DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2009/36

Seismic facies and log pattern of fluvio-deltaic deposits: with special emphasis on the distribution of thick sandrich aquifers

Med dansk sammendrag

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

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Contents

Abstract

Deltaic sediments of the Billund and Bastrup sands were deposited in a ramp setting in the storm-dominated North Sea during the early Miocene. A marked relief in the hinterland and relatively high precipitation resulted in a high sediment supply to the sea and progradation of major delta-coastal plains south of the present day Norway. The focus of this study is on the forced regressive wedge system tracts of the two delta complexes, which show remarkably well-developed marine erosional surfaces associated with sand-rich packages characterised by steeply dipping clinoforms (up to 10^0). The well-developed clinoformal packages indicate that deposition occurred in water depths of 60 – 100 m even under a sea-level fall. The sand-rich delta lobes also demonstrate that it was a high energy environment and that wave-generated re-suspension at the delta front effectively re-sorted the sediments and sand-rich systems became separated from mud-dominated portions of the delta complexes. The evolution of the above occurred in a basin that has been exposed by inversion tectonism. The sediment supply was consequently high. During deposition eustatic sea-level changes strongly controlled the evolution of sequences. The results found in this study may be applicable for mapping reservoir sands in ramp settings and in rift basins especially when looking for reservoir rocks in the basinal setting or when doing detailed reservoir mapping in already existing hydrocarbon fields.

Keywords North Sea, deltas, ramp, Miocene, Denmark.

DANSK SAMMENDRAG

Deltaiske sedimenter tilhørende Billund og Bastrup sand blev aflejret på soklen i det stormdominerede Nordsø i tidlig Miocæn. Et markant relief i baglandet og relativ høj nedbør resulterede i et højt sediment tilførsel til Nordsøen og dermed udbygning af større delta-komplekser syd for Norge. I dette studie fokuseres der på det tvungne regressive kompleks, der viser bemærkelsesværdig veludviklede erosionsflader associeret med tykke sandpakker, som er karakteriseret ved klinoformer, der dykker 7 – 10^0. Aflejringen af sandpakken foregik på 60 – 100 m vanddybde, selv under faldende havspejl. De sandrige delta-lober blev dannet i et højenergisk miljø, hvor bølge dannet suspension ved deltafronten effektivt sorterede sedimenterne, således at sand blev separeret fra ler og aflejret i sandrige lober. Under dannelsen kontrolerede havspejlet også udviklingen af sekvenserne og dermed lokaliseringen af de bedste grundvandsmagasiner.

Introduction

The mapping of the shoreline trajectory has proved to be a useful tool in the prediction of reservoir sand (Helland-Hansen & Gjelberg, 1994; Helland-Hansen & Martinsen, 1996). However, widespread erosion during sea-level fall and subsequent transgression may hamper the identification of the shoreline trajectory. During falling sea level, erosion surfaces are often formed at the base of the delta due to a lowering of the base level (Dominguez & Wanless, 1991; Nummedal et al., 1993; Plint & Nummendal 2000). The preservation potential for these surfaces is high and they are therefore important in the search for good reservoir sands. Sand-rich delta deposits prograding into the sea are characterised by dipping foresets, the morphology of which reflects the grain-size, water depth, the proximal/distal location on delta lobes and the type of delta system (fluvial-, tide- or wave-dominated; Galloway 1975; Orton & Reading 1993). This morphology is imaged on seismic data as clinoforms with various geometries, i.e. shingled, sigmoid, oblique-parallel, oblique-tangential clinoforms.

High-resolution shallow seismic data from Denmark (Fig. 1) indicate that mapping of the marine erosional surfaces and the geometry of the clinoforms is a robust tool for identifying the thickest and most widespread reservoir sand. The examples are from two wave- to fluvial-dominated delta complexes. The two delta complexes, the Billund and Bastrup deltas, prograded into the North Sea during the early Miocene. The average sand thickness in each delta complex is on the order of 15 to 20 m, but over 50 m of sands are found locally. The latter accumulate when progradation of a delta lobe is steady and dominated by bedload transport giving rise to the deposition of a thick sand-rich package. The thick sands are found on seismic data as a package characterised by oblique-parallel clinoforms dipping from 7 to 10^0 The base of the package is often characterised by a series of erosional surfaces.

The aim of this study is to show an additional or alternative analysis to shoreline trajectory analysis in order to predict reservoir sand in prograding fluvio-deltaic systems. In the examples shown, the combination of steeply dipping clinoforms and marine erosional surfaces are found in the late stage of delta-coastal plain progradation (forced regression) and is thus applicable in the study of basinal settings. This study focuses on the development of the Billund and Bastrup sands, as these are covered by high-resolution seismic data and a high number of boreholes have been drilled to test the evolution of reservoir sand.

Geological setting

The eastern North Sea Basin constitutes a mosaic of structural elements fringing the Fennoscandian Shield. The structural elements were formed in late Carboniferous – Permian times (Berthelsen, 1992; Ziegler, 1982, 1990) and were reactivated several times during the Mesozoic and Cenozoic Eras (Liboriussen *et al.*, 1986; Thybo, 1997; Berthelsen, 1992; Mogensen & Jensen 1994; Vejbæk & Andersen 2002; Rasmussen, 2004a). The border zone was formed by the Sorgenfrei-Tornquist Zone. South-east of this zone, lows and highs named the Norwegian-Danish Basin, Ringkøbing-Fyn High and North German Basin are the most important structural elements (Fig. 3).

During the early Miocene the climate was temperate. Minor changes from cool to a warm temperate climate have been detected (Mai 1967; Lotsch 1968; Utscher *et al*. 2000; Mosbrugge *et al.* 2005). The variation of climate is strongly correlated to climatic changes on a globale scale. Precipitation fell dominantly during summer and the rate was on the order of 1500 mm/year. The North Sea was located in the northern hemisphere westerly wind belt.

The eastern North Sea Basin was filled by siliciclastic sediments sourced from the Fennoscandian Shield during the early Miocene (Larsen & Dinesen, 1959; Ziegler, 1982, 1990; Friis *et al.*, 1998; Rasmussen 2004b; Rasmussen & Dybkjær, 2005). The sediment supply was high due to tectonic uplift of the Fennoscandian Shield associated with the Savian Phase (Rasmussen, 2004a). The east – west elongation of the North Sea resulted in a long fetch, so the wave action on the shoreline was prominent. The tidal range is interpreted to be micro- to mesotidal (Friis *et al*. 1998; Rasmussen & Dybkjær 2005). The evolution of the early Miocene succession following the Savian Phase was strongly controlled by eustatic sea-level changes (Rasmussen, 2004a). During the early Miocene the shoreline prograded into the North Sea two times. Sand deposited within these prograding units are referred to as the informal units of the Billund sand and the Bastrup sand (Fig. 2). Sand deposited adjacent to the delta mouth or in association with topographic highs was rapidly redistributed and deposited as either spit complexes or barrier islands in the down-drift areas of delta lobes (Rasmussen & Dybkjær, 2005; Hansen & Rasmussen, 2008) referred to as the Vejle Fjord Sand Member and Hvidbjerg Sand. The thicknesses of these sand-rich successions are commonly 20 m. However, delta lobes filling topographic lows, i.e. graben structures and thus deeper water, are characterised by thick and well sorted sand; the maximum thickness of the delta sand is up to 70 m (Hansen & Rasmussen, 2008). The late part of the progradation of delta lobes into the basin was associated with a sea-level fall.

Data and methodology

This study is based on c. 1000 km new of high-resolution seismic data and 2000 km of older multi-channel seismic data (Fig. 3). The borehole database consists of c. 50 new stratigraphic boreholes with wire-line logs (gamma ray), plus 1 cored borehole and c. 20 outcrops (Fig. 3). The succession studied here has been subdivided into unconformity bounded sequences (Rasmussen, 2004b) based on the principles of Hunt and Tucker (1992, 1995), which is a modification of Posementier *et al.* (1988). Biostratigraphic dating of the succession is based on dinoflagellate cysts and has been carried out on all boreholes and outcrops (Dybkjær, 2004a, b; Dybkjær & Rasmussen, 2000, 2007; Rasmussen & Dybkjær 2005; Rasmussen *et al*. 2006).

Seismic facies

New seismic data across Jylland, Denmark has revealed progradation of two delta complexes, the Billund and Bastrup, during the early Miocene (Fig. 4). The acquisition of high resolution seismic data in the study area has resulted in the recognition of 5 typical seismic facies associations associated with delta formation. The delta deposits are categorised into prograding stacking pattern, aggrading stacking pattern and channel/valley-fill pattern. The facies association are: The FA 1: Shifting lobe facies, FA 2; fixed lobe facies, FA 3; bottomset facies, FA 4; topset facies and FA 5; channel facies.

Shifting lobe facies association: FA 1

FA 1 is characterised by oblique-parallel and sigmoidal reflection patterns (Figs. 5 and 6). Internally, the facies consists of low dipping clinoforms with measured dip varying from 1 to 5^0. The facies association is characterised by a moderate amplitude. Occasionally, the sigmoidal packages may be transparent (Fig. 5). The lower boundary of FA 1 is weak or gradational towards the underlying FA 3. The gamma log shows a serrated pattern with a general decreasing gamma-ray reading upwards (Fig 6). Where boreholes penetrated a succession characterised by the oblique-parallel seismic reflection pattern, low gamma-ray readings are seen (Fig.5). Here both coarsening and fining upward trends have been recognised. This facies is common in the central and northern part of the study area.

In boreholes penetrating FA 1 the lithology is composed of alternating mud-dominated and sand-dominated parts (Figs. 5, 7a, b and d). The sand may be found associated with steeply dipping oblique-parallel clinoforms (Fig. 5) or in a sigmoidal reflection pattern where the lower part is dominated by mud with an upwards increasing intercalation of sand beds as seen in the Billund delta complex at Vorslunde (Fig. 4). Here the upper part is dominated by sand where clinoforms are common, but where a transparent seismic pattern dominates, the whole succession consists of mud. The typical log pattern of this facies is a gradual decrease in gamma log response upwards, indicating a coarsening upward succession and thus a prograding succession. The muddy part of the succession is rich in marine dinoflagellates (Dybkjær, 2004a) indicating a marine depositional environment. The FA1 is interpreted as prograding delta and where lobe swifting is common. The FA1 is most common when delta progradation occurred during rising sea level. (Hansen & Rasmussen, 2008)

Fixed lobe facies association: FA 2

FA 2 is characterised by a pure oblique-parallel seismic reflection pattern. It is composed of high frequency clinoforms dipping at an angle of 7 to 10^0 (Fig. 8). The amplitude is highest in the upper part and decreases gradually downwards. The thickness of the facies varies between 75 and 100 m. FA 2 has a sharp often erosive lower boundary and occasionally the underlying FA 3 may be totally eroded (Fig. 8). The upper boundary is sharp and erosion is commonly seen. Above this erosive boundary, high amplitude reflections may occur and are always associated with internal downlap (Fig. 8). The gamma log pattern is characterised by low gamma-ray readings (Fig. 8). The gamma log shows an overall serrated pattern stacked in minor coarsening upward units (Fig. 8). FA 2 is restricted to the southern part of the study area.

This facies is dominated by medium- to coarse-grained sand with some gravel (Figs. 8 and 7e). The close link to FA1 indicates that it forms a sand-rich part of a prograding delta (see also Hansen and Rasmussen 2008). The sharp and erosive lower boundary, often showing a down stepping pattern, is interpreted as formed by submarine erosion due to successive lowering of the base level. The interpretation of the high amplitude reflections is difficult, because they are not penetrated by any boreholes. High amplitude reflections found at the toe of clinoforms on a Triassic progradational system on the Finnmark Platform (Hadler-Jacobsen et al. 2005) is interpreted as a submarine fan. Thin turbidites have been recognised in bottom sets of the delta complex (see below) in the cored borehole, Sdr. Vium (Fig. 7c), but it seems not to be a widespread phenomenon in these Miocene deposits. As no basin floor fans have been found it is also unlikely that it represents a sediment by-pass zone (e.g. Plink-Björklund et al. 2001). Delta lobe switching may also change the equilibrium profile of the delta slope causing successively deeper erosion at the location of the seismic section. However, the study of the shoreline trajectory carried out by Hansen and Rasmussen (2008) still indicate a descending pathway in concert with successively deeper erosion into the substratum at the delta toe and thus indicates deposition during falling sea level. A conclusive interpretation, however, needs additional seismic data across the delta complex. An alternative interpretation is that more consolidated parts of the clay-rich Vejle Fjord Formation has been eroded, resulting in a higher acoustic impedance contrast at the boundary and producing a high amplitude reflection. A similar seismic pattern as FA 2 has been described from a late Pleistocene prograding unit on the Bengal Shelf (Hübscher & Spiess 2005). They interpreted the prograding unit as belonging to the forced regressive systems tract. FA 2 was deposited associated with a flat or descending shoreline trajectory (see Hansen & Rasmussen 2008) and is accordingly interpreted as prograding delta lobe deposited during falling sea level.

Bottomset facies association: FA 3

FA 3 is characterised by a parallel to sub-parallel reflection pattern (Fig. 6). The amplitude is moderate to low. The lower boundary is marked by a high amplitude, continuous reflection. The upper boundary often forms an erosional surface with down lap. Scattered high amplitude reflection may occur at the boundary to the overlying facies. The gamma log is characterised by medium to high gamma-ray response (Fig. 6). No systematic log pattern has been recognised. FA 3 is found in most of the study area, but may be eroded locally.

FA 3 is always found below FA 1 and 2 and sometimes also FA 4 (Fig. 6). From boreholes, the lithology is composed of mud with some intercalation of thin sand beds (Fig. 7c). Marine dinoflagellates are common (Dybkjær, 2004a). FA1 and FA2 are seismic facies indicating a prograding delta and therefore FA3 can be interpreted as bottom sets laid down in front of a prograding delta complex.

Topset facies association: FA 4

FA 4 is characterised by a parallel to sub-parallel reflection pattern (Fig. 6). The amplitude is moderate to low. The thickness of the facies varies between 10 and 150 m. Locally, the facies may be characterised by a more continuous, high amplitude, parallel reflection pattern (Fig. 6). FA 4 has a sharp often erosive lower boundary. The upper boundary is sharp and characterised by a high amplitude reflection. The gamma log shows a high variability in log response (Fig. 6). In the Hammerum, borehole low gamma-ray readings are common and these often show a fining upward trend. In the Isenvad borehole, FA4 is dominated by generally high gamma-ray readings with a serrated log pattern. This part shows both coarsening and fining upward trends (Fig. 6). FA 4 is distributed for 10^{th} of km^2 and is widespread in the northern part of the study area.

FA 4 is found above FA 1 and 2. The log pattern is often characterised by a fining upward trend (Rasmussen *et al.* 2006). Marine dinoflagellates are rare (Rasmussen *et al*. 2006). The FA4 outcrops at several places in central Jylland and here it is interpreted as dominantly braided fluvial deposits alternating with floodplain deposits (Fig. 7f); Hansen, 1985; Hansen, 1995; Jesse, 1995; Rasmussen *et al*., 2006). Point bar deposits capping the braided fluvial deposits (Fig. 7f) indicate, however, sedimentation in meandering river systems. This facies is most sand-rich where it correlates with a continuous, high amplitude reflection pattern (Fig. 6).

Channel facies association: FA 5

FA 5 is dominated by a transparent to sub-parallel reflection pattern (Fig. 9a). Over short distances a shingled reflection pattern may occur (Fig. 9b). The lower boundary is sharp and formed by a concave upward, often erosive, surface (Fig. 9a). The upper boundary is sharp. The width of the facies varies from a few hundred metres to several kilometres and the depth may be up to 50 m. The gamma log pattern is characterised by low gamma readings (Figs. 6 and 9a). The lowest gamma-ray readings are found in the basal part of the facies association. Upwards, a slight increase in gamma-ray readings is seen (Figs. 6 and 9a). The top of the facies may be characterised by extreme high gamma-ray readings (Fig. 6). FA 5 may occur in the whole study area, but is most widespread in the central part of the study area.

This facies is always capping one of the other facies (Fig. 6). Boreholes penetrating the facies reveal commonly coarse-grained sand or gravel, but mud and coal clast may also occur. The facies is depleted of marine dinoflagellates (Rasmusen 2004b) and coal occurs abundantly in the upper part. The facies is interpreted as incised channels or fluvial channels, where a shingle seismic pattern represents point bars (Posamentier, 2003; Rasmussen *et al*., 2007). The point bars are commonly capped by a coal layer (Fig. 6).

Distribution of seismic facies association and lithology in the Billund and Bastrup delta complexes

The Bilund delta complex

The Billund delta complex prograded into the North Sea during the Aquitanian, earliest early Miocene time; the progradation was from the north towards the south (Fig. 2; 10). The depositional environment was strongly controlled by the antecedent topography formed during an inversion phase at the Oligocene – Miocene boundary (Rasmussen, 2004a; Rasmussen & Dybkjær, 2005; Hansen & Rasmussen, 2008). Water depth ranged from 100 m in structural lows to less than 20 m on structural highs. The two main delta lobes of the Billund delta complex, named the Ringkøbing and Brande lobes (Hansen & Rasmussen 2008), were confined to structural lows and were consequently deposited in relatively deep water; c. 100 m (Fig. 11).

During the initial phase, delta progradation occurred during a sea-level rise (HST) that was characterised by sedimentation of sand and mud in frequently shifting delta lobes (Hansen & Rasmussen, 2008). Under the succeeding sea-level fall, increasing erosion of former sand-rich fluvial deposits resulted in high bed-load transport and thus sedimentation of sand-rich foresets in front of the delta complex. Delta progradation was laterally confined in this phase due to the structural control on the feeder system.

The Billund delta complex example (Fig. 12), which represents the area between the Vorslunde and the Billund boreholes, contains four seismic facies associations labelled 1, 2, 3 and 5 are represented. A distance of c. 10 km is dominated by FA 2. The dip of the clinoform is 7^0 to 10^0. At the base of these clinoforms distinct erosion is seen (Fig. 12). The erosion successively cuts deeper into the substratum towards the south (direction of progradation). These erosional features are only seen in the fringe area of the delta lobes and are always associated with descending shoreline trajectories (Fig. 4; Hansen & Rasmussen 2008). Clinoforms downlap these erosional surfaces successively, also when deeper scouring are seen. Therefore, these features are most likely formed by marine erosion during falling sea level. The upper boundary is sharp, but channel formation is only present in the northern part close to the Vorslunde Borehole. In the area where FA 2 is present it has a lobate shape (Hansen & Rasmussen 2008) and covers an area of c. 300 km^2.

In boreholes, the delta successions show a change from a simple coarsening- and thickening-upward trend at the Vorslunde borehole (Fig. 13) to a more sharp-based blocky succession with low gamma readings at the location of the Billund borehole. The lithology at the Vorslunde borehole is composed of mud with intercalated thin, fine-grained sand beds that evolved into c. 20 m of amalgamated fine- to medium-grained sand (Fig. 7d). This is topped by a thin, coarse-grained, pebbly sand layer. At the Billund borehole a thick, 50 m succession of medium- to coarse-grained sand has been penetrated (Fig. 7e).

The change from a mud and fine-grained sand dominated succession to a more coarse-grained sand dominated section occurs where FA 2 is present, where the dip of clinoforms are over 7^0 and where distinct erosion is common at the base of the prograding unit. This evolution is interpreted to be associated with, a highstand progradation followed by progradation under falling sea level (Hansen & Rasmussen, 2008). Increased erosional power at the base of a delta slope is common during falling sea level and is described in the literature as the regressive surface of marine erosion (Dominguez & Wanless, 1991; Nummendal *et al*., 1993; Plint & Nummendal 2000). However, an alternative interpretation could be that the prograding delta reaches an elevated area, here the Ringkøbing-Fyn High, thus forcing tidal currents to erode deeper. Cored sections of the delta foresets are need, however, in order to clarify this problem. The present example shows that the thickest (ca. 50 m) and most coarse-grained sand (Fig. 7e) is found where these marine erosion surfaces are common and where it is overlain by FA 2.

The Bastrup delta complex

The Bastrup delta complex built out into the North Sea during the early Burdigalian, early Miocene time (Fig. 2; 14). The delta complex prograded into the North Sea on top of the Billund delta complex. The basin-floor topography was therefore smooth and the water depth was c. 60 m. Due to this physiographic setting, the Bastrup delta complex formed a huge sand-rich uniform delta complex (Fig. 11).

The Bastrup delta complex is illustrated on seismic data by two sections. The first is characterised by facies associations 2, 3 and 5 (Fig. 15). In the northern part of the section, at the Billund borehole, FA 2 is overlying FA 3 (Fig. 15). In the upper part of the Bastrup delta system, the clinoforms are commonly truncated by channels (FA 5). Going southwards a weak surface of erosion is seen (Fig. 15). South of this surface the whole section is characterised by FA 2.

The log pattern in the Billund borehole is characterised by relatively high log responses in the lower part. The log pattern is serrated here. Above 127 m a marked shift towards low gamma readings and a blocky log pattern is seen (Fig. 16). The lithology in the Billund borehole is dominated by sand (Fig. 16). In the lower part, c. 25 m of fine-grained sand is found while above the marked decrease in gamma log readings, at 127 m c. 20 m of coarse-grained sand dominates. In the Vandel Mark borehole the lower part is characterised by serrated but generally high gamma readings and is dominated by mud, according to borehole samples. The upper part, c. 25 m, consists of medium- to coarse-grained sand. The log pattern in the Almstok borehole occasionally shows a serrated log pattern, but is generally characterised by a blocky log signature from 157 m 134 m with low gamma log response. Above 134 m a generally low, but varying log pattern is seen (Fig. 16). In the Almstok borehole, a thicker c. 50 m thick medium-grained sand succession characterised the whole succession. However, intercalation of coarse-grained sand is common in the upper part. This example shows how the lithology changes from a bipartite delta succession at the Billund and Vandel Mark boreholes to a more homogenous succession of sand at Almstok, which is located south of the surface of marine erosion identified on seismic data and where FA 2 dominates (Figs 15 and 16).

The second example of the Bastrup delta complex shows a seismic section where facies associations 1, 2, 3, 4 and 5 are present (Fig. 17). In the northern area, the lower part is dominated by FA 1. This is succeeded by FA 4 and FA 5, the latter representing the top of the succession. Southward, a marked erosion surface resulted in a total change in facies pattern. Here FA 2 overlies the erosion surface and is upward succeeded by FA 4 and 5. The lithology here can only be revealed from the Stakroge borehole, which penetrates the section south of the erosion surface. The lower c. 10 m is composed of mud. Above the surface of marine erosion, 25 m of fine- to coarse-grained sand characterised by a general coarsening upward succession represents FA 2. This is followed by medium- to coarse-grained sand with some intercalation of fine-grained sand which represents FA 5. Although there is no comparison of lithology north and south of the surface of erosion because there is only one borehole, it is evident that thick and sand-rich deposits are found associated with this surface of erosion and steeply dipping clinoforms (FA 2).

DISCUSSION

The present study of the thick sand-rich packages in the Billund and Bastrup delta complexes revealed that they are always associated with deposition during falling sea level in areas with relatively deep water (60 – 100 m). The falling sea level resulted in deposition of clean sand as the falling ground water table hindered coal formation. Successful erosion of sediments also reduces preservation of fine-grained deposits and constant reworking promoted bedload transport in rivers with subsequent deposition of sand-rich systems at the delta mouths. The deep water in structural lows allowed deposition of thick sections of sand due to the high accommodation space (e.g. Martinsen, 2003), especially in the case of the Billund delta complex.

During a transgression, 5 to 20 m of sediments are commonly removed. From studies of outcrops of the Billund complex upper shoreface deposits are normally preserved (Rasmussen & Dybkjær, 2005) while the uppermost shoreface, beach and subariel dune deposits are reworked. In the Bastrup complex fluvial channel deposits with coal layers are abundantly preserved (Rasmussen *et al*., 2007). It is therefore assumed that c. 10 m (uppermost shoreface – subarial dunes deposits) was reworked during a transgression in the Miocene successions. Despite this, shoreline trajectory analysis has been shown to be useful in the study of the Miocene succession in Jylland (Hansen & Rasmussen, 2008). In other settings where transgressions are stronger and removed most of the shoreface deposits, i.e. 20 m or in deeply buried delta systems, e.g. Jurassic successions in the North Sea, this method must be strongly invalidated. In these cases, the high preservation of the marine erosional surfaces revealed from this study, accompanied by the geometry of the clinoforms may in contrast to shoreline trajectory analysis be applicable. Therefore the focus of this discussion will be on depositional processes responsible for the formation of these.

Sediment supply and distribution

At the Oligocene – Miocene boundary major inversion of former graben structures within the North Sea and adjacent areas occurred (Rasmussen 2004a; 2009). Apatite fission track data indicate initial uplift of present day Norway at the end of the Oligocene (Japsen *et al*., 2007). Heavy mineral studies of lower Miocene sediments show that present day Norway and western central Sweden formed the source area for the studied succession (Knudsen *et al*., 2005; Mette Olivarius, 2008). As a consequence of the increased relief in the hinterland and relatively high precipitation, c. 1100 – 1500 mm pr. year braided river systems evolved. These were funnelled through valleys along southern Norway and central Sweden southward into the North Sea and formed a major delta-coastal plain south of present day Norway. Palaeoflow data in the study area indicate a dominant flow towards the south and south-west (Hansen, 1995), which is consistent with a possible transport path. Fluvial channel deposits are dominated by medium- to coarse-grained sand, but grain sizes of up to 5 cm are found in the basal part of fluvial channels and in transgressive lag deposits. Thicknesses of stacked sand-rich, fluvial channel deposits of up to 50 m occur commonly. In such a coarse-grained system bed load transport was the dominant transport mechanism (Miall, 1996). The fluvial channel complexes that are dominated by sand and gravel, are on the order of 20 km wide and can be traced for 100 km, but might have been even longer, perhaps up to c. 500 km, the distance from the study area to the source area. The latter is, however, obscured by late Neogene tilting and glacial erosion. Mud dominated flood plain deposits are found between the fluvial channel complexes and dominate the depositional system for 100´s of km^2. The development of the lower Miocene sequences in Denmark is strongly controlled by eustatic sea-level changes (Rasmussen, 2004a). The sediment supply to the shoreline is therefore punctuated and may be extremely high during falling sea level due to constant reworking. Climatically caused floods on a time-scale of ?100 years may also have resulted in peaks in sediment supply to the delta mouth.

During the early Miocene, the North Sea was an elongated east – west trending sea (Rasmussen *et al.* 2008). As the sea was located in the northern westerly wind belt, the long fetch promoted a dominance of wave processes. Much of the sediments were presumably laid down in front of the deltas as mouth bars (Wright, 1977) but later reworked, mainly during winter times, to form spit complexes and barrier islands in the down-current deriction (Bhattachaya & Giosan, 2003). Major storms may also have triggered gravity flows at the delta front (see below).

Physiography

The two delta complexes studied here were deposited under different physiographic conditions. The Billund complex was deposited on top of a topographically irregular surface that was formed during the early Miocene inversion. Therefore a strong structural control on the distribution of delta lobes and spite systems characterises the Billund complex (Rasmussen & Dybkjær, 2005; Hansen & Rasmussen, 2008). Consequently, thick sand-rich sediment bodies are quite local in distribution, but may be up to 100 m in thickness. The Bastrup delta complex prograded into the North Sea through the same pathways as the Billund system, but the basin floor was smooth due to the early fill of the Billund complex. This resulted in a more regular distribution of sand-rich delta lobes. The thicknesses of sand-rich delta deposits for the Bastrup complex are rarely over 50 m thick, but the extension is much larger than the Billund complex.

Climate

During the Miocene, climatic changes are well documented (Mai, 1967; Lotsch, 1968; Miller *et al*., 1998, 1995; Zachos *et al*., 2001; Utescher *et al*., 2000; Larsson *et al*., 2006). Build up of icecaps in the Antartic during the early Miocene resulting in global sea-level changes that are well documented in the literature (Prentice & Matthew, 1988; Miller *et al*. 1998; Zachos *et al*., 2001). The development of marine erosion in both the Billund and Bastrup complexes always occurred in the late stage of progradation and capped by a sharp often erosive surface (Figs 12; 15; 17). For the Billund delta complex a descending shoreline trajectory has been mapped (see, Hansen & Rasmussen 2008). This clearly indicates that these large packages of sand were developed in association with progradation during climatic deterioration.

Clinoform geometry

The formation of clinoforms is far from fully understood. Deltas with similar seismic images are known from the Gulf of Mexico and interpreted to be formed in a high energy environment (McKeown et al. 2004). Hansen and Rasmussen (2008) discuss the formation of the sand-rich clinoforms of the Billund complex. Here two possible scenarios were outlined. First is the deposition of high concentrated bed load transported sediments on the delta front as gravity flow deposits and the second is that the high concentration of sand was due to active currents running along the whole slope of the delta front (Uličný, 2001). There are no outcrops showing details of the clinoforms in the Miocene of Denmark and the succession has not been penetrated by cored boreholes. Therefore the development of clinoforms cannot be revealed from this study. It can, however, be stated that the dip of the clinoforms of 7–10^{o} is typical for mixed gravel–sand systems (Fig. 7e; Orton & Reading 1993). Low frequency of intercalated mud layers, which characterise the delta complexes here, resulted in more stable slopes. This is in line with the general absence of turbidites in front of the delta slope. Progradation into deep water, e.g. 100 m, also promotes the formation of delta slopes with a high gradient (Orton & Reading 1993). Furthermore, the short pinch out distance recognised on the mapped deltas is characteristic for wave-dominated systems (Løseth & Helland-Hansen, 2001), which again is due to grain size and effective sorting in a wave-dominated environment.

In the Billund and Bastrup deltas, sand-rich successions are always found in association with dipping clinoforms. Where clinoforms dip 7 – 10^0 the succession is composed of medium- to coarse-grained sand and with very few intercalation of mud layers. Consequently, the grain size is very important for the formation of sand-rich packages characterised by clinoforms. The basic facies in prograding clinoform strata along a shelf margin at Svalbard are turbidites (Johannnessen & Steel, 2005). A substantial part of this system is mud, however, and the dip of the clinoforms is only 2 – 4^0, which is lower than the clinoforms found in this study. Relatively thick, c. 35 m of delta front sand and gravel has been described in the Pliocene Loreto basin, Baja California Sur, Mexico (Falk & Dorsey, 1998). The dip of these delta foresets is high, c. 25^0 and thus substantially higher than that of the Billund and Bastrup deltas. The depositional processes on the slope are interpreted as being dominated by cohesionless debris flows and high density turbidity flows. Shelf clinoforms seaward of rivers with high sediment discharge in a wave-dominated environment and wave driven resuspension can initiate gravity flows that flow down the clinoform foreset. The resuspension may further resort the sediment and winnow away the fine-grained sediments resulting in a concentration of coarse-grained gravity flows that dominate the clinoform sets. If gravity flows are the dominant process in deposition of the clinoform sets of the Billund and Bastrup delta complexes, deposition must have occurred from rapid settling of unconfined turbidite currents due to high friction at the base of the turbidity flows (Steel *et al*. 2001), because sand-rich bottom sets are very rare. This excludes a fluvial dominated system because such a system will tend to discharge sediments from a fixed point which will result in formation of funnels or channels that will promote an acceleration of gravity flows down the slope (Steel *et al*., 2001) and deposition of basin floor fans. According to Carvajal and Steel (in press) offshore flows towards the slope during storms had an insignificant capability to channel the slope and consequently downslope sand delivery is unconfined flows that easily loose momentum. Plink-Björklund and Steel (2002) also argued that high rates of sediment fallout at the slope can hinder incision. The development of the delta complexes occurred after the Savian inversion tectonism and a high sediment supply is inferred (Rasmussen 2009). The rate of progradation was more than 50 km/Ma. A similar rate of progradation has also been found by Carvajal and Steel (in press) and interpreted to indicate high sediment influx. Therefore, a wave-dominated high energy environment characterised by a high sediment supply is the most likely depositional setting if the clinoform sets are formed by gravity flows. Sand-rich delta complexes that are characterised by clinoform sets are also found in the Cretaceous of Bohemian (Uličný, 2001). Here sand-rich clinoform sets are up to 50 – 80 m thick and dip 10 – 30^o and are thus very comparable to the deltas studied here The foresets in the Cretaceous Bohemian deltas is built up of 3 and 2D dunes indicating deposition from a current running along the slope of the delta clinoform (Uličný, 2001). The current is interpreted to have a tidal origin. In the Miocene North Sea there are many indications of tidal regime (Friis *et al*., 1998; Schäfer *et al*. 1996; Rasmussen & Dykjær, 2005). Tidal currents acting at water depths of 100 m has been described by Hart and Long (1996) for holocene deltas in Canada. Consequently, it cannot not be ruled out that a similar depositional process was responsible for the development of erosional features of the Billund and Bastrup delta complexes.

Summary and conclusions

During the early Miocene, two delta complexes, the Billund and Bastrup, prograded into the North Sea Basin from the north. The development of both delta complexes was strongly controlled by eustatic sea-level changes. Due to inversion tectonism predating the deposition of the delta complexes a very high sediment influx occurred into the basin. The lower delta complex, the Billund complex, was further controlled by the antecedent topography formed during the inversion phase.

Based on seismic data, the use of shoreline trajectories in the study of delta evolution and prediction of sand-rich packages has successfully been used. However, good reservoir sands in the basinal setting are also found by other criteria .

- A seismic facies pattern of oblique parallel clinoformal reflection pattern characterised by a dip of 7 – 10^0 was found to indicate the presence of medium- to coarse-grained sand.

- The development of marine erosion surfaces characterised by downlap of the oblique parallel clinoformal seismic reflection pattern also indicates the presence of good reservoir sands.

- The thickest reservoir sands are found in the Billund delta complex where progradation occurred into depressions/lows formed in association with inversion tectonism, but these may be of local extent.

- Uniform and widespread sands chracterised the Bastrup delta complex due to smoothing of the basin floor after the deposition of the Billund delta complex. But the best reservoir sand in the fringe area of the delta complex is still found to be associated with marine erosion surfaces and where an oblique clinoformal reflection pattern dominates.

- The above criteria benefit from having a high preservation potential compared to shoreline trajectory analysis as the shoreline is exposed to erosion during both regressions and transgressions.

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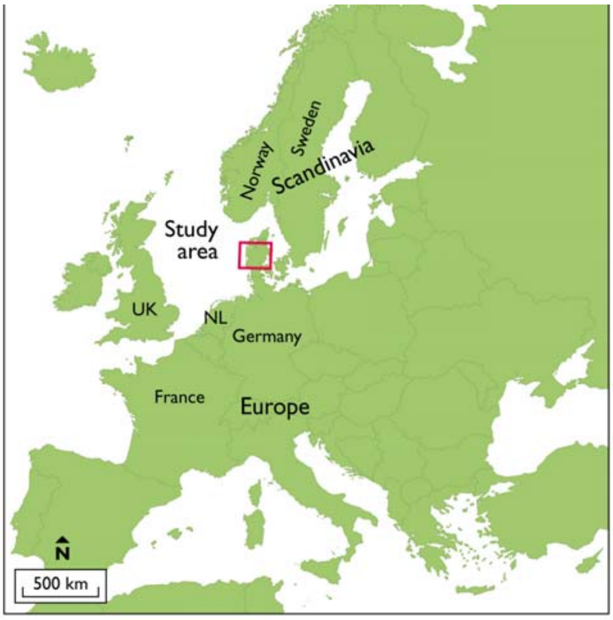

Fig. 1: Study area

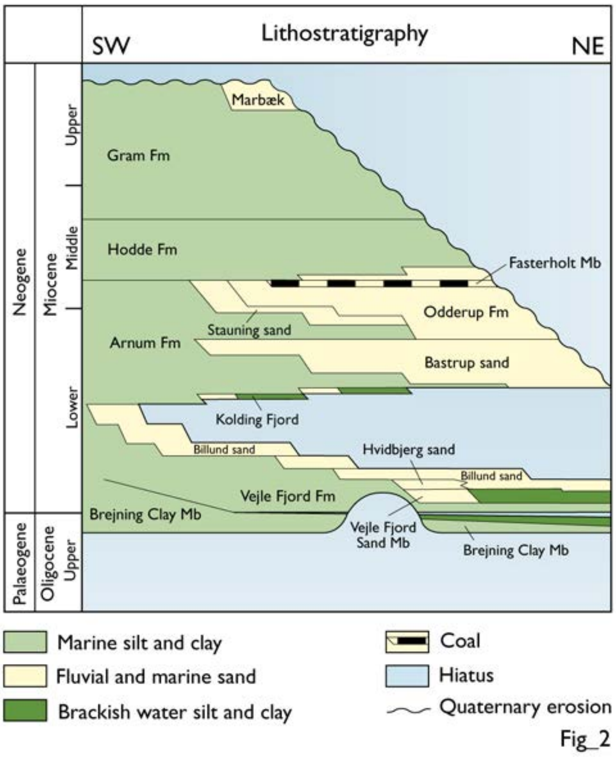

Fig. 2: Lithostratigraphy of the Miocene of Denmark (modified from Rasmussen 2004b)

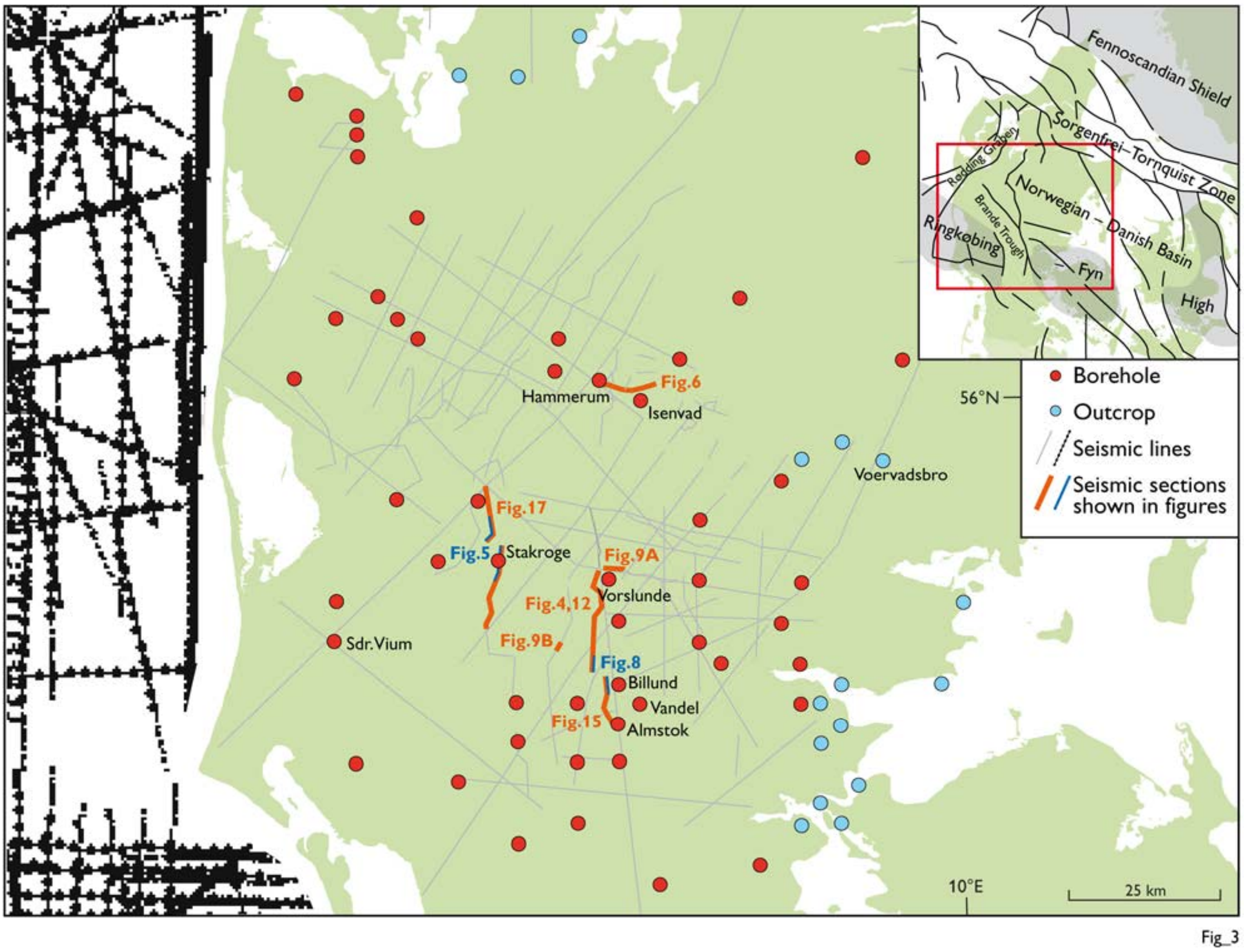

Fig. 3: Map showing Sesimic data, boreholes and outcrops. Main structural elements are shown on the inserted map.

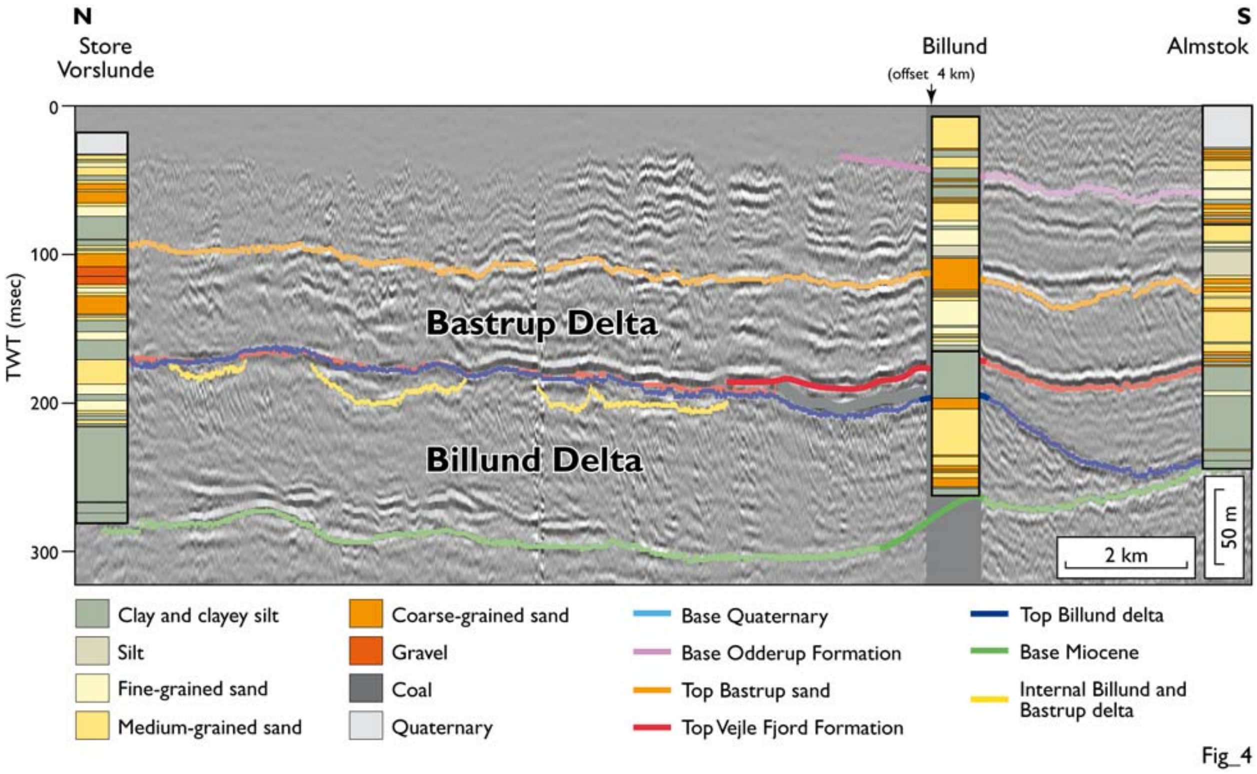

Fig. 4: North – south section of the Miocene succession in Jylland and lithology of boreholes penetrating the succession at the seismic section. For location, see figure 3. Seismic courtesy COWI A/S and MC Ribe.

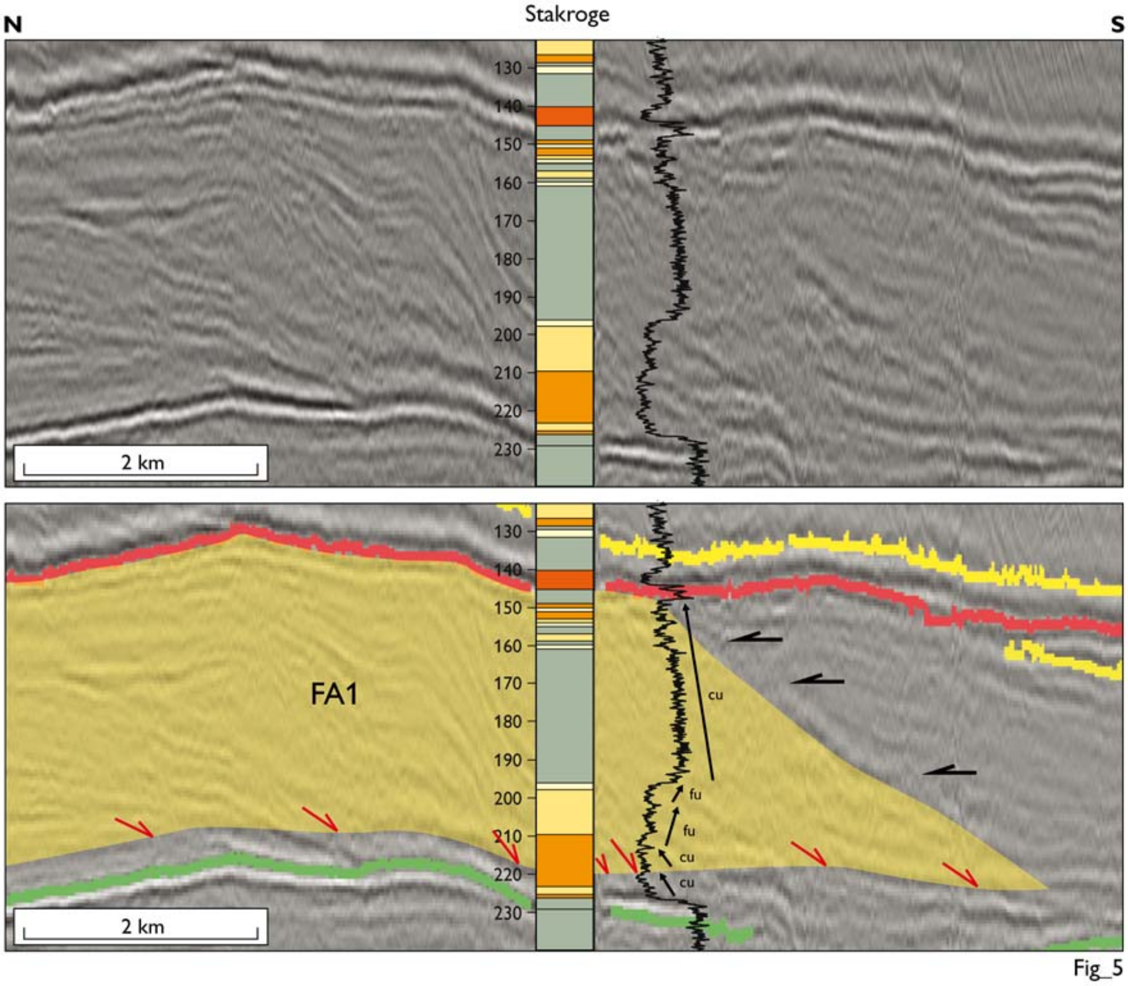

Fig. 5: Seismic FA 1 showing the typical seismic image, lithology and gamma log response. Note the alternation of sigmoidal and oblique-parallel seismic reflection pattern. At this location, the toe of a package dominated by oblique-parallel reflection pattern has been penetrated as indicated by the sand-rich lower part. Downlaps are indicated by red arrows. Note also the onlap of marine succession south of the Stakroge borehole. For location, see figure 3. Legend is shown in figure 4. Abbreviations: CU–coarsening upward, FU–fining upward. Seismic courtesy Rambøll A/S and MC Ringkøbing.

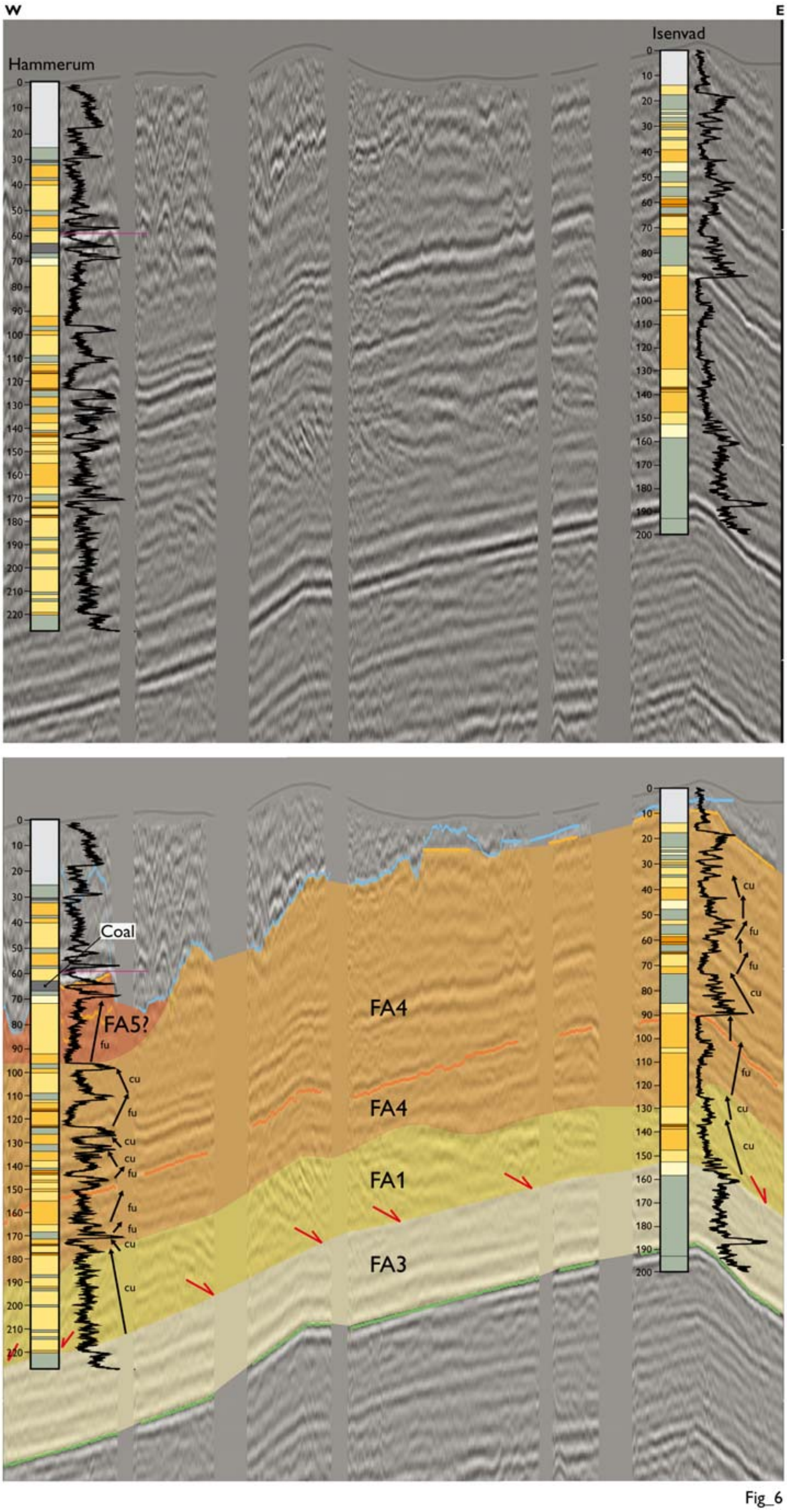

Fig. 6: Seismic FA1, FA 3 and FA4 showing the typical seismic image, lithology and gamma log response. Note the high amplitude, parallel reflection pattern near the Hammerum borehole within the Bastrup delta complex which correlates with a sand-rich package. Eastwards, towards the Isenvad borehole, this facies changes into a more low amplitude, parallel reflection pattern which correlated with a muddy succession at the Isenvad borehole. Downlaps are indicated by red arrows. For location, see figure 3. Legend is shown in

figure 4. Abbreviations: CU–coarsening upward, FU–fining upward. Seismic courtesy Rambøll A/S and MC Ringkøbing.

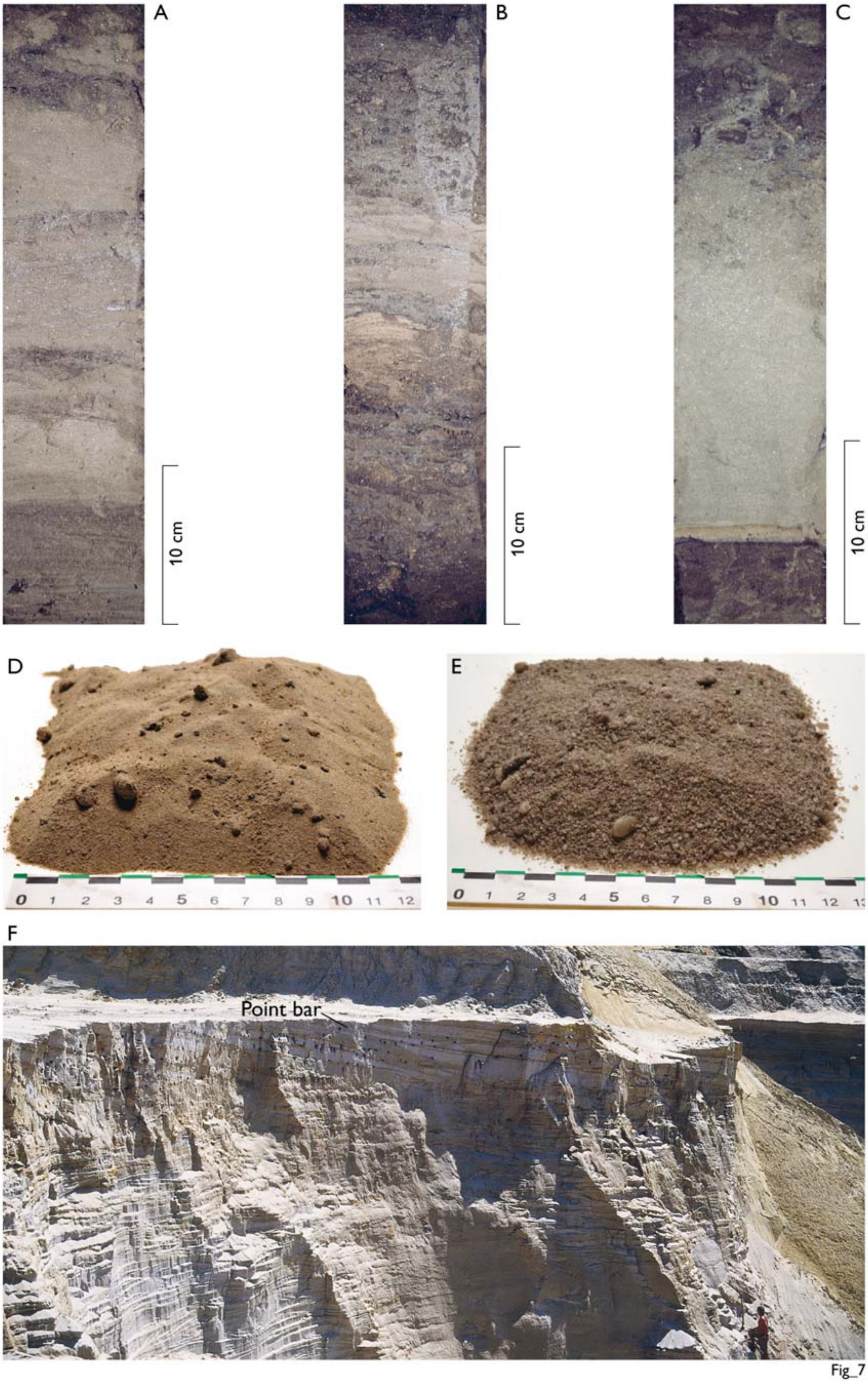

Fig. 7: Cores, borehole samples and the Voervadsbro outcrop. A, B and C are from the cored borehole Sdr. Vium. A and B represent alternating sand and mud from facies FA2. C

illustrates a thin turbidite from FA3. D is a borehole sample of fine- to medium-grained sand of FA1 from the Vorslunde borehole. E is a borehole sample of pebbly, medium- to coarse-grained sand of FA2 from the Billund Borehole. F shows coarse-grained sediments from the dominantly braided river system. Note the inclined bedding in the upper part of the section which is interpreted as lateral accretion of a point bar deposited in meandering river system. The scale is indicated by the person in the lower right corner.

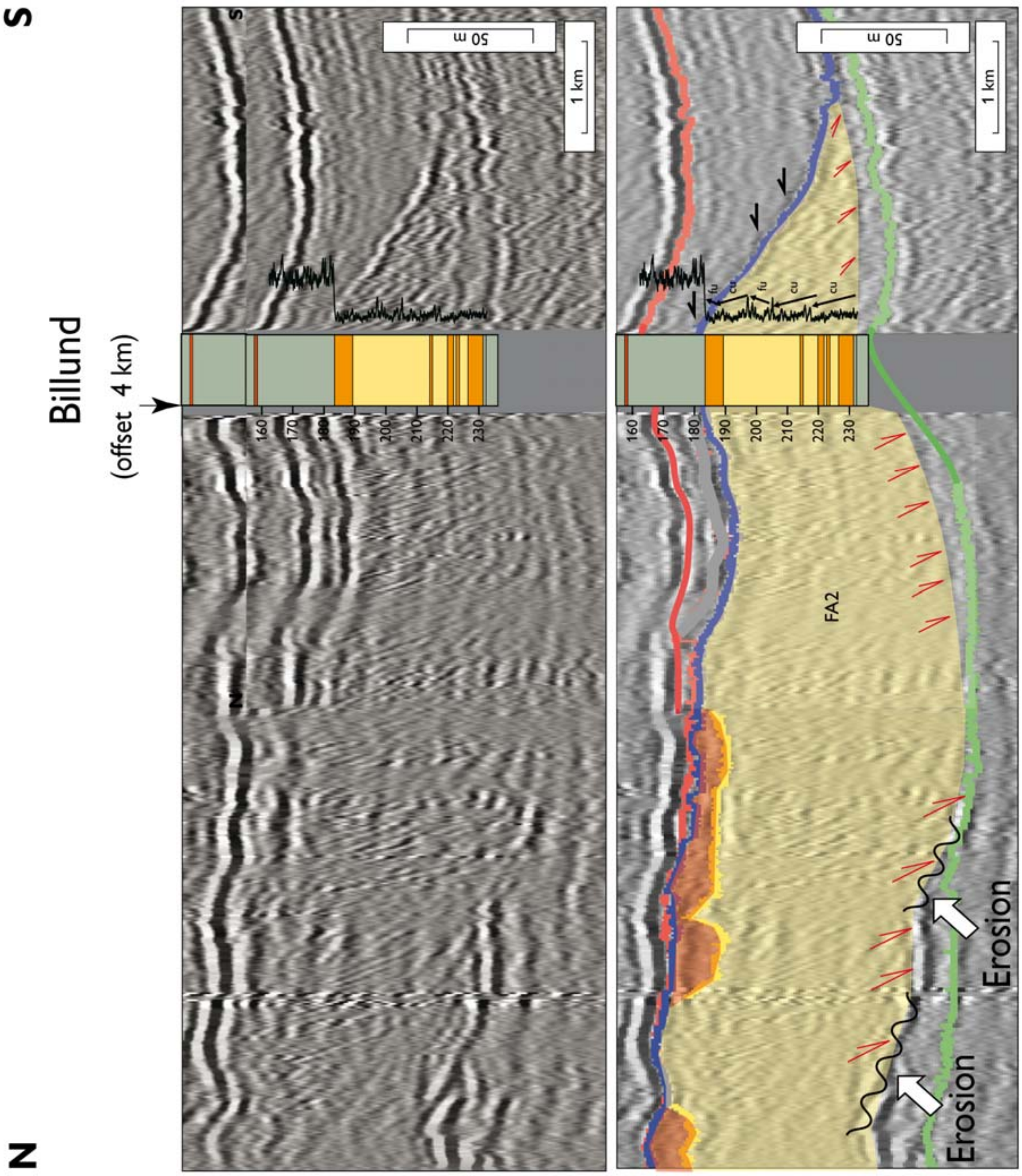

Fig. 8: Seismic FA 2 showing the typical seismic image, lithology and gamma log response. Note that the entire penetrated succession of oblique-parallel reflection pattern correlates with a sand-rich package. Downlaps are indicated by red arrows. Note also the onlap of the marine succession south of the Billund borehole. For location, see figure 3. Legend is shown in figure 4. Abbreviations: CU–coarsening upward, FU–fining upward. Seismic courtesy COWI A/S and MC Ribe.

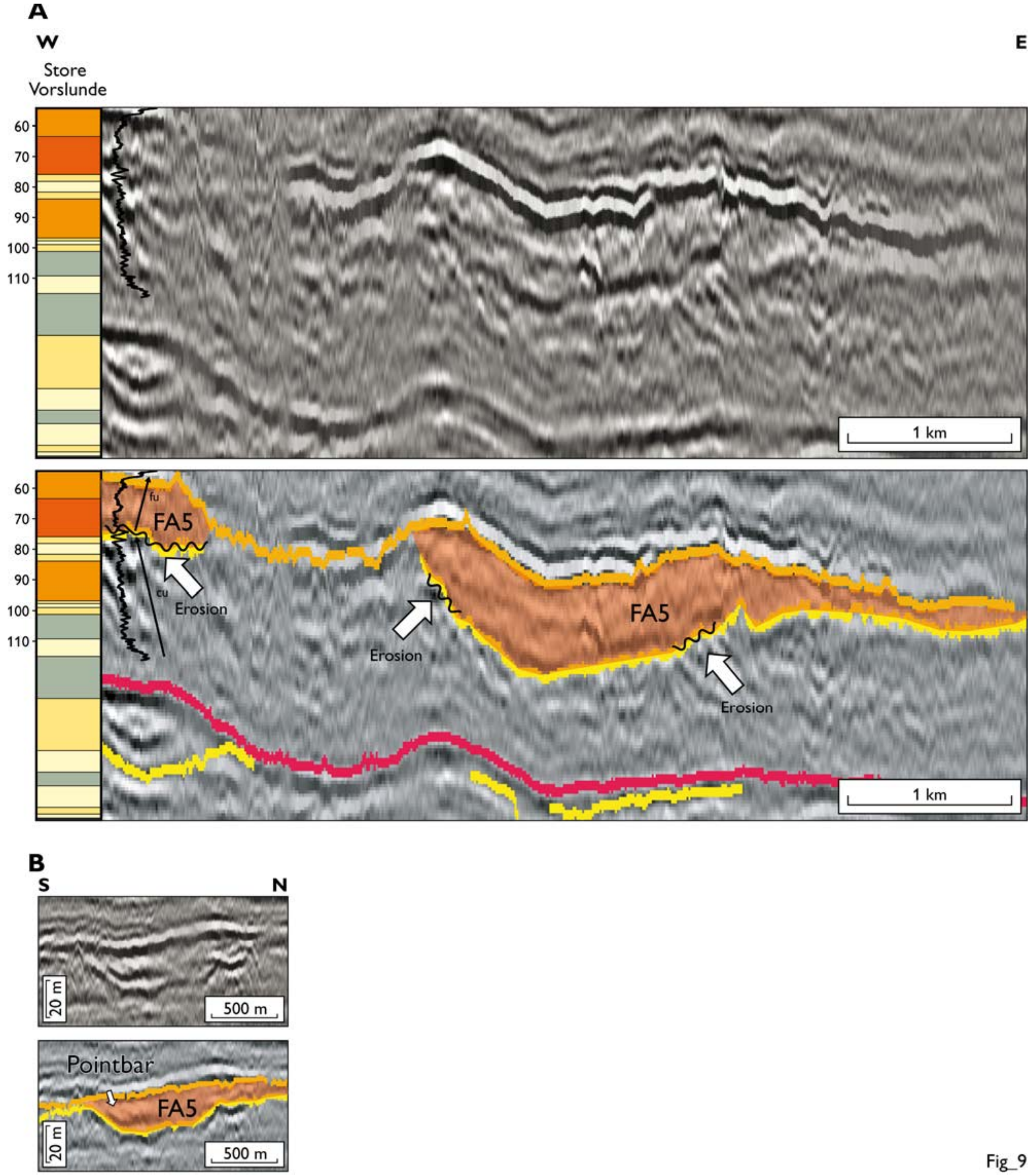

Fig. 9: Seismic FA 5 showing the typical seismic image, lithology and gamma log response. A) incised valleys at and east of the Vorslunde Borehole. B) Fluvial channel showing lateral accretion (shingled seismic reflection pattern) associated with point bar migration. For location see figure 3. Abbreviations: CU–coarsening upward, FU–fining upward. Seismic courtesy COWI A/S and MC Ribe.

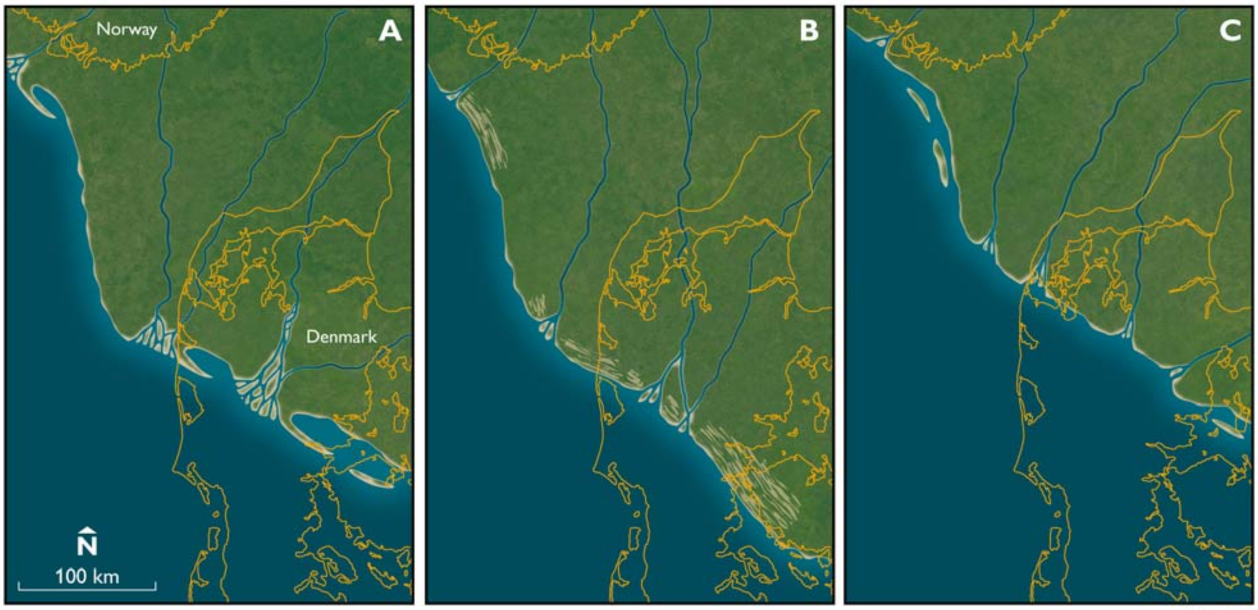

Fig. 10: Palaeogeography of Billund delta complex: A) highstand systems tract, B) forced regressive wedge systems tract and C) transgressive systems tract.

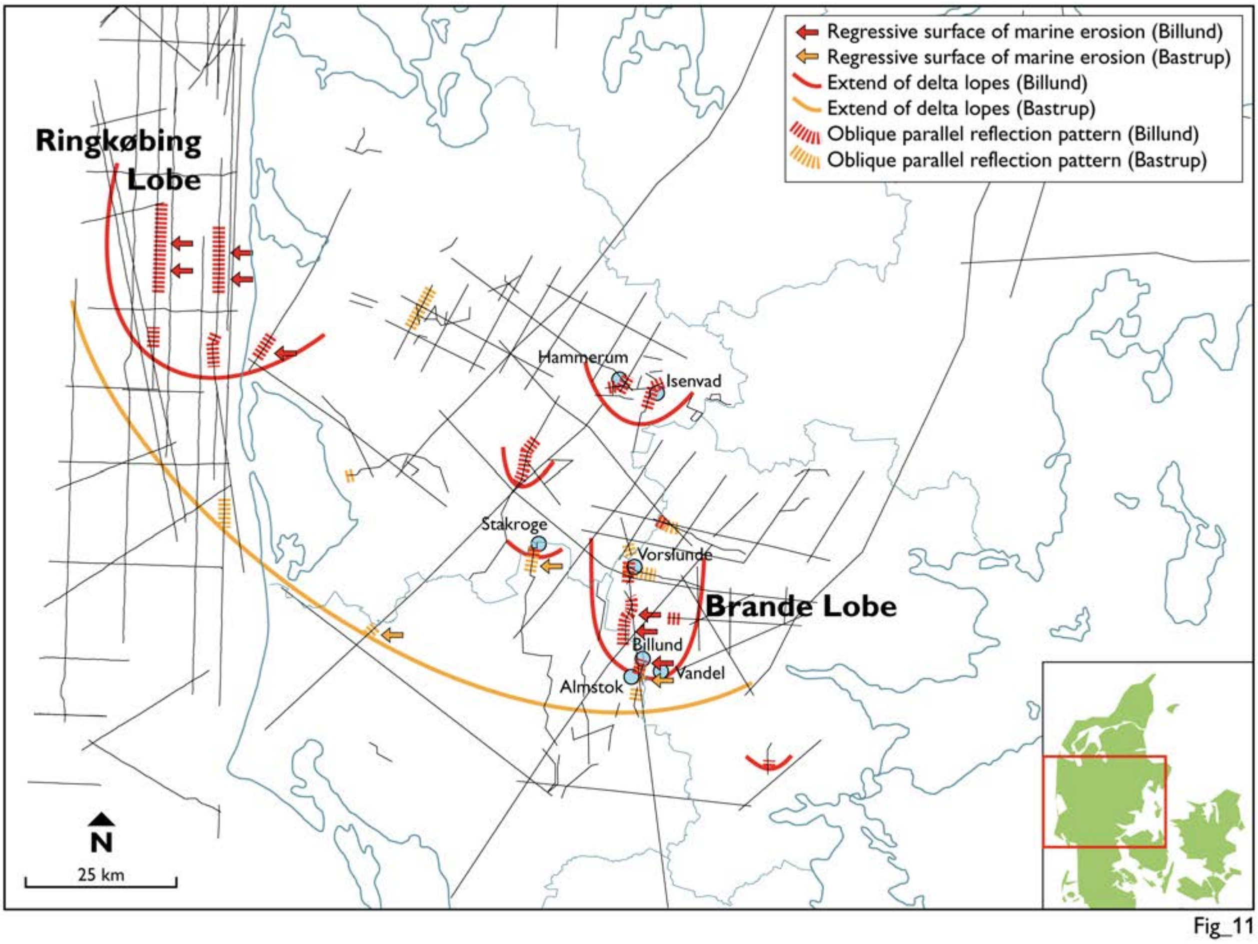

Fig. 11: Facies map showing the distribution of FA 2 and marine surfaces of erosion for both the Billlund and Bastrup delta complexes.

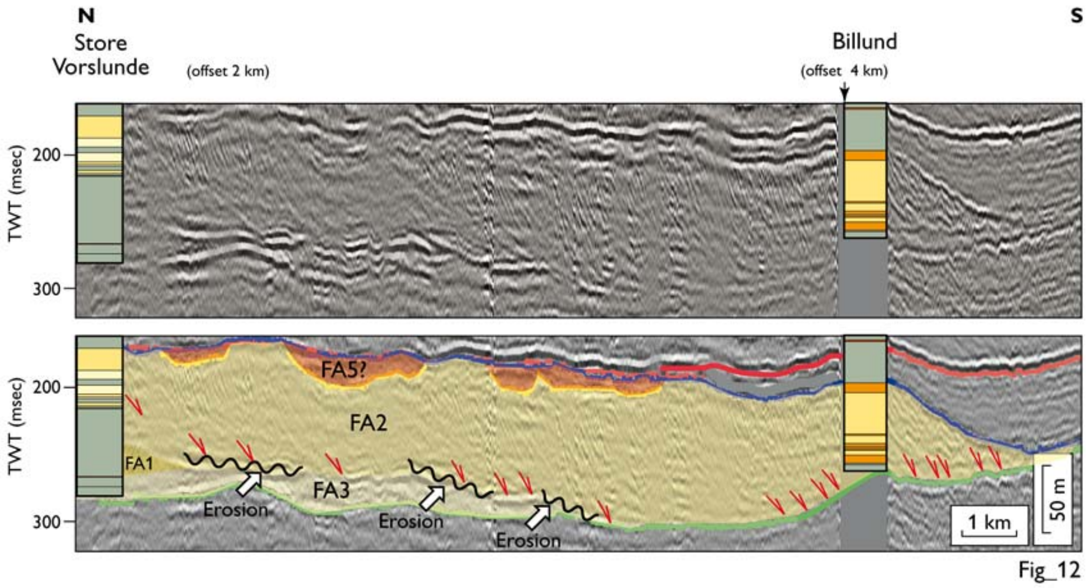

Fig. 12: Seismic section of the Billund complex. Note the distinct erosion (arrows) south of the Vorslunde borehole and the marked change in lithology between the two boreholes. Downlaps are indicated by red arrows. For location, see figure 3. Legend is shown in figure 4. Seismic courtesy COWI A/S and MC Ribe.

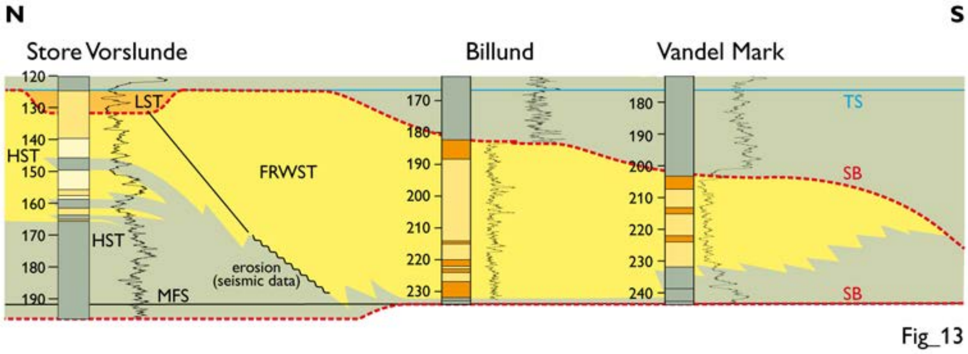

Fig. 13: Log pattern and lithology of the Billund delta complex of three boreholes in the Billund area. Note that the most coarse-grained and thickest sand is found south of the erosional surfaces seen on seismic data and within the forced regressive wedge systems tract. Abbreviations: SB–sequence boundary, MFS–maximum flooding surface, HST–highstand systems tract, FRWST–Forced regressive wedge systems tract, LST–lowstand systems tract, TS–transgressive surface.

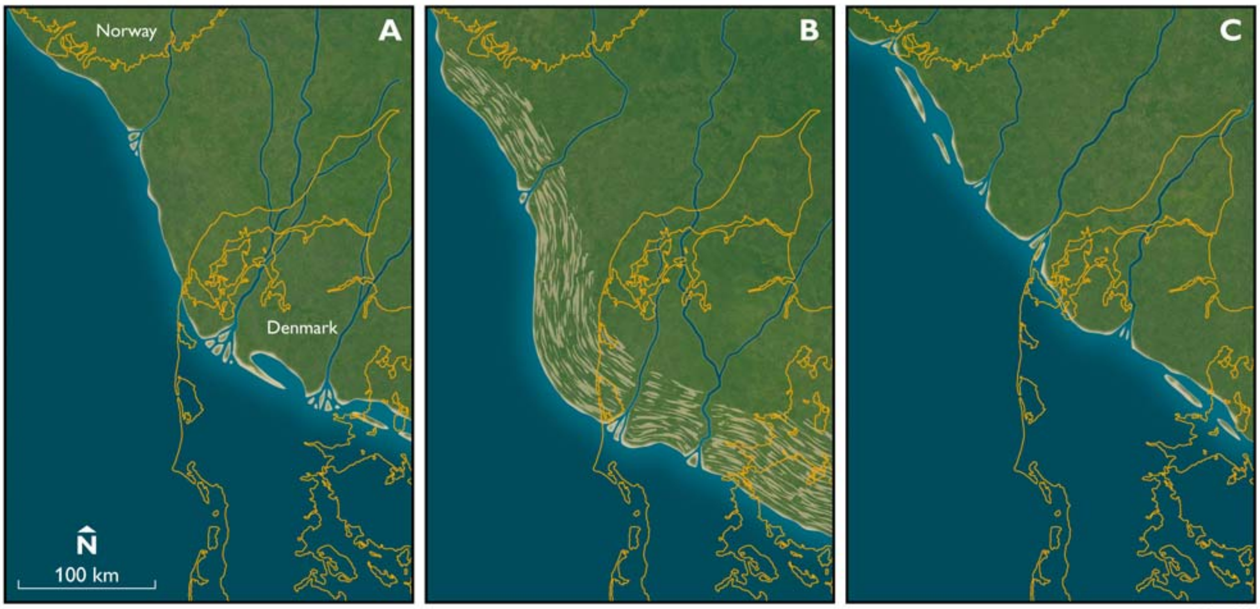

Fig. 14: Palaeogeography of Bastrup delta complex: A) highstand systems tract, B) forced regressive wedge systems tract and C) transgressive systems tract.

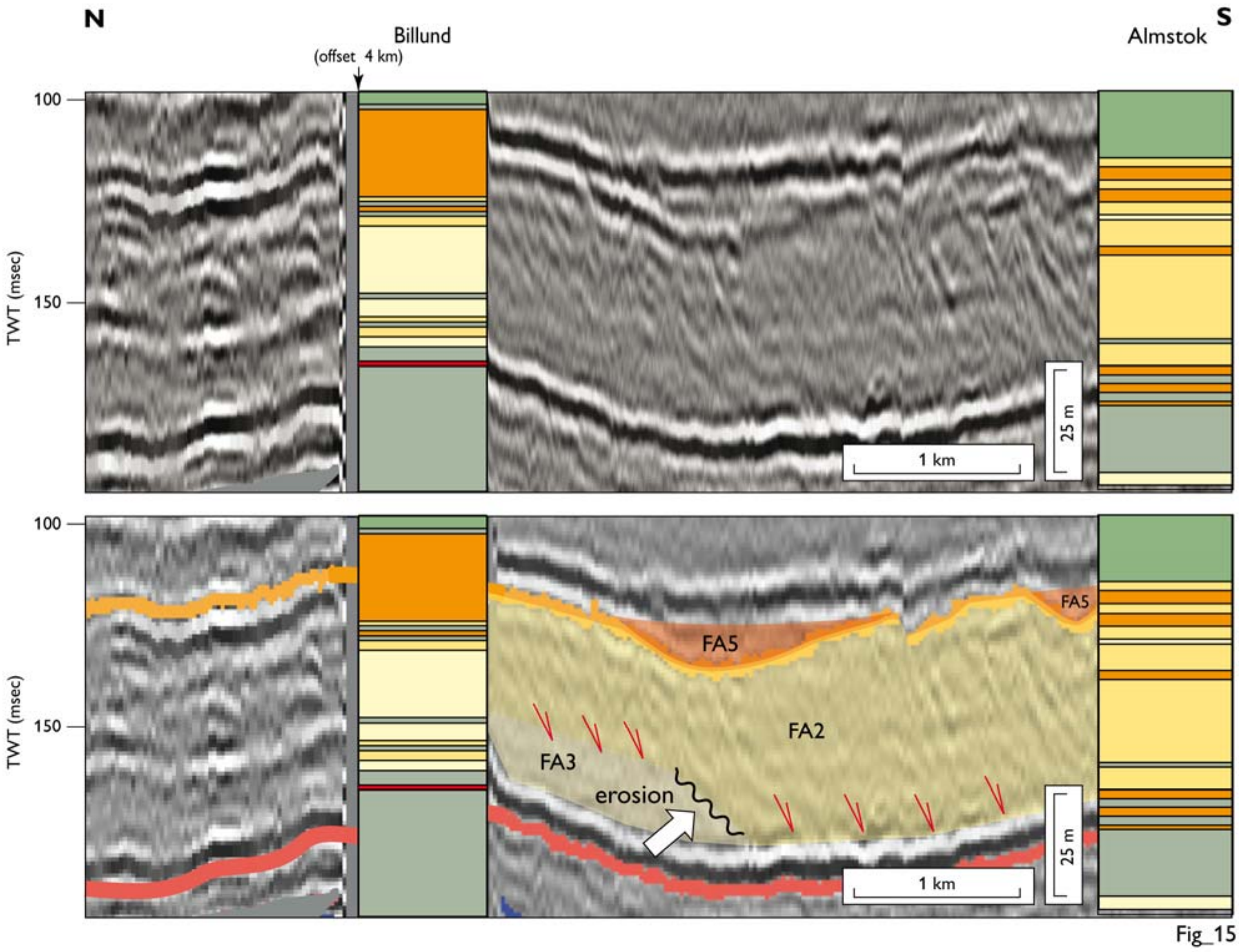

Fig. 15: Seismic section of the Bastrup delta complex. Note the erosion (arrow) between the Billund and Almstok boreholes. Downlaps are indicated by red arrows. For location, see figure 3. Legend is shown in figure 4. Seismic courtesy COWI A/S and MC Ribe.

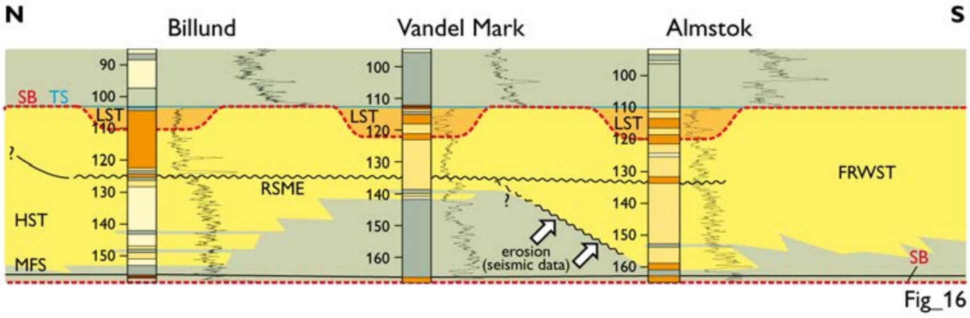

Fig. 16: Log pattern and lithology of the Bastrup delta complex of three boreholes in the Billund area. Note that the most coarse-grained and thickest sand is found south of the erosional surfaces seen on seismic data and within the forced regressive wedge systems tract. Abbreviations: SB–sequence boundary, MFS–maximum flooding surface, HST–highstand systems tract, FRWST–Forced regressive wedge systems tract, LST–lowstand systems tract, TS–transgressive surface, RSME–regressive surface of marine erosion.

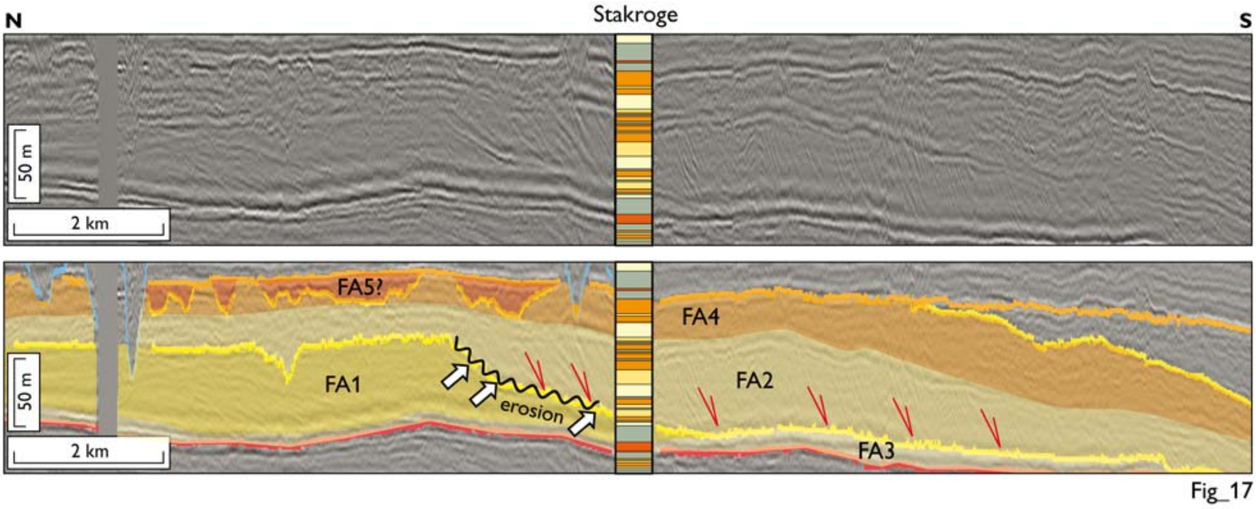

Fig. 17: Seismic section of the Bastrup delta complex. Note the distinct erosion just north of the Stakroge borehole which is characterised by a thick sand-rich package in the interval dominated by a oblique parallel and horisontal, parallel reflection pattern. Downlaps are indicated by red arrows. For location see figure 3. Legend is shown in figure 4. Seismic courtesy Rambøll A/S and MC Ribe.