple amid a field of floccule streamers. White arrow indicates flow direction. (B) Floccules forming transverse ripples. Arrow indicates flow direction. (C) Abundant barchanoid ripples migrating from left to right. (D) Close-up view of one ripple from the same general area. The migrating ripple in the center leaves behind a thin layer of sediment within which the foreset laminae (small white arrows) of the ripple are still preserved. Stacking of such ripple trains leads to formation of rib and furrow structure.

The described approach to find the critical velocity of sedimentation mirrors the methodology used in civil engineering experiments with muds. Although the latter are typically conducted with annular flumes, the step-down patterns are comparable to that shown in Fig. 16 (e.g. Berlamont et al., 1993; Maa et al., 2008). Likewise, erosion test that we conducted on clay beds deposited in our flumes showed the same step-wise pattern (Fig. 19) as reported in the engineering literature (Parthenaides, 1965; Parchure and Mehta, 1985; Teisson et al., 1993; Schweim et al., 2001; Stone et al., 2008), and the threshold of erosion shear stresses reported in the literature from comparable sediments are quite comparable those derived from near wall velocity profiles in our flumes (Schieber et al., 2010). The latter range from 0.009 Pa (10 cm/s) to 0.044 Pa (50 cm/s) at 23 °C (Schieber, unpublished data), and it appears therefore that our measurements of critical velocities and shear stresses are compatible with those that have been reported in the engineering literature, and that the engineering data can benefit the advancement of shale sedimentology.

We have run a number of experiments where, after reaching the critical velocity of sedimentation, the suspended sediment concentration did indeed decline until the flow was rendered transparent. This property is best developed when the grain size distribution of the original sediment is comparatively narrow, when the initial suspended sediment concentration is at most a few grams per liter, and when the experiment is run at higher salinity. At higher sediment concentrations (>3 g/l) and when the original sediment shows a broad grain size distribution (e.g. coarse silt to fine clay), or if it is

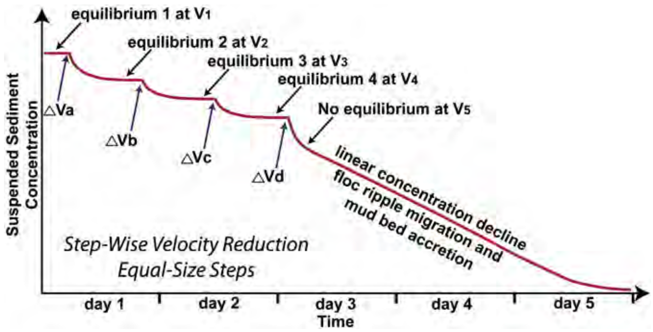

Fig. 16. Illustration of experimental approach where velocity is lowered step-wise to find the critical velocity of sedimentation. As long as the velocity (shear stress) is too large, a new equilibrium concentration of suspended sediment is established. Once the velocity (shear stress) falls below the critical level, sediment will continuously leave the flow and concentration will no longer equilibrate.

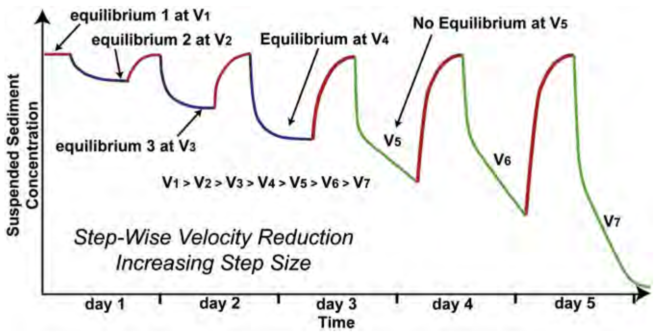

Fig. 17. Illustration of experimental approach where velocity is lowered step-wise by increasing amounts to find the critical velocity of sedimentation. As long as the velocity (shear stress) is too large, a new equilibrium concentration of suspended sediment is established. Once the velocity (shear stress) falls below the critical level sediment will continuously leave the flow and concentration will no longer equilibrate. The steepness of the concentration drop reflects the difference between actual velocity and critical velocity.

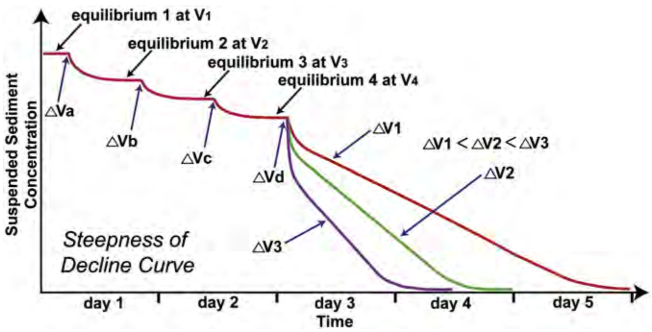

Fig. 18. A companion figure to Fig. 16. Velocity is lowered step-wise to find the critical velocity of sedimentation. Once the velocity (shear stress) falls below the critical level sediment will continuously leave the flow and concentration will no longer equilibrate. The steepness of the decline curve will increase as the difference between actual velocity and critical velocity increases.

bimodal or even multimodal, we may see a modified behavior. In that case we might see a decline curve developing when the coarser grain population transfers into bedload, but the decline may stop at some point because the floccules formed from the finer grain population are still above the critical velocity of sedimentation that applies to them. So, when more complex sediment mixtures are used, the depositional behavior should not be expected to be as simple as depicted in Figs. 17 and 18.

In our laboratory we conduct flume experiments with natural muds as well as with pure clay minerals and other fine grained materials. Typical fluids range from freshwater to 2% salinity, because higher salinities do not appear to further improve flocculation efficiency. In cases, however, where we try to model specific sedimentary features found in ancient marine shales, we may choose to use full marine salinity (3.5%) to remove residual doubts as to whether what we were doing was done in a realistic setting.

2.4.2.2. Flocculation and floccule formation. Muds are complex mixtures of water (with variable salinity), clay minerals, various types of organic matter, and commonly also small amounts of sand and silt. A key factor for their characterization is flocculation, a phenomenon influenced by a large number of controlling parameters, such as settling velocity, floc size, grain size distribution, ion exchange behavior, organic content, etc. Defined as the joining of smaller particles to form larger aggregates, flocculation enhances the deposition rate of fine-grained sediments and its understanding is critical for deciphering the behavior of mud in sedimentary environments (e.g. van Olphen, 1963). Although considerable effort has been invested towards understanding flocculation, we still miss critical data on floc formation, and the influence of floc structure and turbulence on the formation of muddy sediments (Winterwerp and Kranenburg, 2002).

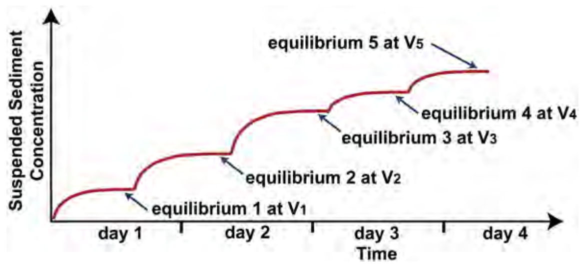

Fig. 19. Illustration of experimental erosion of a previously deposited mud bed. The velocity is increased step-wise and the suspended sediment concentration stabilizes once all erodible material has been resuspended. The resistance to erosion increases as deeper and more compacted portions of the bed are exposed.

The problem of trying to understand flocculation is compounded by the fact that researchers of different disciplines, such as sedimentologist, engineers, modelers, ecologists, etc., all have their own definitions, methodologies and even literature references. Thus, a parameter that engineers spend lots of effort to define may be of no immediate relevance to sedimentologist and vice versa (Black et al., 2002). For engineering applications, studies of fine-grained sediment transport and deposition have usually been empirical and site specific, and physically based empirical relationships with "lumped" parameters have been used to describe sediment processes (Delo, 1988; Mehta, 1989; Teisson et al., 1993). A survey of the literature of sanitation, hydraulic, and civil engineering (e.g. Parker et al., 1972; Bache et al., 1997; Boller and Blaser, 1998; Black et al., 2002; Winterwerp and Kranenburg, 2002) shows that there is a lot of information out there that is of potential interest to sedimentologists, but because the physics of the underlying processes is hidden behind these "lumped" parameters, utilizing such data for a general understanding of mud sedimentation is quite difficult.

The major factors that affect flocculation are the concentration of particles within the fluid and the intensity of turbulence (Einstein and Krone, 1961; Parthenaides, 1965; McCave, 1984). Over time flocs get progressively larger and reach a maximum equilibrium diameter that is related to the intensity of turbulence. Deposition occurs when the flocs are strong enough to resist disruptive shear stress near the bed (Parthenaides, 1965) and are able to settle to the bottom. The most important factors that influence deposition are flow turbulence, bed shear stress, sediment concentration, and settling velocity. Although one might expect to see significant differences in flocculation behavior and depositional characteristics between different clay minerals, all the tested clays (kaolinite, Ca-smectite, and illite) flocculated under variable salinities and showed very similar critical velocities of sedimentation at a given sediment concentration and salinity. Differences in erosion behavior were better developed. At a given erosion velocity, Ca-smectite beds eroded fastest, and kaolinite beds persisted the longest. Whether biofilms on sediment grains enhance floccule formation and floccule stability, or whether biofilm effects are similar in magnitude as van der Waals forces, is the subject of ongoing experiments. The fragile nature of flocs makes common methods of grain size analysis ineffective. The sediment is therefore best analyzed while still suspended and without being removed from its formative environment for any length of time (Kranck, 1975).

In our experiments the importance of flocculation for the understanding of mud deposition is quite obvious. We typically mix the sediment input with water, then stir it in a blender for 10 min, and then the blended slurry is washed through a 63 μm sieve directly into the flume (Fig. 20). Even in the very first experiments that we ran in distilled water and with quite small sediment loadings (15 to 240 mg/l) of finely ground kaolinite (91% finer than 0.01 mm, 80% finer 0.005 mm, and 60% finer than 0.002 mm), boundary layer streaks of flocculated material formed within minutes of the start of sediment input when flow velocity was 50 cm/s (Fig. 21). We know so because we saw individual particles in these sediment streaks with the naked eye (Fig. 21B and C), and given the speed they were moving they had to be at least of fine sand size to be visible to us. Thus, they had to be aggregates of the much smaller particles (Fig. 20) that we added to the flow (Schieber et al., 2007a).

In order to get a better idea of floccule sizes we try to capture intact flocs on grooved glass slides that are placed in the flow. When these are extracted from the flume successfully we either place the material into an environmental scanning electron microscope (SEM) to examine them when still moist, or we dry the slide and examine the surface under the SEM in low vacuum mode (Fig. 22). It is also possible to place a HD video camera with macro-zoom capability very close to the transparent flume bottom, shine a strong light from above the flow lid through the flow, and make short records of the moving floccules with backlighting. Individual frames can then be

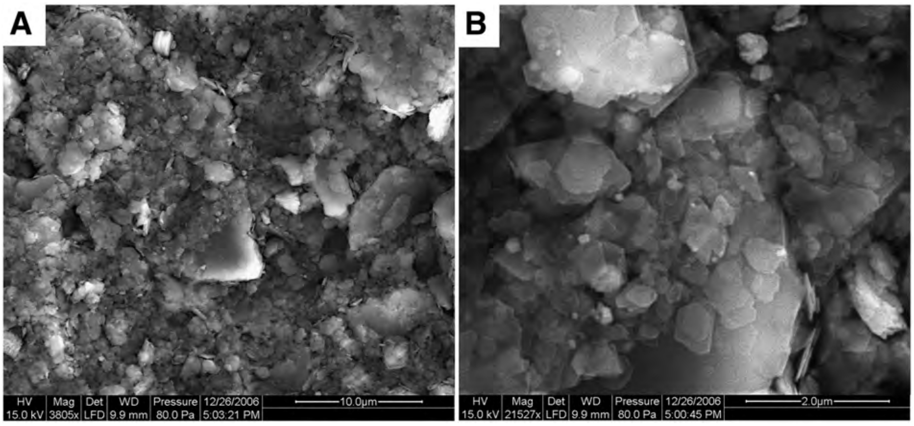

Fig. 20. SEM photos of clay used in kaolinite experiments at different magnifications. (A) Most clay particles are less than ten microns in diameter. (B) Close-up of clay platelets that show euhedral hexagonal character.

examined and floc sizes determined with image analysis software. Preliminary data on floccule sizing from our experiments indicates that, as expected, floccule size increases as velocity and shear stress is reduced.

Other methods for floccule size determination are laser forward scattering (LISST instrument), and the use of a Coulter counter. The drawback of the LISST is that although it is a very effective method for very dilute suspensions, it cannot operate in the sediment concentrations used in our experiments. Thus, we have to strongly dilute the sample with sediment-free water in order to get enough laser transmission. The danger is that when we add water to the sample, we may inadvertently change the flocculation characteristics of the fluid. What we measure after dilution will be sizes the instrument "sees", but whether these floccules are the same size as before mixing requires verification. In Coulter counters the floccule bearing fluid has to pass through narrow tubing and orifices, and larger floccules are liable to be destroyed in the process. A rapid and non-destructive floccule sizing method for flows with sediment concentrations of several grams per liter would constitute a considerable advance in the study of muddy suspensions (VID-2).

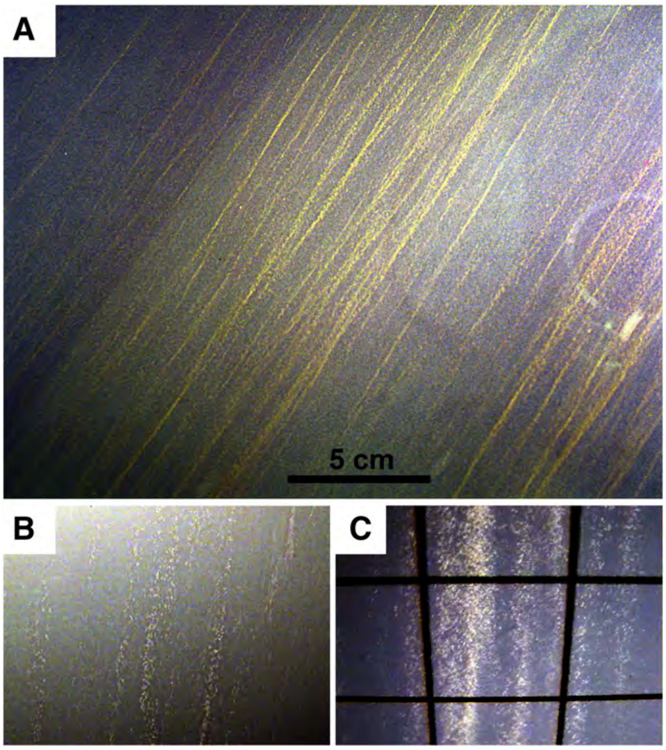

Fig. 21. (A) Boundary layer streaks forming at 40 cm/s mean flow velocity in a flow with 15 mg kaolinite per liter. Photographed through the flow lid. (B) Video frame (~4 cm wide field of view) from same area as in (A), seen through flow lid. Note "granularity" of material in the streaks. The floccules are on the order of 100–200 µm in size. (C) Video frame of boundary layer streaks recorded through the transparent flume bottom. Black grid is 10 mm by 10 mm. Image was acquired during flow with average velocity of 30 cm/s. Boundary layer streaks are composed of floccules.

2.4.2.3. Floccule ripple formation. When the critical velocity of sedimentation is reached for a muddy suspension, the suspended sediment concentration declines continuously and more and more of the floccules transfer into the very bottom of the flow and are moved along as bedload. Because in all but the lowest sediment concentrations the water is so turbid that no direct observations of the flume interior are possible, we shine strong lights from above and are in that way able to see the sediment that is moving directly above the flume bottom. At comparatively high velocities these are the floccule streamers that are shown in Fig. 21. As flow velocity is reduced, however, the bottom floccules travel slower and slower and more sediment continues to be added to the bedload. Traffic congestion ensues and results in the formation of ripples that consist of flocculated mud or clay (Schieber et al., 2007a; Schieber and Southard, 2009). These floccule ripples migrate down the flume channel just like a sand ripple would, and they are easily imaged via backlighting (Fig. 15). At this juncture it is an issue of concern whether observations of floccule transport over a smooth plastic surface are actually applicable to processes of floccule transport and deposition over fully covered mud beds. Details on how we were able to provide proof of ripple migration for the duration of mud bed accretion in multiple experiments (Schieber et al., 2007a) are given in Section 2.4.2.4 (VID-3).

The critical velocity for sedimentation is dependent on initial sediment concentrations, and ranges from ~10 cm/s for small sediment concentrations (0.03 g/l) to 25 cm/s for sediment concentrations in the 1 to 2 g/l range. Depending on the composition of the mud we can expect critical velocities as high as 35 cm/s. When initial sediment concentrations are low (0.03 g/l to 0.5 g/l) only a small number of ripple patches will form in the flume channel, but as sediment concentrations increase (1 to 5 g/l), ripples coalesce and gradually cover the entire flume bottom (VID-4).

When ripple deposited mud is sampled and analyzed for water content, it contains approximately 90 vol.% water. Interestingly, however, the vertical profiles of ripples (Fig. 23) are indistinguishable from current ripples formed in sand. The ripple index of the ripple in Fig. 23 is ~13, and just as in sand ripples, there is a crest and brink, and the ripple lee-slopes vary from 25 to 30°. Trace amounts of iron oxide

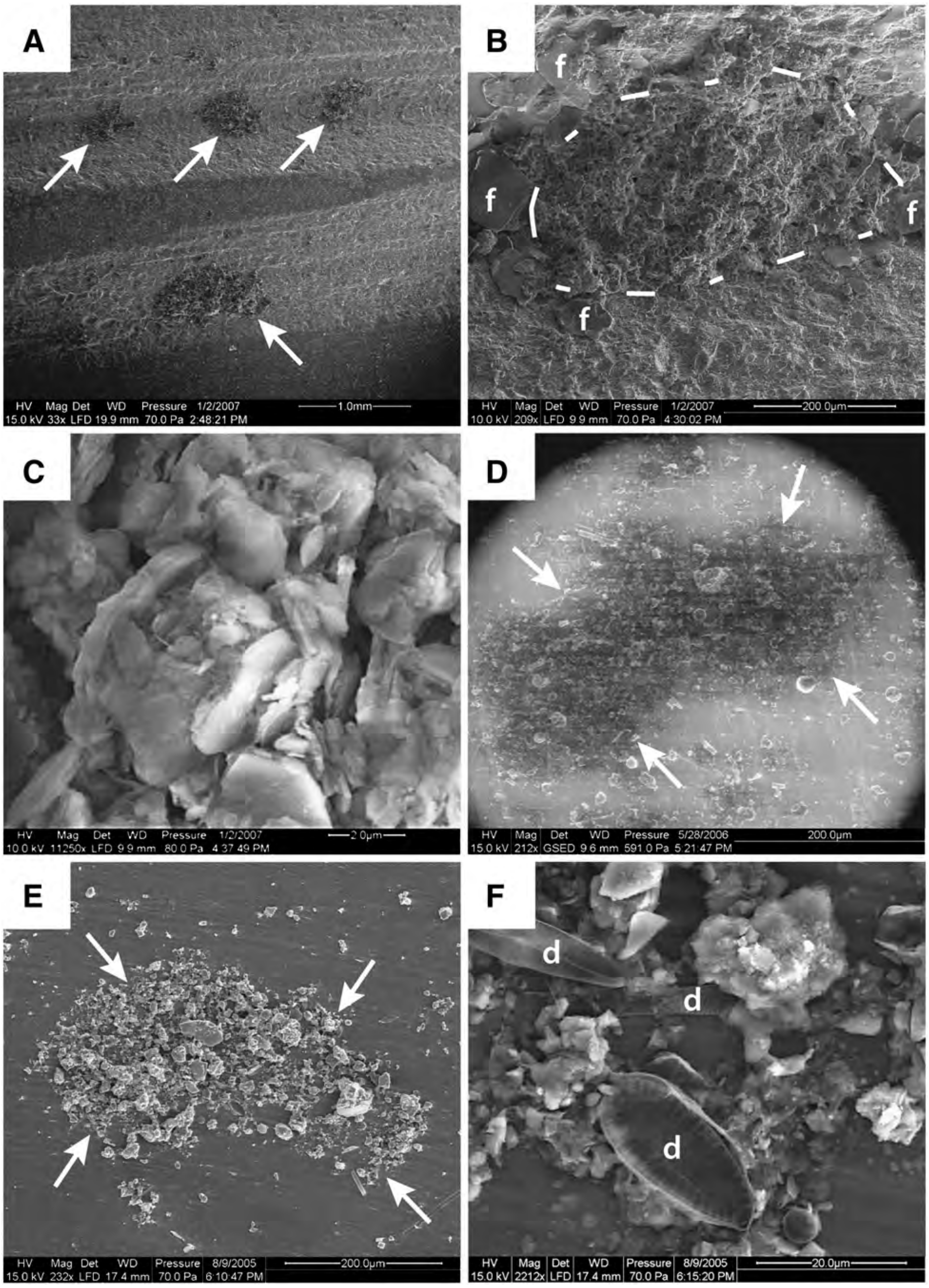

Fig. 22. SEM images of floccules collected from experiments. (A) Large kaolinite floccules (arrows) captured with a grooved glass slide that was placed on the flume bottom. These floccules collapsed due to desiccation, but their outlines give an idea of their original size. (B) Close-up of one of the floccules (marked with dashed white line). Large flakes of kaolinite (marked f) were trapped in the grooves as well, but they do not appear to be part of the floccule. (C) Close-up of the surface of a floccule from (A). Shows card-house structure of kaolinite platelets. (D) ESEM image of a floccule (marked with arrows) from an experiment with sieved lake mud. The floccule is imaged at approximately 90% relative humidity, but removal of most of the interstitial water still made the floccule collapse, just like those in (A) and (B). (E) Another floccule from the same lake mud experiment (marked by arrows). (F) Close-up of floccule in (E) that shows that floccules can also contain biogenic components, such as diatom tests (marked d).

and sorting due to differences in settling velocity lead to some variability in foreset composition and allow recognition of faint cross-laminae (Schieber and Southard, 2009). Movement of larger floccules delineates flow separation over the crest. These general features can be observed in experiments with various clay types and in freshwater as well as saltwater experiments.

The migration speed of floccule ripples is dependent on flow velocity and sediment availability and may range from as much as ~60 cm/h at 35 cm/s (5 cm depth of flow) to as little as a 10 cm/h at 15 cm/s (5 cm depth of flow). Ripples advance by sediment deposition on the lee-side slip face. Sediment is transported up the stoss-side of the ripple, issues forth from point sources along the brink line, and then forms gravity-driven lobes that flow down the slip face (Fig. 24). The sediment lobes spread out at the base of the slip-face and form rounded lobes that can be seen from the flume bottom (Fig. 25). Through build-out and overlap of multiple sediment lobes the ripple front advances. At comparatively small flow velocities (0.15–0.2 m/s, 5 cm flow depth) mud ripples advance by build-out of small sediment lobes as seen in Fig. 24, and at higher velocities (0.2–0.3 m/s, 5 cm flow depth) these lobes broaden and cover an increasing fraction of the lee-side slope. When we reach the upper limits of floccule ripple stability (as currently explored 0.35–0.40 m/s) the downstream end

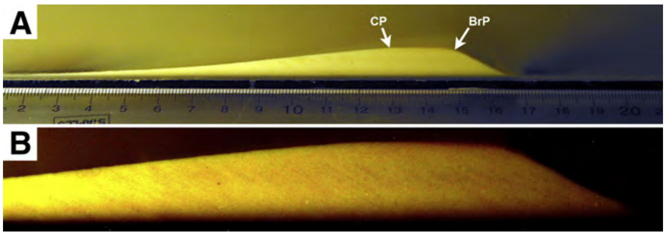

Fig. 23. (A) Floccule ripple that intersected the transparent flume wall, affording us a view of its cross-section. The cross-section is the same as that of a sand ripple and it has a well developed crest point (CP) and brink point (BrP). The scale in the foreground is in cm. (B) Closer view of same ripple with contrast enhancement shows faint internal cross-laminae that dip downstream (to right).

of the slipface takes on the appearance of flames leaping from a vigorously burning fire and we no longer see incremental accretion of well defined foreset lobes. At this point the lee-side eddy and upslope directed backflow are so strong that sediment clouds partially detach from the lobes and dissipate into the flow (Schieber and Southard, 2009). Floccule ripples migrate approximately 3 to 4 times slower than comparable sand ripples because of the fundamentally cohesive nature of floccule ripples (VID-5).

A coherent model of floccule ripple migration that integrates recent observations and conclusions is shown in Fig. 26 (Schieber and Southard, 2009). Work to date demonstrates that flows that produce "standard" ripples in sandy sediments also produce ripples of comparable size and shape in muddy sediments that consist largely of water (see Fig. 23). The latter are held together by weak van der Waals forces between clay particles and offer no noticeable resistance to touch (they behave like a shear-thinning fluid), whereas the sand resists touch owing to framework grain support. Interestingly, the observation that sediments of quite variable density can produce similar bedforms under shear is not a new one. Bagnold (1955) conducted experiments where he produced ripples in sediments (plastic beads) that were only slightly denser than the transporting fluid. It is indeed most intriguing that low-density non-cohesive grains (Bagnold, 1955), high-density non-cohesive grains (quartz sand), and low-density cohesive grains (floccules) all give rise to similar ripple bedforms under the same flow conditions.

To date, floccule ripples have been generated in flows that contained between 0.05 and 7 g/l suspended sediment. There have been observations that suggest that turbulence dampening occurs at high suspended sediment concentrations (Baas and Best, 2002), an effect that could potentially favor slurry-like transport over transport via individual floccules. The suspended sediment concentrations in our experiments, however, are safely below those (~10 g/l) reported by Baas and Best (2002) where this effect may become important.

2.4.2.4. Mud bed accretion and internal structure. Once the flume bottom is fully covered with mud, we can no longer observe sediment motion directly and we have to deduce the remainder of sedimentation history from the accumulating deposit, the known history of further sediment addition and velocity changes, and the final bedforms preserved on top of the bed. We also injected color spikes (hematite dust) into the flow to mark surfaces at certain points in bed history (Schieber et al., 2007a). Repeated addition of color spikes and further mud increments produce mud layers of up to 2 cm uncompacted thickness. After completion of an experiment, once the residual sediment has settled or once the water is drained, bed thickness typically is not uniform and we see elongate ripples at the surface of the bed (Fig. 27).

The hematite color spikes outline internal layering once the sediment is sectioned. This works quite well if we allow the mud bed to dry to the consistency of soft butter, and then scrape a grid of grooves into the bed with a butter knife (Fig. 28A). This simple

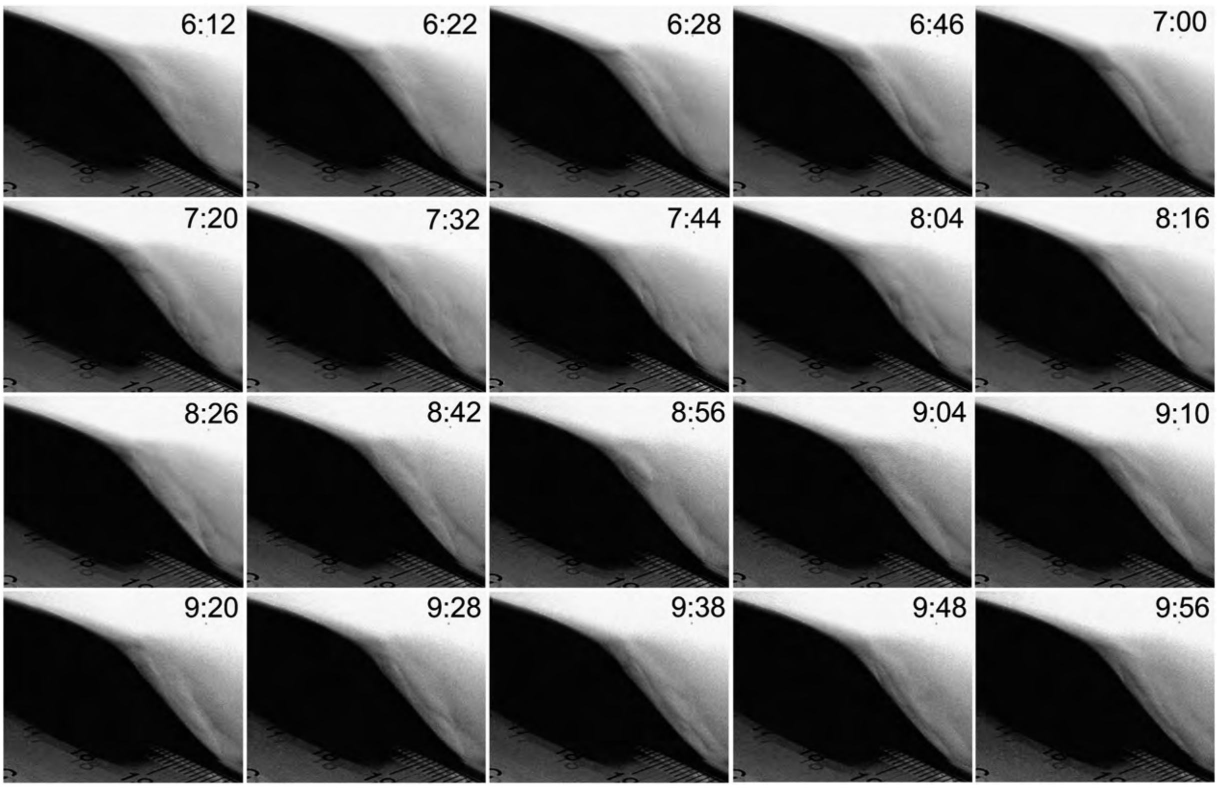

Fig. 24. A series of snapshots of foreset motion from the same ripple as seen in Fig. 25. Shows the successive downslope motion of lobes of floccule material on the foreset of the ripple. The time index in the upper right corner of each frame is in minutes:seconds. The scale in the foreground is in centimeters with mm subdivisions.

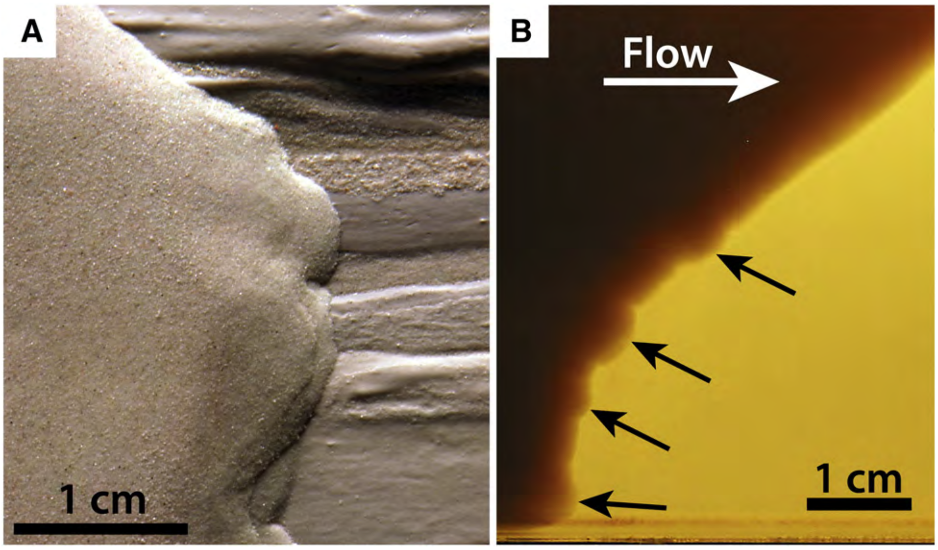

Fig. 25. Detail view of sediment lobes on ripple foresets. (A) View from above shows multiple sediment lobes on the lee-side slope of a kaolinite ripple (flow to right). (B) View through the flume bottom shows sediment lobes (arrows) at the forward edge of a smectite ripple. Flow to right.

technique revealed internal clinoforms in our mud beds that reflect the advective mud transport that is implicit in ripple migration (Fig. 28B).

If one probes a little deeper, more evidence for pervasive ripple migration emerges. For example, during drying the clay beds tend to split along fractures that run parallel to the clinoform surfaces that are marked by our hematite spikes. On the fracture surfaces one finds multiple sets of low-angle, downcurrent-dipping, cross-strata (Fig. 29). Each set of cross strata represents a ripple that had migrated by and was partially preserved, and the plan view geometry of these sets looks exactly like the rib-and-furrow structures that are familiar from ripple laminated sandstones. The curved "ribs" in Fig. 30 are downcurrent dipping foresets of clay particles or other fine grained material, and we can also observe the formation of future "rib and furrow" laminae during flume experiments (Fig. 15D). In uncompacted beds one may be able to see in these foresets a "bumpy" surface pattern of closely packed ovoid bodies of some hundred microns in size (Fig. 30). The latter are the partially preserved floccules from which the migrating ripples and the accreting clay bed were constructed (VID-6).

2.4.2.5. From current deposited mud to laminated shales. Geoscientists have in the past assumed, and it is stated so in numerous contemporary text books, that mud generally accumulates by settling out

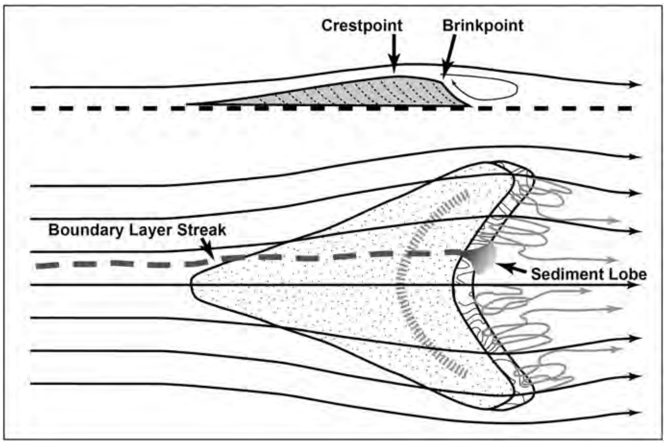

Fig. 26. Summary of flow patterns across floccule ripples as inferred from geometry and study of video observations. At top, cross section of ripple (CP = crestpoint and BP = brinkpoint) with leeside eddy and backflow region. At bottom, flow over idealized ripple with lee-side eddies in the zone of flow separation. Narrowly dashed line marks plan view position of crestpoint. Dashed line marked BLS is a boundary layer streak that moves over the back of the ripple and supplies sediment for a lee-side sediment lobe (SL).

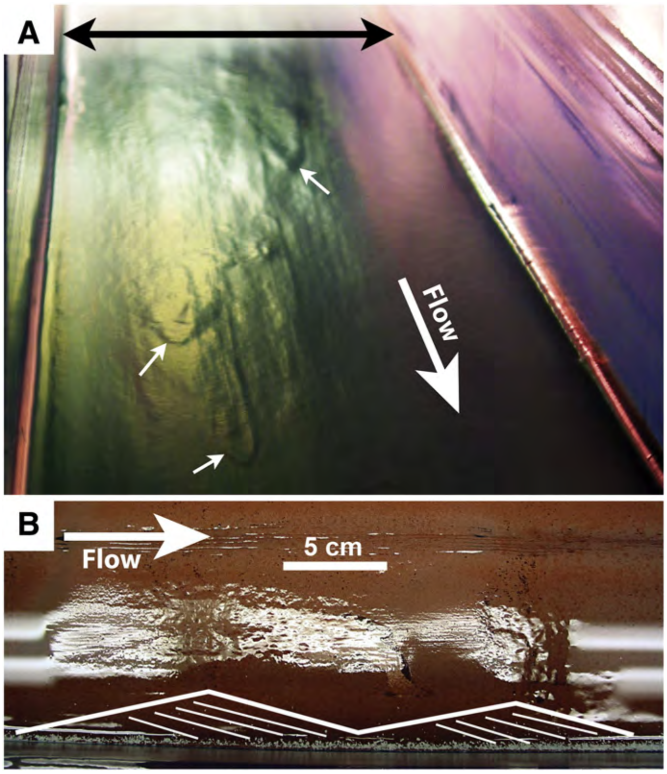

Fig. 27. Floccule ripples at the bed surface. (A) Oblique view of kaolinite bed that has dried to the consistency of butter. Bed shows elongate, tongue like ripple forms (white arrows) that point in downcurrent direction. The channel width (black double arrow) is 25 cm. (B) Top view of kaolinite bed with hematite stain. Shows two successive ripples (sketch shows side view with cross-laminae) with a smooth upcurrent slope and a more irregular looking downcurrent slope. The irregularities reflect slumping on the lee-side.

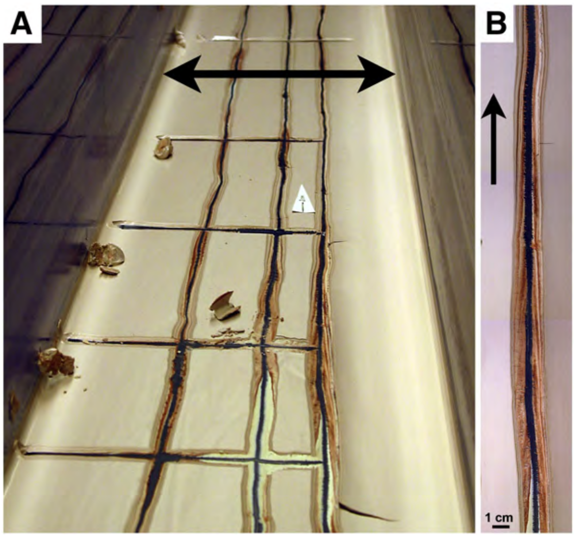

Fig. 28. (A) Photo of flume bottom after an experiment. The bed has been dried to the consistency of soft butter and scraped parallel and perpendicular to the flow with a butter knife. The shallow slope of the resulting groove enhances minute differences in layer thickness and orientation. The channel width, indicated by the black double arrow is 25 cm. Arrow indicates the flow direction. (B) Groove detail that shows clinoforms that dip in flow direction and are outlined by hematite color spikes. This observation confirms lateral bed accretion via ripple migration.

from suspension in quiet bottom-water settings with weak currents (e.g. Potter et al., 2005). Yet, recent experiments (Schieber et al., 2007a; Schieber and Southard, 2009), as well as past observations in nature (e.g., Walker and Harms, 1971; Rine and Ginsburg, 1985; Schieber, 1998), indicate that mud accumulation in more energetic settings should be expected and probably is quite common.

In the context of this review of experimental work on shale deposition, there are several questions that issue logically from the realization that flocculated mud can be deposited from currents that run strong enough to move sand (Schieber et al., 2007a; Schieber and Southard, 2009). The foremost one, of course, is whether and how we could recognize current deposited muds in the rock record.

The first step towards a better appreciation of this issue is to look at the sediments that were produced in our experiments and pretend that they have become rocks. To do so we can for example take the dried out crusts our flume, infuse them with epoxy resin, and then cut and smooth them just like we would with a piece of shale. Of course, at that point the sediment still has abundant porosity and is not as compacted as it would be after some burial. Nonetheless, we can already see without compaction that our sediment that accreted from migrating floccule ripples looks like a finely laminated shale on casual

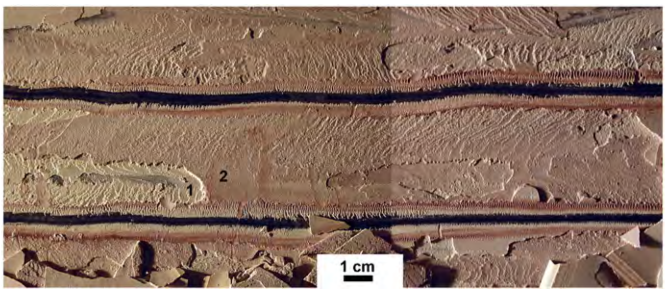

Fig. 29. Example of rib and furrow structure in previously scraped clay bed. Shows clinoforms along the sides of the butter knife grooves (flow to right), and multiple thin layers (for examples 1 and 2) that consist of inclined (to the right) and curved foreset laminae that are the remains of ripples that migrated over the bed as it accreted.

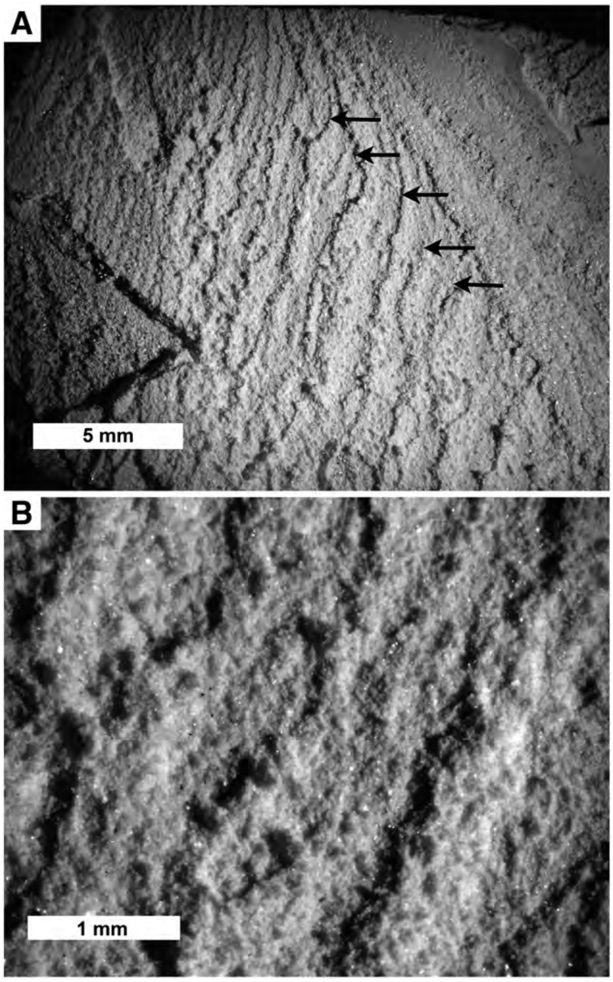

Fig. 30. Binocular microscope photos of ripple cross-laminae. (A) Underside of a kaolinite bed with exposed cross-laminae (arrows). (B) Close-up of cross-laminae from (A) that shows a bumpy texture of ovoid objects that are some hundred microns in size. This texture most likely reflects the originally deposited clay floccules.

inspection (Fig. 31), and that if it were an actual rock this would be interpreted as a result of low energy settling. To simulate compaction to zero porosity with the help of image manipulation software (e.g. Lobza and Schieber, 1999), makes it appear even more finely and parallel laminated (Fig. 31), and would lead to the same interpretation if "conventional wisdom" were applied.

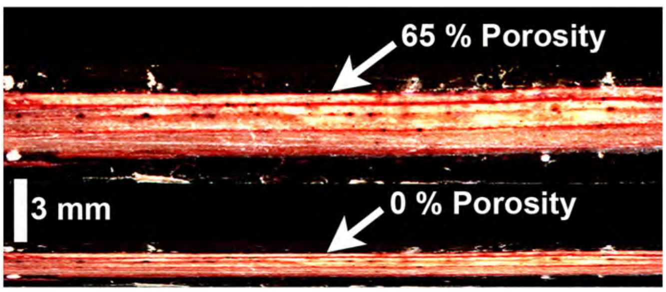

Fig. 31. Cross-section view of clay layer (kaolinite) that was produced in a flume by vertical accretion of migrating floccule ripples. The red lines are the hematite spikes that were injected to outline bed buildup. The upper image displays the laminae in an air dried sample with ~65% porosity. It has a perfectly parallel laminated appearance. The lower image has been "virtually" compacted by reducing the vertical dimension by a factor of 0.35. It now has a finely parallel laminated appearance.

So, even if a mud has been deposited by migrating floccule ripples, any cross-laminae or clinoforms (Fig. 28) would be largely oriented parallel to bedding after compaction. Also, because floccule ripples in experiments were spaced 10 or more centimeters apart, in a thin section or in a piece of drill core, any vestiges of cross-lamination would easily be missed and the rock described as parallel laminated. The question then is, how do we approach this problem?

Although many have given in to the urge to "abandon the inquiry" (Sorby, 1908) in the past, there are some intrinsic features associated with cross-lamination that are detectable through careful examination of rocks. For example, in the case of an appropriately placed or sufficiently large specimen one can find laminae that lap down onto a basal surface or that show updip truncation. Over the past few years my students and I, as well as others (e.g. Macquaker and Bohacs, 2007), have pursued this issue and were able identify such features in rocks from a wide range of ages. Some examples shown are from Cambrian shales of the mid-continent US (Fig. 32; Schieber and Yawar, 2009), from Devonian black shales of the eastern US (Fig. 33; Schieber et al., 2007a), and from the Cretaceous Mowry Shale of Wyoming (Fig. 34). In all of these examples a case can be made that mud beds formed by floccule ripple migration and lateral accretion, instead of simple settling out from the water column. These observations also suggest that many other parallel laminated shales like those in Figs. 33 and 34 probably accumulated by ripple migration as well.

2.4.2.6. More connections to the rock record — lenticular shale fabric. Given that lamination is only one of many sedimentary features that can be observed in shales (Kuehl et al., 1986, 1988, 1991; Nittrouer et al., 1986; Schieber, 1986, 1989, 1990, 1991, 1998, 1999; O'Brien and Slatt, 1990; Macquaker and Gawthorpe, 1993; Segall and Kuehl, 1994), one may ask what other sedimentary structures might be amenable to experimental study, be it by flumes or other devices. A possible example on how to expand on first-order depositional flume work is a recent study by Schieber et al. (2010), elucidating the potential origin of lenticular fabric in shales.

Lenticular fabric is common in shales of all ages (e.g., Wignall, 1994; Schieber et al., 2007c), and implies that these rocks consist of mm to sub-mm size lenses of variable composition that are arranged in wavy layers (Fig. 35A). Explanations that have been proposed to explain this fabric include accumulation of fecal pellets or closely spaced and

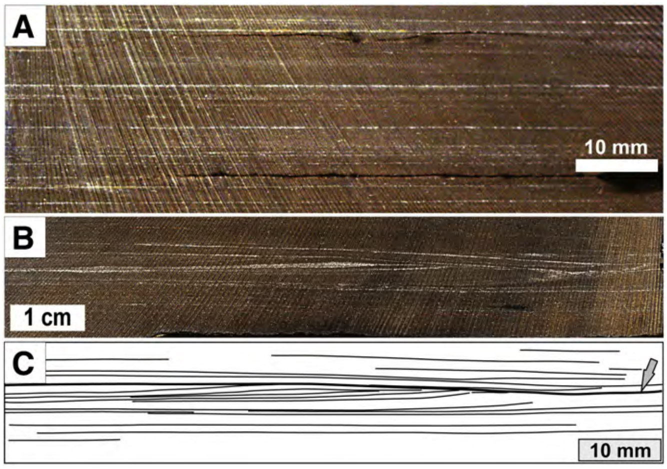

Fig. 33. (A) Photo of a piece of drill core from the Devonian New Albany Shale of Indiana. It looks parallel laminated and the lighter laminae are silt enriched. (B) A photo of a core sample from just below the one shown in (A). This sample shows clear cross-lamination, and the lamination is again outlined by silt-rich laminae. Most of the laminae in this ripple consist of a mixture of organic matter, clay, and silt. (C) Tracing of silt laminae visible in part C. Arrow marks an internal erosion surface, and in the center we see inclined (to the left) and truncated laminae, forming the outline of a compacted and mud-dominated ripple. The present-day relief of this ripple is 3 mm, but its original relief would have been on the order of 20 mm (assuming 85% water content), the same magnitude as observed in our experiments (Fig. 23).

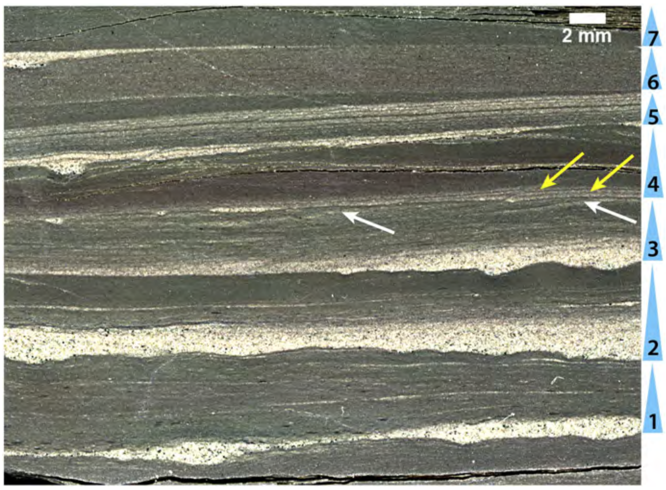

Fig. 32. Photo of a piece of drill core showing a succession of graded silt/mud couplets (numbered blue arrows) that are separated by erosion surfaces (Cambrian Eau Claire Formation of Indiana). Couplets one and two show very gently inclined silt laminae. Couplet three shows inclined silty laminae (white arrows), and couplet four shows downlapping silty laminae (yellow arrows) in its base. Couplet five shows silty laminae that are essentially horizontal with subtle indications of downlap and truncation. Couplet seven has a mere hint of silt in the base, but the base is nonetheless most likely erosive.

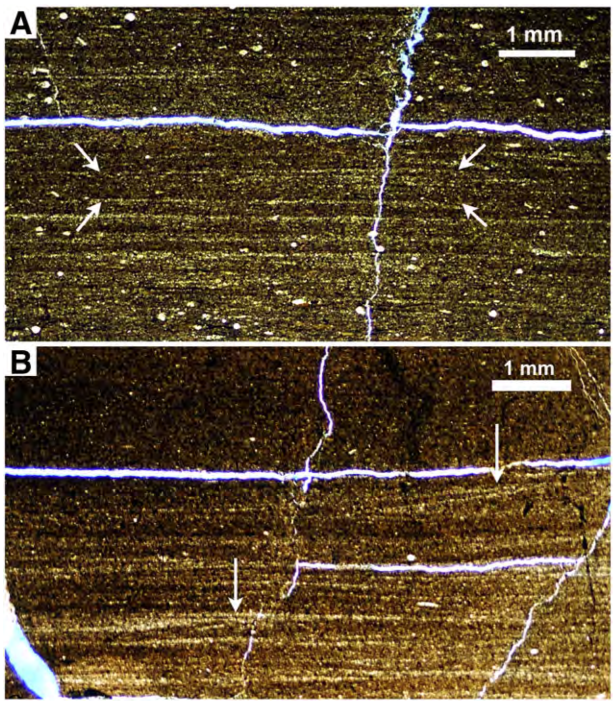

Fig. 34. Photomicrographs of various portions of a sample of Cretaceous Mowry Shale, Wyoming. Thin silt-rich laminae highlight internal stratification. (A) Sample with predominant parallel lamination and one bundle of convergent (towards the left) laminae that is bracketed between white arrows. This convergent bundle is interpreted as a partial view of a compacted floccule ripple, similar to the one in Fig. 33. (B) Another view with parallel and shallow inclined laminae that dip to the left (marked with white arrows). These as well are interpreted as compacted floccule ripples like the one in Fig. 33. Note that although silt laminae outline the structure of these ripples, most of the volume of the ripple consists of organic matter, clay, and silt. The parallel laminae in both (A) and (B) are interpreted as ripple produced as well, analogous to Fig. 31. Photos courtesy of Joe Macquaker.

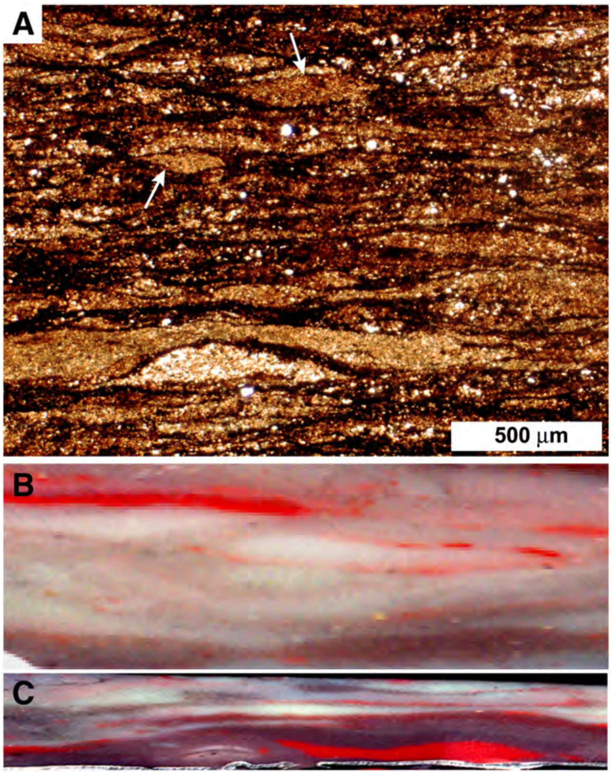

Fig. 35. A comparison of rock record and experimental product. (A) Photomicrograph of a lenticular laminated Proterozoic shale (Rampur Shale, Vindhyan, India; described by Schieber et al., 2007c). Several of the shale lenses are well defined compressed clasts (arrows). (B) and (C) represent flume samples that were "virtually compacted" to 15% porosity (using Photoshop) and are shown at the same scale as (A). Note wavy-lenticular nature of compressed clasts, pinched lateral terminations of clasts, and lenticular laminated nature of overall deposit. All views are perpendicular to bedding.

compressed burrow fills. On the other hand, careful examination of this fabric also suggests (Fig. 35A) that it may have formed when soft mud rip-up clasts were re-deposited and compacted upon burial.

Although one would assume initially that water-rich surficial muds lack the strength to be eroded and transported as larger aggregates, we did some experiments to test that assumption. Eroding a flume-deposited mud (70 wt.% water content by weight) at flow velocities between 15 and 35 cm/s produced mm to cm-size fragments that were transported over the bed by the current. Fragment size diminishes during transport, but sand-size to millimeter-size fragments can potentially be transported for tens of kilometers. Accumulations of these clasts were allowed to deposit in areas of lower flow velocity, and resin impregnated samples were examined for textural features after the experiment (Schieber et al., 2010). Manipulating digital images of these experimental deposits showed a lenticular-laminated fabric (Fig. 35B and C) that was a direct match to lenticular lamination observed in shales from the rock record (Fig. 35A). Petrographic criteria (using thin sections cut parallel to bedding) allow distinction of lenticular fabric due to compacted soft rip-up clasts from those that represent compacted fecal pellets or compacted burrow fills. Given the widespread occurrence of this fabric in Proterozoic and Phanerozoic shales, application of these criteria to the rock record should allow the identification of many more shale successions that consist of eroded and redeposited soft mud clasts (VID-7).

3. Conclusion

When studied in some detail, shales and mudstones can be seen to contain such a bewildering variety of textures and structures that one may indeed wonder whether the inherent questions have any hope to ever be answered in full. Thus, and I hope to have illustrated this, experimental approaches to the sedimentology of shales are by necessity as varied as these rocks themselves. Some questions may well be investigated by playing with a few buckets of mud (something I strongly encourage), whereas others will require large scale flume setups and sophisticated monitoring equipment. The exact experimental approaches may be quite involved and complex, and most likely will be as varied as the structures in question. Nonetheless, with some inventiveness and imagination one can tackle many problems that long were thought intractable.

Shales and mudstones are by far the most common sedimentary rocks, accumulate in a wide range of environments, and contain the bulk of recorded earth history. This history is written in a well-defined special language that is still imperfectly understood. Yet, because shales play an important role in the global carbon budget and are widely used to infer past climates, ocean conditions, and orbital variations, as well as being a critical source of hydrocarbons (oil and shale gas), minerals, and metals, it is imperative that we get serious to learn this language.

If the history of research on sandstones and carbonates is any guide, serious sedimentological research on shales has just begun and will require several decades of sustained effort by multiple investigators to come to maturity. Shale research is a frontier area of sedimentary geology, and it seems appropriate that I should conclude this overview with a quote by the man that saw it all coming over a century ago:

> *"Possibly many may think that the deposition and consolidation of fine-grained mud must be a very simple matter, and the results of little interest. However, when carefully studied experimentally it is soon found to be so complex a question, and the results dependent on so many variable conditions, that one might feel inclined to abandon the inquiry, were it not that so much of the history of our rocks appears to be written in this language."* Sorby, 1908

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