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Clay fabric of fluid-mud deposits from laboratory and field observations: Potential application to the stratigraphic record

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ABSTRACT

The clay fabric of fluid-mud deposits was investigated with the aim of identifying characteristic features that potentially apply to the recognition of fluid-mud deposits in the stratigraphic record. We examined both experimentally formed and natural fluid-mud deposits. The clay fabric of experimentally formed fluid-mud deposits is characterized by aggregates of clay particles in face-to-face contact with each other (herein termed 'FF-aggregates'), with long-axis lengths of up to 20 μm. Some flocs that formed in fluid with a high initial suspended sediment concentration (ISSC), such as fluid mud, would have a high preservation potential as FF-aggregates; once they have settled to the sea floor, to distinguish them from flocs that form in fluids with a lower ISSC. Aggregates that are similar to FF-aggregates are also observed in natural fluid-mud deposits that formed in a modern tide-dominated estuary at the mouth of the Rokkaku River in Kyushu, Japan. Thus, in conjunction with formally proposed lithofacies and ichnofacies features of fluid-mud deposits, the observation of FF-aggregates is potentially useful in identifying fluid-mud deposits when examining limited volumes of muddy samples or thin- to very thin-bedded muddy deposits in the stratigraphic record.

1. Introduction

The depositional processes and environments of muds and mudstones have recently been reconsidered in terms of energetic wave and current conditions in coastal and shallow-marine environments, based on detailed studies in modern environments (Wells and Coleman, 1981; Rine and Ginsburg, 1985; Kuehl et al., 1986; Kineke and Sternberg, 1995), experimental studies (Baas and Best, 2002; Schieber et al., 2007; Baas et al., 2009; Schieber and Southard, 2009), and examinations of stratigraphic records (Varban and Plint, 2008; Bhattacharya and MacEachern, 2009; Ichaso and Dalrymple, 2009; Ghadeer and Macquaker, 2011; Mackay and Dalrymple, 2011). This recent interpretation contrasts with the 'traditional' idea that shallow energetic environments are typified by sandy deposits. The reconsideration of the depositional environments of muds and mudstones was stimulated by the finding that fine-grained sediment particles are affected by active flocculation in river mouths and adjacent coastal environments to form aggregates of clay particles, and that these aggregates become concentrated at the bottom of the water column, resulting in high-density fluids known as fluid mud (suspended-sediment concentrations of >10 g/L; Kirby and Parker, 1983; Ross and Mehta, 1989).

Fluid mud is formed at the turbidity maximum in tide-influenced river-mouth environments (Wells, 1995) or in response to high rates of discharge of fine-grained suspended sediment from rivers into coastal and shallow-marine environments during flood events (Hill et al., 2007). The resuspension of muddy deposits, including deposits that originally formed from fluid mud, also results in the development of fluid mud (Whitehouse et al., 2000) that can be transported along the shore (Allison et al., 1995) and to farther offshore environments as wave- or current-induced sediment-gravity flows (Wright et al., 2001; Wright and Friedrichs, 2006; McAnally et al., 2007). Thus, fluid-mud deposits may form in a variety of depositional systems in coastal and shallow-marine environments, thereby producing a mud-dominated stratigraphic succession (Hovikoski et al., 2008).

The recognition of high rates of accumulation of muddy deposits in coastal and shallow-marine environments would necessitate a substantial reorganization of traditional facies models, which generally state that mud accumulates in deeper-water environments, closer to storm-wave base, on the middle and outer shelf (Dalrymple and Cummings, 2006; Plint, 2010). Such models have been widely used for facies and sequence-stratigraphic analyses of coastal and shallow-marine successions (Walker and Plint, 1992; Posamentier and Allen, 1999).

Recent studies have examined the criteria used to identify fluid-mud deposits in coastal and shallow-marine successions, on the basis of a combination of lithofacies and ichnofacies features (Dalrymple et al., 2003; Hovikoski et al., 2008; Bhattacharya and MacEachern, 2009; Ichaso and Dalrymple, 2009; Macquaker et al., 2010; Mackay and

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Dalrymple, 2011). In addition to these criteria, micro-scale features of fluid-mud deposits are likely to be crucial for any re-evaluation of depositional processes and environments of thick muddy successions, because a fabric of randomly oriented clay particles has been interpreted to be ubiquitous in muddy deposits formed from suspensions with low concentrations of mud in marine and transitional marine environments (Bennett et al., 1981, 1991).

In the present study, we investigated the clay fabric of fluid-mud deposits produced in laboratory experiments and of deposits from a modern estuary environment, and we propose a potential new micro-scale criterion for identifying fluid-mud deposits in the stratigraphic succession, in conjunction with lithofacies and ichnofacies features of these deposits, which have been discussed elsewhere (Hovikoski et al., 2008; Bhattacharya and MacEachern, 2009; Ichaso and Dalrymple, 2009; Mackay and Dalrymple, 2011).

2. Experiments on fluid mud

2.1. Procedure

2.1.1. Settling under motionless conditions

We conducted laboratory experiments that involved the formation and deposition of fluid mud, using a commercial bentonite sample with a median grain size of 5.2 μm and containing 45 wt.% clay-size particles (≤4 μm). The sample is dominantly smectite, with lesser clinoptilolite, illite, and minor quartz.

First, the bentonite samples were agitated using ion-exchanged distilled water in beakers using an ultrasonic cleaner for 10 min. Subsequently, salt water was added to each of the stirred samples to produce a salinity in the beakers of 5‰, which corresponds to that in the mixing zone of freshwater and seawater required for the active formation of fluid mud at the turbidity maximum of a modern estuarine environment (Uncles et al., 2006). Finally, we prepared four different samples of muddy fluid (700 mL each) with an initial suspended-sediment concentration (ISSC) of bentonite of 1, 10, 20, and 30 g/L, and a salinity of 5‰ (Fig. 1). The three latter samples (i.e., 10, 20, and 30 g/L) are consistent with the fluid-mud conditions, in terms of the ISSC, reported in modern environments (Kirby and Parker, 1983; Ross and Mehta, 1989). All four samples were used in the experiments, in which we observed the settling processes of suspended sediments at various ISSC values under motionless conditions, in polyvinyl chloride tubes (length, 700 mm; internal diameter, 35 mm) (Fig. 1A and B). The bottom of each tube contained a trap (60 mm in height) to collect muddy deposits after settling (Fig. 1C).

2.1.2. Settling under turbulent conditions

In modern coastal and shallow-marine environments, fluid muds are mobile, and their development and settling on the seabed are influenced by turbulence induced by currents and waves (Wells and Coleman, 1981; Whitehouse et al., 2000). Although some sophisticated flume experiments have been conducted in order to clarify the dynamic conditions required for the development of both fluid muds and fluid-mud deposits (e.g., Baas and Best, 2002; Baas et al., 2009), we conducted simple experiments that created turbulence in fluid muds before their final settling, in order to compare the results with those obtained previously under motionless conditions.

We prepared samples with ISSC of 15 g/L and salinity of 5‰, and generated turbulence in the muddy fluids before their settling to form fluid-mud deposits. To generate turbulence, we placed the sample in a 1050-mm-long polyvinyl chloride tube (diameter, 60 mm) and swung the tube horizontally, using a motor, over a distance of 150 mm in each direction from the mid-point and with a period of 1 s (Fig. 2). The agitation continued for 30 min, after which the muddy fluid sample was poured from the tube into beakers for final settling.

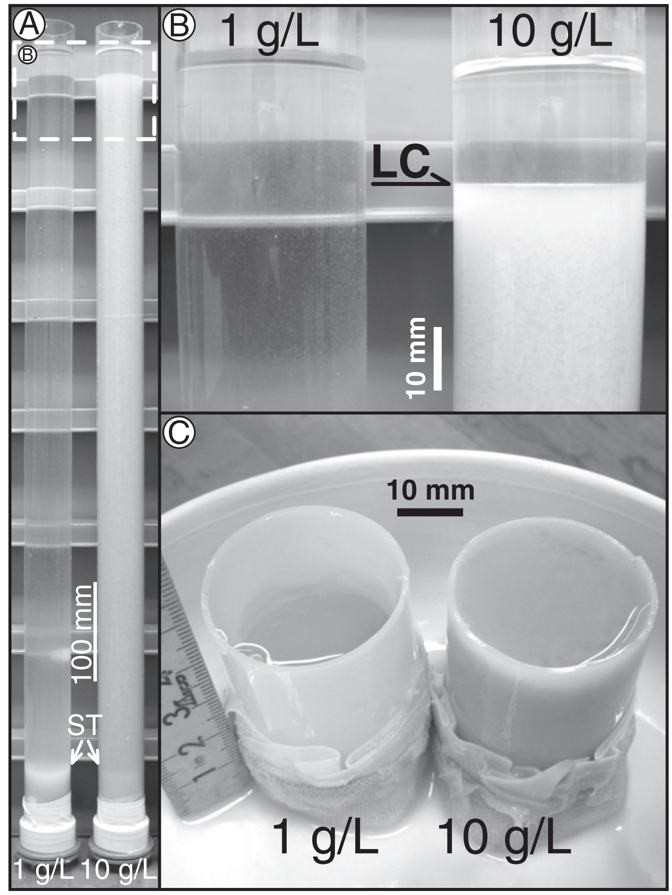

Fig. 1. A: Different settling processes in response to different values of initial suspended sediment concentration (ISSC) (1 and 10 g/L) in the water column. The photograph shows settling conditions after 1 h from the start of settling. ST: sediment traps. B: Close-up image of the upper parts of the water columns in A. A lutocline (LC) is clearly developed in a water column with an ISSC value of 10 g/L, whereas a gradual vertical change in turbidity is observed in the water column with an ISSC value of 1 g/L. C: Muddy deposits formed in sediment traps at the base of polyvinyl chloride tubes, from muddy fluids with ISSC values of 1 and 10 g/L.

2.2. Settling process

We identified two types of settling process of suspended sediment particles under the final motionless conditions (Fig. 1A and B). The first type, observed in the sample with ISSC of 1 g/L, is characterized by an increase in turbidity from the top to the bottom of the salty-water column, as inferred from the color strength of the muddy fluid. All of the suspended sediment in this type settled within 48 h of the start of the experiment, and a 30-mm-thick mud layer developed in the bottom of the tube. The second type of settling process, observed

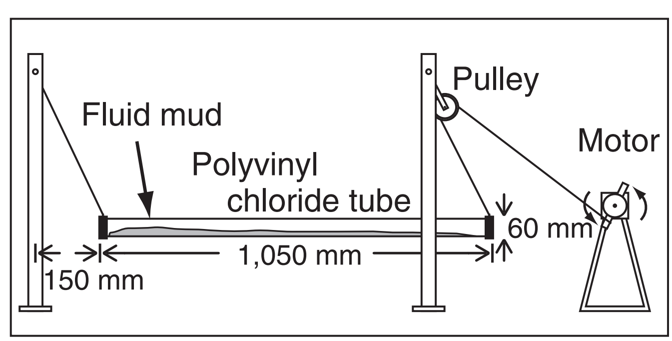

Fig. 2. Experimental equipment for generating turbulence in fluid mud before settling to form a fluid-mud deposit.