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Shifting Paradigms in Shale Sedimentology - The Implications of Recent Flume Studies for Interpreting Shale Fabrics and Depositional Environments

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Summary

Flume experiments with clays and other fine-grained suspensions demonstrate that low energy settings are not a prerequisite for the accumulation of muds and shales. Irrespective of salinity, flocculation produces deposition prone aggregates which in turn form bedload ripples at flow velocities in the 15 to 35 cm/s range (5 cm flow depth). At such flow velocities and otherwise identical conditions, sandy sediments would produce ripples. The observed floccule ripples are cross-laminated and of the same size and geometry as sand ripples, but have a water content of 80-90 % by volume. They are therefore subject to substantial compaction and original cross-laminae become severely flattened and are difficult to recognize in the rock record. Nonetheless, examination of multiple ancient shales has shown that certain intrinsic features of cross-lamination, such as basal downlap and top truncation of laminae, are still recognizable and allow identification of current deposited muds. Thus, many laminated shales in the rock record were likely emplaced by currents in bedload, rather than simply settling out of the water column. Additional experiments demonstrated that transport segregation of clay floccules, silt, and other components leads to laminated deposits as the residuals of successive ripples vertically accrete. From experiments conducted so far it is clear that flume experiments can probe a wide variety of depositional scenarios of mud deposition when properly designed. The data clearly indicate that many depositional and erosional textures in shales and mudstones are amenable to flume modeling and the continued accumulation of data will significantly change our perception of the depositional setting of mudstone successions.

Bed Accretion Experiments

Figure 1: The current flume lab at Indiana University contains two racetrack flumes for the simulation of mud deposition and erosion.

For the past 6 years the IU flume lab (Fig. 1) has conducted extensive experimentation with common clays (illite, smectite, kaolinite), aragonite mud, and silt, at salinities ranging from 0 to 35 per mill (Schieber et al., 2007; Schieber and Southard, 2009; Schieber and Yawar, 2009) In all of these experiments the fine grained mixtures formed floccules that below a critical shear stress/velocity transferred into bedload and formed migrating ripples (Fig. 2). The

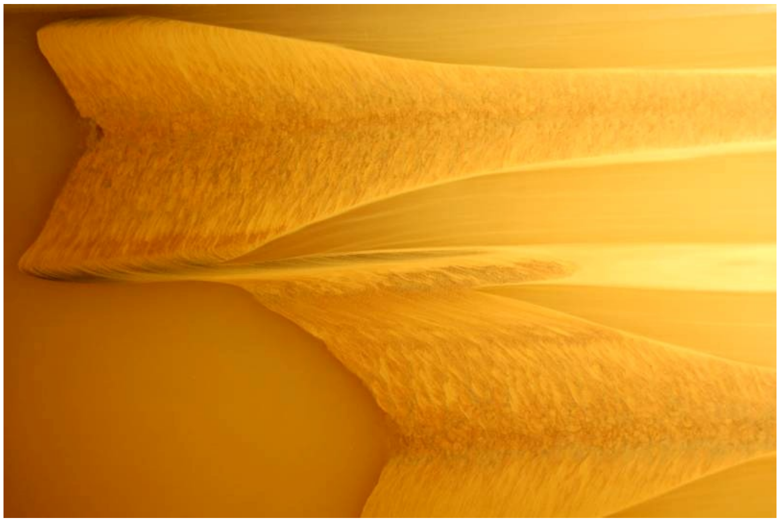


Figure 2: Migrating mud ripples as seen through the bottom of one of our flumes. The field of view is ~20 cm high. The ripples migrate towards the left and foreset accretion is clearly visible. Contrast has been enhanced by adding a brownish silt component to the kaolinite clay that forms the bulk of the ripples.

critical velocity of sedimentation depends on the type of suspended material and the suspended sediment concentration and falls largely in the 15 to 35 cm/s range. Once flow velocity drops below this critical value sedimentation commences and a bed accretes.

Although these suspensions generally do not permit direct observation of the accreting bed, we are able to observe the ripples by shining strong lights through the turbid and milky looking clay suspensions, and then observing and recording from below their projections on the transparent flume bottom (Fig. 2). In select experimental setups we also succeeded to directly observe sediment transport across floccule ripples and to show how sediment accreted on the lee sides of ripples (Schieber and Southard, 2009). The bedload floccule freight moves over the stoss-side of ripples in boundary layers streaks, accumulates on the crest, and then avalanches down the lee-side once enough sediment has accumulated. Over time composite foresets build up as multiple and overlapping sediment lobes avalanche the lee-side of ripples. Migration rates of floccule ripples range from 20-60 cm/hour at 15 to 30 cm/s flow velocity respectively, approximately 3-4 times slower than comparable sand ripples (a consequence of cohesive forces).

Floccule ripples display the same geometry as sand ripples and show downcurrent dipping cross-laminae, but their deposits take on a parallel laminated appearance after compaction (Fig. 3). Nonetheless vestiges of ripple origin are preserved in the form of rib and furrow structure (plan view, Fig. 4), basal downlap of laminae, and top truncation of laminae (side view).

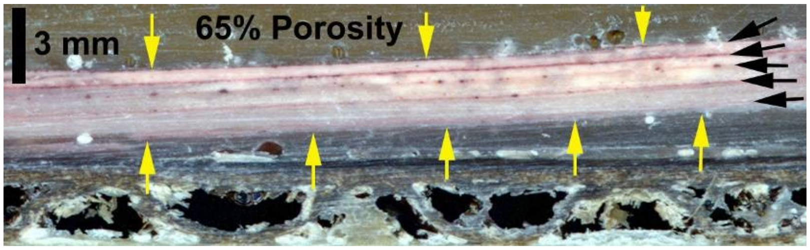
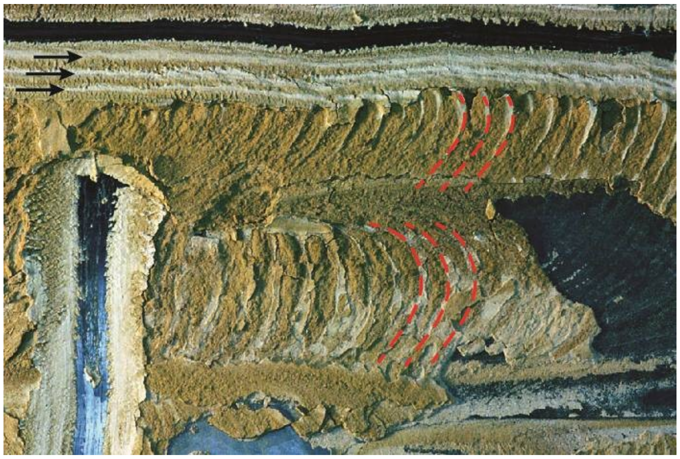


Figure 3: Side view of a dried out experimental deposit (between yellow arrows). The black arrows mark reddish hematite markers that were injected into the flume during the experiment. Although the deposit resulted from ripple accretion, it does have a distinctively laminated look. This parallel laminated appearance would be even more pronounced if this deposit had been fully compacted.

Figure 4: Plan view of the interior of a flume-produced mud bed that originated by floccule ripple accretion. Towards the top we see alternating silt (brownish) and clay laminae (black arrows) in an oblique cut of the deposit. Once compacted this would thus be a parallel laminated appearing deposit. The central portion of the image shows rib and furrow structure due to the migrating ripple origin of the deposit. Dashed red lines mark the foresets of two ripples, migration is towards the left. What appears as a single lamina in side view consists in reality of compacted ripple trains and typically consists of multiple over-riding ripples. The image measures 8 cm in the vertical dimension.



Soft Mud Erosion Experiments

Flume experiments into the erosion of soft watery muds also produced interesting and surprising results (Schieber et al., 2010). Beds of water-rich mud (~85% water by volume, aged between 2-9 weeks) were eroded in a flume at flow velocities between 15 to 25 cm/s and yielded sub-millimeter- to centimeter-size fragments that can be transported in bedload for distances of ten kilometers or more (Fig. 5). The clasts undergo rounding during transport and once they accumulate form deposits of sand-size rounded grains. Contrast between particles was produced by eroding a clay deposits with multiply colored layers. We collected these soft clast deposits and stabilized them with Spurr resin for further examination. Photographs of sectioned clast deposits were shortened vertically in Photoshop to simulate compaction of these water-rich particles (Fig. 6). The resulting images show that compacted deposits should consist of severely flattened lenticular particles with tapering ends and an overall lenticular-wavy appearance. This texture closely matches what is known as lenticular fabric from shales in the rock record (Schieber et al., 2010).

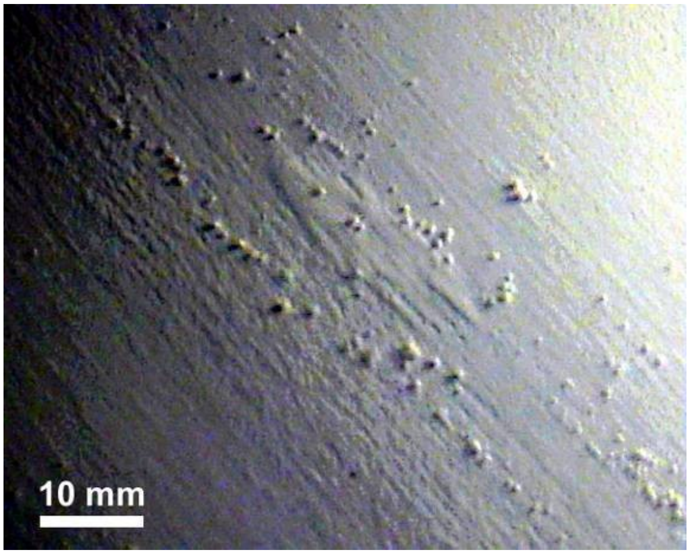


Figure 5: (at left) Video frame from experimental erosion of thin flume deposited clay bed (flow velocity = 16 cm/sec, flow depth = 5 cm). Initial products of erosion are small clay rip-ups that travel across the flume bottom (view from above) and become well rounded within 1-2 trips around the race track (a distance of 25-50 m). The size of visible fragments ranges from 0.5 to 2 mm.

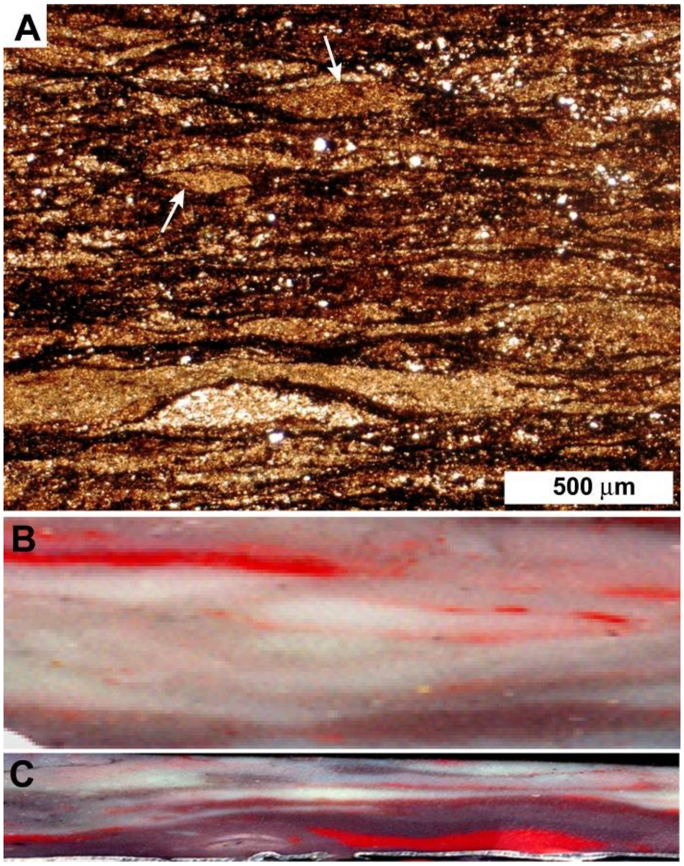


Figure 6: (at right) Comparison of lenticular shale fabrics in rock record and experiment. (A) Photomicrograph of a Proterozoic Shale from India with lenticular fabric. (B & C) Photos of epoxy stabilized water-rich mud clasts. The images were vertically shortened in Photoshop to simulate compaction. In these “virtually compacted” deposits the original rounded clay clumps take on a lenticular-tapering appearance and produce a lenticular fabric that compares closely to ancient lenticular shale fabrics (such as in A).

Whereas one would have assumed that freshly deposited water-rich muds lack the strength to be eroded and transported as larger aggregates, our experiments demonstrate otherwise. When seen in the rock record, lenticular fabric thus seems to imply erosion of surficial muds by gentle currents and lateral displacement of these materials over significant distances. Although lenticular fabric can also result from accumulation of fecal pellets and compression of burrow fills, petrographic criteria (using thin sections cut parallel to bedding) such as uniformity of features, degree of rounding, size distribution, and lateral continuity allows distinction of those fabrics from lenticular lamination that records intermittent erosion and transport of surficial water-rich muds by currents.

Conclusions

The presented observations apply to two shale fabric types that are widely observed in the rock record, and illustrate how experimentation can significantly change our preceptions of depositonal conditions for mudstones. In the case of laminated shales we now can say with some confidance that many of them most likely represent bedload transport and current activity, and thus imply more energetic conditions than previously assumed. In the case of laminated black shales this also suggests that anoxic bottom water become a less important factor in organic matter preservation than previously thought. The distinction between current produced and settling induced laminated shale fabrics is a high priority topic for further investigations. The lenticular fabric experiments as well connect a widespread shale fabric to current activity and bedload transport.

Essentially, the experiments presented here demonstrate that many long-held assumptions about mud deposition and erosion do not agree with physical realities. Examination of the rock record increasingly shows that, once studied in some detail, shales and mudstones contain such a bewildering variety of textures and structures that one may indeed wonder whether the inherent questions about depositional conditions have any hope to ever be answered in full. By necessity, experimental approaches to the sedimentology of shales will therefore have to be as varied as these rocks themselves. Whereas some questions might in fact be investigated by playing with a few buckets of mud (something I strongly encourage), others will require large scale flume setups and sophisticated monitoring equipment. Fundamentally, however, with some inventiveness and imagination one can tackle many problems in shale sedimentology that long were thought too intractable to bother with.

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 poorly 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, shale gas), minerals, and metals, it is imperative that we get serious to learn this language. Shale research is a frontier area of sedimentary geology and will require several decades of sustained effort by multiple investigators to come to maturity. Serious sedimentological research on shales has just begun, but flume experiments of the type illustrated above demonstrate that understanding the "language of shales" is not an elusive goal.

Acknowledgements

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