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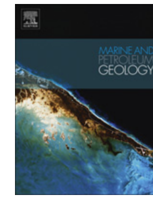

Oligocene climate changes controlling forced regression in the eastern North Sea

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ABSTRACT

In this paper we investigate the Early Oligocene (Rupelian) high-angle clinoform complex from the western part of the Norwegian–Danish Basin. The study consists of an integrated analysis of 3D seismics, petrophysical well logs and micropaleontological data.

A series of erosional features and geometry of prograding units, e.g. the high-angle clinoform complex, interpreted as a forced regressive unit, is identified. The proposed depositional model accounts for lithological variations, climate-induced sea-level fluctuation and depositional environment. The characteristic high-angle clinoform complex has been estimated to be of Late Rupelian age. Paleoenvironmental reconstruction of the unit (based on dinocyst analysis) suggests that the deposition of the succession took place in submarine conditions. Presence of a cold-water dinoflagellate *Svalbardella* within the unit containing high-angle clinoforms suggests that the unit was deposited during one of the Oligocene glacial maxima (the most probably the Oi2 cooling event).

1. Introduction

Factors controlling the Cenozoic infill of the North Sea Basin were in focus of numerous sequence stratigraphic studies since the early nineteen eighties. There is an ongoing discussion on the relative importance of climate and tectonism on sediment production of Oligocene succession in the North Sea Basin (Nielsen et al., 1986; Jordt et al., 1995; Clausen, 1998; Clausen et al., 1999; Huuse, 2002; Rasmussen, 2009; Śliwińska et al., 2010; Gołędowski et al., in press). It has been suggested that the climate might have played a major role in the Oligocene sedimentation patterns in the North Sea Basin (Nielsen et al., 2009; Śliwińska, 2011). The greenhouse–icehouse transition at the Eocene/Oligocene boundary the depositional system in the eastern North Sea Basin changed significantly and the climate-induced changes in relative sea-level influenced the architecture of the Oligocene succession (e.g. Huuse, 2002; Śliwińska et al., 2010).

The Paleocene–Eocene succession in Eastern North Sea has been investigated in detail since it is a reservoir for the only Danish commercial hydrocarbon play outside the hydrocarbon-prone Central Graben (Fig. 1). The hydrocarbons have been sourced from the Central Graben and migrated laterally up to 70 km before they were trapped in a reservoir of Late Paleocene–Eocene glauconitic silty-sandy turbidites of the Siri Fairway (Hamberg et al., 2005; Ohm et al., 2006). A Late Oligocene mound consisting of turbidites and reworked turbidites located basinward of the major Oligocene clinoforms (the Freja Mb.) was penetrated in the Fransisca-1 well (Schiøler et al., 2007) but so far no commercial HC plays have been discovered in the post-Eocene succession.

In the western Norwegian–Danish Basin a complex of high-angle clinoforms dipping up to 5° toward the southwest has been identified on seismic data. This depositional body and associated erosional features give a unique possibility to study mechanisms generating high-angle clinoforms in an area normally dominated by shallow-dipping clinoforms. It also allows enquiring how are the individual clinoforms related and how the sediments were transported.

The objectives of this study are thus

- to analyze the internal geometry of a complex of high-angle clinoforms and the local erosion associated with the generation of the clinoforms
- to discuss the factors controlling the generation of the high-angle clinoform complex during infilling of an intra-cratonic basin
- to elucidate the paleoenvironment during deposition of the Oligocene in the North Sea

1.1. Geological setting

The high-angle clinoform complex is located in the western part of the Norwegian–Danish Basin at the northern flank of the

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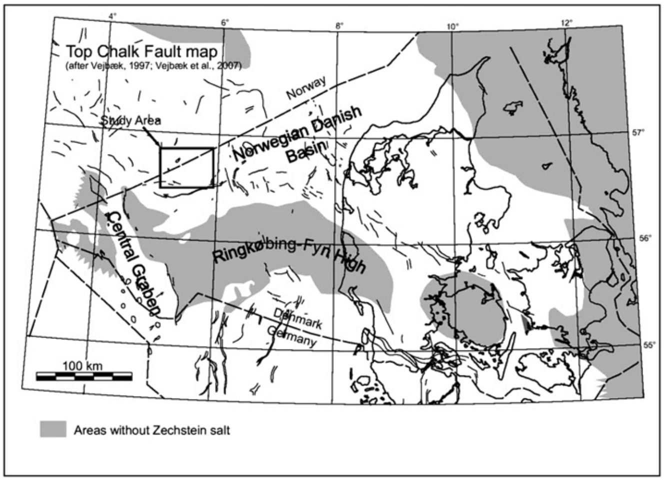

Figure 1. Map of the Danish sector covering part of the eastern North Sea Basin. The location of major structural elements is indicated as well as the extent of the potential mobile Zechstein salt. The Norwegian–Danish Basin and the Ringkøbing-Fyn High are structural elements in the intra-cratonic North Sea Basin. The faults indicated cut the Top Chalk Group (affecting the Cenozoic succession) and are generated due to a combination of minor basement-related faulting (e.g. in the Central Graben area) and salt-related faults, following the pinch-out line of the Zechstein salt (Clausen and Huuse, 1999). The study area is located in the eastern part of the Norwegian–Danish Basin.

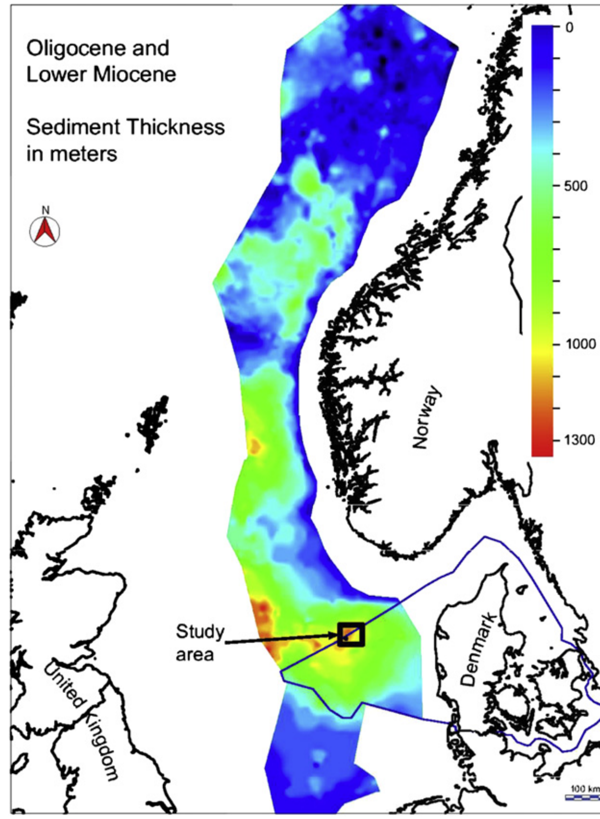

Figure 2. The regional distribution of Oligocene and Lower Miocene sediments. Note that the study area is located within a significant depositional maximum characterized by WSW-ward prograding major clinoforms (Michelsen et al., 1995, 1998).

Ringkøbing-Fyn High (Fig. 1). Over the last 65 Myr the regional subsidence of the North Sea Basin was centered in the Central Graben area, west of the high-angle clinoforms complex. The subsidence was a post-rift thermal subsidence located above the Late Jurassic Central Graben. There are no indications of Cenozoic basement faulting (Coward et al., 2003). However, the Norwegian–Danish Basin is characterized by the presence of Zechstein evaporites generating a large number of salt structures (pillows, walls and diapirs), which has deformed the Cenozoic succession. Furthermore, a major Cenozoic salt-related fault complex, striking E–W, is located just south of the high-angle clinoforms complex (Petersen et al., 1992; Sørensen, 1998).

The Cenozoic siliciclastic sediments in the Central Graben area are up to 3000 m thick and are characterized by a generally upward-coarsening trend (Huuse et al., 2001; Kristoffersen and Bang, 1982; Schiøler et al., 2007). The western part of the Norwegian–Danish Basin is characterized by an Oligocene depocenter (Fig. 2), dominated by SW-ward prograding siliciclastic units, which are unconformably overlying the Eocene hemipelagic deposits (Michelsen et al., 1995, 1998; Schiøler et al., 2007) and reach over 1000 m of thickness. Michelsen and Danielsen (1996) and Danielsen et al. (1997) showed that the Oligocene sediments originated from the north east, and that the depocenters of the individual sequences migrated westwards, parallel to the pinch-out line of the Zechstein salt and onto the northern flank of the Paleozoic Ringkøbing-Fyn High.

The Oligocene succession in the eastern North Sea belongs to the Lark Fm., which is subdivided into 4 subunits (L1–L4) (Schiøler et al., 2007). The Lark Fm. is dominated by mudstones comprising sandstone stringers and discrete sandstone units in the eastern parts of the Danish area (Schiøler et al., 2007). The older sandstone unit is defined as the Dufa Mb., which is characterized as a deltaic shallow-marine sediment. The younger unit, the Freja Mb., is interpreted as stacked turbidites, partly reworked by submarine currents. The lateral extent of the two sand units (Schiøler et al., 2007), with respect to the clinoforms analyzed here, is shown in Fig. 3.

1.2. Data used

During the exploration for hydrocarbons in Paleocene and Eocene sediments east of the Danish Central Graben, a number of 3D seismic data has been acquired. These data are now available for analysis in the public domain. The study area is covered by the NODAB 3D survey (bin distance: 12.5 m, area covered 323 km^2). The vertical seismic resolution in the investigated interval in the area is approximately 10 m (Andresen et al., 2008). The petrophysical well logs from the Nini-1 well are used for detailed lithology interpretation. The seismic and well log interpretations are carried out using the Kingdom Suite® software (courtesy of Seismic Micro-Technology, Inc.). Palynological studies from the Nini-1 well are used for the dating and paleoenvironmental reconstructions. The sample preparation technique is described in Śliwińska et al. (2010). For dating, at least 200 dinocysts specimens were counted in each sample. In another slide from the same sample, at least 300 dinocysts were counted for environmental analysis. Counted dinocysts were referred to one of the groups shown in Table 1, as well as the dinocyst distribution within the investigated interval. We have used the taxonomic nomenclature of Williams et al. (2004). In the text we refer to the timescale of Luterbacher et al. (2004) and the cooling events of Miller et al. (1998).

2. Geometry and lithology of the observed high-angle clinoforms

The high-angle clinoforms are confined by two horizons (H3 and H4), which are characterized by basinward downlap, landward onlap and incisions. In order to understand the evolution of these