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Notes

Tide- and wave-generated fluid mud deposits in the Tilje Formation (Jurassic), offshore Norway

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ABSTRACT

The Tilje Formation (Early Jurassic; 120–300 m thick) consists predominantly of heterolithic deposits and is thought to have accumulated in tide-dominated estuarine and deltaic environments in an active rift setting. Anomalously thick (>0.5 cm) and internally structureless mudstone layers, which are interpreted to represent fluid-mud deposits, are widespread and occur in three different environmental settings: (1) in the basal part of upward-fining tidal-fluvial channels where they generate upward-sanding successions: (2) in the deposits of mouth bars and terminal distributary channels where they are associated with the coarsest sands and the least-bioturbated sediments, suggesting deposition during tidally modulated river floods; and (3) in delta-front successions where they immediately overlie thick, wave-generated storm beds, suggesting that these fluid-mud deposits result from wave resuspension of previously deposited mud. These observations provide criteria for the recognition of ancient fluid-muds and for interpreting their origin. The tectonic setting may be responsible for their abundance.

INTRODUCTION

Our understanding of the dynamics of mud transport and deposition has undergone a revolution over the last 10–20 yr. One of the most exciting new discoveries has been the recognition that fluid mud (i.e., any mobile body of fine-grained sediment with a solid concentration of >10 g L^{-1}) is a common near-bed phenomenon in many coastal and shelf environments. Indeed, the formation, movement and deposition of fluid mud may represent one of the most fundamental mechanisms involved in the transfer of fine-grained sediment (which makes up as much as 60% of all terrestrial-derived material) to the world ocean. Fluid mud appears to be especially common in areas beneath the turbidity maximum in tidally influenced to tidally dominated estuaries (e.g., Gironde and Severn–Kirby and Parker, 1983), and deltas (e.g., Amazon–Kineke et al., 1996; Fly–Dalrymple et al., 2003), but they have also been observed in more wave-influenced settings including delta-front areas (e.g., Amazon–Gabioux et al., 2005; Fly–Dalrymple et al., 2003) and continental shelves (e.g., Eel shelf–Hill et al., 2007). Thus, both tidal and wave processes are apparently capable of generating very high, near-bed suspended-sediment concentrations.

Despite the rapidly growing body of work on fluid-mud occurrences in modern environments, important questions remain about the range of settings in which they can form. In addition, the applicability of the process-oriented observations on fluid-mud genesis to ancient sedimentary successions remains largely untested. Outstanding issues include the criteria for the recognition of fluid-mud deposits and the range of environments in which they occur. The purpose of this study is to examine these issues, in order to demonstrate how such deposits may be recognized and interpreted. The focus of our study is the tide- and wave-influenced deposits of the Early Jurassic Tilje Formation, which contain an overall transgressive succession (120–300 m thick) of deltaic and estuarine deposits (Martinius et al., 2001; this study) located beneath the Halten terrace of offshore mid-Norway (Fig. 1). Sedimentation is thought to have occurred in a coast-parallel (NE-SW) rift basin during the early stages of the opening of the modern Atlantic Ocean (Doré, 1991). Our database consists of 20 cores ranging in length from 50 to 200 m that sample the entire thickness of the Tilje Formation.

FLUID MUDS: DEPOSITIONAL PROCESSES AND DEPOSIT CHARACTERISTICS

A fluid mud is defined as a bottom-hugging mobile subaqueous body of fine-grained sediment with a concentration of solids >10 g L^{-1} (Kirby and Parker, 1983), which consists primarily of clay- and silt-sized-particles with variable amounts of organic material. These dense suspensions display a variety of rheological behaviors ranging from elastic to pseudo-plastic, and are capable of moving horizontally in response to an overriding shear flow, or downslope in response to gravity (McAnally et al., 2007). In tidal environments, fluid mud forms beneath the turbidity maximum, where elevated suspended-sediment concentrations are created by flocculation and estuarine circulation tends to trap fine-grained sediment in the mixing zone between fresh and salt water (Wright et al., 1988; Uncles et al., 2006; McAnally et al., 2007). During slack-water periods, settling of the suspended sediment into the near-bottom layer leads to the development of fluid mud when the concentration becomes high enough that hindered settling inhibits consolidation (Mehta and McAnally, 2002). During the subsequent tidal cycle, turbulence can resuspend some or all of the fluid mud. In environments with significant wave action, shear in the wave-generated boundary layer can also resuspend mud. During storms when wave energy is high, suspended-sediment concentrations may become high enough to form fluid muds, which then inhibits further resuspension because of the suppression of turbulence (Traykovski et al., 2000; Hill et al., 2007).

Based on documented modern examples, fluid-mud deposits are characterized by homogeneous and structureless mudstone layers with a thickness >~1 cm (Dalrymple et al., 2003; perhaps >0.5 cm after compaction). This minimum thickness is used to distinguish fluid-mud layers from those that accumulated by slow, particle-by-particle settling from suspension. In tidal environments where fluid muds are especially common, the short duration of tidal slack-water

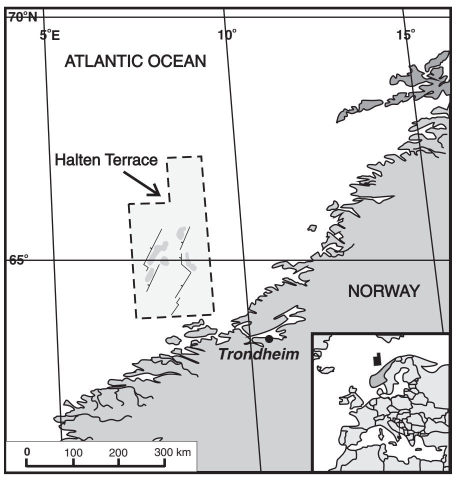

Figure 1. Location map of the Halten terrace area (rectangle), continental shelf, offshore mid-Norway, showing oil fields (gray color) from which cores were used in this study, and main active faults (dark lines) that define the rift system at time of deposition of Tilje Formation.

periods (a few minutes to 1–2 h), coupled with normal suspended-sediment concentrations for dispersed sediment (typically <0.1 g L^{-1}), indicates that a slack-water drape is unlikely to be more than 1–2 mm thick (cf. McCave, 1971). Because fluid muds accumulate geologically instantaneously (i.e., within a matter of hours), they can be distinguished from those that accumulated by slow settling over long periods of time by the absence of bioturbation, except for post-depositional, top-down colonization. Because of their high viscosity and finite internal yield strength (Mehta, 1991), grain segregation to form grading or lamination is strongly inhibited. Grading, if present, is limited to the base of the layer; just as commonly, however, the base of fluid-mud deposits can be sharp, reflecting migration of a fluid-mud body over a preexisting bed. The plastic-like behavior of fluid muds also leads to the random dissemination of organic material within them, and to the presence of "floating" grains of fine to very fine sand.

FLUID-MUD OCCURRENCES IN THE TILJE FORMATION

Mudstone layers interpreted to be the product of fluid muds are common in the Tilje Formation (Figs. 2, 3). Environmental interpretations based on grain-size profiles and physical and biogenic structures indicate that they occur in three different environmental settings: (1) channels in the fluvial marine transition in both estuarine and deltaic deposits; (2) proximal mouth-bar deposits; and (3) more distal delta-front successions.

Tidal-Fluvial Channel Deposits

These deposits (Fig. 3A) are erosionally based successions as much as a few meters thick that display upward thinning and fining of the sand and gravel beds. Current-generated sedimentary structures produced by the migration of dunes and ripples are ubiquitous. Paleocurrents are predominantly unidirectional, but bi-directional cross-stratification is present locally, implying a tidal influence, as does the presence of abundant mudstone layers, some of which show thick-thin alternations, suggestive of a tidal diurnal inequality. The presence of a sparse (bioturbation index, BI, 0–1), low-diversity trace-fossil assemblage (*Diplocraterion* and *Skolithos*) indicates the presence of brackish-water conditions. In these deposits, the fluid-mud layers, which reach 15 cm in thickness (Figs. 2A and 2B), occur only in the lower part of the channel successions (Fig. 3A), in association with the coarsest sediment, and interbedded with dune cross beds up to 40 cm thick. Although the channel successions fine upward over, with the coarsest sand at the bottom, the abundance of fluid-mud layers at the channel base produces an upward-sanding trend in the lower part of each channel succession. Overall, the thickness of the mudstone layers decreases upward from several centimeters at the base to 1–2 mm at the top. These observations indicate that the thick mudstone layers were formed by channel-bottom fluid muds, similar to those reported from the tidal-fluvial transition zone of many modern estuaries (e.g., Kirby and Parker, 1983) and deltas (e.g., Dalrymple et al., 2003). The upward thinning reflects an upward decrease of the suspended-sediment concentrations within the channel.

Mouth-Bar and Terminal Distributary Channel Deposits

The mouth-bar deposits are comprised of stacked coarsening and thickening-upward successions (2–3 m thick) that are punctuated by thin (commonly <1-m-thick) sharp-based upward-fining successions interpreted as terminal distributary channels (Fig. 3B). Sand grain sizes are typically medium to fine with some coarse-grained sand. Cross-stratification generated by the migration of ripples and dunes is abundant, with evidence for current reversals. The deposits are pervasively heterolithic, with well-developed wavy, flaser and lenticular bedding. Wave-generated structures, like waves ripples and small scale hummocky cross-stratification, are present. Bioturbation is not abundant, but it is more pervasive and ichnologically diverse than in the tidal-fluvial channels and indicates that the setting was not fully marine.

At a 10–30 cm scale, the mouth-bar deposits show an alternation between two types of deposits (Fig. 3B). The first consists of thin (0.5–3-cm-thick) beds of fine to very-fine grained sand separated by thin mudstone layers (typically <5 mm thick). Current-ripple bedding, wave ripples and hummocky cross-stratification are present. Bioturbation is relatively abundant (BI up to 4) and diverse (small-diameter *Planolites*, *Paleophycus*, *Asterosoma, Skolithos*, and *Diplocraterion*). The second type of deposit contains distinctly coarser sand, and even granules, together with fine to very-

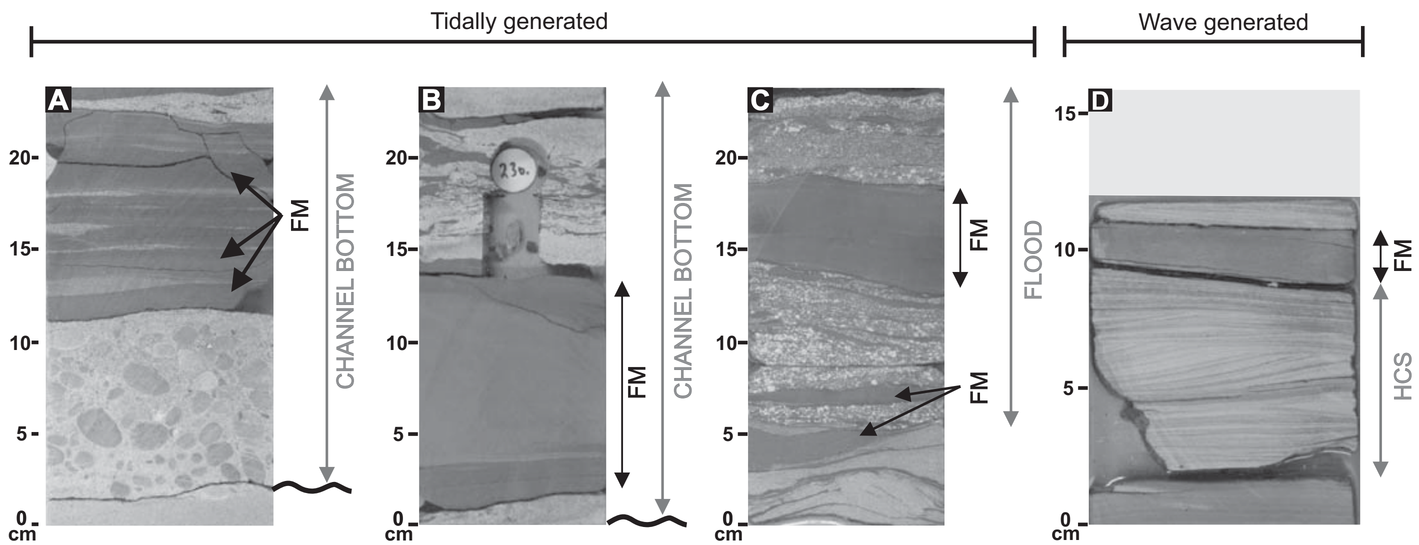

Figure 2. Core photographs showing occurrences of fluid-mud deposits (FM) within the Tilje Formation. A: Succession of fluid-mud deposits overlying coarse lag gravel at the base of a tidal-fluvial channel. The fluid-mud deposits display non-cyclic rhythmites of probable tidal origin. B: Medium- to- thick homogeneous mudstone at the base of a tidal-fluvial channel, overlain by mud-pebble conglomerate. C: Homogeneous fluid-mud deposits associated with granule-bearing river-flood deposits in a terminal distributary channel. The abundant mudstone drapes indicate the action of tidal currents. D: Storm bed from the delta-front region, showing homogeneous mudstones immediately overlying event bed with hummocky cross-stratification (HCS).

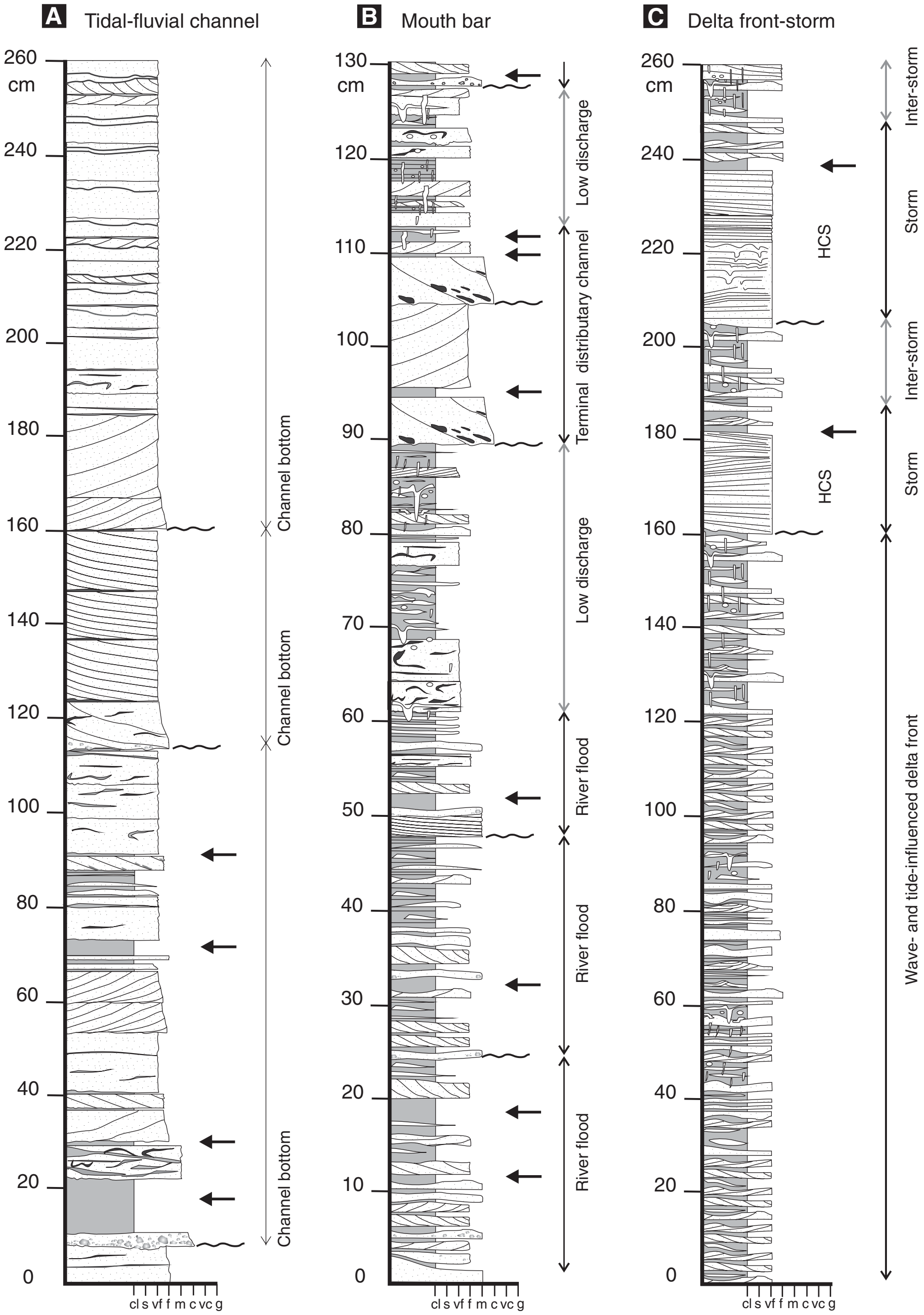

Figure 3. Schematic vertical successions showing the occurrence of fluid-mud deposits (black arrows). A: Tidal-fluvial channel. Fluid-mud deposits occur above channel bases, in association with cross-bedded and current-rippled sandstones and both extra-basinal and intraformational mud-pebble conglomerates. Note how the fluid muds are replaced upward in the channel successions by thinner mud layers. B: Mouth bar and terminal distributary channels. Heterolithic mouth-bar deposits alternating with terminal distributary channels, both of which contain sharp-based 0.5–5-cm-thick homogeneous mudstones. Fluid-mud deposits are associated with anomalously coarse river-flood deposits. C: Delta front. Wave- and tide-influenced and bioturbated deposits alternating with event beds consisting of thick very-fine sand layers containing HCS and wave-generated ripples. Thick weakly laminated mudstones occur on top of event beds. Grain-size scale: cl—clay; s—silt; vf—very fine sand; f—fine sand; m—medium sand; c—coarse sand; vc—very coarse sand; g—gravel.

fine sand. Relative to the first type of deposit, the thickness of the sand beds is greater (up to 5 cm) and cross-stratification is more pronounced. The degree and diversity of bioturbation is overall lower than in the first type of deposit (BI up to 1). Notably, the mudstone layers are typically 0.5–3 cm thick, sharp-based and internally homogeneous (Fig. 2C). They overlie and are interbedded with the coarsest sands and gravels, in overall upward-fining and thinning successions as much as 30 cm thick (Fig. 3B).

Based mainly on the differences in the grain size and degree of bioturbation, we interpret the two deposit types to reflect the alternation between times of low (fine-grained and thin-bedded) and high (flood) (coarse-grained and thicker-bedded) river discharge, respectively. The presence of bipolar paleocurrent indicators, mud drapes and a stressed ichnological assemblage indicate that the river flow was modulated by tidal currents and that the salinity was depressed (i.e., brackish) at all times. The fluid-mud layers occur only in association with the flood deposits (i.e., in the upward-fining, waning-stage deposits), indicating either that overall suspect-sediment concentrations were raised during times of high river discharge and/or that the turbidity maximum was pushed further seaward at these times. Fluid-mud deposition occurred during tidal slack-water periods.

Delta-Front Deposits

The delta-front deposits thicken and coarsen upward and lack channels (Fig. 3C). They are composed mainly of wavy-laminated heterolithics (Fig. 3C) characterized by sharp-based thin-bedded (0.5–3 cm) very-fine to fine-grained sandstones containing abundant wave-generated structures (wave ripples and hummocky cross-stratification); some bipolar ripple cross-lamination is also present, indicating a tidal influence. Mudstone beds and laminae are common. They contain syneresis cracks and are moderately to intensely burrowed (BI 2–4) with a diverse suite of small to large-diameter burrows (*Planolites*, *Chondrites*, *Asterosoma, Thalassinoides, Skolithos, Teichnichnus*, *Rhizocorallium*, and *Diplocraterion*). These wave-influenced delta-front deposits commonly contain thick (up to 1.5 m), erosively based storm beds containing hummocky cross-stratification. Sharp-based, 0.5–3-cm-thick, weakly laminated to homogeneous mudstone layers, which are interpreted to be fluid-mud deposits, occur immediately on top of these beds (Fig. 2D). Bioturbation in the mudstone layers is sparse (BI 0–1), post-depositional, and shows a low-diversity stressed assemblage dominated by *Planolites, Skolithos*, and *Diplocraterion.*

The unique association of the inferred fluid-mud deposits with the thick storm beds, and their absence from the remainder of the delta-front deposits, indicates that they owe their formation to the intense wave action generated by storms, although increased sediment supply caused by storm-induced runoff cannot be discounted. Thus, we suggest that these fluid-mud deposits are analogous to those reported from the Eel River shelf (Traykovski et al., 2000; Hill et al., 2007). Presumably, storm-wave action was responsible for the resuspension of mud deposited previously (cf. Mehta et al., 1994; Lamb and Parsons, 2005). The fluid mud generated in this way was then advected along shore and downslope, coming to rest on top of the sand bed created by the same storm. Unlike the structureless fluid-mud deposits of the tidal-fluvial channels and mouth-bar area, the fluid-mud deposits of the delta-front region display weakly developed internal lamination, although they are otherwise similar with respect to their thickness and lack of bioturbation. The presence of lamination in the delta-front deposits may be due to the action of waves during emplacement of the fluid mud, given that wave-generated turbulence is required for the maintenance of the high suspended-sediment concentrations.

DISCUSSION AND CONCLUSIONS

Bottom-hugging fluid muds are being found with increasing frequency in a range of coastal and shelf settings, but ancient counterparts are not well documented. We suggest that any mudstone layer that is more than ~5 mm thick and lacks internal lamination and syndepositional bioturbation (as opposed to post-depositional, top-down colonization) is a good candidate to be a fluid-mud deposit. Care must be taken to distinguish such layers from thinner tidal mud drapes that form by slow settling of individual particles, and from thick mudstone layers that accumulated slowly over long periods of time. Based on these criteria, fluid-mud deposits are documented from a range of coastal environments in the Tilje Formation (Early Jurassic) of offshore mid-Norway. Based on a detailed process interpretation of the deposits in which the fluid-mud layers occur, the depositional conditions responsible for their formation are similar to those conditions documented from the modern. They are spatially associated with river mouths, occurring in tidal-fluvial channels and channel-proximal deltaic environments. They are also associated with the turbidity maximum zone, which is the area where tidal processes and the mixing of fresh and salt water trap the suspended sediment supplied by the river. Many of the fluid-mud layers represent tidal slack-water deposits, further enhancing the association between tidal processes and fluid muds. However, fluid muds also occur in temporal association with river floods (perhaps because of increased sediment discharge) and with storms that generate waves that resuspend previously deposited mud.

Fluid-mud deposits appear to be especially common in the Tilje Formation, although the database of ancient deposits against which we can make comparisons is small. Perhaps the tectonically active, rift-basin setting in which these deposits accumulated favored the formation of fluid muds. As shown by Mulder and Syvitski (1995), short steep drainage basins, such as one might expect in an active rift basin, are especially prone to the occurrence of pronounced floods with exceptional suspended-sediment concentrations. Thus, it remains to be seen to what extent the observations in the Tilje Formation are representative of the abundance of fluid muds in other tectonic settings.

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