

3D seismic geomorphology and sedimentology of the Chalk Group, southern Danish North Sea

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Summary

The Upper Cretaceous to lower Paleogene Chalk Group of NW Europe is classically assumed to represent the settlement of homogeneous calcareous ooze from suspension draping submarine morphology under quiet pelagic conditions. Redeposited chalk units have, however, also been identified in the Central North Sea. Recently, the documentation of prominent intra-Chalk and Top Chalk reflection discontinuities on 3D seismic data led to a revision of some general ideas of the chalk deposition.

Several important issues concerning the understanding of highly irregular and discontinuous features of the Upper Cretaceous to lower Palaeogene age Chalk Group in the Danish North Sea are not yet fully understood. These irregular and discontinuous features include: intra-chalk incision features, Top Chalk depression features and a Top Chalk hummocky facies. These irregularities and discontinuities form a marked contrast to the chalk deposited under quiet, homogeneous pelagic conditions.

This study tackles the observed geometries by focusing on the interpretation and analysis of discontinuous chalk reflections detected on a 2000 km² 3D seismic-reflection dataset of the Central Graben, Danish North Sea provided by Maersk Oil and Gas. The 3D seismic analysis consisted of a horizon interpretation, the selection of chalk target areas for interpretations in detail, and a systematic analysis of the Chalk Group to search for similar features that might have a causal relationship with these discontinuities. The results of these interpretations and analyses are expected

to reveal the processes which are responsible for creating the irregular features in the study area.

In this thesis it is documented that:

(1) Several intra-Chalk channels are preserved in the subsurface of the Danish North-Sea Central Graben. The main channel system trends approximately 25 km in N-S direction between the Bo-Jens Ridge and Adda Ridge into an area west of the Gorm salt structure. Intra-chalk incisions developed in response to strong turbidite currents vs. contour currents affecting the Late Cretaceous “chalk sea”.

(2) More than 170 depressions are observed in an interval immediately below and above the Top Chalk surface in the southeastern Danish Central Graben. Based on their plan view geometry and their degree of symmetry, three types of depressions were classified: Type 1, comprising sub-circular and symmetrical depressions, Type 2, elongated and symmetrical depressions and, Type 3, elongated and asymmetrical depressions. The observed depressions on the Top Chalk surface are pockmarks caused by fluid escape.

(3) Several areas characterized by a hummocky seismic-reflection facies that occur in an interval from ca. 15 ms below to 25 ms above the Top Chalk surface were identified. Depressions associated with this facies can be recognized as a sub-circular, elongate or a lunar features. These depressions at Top Chalk are interpreted as collapse structures formed by fluid or gas escape which was possibly linked to a minor pulse of regional tectonic inversion during Danian times.

Zusammenfassung

In der Vergangenheit wurde generell angenommen, dass die oberkreidezeitlichen bis unterpaläogenen Kreideformationen in Nordwesteuropa Ablagerungen homogenen kalkhaltigen Schlammes darstellen, der sich aus einer Suspension kleinster Kalkpartikel unter ruhigen, pelagischen Bedingungen bildete. Desweiteren sind gerutschte and wiederabgelagerte Kalkformationen in der zentralen Nordsee entdeckt worden. In neuester Zeit führte die Dokumentation auffallender Reflexionsdiskontinuitäten in seismischen 3D-Daten zu einer Überprüfung der allgemeinen Annahmen über die Kalkablagerung. Einige wichtige Fragen zum Verständnis der diskontinuierlichen Merkmale der oberkreidezeitlichen und unterpaläogenen Kreideformationen in der dänischen Nordsee sind bis jetzt nicht vollständig geklärt. Diese betreffen Unregelmäßigkeiten sowie Einschnitte, Rinnen und morphologische Senken innerhalb der Kreideeinheit sowie eine beulenartige seismische Fazies (hummocky facies) auf der Oberfläche der Kreideformation. Diese Besonderheiten stehen im deutlichen Unterschied zu bisher interpretierten Kalkablagerungen, die sich unter ruhigen, pelagischen Bedingungen ablagerten.

Die vorliegende Forschungsarbeit erläutert diese Eigenschaften mit dem Fokus auf der Interpretation und Analyse der diskontinuierlichen Reflexionen der Kreide-Einheit, beobachtet in einem 2000 km² 3D-reflexionsseismischen Datensatz des Zentralgrabens der dänischen Nordsee, der von der Firma Maersk Oil und Gas zur Verfügung gestellt wurde. Die seismische 3D-Analyse besteht aus der Interpretation von Horizonten, aus der Auswahl detailliert zu betrachtender Regionen, und aus genauen Untersuchungen der Kreide, um Gemeinsamkeiten zu finden, die eine kausale Beziehung zu diesen irregulären Eigenschaften aufweisen könnten. Diese

Analysen und Interpretationen sollen helfen, die Vorgänge, die die Diskontinuitäten in der Kreide-Einheit verursachten, besser zu verstehen.

Die Ergebnisse dieser Studie bestätigen:

(1) Einige Rinnen innerhalb der Kreideeinheit sind im Untergrund des Zentralgrabens der dänischen Nordsee erhalten. Das Hauptrinnensystem erstreckt sich über ungefähr 25 km in Nord-Süd-Richtung zwischen Bo-Jens Ridge und Adda Ridge in eine morphologische Senke westlich der Gorm Salzstruktur hinein. Es wird interpretiert, dass die Einschnitte innerhalb der Kreide aufgrund starker Turbiditströmungen oder Konturströmungen, die den spätkreidezeitlichen Ozean beeinflussten, entstanden sind.

(2) Über 170 kleine, runde morphologische Senken sind in einem Intervall direkt unter und über der Oberfläche der Kreide im südöstlichen Zentralgraben der dänischen Nordsee zu finden. Basierend auf den Geometrien ihrer Ansichtsebenen und ihrem Grad der Symmetrie wurden drei Senkentypen klassifiziert: Typ 1, bestehend aus sub-zirkularen Senken; Typ 2, lang gestreckte und symmetrische Senken und, Typ 3, lang gestreckte und asymmetrische Senken. Es wird interpretiert, dass diese Senken sogenannte Pockmarks sind, die wahrscheinlich in der Vergangenheit durch die Migration von Fluiden verursacht wurden.

(3) Eine beulenartige seismische Fazies (hummocky facies), die in einem Intervall von ca. 15 ms unter bis zu 25 ms über der Oberfläche der Kreide auftritt, wurde ebenfalls identifiziert. Hierzu gehörige morphologische Senken können als sub-zirkulare, lang gestreckte oder lunare Senken beschrieben werden. In dieser Studie werden diese Strukturen als Einsturzstrukturen interpretiert, die durch Fluide oder entweichende Gase geformt wurden.

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General Introduction

General Introduction

The Upper Cretaceous sedimentary succession of the southern Danish North Sea is dominated by chalk deposits (Morton et al., 1993; Clausen and Huuse, 1999; Surlyk, 2003). The Upper Cretaceous series consist of the Cenomanian to Maastrichtian stages, and the lower Paleocene (Danian) is also part of the Chalk Group because of lithological similarity (Surlyk, 2003).

Chalk sediments occur widely across the North Sea and range in depth from the sea bed to over 3500 m; they reach a maximum thickness of greater than 1500 m in the Central Graben (Surlyk, 2003). The Late Cretaceous climate was warm temperate to subtropical. The diverse faunas such as abundant stenohaline forms indicate that the water salinity was normal but the water temperature was relatively high during Upper Cretaceous (Surlyk, 2003). The Cretaceous chalk is a micritic limestone, mostly debris from planktonic algae largely in micron-sized plates, but some still in their original circular groupings called coccoliths (Hancock, 1975).

The Upper Cretaceous to lower Palaeogene Chalk Group of Northwest Europe is classically assumed to represent the settlement of calcareous ooze from suspension, draping pre-existing submarine morphology by a monotonous 'blanket deposit' with mainly parallel bedding relationships and high lateral continuity (for a critical discussion see, e.g. Evans et al., 2003; Surlyk et al., 2008). However, redeposited, less homogeneous chalk sediments have also been identified in the past, mainly in and adjacent to tectonically active areas (e.g. Hardman, 1982; Brewster and Dangerfield, 1984; Hatton, 1986; Bromley and Ekdale, 1987; Cartwright, 1989;

Clausen and Huuse, 1999; Evans et al., 2003; Lykke-Andersen and Surlyk, 2004; van der Molen et al., 2005). The deposition of the Chalk Group was greatly influenced by halokinetic movements and fault-controlled subsidence or inversion (Kennedy, 1980; Watts et al., 1980; Hardman, 1982; Brewster and Dangerfield, 1984; Munns, 1985; Hatton, 1986; Bromley and Ekdale, 1987; Barmwell et al., 1999; Farmer and Barkved, 1999; Surlyk et al., 2003). Most of the inversion is believed to have occurred during the deposition of the Chalk Group, as indicated by the termination of most reverse faults below the top surface of the Chalk Group (Vejbæk and Andersen, 1987). Finally, the top surface of the Chalk Group is extinguished at the end of the Danian when siliciclastic deposition introduced into the basin (Clausen and Huuse, 1999; Surlyk, 2003)

The understanding of chalk depositional processes during the Upper Cretaceous to lower Palaeogene is still limited, and the vast amount of literature is focussing particularly on the sedimentology and diagenesis of chalk reservoirs (Egeberg and Saigal, 1991; Scholle et al., 1998; Hjuler, 2007; Lindgreen et al., 2008). Many aspects of the deposition and re-deposition of chalk sediment in the Danish North Sea are not yet fully analysed, despite many detailed investigations during many years. Recently, the observation of highly discontinuous reflection patterns on 2D and 3D seismic-reflection data from the NW European Chalk Group initiated a revision of some general ideas about the chalk deposition, proposing that strong oceanic currents and large scale gravitational processes led to the development of a significant discontinuity within chalk strata (e.g. Lykke-Andersen and Surlyk, 2004; van der Molen et al., 2005; Surlyk and Lykke- Andersen, 2007; Esmerode et al., 2007; Esmerode et al., 2008; Surlyk et al., 2008; Back et al., 2011). The chalk

sediment of the study area is characterised by highly discontinuous reflection patterns on 2D and 3D seismic reflection. The vertical display of the reflectivity data shows major seismic discontinuity with numerous reflections terminating at steep truncation surfaces interpreted as channels. Lobate reflections are also identified in the chalk units and interpreted as mass-transport deposits. Various channels are located on, or in the immediate vicinity of tectonically active structures, in particular in a kilometre-scale master valley between the Adda and Bo-Jens ridges, structural highs that formed in response to Late Cretaceous syndepositional tectonic inversion. The key aim of this doctoral thesis is to provide a documentation of discontinuous reflection patterns on 3D seismic-reflection data of the southern Danish North Sea (see Fig. 1-1).

The research study presented is subdivided into three main chapters:

Chapter I aims to document the interplay between intra-chalk channel and mass-transport processes in the study area. Later, the mechanisms and the effects of inversion on the location of the channel system and its relationship to salt tectonics are discussed.

Chapter II describes the distribution of depression features on the Top Chalk surface. More than 170 depressions in an interval surrounding the Top Chalk surface in the southeastern Danish Central Graben were mapped from 3D seismic data. The depressions either have a sub-circular or an elongate shape in plan form. I interpret the depressions as pockmarks formed by the expulsion of fluids or gas. The detailed analysis of their 3D morphology contributes to the understanding of palaeocirculation

patterns during the sedimentation of the terminal Chalk Group in the southern Danish North Sea.

Chapter III documents the presence of depression features on the eastern part of the study area which occur in an interval around the Top Chalk surface. In plan view the depressions have a sub-circular, an elongate or a lunar appearance. The detailed analysis of the 3D morphology of depression features in this area contributes to the understanding of distribution of depressions on the Top Chalk surface in southern Danish North Sea. The possible origin of the depressions is discussed in this chapter with a particular emphasis on partial fluids involved.

The results of these interpretations and analysis are expected to improve understanding of the processes which are responsible for creating the discontinuous and irregular features of the Chalk Group in the southern Danish North Sea.

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- 2) Masoumi S., Back S., Reuning L., Kukla P., (2013), "Detailed Small-scale circular/elliptical depression features on the Top Chalk Surface, Southern Danish North Sea" 29th IAS Meeting of Sedimentology, 10-13 September 2012, Schladming, Austria.

- 3) Masoumi S., Back S., Reuning L., Kukla P., (2011) "3D Seismic Geomorphology of Channel Systems in the Chalk Group, Southern Danish North Sea". AAPG International Conference and Exhibition, 23 - 26 October 2011, Milan, Italy.

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Chapter I

3D Seismic Geomorphology of Channel Systems in the Chalk Group, Southern Danish North Sea

3D Seismic Geomorphology of Channel Systems in the Chalk Group, Southern Danish North Sea

Abstract

The Upper Cretaceous to lower Palaeogene Chalk Group of NW Europe is classically assumed to represent the settlement of homogeneous calcareous ooze from suspension draping submarine morphology under quiet pelagic conditions. Recent studies however showed that this quiet depositional setting was recurrently affected by chalk movement and redeposition in and adjacent to tectonically active areas, and in areas affected by halokinetic movement. In this study, three-dimensional (3D) seismic data from the southern Danish North Sea that concentrate on an intra-chalk regional unconformity were used to analyse channel systems transporting redeposited chalk.

This chapter presents a detailed analysis of several intra-Chalk channels preserved in the subsurface of the Danish North-Sea Central Graben. The largest of these systems trends over approximately 25 km in N-S direction, exhibiting a sinuous downslope course flanked by large master levees, and an infill characterized by well-developed inner-levees on the outer bends of the channel thalweg. The main incision pathway trends between the Bo-Jens Ridge and Adda Ridge into an area west of the Gorm salt structure, following the course of the structurally defined depressions.

The seismic-geomorphological analysis of this channel system displays many of the architectural elements of gravity-driven deep-water channels, supporting its interpretation as a turbidite system. Turbulent erosive flow was interpreted as the main initiation mechanism for channel development. The stable location of the channel and a probably rather constant flow in the master valley is interpreted to represent the restriction of the course of the channel between pre-existing ridge structures.

The 3D seismic interpretation of channel system presented in this paper contributes to the understanding of sediment-distribution patterns and turbiditic flow directions during the sedimentation of the Chalk Group in the southern Danish North Sea.

Keywords: Chalk, channel-system, Danish North Sea, bottom and turbidite currents

Introduction

Stratal discontinuities in Danish Central Graben were previously identified on the 3D seismic data and interpreted as submarine channel system (e.g. Esmerode et al., 2007; Back et al., 2011). Channel systems can be formed by bottom currents, turbidity currents or by interaction of the two processes (Heezen et al., 1966; Normark, 1970; Hollister and Heezen, 1972; Faugères and Stow, 1993; Habgood et al., 2003; Akhmetzhanov et al., 2007; Surlyk et al., 2008). Intra-chalk channels in the Danish North Sea were previously identified on 2D and 3D seismic data and interpreted as bottom current channels (Esmerode et al., 2008) or turbidite channels

(Back et al., 2011). Submarine channels can respond to sea-level change, variation in sediment flux, tectonics and climate, and have a significant impact on the sedimentary architecture of continental margins (e.g. Damuth et al., 1988; Satterfield and Behrens, 1990). Esmerode et al. (2008) described a Turonian–Campanian intra-chalk channel system in the Danish part of the Central Graben, demonstrating that the channel system was controlled by actively rising ridges, and also showed that channel development was contemporaneous with the local relaxation of the tectonic inversion. In tectonically active areas the interplay between downslope and alongslope sediment transport mechanisms is a common phenomenon (Faugères and Stow, 1993). Many studies have demonstrated the combined action of downslope gravity-driven processes and alongslope processes linked to bottom currents in the sedimentary construction of oceanic margins (Heezen et al., 1966; Hollister and Heezen, 1972; Esmerode et al., 2008; Back et al., 2011).

This study provides a detailed observation of a channel system produced by turbidite currents and mass-transport processes adjacent to tectonically active areas in the Upper Cretaceous chalk of the southern Central Graben in the North Sea (Fig. 1-1). This system is used to analyse the interplay between turbidite currents and mass-transport processes in the study area. The interpretation is assisted by a reconstruction of the main topographic elements of the sea-floor in the channel area. Finally, the mechanisms and the effects of inversion on the location of channel system and its relationship to salt tectonics are discussed.

Danish North Sea Central Graben

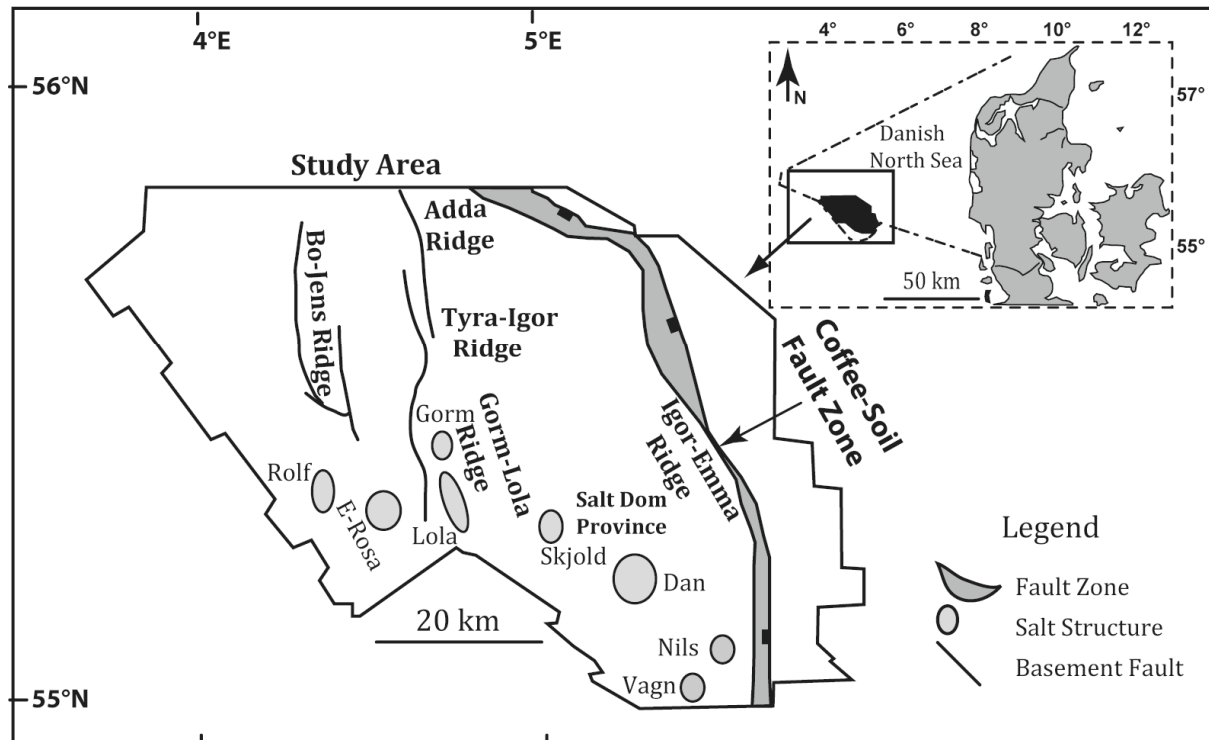


Figure 1-1 Location of the study area in the Danish North Sea Central Graben. The regional map is showing the main structural elements during Late Cretaceous (modified after Cartwright, 1991; Vejbæk and Andersen, 2002; Japsen et al., 2003; Esmerode et al., 2008). The study area covers approximately 2000 km² of the Central Graben, and is bound by the Tyra-Igor and Igor-Emma Ridges in the east, the Bo-Jens and Adda Ridges in the north, and the Danish Salt Dome province in the south.

Geological setting

The study area is located in offshore Denmark, 200 km west of the Danish mainland, between 4° to 5° eastern longitude and close to 56° northern latitude (Fig. 1-1). The Danish North Sea Central Graben consists of a system of generally NNW–SSE trending half-graben structures bounded by the Coffee-Soil Fault to the east (Fig. 1-1). The study area encompasses the Tyra-Igor and Igor-Emma Ridges in the east, the Adda Ridge in the northeast, the Bo-Jens Ridge in the northwest and the salt structures to the south (Fig. 1-1). The interval under study is the Chalk Group that spreads over the Central North Sea and extends into the south Viking Graben and

onto the east Shetland Platform (Surlyk et al., 2003). It is of Cenomanian to Danian age and is commonly 1-2 km thick in the Graben areas (Surlyk et al., 2003; Vejbæk et al., 2007). The sediments mainly consist of pure chalk and limestone, marly chalk, marl and calcareous shale (Hardman, 1982; Surlyk et al., 2003).

Chalk is a cool-water carbonate sediment and is classically assumed to represent the settlement of calcareous ooze from suspension, raining and draping on pre-existing submarine morphology by a monotonous 'blanket deposit'. These pelagic chalks are deposited with mainly parallel bedding relationships and high lateral continuity. However, redeposited, less homogeneous chalk sediments have also been identified in the past, mainly in and adjacent to tectonically active areas and areas affected by halokinetic movements (Brewster and Dangerfield, 1984; Hatton, 1986; Cartwright, 1989; Clausen and Huuse, 1999; Skirius et al., 1999; Evans et al., 2003; Lykke-Andersen and Surlyk, 2004; van der Molen et al., 2005). Recently the observation of highly discontinuous reflection patterns on 2D and 3D seismic-reflection data from the NW European Chalk Group initiated a revision of some general ideas about the chalk deposition, proposing that strong oceanic currents processes and synsedimentary tectonic movements led to the development of a significant discontinuity within chalk strata (e.g. Lykke-Andersen and Surlyk, 2004; van der Molen et al., 2005; Surlyk and Lykke-Andersen, 2007; Esmerode et al., 2007; Esmerode et al., 2008; Surlyk et al., 2008; Back et al., 2011). Through geological time a close inter-relation between tectonic and sedimentation generated paleo-highs and paleo-depressions that effected the later geometry and depositional pattern of the Chalk Group in the study area.

Chalk deposition was greatly influenced by halokinetic movements, fault-controlled subsidence and inversion (Kennedy, 1980; Watts et al., 1980; Hardman, 1982; Brewster and Dangerfield, 1984; Barmwell et al., 1999; Surlyk et al., 2003; van der Molen et al., 2005). Late Cretaceous regional subsidence happened in result of widespread inversion and Zechstein salt movements (Vejbæk and Andersen, 1987 and 2002). Three major tectonic events resulted in inversion phases in the Danish North Sea; (1) a Turonian–Santonian inversion followed by (2) a Mid- Maastrichtian and (3) a Post-Danian-Early Tertiary inversion (Vejbæk and Andersen, 1987). Inversion in the study area is constituted by the occurrence of bathymetric elevations and the formation of several depocentres (Fig. 1-2a, b and c; Oakman and Partington 1998).

Four ridges were identified in the study area (e.g. Fig. 1-1). The ridges are created as a result of the interaction between tectonic activity including normal faulting, tectonic subsidence, fault reactivation and uplift and contemporaneous sedimentation (Kennedy, 1980; Watts et al., 1980; Hardman, 1982; Brewster and Dangerfield, 1984; Barmwell et al., 1999; Surlyk et al., 2003).

The Bo-Jens Ridge and Adda Ridge are Top Chalk topographic elements (Kennedy, 1987b; Farmer and Barkved, 1999) that show a thinning of the Upper Cretaceous succession over their crests (Fig. 1-2 a and b). Adda Ridge parallels a NW–SE trending segment of the Coffee Soil Fault (Fig. 1-1) and initiated as a result of dextral movement of a deeply seated fault (Vejbæk and Andersen, 2002). Bo-Jens Ridge is oriented from north to south and is related to the reactivation of extensional basement faults which influenced the Zechstein salt movement (Vejbæk and

Andersen, 2002). Tyra-Igor Ridge trends NW-SE and crosses the Salt Dome Province at the southern edge of study area (Fig. 1-1). This ridge was initiated as a result of the Late Paleocene–Eocene inversion episode (Jakobsen and Andersen, 2010).

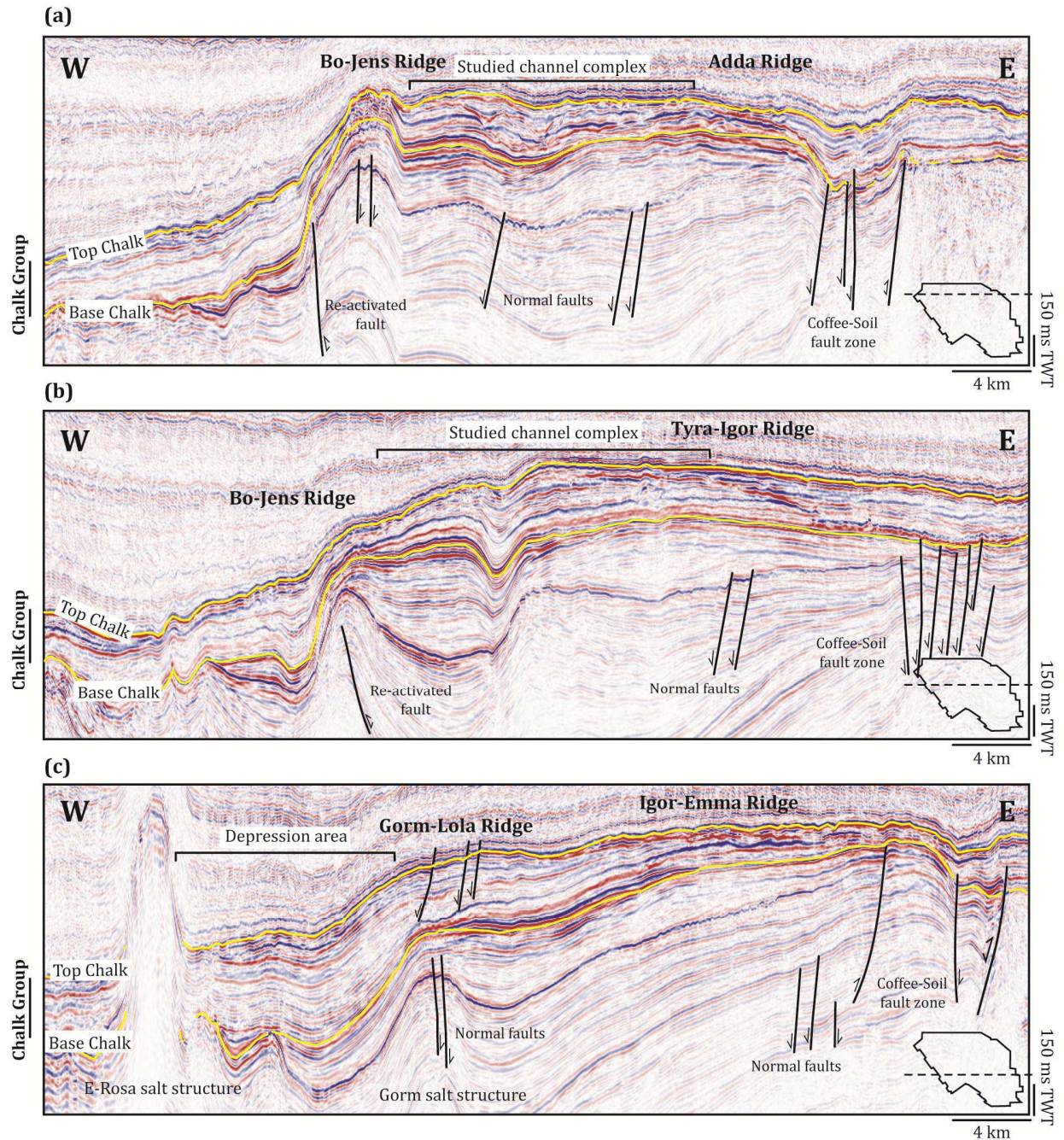


Figure 1-2 Vertical reflectivity section illustrating the base and top of the Chalk Group from north to the south. Also shown are the location of the ridges and depocentre.

Igor-Emma Ridge is a N–S trending structure that is sub-parallel to Coffee-Soil fault at the eastern edge of the study area (Figs. 1-1 and 1-2c). This structure is an asymmetric anticline which is initiated as a result of both intra-chalk and post-chalk compressional movements (Jakobsen and Andresen, 2010). Finally, the Gorm-Lola Ridge of the southern part of the study area is associated to the Zechstein salt movement (Fig. 1-2c; Vejrbæk and Andersen, 2002). Halokinetic movements related to the Zechstein salt interval started during the Triassic time and continued throughout the Late Cretaceous (Surlyk et al., 2003). Halokinetic movements started during the Triassic and intrusive activity continued through-out the Late Cretaceous, resulting in the formation of salt pillows, domes, ridges and diapirs (Figs. 1-1 and 1-2c ; Surlyk et al., 2003).

Database

The database used in this study comprises ca. 2000 km² of 3D multichannel seismic-reflection data processed in zero phase following European polarity convention, i.e. an increase in acoustic impedance is represented by a reflectivity trough. The bin spacing of the 3D seismic survey is 25 m in inline and crossline directions, and the vertical sampling rate of the data is 4 ms.

Results

Seismo-stratigraphic units

The chalk Group in the study area can be subdivided into five seismo-stratigraphic units (Fig. 1-3). These units are separated by strong reflections or major seismic

discontinuities, with the latter built of multiple lap surfaces, truncation surfaces, or pronounced lateral facies variations (Fig. 1-3).

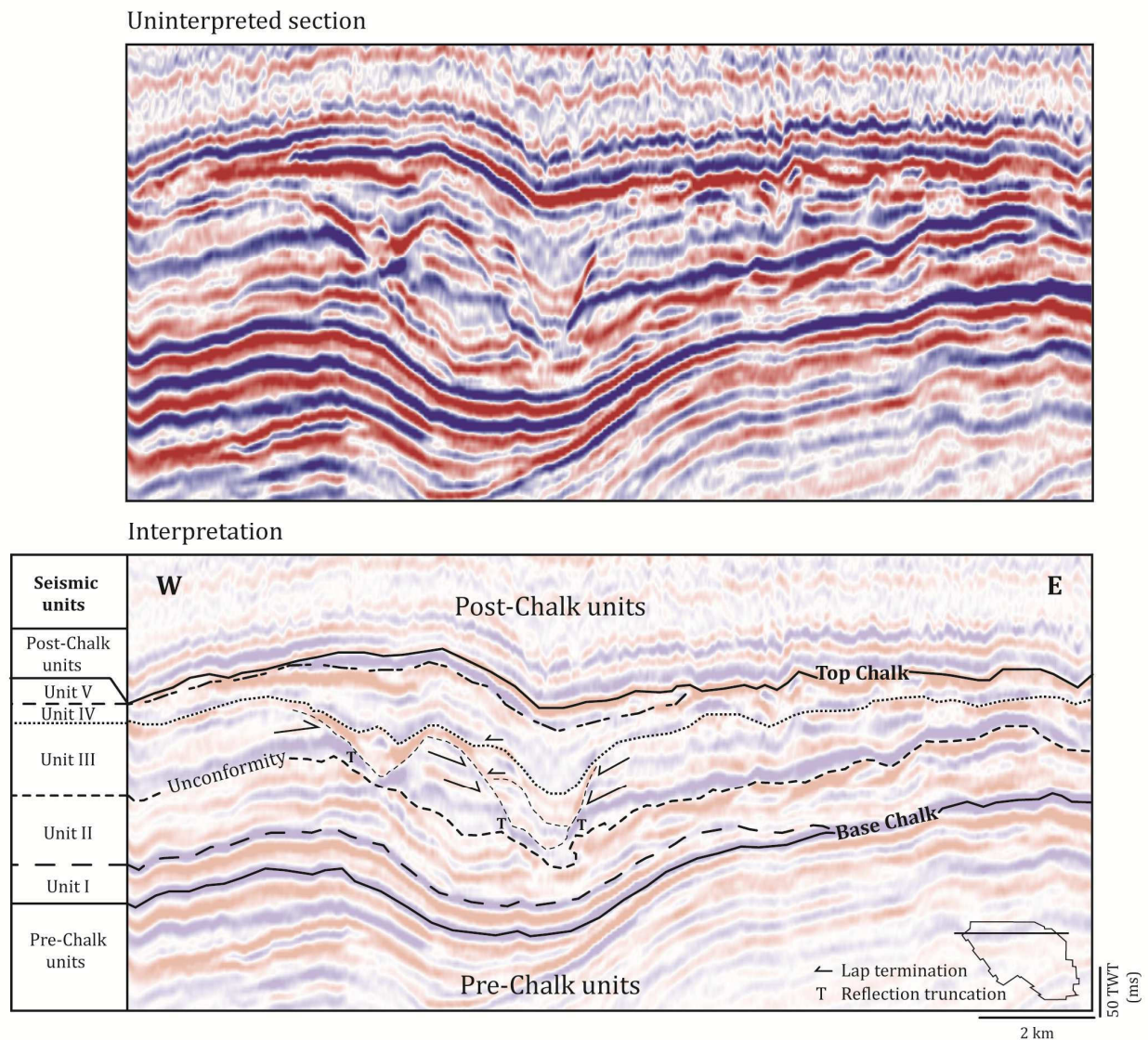


Figure 1-3 The study area is subdivided into five seismo-stratigraphy units. Unit I, unit II, unit III, unit IV, and the upper part is seismic unit V (for more detail see the text).

Seismic unit I is located above the Base Chalk surface and bounded at the top by a relatively high amplitude, homogeneous and continuous seismic reflection. This unit is thin and its thickness varies between 0 to 70 mili-seconds (ms) in the study area. Seismic unit II is relatively thick (120 ms) and dominated by large-scale mounded features and strong seismic discontinuity (Fig. 1-3). The reflection polarity changes frequently from high to low amplitudes laterally along unit II. The minimum thickness

of unit II is about 40 ms over Adda Ridge and its maximum thickness of about 150 ms is measured in the depression area between the ridges (Fig. 1-2a, b and c). Seismic unit II is bounded at its top by a high amplitude seismic reflection interpreted as a regional unconformity (Fig. 1-3). Unit III comprises a multitude of reflection discontinuities including onlaps, downlaps and truncations and is highly incised into the underlying seismic unit II. The reflection continuity within unit III is generally low and limited to few kilometres; the polarity pattern of this unit varies from low/transparent to high amplitude (Fig. 1-3). The unit III thickness is about 20-50 ms over the Adda Ridge, 50-70 ms over Bo-Jens Ridge, 40-80 ms over Tyra-Igor Ridge, and 100-180 ms over Gorm-Lola Ridge. The thickness of unit III is about 110-200 ms between the ridges in the depression areas. Seismic unit IV is characterised by regular and relatively continuous seismic reflections (Fig. 1-3). The minimum thickness of this unit is measured over Bo-Jens Ridge with around ca. 20 ms, and over Adda Ridge ca. 10 ms; the thickness of unit IV is about 180 ms over Gorm-Lola Ridge. The uppermost seismic unit in the study area is unit V that is located right below the Top chalk boundary. This unit is characterised by continuous and high amplitude reflections (Fig. 1-3). Unit V is very thin; the thickness of unit V is about 20-40 ms.

Paleotopography of base unit III surface (Seismic Unit III surface)

This section is focusing on the basal surface (unconformity) of seismic unit III as the key interpretation target. A topography map of this surface is constructed which served as an indicator for the location of structural highs and depressions (Fig. 1-4a). The topography map of the northern part highlights the presence of two elevated areas including the Adda Ridge and the Bo-Jens Ridge (Fig. 1-4a and b). The Adda

Ridge is located in the northeast of the study area and trends from NW to SE. The Bo-Jens Ridge is located in the northwest and trends from north to south (Fig. 1-4a and b). The central part of the study area is occupied by the Tyra-Igor Ridge (Fig. 4a and b). This ridge trends NW-SE and crosses the salt structures in the south. Gorm-Lola Ridge is observed in the southern part and associated with the Gorm salt structure (Fig. 1-4a and b). The Bo-Jens Ridge (in the western part) is separated from the Adda, Tyra and Gorm-Lola ridges (in the eastern part) by a north-south oriented elongate depression (Fig. 1-4c and d). This structure is interpreted as a master valley that extends along a rather straight course over 20 km into the deep-water areas west of Gorm-Lola Ridge. Four major channel systems and a down-slope mass-transport structure are identified within this master valley (Fig. 1-4c and d). From north to the south these channels are labelled channel A to D (Fig. 1-4b). The following section describes the morphology of the channels and the seismic characterization of the down-slope mass-transport in more detail.

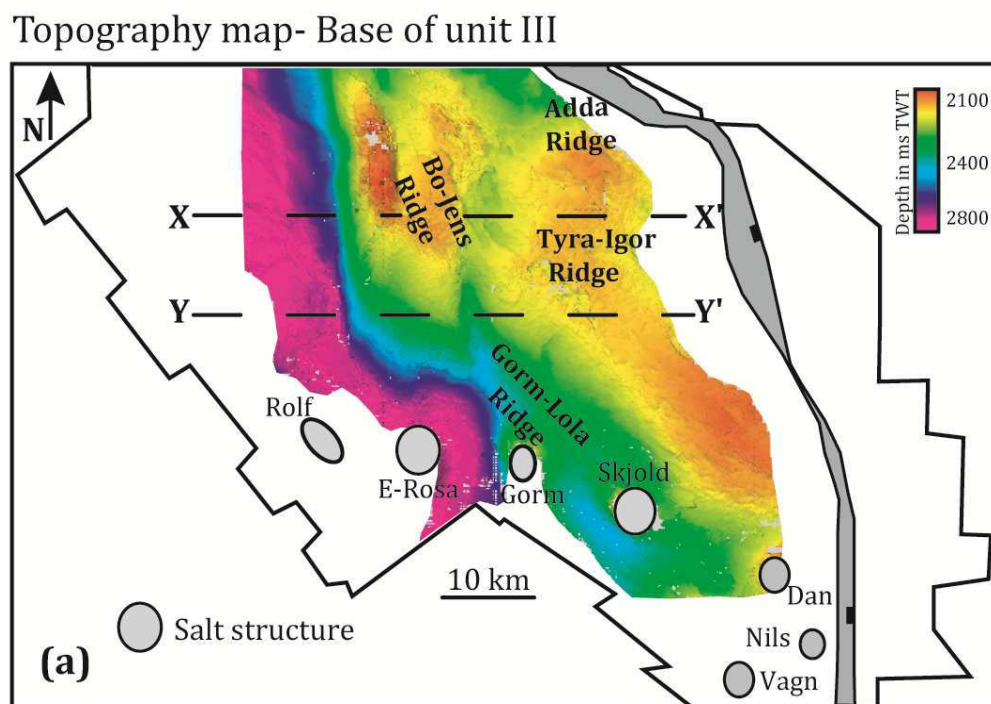


Figure 1-4 to be continued

Topography map- Base of unit III (interpretation)

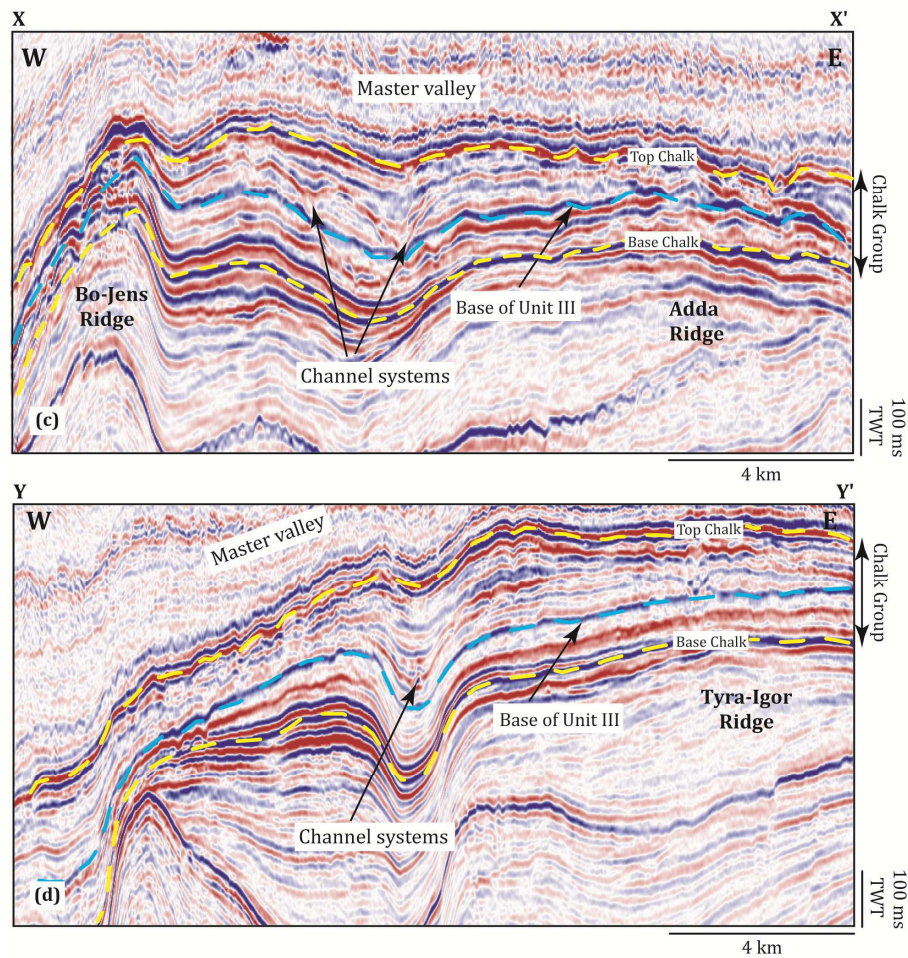
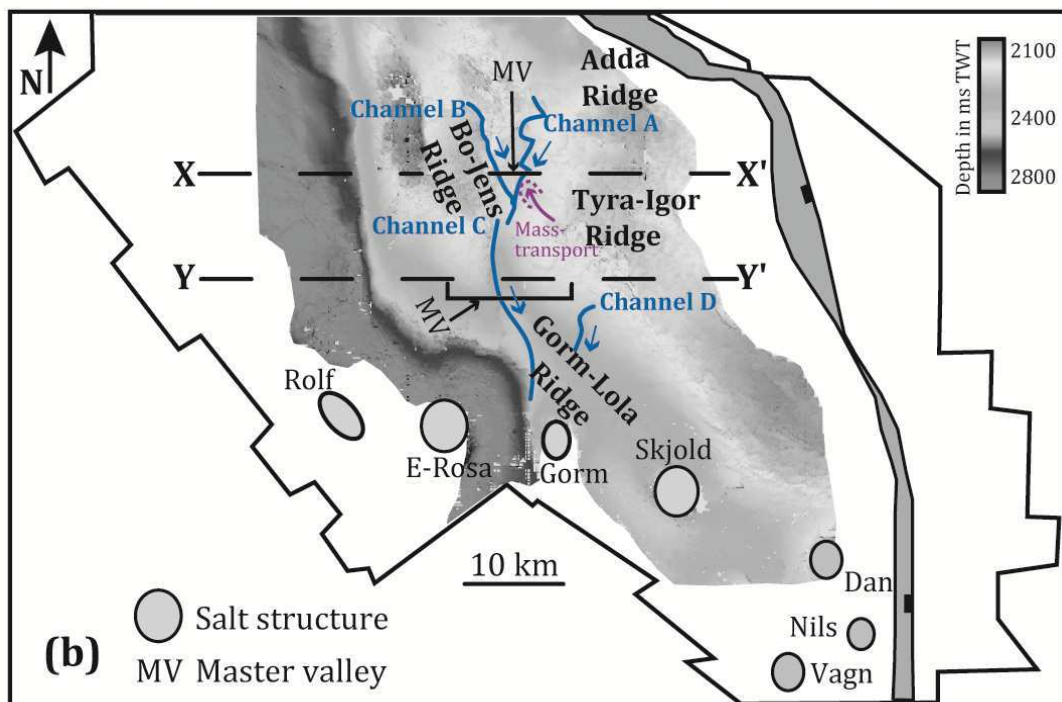


Figure 1-4 a) Topography map of seismic unit III surface, and b) interpretation. Topography map is indicated the location of structural highs and depression. Structural highs are

identified as ridges and depression as master valley (dashed line). From north to the south four channel systems and a mass-transport unit are identified in the study area. The black horizontal line indicates the positions of the seismic lines shown below. c and d) The ridges are separated from each other by a large N-S oriented master valley. The master valley is the main pathway for channel systems observed in the study area.

Channel-like features

From north to the south of the study area there are several reflection truncations and incisions interpreted as channels (Fig. 1-4a and b). The vertical display of the reflectivity data shows a major seismic discontinuity at the base of seismic unit III with numerous reflections terminating at steep, U-shaped truncation surfaces interpreted as channel A (Fig. 1-5 sections A-A' to C-C'). Channel A is located in the master valley between the Bo-Jens, Adda, and Tyra-Igor Ridges and trends over 12 km in N-S down-slope direction with a width of approximately 3 km and depth of 100 ms (Figs. 1-4a and 1-5 section A-A'). The channel is highly incised into seismic unit II. The maximum downward incision of this system is interpreted here as the Channel Erosional Base, CEB (Fig. 1-5 sections A-A' to C-C'). The gull-wing shaped reflections at the outer edges of the incision are interpreted as master levees, ML, showing the maximum width of channel system (Fig. 1-5 section A-A' to C-C'). These levees are often steep and flanked on both sides along channel course. Within the channel, small-scale onlaps to the sidewall and downlaps onto the channel incision interpreted as inner levees (Fig. 1-5 section A-A'). The inner levees of the system occur in the outer bends of the channel thalweg and are well-defined levees in the proximal part; in the distal part the development of inner levees is very limited. Section C-C' of figure 1-5 documents channel A that terminates in the area between the Bo-Jens Ridge and the Tyra Igor Ridge where another channel system can be identified in the study area.

At Bo-Jens Ridge another incision with NNW-SSE orientation is identified in the study area and interpreted as channel B (Figs. 1-4b and 5 section A-A'). The channel can be traced for ca. 12 km into a region between Bo-Jens Ridge and Tyra-Igor Ridge with a width of around 2 km and a depth of 60 ms. Section A-A' of figure 1-5 illustrates the inner levee onlap to the western sidewall and downlap to the channel base. In the south, channel B and channel A are joined and form a wide channel system (Fig. 1-5 section B-B').

In the centre of the study area, a downslope incision feature with a length of around 13 km enters the master valley. This incision is labelled as channel C and it is characterised by a width of about 3 km and a depth of 80 ms (TWT). The main channel pathway can be traced from an area between Bo-Jens Ridge and Tyra-Igor Ridge to a salt-rim syncline region west of the Gorm-Lola Ridge (Figs. 1-4b and 1-5 section G-G'). Externally, the channel is characterised by steep master levees that flank both sides of the channel (Fig. 1-5 sections D-D and E-E'). Channel C is less incised and less erosive than channel A and identified by narrow and deep geometry in the proximal part (Fig. 1-5 section D-D). In the vicinity of the Gorm-Lola Ridge, channel C is enlarged and appears in a nearly horizontal configuration (Fig. 1-5 sections E-E' and F-F').

In the south of the Tyra-Igor Ridge, an U-shaped incision with NE-SW direction enters the study system; this incision is named channel D. The incision trends 4 km and is characterised by a width of 1 km and a depth of 80 ms (TWT, Fig. 1-4b). This channel is highly incised into the surface unit II (Fig. 1-5 section E-E'). A low sinuosity

and steep master levees on both sides characterize this channel (Fig. 1-5 section E-E').

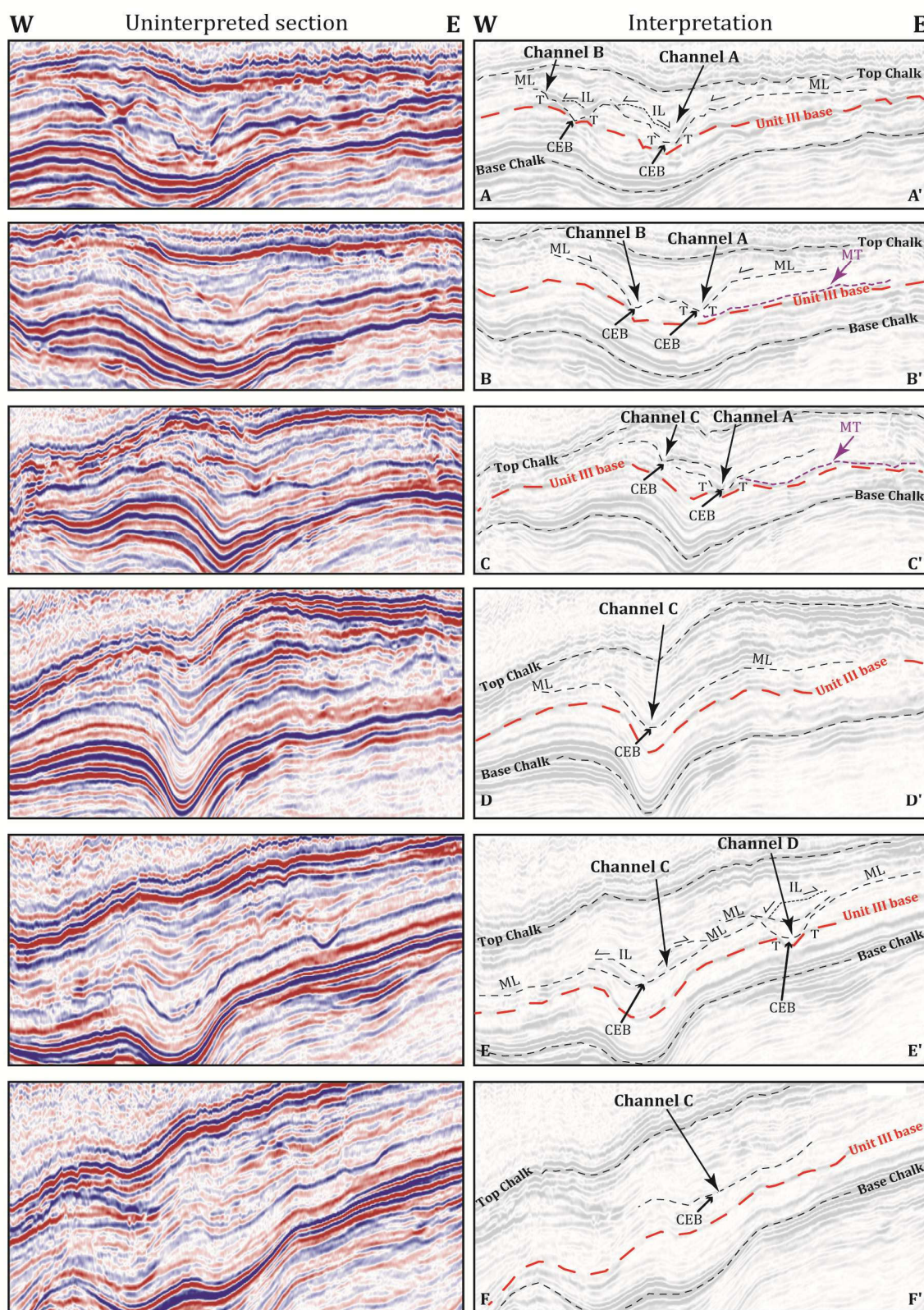


Figure 1-5 to be continued

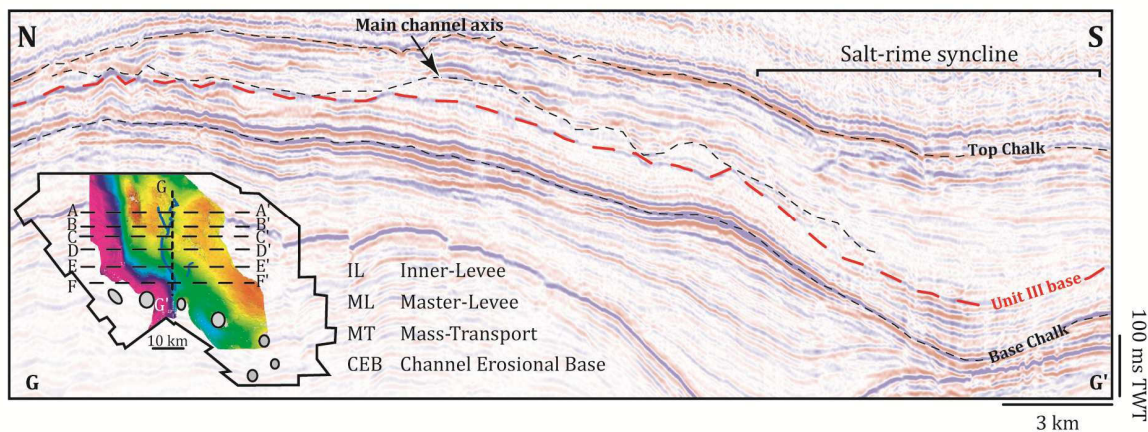


Figure 1-5 Detailed interpretation of channel systems between the Bo-Jens, Adda, Tyra_Igor and Gorm-Lola Ridges. Reflection picks defining the channel outline are indicated on vertical reflectivity sections by black dash-line. The maximum downward incision interpreted here as channel erosional base (CEB). Channel A and channel B is highly incised into surface below (unit III) and marked the truncational surfaces (T). The prominent master-levee flanks the channel A on both-sides is observed in proximal part (section A-A' and B-B'). These surfaces are less clear in southern part (section C-C'). Within the channel, small-scale onlaps to the sidewall and downlaps onto the channel incision interpreted as inner levees. Section C-C' also is shown channel A and channel are joined and form a wide channel system. The eastern flank of channel A is interrupted by SE-NW mass-transport. Channel C starts at termination of channel A and is characterised by narrow and deep geometry in the proximal part (sections C-C' to D-D'). In the south of the Tyra-Igor Ridge, an U-shaped incision with NE-SW direction enters the study system (section E-E'). Section F-F' illustrates channel C is enlarged and appears in a nearly horizontal configuration. The main channel pathway is traced from an area between Bo-Jens Ridge and Adda Ridge in the north to a salt-rim synclines region west of the Gorm-Lola Ridge (section G-G').

Channel outline and channel infill description

The channel slope and channel infill is studied based on three time slices (Fig. 1-6). Time slice A at -2214 ms is above the channel erosional base and marks the channel A course between the Bo-Jens, Adda and Tyra-Igor ridges (Fig. 1-6a). The thalweg interpretation on the reflectivity horizon-slice extractions displays a medium sinuosity for channel A. At this depth level, the channel system shows high lateral migration and small vertical aggradation. Near the termination of the channel, SE-NW oriented lobate reflections with a downslope direction enter channel A from the eastern master

levee. This feature is interpreted as mass-transport system (slide or slump) (Fig. 1-6a).

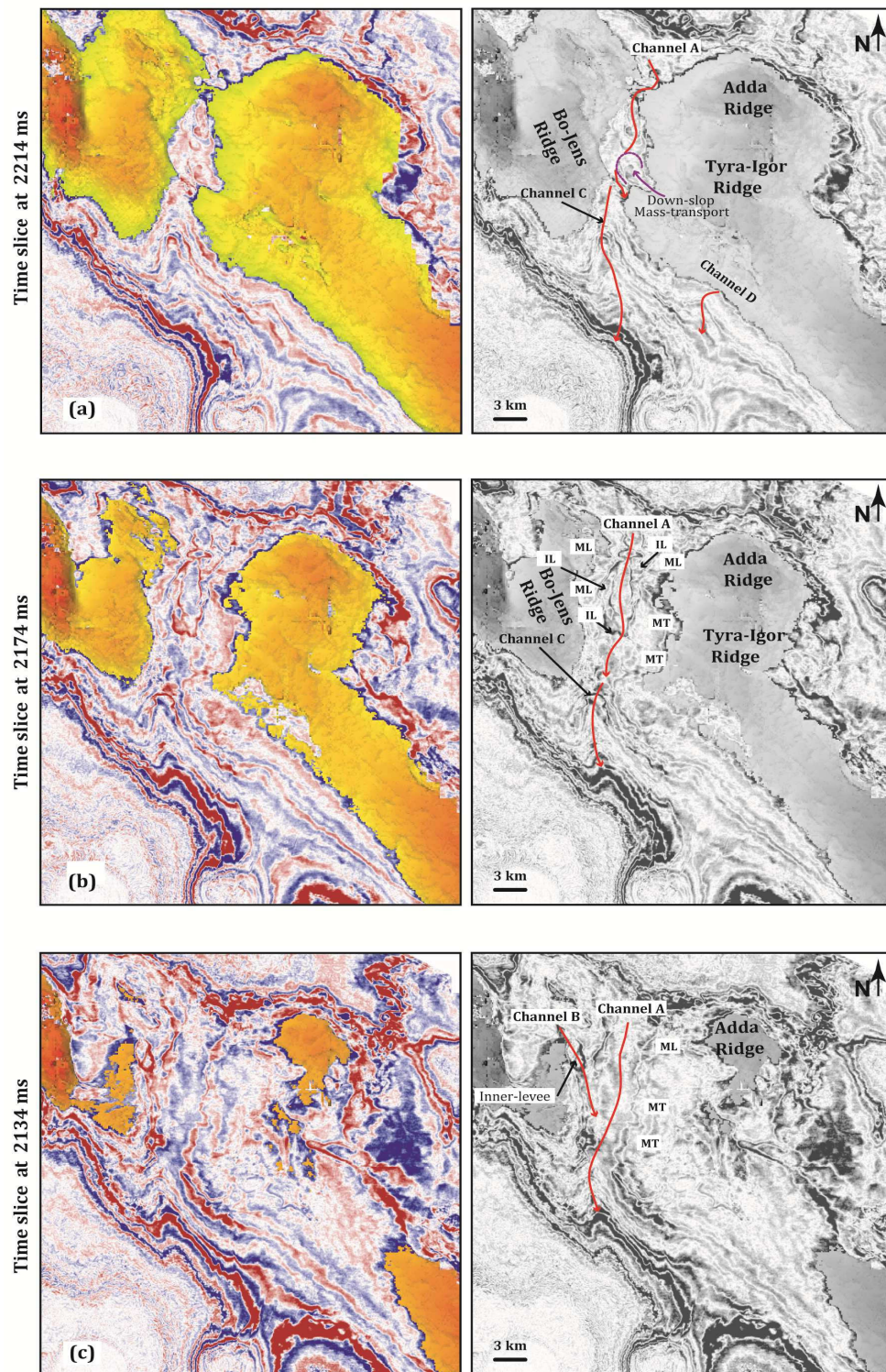


Figure 1-6 The channel outline and channel infill is studied by producing three time slice surfaces. The time slice surfaces are at 2214, 2174, and 2134. The thalweg interpretation also shown on the surface slices (for details see text).

In the center of the study area between Bo-Jens and Tyra-Igor Ridges and south of the Tyra-Igor Ridge, channel C and channel D can be identified in the master valley. These systems show a straight channel thalweg in a southward orientation (Fig. 1-6a). The channel A infill at -2174 ms time slice is characterised by bow-shaped reflections in the outer bend of the channel interpreted as inner levees (Fig. 1-6b). The inner levees are well-developed along the channel course from the northern part to the southern part. The thalweg interpretation shows a medium sinuosity to straight channel thalweg. At this depth level, channel A covers a part of channel C (Fig. 1-6b). The time slice at -2134 ms shows channel B entering channel A across master levee (Fig. 1-6c). At this time slice, the channel A thalweg is straight and internally marked by aggradation (Fig. 1-6c). The main channel A pathway can be traced from the area between Bo-Jens Ridge and Adda-Ridge into a region west of the Gorm-Lola Ridge. In the central part and southern part of the study area, channel A follows the orientation of channel C.

Discussion

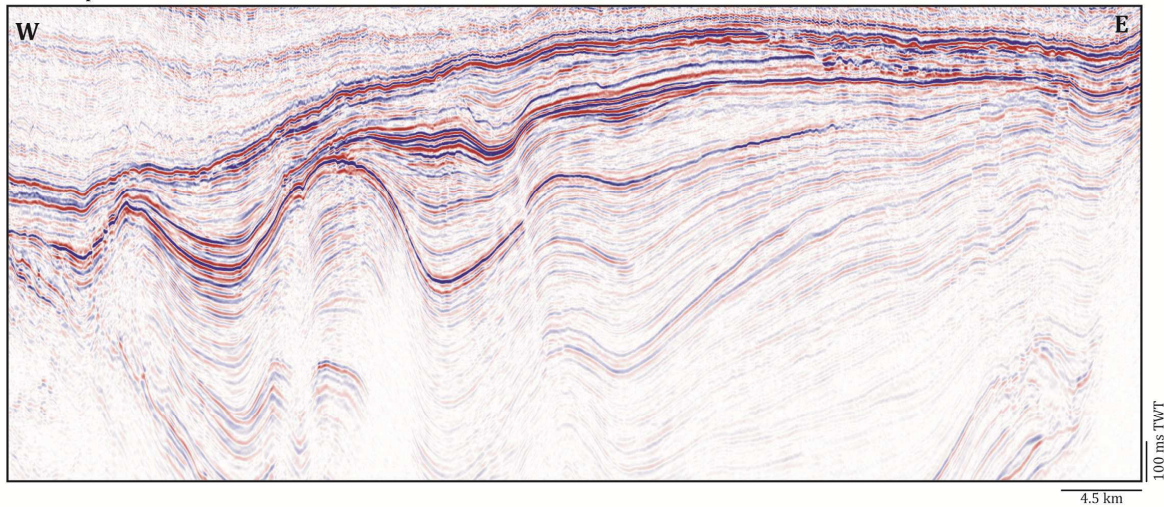
The seismic reflection data and the interpretations of this study strongly suggest that the North Sea chalk is characterized by a multitude of stratal irregularities, of which many can be interpreted as channel systems. The channels are located on or in the immediate vicinity of tectonically active structures, in particular in the master valley between ridges that formed in response to Late Cretaceous syndepositional tectonic inversion (e.g. Vejbæk and Andersen, 1987, 2002; Esmerode et al., 2008). Channel system (channel A plus channel C) as a key interpretation target is descending from the master valley between the Bo-Jens Ridge in west and the Adda Ridge in

northeast, and is terminating in salt-related depressions near the Gorm and E-Rosa salt structures (see Fig. 1-4). The current direction analysis shows that the channels always follow the course of the structurally defined depressions (see Fig. 1-6). Where the ridges terminate the currents lose their capacity for the transport of material and deposit their load in salt-rim synclines created by Gorm and E-Rosa salt structure (see Fig. 1-5 section G-G'). The stable location of the channel and a constantly flowing in master valley between the ridges indicates the channel system was controlled by actively rising ridges. The rising structure limit the channel migration and a minor migration of channel could be happen during the local relaxation of the tectonic inversion. Thus the channel development in the area between ridges in the northern and central part of the study area is controlled by synsedimentary inversion of the underlying faults (Vejbæk and Andersen, 1987, 2002; Esmerode et al., 2008). In contrast, in the southern part, the channel development is being restricted by synsedimentary salt movement throughout the Late Cretaceous (Vejbæk, 1986; Surlyk et al., 2003).

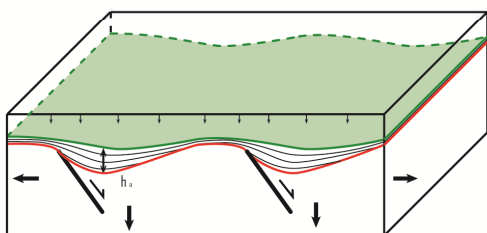
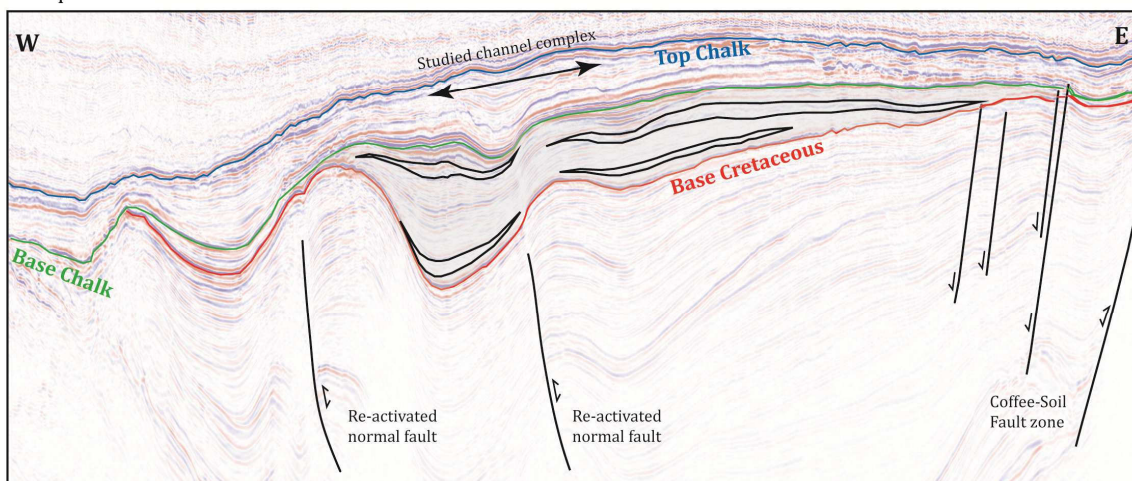
Figure 1-7 illustrates the proposed mechanism and the effect of inversion first on the depositional patterns and the geometry of sedimentary units and later on the location of the studied channels. The seismic interpretation presented in this study highlights the very little horizontal channel migration through time. The cartoon shows that during an initial extensional phase the maximum subsidence and accommodation is created on the hanging-wall side of normal faults, and that this area receives more sediment than the areas located on the footwall. Such a heterogeneous depositional pattern creates locally thickening sedimentary units with the thickest part in the

hanging-wall and thinning laterally on the footwall area and in the areas at distance from the main bounding fault.

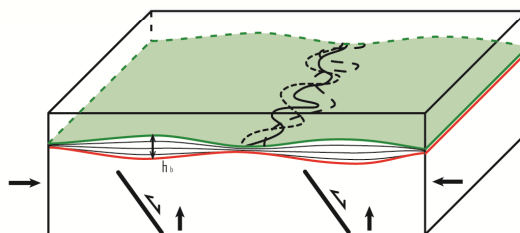
Uninterpreted section



Interpretation



1) Normal faulting initiates hanging wall subsidence resulting in additional accommodation which is filled up by sediments syn-kinematically. Sedimentary units are lenticular with maximum thickness in the central part.



2) Inversion and reactivation of old normal faults resulting to the uplift and folding of sedimentary units. HW uplift is more important as FW uplift due to the nature of normal fault reactivation as classically former HW sediments sliding over FW units. Therefore this heterogeneous uplift plus lenticular sediments on the HW generates new highs at the location of former depression on top of the HW areas of former bounding normal faults.

Figure 1-7 This figure illustrates the mechanism and the effect of inversion first on the depositional patterns and the geometry of sedimentary units and later on the localisation of studied channel complex (for details see text).

In the compressional phase (second cartoon) the pre-existing normal faults became active as reverse faults. Compression and shortening by fault reactivation generated minor uplift and folded the preexisting sediments. The existing sedimentary units are uplifted which creates new depressions located above former high lands on the footwall sides, and newly elevated areas on the tops of the former hanging-wall depressions.

During the extensional phase the channel flow is more on the downthrown side sub-parallel to the bounding normal faults. The location of the channels may change during inversion phase triggering a migration laterally to the newly initiated depression areas. It has to be kept in mind however, that such a channel migration can happen if the rate of uplift is greater than the erosional force at the channel base (incision rate).

Channel systems can be formed by bottom currents, turbidity currents or by interface of the two processes (Heezen et al., 1966; Normark, 1970; Hollister and Heezen, 1972; Faugères and Stow, 1993; Habgood et al., 2003; Akhmetzhanov et al., 2007; Surlyk et al., 2008). The bottom-current channels are most commonly produced by along-slope currents and exhibit less steep levees (Faugères et al., 1999; Habgood et al., 2003) while the turbidity channel can be identified by a deep erosional surface and rather steep levees (Faugères et al., 1999; Habgood et al., 2003). It is notable in this study that the orientation of the main channel system is down-slope towards the south (Fig. 1-8). The studied channel can thus represent a conduit for density flows. If density flows become sufficiently diluted and turbulent, they will convert into the turbidite flows and will run for some distance along channel axis (Hampton, 1972;

Ferentinos et al., 1988; Weirich, 1989; Nemec, 1990; Surlyk, 2008). In this case, a steep levee in result of overflow would be expected (Surlyk, 2008). However, such levees have been observed in the large channel A only in the proximal part (see Fig. 1-5 section A-A' to C-C'). A clear sinuosity of the channel (see Fig. 1-6a), a highly downward incision, well-defined inner-levee in outer bends of channel thalweg, and the development of master-levee on both flanks (Fig. 1-6b), indicate a turbulent erosive flow as the initiation process for the development of channel A. Thus, based on the channel system geometry and morphological comparison with the similar features described in the literature (e.g. Normark, 1970; Deptuck et al., 2003, 2007; Posamentier, 2003; Heiniö and Davies, 2007; Kolla et al., 2007) the mapped channel system A can be interpreted as gravity driven turbidite system.

The observation of the down-slope channel system (channel A) produced by turbidite currents and along-slope processes occurred as a result of mass-transport are pointed to interaction between down-slope and along-slope sediment transport mechanism in the study area (e.g. Stow et al., 1998; Faugères et al., 1999; Esmerode et al., 2008). The inferred further geological development of the channel system from old to young as interpreted from the seismic data is illustrated on figure 1-8. This figure illustrates that the channel A flows from north to south in the master valley between the Bo-Jens Ridge and Adda Ridge. Near the termination of the channel A, a SE-NW mass-transport with downslope direction entered into channel A from eastern master-levee. The inversion tectonics might have caused the instability and failure of slope sediment of the NE flank of Tyra-Igor Ridge, and triggered downslope mass-movement (Fig. 1-8b).

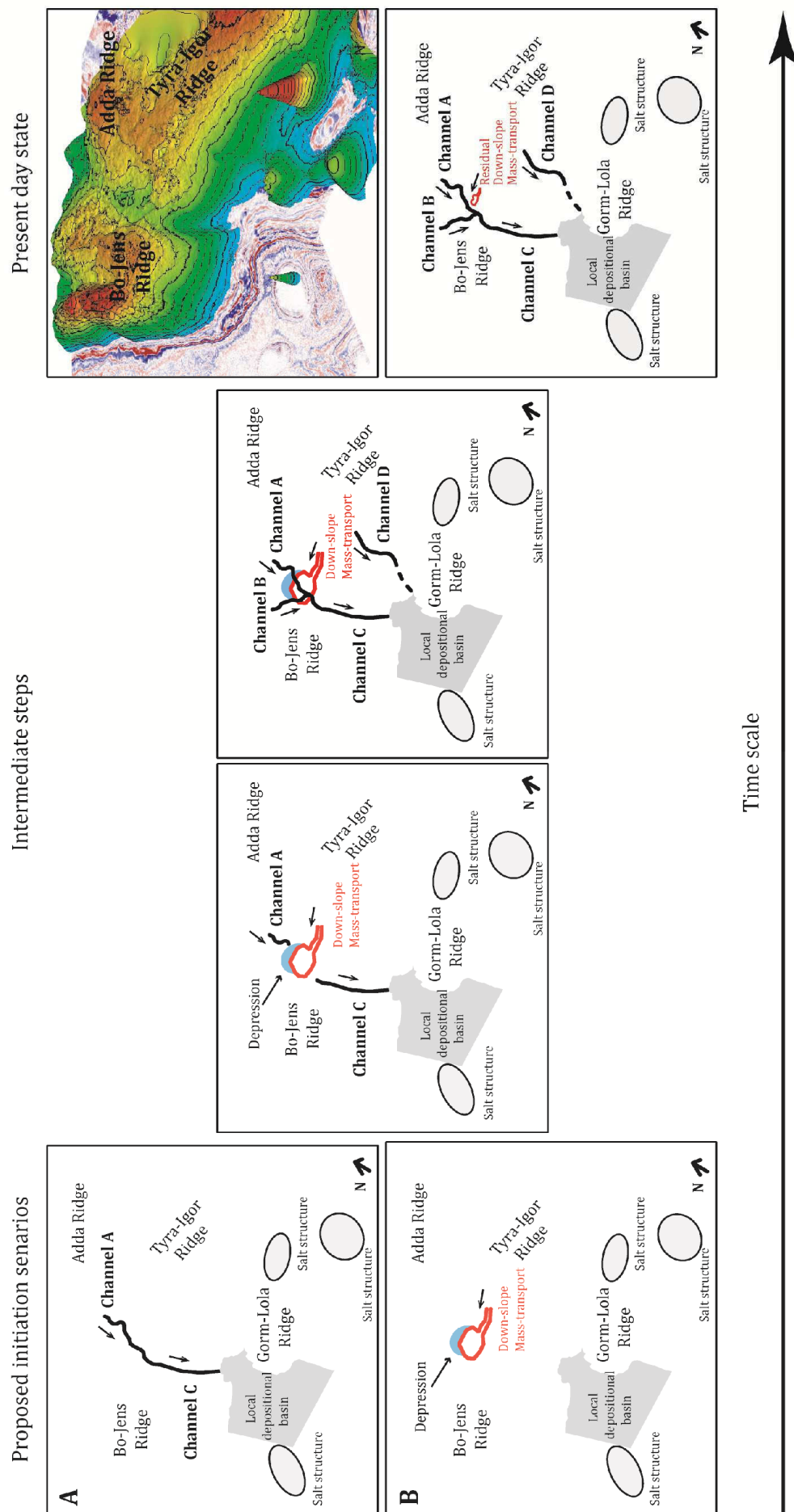


Figure 1- 8 Summary of the channel development of the studied chalk through time.

Further downslope channels A, B and C deposit their load in the local depositional basin in the west of Gorm-Lola Ridge. Figure 1-8 also illustrates that the NE-SW oriented channel D in the southern part of study area is also terminating in a local depositional basin created by salt structure.

A final observation to discuss about the channel system (channel A plus channel C) is the channel infill. The rising ridges and the increasing slope inclination during inversion could have led to an instability of sediments, triggering gravity-driven redeposition in the channel system (e.g. sensu Hansen et al., 2004). Consequently, the channel locally could have been feed by the mass-transport material, slump or slide that came from active ridges (Bo-Jens Ridge, Adda Ridge and Tyra Igor Ridge). However, channels A and C are characterized by steep master-levee (see Fig. 1-5). Thus, the channel fill might be alternatively provided by material derived from steep channel wall.

Conclusions

High resolution 3D seismic data of the southern Danish North Sea show that the intra-Chalk channel systems is created by down-slope gravity driven turbidite currents. A clear sinuosity of the channel, well-defined inner-levee in outer bends of channel thalweg, and the development of master-levee on both flanks, which is indicating that turbulent erosive flows form the initial mechanism for the channel system development. The current direction analysis demonstrates channel always follows the course of the structurally defined depressions. The stable location of the channel indicates the channel system was controlled by actively rising ridges. Thus the channel development in the area between ridges in the northern and central part

of the study area is controlled by synsedimentary inversion event and in the southern part, the channel development is being restricted by synsedimentary salt movement. Locally between ridges, the channel is fed by slumped material derived from active ridges (Bo-Jens Ridge in the west, Adda Ridge in the northeast, Tyra Igor Ridge in the east and Gorm-Lola Ridge) or channel infill by the material derived from steep channel wall collapse.

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Chapter II

Buried pockmarks on the Top Chalk Surface of the Danish North Sea and their potential significance for interpreting palaeocirculation patterns

Buried pockmarks on the Top Chalk Surface of the Danish North Sea and their potential significance for interpreting palaeocirculation patterns

Abstract

Three-dimensional (3D) seismic data from the southern Danish North Sea were used to analyse the morphology and spatial distribution of depressions in the Danian chalk deposit. Previously these depressions were either interpreted as karst structures or pockmarks.

The observed depressions occur in an interval from 25 ms below to 12 ms above the Top Chalk surface. Three types of depressions were differentiated based on their plan view geometry and their degree of symmetry: Type 1, comprising sub-circular and symmetrical depressions, is the dominant group (ca. 70%). Type 2, elongated and symmetrical depressions, represents only a small fraction (ca. 5%). The elongated and asymmetrical depressions of Type 3 compose ca. 25%. In cross section, each depression type can be either characterized by a V- or a U-shape. The maximum size of the depressions ranges from 50 m to 580 m, with an average internal depth of 10 m. We interpret the depressions as pockmarks formed by the expulsion of biogenic or thermogenic fluids at the Danian sea floor. Likely, the initial form of the pockmarks has been circular (Type 1) and was subsequently modified for Type 2 and 3 to an elongated form by currents. The long axis of the pockmarks is interpreted to represent the effective current direction. The inferred direction is sub-parallel to the palaeobathymetric contours.

The 3D seismic interpretation of pockmarks presented in this paper contributes to the understanding of fluid-migration and palaeocirculation patterns during the sedimentation of the terminal Chalk Group in the southern Danish North Sea.

Keywords: Top Chalk, Pockmark, Chalk Group, bottom current

Introduction

The Upper Cretaceous to lower Palaeogene Chalk Group of Northwest Europe represents a period in the Earth's history when a high eustatic sea level, coinciding with a relatively low detrital influx, permitted biogenic sedimentation mainly of pelagic origin on the continental shelves (Hancock, 1975; Kennedy, 1987; Surlyk, 1997; Surlyk et al., 2003; van der Molen et al., 2005; Esmerode et al., 2008). Chalk deposition is classically assumed to represent the settlement of calcareous ooze from suspension, draping pre-existing submarine morphology by a monotonous 'blanket deposit' with mainly parallel bedding relationships and high lateral continuity (for a critical discussion see, e.g. Evans et al., 2003; Surlyk et al., 2008). However, redeposited, less homogeneous chalk sediments have also been identified in the past, mainly in and adjacent to tectonically active areas (e.g. Hardman, 1982; Brewster and Dangerfield, 1984; Hatton, 1986; Bromley and Ekdale, 1987; Cartwright, 1989; Clausen and Huuse, 1999; Evans et al., 2003; Lykke-Andersen and Surlyk, 2004; van der Molen et al., 2005). Recently the observation of highly discontinuous reflection patterns on 2D and 3D seismic-reflection data from the NW European Chalk Group initiated a revision of some general ideas about the chalk deposition, proposing that strong oceanic currents and large-scale gravitational

processes led to the development of a significant discontinuity within chalk strata (e.g. Lykke-Andersen and Surlyk, 2004; van der Molen et al., 2005; Surlyk and Lykke-Andersen, 2007; Esmerode et al., 2007; Esmerode et al., 2008; Surlyk et al., 2008; Back et al., 2011).

The top surface of the Chalk Group, one of the most important unconformities in the North Sea Basin, is characterised as the surface that separates the Upper Cretaceous–Danian Chalk Group from succeeding siliciclastic deposition (Clausen and Huuse, 1999). Morphologic depression features on the Top Chalk surface of the Norwegian-Danish Basin and in the Central Graben were previously identified in 2D and 3D seismic data and interpreted alternatively as karst features (e.g. Clausen and Huuse, 1999) or pockmarks (Gemmer et al., 2002).

Pockmarks are crater-like depressions on the sea floor often originating from seepage of gas or interstitial liquids (King and MacLean, 1970; Hovland, 1982, 1984; Hovland and Judd, 1988; Van Weering et al., 1997; Judd and Hovland, 2007). Their morphology can be modified by eroding bottom currents (Hovland, 1983, 1984). Andresen et al. (2008) described mid-Oligocene and late Miocene, highly elongated pockmarks in the Danish part of the Central Graben. They interpreted these depressions mainly as a product of fluid expulsion and subsequent erosion by bottom currents. Buried pockmarks hence can be used to reconstruct palaeo-fluid migration pathways (Heggland, 1998; Hovland et al., 2002; Andresen et al., 2008) and a detailed morphologic interpretation of pockmarks allows a reconstruction of bottom-current directions. Within this study, more than 170 depressions in an interval immediately below and above the Top Chalk surface in the southeastern Danish

Central Graben were mapped from seismic data (Fig. 2-1). The detailed analysis of their 3D morphology contributes to the understanding of palaeocirculation patterns during the sedimentation of the terminal Chalk Group in the southern Danish North Sea.

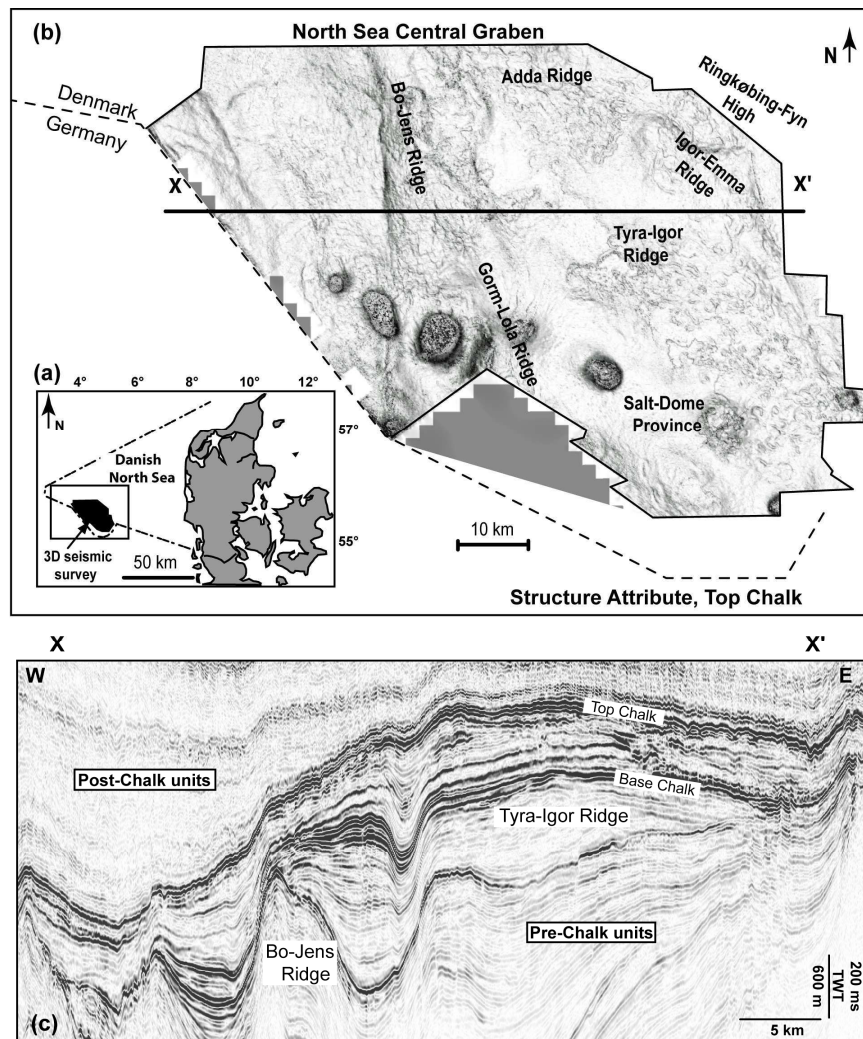


Figure 2-1 a) Location of the study area in the Danish North Sea Central Graben. b) Structure-attribute map (horizon slice) of the Top Chalk surface generated from 3D seismic-reflection data. The black horizontal line indicates the position of the seismic-reflectivity line shown below. c) Vertical reflectivity section illustrating the base and top of the Chalk Group.

Geological setting

The study area is located in the south of the Danish North Sea Central Graben, which consists of a system of generally NNW–SSE-trending half-grabens bounded by the

Coffee-Soil Fault to the east. The study area encompasses the Tyra-Igor and Igor-Emma Ridges in the east, the Bo-Jens and Adda Ridges in the north, and the Danish Salt Dome province in the south (Fig. 2-1). The interval under study is the Chalk Group that spreads over the Central North Sea and extends into the south Viking Graben and onto the east Shetland Platform (Surlyk et al., 2003). It is of Cenomanian to Danian age and is commonly 1-2 km thick in the Graben areas (Japsen 1998; Surlyk et al., 2003; Vejbæk et al., 2007). The sediments mainly consist of pure chalk and limestone, marly chalk, marl and calcareous shale (Hardman, 1982; Surlyk et al., 2003). The Chalk Group can be subdivided into the Hydra, Blodøks, Plenus Marl, Hod, Tor and Ekofisk formations (Fig. 2-2). The Ekofisk Formation forms the uppermost part of the Chalk Group. It is of earliest Palaeocene (Danian) age and consists of fine-grained, strongly bioturbated chalky limestone with interbedded mudstone (Mortimer, 1987; Surlyk et al., 2003). The top of the Chalk Group forms a prominent seismic marker across the Central North Sea that represents the changeover to siliciclastic sedimentation in the middle Palaeocene (Morton et al., 1993).

Chalk itself is a cool-water carbonate sediment, consisting predominantly of coccoliths with minor components of foraminifera and calcispheres. During the Late Cretaceous-Early Palaeocene sea-level highstand these sediments were deposited in water-depth of up to several hundred meters within an epeiric sea that flooded most of NW Europe (Gemmer et al., 2002; Surlyk et al., 2003). Chalk deposition was highly dynamic, with large-scale gravity flows and bottom-current activity creating considerable sea-floor morphologies such as channels, drifts and moats (Lykke-Andersen and Surlyk, 2004; van der Molen et al., 2005; Surlyk and Lykke-Andersen, 2007; Esmerode et al., 2007; Esmerode et al., 2008; Surlyk et al., 2008; Back et al.,

2011; Gennaro et al., 2013). Seismic evidence indicates the presence of contour-parallel bottom currents that possibly belonged to a circulation system connecting the Tethyan with the Boreal realm. Fluctuations in the intensity of these currents are thought to be due to eustatic sea-level variations and synsedimentary tectonic movements (Lykke-Andersen and Surlyk, 2004; Surlyk and Lykke-Andersen, 2007; Esmerode et al., 2007).

The deposition of the Chalk Group was greatly influenced by halokinetic movements and fault-controlled subsidence or inversion (Kennedy, 1980; Watts et al., 1980; Hardman, 1982; Brewster and Dangerfield, 1984; Munns, 1985; Hatton, 1986; Bromley and Ekdale, 1987; Barmwell et al., 1999; Farmer and Barkved, 1999; Surlyk et al., 2003). Most of the inversion is believed to have occurred during the deposition of the Chalk Group (Fig. 2-2), as indicated by the termination of most reverse faults below the top surface of the Chalk Group (Vejbæk and Andersen, 1987). Several inversion events took place during the Late Cretaceous and some minor inversion tectonism occurred more or less continuously between these major events (Vejbæk and Andersen, 1987; Cartwright, 1989). The southern part of the Danish Central Through was mainly affected by inversion during the mid-Maastrichtian and in the early Tertiary after the end of chalk sedimentation (Van Hoorn, 1987; Van Wijhe, 1987). Halokinetic movements started during the Triassic and intrusive activity continued throughout the Late Cretaceous, resulting in the formation of salt pillows, domes, ridges and diapirs (Surlyk et al., 2003).

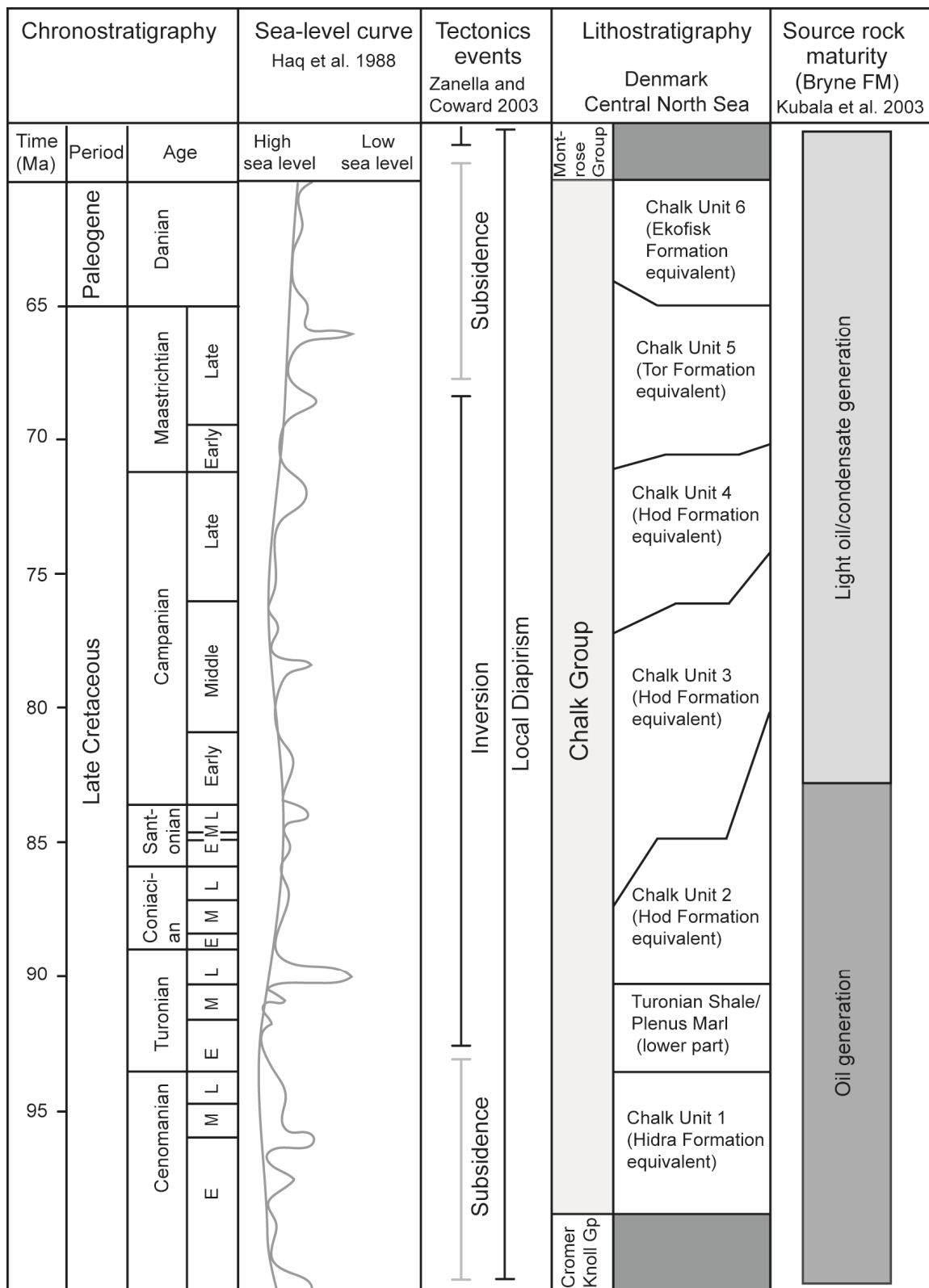


Figure 2-2 Chronostratigraphic and lithological context of the Upper Cretaceous succession (after Deegan and Scull, 1977; Lieberkind et al., 1982; Isaksen and Tonstad, 1989; Johnson and Lott, 1993). Chalk deposition was greatly influenced by halokinesis in addition to local fault-controlled subsidence or inversion (Zanella and Coward, 2003) and sea level (Haq et al., 1988). Also shown is the source rock maturity of the Bryne Formation (after Kubala et al., 2003).

The Upper Jurassic sedimentary succession of the North Sea (i.e. the Kimmeridge Clay Formation) is the primary source rock for the North Sea, and is in vast areas mature for oil or gas generation (Surlyk et al., 2003; Kubala et al., 2003; Johnson et al., 2005). In the Danish part of the North Sea, the Farsund Formation is the stratigraphic equivalent of the Kimmeridge Clay (Kubala et al., 2003) and covers the entire Danish Central Graben excluding some structural highs (Hemmet , 2005). The Farsund Formation was mature for oil generation at 40 Ma (Eocene) and advanced in this window until 25 Ma (Andresen et al., 2008). In the Miocene the Farsund Formation source rock progressed into the light oil / condensate window, and in Pliocene it started to produce gas (Kubala et al., 2003; Andresen et al., 2008). An additional source rock potential was assigned to the Lola Formation (lower Upper Jurassic), the Lulu Formation (upper Middle Jurassic) and the Middle Jurassic Bryne Formation (Kubala et al., 2003; Petersen et al., 2008) (Fig. 2-3). The Lola Formation reaches up to 700 m thickness in the Central North Sea and is late to post-mature for oil generation in the Central Graben (Kubala et al., 2003).

The Middle Jurassic Bryne Formation acts as a source rock for the reservoir rocks of the Upper Cretaceous/Danian (Kubala et al., 2003). The Bryne Formation consists of fluvial deltaic sandstones interbedded with siltstones, mudstones and coals (Hemmet, 2005). The Bryne Formation became mature for oil generation at about 145 Ma and progressed through the oil windows until about 83 Ma (early Cretaceous). Since then the Bryne Formation generated light oil / condensate (Fig. 2-2) until the onset of gas generation during the early Oligocene (Kubala et al., 2003).

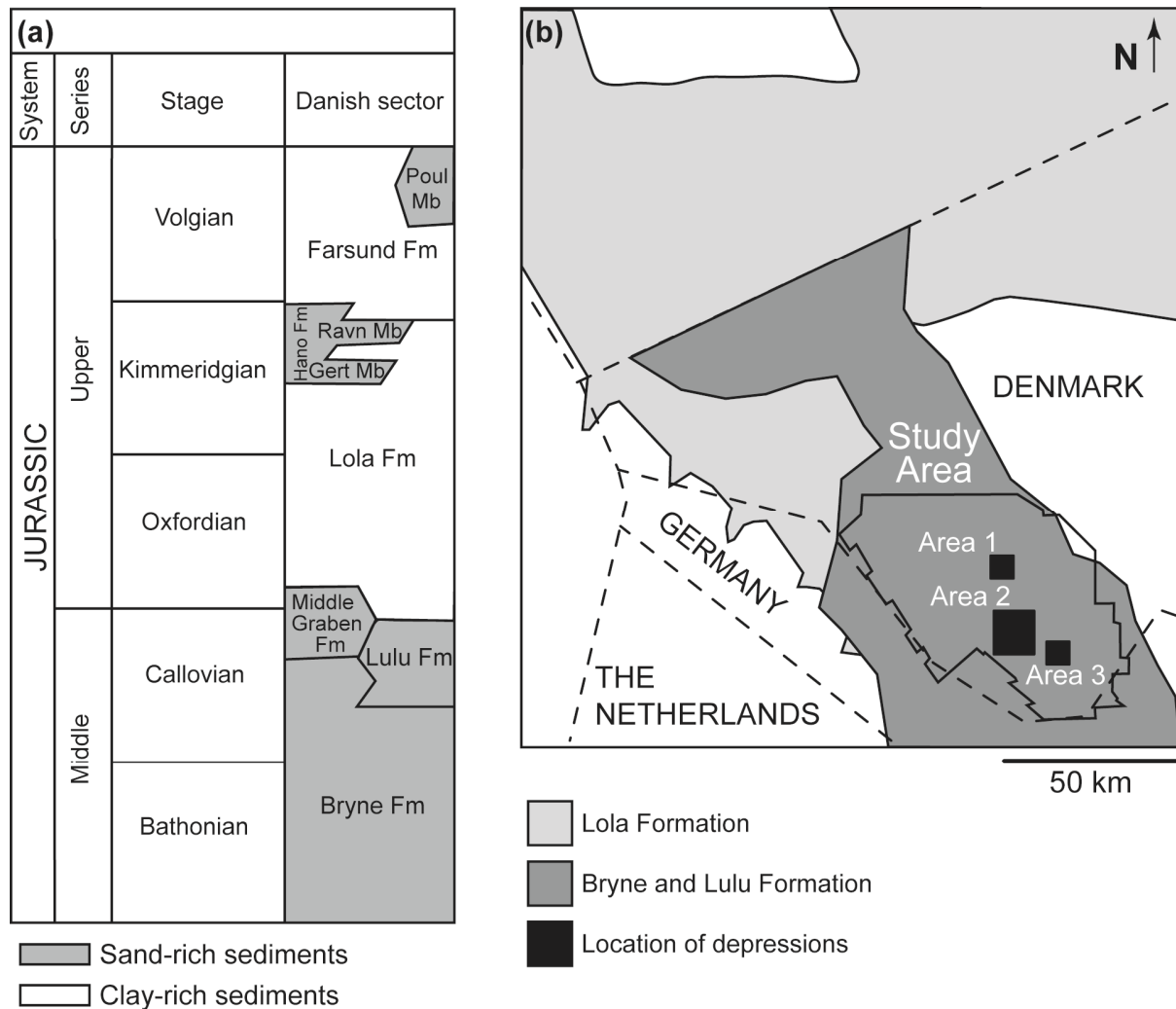


Figure 2-3 a) Middle and Upper Jurassic lithostratigraphy from the Danish sector of the Central Graben, North Sea (after Michelsen et al., 2003). b) Location of depressions with respect to potential source rocks (after Kubala et al., 2003).

Database and Methodology

The database of this study comprises ca. 2000 km² of 3D multichannel seismic-reflection data processed in zero phase following European polarity convention, i.e. an increase in acoustic impedance is represented by a reflectivity trough. The bin spacing of the 3D seismic survey is 25 m in inline and crossline directions, and the vertical sampling rate of the data is 4 ms. The strong impedance contrast between the studied Chalk units and the overlying clastic sediments results in a high

detectability (visibility sensu Brown, 1999) of a few meters. Further detailed analyses of the most prominent lateral seismic discontinuities in the data were carried out on a Landmark structure attribute volume (3x3 traces and 4 samples). Density, gamma-ray and velocity well logs from several wells within the study area were used to identify the seismic-reflection response of the Top Chalk surface (seismic-to-well tie: Fig. 2-4).

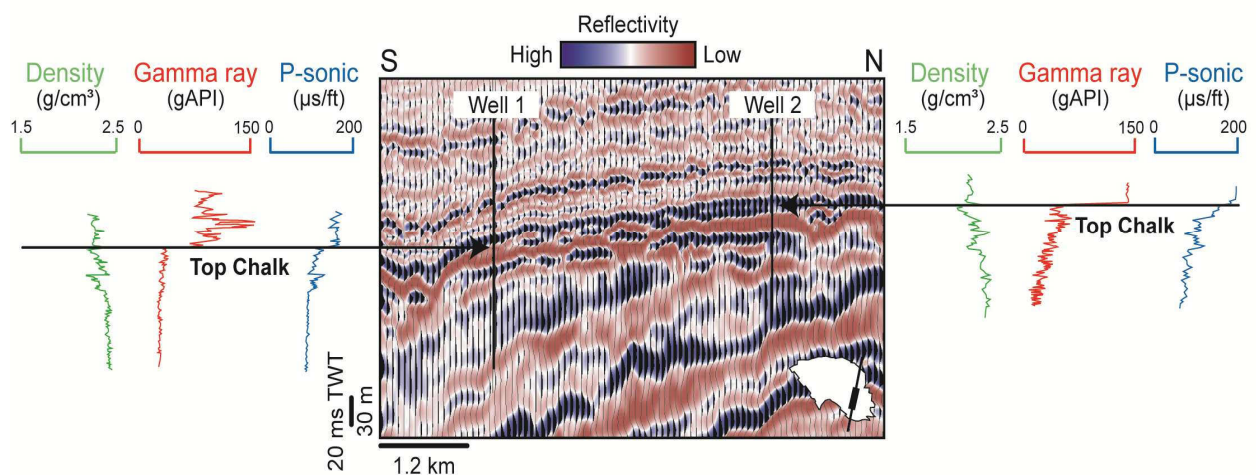


Figure 2-4 Seismic-to-well tie for the Top Chalk surface. The Top Chalk surface is characterized by an upward increase in gamma-ray, density and interval transit-time. On reflectivity data, this change commonly coincides with a seismic trough (well 1). In gas-affected areas, the continuity and amplitude of the reflection peak can be reduced or a polarity reversal can occur (well 2).

Circular to elongate morphological depressions on the seismic data of the Top Chalk surface were interpreted in detail using seismic cross-sections and horizon slices. Based on their ellipticity the depressions were classified in two end-member categories, 1) sub-circular and 2) elongate. This subdivision is based on the ellipticity index (length of long axis / length of short axis). The sub-circular depressions have an ellipticity index < 1.1 . A higher ellipticity index characterises elongate depressions. The degree of symmetry and their cross-sectional geometries (U- or V-shaped) were

evaluated qualitatively from vertically exaggerated seismic profiles. The respective lengths of the long and short axes were measured on structural attribute map displays. The direction of the long axes was used to calculate the orientation of the high elongate depressions. The depth of the depressions was measured on seismic cross sections as vertical distance between the deepest point and a straight line connecting the flanks of the depressions. Finally the TWT measurements were converted to meters by using well-velocities.

Results

This study focuses on the top of the Chalk Group as key interpretation target. This surface (Top Chalk) is interpreted to have formed at the end of the Danian when first siliciclastic sediments were introduced to the basin (Surlyk et al., 2003). Density and gamma ray logs were used to identify the seismic expression of this lithological change (e.g. Fig. 2-4). The Chalk Group deposits are characterized by generally low gamma-ray values that can increase slightly towards the top of the Chalk Group. The lithologic boundary to the post-Danian siliciclastics is marked by a rapid shift to high gamma-ray values. Density logs in the Chalk Group commonly show a progressive upward decrease with relatively low values within the terminal Chalk unit. Sonic logs are marked at Top Chalk level by a rapid upward increase in the interval transit-time (decrease in velocity). This velocity change commonly coincides with a trough in reflectivity on seismic cross-sections that was used for the interpretation of the Top Chalk surface (Fig. 2-4, well 1). In gas-affected areas, where the continuity and amplitude of the reflection peak was reduced or a polarity reversal was encountered (Fig. 2-4, well 2), gamma-ray logs were used to identify the Top Chalk surface.

The structure-attribute map generated for the Top Chalk surface (Fig. 2-5) shows clusters of isolated depressions. About 20 depression features can be found in the southwest of the Tyra-Igor Ridge (Fig. 2-5, Area 1). A total of ~140 depression features were identified around the Skjold salt-diapir. These depressions are distributed on the northwestern, southwestern and southeastern flanks of the Skjold salt-diapir (Fig. 2-5, Area 2). About 10 depressions were found on the southwestern flank of the Dan salt structure (Fig. 2-5, Area 3).

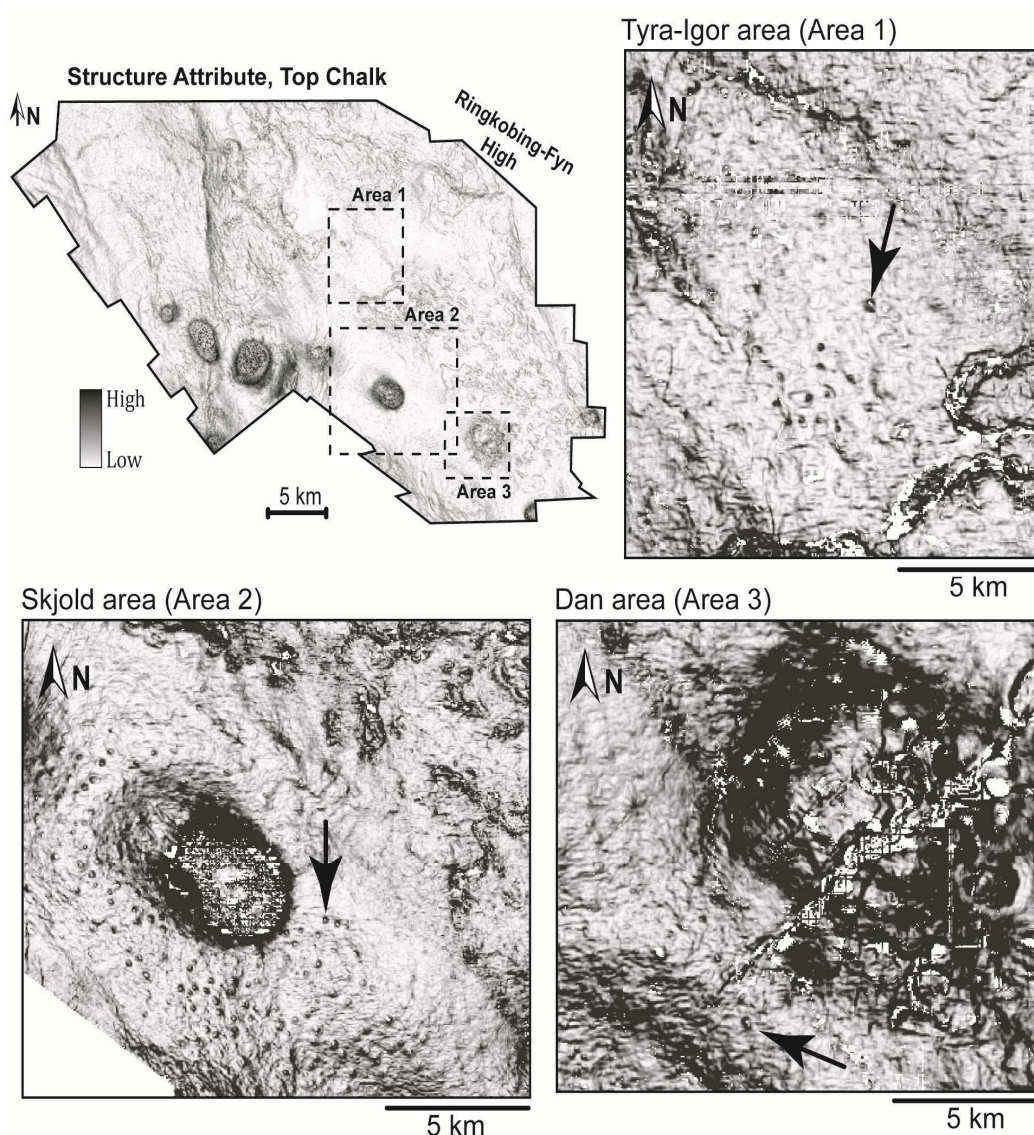


Figure 2-5 Structure-attribute maps of the Top Chalk surface within the study area. Depressions cluster in three areas: southwest of the Tyra-Igor Ridge (Area 1), the northwestern, southwestern and southeastern flanks of the Skjold salt-diapir (Area 2) and the southwestern flank of the Dan salt structure (Area 3). Black arrows exemplarily point to individual depressions.

All depressions appear concurrently within an interval from about 25 ms TWT below to about 12 ms TWT above the Top Chalk surface (Fig. 2-6).

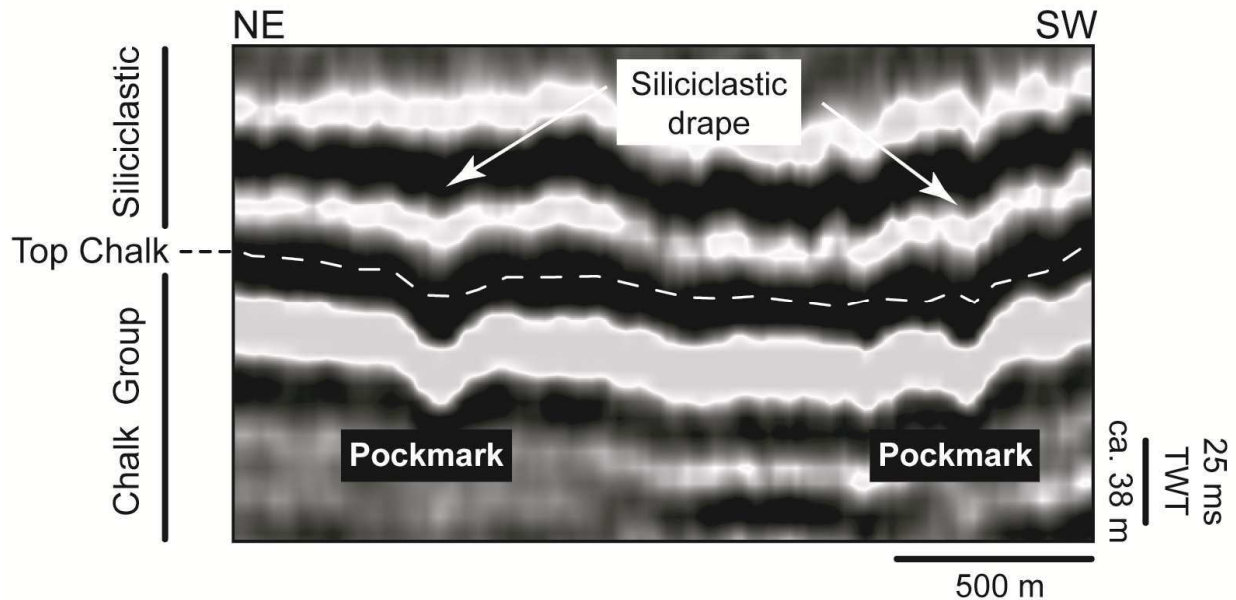


Figure 2-6 Seismic cross section showing that the depressions are reduced in depth above the Top Chalk surface. This is interpreted as a passive drape of the pockmark morphology by post-Danian siliciclastic sediments.

In plan view the shape of the depressions varies from sub-circular to elongate (Figs. 2-7, 2-8 and 2-9a). The degree of symmetry was evaluated for all depressions based on the position of their deepest point on cross sections. Elongate depressions were classified as symmetrical or asymmetrical, if their deepest point was located on or off the middle of their long axis respectively. The deepest point of sub-circular depressions is always located in their centre (Figs. 2-7 and 2-8). On vertical cross-sections, the depressions are usually characterized by well-defined, smooth basal reflectors (Fig. 2-7); however in exceptional cases the depressions can show a rough, irregular and wavy base. The depressions do not show any internal reflector due to the limited seismic resolution or a homogenous infill with no internal stratification. The geometry of the depressions varies gradually (Fig. 2-9), but based

on their geometry in plan view and their degree of symmetry, three different end-member types could be defined. Additionally, each of these depression types can either have a V- or a U-shape in cross section (Figs. 2-7 and 2-8).

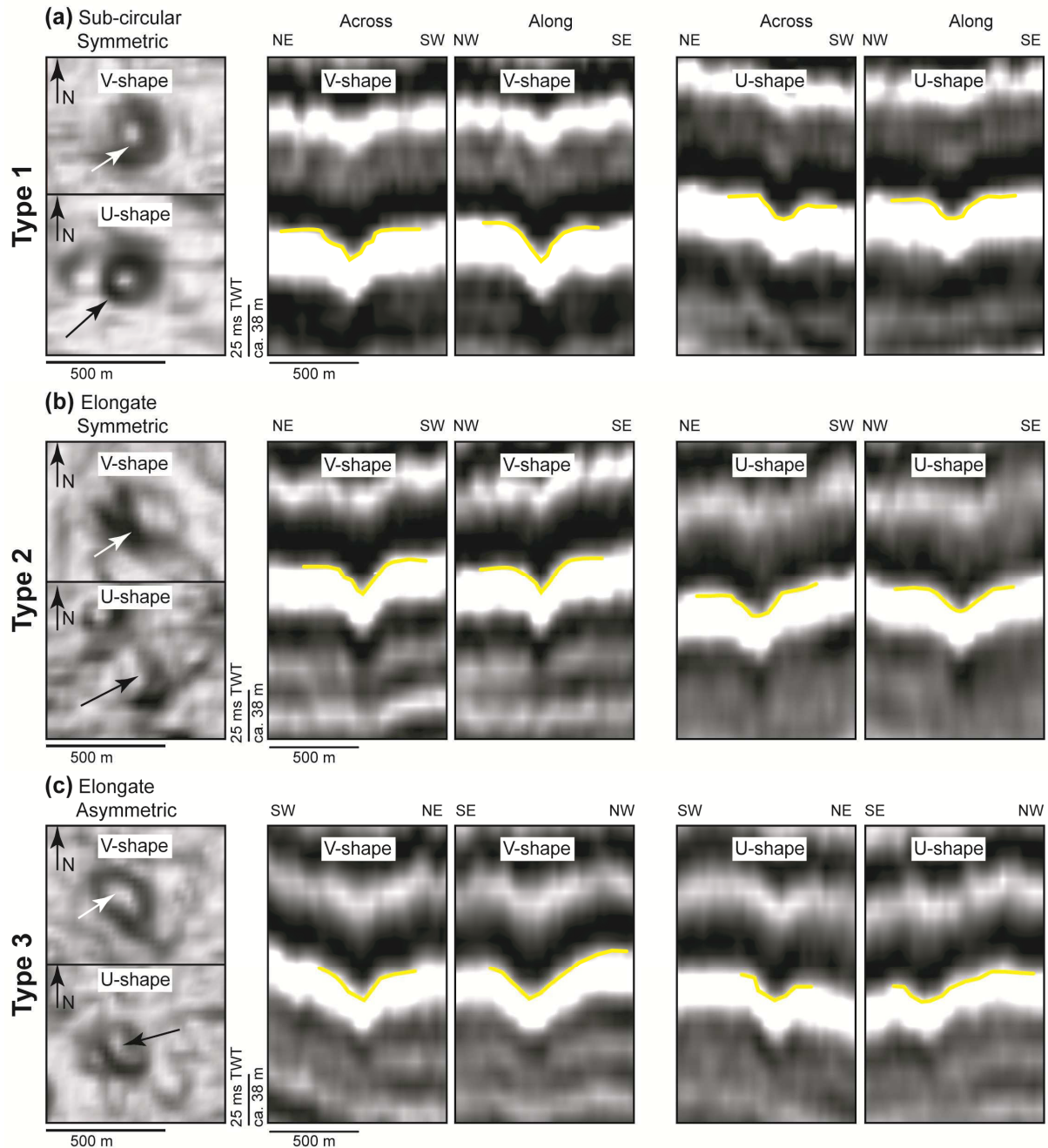


Figure 2-7 Structure attribute maps and seismic sections along and across typical depressions: a) Sub-circular and symmetrical depressions (Type 1); b) Elongate and symmetrical depressions (Type 2); c) Elongate and asymmetrical depressions (Type 3). All depression types can either appear as U- or V-shaped in cross-section.

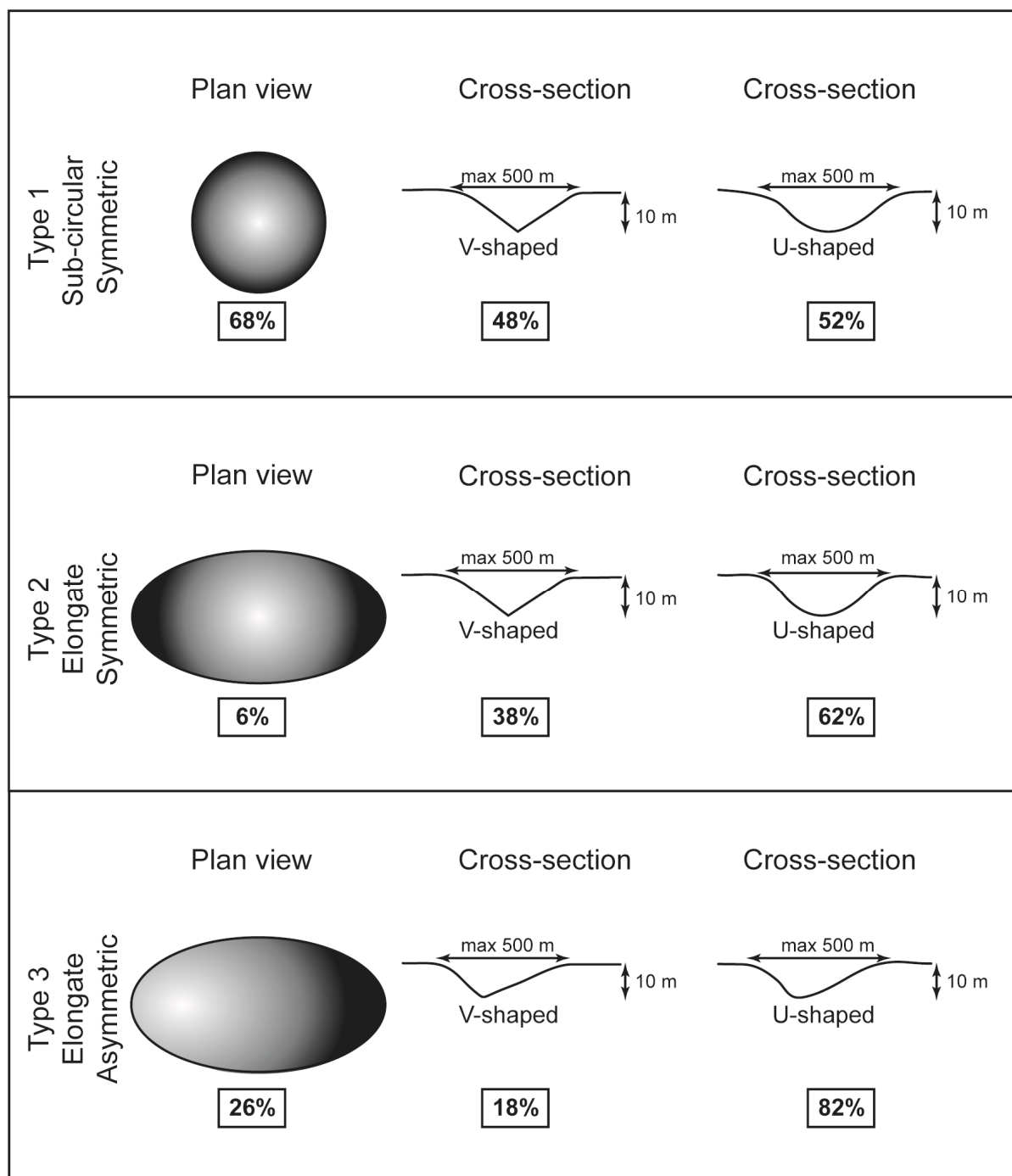


Figure 2-8 Schematic plan view geometry and cross-section shape of the three end-member types of depression and their relative abundance in the study area.

Depression Type 1 comprising sub-circular and symmetrical depressions is the most abundant group (68%) of depression in the study area. Within this group, U-shaped cross sections are only slightly more common (52%) than V-shaped ones (48%).

Depression Type 2, elongate and symmetrical depressions, form only a small fraction (6%). Of this type, 62% are characterized by a U-shape. Type 3, elongate and asymmetric depressions, form 26% of all depressions. U-shaped cross-section predominate (82%) this group (Fig. 2-8).

In the Skjold area, the diameters of Type 1 depressions range from 50 m to 460 m, with an average of ~ 160 m. The length of the short axis of Type 2 and 3 depressions varies between 70 m and 400 m, with a significantly ($p < 0.05$) but only somewhat higher average of ~ 200 m (Fig. 2-9). The length of the long axis of Type 2 and 3 is larger than the diameter of Type 1 ranging from 110 m to 580 m, with a significantly ($p < 0.05$) larger mean of ~ 280 m (Fig. 2-9). The ellipticity index of Type 2 and 3 depressions ranges from 1.1 to 2.7, with a mean of around 1.5 (Fig. 2-9). The long axes of depression Type 2 and 3 depressions are oriented either SE-NW (140° - 160° , 74%) or E-W (90° - 100° , 26%; Fig. 2-9).

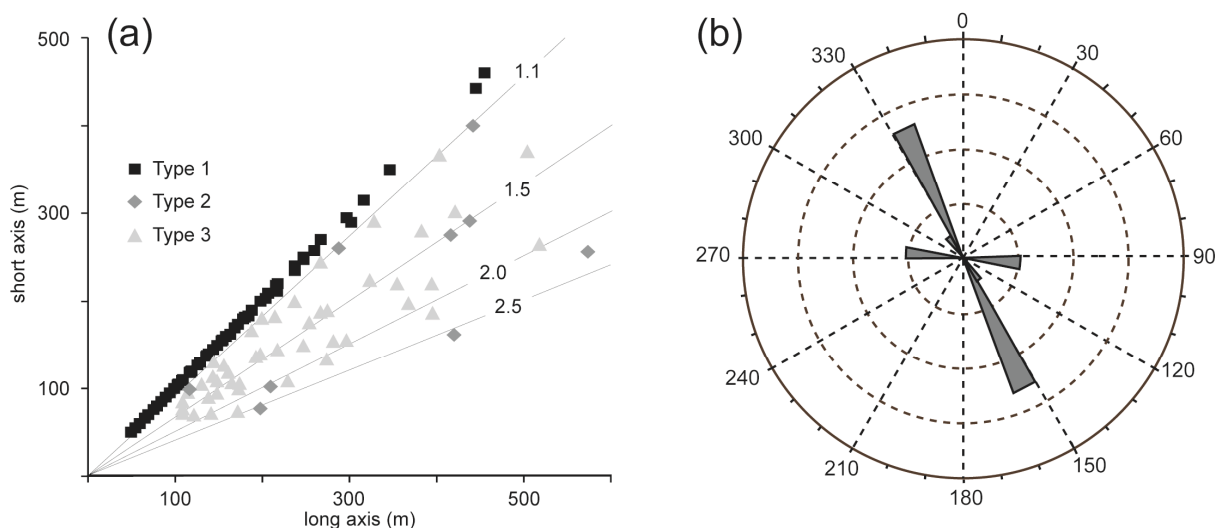


Figure 2-9 a) Plot of long vs. short axes length for all depressions from the Skjold and Dan area. Ellipticity indices from 1.1 to 2.5 are shown as straight lines. b) Long axes orientation of the elongate depressions. The majority (74%) of the long axes strike 140° - 160° (NW-SE) and the minority (26%) strike 90° - 100° or (W- E).

The deepest point within the SE-NW (E-W) oriented depressions of Type 3 is located towards the SE or E with respect to their centre. The sub-circular depressions of Type 1 are located near the salt-diapir in the Skjold area. Most of the elongate ones of Type 2 and 3 with U-shaped are placed further away from the salt-diapir (Fig. 2-10). The depth of the Skjold area depressions is about 10 m for all three types.

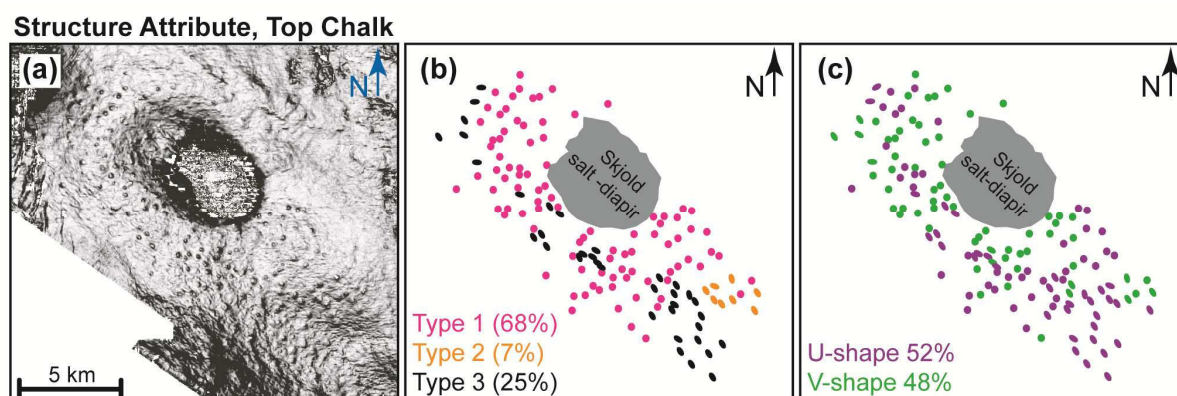


Figure 2-10 a) Structure attribute map of the Top Chalk surface in the Skjold salt-diapir area. b) Distribution of the three different depression types. The sub-circular depressions of Type 1 are dominantly located near the salt-diapir. Most of the elongate ones of Type 2 and 3 occur on the SW flank or further away from the salt diapir. c) Distribution of different cross-sectional shapes. U- and V-shapes are nearly equally common in Type 1 depressions, but U-shapes clearly dominate depression Type 2 and 3.

All depressions of the Tyra area belong to Type 1 and are characterized by U-shaped cross sections. They are significantly ($p < 0.05$) smaller if compared to the other areas, with a diameter ranging from 60 m to 155 m and a mean of around 120 m. The average depth of the Tyra depressions is ca. 10 m. All depressions close to the Dan salt structure belong to Type 3 and are characterized by U-shaped cross sections. The length of their long axes varies from 125 m to 270 m, with an average of 180 m (Fig. 2-9). The length of their short axes varies from 70 m to 190 m, with an average of 120 m (Fig. 2-9). Their ellipticity index ranges from 1.3 to 2 (Fig. 2-9). Their mean ellipticity index of around 1.6 is not significantly different ($p > 0.05$) from Type 2 and 3

depressions in the Skjold area. All long axes of the depressions are oriented SE-NW (150°-160°; Fig. 2-9). Their deepest point is located towards the SE with respect to their centre, and the depth of the depressions is also around 10 m.

Discussion

Previously, depression features at Top Chalk level in the Norwegian-Danish Basin and the Danish Central Graben were interpreted as pockmarks (Gemmer et al., 2002) or karst phenomena (Clausen and Huuse, 1999; Huuse, 2001), since both processes are able to generate sub-circular structures visible on 3D seismic data (Stewart, 1999; Rosleff-Soerensen et al., 2012). Geodynamic modelling of the Mid-Palaeocene palaeogeography by Gemmer et al. (2002) indicated palaeo-water depths of several hundred meters in the southeastern Danish Central Graben. Therefore Gemmer et al. (2002) ruled out karst related to subaerial exposure as a possible explanation for the formation of the depressions. However, subsurface hypogenic karstification can create very similar morphologies to subaerial epi-karst and can occur independently of the palaeogeographical setting. Hypogenic karst is characterized by dissolution, where aggressive fluids are continuously delivered to the dissolution front (Palmer, 1991; Tóth, 1999) often in the vicinity of fault and fracture systems overlain by impermeable facies (Immenhauser et al., 2007). In the Tyra area, the depressions are located in close proximity to a major fault system. This fault seems to have been an active fluid pathway since at least Eocene times (Fehmers et al., 2012). In the Skjold and Dan areas, however, horizon-slice data in structure attribute display show no direct connection between the observed depression features and seismically resolved faults (Fig. 2-11). If aggressive fluids

ascending along fault or fracture networks would be responsible for depression formation, we would expect these to be clustered along lineaments. In contrast, we observe isolated depressions that do not show a linear arrangement (see Fig. 2-5).

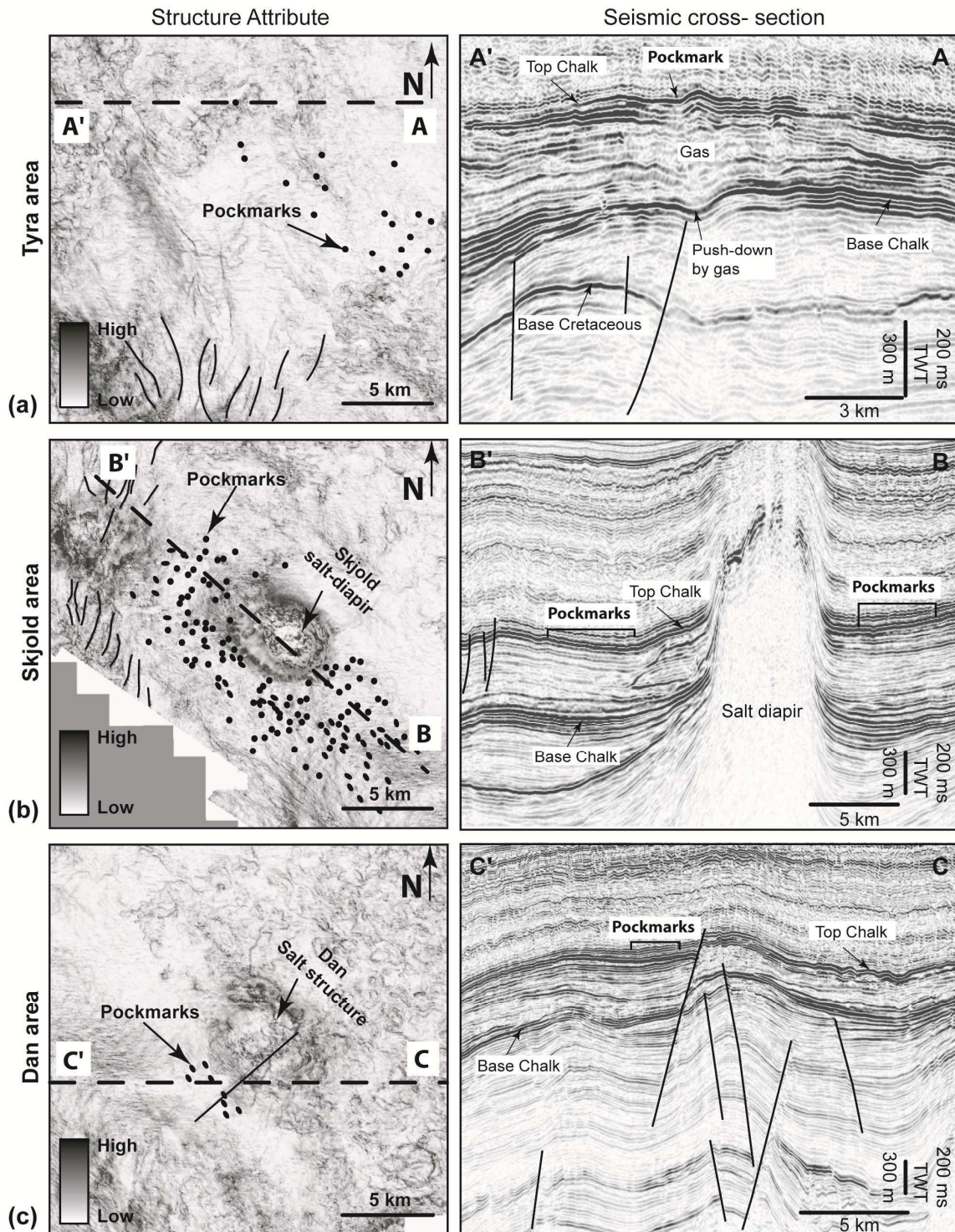


Figure 2-11 Structure attribute maps 25 ms (TWT) below Top Chalk, and vertical seismic reflectivity sections. Dashed lines indicate location of seismic sections. Solid lines represent

faults. a) Pockmarks in the Tyra area showing a pockmark example possibly related to the migration of thermogenic gas from Middle Jurassic source rocks along faults. b) Pockmarks concentrating around the Skjold salt-diapir. This possibly indicates that the diapir flanks may have focused the vertical migration of overpressured fluids. c) Pockmarks of the Dan area; these pockmarks occur in the vicinity a fault formed above the Dan salt-dome, but trend in a different direction. Gas seepage could have been initiated by salt tectonic movement creating sub-seismic fractures contributing to fluid escape.

The apparent lack of a direct link between faults and depressions therefore likely contradicts an interpretation as hypogenic karst around the Skjold and Dan structures. Thus, based on their palaeobathymetric setting and distribution within the study area and a morphological comparison with similar features described in the literature (Hovland, 1982; Prior et al., 1989; Fader, 1991; Kelley et al., 1994; Bizarro, 1998; Bøe et al., 1998; Heggland, 1998; Huuse, 1999; Stewart, 1999; Cole et al., 2000; Gemmer et al., 2002; Hovland et al., 2002; Çifçi et al., 2003; Ussler et al., 2003; Sumida et al., 2004; Hovland et al., 2005; Gay et al., 2006; Andresen et al., 2008; León et al., 2010) the mapped depressions are here interpreted as palaeo-pockmarks.

All pockmarks appear simultaneously at ca. 25 ms below the Top chalk surface with no apparent difference in timing between the three pockmark types. They can be traced as morphologic depressions up to 12 ms above the Top Chalk surface (Fig. 2-6). However, above the Top Chalk surface, the amplitude of the depressions diminishes continuously until they are unrecognizable in cross-section and map view. It is therefore assumed that the active pockmark formation ceased around the Top Chalk surface. The reduction in amplitude above the Top Chalk surface is interpreted as a later drape and passive infill of the topography created by the pockmarks (Fig. 2-6). The interval down to 25 ms below the Top Chalk surface is situated completely within the Ekofisk Formation, thus dating the pockmark formation to the Danian.

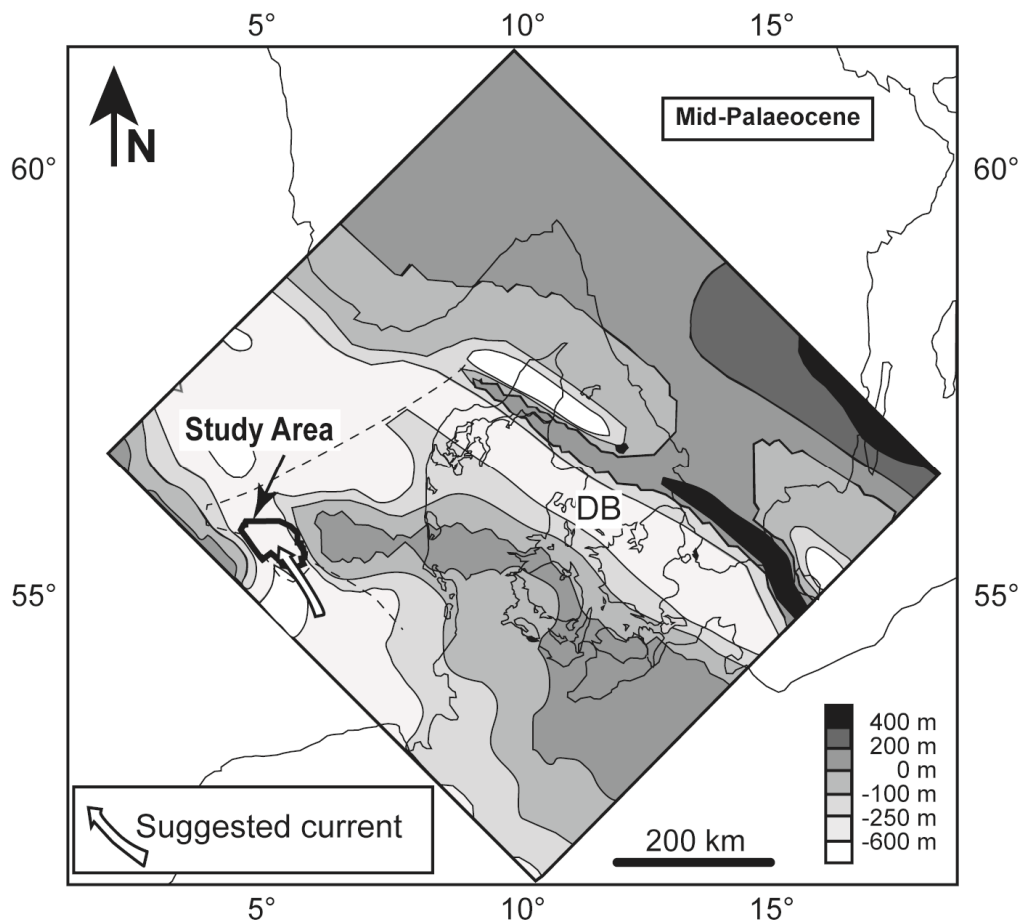


Figure 2-12 Palaeotopographic map of the Top Chalk surface (after Gemmer et al., 2002) with inferred bottom current directions derived from the orientation of the long axes of elongated pockmarks and the asymmetry of Type 3 depressions. Bottom currents of similar orientation were reconstructed for the Maastrichtian of the Danish Basin (DB, Lykke-Andersen and Surlyk, 2004; Surlyk and Lykke-Andersen, 2007).

High seismic amplitudes in the centre of the pockmarks are often interpreted either as accumulation of coarse sediments by gas winnowing or as authigenic carbonate precipitates (Hovland et al., 2002; Andresen et al., 2008). The absence of such reflection anomalies in this study (Fig. 2-12) might instead point to short lived expulsion events, preventing the precipitation of diagenetic cements that are typical for systems active over long time periods (Andresen et al., 2008). Violent fluid escape and rapid pockmark formation takes place when a seal close to the seafloor is breached by accumulating fluids and the associated pressure build-up (Judd and

Hovland, 2007; Hovland et al., 2010). Betzler et al. (2011) point out that fine-grained carbonate sediments in basinal settings could provide a capillary seal (*sensu* Cathles et al., 2010). Such a capillary seal would allow the formation of pressurised gas pockets close to the seafloor in the fine-grained carbonates of the Ekofisk Formation.

Seepage of gas, oil, brine and hydrothermal fluids (Hovland and Judd, 1988; Judd and Hovland, 2007) can generate pockmarks. Some pockmarks are interpreted to have formed by gas hydrate dissociation (Bünz et al., 2003; Gay et al., 2006), but relatively high-pressures and low-temperature are necessary for the formation of gas hydrates. The water–depth within the southeastern Central Graben was estimated to be ~ 250-600 m during the Mid-Palaeocene (Gemmer et al., 2002), and the climate was warm. Thus, the pressure and climate conditions were not favourable for the generation of gas hydrates.

Biogenic gas can form within organic rich sediments during shallow burial (Hovland and Judd 1988). The Quaternary sediments of the Great Australian Bight are lithologically similar to the Upper Cretaceous–Danian limestone of the North Sea (*cf.* Surlyk, 1997). Large concentrations of biogenic methane and hydrogen sulfide were discovered in the shallow subsurface of the Great Australian Bight (Swart et al., 2000). In analogy it seems thus possible that biogenic gas might have been produced from Late Cretaceous and early Palaeocene coccolith ooze that could have led to pockmark creation at the Top Chalk surface (Huuse et al., 2001). Alternatively, thermogenic fluid/gas could have been provided by the maturation of the Jurassic source rock during burial (Jensen and Schmidt, 1993; Danielsen et al., 1997). The pockmarks in the study area in the southern Danish Central Graben are located in a

hydrocarbon producing area. The possible source rocks that were mature for hydrocarbon generation during the Danian were the Bryne Formation and possibly the Lulu and Lola Formations (Kubala et al., 2003; Petersen et al., 2008). These source rocks covered the southern part of the Danish Central Graben (Figs. 2-2 and 2-3) and could have provided light oil and/or condensate by vertical migration. Most of the pockmarks are located around salt structures (see Fig. 2-5), which form potential fluid flow barriers contributing to overpressure build up within the sediments (Kukla et al., 2011). The concentration of pockmarks around salt structures possibly indicates that their flanks may have focused the vertical migration of overpressure fluids (Lewis and Holness, 1996; Reuning et al., 2009; Andresen et al., 2011). In this line of arguments it should be noted that gas sampled in the water column immediately above the "Delta"-salt diapir of the Tommeliten field of the Norwegian sector of the North Sea (Hovland and Judd, 1988) was of thermogenic origin. This example documents that there may exist fluid flow around and also above salt diapirs (Lewis and Holness, 1996; Schroot et al., 2005). It should also be noted that Hovland and Judd (1988) and Judd and Hovland (2007) describe pockmark features and active gas seeps above the buried "Delta"-salt diapir. It has also been suggested that gas seepage could be initiated by salt tectonic movement that can possibly create sub-seismic fractures contributing to fluid escape (Etiope et al., 2006). This mechanism might have facilitated vertical fluid migration in the study area since salt tectonic movements in the central North Sea were active during the entire Late Cretaceous and Palaeocene (Fig. 2-2).

Fehmers et al. (2012) have mapped gas charge for the Tyra Field with consequent discharge in the early Tertiary. Seismic data indicate the presence of vertical gas

chimneys that extend from the Callovian level into the Top Chalk reservoir along a major fault. Fehmers et al. (2012) further documented the presence of limestone stringers in the Eocene-Oligocene units of the Tyra Field. Stable isotope analyses suggest that these limestones possibly formed by organisms supported by venting of methane of (partially?) thermogenic origin. Additionally, Sandrin et al. (2012) showed at Tyra that polygonal faults occur within the Tor Formation (Maastrichtian) below the Top Chalk reservoir (Danian). These structures may have acted as additional pathways for vertically migrating hydrocarbons (Hustoft et al., 2007; Antrett et al., 2012).

In general pockmarks tend to have a circular shape if they are formed by fluid escape from a point source (Hovland et al., 2002; Betzler et al., 2011). The sub-circular pockmarks of Type 1 (Fig. 2-7) therefore likely represent this initial stage of pockmark formation. Originally, the elongated pockmarks of Type 2 and 3 might also have been circular. Thus the length of the short axis of the elongated pockmarks gives us a general idea about their initial minimum size (Andresen et al., 2008). Elongated pockmarks can form by merging of circular pockmarks especially through gas escape from line sources, such as faults (Çifçi et al., 2003). However, the elongated pockmarks of Type 2 and 3 are characterized by smooth elliptical rims and an apparent lack of a direct structural control (Fig. 2-11). Bottom currents are thought to play an important role in the formation of pockmarks (Cathles et al., 2010). Elongated pockmarks are often interpreted to reflect bottom current erosion (Andresen et al., 2008; Dandapath et al., 2010). Consequently, we interpret that the elongation and mostly uniform orientation of the pockmarks of Type 2 and 3 is associated with bottom currents. The long axes of these depressions strike either SE-NW (140°-160°;

74%) or E-W (90° - 100° , 26%; Fig. 2-9). The SE-NW orientation is generally sub-parallel to the reconstructed contour lines of the Mid-Palaeocene bathymetry after Gemmer et al. (2002), possibly indicating that the bottom currents belonged to a larger oceanic current system (Fig. 2-12). The E-W orientation, however, might reflect a bottom-flow direction deviating from the main trend possibly controlled by varying seafloor morphology.

In the study area, most of the elongated pockmarks are asymmetrical. According to Josenhans et al. (1978) the asymmetry can be explained by current impingement on the pockmark wall or a deflection of the fluid plume escaping the pockmark. In both cases erosion would be most intense on the downstream side of the pockmark, leading to an elongate shape with the deepest point situated on the upstream side of the pockmark (Fig. 2-13). Some erosion might also occur at the upstream wall of the pockmark if current velocity is sufficiently high to induce turbulence (Josenhans et al., 1978; Andresen et al., 2008). Such a scenario with simultaneous erosion on the up- and downstream side of the pockmarks could explain why some of the elongated pockmarks (Type 2) are symmetrical. This view is supported by numerical-modelling results that show that eddies can form by converging currents on the upstream side of pockmarks (Hammer et al., 2009) due to an increase in the length of the water column inside the pockmark and an associated pressure drop (Fig. 2-13).

The majority of the asymmetrical (Type 3) pockmarks in our study area are characterized by deepest points situated toward the SE or E, suggesting a contour current flow directed towards the NW and W during Danian times (Fig. 2-12). This direction is similar to the reconstruction of bottom-current flow towards the NW from

the Maastrichtian succession of the Danish Basin, which was interpreted to belong to a larger circulation system linking the Tethys to the Boreal Sea (Lykke-Andersen and Surlyk, 2004; Surlyk and Lykke-Andersen, 2007; Esmerode et al., 2007). On the other hand, it is opposite to the interpretation of SE-ward oriented currents from the Maastrichtian of the Norwegian Central Graben (Gennaro et al., 2013) and the Maastrichtian to Danian succession from the German North-Sea (Surlyk et al., 2008). Hitherto, it is unclear if these different reconstructed bottom-current directions reflect temporal changes, variation of current direction with water depth or mesoscale eddy currents.

The elongated Type 2 and 3 depressions are concentrated at the SE flank of the Skjold diapir and in some distance away from the diapir. This distribution pattern could result from the interaction of the bottom currents with the seafloor topography created by salt diapirism during the Danian (Fig. 2-2). The influence of seafloor topography on the oceanic flow regime was studied intensively for seamounts (Beckmann and Mohn, 2002) and was compared to sedimentation patterns in the vicinity of salt domes (Lowrie, 1984). The circulation pattern created by seafloor topography can be very complex. When water is flowing over a domal structure at the sea floor, the water is forced to move upward and sideward possibly creating eddies. Generally, this can lead to a deceleration of the flow on the upcurrent and downcurrent side of the obstacle and acceleration on its flanks (Lowrie, 1984). This deceleration of the flow regime could explain why the shape of most pockmarks directly adjacent to the salt dome (Type 1) was not overprinted by the regional current system. The elongated pockmarks on the SE flank of the diapir (Type 2 and 3) in contrast could be caused by erosion by the deflected and accelerated waters.

This is consistent with the observation of moats forming on the sides of seamounts due to the same affect (Lowrie and Heezen, 1967; Johnson and Lonsdale, 1976; Lowrie, 1984). Consequently, all depressions could have formed simultaneously as Type 1 pockmarks. The pockmarks that were sheltered by the sea-floor topography from scouring bottom currents remained unchanged. In contrast, pockmarks that were exposed to accelerated bottom currents were modified to Type 2 and 3. This would be consistent with the observation that all pockmark types appear concurrently at ca. 25 ms below the Top Chalk surface.

All types of depressions show either U or V-shapes in cross section (Figs. 2-7 and 2-8). Generally, U-shapes represent the more common, of all depression types. However, in Type 1 U- and V- shapes are nearly equally common, while Type 2 and 3 depressions are clearly dominated by U-shapes (62 and 82 % respectively). The V-shaped depressions most likely represent erosion from a point source due to fluid escape during the initial stage of pockmark development (Fig. 2-13). This initial shape presumably was later overprinted to a U-shape by processes that led to erosion of the pockmark walls, such as slumping or current scour (Betzler et al., 2011). This is consistent with the fact that V-shapes are more common in Type 1 depressions, which are interpreted to represent the initial pockmark morphology. The morphology of Type 2 and 3 depressions was interpreted to be overprinted by bottom currents. The predominance of U-shapes in these groups therefore might also be caused by erosive bottom currents (Kilhams et al., 2011). Alternatively, slumping of the pockmark wall was proposed to modify the morphology of pockmarks from a V- to a U-shape (Dimitrov and Dontcheva, 1994).

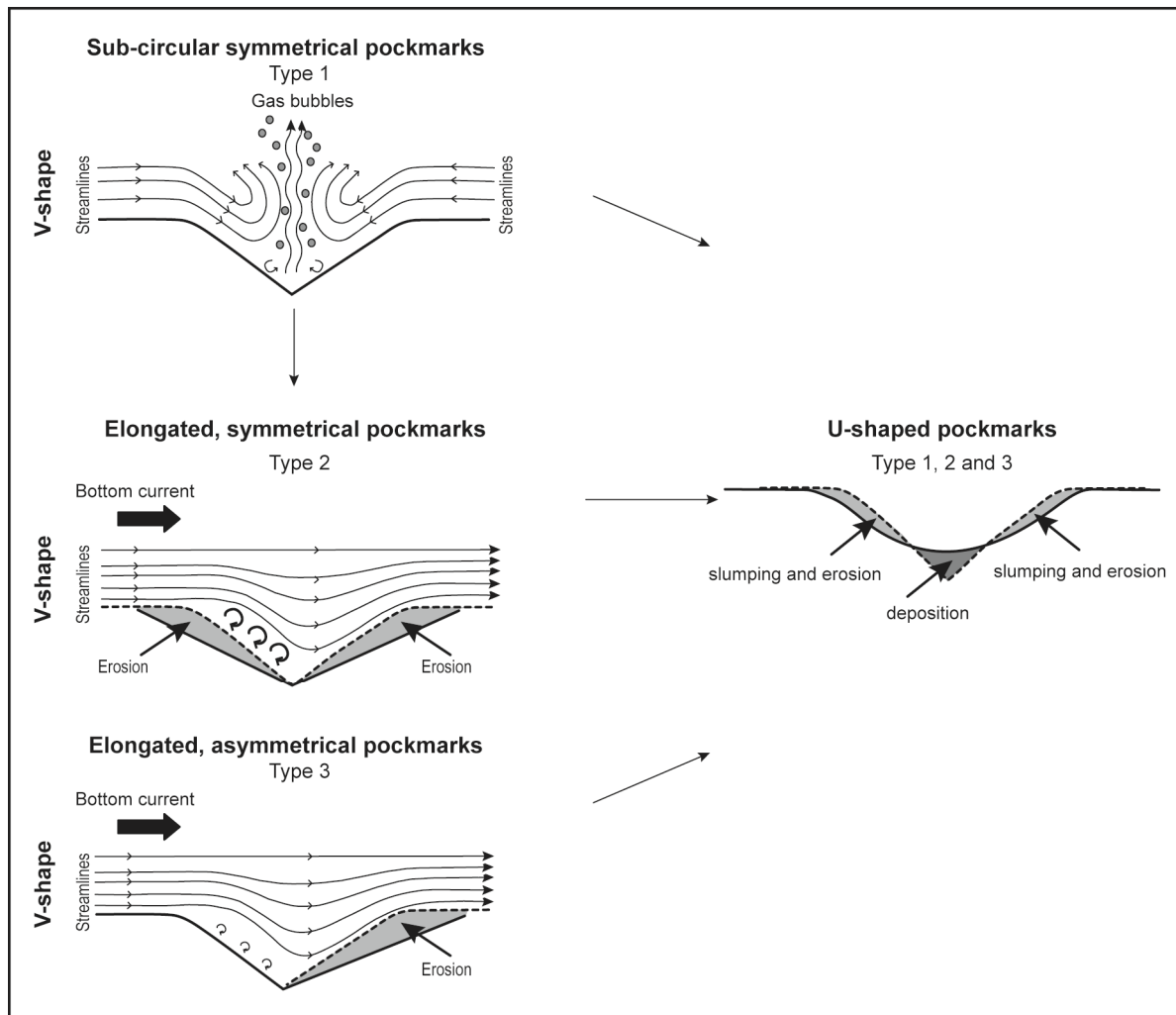


Figure 2-13 Conceptual model for the development of different types of pockmark morphologies modified after Josenhans et al. (1978). Sub-circular, symmetrical Type 1 depressions are thought to show the original pockmark form during active venting. Elongated Type 2 and 3 depressions are interpreted to be overprinted by bottom currents eroding either both, up- and down-stream sides of the pockmark (symmetrical Type 2) or only the downstream side of the pockmark (asymmetrical Type 3). The extent of erosion on the up-current side depends on the current velocity and turbulence created by eddy currents. All three pockmark types can show V- or U-shapes. V-shaped depressions most likely represent the initial stage of pockmark development, later overprinted to a U-shape by processes eroding the pockmark walls, such as slumping or current scour.

Betzler et al. (2011) observed irregular and mounded layering at the bottom of large bowl shaped pockmarks in fine-grained carbonates of the Maldives Archipelago. They interpreted these deposits as slumps originating from the pockmark walls (Fig. 2-13). The rapid expulsion of fluids along the sidewall of the pockmarks might have

contributed to sediment instability and slumping towards the centre (Dandapath et al., 2010).

Conclusions

Three-dimensional (3D) seismic data were used to analyse the morphology and spatial distribution of circular/elliptical depression features in the Danian Chalk of the southern Danish North Sea. Three types of pockmarks were differentiated based on their plan view geometry and degree of symmetry: Type 1 depressions which are sub-circular and symmetrical. Elongated and symmetrical Type 2 depressions that represent only a small fraction. The depression Type 3 is elongated and asymmetrical. All depressions occur in an interval from ca. 25 ms below to 12 ms above the Top Chalk surface. The reduction in amplitude above the Top Chalk surface is interpreted as a later drape and passive infill of the topography created by the pockmarks. The interval down to 25 ms below the Top Chalk surface is situated completely within the Ekofisk Formation, thus dating the pockmarks formation to the Danian.

Expulsion of biogenic or thermogenic fluids is suggested as the main driver for the pockmark formation during the Danian. The main Jurassic source rocks which were mature during the Danian could have provided light oil and/or condensate by vertical migration. Most pockmarks are situated close to salt diapirs (Skjold and Dan), possibly indicating that their flanks may have acted as foci for the vertical migration of fluids. The sub-circular pockmarks of Type 1 likely represent the most original stage of pockmark formation, whereas the elongated pockmarks of Type 2 and 3 were most likely modified by bottom currents. The majority of the elongated pockmarks in our

study area are asymmetrical with the deepest points situated toward the SE or E, indicating a current flow directed towards the NW and W. The distribution of the elongated pockmarks around the Skjold salt dome suggests that contour currents might have interacted with the sea-floor morphology created by the diapir. The scarcity of elongated pockmarks on the up- and down-current flanks of the diapir possibly indicates a deceleration of the bottom current velocity at these locations.

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Chapter III

Investigation of collapse structures on the Top Chalk surface of the Danish North Sea

Investigation of collapse structures on the Top Chalk surface of the Danish North Sea

Abstract

The Upper Cretaceous to lower Palaeogene Chalk Group of NW Europe is classically assumed to have formed by the settlement of homogeneous calcareous ooze from suspension and thereby draping submarine morphology under quiet pelagic conditions. Investigations of the Chalk and especially the Top Chalk surface in the southern Danish Central Graben concentrated on the Adda Ridge, Igor-Emma Ridge, Dan area and Bo-Jens Ridge. These areas are characterised by irregular and hummocky depression features visible in the Top Chalk interval. Three-dimensional (3D) seismic data from the southern Danish North Sea were used to analyse the morphology and spatial distribution of the depression features in the Danian chalk deposit. Previously the depression features in the Danish North Sea were interpreted alternatively as karst structures (subaerial exposure), submarine pockmarks, collapse structures or gravitational slumps and slide scars.

This study presents a detailed morphological analysis of depression features which occur in an interval from ca. 15 ms below to 25 ms above the Top Chalk surface. The depression reflections are measuring approximately 0.5 to 1 km length, 100-300 m width and approximately 10-30 ms (TWT) depth. In plan view the depressions have a sub-circular, an elongate or a lunar appearance. On vertical cross-section, the depressions are usually characterized by well-defined, smooth basal reflectors.

Based on their morphological comparison with similar features described in the literature the depression features here interpreted as collapse structures formed by loss of pore-water or biogenic gas escape during Danian. The location of the large ridges and of collapse structures at Top Chalk surface correlate and both are thus interpreted to result from a minor pulse of regional inversion during Danian.

The 3D seismic interpretation of mapped depression features thus contributes to the understanding of palaeo-morphology and palaeo-fluid flow during the sedimentation of the final Chalk Group in the southern Danian North Sea.

Keywords: Top Chalk, Collapse structure, Chalk deposition

Introduction

The Upper Cretaceous to lower Palaeogene Chalk Group of Northwest Europe are deposited under quiet condition; in this period of time a high eustatic sea level resulted in relatively low detrital influx, (e.g. van der Molen et al., 2005; Hancock and Rawson, 1992). Marine biogenic deposits mostly of pelagic origin such as coccoliths and debris of planktonic algae (e.g. Hancock, 1975; Kennedy, 1987; Surlyk, 1997; Surlyk et al., 2003, 2008; van der Molen et al., 2005; Esmerode et al., 2008) draped on pre-existing submarine morphology with laterally continuous bedding (e.g. Evans et al., 2003; Surlyk et al., 2008).

The top surface of the Chalk Group is characterised as surface that separates the Upper Cretaceous–Danian Chalk Group from siliciclastic deposition; this is one of the most important unconformities in the North Sea Basin (Clausen and Huuse, 1999; Huuse, 1999; Surlyk et al., 2003). Morphologic depression features on the Top Chalk surface of the Norwegian-Danish Basin were previously identified on 2D and 3D seismic data and interpreted alternatively as karst features (e.g. Clausen and Huuse, 1999), pockmarks (Gemmer et al., 2002), collapse structures (Surlyk et al., 2003) or gravitational slumps and slide scars (Jakobsen and Andresen, 2010; Back et al., 2011).

Collapse structures are principally negative topographic features (Hovland and Judd, 1988) and are in contrast to pockmarks not caused by erosion of material or sediment (Hovland and Judd, 1988). They can form by loss of pore-water or shallow gas escape leading to a reduction in volume of sediments and inducing collapse (Butenko, 1985; Prior and Coleman, 1985; Molina, 1979). Moss and Cartwright (2010) described Neogene, ovoid and elongate collapse structure from the offshore Namibia. They interpreted these depressions mainly as a product of fluid escape and subsequent volume loss due to fluidization. Buried collapse depressions in the Danish North Sea will be described below in the light of these findings. The detailed analysis of 3D morphology of depression features in this study is used to propose an explanation for these features on the Top Chalk surface in southern Danish North Sea (Fig. 3-1a and b). The possible origins of these depressions are discussed with particular emphasis on the fluids involved.

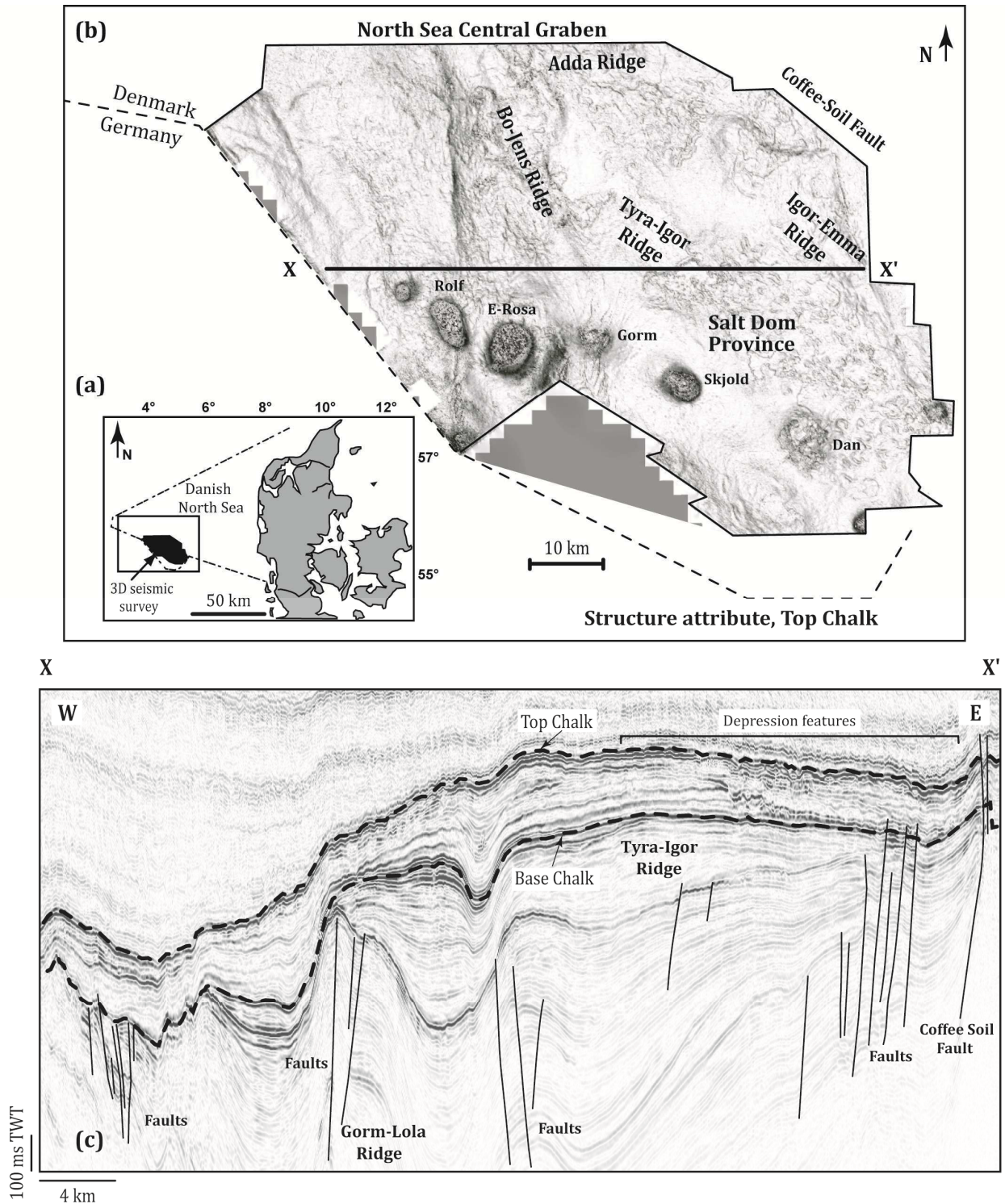


Figure 3-1 a) Location of the study area in the Danish North Sea Central Graben. b) Structure-attribute map (horizon slice) of the Top Chalk surface generated from 3D seismic-reflection data. The black horizontal line indicates the position of the seismic-reflection profile shown below. c) Vertical reflectivity section illustrating the base and top of the Chalk Group.

Geological setting

The study area offshore Denmark is located 200 km west of the Danish mainland, between 4° to 5° eastern longitude and close to 56° northern latitude (Fig. 3-1a). The 3D seismic reflection survey analysed in this study covers c. 2000 km² of the Danish North Sea Central Graben, bound by the Ringkøbing–Fyn High in the east, extending in its central part across the Bo-Jens, Gorm-Lola, Tyra-Igor, Igor-Emma and Adda Ridges, and reaching in the south the Danish Salt Dome province (Fig. 3-1b and c). The interval under study is the Chalk Group that spreads over the Central North Sea and extends into the south Viking Graben and onto the east Shetland Platform (Surlyk et al., 2003). The age of sediments is Cenomanian to Danian and the Chalk Group has 1-2 km thickness in the Central Graben area (Japsen, 1998; Surlyk et al., 2003; Vejbæk et al., 2007). The Chalk Group of the Danish North Sea can be subdivided into the Ekofisk Formation (Danian–Early Palaeocene age), Tor Formation (Maastrichtian age), Hod Formation (Late Turonian to Campanian age), and Hydra Formation (Cenomanian age) (Mortimer, 1987).

The halokinetic movements, fault-controlled subsidence or inversion influenced chalk deposition during Upper Cretaceous to lower Palaeogene (Watts et al., 1980; Hardman, 1982; Brewster and Dangerfield, 1984; Munns, 1985; Hatton, 1986; Bromley, 1987; Barmwell et al., 1999; Farmer and Barkved, 1999; Surlyk et al., 2003). Late Cretaceous regional subsidence was, however, interrupted by tectonic inversion in the form of a reversal of faults, a reactivation of older faults, and folding of the basin infill (Vejbæk and Andersen, 1987, 2002). Four major events controlled the inversion in Danish North Sea, the first event was during the Turonian -

Santonian, a second event was during the mid-Maastrichtian and then followed by a minor pulse of inversion during the Danian, and the final events took place during post Danian–early Tertiary (Vejbæk, and Andersen, 1987; Gennaro, 2013). The inversion resulted in bathymetric elevations and local depocentres in low areas (Oakman and Partington, 1998).

Four ridges were identified in the southern Danish North Sea (Fig. 3-1b). The Bo-Jens Ridge and Adda Ridge were syndepositional sea-floor topographic elements that reflected thinning of the Upper Cretaceous succession over their crests (Kennedy, 1987; Farmer and Barkved, 1999). The Adda Ridge parallels the adjacent NW–SE-trending segment of the Coffee Soil Fault and Adda Ridge parallels a NW–SE trending segment of the Coffee Soil Fault and initiated as a result of dextral movement of a deeply seated fault (Vejbæk and Andersen, 2002). The Bo-Jens Ridge is oriented from north to south and attached to the extensional basement faults which influenced the Zechstein salt movement (Vejbæk and Andersen, 2002). Tyra-Igor Ridge trends NW-SE and crossed the Salt Dom Province (Vejbæk and Andersen, 2002). Igor-Emma Ridge is a NW–SE trending structure and is located along Coffee-Soil Fault. Igor-Emma Ridge is characterised by asymmetric anticline which is a result of both intra-chalk and post-chalk compression movements (Jakobsen and Andresen, 2010). The influence of halokinetic movements increases towards the Salt Dome Province (Vejbæk, 1986). Salt movements started during the Triassic and the invasive activity continued throughout the Late Cretaceous–Paleocene, resulting in the formation of salt domes, salt diapirs and ridges (Surlyk et al., 2003).

Database and Methodology

The data base of this study comprises 2000 km² of 3D seismic reflection data (zero phased, European polarity convention) The bin spacing of the seismic survey is 25 m in inline and crossline directions with a vertical sampling rate of 4 ms. Density and gamma-ray well logs from several wells within the study area were used to identify the seismic reflection pattern representing the Top Chalk surface. The structure map was constructed for the Top Chalk surface. The structure attribute was particularly used for discontinuity highlighting and served as a first-pass indicator for zones of particular stratal inhomogeneity, which are subsequently selected for detailed interpretation (Masoumi et al., 2013) (see Fig. 2-4). Structure attribute map was constructed for the Top Chalk surface and particularly used for discontinuity highlighting and served as a first-pass indicator for zones of particular stratal inhomogeneity. The discontinuous surface is subsequently selected for detailed interpretation.

Three types of depressions could be differentiated based on their plan view geometry on structural attribute map (Fig. 3-2). 1: sub-circular shaped with a ring-shaped geometry around a central elevation, 2: half-moon shaped or horse-shoe-formed with a half-ring-shaped geometry around a central elevation, labelled as “lunate”, and 3: elongate shaped with a horizontal geometry (Fig. 3-3). Sub-circular, lunate and elongate morphological depressions on the seismic data of the Top Chalk surface were interpreted in detail using seismic cross-sections and horizon slices. The respective length and width of the depressions were measured along the depression on structural map displays. The depth of the depressions was measured on seismic

cross-sections as vertical distance between the deepest point and a straight line connecting the flanks of the depressions.

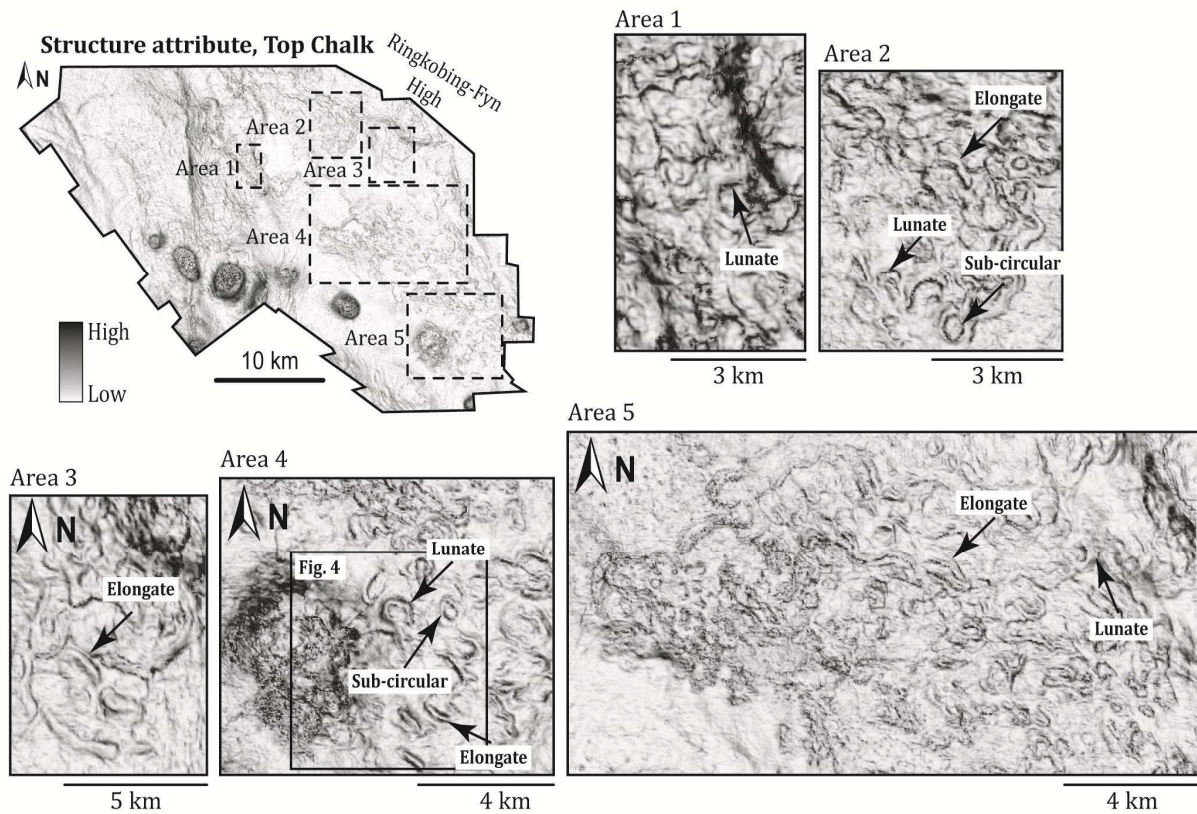


Figure 3-2 Structure-attribute maps of the Top Chalk surface within the study area. In plan view the depressions either have a sub-circular, an elongate or a lunate appearance. Depressions located in five areas: on the Bo-Jens area (Area 1), on the Adda area (Area 2 and 3), Igor-Emma Ridge (Area 4) and the southeastern flank of the Dan salt structure (Area 5).

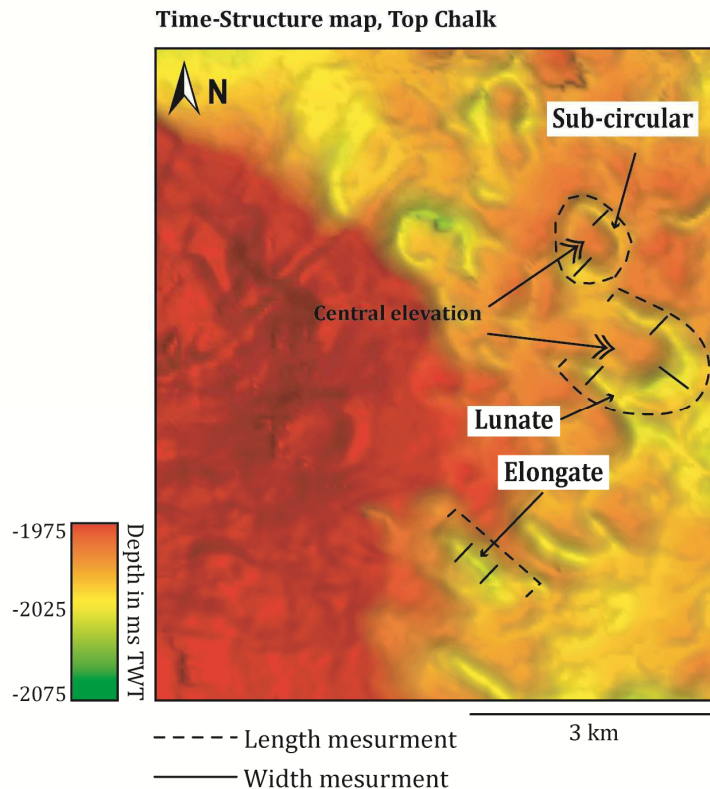


Figure 3-3 TWT time structure map of the Top Chalk in location of Dan salt structure (Area 5) illustrated three types of depressions 1: sub-circular shaped with a ring-shaped geometry around a central elevation, 2: half-moon shaped or horse-shoe-formed with a half-ring-shaped geometry around a central elevation, labelled as “lunate”, and 3: elongate shaped with a horizontal geometry. Also shown is the length and width of the depressions.

Results

This study focuses on the top of the Chalk Group as key interpretation target. This surface (Top Chalk) is interpreted to have formed at the end of the Danian when first siliciclastic sediments were introduced to the basin. Density, gamma ray and sonic logs were used to identify the seismic expression of this lithological change (e.g. see Fig. 2-4). The Chalk Group deposits are characterized by generally low gamma-ray values that can increase slightly towards the top of the Chalk Group. The lithologic boundary to the post-Danian siliciclastics is marked by a rapid shift to high gamma-ray values. Density logs in the Chalk Group commonly show a progressive upward decrease with relatively low values within the terminal Chalk unit. Sonic logs are

marked at Top Chalk level by a rapid upward increase in the interval transit-time (decrease in velocity). This velocity change commonly coincides with a trough in reflectivity on seismic cross-sections (see Fig. 2-4, well 1). In gas-affected areas, where the continuity and amplitude of the reflection peak was reduced or a polarity reversal was encountered (see Fig. 2-4, well 2), gamma-ray logs were used to identify the Top Chalk surface.

The structure attribute map generated for the Top Chalk surface concentrated on the Bo-Jens Ridge, Adda Ridge, Igor-Emma Ridge and Dan area shows a variable seismic facies including the rugged, irregular and hummocky depressions (Fig. 3-2). In plan view the depressions are discontinuous and they have circular to sub-circular, elongate or a lunate appearances (Fig. 3-2). The elongate and lunate shaped depressions are not following any preferred orientation and illustrate different directions (Fig. 3-2 and 3-3). On vertical cross-section each depression can be either characterized by a symmetric or an asymmetric formation and they are usually identified by well-defined and smooth basal reflectors (Fig. 3-4a and b). The underlying seismic reflection peak (right below the Top Chalk surface) is reduced in thickness or pinches out completely toward the centre of the depressions (Fig. 3-4).

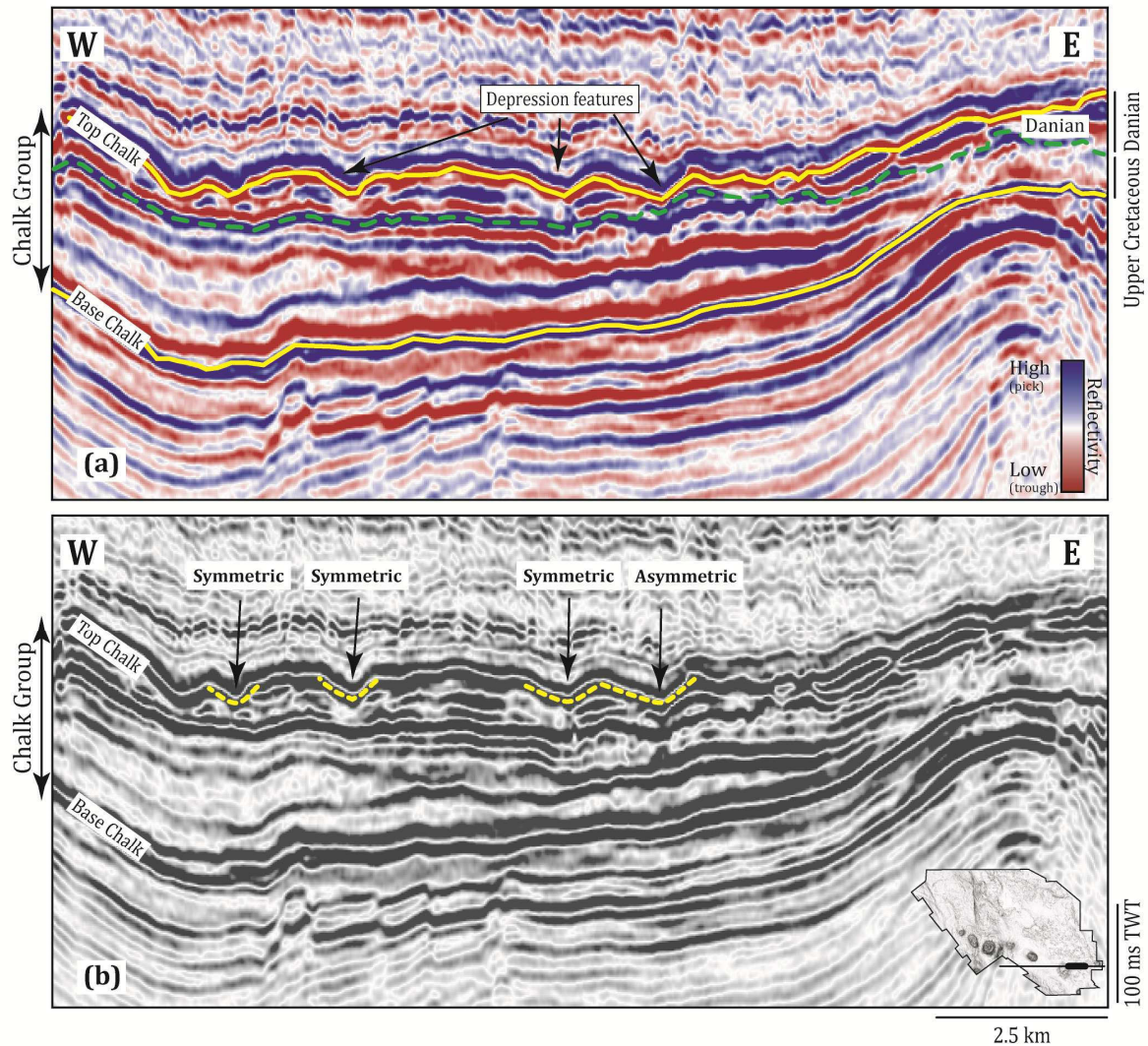


Figure 3-4 a) Seismic section showing depression features in the southeastern Danish North Sea. The depressions are characterized by well-defined, smooth basal reflectors. The depressions are belonging to the upper part of Danian succession. b) Each depression can be either characterized by a symmetric or an asymmetric formation.

The depression reflections measure ca. 0.5 to 1 km in length, 100-300 m in width and approximately 10-30 ms (TWT) in depth (Figs. 3-2 and 3-3). All depressions appear concurrently within an interval from about 15 ms TWT below to about 25 ms TWT above the Top Chalk surface. Internally all depressions do not show any internal reflector, suggesting that internal reflections are below seismic resolution or possibly reflect a homogenous infill with no internal stratification.

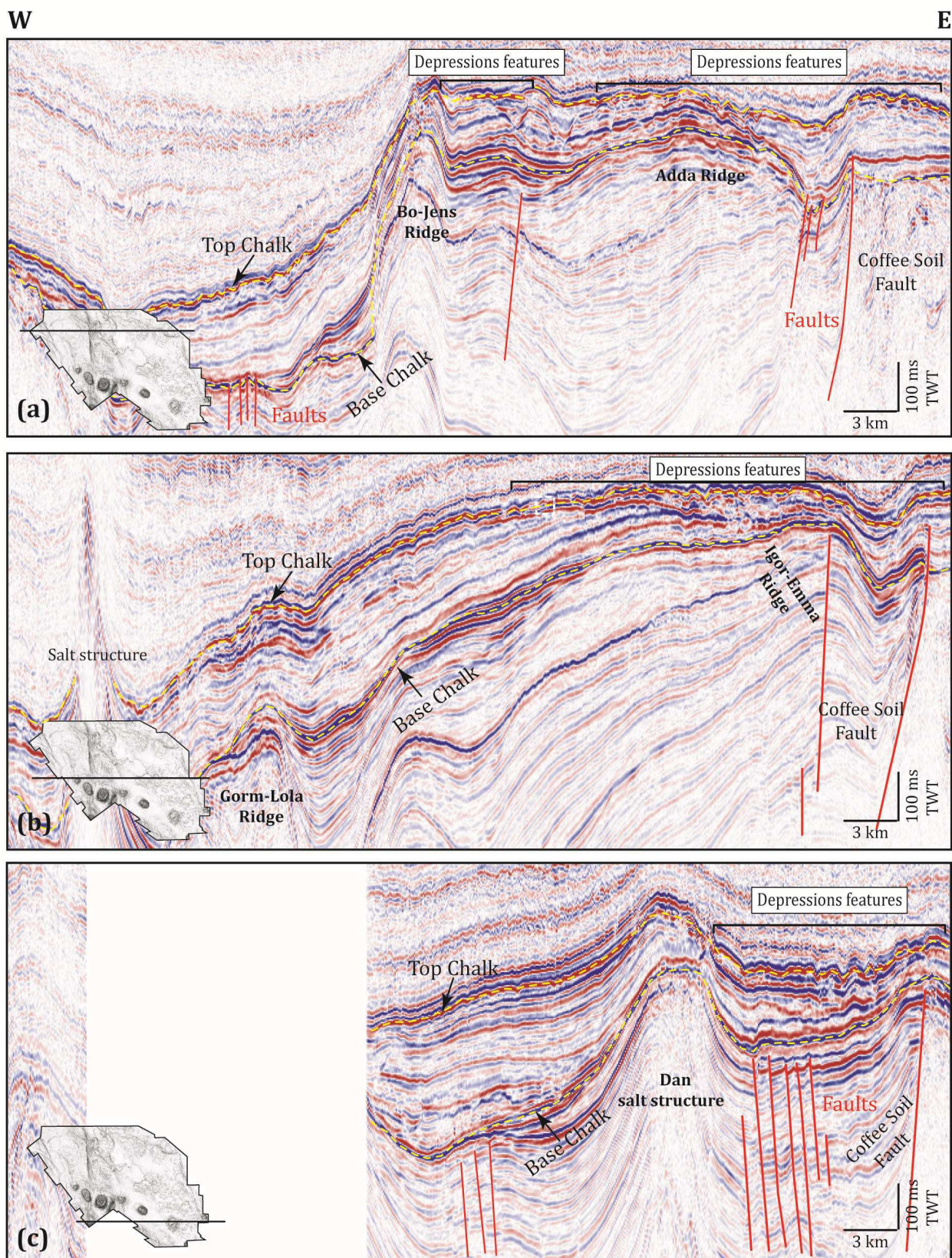


Figure 3-5 a, b and c) Seismic sections from north to the south of the study area indicate the location of the depression features at Top-Chalk surface. Also shown is the presence of several normal faults underneath of Chalk Group.

Figure 3-5 illustrates W-E profiles that cross the Coffee Soil Fault. It shows several normal faults underneath the Chalk Group in the east of the study area. Upper tips of the numerous faults are below the Chalk Group but some of them extend into the chalk sediments (Fig. 3-5). Also figure 3-5 shows an asymmetrical basin development with thinning over the ridges/Dan salt structure and thickening into the centre and west of the study area.

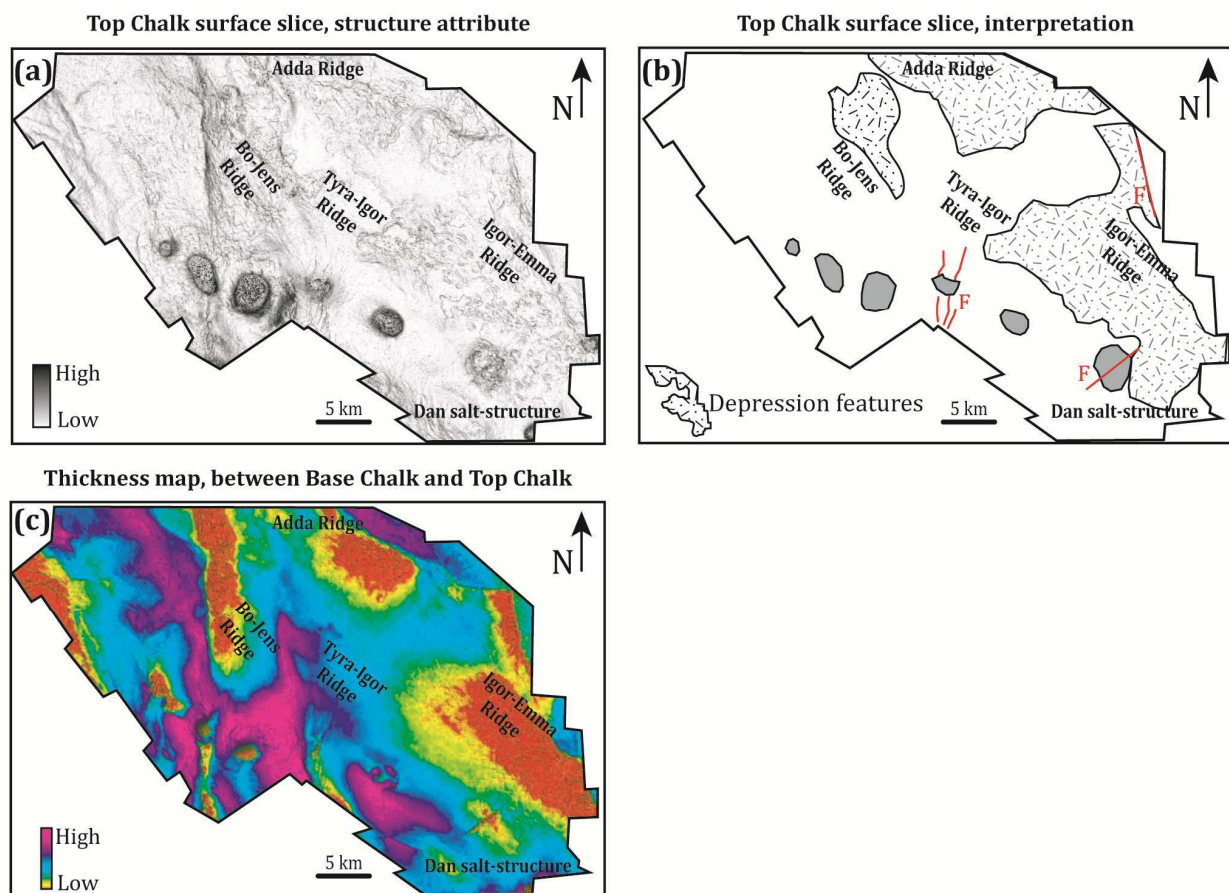


Figure 3-6 a) Structure-attribute map of the Top Chalk surface within the study area. b) Top Chalk surface slice interpretation. c) The thickness map shows Chalk Group is thinning over the Bo-Jens Ridge, Adda Ridge, Igor-Emma Ridge and east of the Dan salt structure.

The overall thickness variation in the location of depression features is illustrated by the thickness map between Base Chalk and Top Chalk surface (Fig. 3-6). This map shows very large thickness variations from less than 100 milli-seconds (ms) on top of the Bo-Jens Ridge, Adda Ridge, Igor-Emma Ridge and east of the Dan salt structure

up to 450 ms in the centre and west of the study area. The thin areas match with the location of depression features at the Top Chalk surface (Fig. 3-6).

Discussion

Previously, depression features at Top Chalk level in the Norwegian-Danish Basin were interpreted as karst phenomena (e.g. Clausen and Huuse, 1999; Huuse et al., 2001), pockmarks (e.g. Gemmer et al., 2002), collapse structures (e.g. Surlyk et al., 2003) or gravitational slumps and slide scars (e.g. Jakobsen and Andresen, 2010; Back et al., 2011). Geodynamic modelling of the Mid-Paleocene palaeogeography by Gemmer et al. (2002) indicated palaeo-water depths of several hundred meters in the southeastern Danish Central Graben. Therefore, based on palaeogeography reconstruction by Gemmer et al. (2002), an interpretation of depressions as karst related to subaerial exposure is unlikely. However, subsurface hypogenic karstification can create very similar morphologies to subaerial epi-karst and can occur independently of the palaeogeographical setting. Hypogenic karst is characterized by dissolution, where aggressive fluids are continuously delivered to the dissolution front (Palmer, 1991; Tóth, 1999) often in the vicinity of fault and fracture systems overlain by impermeable facies (Immenhauser et al., 2007). If aggressive fluids ascending along fault or fracture networks would be responsible for depression formation, we would expect these to be clustered along lineaments. In contrast, we observe unorganised depressions that do not show a linear arrangement (see Fig. 3-2). The apparent lack of a direct link between faults and depressions therefore likely contradicts an interpretation as hypogenic karst for depression features at the Top Chalk surface in the study area.

Jenyon (1984) interpreted Danian dissolution collapse in the southern North Sea causing major disruption of the overlying sequences. In their analogues used from dissolution pipes in the carbonates of the south of China (Sun et al., 2013) the seismic reflection above the dissolution features are characterised by chaotic facies. We therefore rule out dissolution features, because there are no indications of dissolution such as chaotic seismic reflection above the depression features (see Fig. 3-4).

Pockmarks are crater-like depressions on the sea floor often originating from seepage of gas or interstitial liquids (King and MacLean, 1970; Hovland, 1982, 1984; Hovland and Judd, 1988; Van Weering et al., 1997; Judd and Hovland, 2007; Masoumi et al., 2013). The lunate and elongated pockmarks are often interpreted to reflect bottom current erosion and they showed mostly uniform orientation in direction of bottom currents (Andresen et al., 2008; Dandapath et al., 2010). In contrast, we observe various directions and no preferential orientation of lunate and elongate depressions (see Fig. 3-2). Thus, interpretation of depressions as pockmark features is unlikely.

Two possible modes of formation have been suggested for the observed depression features in the southern Danish North Sea: Collapse structures by Surlyk et al. (2003) and gravitational slumps and slide scars by Jakobsen and Andresen (2010) and Back et al. (2011). On map view, the lunate depressions are similar in morphology to structures described by Surlyk et al. (2003) at the Top Chalk surface in the Dan area whilst the sub-circular and elliptical forms are similar in morphology to depressions described by Moss and Cartwright (2010) in offshore Namibia. These authors

documented the ovoid and elongate depressions in plan form with unbroken reflections base. It is presumed that the trough-shaped structures are corresponding to collapse structures. Quine and Bosence (1991) have studied the depression structures of Upper Cretaceous chalk of Normandy. They argue that depressions which may link to slumps and slide scars form as a result of gravitational instabilities in sediment piles and can be recognised in the stratigraphic record as spoon-shaped (Quine and Bosence, 1991; Nichols, 2009). Accordingly, the failure process occurs on weak horizons and propagates upwards to form a spoon-shaped fault (a listric fault) within the sedimentary succession (Nichols, 2009). Lower surface to slumps and slide scars are commonly erosional surfaces and the underlying beds are defined by truncational surfaces (Kennedy and Juignet, 1974; Bromley, 1987). The spoon-shaped or listric shapes and the described erosional surface associated with depressions can not be observed on different seismic cross sections (see Fig. 3-4). However, in cross-section, the reflections immediately below the depression features are reduced in thickness or pinches out completely. The missing of reflections below the depressions interpreted as a “pull-down” of the Top Chalk caused by the collapse structures. Thus, based on morphological comparison with similar features described in the literature (Prior and Coleman, 1985; Butenko, 1985; Molina, 1979; Hovland and Judd, 1988; Surlyk et al., 2003; Moss and Cartwright, 2010) the depression features here are interpreted as collapse structures.

The depression features in the study area were observed in an interval from ca. 25 ms below to 15 ms above the Top Chalk surface. However, the downward deflection of reflections above the Top Chalk surface is relative to the depressions at the Top Chalk surface; the amplitude of the depressions diminishes continuously until they

are unrecognizable in cross-section and in map view. It is therefore assumed that the collapse structures cease around the Top Chalk surface. The reduction in amplitude above the Top Chalk surface is interpreted as a later drape of the topography created by the collapse structures (Fig. 3-7). The interval down to 25 ms below the Top Chalk surface is situated completely within the Ekofisk Formation, thus dating the collapse structures to the Danian.

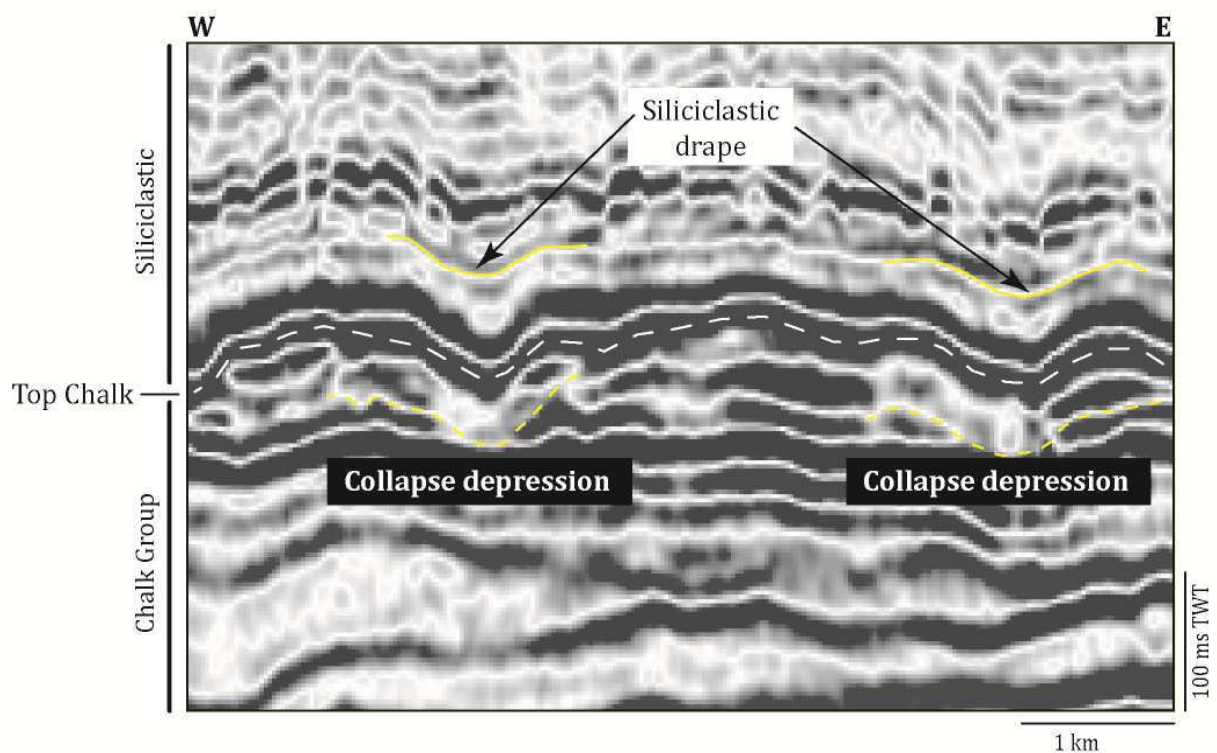


Figure 3-7 Seismic cross section showing that the depressions are reduced in depth above the Top Chalk surface. This is interpreted as a passive drape of the collapse structures morphology by post-Danian siliciclastic sediments.

A minor pulse of inversion took place during Danian in the Danish North Sea (Gennaro, 2013). The inversion caused bathymetric elevations (ridges) and local subsidence (Oakman and Partington, 1998). In the study area during the compressional phase (inversion), earlier normal faults were reactivated as reverse faults. Compression and shortening thus lead to minor local uplift and folding. This mechanism most likely leads to thinning of the chalk sediments at locations of collapse

structures. The distribution of collapse structures in the study area is matched with the location of the observed ridges (see Fig. 3-6). The working model in this study is that the collapse structures formed as a response to the minor pulse of inversion during the Danian

Collapse structure formation has been related by some authors in the past to fluid movements in sediments. Nichols (2009) proposed small-scale liquefaction during early compaction as a mechanism. Prior and Coleman (1985) suggested seepage of gas and interstitial liquids during sedimentation in the Mississippi River Delta to have generated collapse structures. Léon et al. (2010) in the Gulf of Cádiz described collapse structures which result from fluid escape at locations of diapiric activity. The development of synsedimentary ridges as a result of inversion (Kennedy, 1987; Farmer and Barkved, 1999) and salt tectonic movement during Late Cretaceous to Paleocene (Surlyk et al., 2003) leads to crustal instability and hence to earthquakes. Earthquake-triggered liquefaction is facilitated by high pore fluid pressures caused by ineffective dewatering of low-permeability sediments (Nisbet and Piper, 1998). Consequently, earthquake-induced liquefaction is often associated with fluid escape features at the sediment surface. The resulting reduction in volume of sediments at such fluid escape sites might lead to collapse structure evolution (Prior and Coleman, 1985).

The Chalk in the North Sea area was initially deposited from suspension as pelagic ooze consisting mainly of coccoliths (Surlyk et al., 2003). Chalk sediments are highly supersaturated with water shortly after deposition (Scholle, 1977). Water escape therefore seems to be a likely explanation for collapse structure generation.

We have no geochemical data of the chalk sediment to constrain the presence of gas, or to identify the composition and origin of the gas (biogenic vs. thermogenic). Biogenic gas can form within organic rich sediments during shallow burial (Hovland and Judd, 1988). The Quaternary sediments of the Great Australian Bight are lithologically similar to the Upper Cretaceous–Danian limestone of the North Sea (cf. Surlyk, 1997).

Large concentrations of biogenic methane and hydrogen sulfide were discovered in the shallow subsurface of the Great Australian Bight (Swart et al., 2000). In analogy it seems thus possible that biogenic gas might have been produced from Late Cretaceous and early Paleocene coccolith ooze that could have led to collapse structure creation at the Top Chalk surface. Thermogenic fluid/gas can be provided by maturation of the Jurassic source rock during burial (Jensen and Schmidt, 1993; Danielsen et al., 1997). The thermogenic fluid/gas was discovered in the study area in location of the pockmarks (Tyra area, Skjold and Dan salt structures) (Fehmers et al., 2012; Masoumi et al., 2013). They interpreted salt flanks and major faults have been an active fluid pathway and played an important role to vertical fluid/gas migration. In the Adda Ridge, Bo-Jens Ridge and Igor-Emma Ridge, however, the vertical cross sections show no direct connection between the observed depression features and seismically resolved faults (see Fig. 3-5). In Dan area, some of the collapse structures are located in close proximity to a salt structure and several of them far from salt structure (see Fig. 3-5). The apparent lack of a direct link between faults/salt structure and collapse structures therefore likely contradicts an interpretation that thermogenic fluid/gas escape plays a chief role during collapse structure formation in the Adda Ridge, Bo-Jens Ride, Igor-Emma Ridge and Dan

areas. Rather a combination of high pressure pore water expulsion and/or biogenic fluids is considered as a mechanism. The link to inversion structures in the study area needs further investigation.

Conclusions

Three-dimensional (3D) seismic data from the southern Danish North Sea were used to analyse the morphology and spatial distribution of circular, elliptical and lunate depression features in the Danian chalk deposit. The depression reflections are measured ca. 0.5 to 1 km length, 100-300 m width and approximately 10-30 ms (TWT) depth. Based on a detailed 3D seismic interpretation the depressions were interpreted as collapse structures. Investigation of three-dimensional (3D) seismic data show that collapse structure are linked to minor pulse of regional inversion and possibly earthquake in the Danish North Sea. Expulsion of pore-water and/or biogenic fluids is suggested as the main driver for the collapse formation during the Danian.

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