Bedload transport of mud by floccule ripples—Direct observation of ripple migration processes and their implications

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ABSTRACT

Flume experiments have shown that muds can be transported in bedload as floccule ripples and deposited at current velocities that would suffice to transport and deposit sand. A new set of experiments provides firsthand observations of the processes that shape and propagate mud ripples. Sediment is transported over the stoss side in the form of diverging boundary-layer streaks, the carriers of the bulk of the bedload floccule freight. At the brinkline these streaks become point sources of sediment that feeds avalanches of floccule-rich sediment lobes. These propagate down the slip face like classic mudflows on a hillside. Geometries of ripples are very similar to those produced in sandy sediments, even though the floccule ripples contain as much as 90 vol% water.

INTRODUCTION

Fine-grained sedimentary rocks (grain size <62.5 µm), commonly known as shales or mudstones, are the most abundant sedimentary rock type. They contain the bulk of geologic history recorded in sedimentary rocks (Schieber, 1998), and are a key element in organic-matter burial, the global carbon cycle, and the hydraulic isolation of groundwater resources and waste materials. Economically, they are an important source of hydrocarbons, minerals, and metals (Sethi and Schieber, 1998). They are susceptible to weathering due to their clay content, and so often appear quite homogeneous to the casual observer. Because of this, they are much more poorly understood than other types of sedimentary rocks, in spite of their importance.

An enduring notion about deposition of muds has been that they are deposited mainly in quiet environments that are only intermittently disturbed by weak current activity (e.g., Potter et al., 2005). Flume experiments have shown, however, that muds can be transported and deposited at current velocities that would also transport and deposit sand (Schieber et al., 2007). Deposition-prone floccules form over a wide range of experimental conditions, regardless of the exact parameters that drive flocculation in a given experimental run. Floccule ripples, ranging in height from 2 to 20 mm, and spaced from centimeters to decimeters apart, migrate over the flume bottom and accrete into continuous mud beds at streamwise velocities from 0.1 to 0.26 m/s.

Our initial knowledge of ripple morphology and migration in our flume experiments was limited because the bed was obscured by a milky clay suspension. We did not know exactly how the floccules were transported across the ripples, and in which way they were able to produce the foresets that we observed in the final deposits. Here we report the first direct observations of sediment transport across ripples and the lee-side processes that produce foreset laminae.

The turbid nature of clay- and mud-bearing suspensions makes direct observation difficult. Thus, in previous experiments we shone strong lights through the flow and photographed and filmed features within the flow by way of the shadows they cast on the flume bottom (Schieber et al., 2007). In this way we observed individual particles that consisted of flocculated clays, as well as ripples and ripple fields made from flocculated clays. We did not succeed, however, in observing directly sediment transport across floccule ripples and sediment accretion on their lee side. To better understand floccule ripples it is critical to know whether floccules move as individual particles, comparable to sand grains, or whether they are transformed into a clay slurry that moves as a viscous fluid across the ripple surface.

To address this issue we developed new methods for direct observation of floccule-ripple processes. Our objective is to illustrate the results obtained with this methodology, and to discuss their significance for the understanding of bedload transport in muddy suspensions. To our knowledge, this is the first report of direct observation of sediment transport processes associated with floccule ripples.

METHODS

We used three approaches to gain a better understanding of ripple processes in muddy flows: (1) continuous time-lapse photography (1–10 s frame frequency) to track ripple progress; (2) filming ripple processes in near-wall situations when a ripple would become attached to the wall of the flume; and (3) stopping the flume during experiments and carefully, yet quickly, draining the turbid suspension and replacing it with clear water. This provided us with a snapshot of migrating ripples, and when we restarted the flow we could film sediment motion over ripples for a few minutes before turbidity increased too much. These observations are illustrated and summarized below, augmented by two video clips that are available as online resources (GSA Data Repository[1]). The flow is fully turbulent, as indicated by Reynolds numbers between 6770 (0.15 m/s) and 11280 (0.25 m/s) at an effective flow depth of 5 cm (kept constant for all experiments) and 25 °C. The corresponding Froude numbers are 0.214 (0.15 m/s) and 0.357 (0.25 m/s).

OBSERVATIONS

Samples of ripple material consist of ~90 vol% water, yet their vertical profile (Fig. 1) is indistinguishable from current ripples in sand. The Ca-montmorillonite that forms the ripple in Figure 1 consists of >80% particles finer than 10 µm, and 90% particles finer than 20 µm, but a large portion of that material is in form of sand-size floccules (Schieber et al., 2007). The ripple index is ~13, and just as in sand ripples, there is a crest and brink. The lee slope of these ripples varies from 25º to 30º. Because the initial clays are finely homogenized, one would expect to see little evidence of cross laminae. However, trace amounts of iron oxide and sorting due to differences in settling velocity produce some variability in foreset composition and allow recognition of faint cross laminae. Figure 1 also shows lee-side scouring. Direct observations show reverse circulation and backflow in that region. Movement of visible particles (larger floccules) in the flow delineates flow separation over the crest. We see a zone of free forward flow, an expanding zone of turbulent mixing, and a zone of backflow at the lee side of the ripple. Particles settle downward in the zone of mixing, and are churned around in the zone of backflow, with an overall motion toward the lee slope of the ripple. The same features were observed in experiments with finely powdered kaolinite (90% finer than 10 µm), and in experiments that used either freshwater or salt water (35‰ salinity).

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[1] GSA Data Repository item 2009116, Figures DR1, DR3, and DR4, and videos DR2 and DR4, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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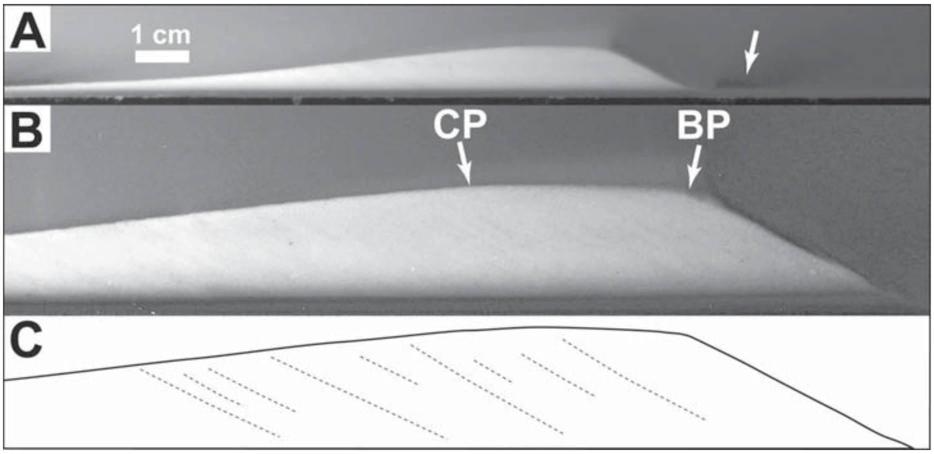

Figure 1. Cross section of floccule ripple that became attached to flume wall. A: Ripple has same asymmetrical profile of a ripple forming in sand, and shows scour pit (arrow) in lee-side backflow region. B: Closer view of ripple that shows crestpoint (CP), brinkpoint (BP), and faint internal cross laminae. C: Cross laminae highlighted in line drawing. Flow velocity is 0.2 m/s at 5 cm effective flow depth.

Figure 2 illustrates ripple migration via the incremental advance of the ripple front; overall migration speed is ~24 cm/h (Fig. 2A). Lee-side sediment accumulation is not uniform. It occurs as sediment lobes that only occupy a fraction of the lee face. Figure 2B shows that sediment lobe buildup is accompanied by sediment clouds that are ejected from growing lobes and then dissipate in the flow. Direct observation and examination of video footage shows that the sediment lobes are in a fluid state and consist of a clay suspension (particles too small to be resolved) with an admixture of larger particles in the 50–200 µm range. Looking at a ripple from above (Fig. DR1 and Video DR2; see footnote 1), we can see boundary-layer streaks extending over the length of the ripple to the brinkline, and the association of these boundary-layer streaks with detaching sediment clouds. Boundary-layer streaks are contra-rotating streamwise vortices in the viscous sublayer (Allen, 1985), and in our experiments are visualized as moving stringers of floccules that are swept into low-velocity streaks by these vortices. A higher concentration of floccules in these streaks is indicated by their darker color in transmitted light (Schieber et al., 2007). Boundary-layer streaks diverge slightly as they move up on a ripple, and reconverge as they move toward the lee side (Figs. DR1C and DR3). In previous experiments boundary-layer streaks were observed to carry most of the sediment that travels across the bed (Schieber et al., 2007). In addition, material is also moving in the spaces between boundary-layer streaks in the form of a thin film. In essence, bedload sediment movement occurs in a thin layer (submillimeter) that is interwoven with boundary-layer streaks (e.g., Schieber et al., 2007).

Processes on the slip face of a floccule ripple are illustrated in Figure DR4 and Video DR5. Sediment issues from point sources along the brinkline and forms gravity-driven lobes flowing down the slip face. At the toe of the slope these spread out and form the rounded lobes seen from the flume bottom (Figs. 2B and 3). Figure 2A illustrates that points of lobe formation shift randomly along the ripple front and over time lead to uniform ripple advance. Multiple build-out of sediment lobes is visible in Figure 3A. In Figure 3B multiple sediment lobes pile up on each other on the slip face of a ripple. When sediment lobes move downslope they can become partially detached because of upslope-directed backflow, and it is at that point that sediment clouds detach and dissipate into the flow. At lower velocities (0.15–0.2 m/s, 5 cm flow depth) mud ripples advance by build-out of small sediment lobes, as seen in Figures 2B and 3A, 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. Near the upper limits (as currently explored) of floccule ripple stability (0.35–0.4 m/s) there is essentially continuous sediment movement along the ripple front. At these velocities we no longer see incremental accretion of well-defined foreset lobes. Instead, the downstream end of the slipface takes on the appearance of flames leaping from a vigorously burning fire.

Ripple migration rates vary with flow velocity. The example in Figure 2 gives 24 cm/h at a velocity of 0.15 m/s and 5 cm flow depth. The latter rate is ~3–4 times slower than that of comparable sand ripples because of the fundamentally cohesive nature of floccule ripples.

DISCUSSION

At the flow velocities and flow depth of our experiments, the cross-sectional geometry of sand ripples compares closely to that of our floccule ripples (Fig. 1); this is remarkable when one considers that floccule ripples consist of as much as 90 vol% water. Poking a finger into a floccule ripple, one feels no resistance whatsoever. Yet when these ripples form they must be subjected to the same shear forces as sand ripples. Our observations of flow separation over the ripple crest also match those from experimental work with sand ripples (Reineck and Singh, 1980; Middleton and Southard, 1984; Allen, 1984).

In sand ripple migration, a heavy-fluid layer at the sediment-water interface contains a high concentration of sediment grains that move by rolling, sliding, saltation, and suspension (Reineck, 1961; Jopling, 1967). The heavy-fluid layer moves up the stoss side of the ripple, dissipates over the crest due to boundary-layer separation (Allen, 1965), deposits sediment at the ripple crest, and this sediment then avalanches down the lee side and forms cross laminae. For our floccule ripples, bedload transport in a thin layer of floccule-carrying clay suspension with interwoven boundary-layer streaks (higher concentration of floccules) is a direct analog to the heavy fluid layer in sand transport. We assume therefore that clay floccule transport in the heavy fluid layer is an essential aspect of mud ripple migration.

In sand ripples (e.g., Allen, 1968), avalanching is an essential aspect of ripple movement. With small sediment discharge, avalanches occur only intermittently and form narrow tongue-like bodies that flow down the foreset surface. Ripples advance by overlap of successive avalanche masses. As sediment discharge increases, avalanching frequency increases and occurs over larger and larger portions of the ripple crests. Finally, with sufficient sediment supply, the entire slip face is in continuous but irregular motion.

What we see in floccule ripples is directly analogous to observations from sand ripples. In floccule ripples the heavy fluid layer consists largely of water, but cohesive forces between clay particles give enough structure to this "fluid" to prevent it from simply dispersing at the ripple crest. Lobe formation occurs in areas where this clay-water-floccules suspension is provided at a high rate (Figs. 3 and DR3), and then the material flows down the slope in a mudflow fashion and builds out the ripple front. Some of the "fluid" can be torn off by lee-side turbulence (Figs. 2B and DR1; Video DR2), but most of the transported sediment is deposited as foresets and leads to ripple propagation.

Our ripples were produced from a flow with ~1 g/L of suspended sediment, but when observed from above (Fig. DR1; Video DR2) the suspended sediment concentration was only on the order of tens of milligrams per liter. At high sediment concentrations turbulence may be dampened (Baas and Best, 2002), potentially

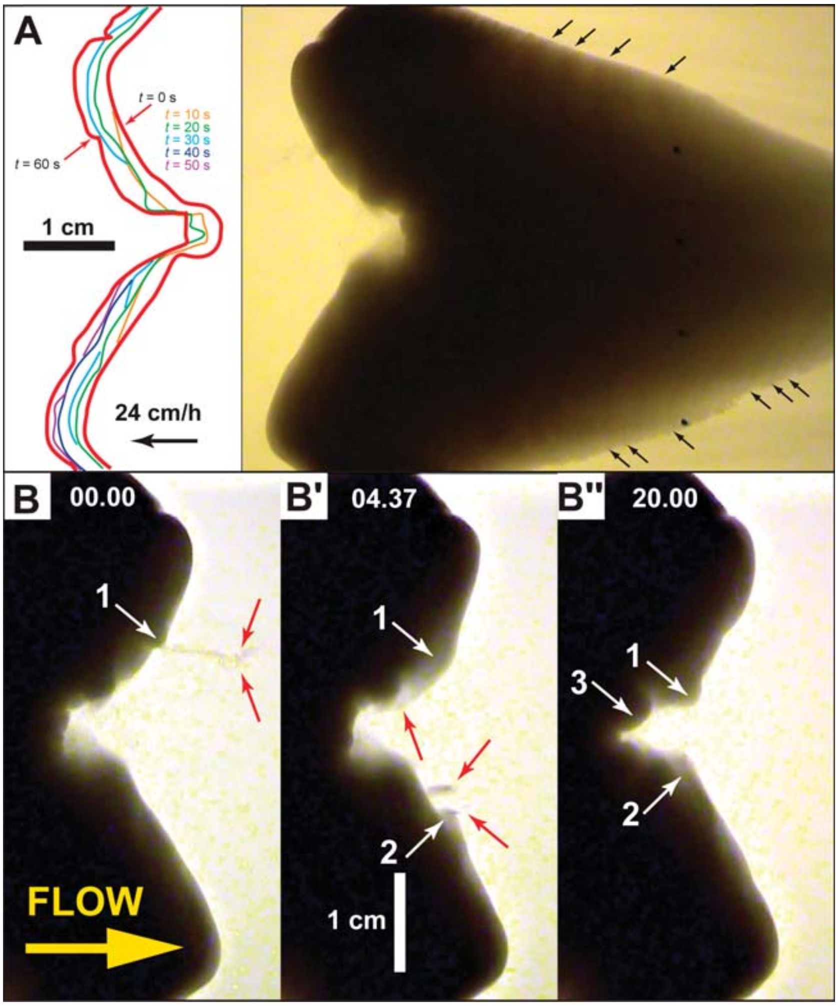

Figure 2. A: Ripple photographed from below through transparent flume bottom. Black dots at right are spaced 1 cm apart. Arrows along ripple margin point to discernable foreset laminae. Drawing at left shows ripple front migration over a 60 s time interval. Colored lines indicate shape of ripple front in 10 s time intervals. Flow velocity was 0.15 m/s at 5 cm effective flow depth. B: Sediment movement at lee side of ripple (bottom view) over a 20 s interval (time stamp at top of images). B and B′ are clouds of sediment drifting off into flow (red arrows). White arrows in all images mark formation and evolution of sediment lobes in the imaged 20 s interval. White arrow 1 tracks growth of one sediment increment that is accompanied by drifting off sediment clouds (red arrows). White arrow 2 tracks another sediment increment that shows detaching sediment clouds in B. White arrow 3 marks addition of third sediment increment and/or lobe.

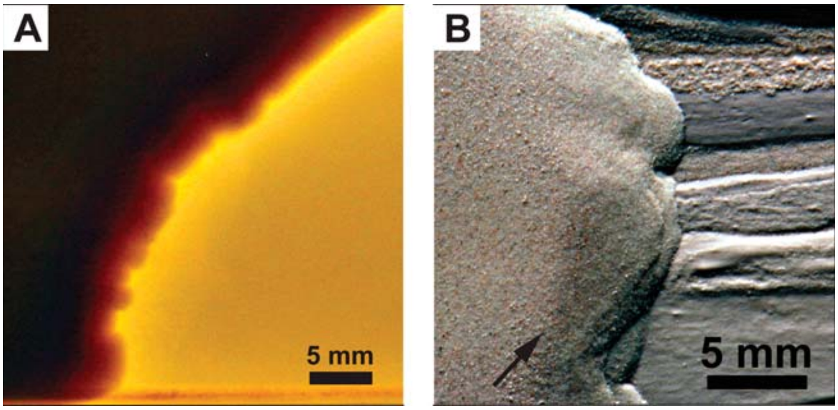

Figure 3. A: Bottom view of ripple that progrades by build-out of sediment lobes as seen in Figures 2 and DR3 (see footnote 1). B: Top view of ripple that shows well-developed multiple sediment lobes on its lee side. Arrow marks brinkline.

affecting the mode of transport and favoring slurry-like transport instead of transport via individual floccules. It would thus be simplistic to assume that at higher sediment concentrations the same flocculated behavior occurs that we see at low sediment concentrations. Yet, we made direct optical measurements of particles moving over the flume bottom over a wide concentration range (50 mg/L to 4.5 g/L) in multiple experiments. These particles are in the coarse silt to fine sand size range, much coarser than our original clay feed. This implies flocculation. Rippled deposits from these experiments retain their original floccule textures (Schieber et al., 2007).

Figure 4 summarizes our observations and conclusions on floccule ripple migration. In our experiments, flows that would produce standard ripples in sandy sediments produce geometrically identical structures with very water rich sediments. Held together by weak Van der Waals forces between clay particles, these ripples offer no noticeable resistance to touch (shear-thinning fluid), unlike sandy ripples. Bagnold (1955) observed ripple development and avalanching in noncohesive sediments only slightly denser than the transporting fluid. That low-density noncohesive grains (Bagnold, 1955), high-density noncohesive grains (quartz grains), and low-density cohesive grains (floccules) all produce similar ripples under the same flow conditions is intriguing.

There is an apparent paradox in mud sedimentation. Whereas mud constituents are cohesive and flocculate, floccules made from cohesive particles appear to act noncohesively in transport. Observation of floccule-ripple migration shows that erosion removes not simply single floccules, but also larger chunks of material. Once moving, these chunks break up into smaller subunits that presumably reflect the maximum equilibrium floccule diameter for a given level of turbulence (Parthenaides, 1965). Floccule-ripples migrate significantly slower than sand ripples under comparable conditions. Thus, cohesive forces between floccules assert themselves once the floccules come to rest next to each other, but they are ineffective as long as the floccules move in turbulent suspension.

CONCLUSION

Sediment ripples have been described and scrutinized from the very beginnings of the study of sedimentary geology (e.g., Sorby, 1859; Allen, 1968; Reineck and Singh, 1980). We might therefore think that the topic has been sufficiently exhausted to be of no further interest. Nonetheless, ripple-forming processes still attract the curiosity of experimentalists and fluid modelers (e.g., Best, 1992; Baas, 1999). Our observations demonstrate that the fluid processes that give rise to the well-known

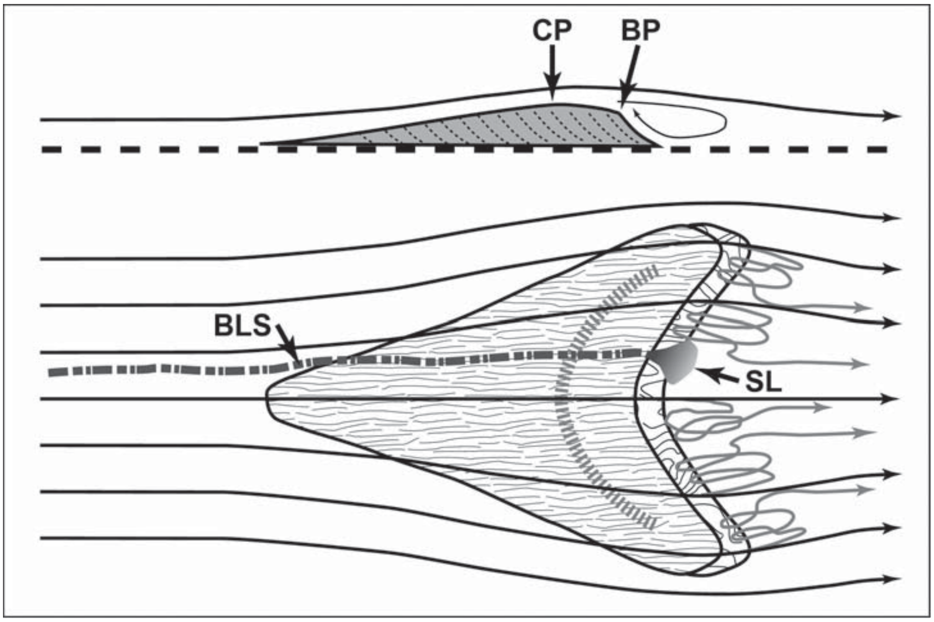

Figure 4. Summary of flow patterns across floccule ripples as inferred from geometry and study of video observations. At top, cross section of ripple (CP—crestpoint; BP—brinkpoint) with lee-side eddy and backflow region. At bottom, flow over idealized ripple with lee-side eddies in the zone of flow separation. Narrowly dashed line marks plan-view position of crestpoint. Dashed line is boundary-layer streak (BLS) that moves over back of ripple and supplies sediment for a lee-side sediment lobe (SL).

ripples in sandy sediments also produce essentially identical bedforms from clays. In both cases, sediment transported in the viscous sublayer of the flow is carried up the stoss side of the ripple. Some floccule transport may also occur above the viscous sublayer, but to image this is a challenge. Cohesive forces between clays are sufficient to maintain the shape of clay ripples that consist largely of water, and cause them to migrate slower than comparable sand ripples. This observation in turn suggests that ripple formation in sediments is not simply a function of grain size, density, and flow velocity, but rather a complex and incompletely understood interaction of sediment transport, bed topography, and fluid flow. It may be that flow properties and fluid dynamics are more important for ripple formation than the material from which they are constructed.

Postdepositional compaction will likely produce planar-parallel lamination in muddy strata deposited by the above mechanism (Schieber et al., 2007). In the rock record, subtle nonparallel lamina geometry, basal downlap, and top truncation should be key attributes of strata produced by migrating floccule ripples. Because mudstones were long thought to record low-energy conditions of offshore and deeper-water environments, our results suggest that published interpretations of ancient mudstone successions and derived paleoceanographic conditions are in need of reevaluation.

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