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Review

Reverse engineering mother nature — Shale sedimentology from an experimental perspective

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A R T I C L E I N F O

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A B S T R A C T

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

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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