Distribution and grain size of sand in the Miocene wave-dominated Billund delta, Denmark

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The distribution of sand in deltas depends on the delta regime: wave, fluvial or tidal-dominated delta (Orton & Reading 1993; Bhattacharya & Giosan 2003). During the Early Miocene, three delta complexes built out from the Fennoscandian Shield into the eastern North Sea Basin (Rasmussen 2004). The oldest delta complex, which is informally named the Billund delta, is located in Jylland (Fig. 1). This delta complex was mainly wave-dominated (Rasmussen & Dybkjær 2005; Hansen & Rasmussen 2008; Rasmussen 2009a). Recently, it has been demonstrated that in modern wave-dominated delta environments sand mostly accumulates on the updrift portion of the delta (Fig. 2) whereas alternating mud and sand, e.g. barrier-lagoon complexes, occupy the downdrift portion of the delta system (Bhattacharya & Giosan 2003). The current study shows that most of the sand in the submarine part of the Miocene wave-dominated Billund delta (mainly lower shoreface and delta slope sand) was deposited downdrift to the delta front and thus differs from the foreshore and uppermost shoreface accumulation found in recent delta complexes.

The aim of this study is to map the distribution of submarine delta sand in the Billund delta complex. A detailed understanding of the distribution of delta sand, such as found in this delta complex, is crucial for developing predictive tools in sequence stratigraphy and for seismic interpretation, especially in the application of seismic attribute analysis of the subsurface.

Geological setting

The eastern North Sea Basin was subject to inversion in the Early Miocene (Rasmussen 2009b). The inversion tectonism resulted in high sediment input into the Norwegian–Danish Basin and progradation of delta complexes. During the Early Miocene, the deltas built far out into the basin (Rasmussen 2004) and were predominantly wave-dominated (Rasmussen & Dybkjær 2005; Fig. 1). The Middle – Late Miocene was characterised by deposition of marine, clayey sediments at water depths of more than 100 m (Rasmussen 2009a). At the end of the Late Miocene and during the Pliocene the shoreline prograded several times across Denmark (Rasmussen *et al.* 2008) and reached the central part of the North Sea both during the latest Late Miocene and Late Pliocene.

In the Early Miocene, a warm temperate to subtropical, humid climate prevailed (Larsson-Lindgreen 2009). The subtropical climate continued into the early Middle Miocene, but was succeeded by a marked climatic cooling in the middle Middle Miocene. Apart from an interval in the Early Pliocene the climate was relatively cool during the remaining part of the Neogene. During the Miocene and Pliocene, the region was located in the northern part of the zone of prevailing westerly winds, which led to a high wave energy regime in the eastern part of the North Sea Basin due to the long fetch across the North Sea (Galloway 2002; Rasmussen *et al.* 2008).

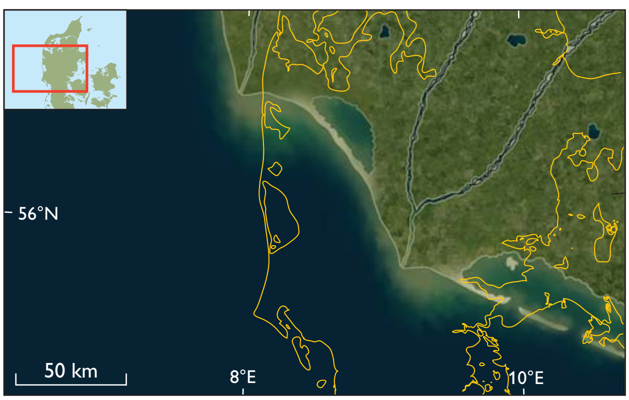

Fig. 1. Palaeogeographical reconstruction of the Billund delta. The Billund delta is located in the central part of Jylland.

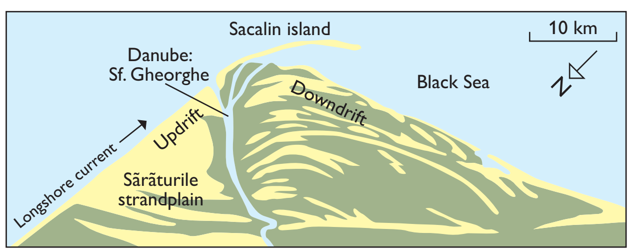

Fig. 2. Example of a modern wave-dominated delta. Note the amalgamation of beach ridges on the updrift portion of the delta, and spits and barriers that enclose lagoons on the downdrift flank. Yellow: sand. Green-grey: mud. Modified from Bhattacharya & Giosan (2003).

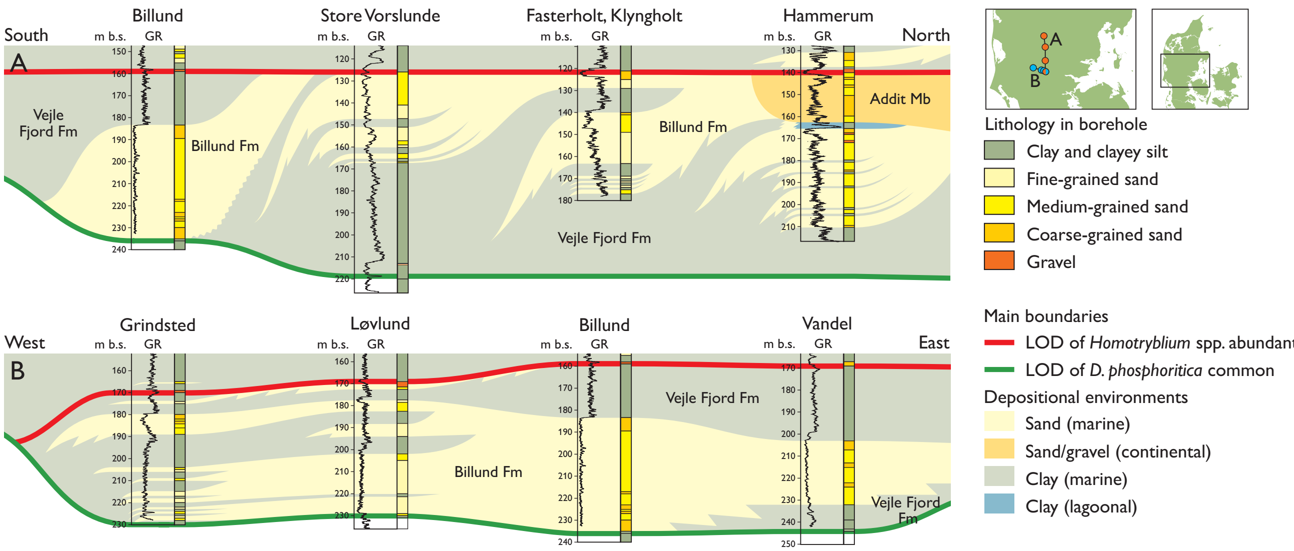

Fig. 3. Two correlation panels of the Billund Formation. **A**: N–S correlation panel showing a strike section of the Billund Formation. The length of the profile is *c.* 45 km. **B**: E–W correlation panel showing a cross section of the Billund Formation. The length of the profile is *c.* 20 km. **GR**: gamma-ray log. **LOD**: last occurrence datum. **m b.s.**: m below surface.

Sand distribution in the Billund delta

The development of the Billund delta complex was studied from high-resolution seismic data and borehole data. The delta complex was deposited during a period of a high rate of sediment supply (Rasmussen 2009a). Based on a number of boreholes drilled in central Jylland it is possible to reconstruct the Billund delta system in the area. The N–S-orientated correlation panel shows a series of sand-rich lobes prograding across clay-rich successions (Fig. 3A). The gamma-ray log of the sand-rich units shows a serrated pattern, with generally decreasing values upwards. The grain size is dominated by fine- to medium-grained sand with the latter dominating in the upper part of the succession. Coarse-grained sand and gravel occur in the uppermost part (Fig. 3A). At the northernmost borehole, the upper part is characterised by coarse-grained sand overlain by a succession of alternating fine- and medium-grained sand. The log pattern at this site is characterised by generally upward increasing gamma-ray values (Fig. 3A). The sand was deposited in clinoforms, with a dip of 7–10° according to seismic data (Hansen & Rasmussen 2008; Rasmussen 2009a). Locally, at the top of the clinoformal package, erosive features are seen with concave-upward structures that are filled with a succession showing transparent or subparallel reflection patterns (e.g. Rasmussen 2009a).

The updrift part of the delta complex is represented by the Løvlund and Grindsted boreholes (Fig. 3B). At these sites alternating sand- and mud-rich successions dominate. The 10–20 m thick sand-rich part is dominated by grey, fine-grained sand. Medium- to coarse-grained sand occurs in the upper part. In the westernmost borehole, at Grindsted, the lower part is dominated by 1–2 m thick sand-rich deposits intercalated in a mud-dominated succession. Large cuttings show that a substantial part of the succession at this site consists of alternating thin sand beds and clay layers. The sand beds are normally graded.

The downdrift flank of the delta complex is characterised by grey, medium- to coarse-grained sand. Pebbles are common and clasts with diameters up to 2 cm have been found. The sand-rich succession is 20–50 m thick (Fig. 3B), but seismic data indicate a thickness up to 75 m immediately north of the Billund well (Hansen & Rasmussen 2008). Thin mud layers have been found in a few samples, but mud is not a common lithology.

Depositional environment

A prograding depositional system is indicated by the sedimentary succession characterised by S–SW- dipping clinoforms and the general coarsening-upward trend seen in the boreholes (Fig. 3). The mud-dominated part of this prograding system is dominated by marine palynomorphs (Dybkjær 2004). Their concentration decreases upward, indicating a shallowing-upward succession with increasing terrestrial influence. The fining-upward succession found in the upper part of the Hammerum well is interpreted as fluvial channel deposits (Rasmussen *et al.* 2006; Rasmussen 2009a).

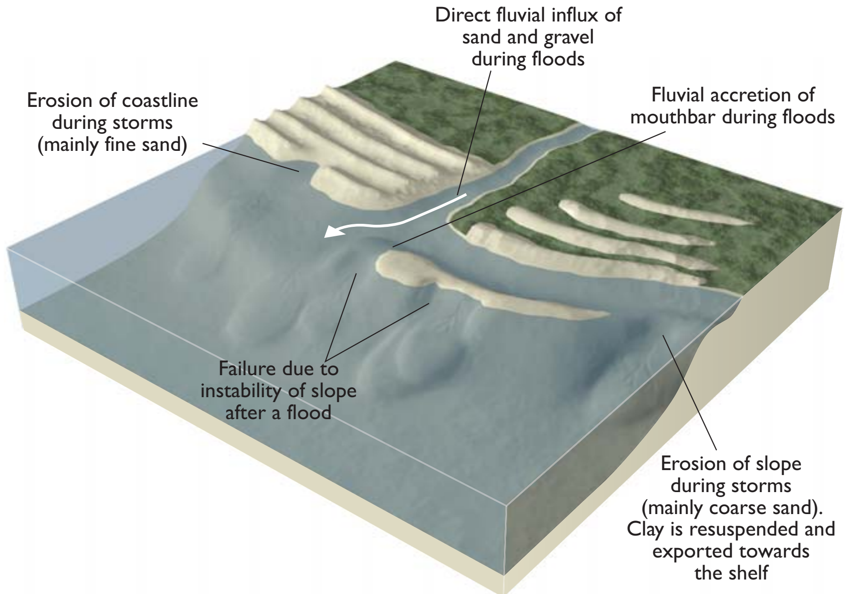

Fig. 4. Depositional model for a wave-dominated delta showing typical areas with erosion and deposition. At the river mouth fluvial sand accretes to the mouth bar, with high potential for slope failure. Direct influx of sediment onto the delta slope may occur during floods. In the downdrift portion of the delta front wave-reworked sand (relatively coarse-grained) forms spits and barriers that may be eroded during storms. On the updrift flank fine- to medium-grained sand is deposited as beach ridges which are a source of sediment supply to the delta slope. Consequently, finer-grained sand is deposited in this area.

A prograding system overlain by fluvial channels (Hansen & Rasmussen 2008; Rasmussen 2009a) indicates a deltaic depositional environment. The development of spits and barrier complexes south-east of the main area of progradation implies a depositional system characterised by longshore transport of sediment (Rasmussen & Dybkjær 2005). The predominance of storm deposits with hummocky and swaley cross-stratification and other types of tempestites (Rasmussen & Dybkjær 2005) indicates a wave-dominated delta front.

In the modern wave-dominated Rhône Delta, sediment (sand) transport to the delta platform and prodelta slope occurs in two ways (Maillet *et al.* 2006). (1) During storms, erosion of the foreshore and upper shoreface leads to transport of sand partly to the outer delta platform and partly to the delta slope and (2) during floods, sand is transported in migrating dunes from the fluvial system towards the mouth bar. Sand accumulations at the slope break of the delta platform may destabilise the area by increasing the angle of the delta slope (the equilibrium profile). Slope failure may result from the steepened slope or from changes in pore-water pressure due to wave action, resulting in deposits being shed directly down the delta front as mass-flow deposits. High sediment supply to the Billund delta occurred from the rivers (Rasmussen 2009a). The supply was probably dominated by bedload transport as indicated by the braided channels that dominated the fluvial system feeding the delta (Rasmussen *et al.* 2006). Therefore, migration of dunes towards the delta platform was more effective than in the modern Rhône Delta, where man-made constructions have significantly reduced the sediment influx to the delta. Direct sediment supply from the fluvial system to the Billund delta complex is indicated by the occurrence of large clasts, up 2 cm, in the lower part of the delta slope. Such large clasts have never been reported from Miocene shoreface deposits (e.g. Rasmussen & Dybkjær 2005) indicating that the hydro-dynamic conditions in the shoreface zone was unfavourable for transport of clasts of that size. The central and the downdrift parts of the Billund delta slope were thus dominated by sedimentation of medium- to coarse-grained sand with its source in the main river system. Failure at the mouth bar, spit and downdrift beach thus sourced sediments for deposition on the delta slope (Fig. 4). The deposition of graded, predominantly fine-grained, sand beds in the updrift part of the delta complex indicates sedimentation from suspended sand clouds generated by storms or from diluted turbidity currents (Fig. 4). The finer-grained character here reflects that the source was the stacked beach ridges from the updrift flank of the delta. The sand in this part of the delta has been effectively sorted during transport along the shoreline before deposition and is therefore finer grained. For example, the barrier and spit systems of the Billund delta found 25 km south-east of the main delta consists of fine- to medium-grained sand with few intercalations of gravel (Rasmsussen & Dybkjær 2005). The clasts of the intercalated gravel layers do not exceed 5 mm.

Discussion

The distribution of sand in recent wave-dominated deltas is characterised by coherent sand accumulation, e.g. amalgamated beach ridges in the updrift portion of the delta complex (Fig. 2; Bhattacharya & Giosan 2003). The downdrift flank is commonly dominated by river-borne clay and sand deposited in lagoons protected by spits and barriers. A different pattern of sand distribution is seen in the Billund delta where most of the sand was deposited in a downdrift position of the main delta (Fig. 4). This different depositional pattern can be explained by both the depositional environment and the geological setting. The Billund delta prograded into a basin with relatively deep water (*c.* 100 m) and the delta front was relatively steep (*c.* 7–10°; Hansen & Rasmussen 2008). Fluvially transported, coarse-grained sediments were at times shed directly down the delta slope as mass-flow deposits (Fig. 4). The high-wave energy regime in the region and the high frequency of storms also enhanced sand transport downdrift of the main delta lobe and some of this was directed offshore beyond the delta slope break and deposited in deeper water (Fig. 4). The distribution of submarine sand in the downdrift setting is important, because foreshore and uppermost shoreface sediments are rarely preserved in the geological record. Therefore, in deltaic systems of the same character as the Billund sand, with steeply dipping, 50–100 m high and asymmetric clinoforms, the reservoir sand is most likely found in the downdrift portion of the wave-dominated delta. This type of delta is best developed in a ramp setting that has undergone a tectonic phase, which resulted in a sudden increase in accommodation space, and is characterised by a high sediment supply due to the formation of a high relief in the hinterland. In such a setting, the fluvial system is dominated by bed-load transport and migration of dunes to the delta front is a common phenomenon. The proportion of river-borne sediment is also important. Longshore currents and wave processes can move the fine-grained fraction downdrift and offshore and thereby lead to concentration of sand on the main delta platform.

Acknowledgements

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