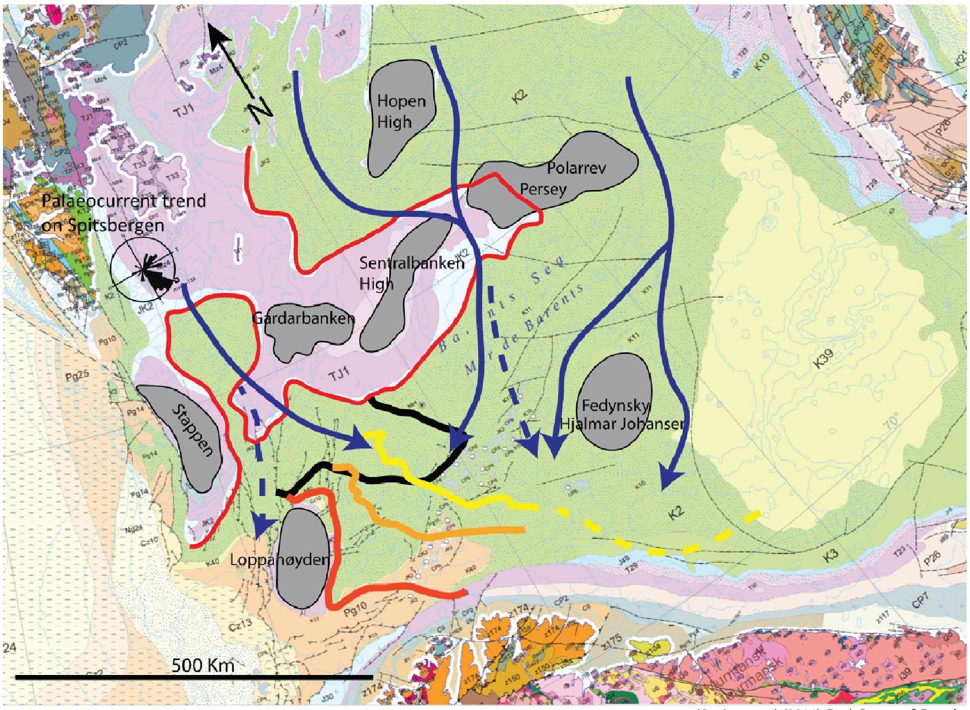
Master Thesis, Department of Geosciences

Lower Cretaceous Prograding Units in the eastern part of the SW Barents Sea

Myrsini Dimitriou



map source: Harrison et al. (2011) Geol. Survey of Canada

UNIVERSITY OF OSLO
FACULTY OF MATHEMATICS AND NATURAL SCIENCES

Lower Cretaceous Prograding Units in the eastern part of the SW Barents Sea

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Master Thesis in Geosciences

Discipline: Petroleum Geology and Petroleum Geophysics

Department of Geosciences

Faculty of Mathematics and Natural Sciences

University of Oslo

June 2014

Στην οικογένειά μου,

για όλα.

Η φύσις μηδέν μήτε ατελές ποιεί μήτε μάτην.

Αριστοτέλης

Abstract

A large-scale 2D seismic sequence analysis of the Lower Cretaceous successions in the eastern part of the south-western Barents Sea is presented. Well and shallow borehole data are used to further constrain and assist the interpretation. Four distinct prograding units are recognized and mapped, each characterized by internal, low-angle clinoforms. They are bounded by a maximum flooding surface at the base and an erosional truncation on top; both types of sequence boundaries are correlated over the entire area.

The lap-out points and the space relationship between the different clinothem packages was mapped. A regional depositional model was developed through the integration of the available data. The interplay between local, regional and supra-regional events was discussed in connection with the unit's depositional history.

In the Early Cretaceous, the eastern part of the south-western Barents Sea was a relatively shallow epicontinental sea, located within the Boreal Basin. It was gradually filled-in during four phases, with two major progradational directions; NW to SE and NE to SW; the latter being the dominant direction. The sediments were sourced from a location north of the northern margin of the present-day Barents shelf; an uplifted area associated with the rising High Arctic Large Igneous Province (HALIP). The clinoform system is connected with the fluvial/paralic system of the Helvetiafjellet Formation on Svalbard, and its likely time equivalent chronostratigraphic units on Franz Josef Land, as the southward continuation of its drainage system. A direct tie between the two systems, within the Norwegian sector, is not possible, due to Cenozoic uplift and erosion. Mantle processes, related to the HALIP, are suggested to account for the creation of accommodation. A widespread condensed carbonate succession of Valanginian to early Barremian age constitutes the downlapping surface, with the clastic deposits being of early to middle Barremian age, according to well and shallow borehole data.

Preface

This thesis entitled "Lower Cretaceous Prograding Units in the south western Barents Sea" has been submitted to the Department of Geosciences, Section of Petroleum Geology and Geophysics (PEGG), at the University of Oslo and it concludes a two years program for the Master of Science degree. It is part of the BarMod program, which is a continuation of the PETROBAR-project. This program focuses mainly on the transitional domain in the central Barents Sea, where the borders with Russia have been recently resolved. The primary objective is to model the structural and thermal evolution of the area, in order to test and refine hypotheses about evolution and petroleum plays potential. It is led by Professor Jan Inge Faleide.

The supervising committee has been Associate Professor Ivar Midtkandal, Professor Emeritus Johan Peter Nystuen and Professor Jan Inge Faleide.

Acknowledgements

I owe my deepest gratitude to my supervisors; Associate Professor Ivar Midtkandal, Professor Emeritus Johan Peter Nystuen and Professor Jan Inge Faleide for their invaluable assistance, guidance and support. It was a great honor and an enlightening experience to work alongside with them. Without the numerous insightful discussions and reviews this thesis would not have materialized. I would particularly like to thank Professor Ivar Midtkandal for his patience, supportiveness, encouragement and the last review.

TGS and Fugro are acknowledged for providing the seismic data used.

I would like to offer my special thanks to Senior Engineer Michael Heeremans and Heleen Zalmstra for preparing all the data needed for the thesis and supporting me with the software used.

I am particularly grateful to Jennifer Porter for reviewing my work. Also, for an amazing week in Paris; the way vacation should be, and for providing a person to “grow up” to be like; herself.

Advice, comments and warm encouragement given by Maria Dahlberg have been a great help and without them this thesis would not have been possible. Times are not as tough when you are around.

I would like to express the deepest appreciation to Evy Glørstad-Clark. Although I never met her, her work has proven to be an invaluable source for inspiration and provocation to do better.

A special thanks goes to everyone in Hotel Bristol, Oslo, banquet and conference department; Kevin, Arthur, Fabian, Hugo (Boss), Marius, Peter, Patrick, Jan Øyvind, Glenn, Camilla, Anneli, Lisa, Grazyna, Carolina, Wendela. Without their help, in every level, it would have been impossible for me to stay in Norway. Their support, friendship, encouragement and, above all, love has given me the strength I needed. Never has a workplace felt more like home.

Lisbeth, Maria, Jen, Alex, Ping, Greg and Deuts a simple thank you is not enough. You have been my family in Norway. There are no words to describe my gratitude and thankfulness for your presence in my life these two years. Hoping for many more to come!

Lis and Maria, things are never quite as scary when you have friends like you. Ευχαριστώ πολύ για όλα.

Table of Contents

1 Introduction

The Barents Sea is an extensive epicontinental basin that was established in late Paleozoic. The area has been studied in length by many workers (Faleide et al., 1984, Faleide et al., 1993, Gabrielsen, 1984, Grogan et al., 1999, Gudlaugsson et al., 1998, Nøttvedt et al., 1993, Smelror et al., 2009, Steel and Worsley, 1984, Stemmerik and Worsley, 2005, Worsley, 2008). In the Mesozoic it was located at the north-western part of Eurasia, with siliciclastic sedimentation prevailing (Faleide et al., 1984, Faleide et al., 1993, Smelror et al., 2009, Worsley, 2008). The Early Cretaceous development mainly depicts the relationship between the Barents Shelf and the Boreal Basin (Smelror et al., 2009, Steel and Worsley, 1984, Worsley, 2008).

The Lower Cretaceous successions were deposited in a dynamic environment, influenced by large scale magmatism, in connection with the High Arctic Large Igneous Province and the evolution of the Amerasia Basin, which induced a pronounced uplift of the northern margins of the Barents Shelf (Smelror et al., 2009, Worsley, 2008, Maher, 2001). A major fall in sea level was initiated as a result of the uplift, with the Helvetiafjellet Formation on Svalbard being the first evidence of this (Midtkandal and Nystuen, 2009, Maher, 2001). However, presently, there is limited information and understanding of the extent, timing and character of this sediment progradation from the northern limits of the Barents Shelf to the southwestern Barents Sea.

The main purpose of this study is to perform a large scale seismic analysis on the Lower Cretaceous strata in the eastern part of the southwestern Barents Sea. The central area of study consists of the parts of the Bjarmeland Platform where Cretaceous successions are still preserved, the Nordkapp Basin, eastern Finnmark Platform and the eastern peripheries of Hammerfest Basin. It will be attempted, on the basis of seismic sequence analysis and mapping, to deduct infill patterns, depositional environments, timing and direction of sediment progradation; and furthermore a prediction on lithologies and potential sediment sources, together with regional implications of accommodation space during the Early Cretaceous. The answer to a crucial question is tried to be found; is there a link between the units deposited in the south-western Barents Sea and those in Svalbard and the northern margins of the Barents Shelf? Well and shallow borehole data are integrated, as a helping tool to provide further insight on lithology and timing issues. The small scale structural elements in the area are considered to be outside the scope of this thesis.

2 Geological Framework

2.1 Regional Setting

The Barents Shelf (Fig. 1), covering an area of 1.3 million km^2, comprises the regional study area of this thesis. It is located in the Arctic, at 16^o-60^oE and 70^o-80^oN (Fig. 1) From north to south, it extends from the Svalbard Archipelago and Franz Josef Land to Northern Norway and Russia and from east to west, from the Norwegian-Greenland Sea to Novaya Zemlya (Fig. 1), respectively (Faleide et al., 1993, Worsley, 2008). It is divided into an eastern and a western province. The eastern province, with the extensive South and North Barents Basins, that lies within the Russian borders, and the western province with a series of basins, platforms and structural highs, lies within Norwegian borders (Fig. 1) (Worsley, 2008, Smelror et al., 2009). The western province is the focus of this study, but the possible implications of the interpretations in the eastern will be discussed.

The western province covers the area between 16^o-40^oE and 70^o-80^oN (Fig. 1). It can be further subdivided into the north and south regions. The north region includes the islands of Spitsbergen, Nordaustlandet, Edgeøya and Bjørnøya, Olga and Sørkapp basins, Edgeøya and Kong Karl's platforms, and its southern limits are defined by Stappen, Gardarbanken and Sentralbanken highs (Fig 1 & 2). The south region comprises the area between the aforementioned highs and the coast of Northern Norway. It encompasses the Bjørnøya, Sørvestsnaget, Harstad, Tromsø, Hammerfest and Nordkapp basins, Bjarmeland Platform and Loppa High (Fig. 1 & 2). A number of faults, ridges and domes shape the area (Fig. 2). The southern region has been further subdivided into 3 provinces: the oceanic Lofoten Basin and the Vestbakken Volcanic Province; the deep basins west of Troms-Finnmark Fault Complex (FC), Ringvassøy-Loppa FC, Bjørnøyrenna FC and Leirdjupet FC; and the less subsided basins east of the above-mentioned fault complexes (Faleide et al., 1984) (Fig 1 & 2). The latter region comprises the local setting of this thesis.

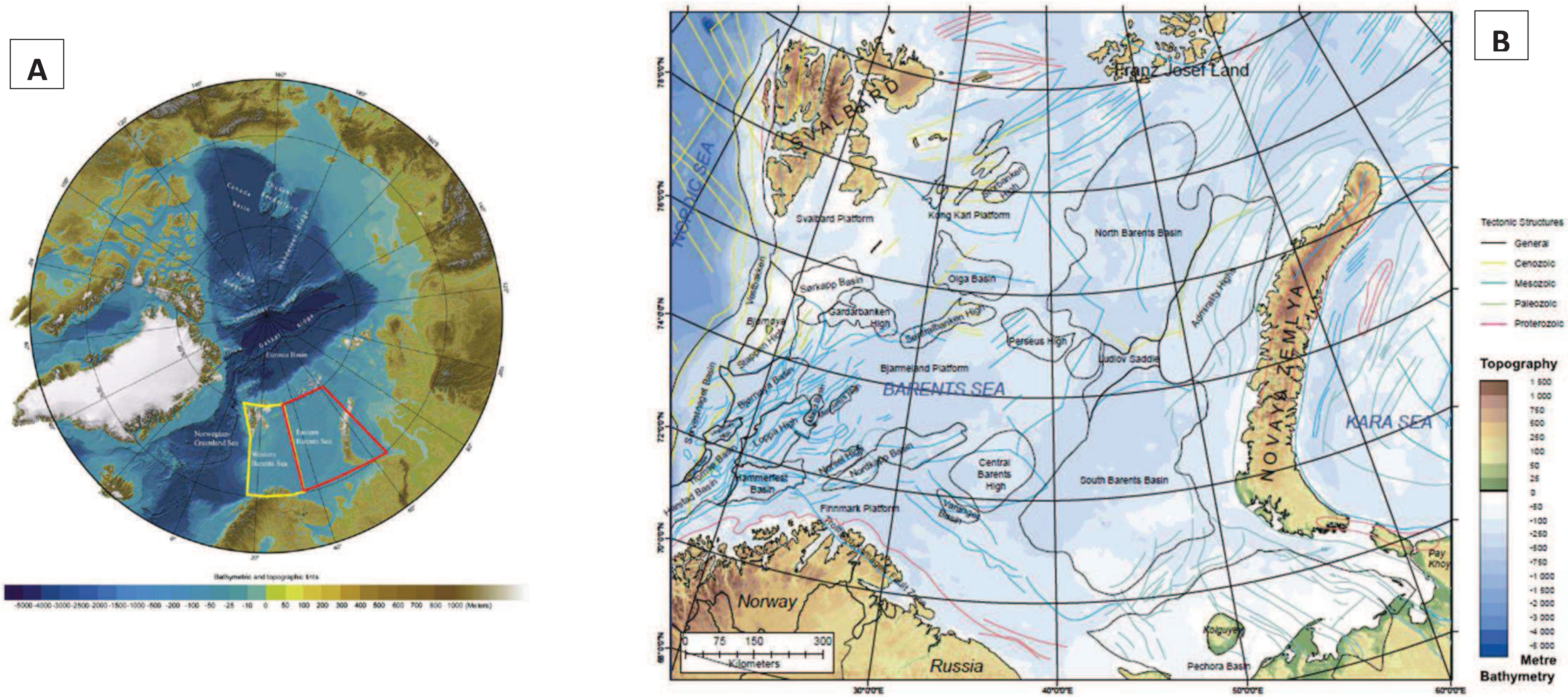

Figure 1 - A) Local and regional setting; yellow area: western Barents Sea-red area: eastern Barents Sea, modified from Glørstad-Clark et al. (2010), bathymetry map from Jakobsson et al. (2008) B) Major structural elements, modified from Smelror et al. (2009)

2.2 Local Setting

The focus area of this study is the eastern region of the Southwest Barents Sea (Fig. 2). It is bounded by the Ringvassøy-Loppa, Bjørnøyrenna and Leirdjupet fault complexes in the west, Northern Norway in the south, Gardarbanken and Sentralbanken highs in the north and the border with Russia in the east (Fig. 2). It includes the Loppa High, Hammerfest and Nordkapp basins and the Bjarmeland and Finnmark platforms (Fig. 2). A number of structural highs, domes, fault complexes and sub-basins further shape the area (Fig. 2). Since the targeted successions are the Lower Cretaceous strata, the area was further limited to where rocks of that age are preserved. Due to later uplift and erosion of the area (Faleide et al., 1993, Vågnes et al., 1992, Dimakis et al., 1998), Cretaceous strata have been removed from a large area in the regional study setting. An outline has been created (Sigmond, 2002, Sigmond and Roberts, 2007) indicating the areas where Cretaceous sediments have been preserved (Fig. 2). As a result of this, the local setting is further focused in the Bjarmeland Platform, Nordkapp Basin, Hammerfest Basin and eastern Finnmark Platform (Fig. 2). All the smaller structural elements that further delineate the area (fault complexes, highs, and sub-basins) were not taken into account in this study.

2.2.1 Bjarmeland Platform (Gabrielsen et al., 1990)

The Bjarmeland Platform is a stable platform area bounded by the Hammerfest and Nordkapp basins in the south and southeast, respectively, Sentralbanken and Gardarbanken highs to the north and the Fingerdjupet Subbasin and Loppa High to the west (Fig. 2). It includes the Norsel and Mercurius highs, Svalis, Samson, and Norvarg domes, Swaen Graben, Maud Basin and Hoop Fault Complex. It has not been affected by any major tectonism since the Palaeozoic and it was established as a platform in the Late Carboniferous. It was affected by the subsequent uplift and erosion, and for that reason older sediments subcrop to the north.

2.2.2 Nordkapp Basin (Gabrielsen et al., 1990, Nilsen et al., 1995)

The Nordkapp Basin is a deep Palaeozoic basin, trending NE-SW, that is 300 km long and 30-80 km wide, bounded by Bjarmeland Platform to the north and Finnmark Platform to the south, with Nysleppen, Måsøy and Thor Iversen fault complexes delineating its margins (Fig. 2). More than 30 salt diapirs are identified. The evaporites triggering the salt structures are of Late Carboniferous age. The diapirism and subsidence were initiated during Early to Mid-Triassic, decreased later on and became reactivated in Late Cretaceous and Middle Cenozoic. During the Early Cretaceous the diapirs were not active.

2.2.3 Hammerfest Basin (Gabrielsen et al., 1990)

The evolution of the Hammerfest Basin has been presented in detail by Berglund et al. (1986). It is a relatively shallow basin with an ENE-WSW axis. It is bounded by the Finnmark Platform to the south and separated from it by the Troms-Finnmark Fault Complex. To the west, the Ringvassøy-Loppa Fault Complex separates it from the Tromsø Basin. To the east, it borders with the Bjarmeland Platform and to the north, the Asterias Fault Complex defines the limit to the Loppa High (Fig. 2). In the Late Carboniferous, the Hammerfest Basin was separated from the Finnmark Platform, and by the Triassic to Early Jurassic it was an active depocenter. During the Early Cretaceous, extensive tectonism established the present day outline.

2.2.4 Eastern Finnmark Platform (Gabrielsen et al., 1990)

The Finnmark Platform is bounded to the west by the Troms-Finnmark Fault Complex, to the north by the Nordkapp and Hammerfest basins, to the south by mainland Norway and in the east by the Tiddlybanken Basin (Fig. 2). It has been stable since the Late Palaeozoic, with the platform established in the Late Carboniferous-Permian.

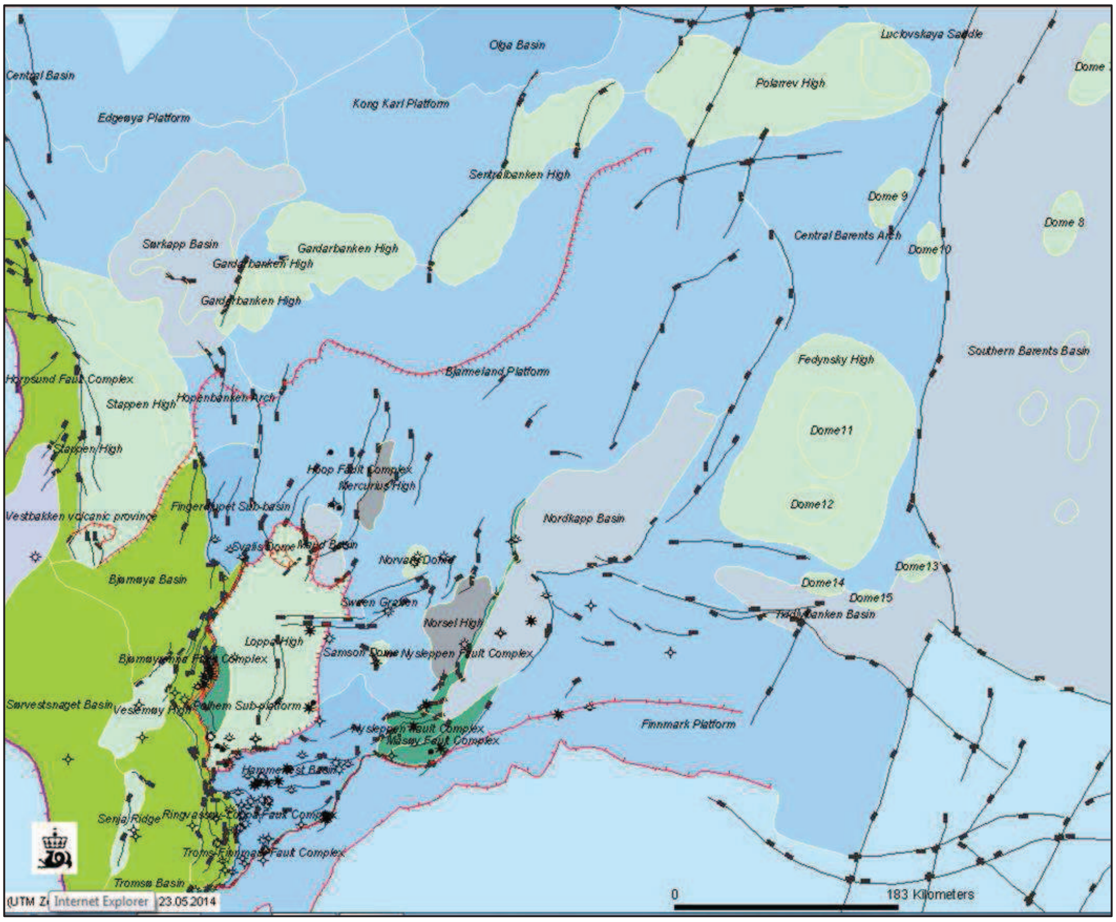

Figure 2 - Structural elements, zoom in of the study area (Directorate, 2014)

2.3 Stratigraphic and Structural Development

The stratigraphic and structural development of the western Barents Sea has been studied and extensively presented by numerous workers (Dallmann, 1999, Faleide et al., 1984, Gabrielsen, 1984, Nøttvedt et al., 1993, Smelror et al., 2009, Worsley, 2008, Gudlaugsson et al., 1998, Faleide et al., 1993). Also, the importance of Svalbard in the understanding of the evolution of the area and the correlation between the two areas has been acknowledged since the early years of research in the region (Nøttvedt et al., 1993, Worsley, 2008).

The top basement reflector is typically positioned at 14 km depth in the western Barents Sea, but with large variations across the area, and with an average of 400 m water depth, a total of more than 10 km of sediments are recognised within the area (Smelror et al., 2009, Gudlaugsson et al., 1998, Faleide et al., 1984). These successions have been deposited and formed in three main stages, the Caledonian, the Devonian-Carboniferous-Permian and the Mesozoic (Smelror et al., 2009).

The Barents Shelf structural evolution has been mainly affected by the Timanian, Caledonian and Uralian orogenies, the proto-Atlantic Rifting, the opening of the Amerasia Basin and the northern North Atlantic Ocean, which together with various secondary tectonic events have shaped it (Faleide et al., 1993, Gabrielsen, 1984, Smelror et al., 2009, Gudlaugsson et al., 1998). Its stratigraphic development mainly depicts the northward movement of the shelf, from the equator in the Silurian to 70^0-80^0 N today (Piepjohn et al., 2012) (Fig 3).

The Precambrian and Palaeozoic evolution has been presented by (Worsley, 2008, Smelror et al., 2009, Stemmerik and Worsley, 2005, Gudlaugsson et al., 1998, Doré, 1991) and a detailed tectonostratigraphic column is shown in Fig. 4. The Precambrian and Lower Palaeozoic basement consists of metamorphic, sedimentary and igneous rocks (Worsley, 2008), affected mainly by the Caledonian orogeny (Smelror et al., 2009). Extensive erosion of the surrounding areas led to the deposition of the “Old Red Sandstones” in the Devonian, with the clear change in sedimentation, marked by the grey sandstones, indicating the shift from southern to equatorial latitudes (Smelror et al., 2009, Worsley, 2008). Widespread extension constructed the platform where carbonate and evaporite sedimentation took place during the Carboniferous and early Permian (Smelror et al., 2009). This culminated in a deposition of a salt layer with an average thickness of 3-4 km (Gudlaugsson et al., 1998). In the Mid- to Upper Permian, a change to cool water carbonates and clastic - organoclastic sediments (Worsley, 2008), reflects the climate change and the transgression that affected the region (Smelror et al., 2009) caused by regional subsidence (Gudlaugsson et al., 1998). The end of the Palaeozoic is marked by the deposition of another evaporite layer in confined and local grabens in the south-western Barents Sea (Fig. X) (Smelror et al., 2009).

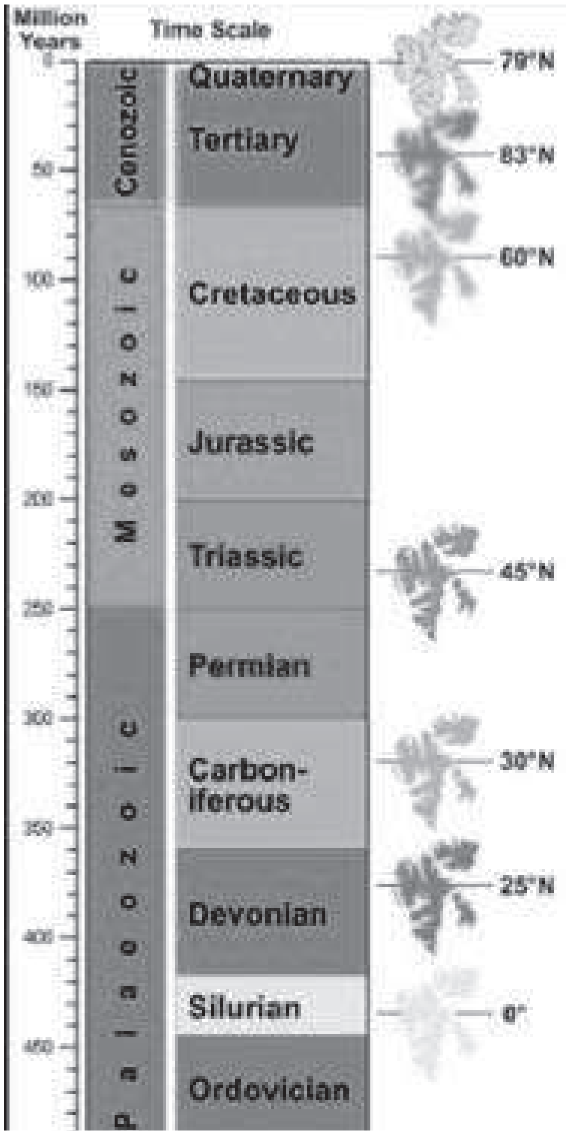

Figure 3 - Barents shelf relative position through time. Modified from Piepjohn et al. (2012)

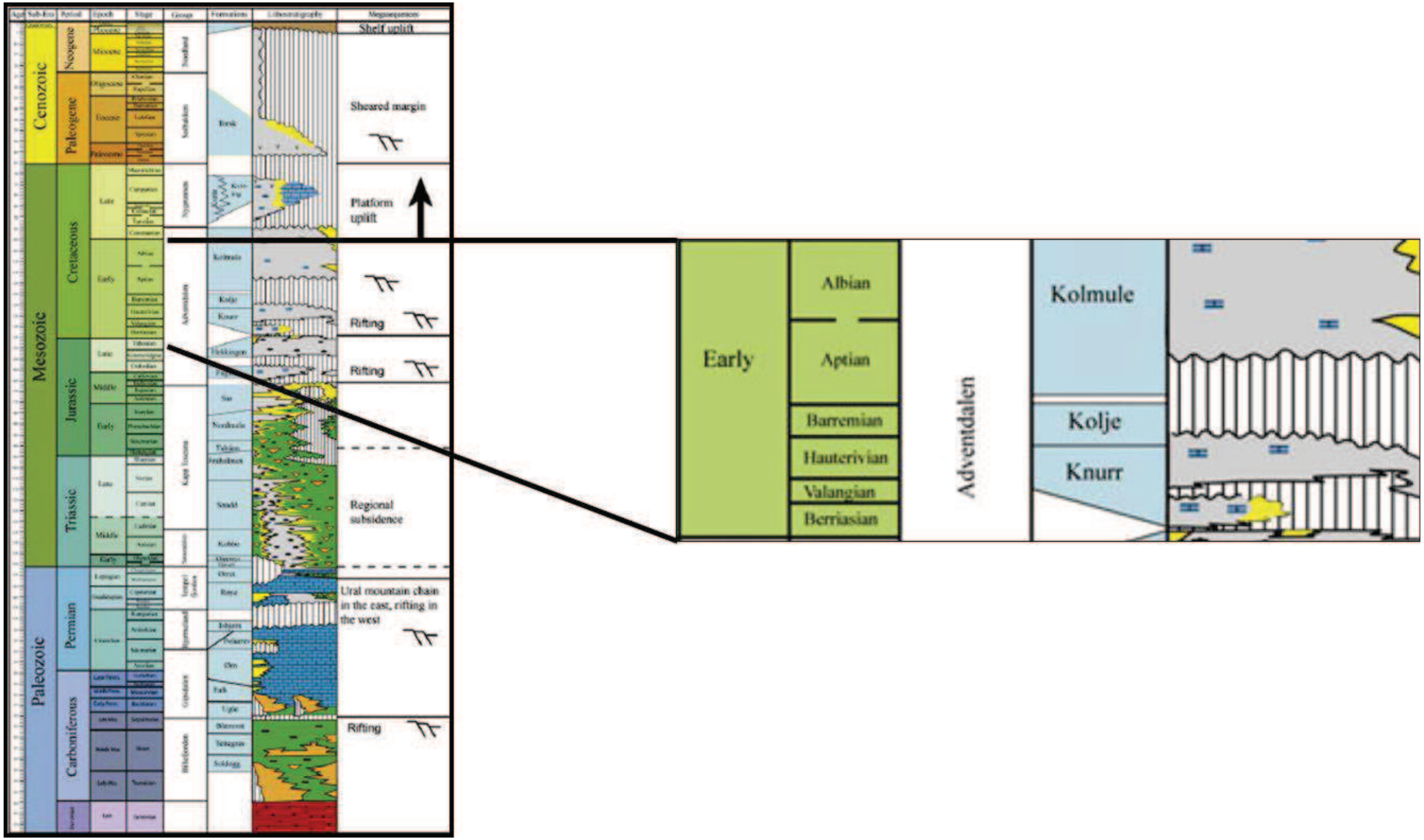

Figure 4 - Lithostratigraphy of the western Barents Sea region, with emphasis on Early Cretaceous, modified from Glørstad-Clark et al. (2010) and Dalland et al. (1988).

Geological Framework

The Mesozoic development of the western Barents Sea and Svalbard has been extensively studied (Dallmann, 1999, Doré, 1991, Faleide et al., 1984, Faleide et al., 1993, Gabrielsen, 1984, Glørstad-Clark et al., 2011, Glørstad-Clark et al., 2010, Nøttvedt et al., 1993, Smelror et al., 2009, Worsley, 2008, Dypvik et al., 1996, Smelror, 1994) and the connection with the local and regional tectonic regimes are well understood. Specifically, the Triassic-Jurassic successions are better understood, mainly because the more prolific petroleum plays in the region are found in rocks of this age (Grogan et al., 1999, Samuelsberg, 2014, Doré, 1995). The Cretaceous is less investigated; both because the petroleum potential was considered limited and because it has been eroded over a large area (Doré, 1995, Grogan et al., 1999, Smelror et al., 2009).

The area located at 45^0N in Triassic, comprises a shelf where Pangea met the Panthalassa Ocean (Piepjohn et al., 2012, Riis et al., 2008). Apart from some local fault movements, no extensive tectonic activity has been documented in the western Barents Sea, with a rifting event at the Permian-Triassic boundary commencing the subsidence into which the siliciclastic material deposited (Glørstad-Clark et al., 2011, Riis et al., 2008). A regional transgression led to the filling of the epicontinental basin and an excellent correlation between the Triassic sediments on Svalbard and the Barents shelf is noted (Mørk and Worsley, 2006, Nøttvedt et al., 1993), but also with the Sverdrup Basin and west Siberia (Mørk and Worsley, 2006). The area was filled mainly from the south and southeast by prograding systems, fed by the erosional products of the surrounding land areas (Glørstad-Clark et al., 2011, Glørstad-Clark et al., 2010, Mørk and Worsley, 2006, Riis et al., 2008).

The Triassic-Jurassic transition is marked by the extensive regional transgression that connected the Tethyan and Boreal Oceans, the change in tectonic and depositional systems in the Arctic; and in the Barents Sea the deposition and subsidence rates declined significantly (Worsley, 2008). The regional source areas were not active any more (Worsley, 2008). There is no significant evidence of fault movement until the Middle-Late Jurassic (Faleide et al., 1993). Significant rifting occurred along the Tromsø and Bjørnøya basins, with minor rifting affecting the Hammerfest Basin. Furthermore, an abrupt change in deposition, from the Middle Jurassic sandstones to the Upper Jurassic anoxic black shales of Hekkingen and Aghardfjellet formations, marks the rejuvenated tectonics in the region (Faleide et al., 1993, Smelror, 1994, Worsley, 2008). These Upper Jurassic shales are one of the most prolific source rocks in the western Barents Sea (Grogan et al., 1999, Doré, 1995).

Tectonism continued in the Cretaceous in the south-western Barents Sea, with the major structural elements being established (Faleide et al., 1993), and sea level changes producing regional unconformities (Nøttvedt et al., 1993). There is no evidence of these unconformities in Svalbard (Nøttvedt et al., 1993). It has generally been accepted that the two areas evolved in a different way, with more pronounced tectonic activity in the south-west Barents Sea and quiescence in Svalbard (Faleide et al., 1993, Midtkandal and Nystuen, 2009, Nøttvedt et al., 1993). However, there is a stratigraphic correlation between the Barents Sea and Svalbard, and although not synchronous, it is evident that the same depositional regime was prevailing in the two regions (Nøttvedt et al., 1993, Worsley, 2008).

The Paleogene was characterised by the rifting and break-up of the Norwegian-Greenland Sea. In the Barents Sea, the tectonism was concentrated along the western margin (Faleide et al., 1993, Worsley, 2008). A regional transgression caused the widespread deposition of sediments, which is correlated over the entire province (Nøttvedt et al., 1993, Worsley, 2008).

Rifting ceased during the Paleogene-Neogene transition, with the establishment of the present day passive margin and oceanic crust (Faleide et al., 1993, Nøttvedt et al., 1993, Faleide et al., 2008). Glacially derived sediments prevailed during the Neogene (Worsley, 2008). The extensive and prolific erosion the area underwent during that time has been documented and thoroughly studied, mainly because of the effects that it had on the petroleum prospectivity of the area (Dimakis et al., 1998, Faleide et al., 1996, Vågnes et al., 1992, Doré and Jensen, 1996). The uplift and erosion increases towards the north of the Barents Sea and Svalbard (Faleide et al., 1993, Vågnes et al., 1992, Dimakis et al., 1998, Faleide et al., 1996).

Summarising the structural and stratigraphical history of the western Barents Sea-Svalbard region is impressively complicated. It is the result of the interplay between global, regional, local tectonism and a myriad of depositional environments. The present day structural outline of the region is shown in Fig. 1. B.

2.4 Early Cretaceous

This section summarises the previously published available information about the Cretaceous development in the Barents Sea. The present study sheds further light on some of the aspects and interpretation, as new data have become available. During Early Cretaceous times, the North Atlantic region was influenced by extensive rifting and a sea level lowstand, something that affected the south-western Barents Sea (Faleide et al., 1993). Early Cretaceous strata and evidence of local tectonism are preserved in greater extent in the Harstad, Tromsø, Bjørnøya and Hammerfest basins (Faleide et al., 1993). Fine clastic sedimentation prevailed over most of the area, with greater thicknesses observed in basins and thinner successions with carbonates in the platform areas (Worsley, 2008). It has been observed that sandstone fans were sourced from local highs (Worsley, 2008).

The Nordvestbanken Group is the lithostratigraphic unit corresponding to the Early Cretaceous of the Barents Sea (Dalland et al., 1988). It is of Valanginian to Cenomanian age and has been subdivided to Knurr, Kolje and Kolmule formations (Dalland et al., 1988). It consists of shales and claystones, interbedded with thin layers of siltstone, limestone and dolomite (Dalland et al., 1988). It has been correlated with the upper parts of the Adventdalen Group in Svalbard (Dalland et al., 1988). However, it has been accepted that there is no evidence of the deltaic progradation observed in Svalbard, corresponding to the Helvetiafjellet Formation, in the southwest Barents Sea (Worsley, 2008, Dalland et al., 1988, Smelror et al., 2009). A regional unconformity marks the lower boundary of the Helvetiafjellet Formation, with mudstone units overlain by a cliff-forming sandstone unit (Midtkandal and Nystuen, 2009). This feature resulted from a pronounced uplift of the northern margin of the Barents shelf due to the development of the polar Amerasia Basin (Midtkandal and Nystuen, 2009, Worsley, 2008). The southern extent of that prograding system has been positioned by (Smelror et al., 2009, Worsley, 2008) on the southern part of Spitsbergen (Fig. 5). Its distal parts reached the Bjørnøya Basin, due to observation of clinoforms in seismic data (Worsley, 2008). On the south-western Barents Sea and specifically on the eastern part that comprises the study area of this thesis, open marine muddy sedimentation is expected without influence from the northern sourced system (Smelror et al., 2009, Worsley, 2008).

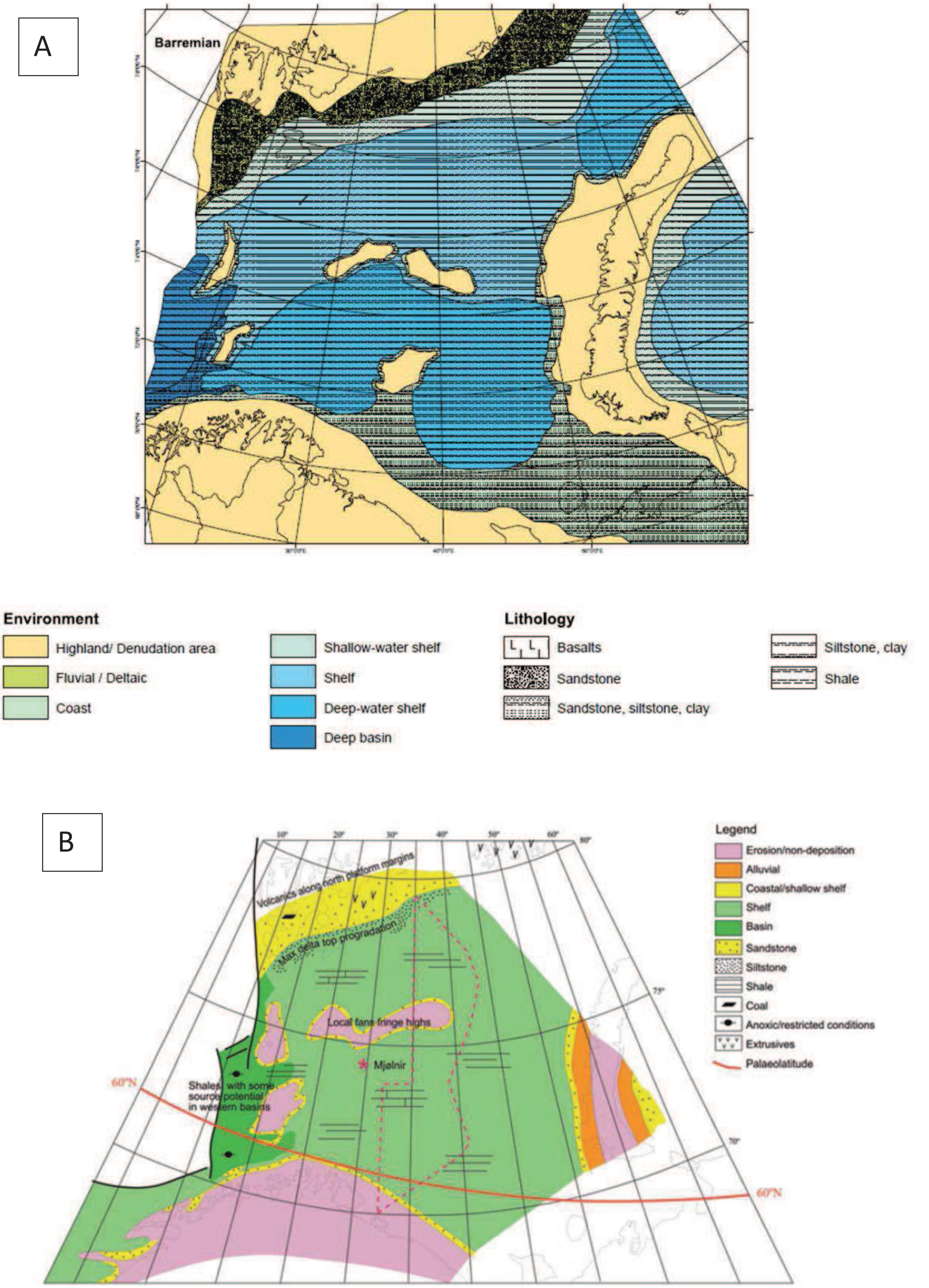

Figure 5 - Early Cretaceous regional paleogeography, modified from A) Smelror et al. (2009) and B) Worsley (2008)

2.4.1 Cretaceous Stratigraphical Units (Dalland et al., 1988)

Knurr Formation: Ryazanian/Valanginian to early Barremian age. Claystones with thin limestone and dolomite layers. Small sandstone units are found in its lower parts. Open and distal marine conditions with locally restricted bottom circulation. It is correlated with the dark shales of the Rurikfjellet Member of the Janusfjellet Formation on Svalbard.

Kolje Formation: Early Barremian to late Barremian/early Aptian age. Shale and claystone with small layers of limestone and dolomite. Thin beds of silt and sandstone are observed in its upper parts. Open, distal marine environment with periods of good and restricted water circulation. It is correlated with the Helvetiafjellet Formation on Svalbard, without the distinctive sandstone units.

Kolmule Formation: Aptian to mid-Cenomanian age. Claystone and shales, with more silty parts, and limestone/dolomite stings. Open marine environment. Correlated with Carolinefjellet Formation on Svalbard.

2.5 Cretaceous High Arctic Large Igneous Province

Lower Cretaceous volcanic rocks that have been identified and correlated in Svalbard, Franz Josef Land, the Canadian Arctic Archipelago and northern Greenland are associated with a High Arctic Large Igneous Province (HALIP), active in that time period (Grogan et al., 2000, Maher, 2001, Nejbert et al., 2011). The center of the HALIP has not be pinpointed yet, but has been connected with the formation of the Alpha Ridge and the Amerasian Basin (Maher, 2001, Grogan et al., 2000) (Fig. X). The indications of the HALIP in Svalbard include mafic sills and basalt flows and the Lower Cretaceous Helvetiafjellet Formation. The Helvetiafjellet Formation's regressive contact with the dark shales of Janusfjellet Formation, points to an abrupt fall in sea level (Midtkandal and Nystuen, 2009, Nejbert et al., 2011) that is associated with an uplift in the north of Barents shelf (Maher, 2001). Maher (2001) argues that the HALIP produced erosional products of more than 1km in thickness. The fluvial/deltaic to paralic units of that prograding system correspond to the Helvetiafjellet Formation in Svalbard, studied by Midtkandal and Nystuen (2009). Nejbert et al. (2011) dated the event to around 125 to 78.3 Ma, with numerous activity peaks, linked to tectonic events corresponding to different phases of the Alpha Ridge evolution. Corfu et al. (2013) further restricted the age of magmatism on Svalbard to 123 to 124 Mya.

2.6 Late Cenozoic Uplift and erosion

The pronounced uplift and erosion of the Barents shelf area has long been studied, primarily because of the implications it has in the petroleum prospectivity of the area (Dimakis et al., 1998, Doré and Jensen, 1996, Faleide et al., 1996, Faleide et al., 1993, Smelror et al., 2009, Vågnes et al., 1992). Since Paleogene times and synchronous with the opening of the Norwegian-Greenland Sea, the region has been uplifted and massive amounts of sediments have been eroded, intensified by glacial processes (Dimakis et al., 1998). The uplift and subsequent erosion has led to limited preservation of Lower Cretaceous sedimentary strata. The term Near Base Cretaceous Unconformity window (near BCU window) is introduced to indicate the area where Cretaceous successions are preserved. In Fig. 6, the depth of the Base Cretaceous reflector is shown.

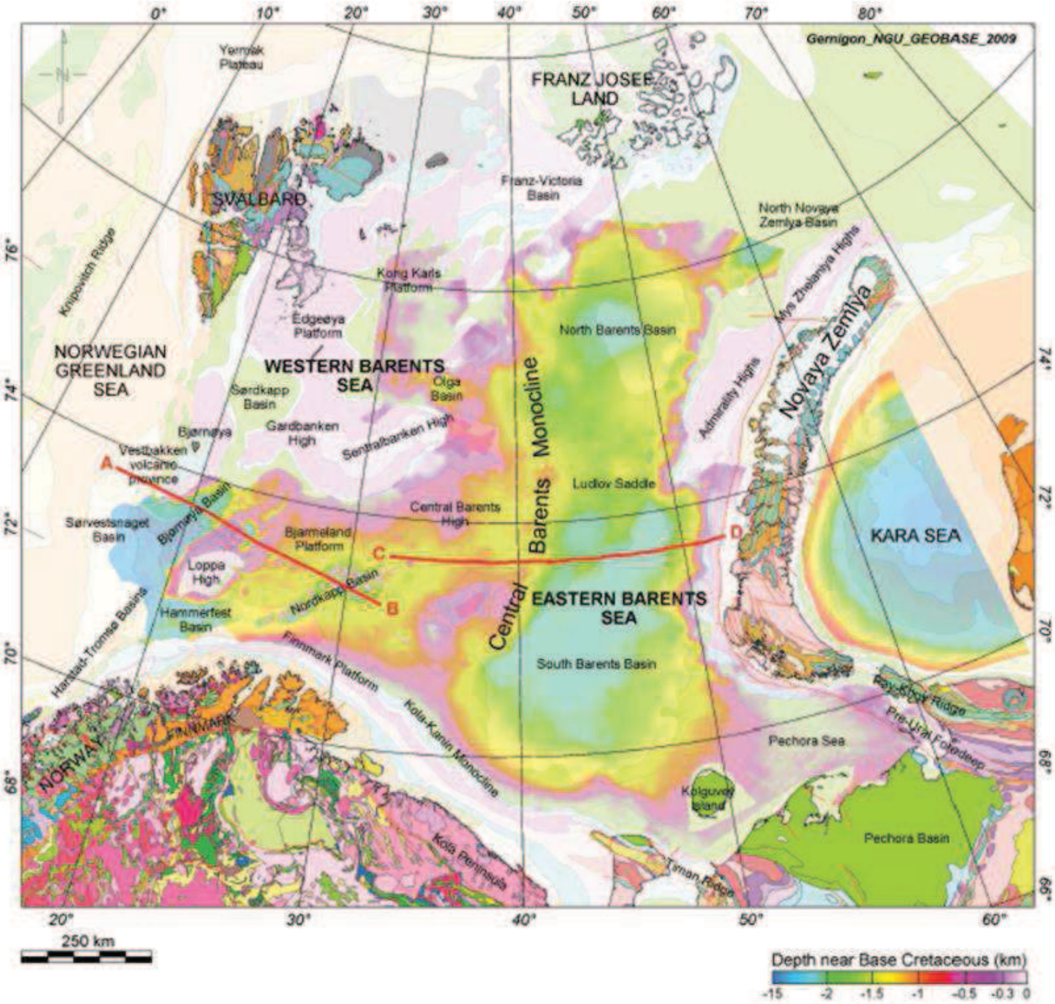

Figure 6 - Main structural elements of the Barents Shelf; with the approximate depth to the Base Cretaceous reflectors highlighted (Smelror et al., 2009)

3 Data and Methods

3.1 Data

The data used in this study are publicly released exploration well data, and 2D seismic data, mainly from the NBR survey of TGS and Fugro, supplemented by NPD data (Fig. 7 & 8). Three shallow boreholes drilled in the area by IKU, in the period 1985-1988, were also integrated.

As seen in Fig. 7, although there is a plethora of wells drilled in the Hammerfest Basin, there are significantly less wells in the Bjarmeland Platform, Nordkapp Basin and East Finnmark Platform, which constitute the main area of this study. In order to have a preliminary picture of likely lithologies in the area, all the available well data were studied (Table 2, Fig. 7). The well data consist of, were available, composite logs from NP (Directorate, 2014).

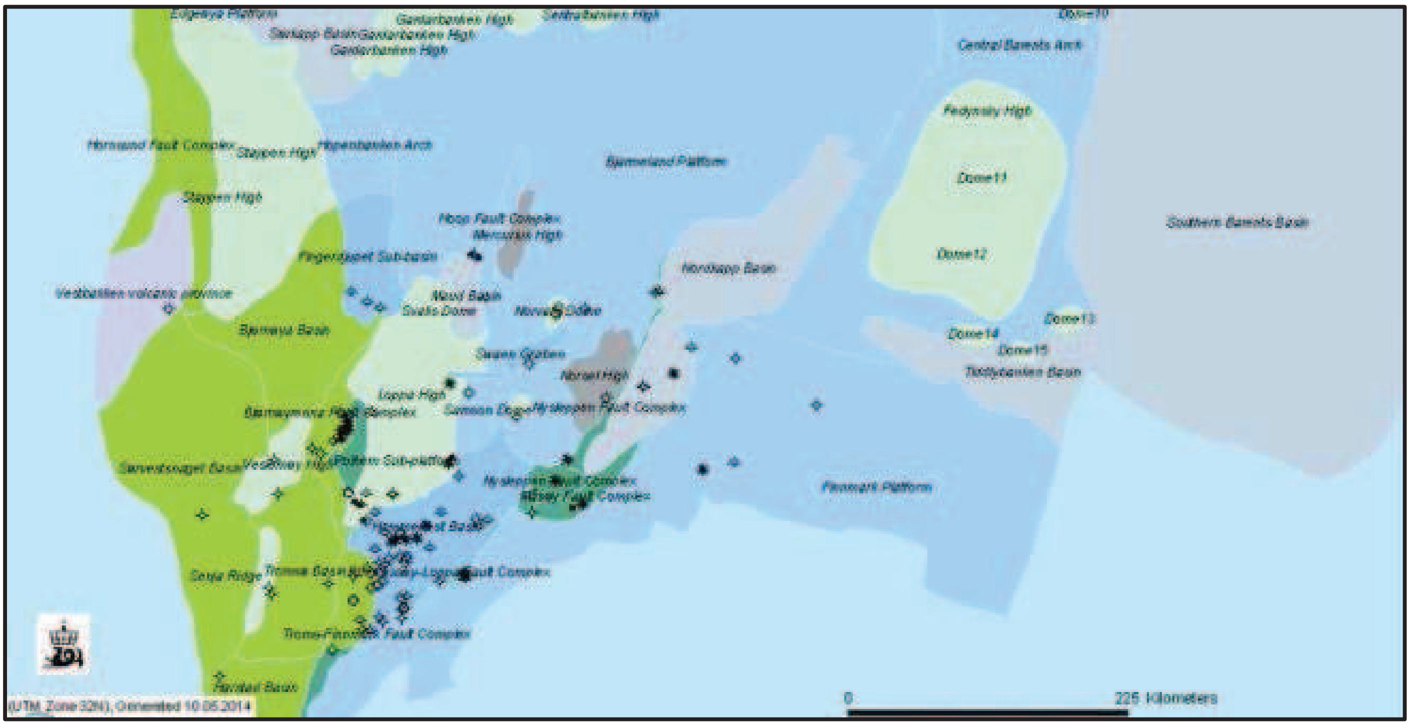

Figure 7 - Exploration wells drilled in the study area, available from Directorate (2014)

The seismic data are of excellent quality and they are cut at 3 s, as the Cretaceous strata that are examined comprise the uppermost stratigraphical levels. No imaging problems were encountered, apart from sparse gas chimneys. In Fig. 8 all the lines interpreted are shown. From these, representative lines were chosen to present the results. In the western parts of the study area, the seismic lines are significantly denser than in the eastern parts (Fig. 8). Specifically, their spacing varies from 2-5 km and up to 20-80 km. No 3D seismic data were utilized, since there are not any available at the moment in the main area of interest.

Seismic interpretation and well examination was performed using Petrel software. Because of the nature of the successions examined, the interpretation was done with the near BCU reflector artificially flattened. Several other features of the software were integrated to the interpretation procedure; the z axis was vertically exaggerated 45-55% and the reflectors amplitude was artificially amplified. All the above were done in order to further assist the interpretation procedure and every artificial element was removed when the final hypothesis were discussed and tested.

Interpretation of both the local and regional geological environment is strongly constrained by the lack of denser 2D/3D seismic and well data.

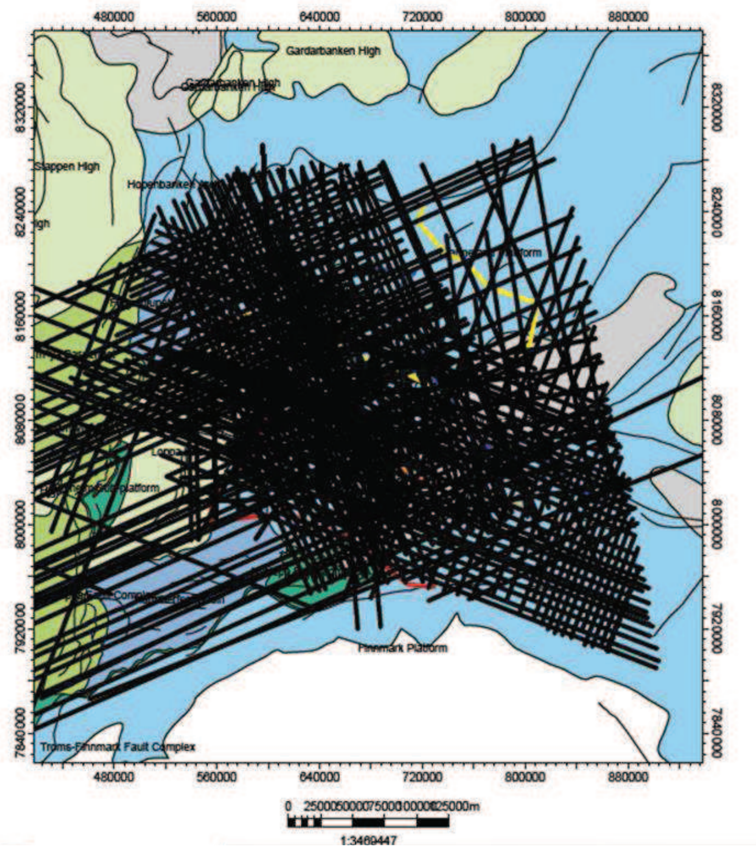

Figure 8 - Seismic lines interpreted

3.2 Methods

A summarized historical overview of sequence stratigraphy and its application in epicontinental basins was presented by Glørstad-Clark (2011). A more extensive one can be found in Nystuen (1998). Both papers were utilized in the interpretation of the data. In this thesis the reflection configuration patterns and infill geometries that were first introduced by Mitchum Jr et al. (1977) are adopted, together with work from Sangree and Widmier (1979), Bertram and Milton (1996) and Myers and Milton (1996).

The approach used to interpret, define and investigate the different depositional environments encountered in the study area is described in (Mitchum Jr et al. (1977), Vail et al. (1977)).

The process of defining the seismic sequences can be summarized in two steps; firstly, a general seismic sequence analysis was performed, and secondly, seismic facies were investigated (Mitchum Jr et al., 1977, Sangree and Widmier, 1979).

Seismic sequence analysis consisted of identifying reflection terminations to subdivide packages that are defining different depositional sequences (Mitchum Jr et al., 1977). The types of boundaries used are those defined in Mitchum Jr et al. (1977) and are shown in Fig. 9. Such boundaries are then identified according to the sequence stratigraphic surfaces that were described by Bertram and Milton (1996) (Fig. 10, Table 1).

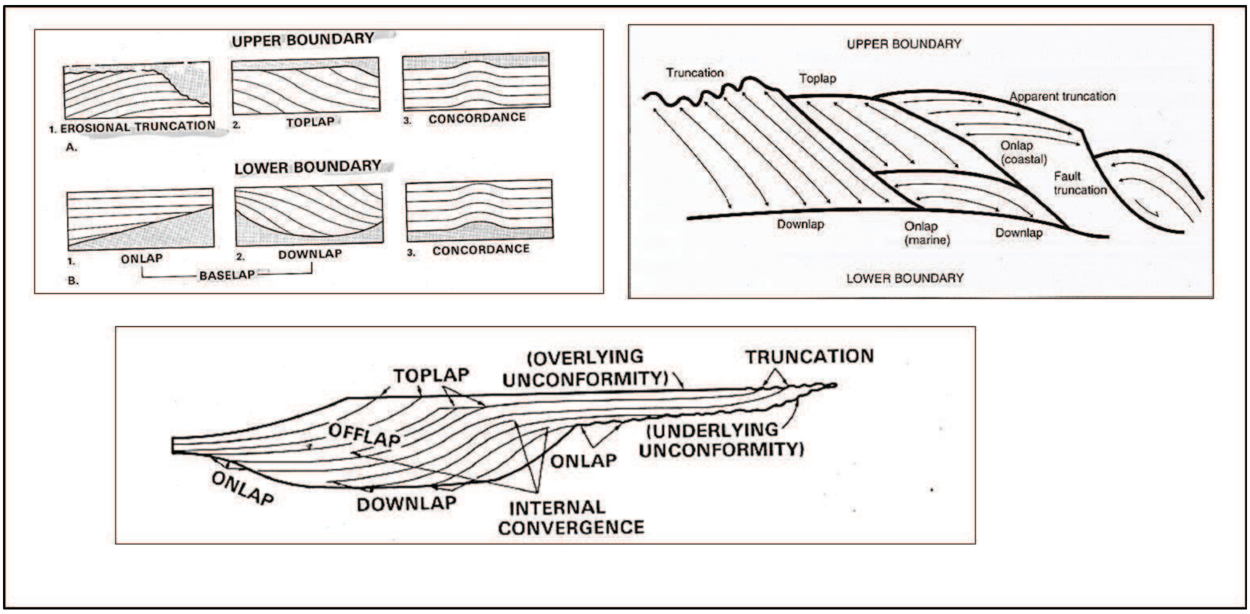

Figure 9 - Boundaries and the reflection terminations that defines them, modified from (Bertram and Milton, 1996, Mitchum Jr et al., 1977)

Table 1 - Reflection terminations, with their description and the seismic surfaces that they represent.

Reflection Terminations	Description	Seismic Surfaces
Downlap	Lapout of the reflections against an underlying reflection seismic surface. Is observed at the base of prograding clinoforms. Indicates progradation of a basin-margin slope system into deep water.	The downlap surface usually represents a Maximum Flooding Surface (MFS).
Onlap	Terminations of low-angle reflections against a steeper seismic surface. In this study only marine onlap can be recognised. It represents a change from marine deposition to marine non-deposition or condensation. It is a result from the partial infill of space by sediments.	The onlap surface represents a Sequence Boundary (SB)
Toplap	Terminations of inclined reflections against an overlying lower angle-surface. It represents a change from slope deposition to non-marine or shallow marine bypass or erosion.	The toplap surface represents an unconformity.
Erosional Truncation	Termination of reflections against an overlying erosional surface.	The erosional truncation surface represents a Sequence Boundary.
Fault Truncation	Terminations of reflections against a syn- or post-depositional fault.	The fault truncation surface does not represent a Sequence Boundary.

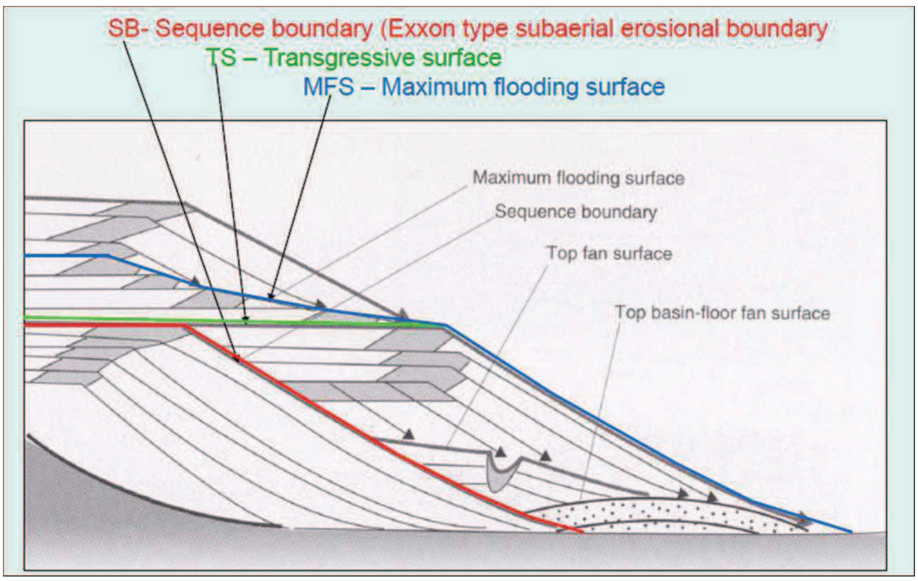

Figure 10 – Sequence Boundaries defined from the reflection terminations, modified from Bertram and Milton (1996)

The seismic facies investigation is based on Mitchum Jr et al. (1977). Although definite geologic interpretation are difficult to obtain only by seismic data, a first attempt will be made based on Sangree and Widmier (1979)_ENREF_7. The Reflection Configuration, Continuity, Amplitude and External Form and Areal Association are used to make some preliminary interpretation of the depositional history.

The seismic investigation revealed successions with progradational architecture/Reflection Configuration, according to what has been described by Mitchum Jr et al. (1977) as “Prograding Reflection Configuration”; platform or shelf edge clinoforms building out/ prograding into the basin. The clinoform reflection patterns are described and interpreted according to (Mitchum Jr et al. (1977), Sangree and Widmier (1979)) with the main configurations in dip and transverse sections presented in Fig. 11. The Sigmoid and Oblique Tangential Configurations (Fig. 11) are recognized in this study.

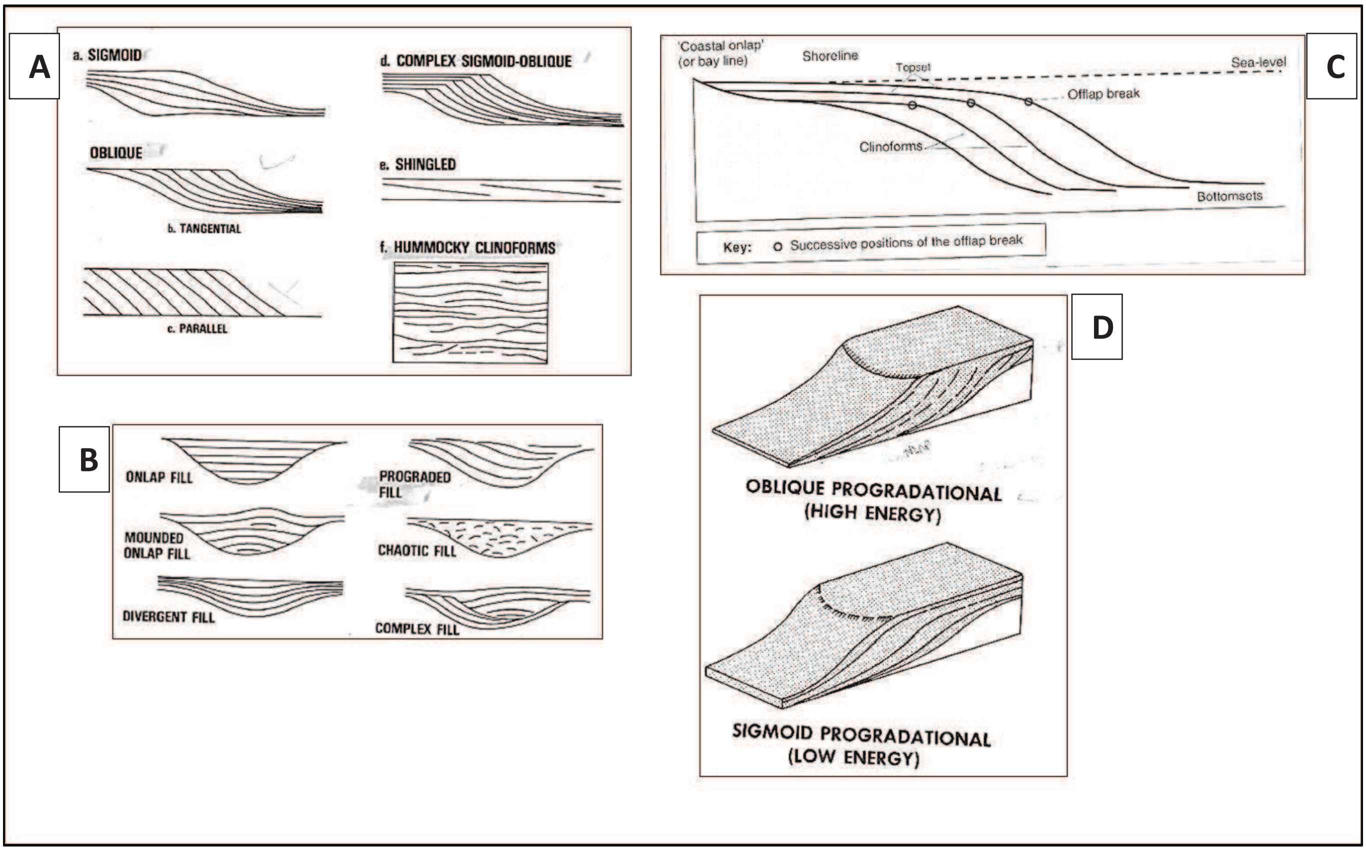

Figure 11 - Clinoform configurations, A) dip section B) transverse section, C) full clinoform profile D)zoom in a dip section of an oblique and sigmoid Progradational Configuration modified from (Bertram and Milton, 1996, Mitchum Jr et al., 1977, Sangree and Widmier, 1979)

Clinothems, separated by clinoform surfaces can be formed either by prograding deltas; then they are tens of meters high and below present day seismic resolution, or by shelf-margin accretions, where they comprise tens of kilometers in length and can reach a height of hundreds of meters (Coe, 2003). The latter are the ones examined in the present seismic data. In Fig. 11 and 12 a typical profile of a clinothem is shown with the topset, foreset and bottomset defined by its bounding clinoforms. This configuration is used to describe the clinoform geometry studied in this thesis.

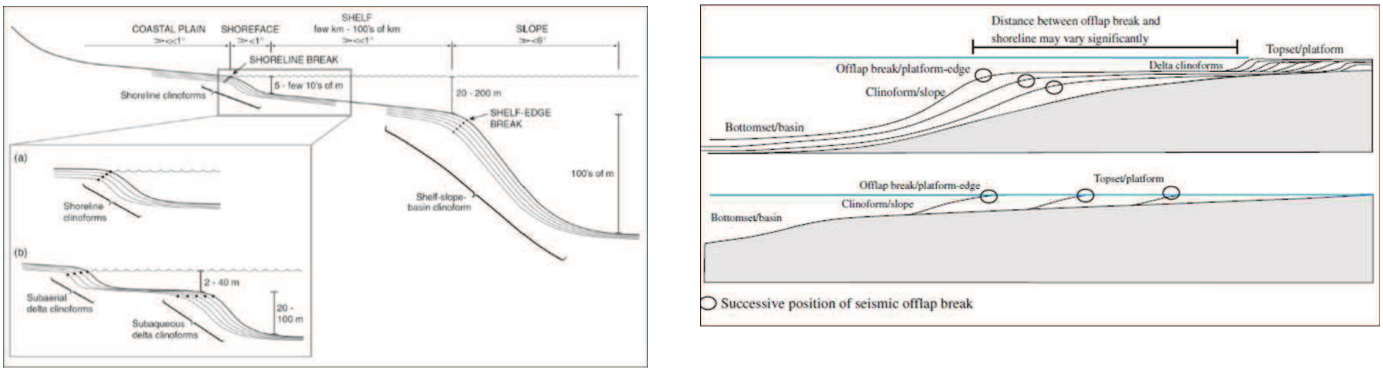

Figure 12 - Clinoform geometry (left fig. from Helland-Hansen and Hampson (2009), right fig. from (Glørstad-Clark et al., 2010)

The topset part of the profile is where the sediments are entering the system, transported by rivers, and represents the adjacent part of the margin (Myers and Milton, 1996). Most commonly the topset appears flat on seismic sections and may contain alluvial, deltaic or shallow marine deposits (Myers and Milton, 1996). Sediments are then distributed downwards through paralic related processes. If a slope is present, the sediments will be further dispersed and the foreset profile, with clinothems and the corresponding clinoforms, will develop (Myers and Milton, 1996). Foresets are characterized by the presence of dipping sediments (> 1°) (Mitchum Jr et al., 1977). Marine sedimentation, usually below the wave base, takes place in this part of the profile (Myers and Milton, 1996) (Fig. 13). Bottomsets develop at the base of the clinothem profiles. These clinoforms show lower gradients than the foreset ones; deep-water sedimentation well below the storm wave base takes place in the environment where the bottomsets are formed (Myers and Milton, 1996) (Fig. 13).

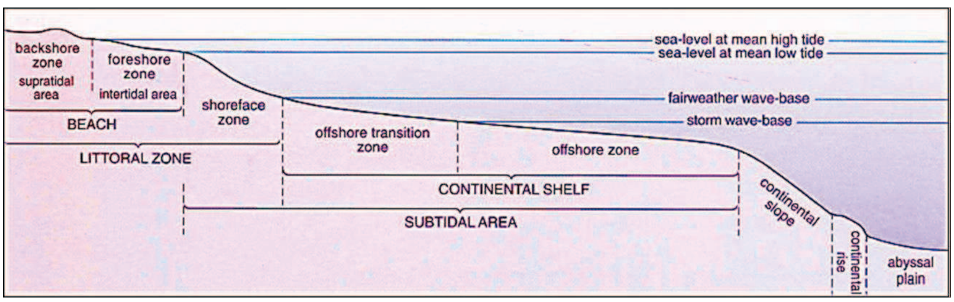

Figure 13 - Depositional environments within a clinoform profile, modified from Coe (2003)

The *Oblique tangential progradational reflection* pattern (Fig. 11, A & D) corresponds to a prograding clinothem, with steep-dipping (10^{o}) reflectors (Mitchum Jr et al., 1977). The upper boundary is usually defined by toplap or a flat surface and the lower boundary by downlap (Mitchum Jr et al., 1977). The depositional environment is typically a high energy one, with a constant or slowly rising sea level (Sangree and Widmier, 1979). The topset and upper foreset parts of the clinoforms have good sand potential, whereas in the lower foreset and bottomset parts, more mud-prone units are expected (Sangree and Widmier, 1979).

The *Sigmoidal progradational reflection pattern* showcases S-shaped clinoforms (Fig. 11, A & D) which are moderately steep. The upper boundary is marked by concordant reflectors on top and the lower downlaps on the bottom surface (Mitchum Jr et al., 1977). The depositional environment is low energy, with a rising sea level or a subsiding basin (Sangree and Widmier, 1979). The clinoform profile is characterized by mud-prone and fine-grained sediments in all its parts (Sangree and Widmier, 1978).

Reflection Continuity and Reflection Amplitude can be subdivided in α) High Continuity/High Amplitude, β) Low Amplitude/Low Continuity and γ) Low Continuity/Variable Amplitude (Fig. 14) (Sangree and Widmier, 1979). *High Continuity/High Amplitude* represents continuous strata, with widespread deposition, indicating interbedded sedimentary strata of different lithologies and alternating energy of the depositional system (Sangree and Widmier, 1979). *Low Amplitude* represents either one type of lithology or beds that are below seismic resolution, indicating either a low energy system; with mud-prone strata expected, or a high energy system; with sand-prone strata expected (Sangree and Widmier, 1979). *Low Continuity/Variable Amplitude* usually represents nonmarine deposits, especially connected with fluvial processes, indicating a variable energy system with mixed sand and mud-prone units (Sangree and Widmier, 1979). The low continuity of the reflectors occurs from the abrupt change of lithologies through the deposition of the sand-channels units, that, also, produce the higher amplitudes (Sangree and Widmier, 1979).

From the External Form and Areal Association of the seismic sequences, a geologic interpretation of both the local and regional depositional environment together with the geological setting and the potential source area can be carried out (Mitchum Jr et al., 1977).

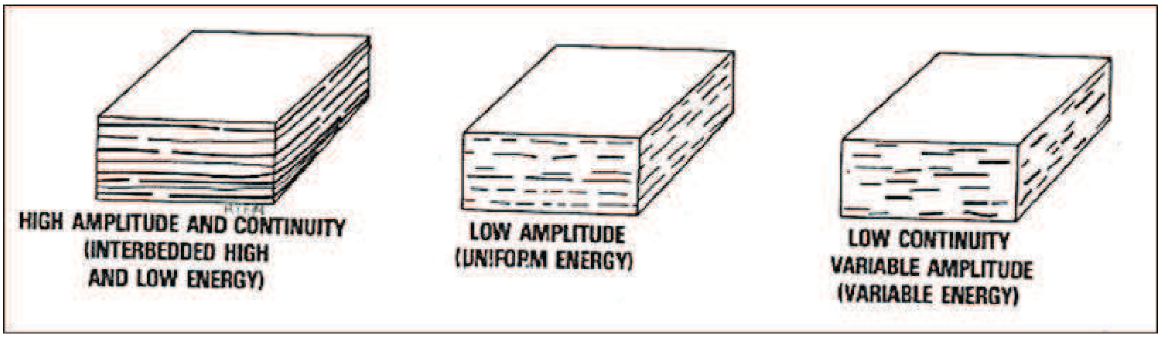

Figure 14 - Reflectors amplitude and continuity relationships, modified from Sangree and Widmier (1979)

The thickness of the clinothem packages found was calculated according to an average velocity of 3.2 km/s (Faleide, 2014) for the Cretaceous sediments in the south-western Barents Sea. The two-way travel time of each package, in ms, was acquired through Petrel software, and with a simple mathematic equation, the thicknesses were calculated. A possible error in the calculations should be taken into account, because the velocity of the Cretaceous strata in the study area could be significantly higher or lower than average and compaction effects are not corrected for. But since no velocity measurements are performed in the area, the average velocity has to be used for a thickness estimation to be performed. The thickness measured corresponds to the present-day preserved one, after the subsequent uplift and erosion removed parts of the sedimentary successions.

4 Results

The available well data together with the seismic interpretation results are integrated to create the outline of the Lower Cretaceous strata depositional history.

4.1 Well Data

The well data were examined in three stages. A preliminary examination of the wells was performed, before the seismic interpretation, to investigate the lithologies in the area and potential sand units. A secondary investigation was performed after the seismic interpretation was completed. The purpose of this was to use specific wells that were drilled through the clinothem packages to obtain any lithological information (gamma ray logs) in an attempt to predict lithologies and ages (assigned lithostratigraphic units) of the observed sequences. The third part included a study of shallow boreholes drilled in the area that had reached the Jurassic-Cretaceous boundary, and could potentially provide more accurate time and lithological constraints for the clinothem packages. Part one is presented in this subchapter and parts two and three are presented after the seismic interpretation results are introduced.

The targeted formations and ages, in all phases, were the Knurr (Valanginian-Barremian), Kolje (Barremian-Aptian) and Kolmule (Aptian-Cenomanian) Formations, which correspond to the Lower Cretaceous lithostratigraphy of the Barents Sea (Dalland et al., 1988).

4.1.1 Well data investigation – part one

The wells examined in the first phase are shown in Fig. 15 and Table 2. In that early stage and without any seismic information, 23 wells from the study area were integrated. Greater focus was given in the wells positioned in the Bjarmeland Platform, Nordkapp Basin and Eastern Finnmark Platform. The Cretaceous strata in these areas are significantly less studied than in the Hammerfest Basin. Unfortunately, in these areas there are fewer wells drilled and most of them are relatively new, so there are no publicly released data. The results are shown in Table 2. Summarizing; all the formations were not present in all the wells. The Kolje Formation is present in just 7 wells, all in the Hammerfest Basin. It is missing in the eastern areas, and the Kolmule Formation lies directly above the Knurr, suggesting a Barremian-Aptian depositional hiatus. The Knurr Formation is missing from 3 wells, and where it is present, it does not have a thickness greater than 60 m. The Kolmule Formation is the best developed and more extensive one. All the above suggests that during earliest Early Cretaceous (Berriasian-Valanginian) there was not an extensive deposition of sediments in the eastern part of the study area. The vast amount of sediments was deposited during the Aptian-Cenomanian (Kolmule Formation). No distinctive or extensive sand units are present in any of the wells. Although there is a coarsening upwards trend, from the top Hekkingen Formation, the gamma-ray log readings vary between 70-100 API; indicative of claystone or shale (Rider, 1996), but not as dark as Hekkingen Formation's shales. The gamma-ray log readings at this point were obtained by the available composite logs on NPD's website (Directorate, 2014). No cores were available. Also, from that initial investigation it became obvious that the lithostratigraphic subdivision of the lowermost Cretaceous (Knurr and Kolje formations) appears to be poorly constrain, since no explanation of why they are or not present in the wells can be given.

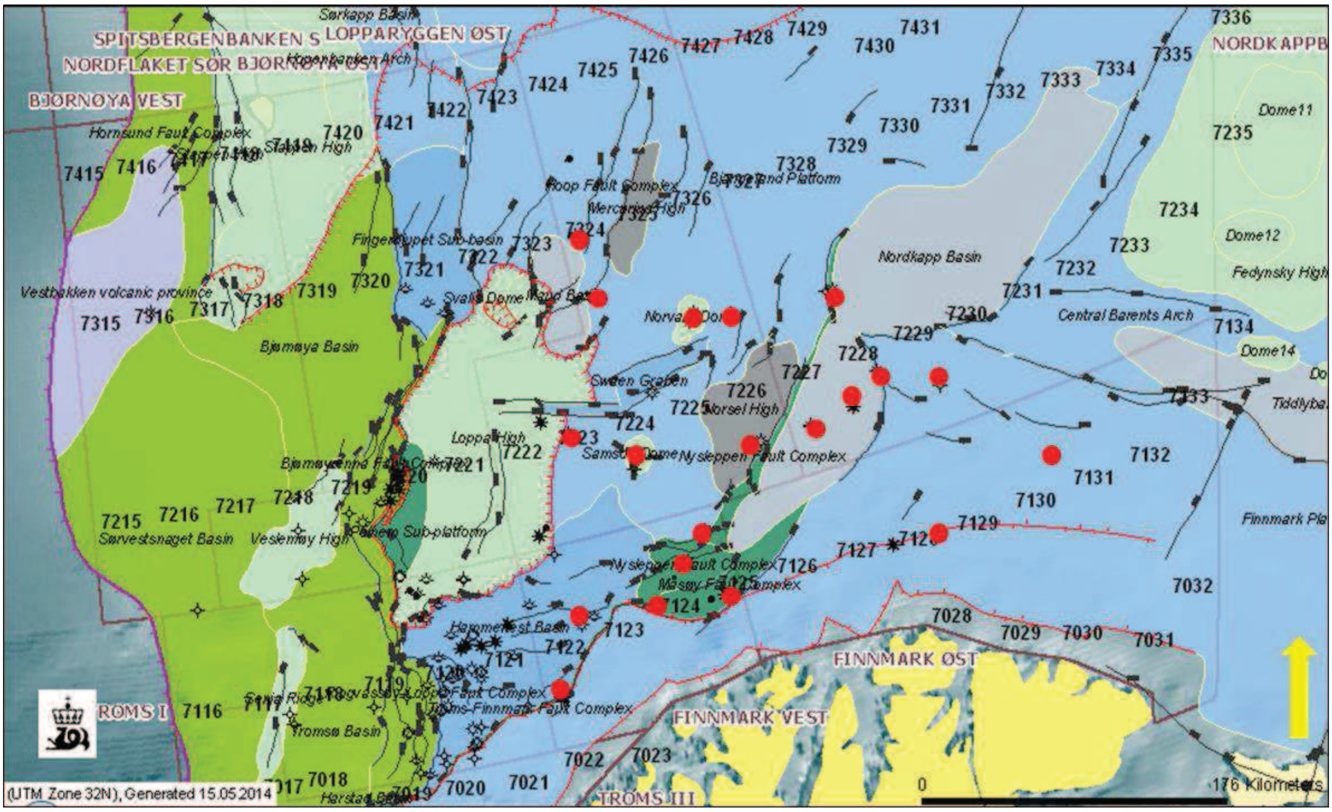

Figure 15 - Major structural elements superimposed with the quadrants. Red dotes denote the location of the wells examined in the first phase (Directorate, 2014).

Table 2 - Formation Thicknesses and Gamma Ray readings of the wells examined in phase one.

Wells	Knurr Fm Thickness	Kolje Fm Thickness	Kolmule Fm Thickness	Knurr Fm API(~)	Kolje Fm API(~)	Kolmule Fm API(~)	Details
7324/7-1 S	-	-	-	-	-	-	no info
7324/8-1	-	-	-	-	-	-	no info
7324/10-1	8 m	-	73m	120	-	120	
7225/3-1	34 m	-	220 m	-	-	-	no GR
7225/3-2	-	-	-	-	-	-	no info
7226/2-1	27 m	-	273 m	170	-	170	
7228/9-1 S	-	-	722 m	-	-	120	
7229/11-1	12 m	-	821 m	120-300	-	60-90	
7131/4-1	15 m	-	394 m	-	-	-	no GR
7225/3-1	34 m	-	220 m	-	-	-	no GR
7224/6-1	16 m	-	471 m	90-110	-	80-90	
7224/7-1	30 m	-	361 m	60-90	-	60-90	
7122/6-1	50 m	265 m	733 m	110-120	60-90	50-90	
7122/6-2	61 m	253 m	771 m	140-180	180-100	120-80	
7122/7-1	38 m	-	349m	40-90	-	60-90	
7124/3-1	-	13 m	602 m	-	40-60	40-60	
7124/4-1	43 m	12 m	554 m	-	-	-	no GR
7125/1-1	26 m	4 m	697 m	70-120	60	40-80	
7125/4-1	38 m	46 m	241 m	230-150	230-150	230-150	
7125/4-2	47 m	12 m	279 m	90-180	110-120	80-120	
7226/11-1	6 m	-	767 m	120-60	-	90-40	
7227/11-1	-	-	829 m	-	-	-	no GR
7228/7-1	14 m	-	966 m	60-40	-	60-40	

4.2 Seismic Interpretation

4.2.1 Near base Cretaceous Surface

A reference surface to be used as a lower boundary for the Cretaceous sequence analysis needed to be identified. Due to lack of constraints from biostratigraphy and well data, a definite Base Cretaceous surface (BCU) is impossible to pinpoint. Hence, a near-BCU reflector that can be traced and correlated across the entire area is required. That reflector needed to fulfil certain requirements; to correlate with the known BCU from the Hammerfest Basin, to correspond with a reflector with a positive reflection coefficient, and to be close to the surface onto which the Cretaceous strata downlap. A double (negative-positive) strong reflector directly below the downlapping one fulfils the above requirements (Fig. 16, A). It was traced and mapped in the study area, and a near Base Cretaceous Unconformity (BCU) surface was established (Fig 16, B & C).

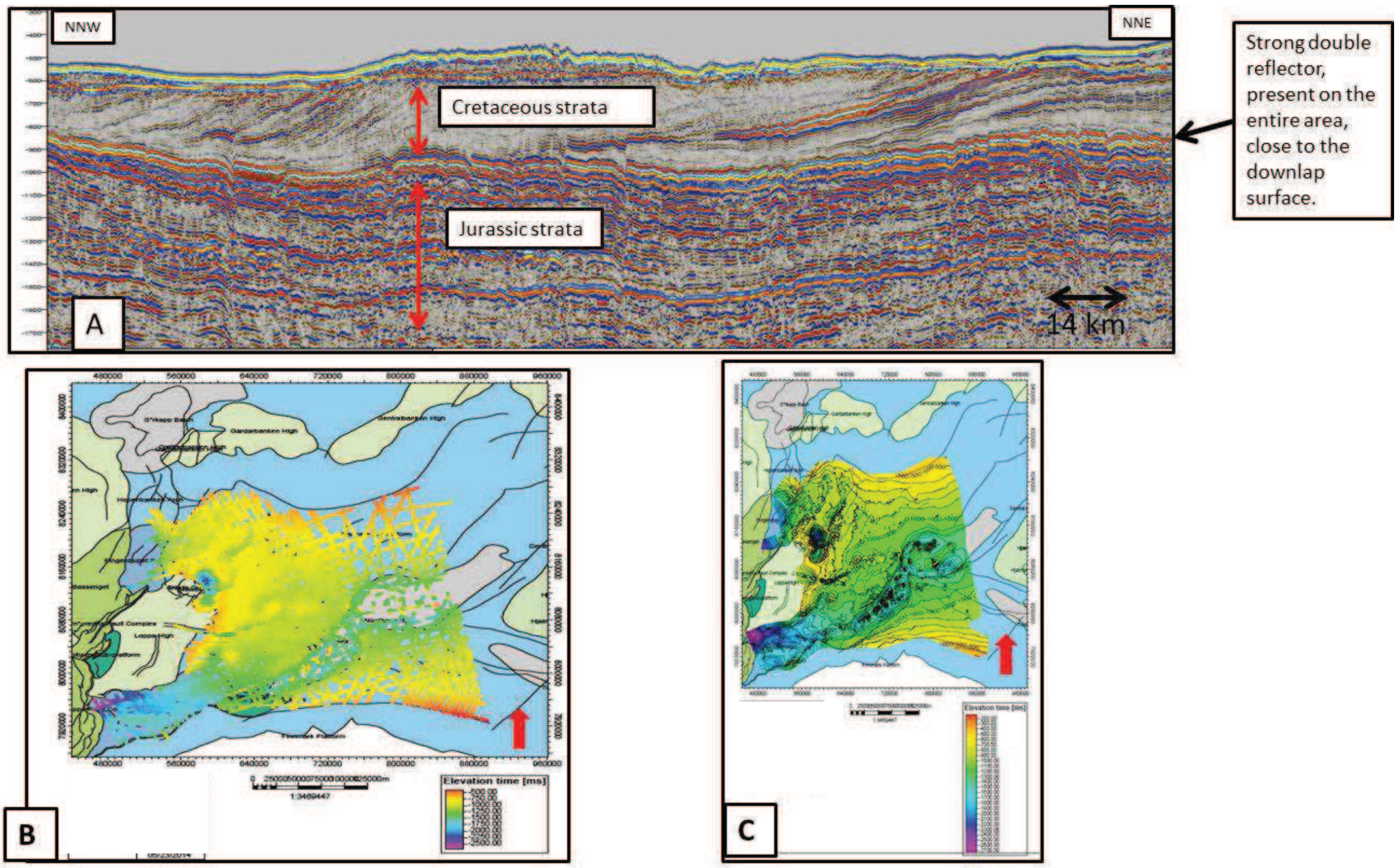

Figure 16 - A) Seismic line with the double reflector corresponding to the near Base Cretaceous highlighted, B) Seismic interpretation of the Base Cretaceous reflectors, superimposed with the area map, C) Base Cretaceous surface superimposed on area map. Map modified from Directorate (2014)

4.2.2 Clinothem packages

A detailed investigation of the area, above the near BCU surface, was performed. Four distinct clinothem packages were identified, all of them bounded at the base by a surface interpreted (thesis section) to correspond to a Maximum Flooding Surface (MFS_1), which is present over the entire study area. The reflector corresponding to the MFS_1 is a downlapping surface almost directly above near BCU and it has variable amplitude strength and continuity. The upper boundary is an erosional truncation, with Quaternary or Tertiary strata above it, produced by the subsequent uplift and erosion (Dimakis et al., 1998, Faleide et al., 1996, Faleide et al., 1993, Vågnes et al., 1992). Three of the clinothem packages show a northeast to southwest progradation trend, while the fourth has prograded from the northwest of the study area to the southeast (Fig. 17, 18). As shown on figure 17, the simplified age relationship between them, is that the older one is the one prograding from the northwest, with the ones coming from the northeast being younger, respectively. However, there are indications that the basin infill history, time wise, is more complex. For that reason, it will be discussed separately. The packages were named and examined according to this relationship; Package A_north, Package B_east, Package C_east, Package D_east, and they will be referred like this or simply: A_north, B_east, C_east and D_east, hereafter.

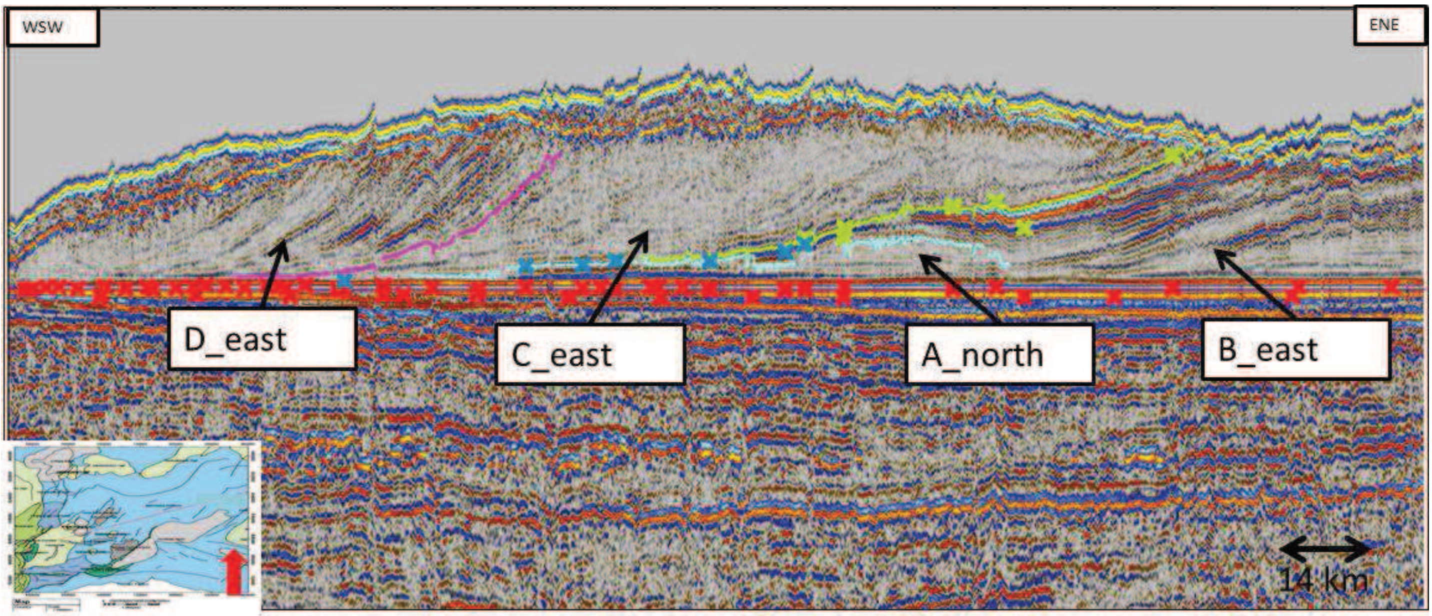

Figure 17 - The four clinothem packages. The Red line in all the seismic lines corresponds to near Base Cretaceous; Green line to Package B_east upper boundary, Magenta line to Package C_east upper boundary and blue line and crosses to Package A_north upper boundary. (Line position on left corner)

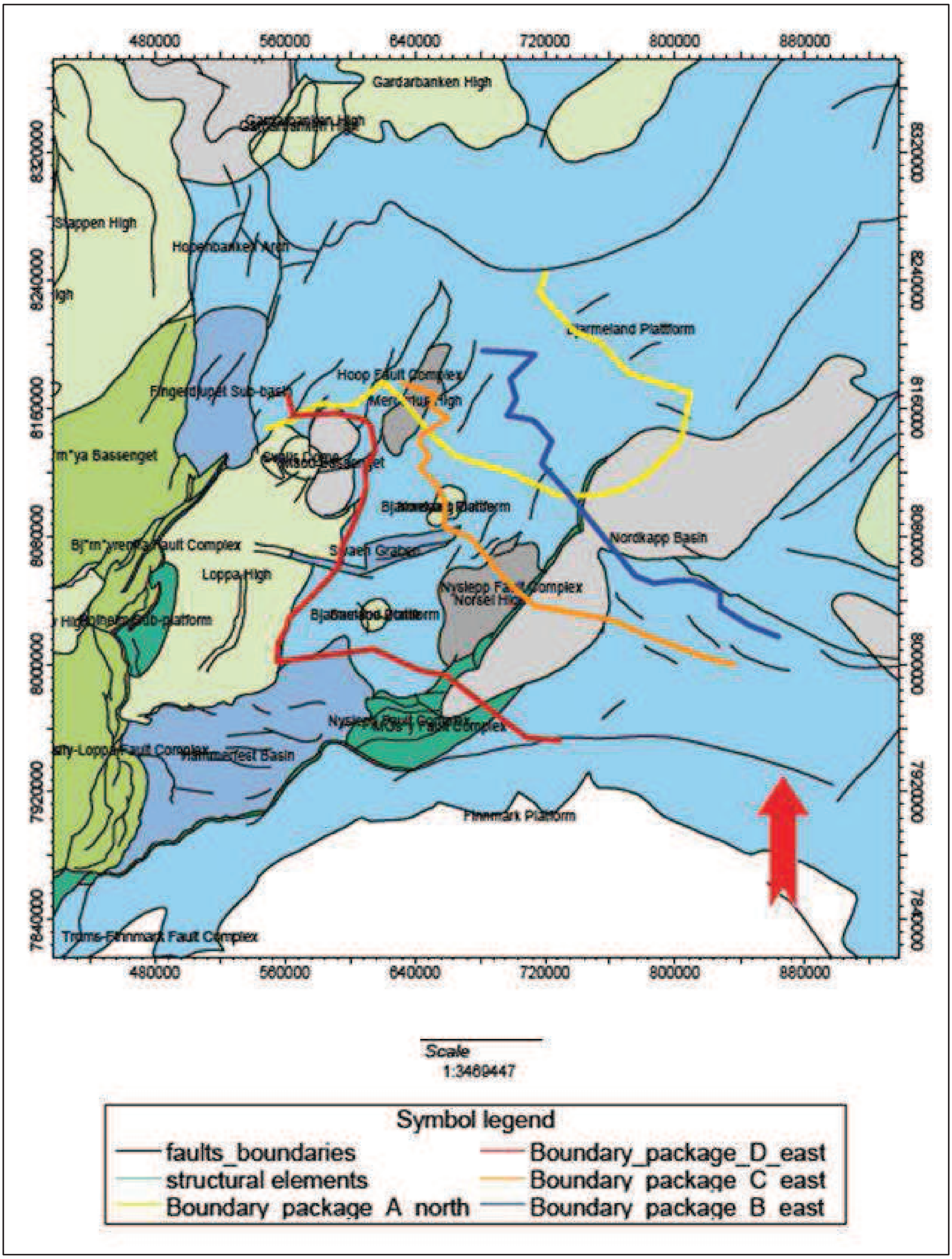

Figure 18 - The four clinothem package boundaries as they were defined by their lap-out points. Map modified from Directorate (2014)

4.2.2.1 Package A_north

This package is located at the northern border of the Base Cretaceous Unconformity (BCU) window. Its full extent can be seen in Fig. 19. Because it is located so close to the BCU window and in an area with a lot of structural elements, it is disturbed by extensive faulting and erosion, making it difficult to establish a clear and complete mapping of its extent and shape. If the near BCU reflector is not flattened, the clinoforms are not distinguishable (Fig 20). Package_A north can be subdivided into two distinct parts; A_α and A_β. Part A_α has greater thickness and lateral extent, with better developed and resolved clinoforms (Fig. 19 & 20). A_α comprises the northwestern part of the Bjarmeland platform (Fig. 19B). Part A_β is thinner with not as well defined clinoforms (Fig. 20). It extents further southwards (Fig. 19C), and although it can be better resolved in the central-east parts of the Bjarmeland Platform, there are indications, see Fig. 21, in the seismic data that the package extended down to Nordkapp Basin. However the exact lap-out points are unresolvable due to the salt structures. There are no seismic indicators south of Nordkapp Basin that suggest further progradation.

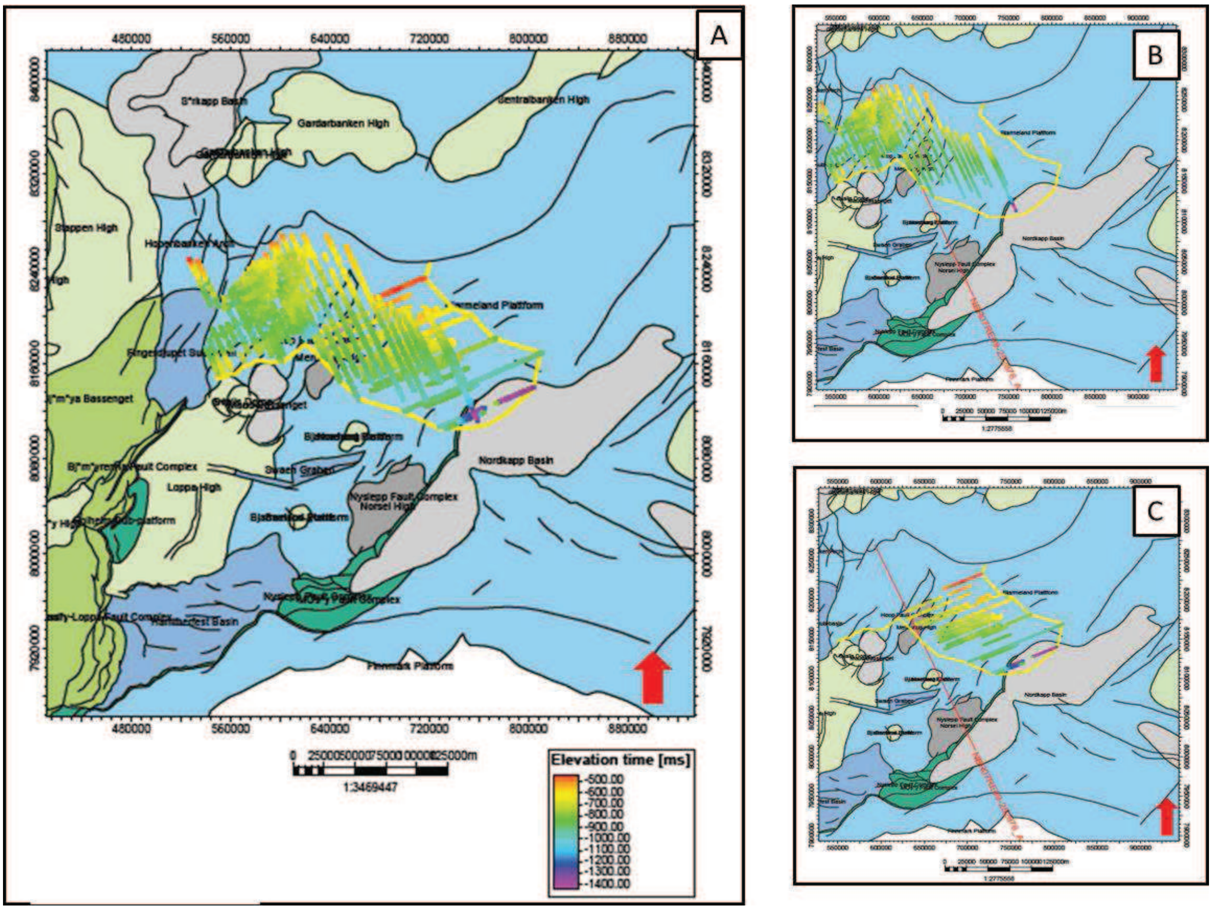

Figure 19 - A) Package A_north areal distribution, B) Package A_α_north areal distribution, C) Package A_β_north areal distribution. Map modified from Directorate (2014) (Map legend fig. 18)

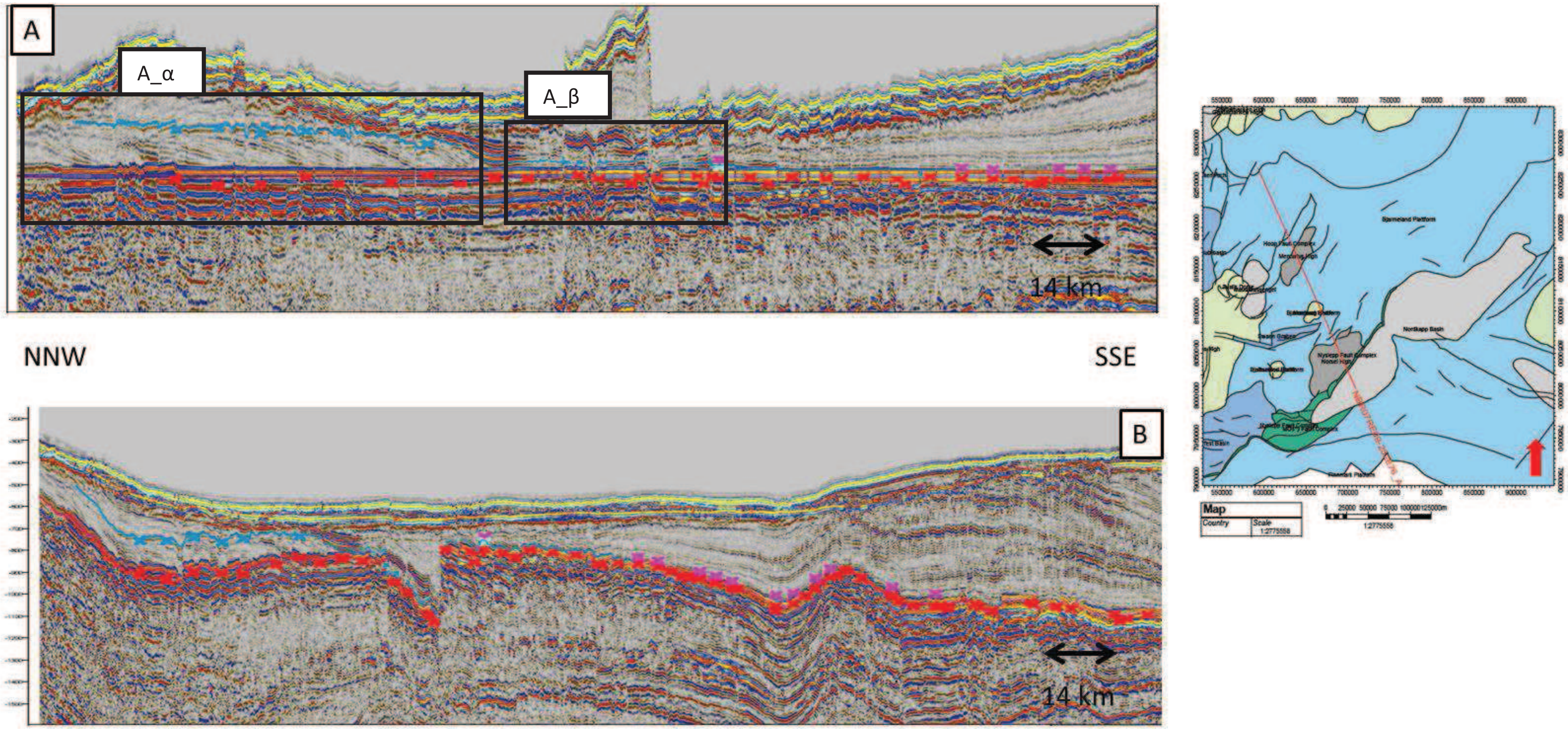

Figure 20 - A) Clinoforms imaged with the near Base Cretaceous reflector flattened and position of A_α and A_β, B) image of the clinoforms when the near Base Cretaceous is not flattened. Map modified from Directorate (2014) (Seismic lines legend fig. 17)

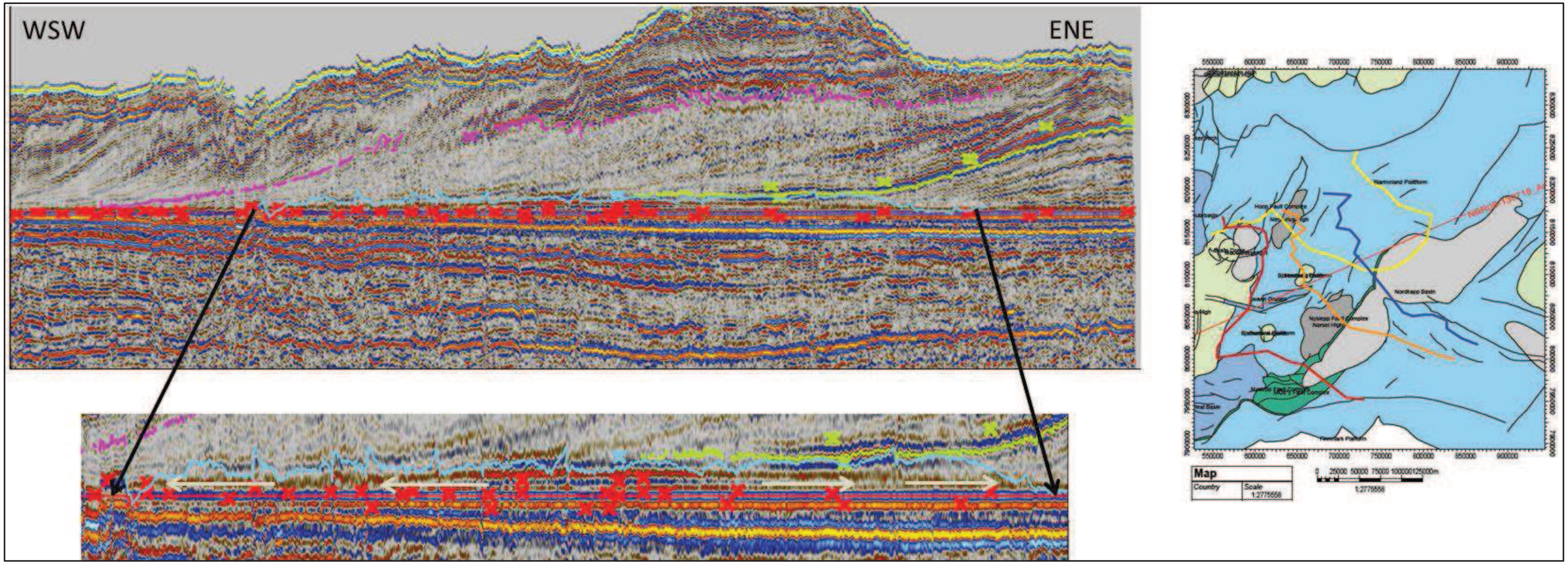

Figure 21 - Zoom in view on the indications that Package A_north prograded to Nordkapp Basin. Notice the reflection terminations. Map modified from (Directorate, 2014) (Seismic line legend fig. 17)

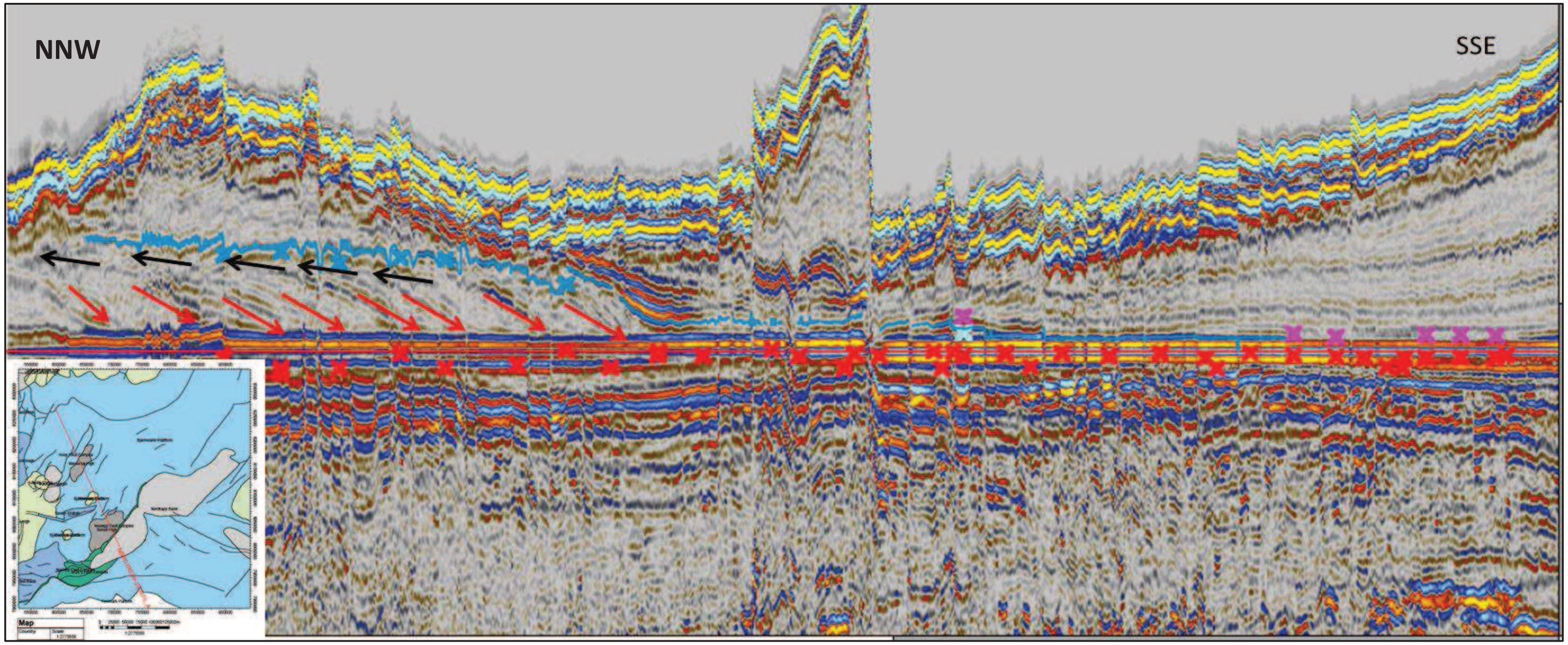

Figure 22 - Clinoform boundaries; downlaps marked by red arrows, upper boundary by black. Map modified from (Directorate, 2014) (Seismic line legend fig. 17)

Results

Both A_α and A_β clinothem packages are bounded at their bases by MFS_1. The upper boundary is either a toplap or a reflector concordant with the reflector above the packages (Fig 22). The lower boundary is clearly marked by downlaps (Fig 22). Packages B, C and D_east onlap onto A_β (Fig. 17). A_α shows a prograding reflection configuration in dip section and a complex fill in transverse section (Fig. 11 & 24) (Mitchum Jr et al., 1977). The level of erosion does not allow a confident distinction between sigmoid and oblique clinoform patterns (Mitchum Jr et al., 1977, Sangree and Widmier, 1979). A more sigmoidal pattern could be inferred from where the reflectors are in concordance with the reflectors above (Fig. 22). A_β part is nearly below seismic resolution in dip section, with one or two reflectors marking it, and shows a mounded onlap fill in the transverse section (Fig. 11 & 22). The reflectors show excellent continuity in both parts, with alteration of stronger and weaker amplitudes (Fig. 17 & 20).

Package A_north has a preserved average thickness of 100m, with Package A_α_north showing a maximum thickness of 160 m and A_β_north 70 m (Fig. 23). Package A_β_north's thickness corresponds to the initial one, since the whole package is preserved.

Interpretation

The two parts are interpreted to correspond to a foreset (A_α) and a bottomset (A_β) of a clinothem package, prograding from the northwest to the southeast of the study area, according to what has been presented in Chapter 3.2. If the inferred sigmoidal pattern is correct, A_north could have been deposited in a relative low energy system. The sediment supply was small with either a rapid subsiding basin or/and rise in sea level, to justify the deposition (Sangree and Widmier, 1979). The good continuity of the reflections suggests the deposition was widespread and stable. The cyclic amplitude alterations point to density contrasts between the different layers. Fine grained sediments are observed in similar environments (Sangree and Widmier, 1979).

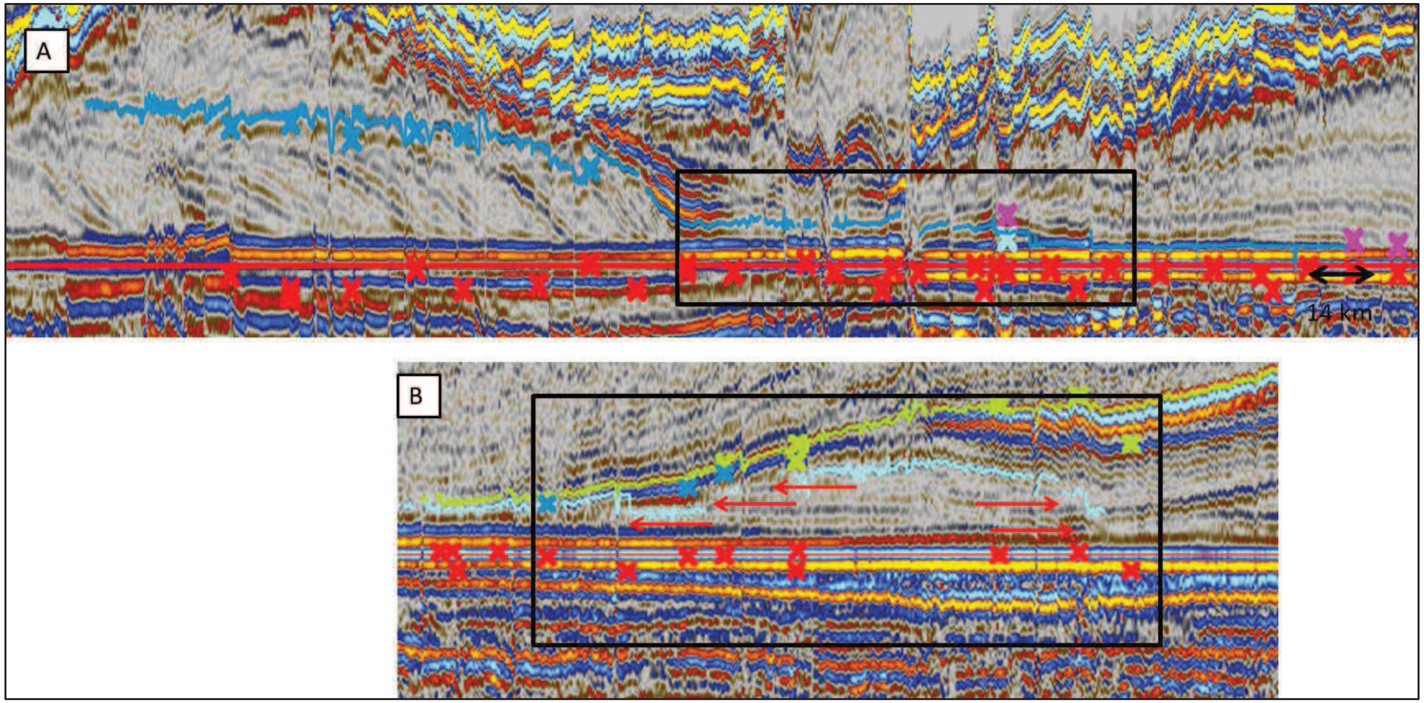

Figure 24 - Zoomed in image of Package A_north, A) dip section, B) transverse section (line position same as Fig. 22 for A and Fig. 17 for B, seismic line legend fig. 17)

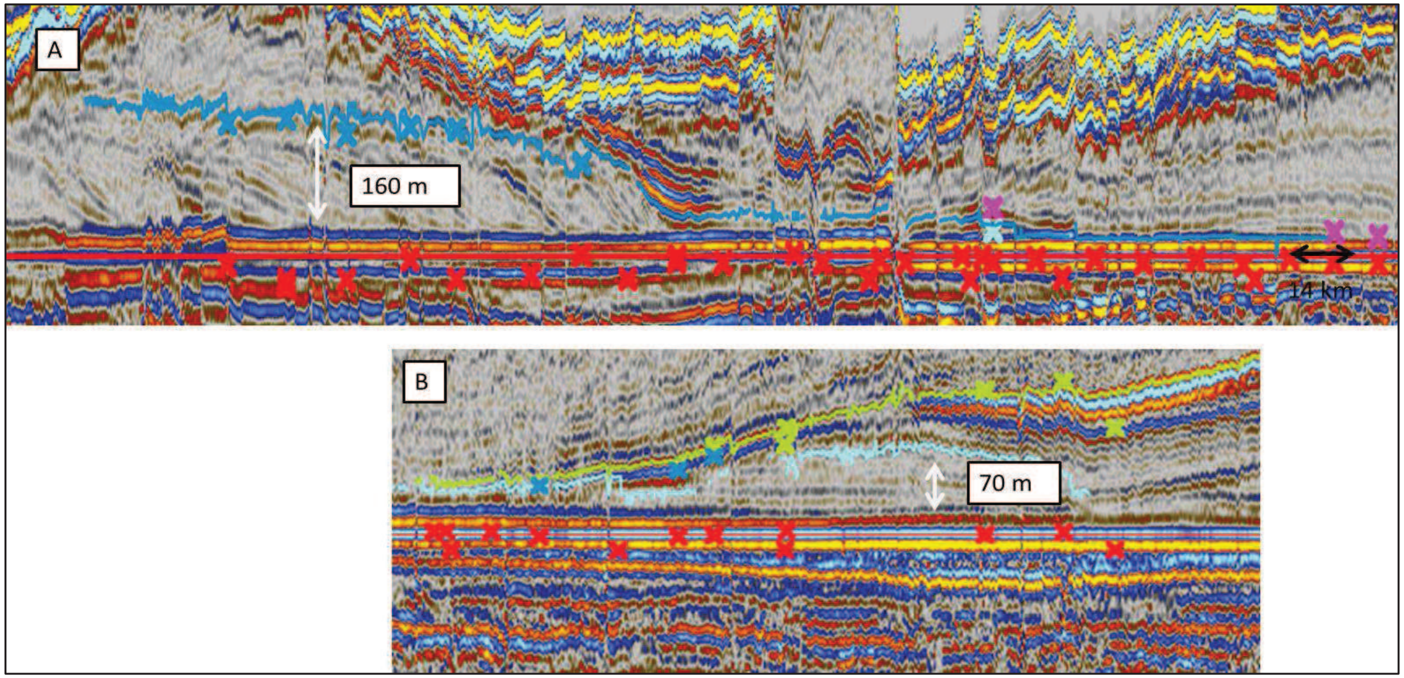

Figure 23 - Package A_north thickness (line position same as Fig. 23, seismic line legend fig. 17)

4.2.2.2 *Package B_east*

Package B_east is located at the northeastern parts of the Bjarmeland platform (Fig. 25). According to the seismic data, it entered the paleobasin from the northeast and prograded towards the southwest, with the lap out points shown in Fig. 25. It extends from the north of the study area, near the BCU window; it crosses the Nordkapp Basin, and continues down to the southernmost part of eastern Finnmark Platform (Fig. 25). The clinoforms are still distinguishable even if the near BCU reflector is not flattened, but the examination is more accurate if it is (Fig. 26). This package was, also, affected by the subsequent uplift and erosion of the area and only limited parts of it are resolved on the majority of the seismic lines. However, on one seismic line a full clinoform profile was preserved, with the topset, foreset and bottomset resolved (Fig. 27). Generally, the package is bounded by an erosional truncation on top and it either gently downlaps onto MFS_1 or onlaps onto A_β_north (Fig. 27). The offlap-breaks can be seen in Fig. 27. They are stacked vertically. The clinoforms show a sigmoid pattern in dip section and a prograded fill in transverse section (Fig. 11 & 28). The reflectors show excellent continuity and high amplitudes.

Package B_east has a preserved average thickness of 400 m, with the maximum thickness being 460 m and the minimum 100 m (Fig. 29).

Interpretation

Package B_east, because of the sigmoid infill pattern, is interpreted as a clinothem unit deposited in a rather low energy system, with significant basin subsidence or rise in sea level during the time of deposition (Sangree and Widmier, 1979). The reflectors' excellent continuity and high amplitude suggest widespread and stable sedimentation (Sangree and Widmier, 1979). In the different clinothem sections, different sediments are expected. Generally, more coarse grained material is expected in the upper parts of the succession (Sangree and Widmier, 1979). The paleo-platform extended to where the topsets are found.

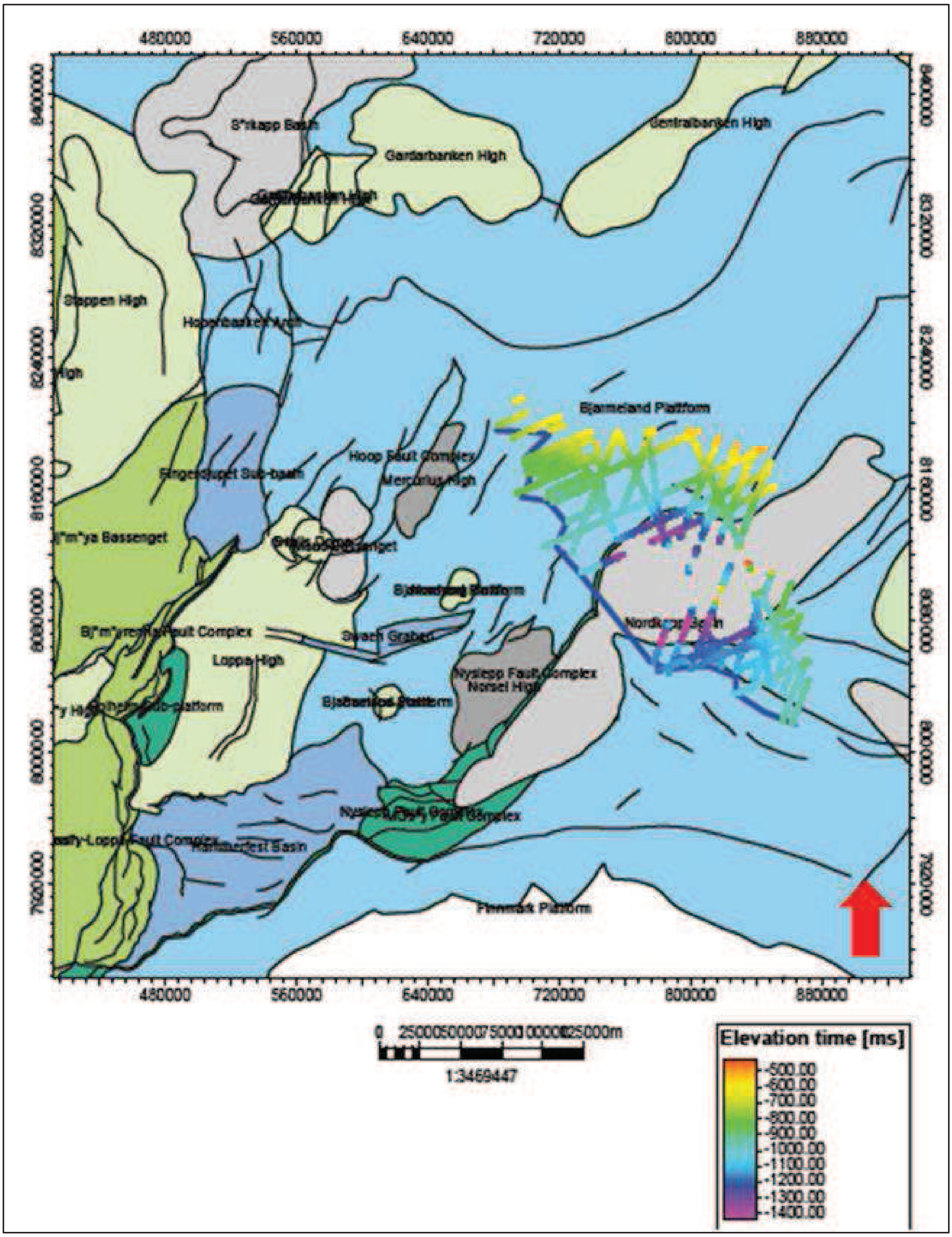

Figure 25 - Package B_east areal distribution. Map modified from Directorate (2014) (legend fig. 18)

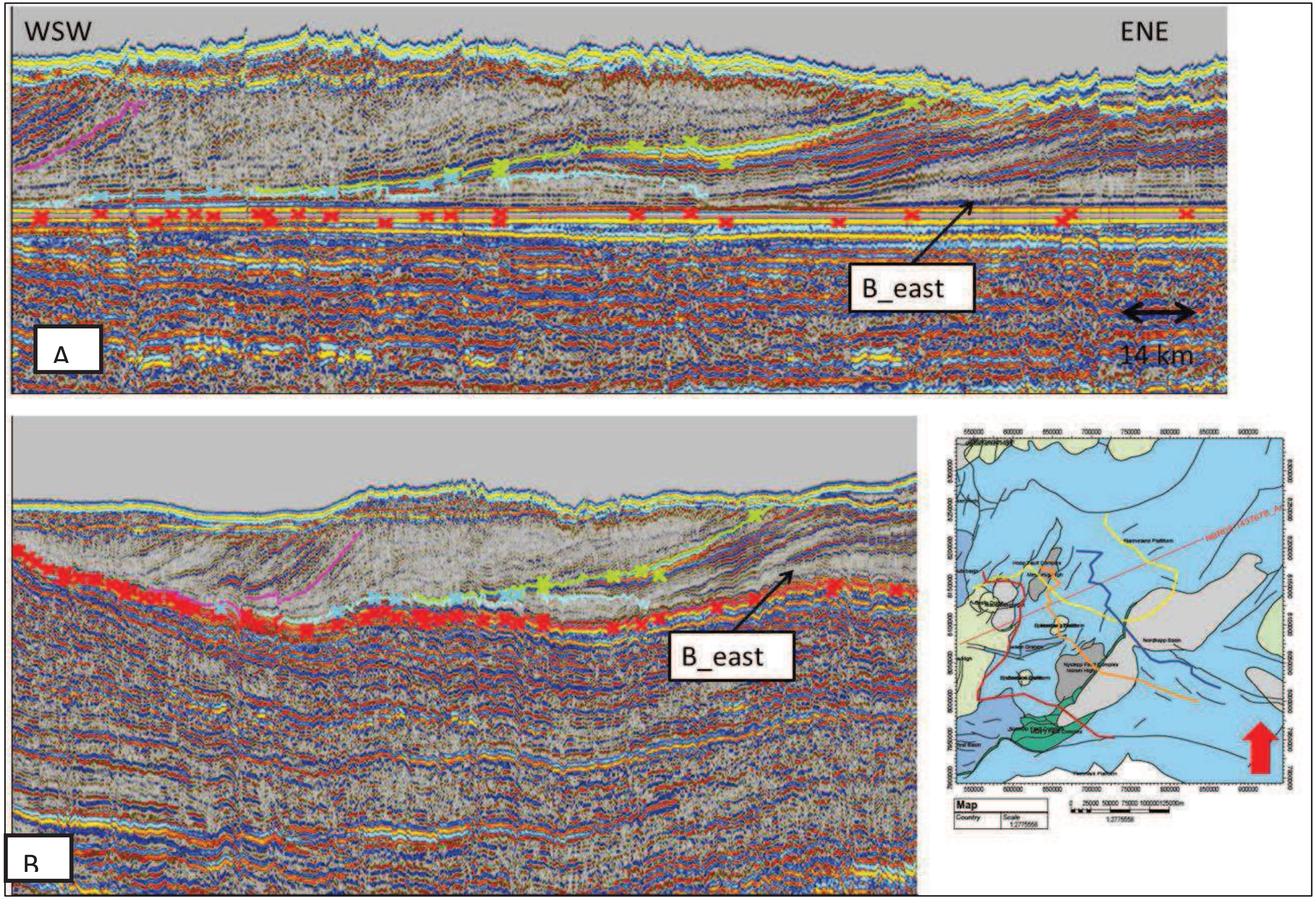

Figure 26 - Package B_east imaged with near Base Cretaceous flattened (A) and not (B). Map modified from Directorate (2014) (seismic lines legend fig. 17)

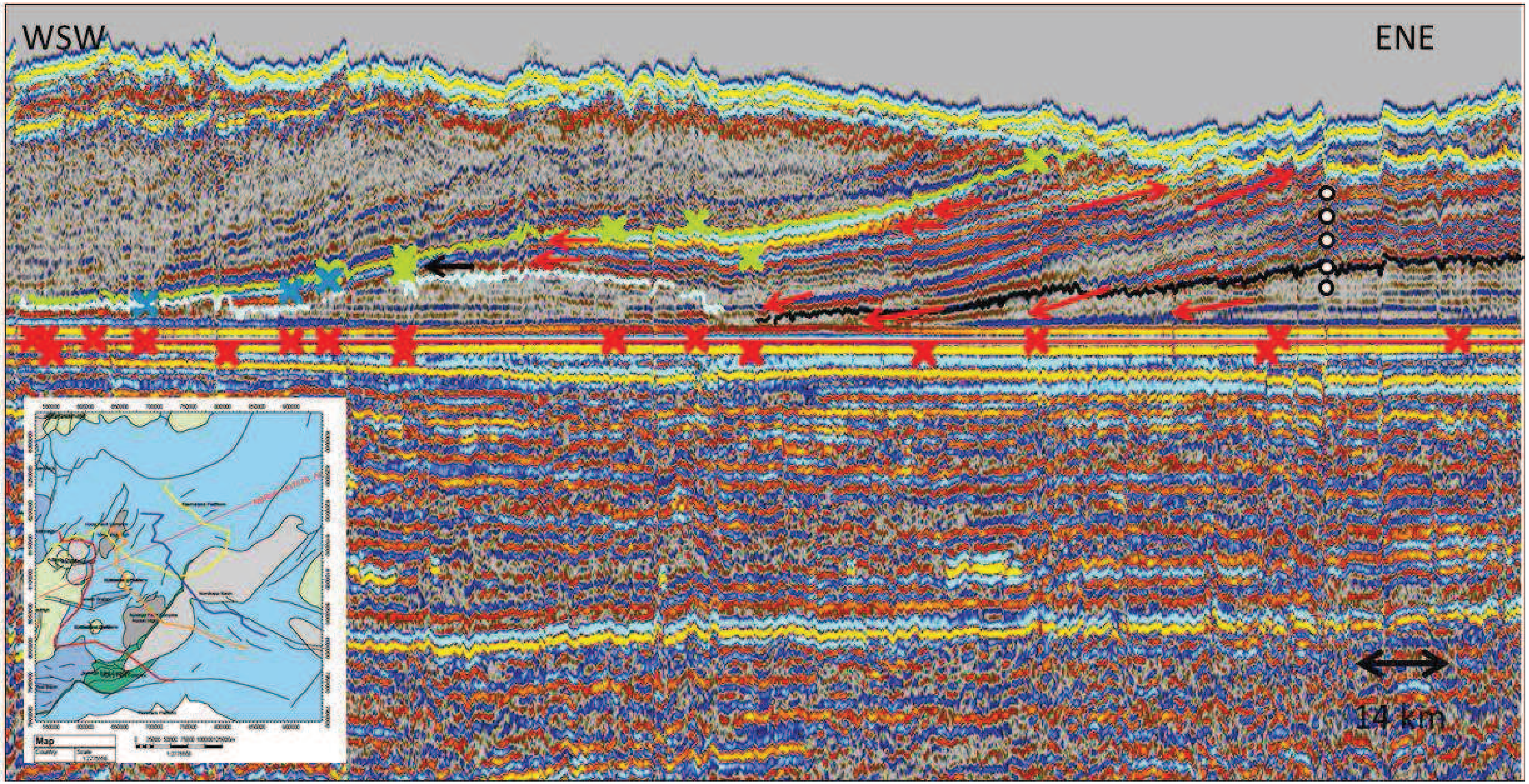

Figure 27 - Package B_east reflector terminations, boundaries and off-lap breaks. Map modified from (Directorate, 2014) (seismic line legend fig. 17)

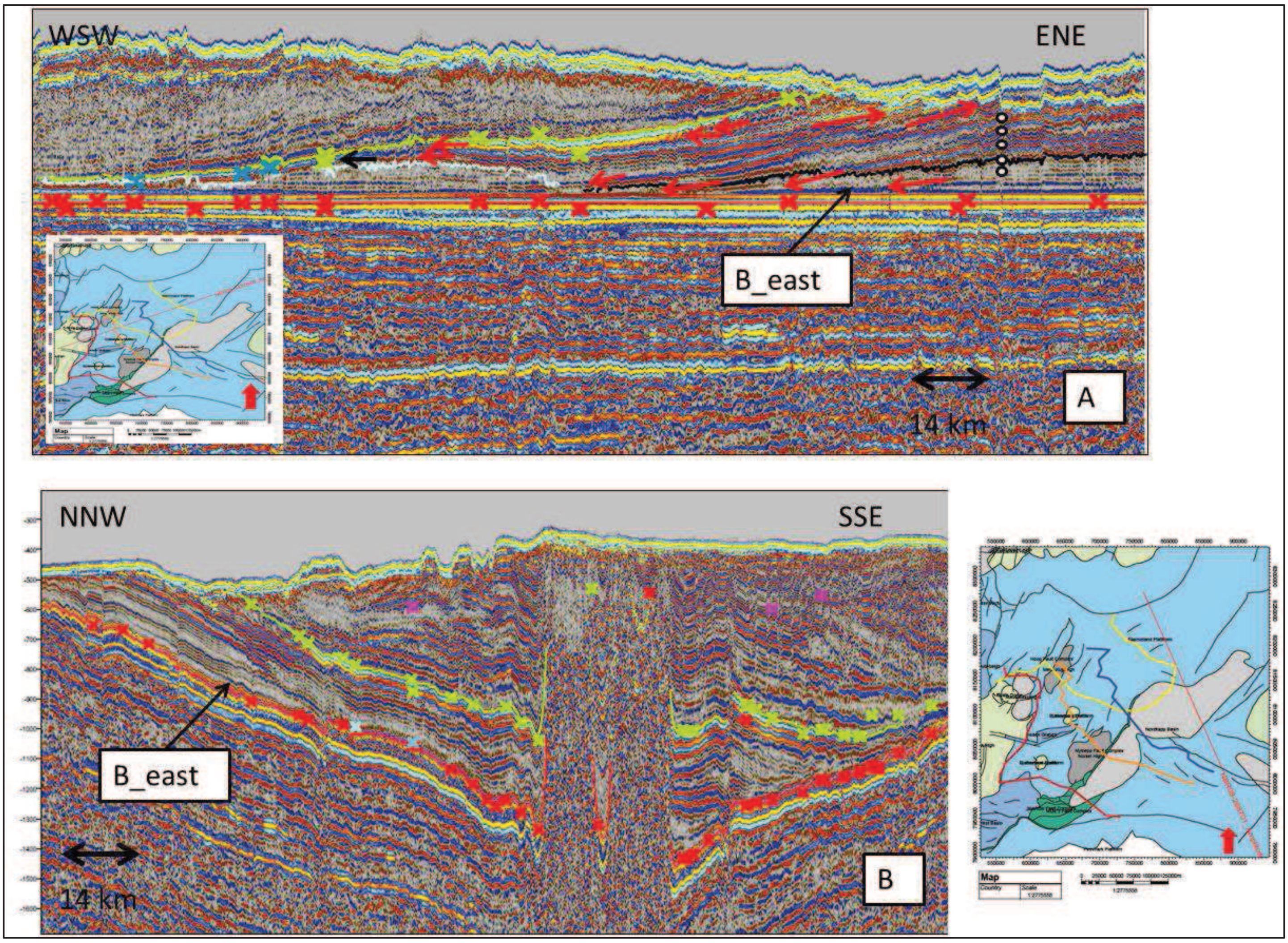

Figure 28 - Package B_east in dip section (A) and transverse section (B). Map modified from (Directorate, 2014) (seismic line legend fig. 17)

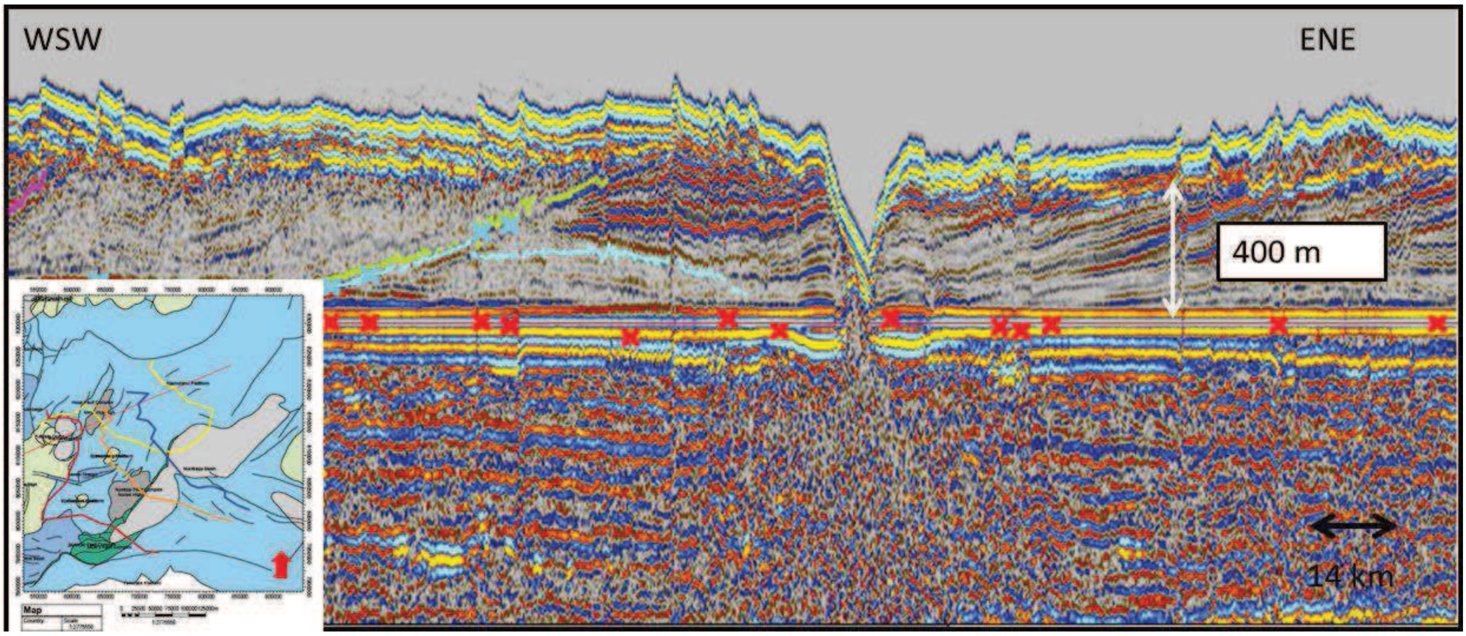

Figure 29 - Package B_east thickness. Map modified from (Directorate, 2014) (seismic line legend fig. 17)

4.2.2.3 Package C_east

Extensive uplift and erosion led to limited preservation of this package. The preserved part covers the central parts of Bjarmeland Platform, with its lateral extent and lapout points shown in Fig. 30. Its progradation direction is northeast to southwest. An erosional truncation marks the upper boundary (Fig. 31). The reflectors are downlapping onto MFS_1 or B_east or A_β_north, marking the lower boundary of the clinothem package (Fig. 31). A sigmoid reflection pattern in dip section and a prograded fill in transverse section describe its geometry configuration (Fig. 11 & 34). Generally, it is characterized by the lowest amplitudes and worst reflector continuity of all observed packages. Even if the reflectors are artificially amplified they are still hardly distinguishable (Fig. 32). A number of faults are cutting the strata and further disturbing the reflectors (Fig. 31). An upwards decrease of the reflectors' amplitude (Fig. 33) is observed, with the feature being more pronounced towards the Nordkapp Basin.

Package C_east has a preserved average thickness of 500 m, with the maximum thickness observed being 650 m and the minimum 460 m (Fig. 35).

Interpretation

This package is interpreted as a clinothem unit deposited in a low energy environment. The parts that have been preserved correspond to foresets and bottomsets (Fig. 31). The unique reflector configuration, weak and discontinuous, together with the abundance of synsedimentary faults indicate the deposition of different sediments, possibly finer grained ones compared with all the other clinothem packages. The change in reflector configuration forms the lower to the upper parts of the package. This indicates that a change in sedimentation occurred between the lower part of the package and the uppermost ones. Since the topsets and the adjacent offlap-breaks are not preserved, the possible sea level fluctuations cannot be inferred.

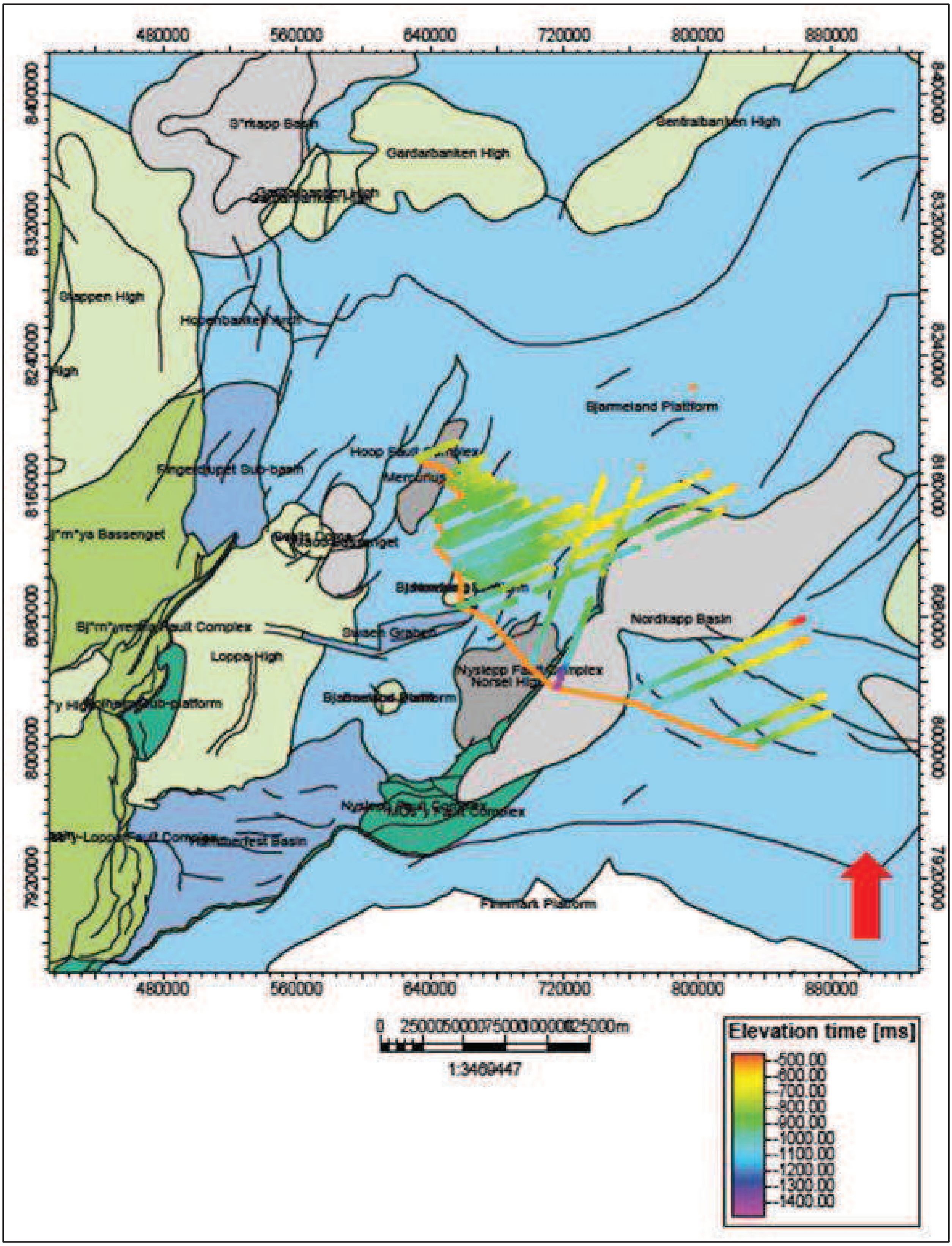

Figure 30 - Package C_east areal distribution. Map modified from (Directorate, 2014) (legend fig. 18)

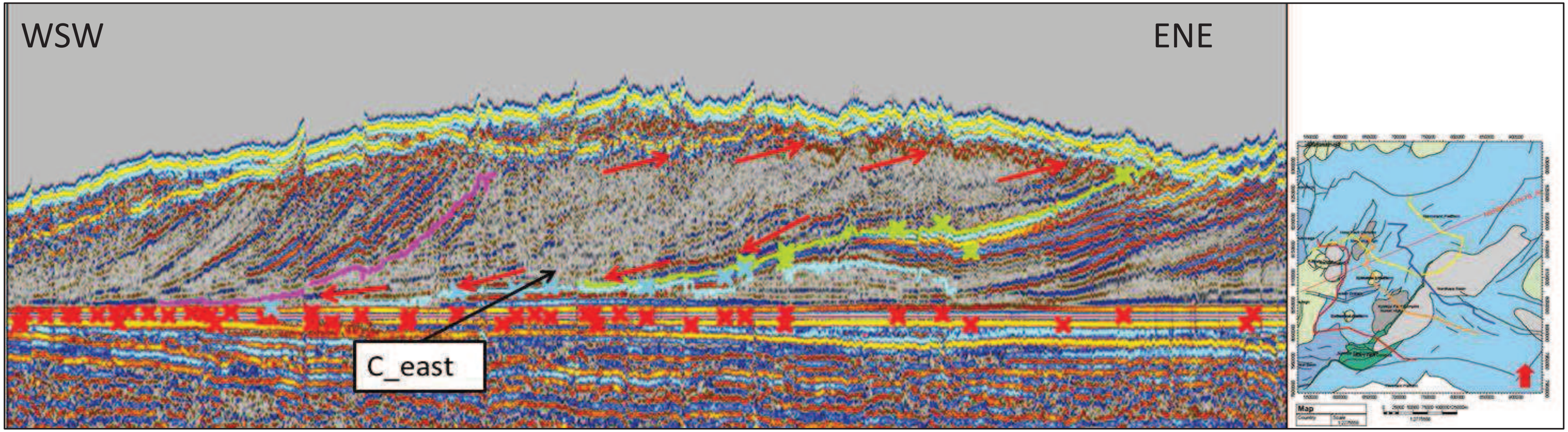

Figure 31 - Package C_east reflection terminations and boundaries. Map modified from (Directorate, 2014) (seismic line legend fig. 17)

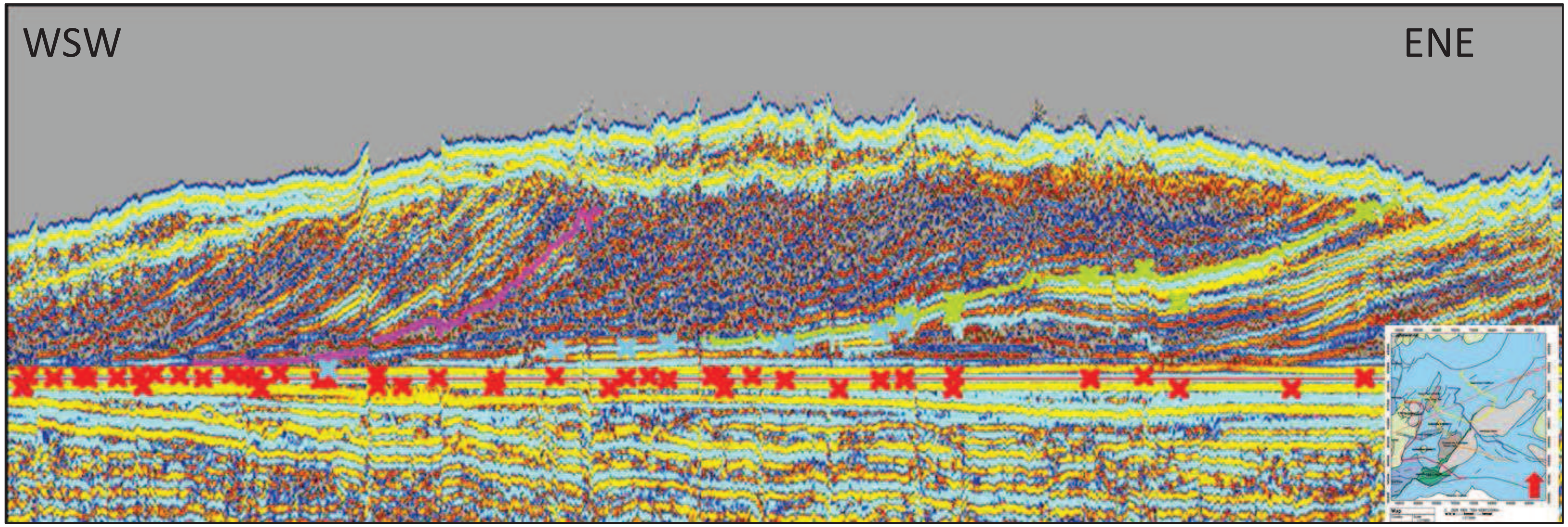

Figure 32 - Package C_east image with amplified reflectors. Notice the difference between the other packages reflectors. Map modified from (Directorate, 2014) (seismic line legend fig. 17)

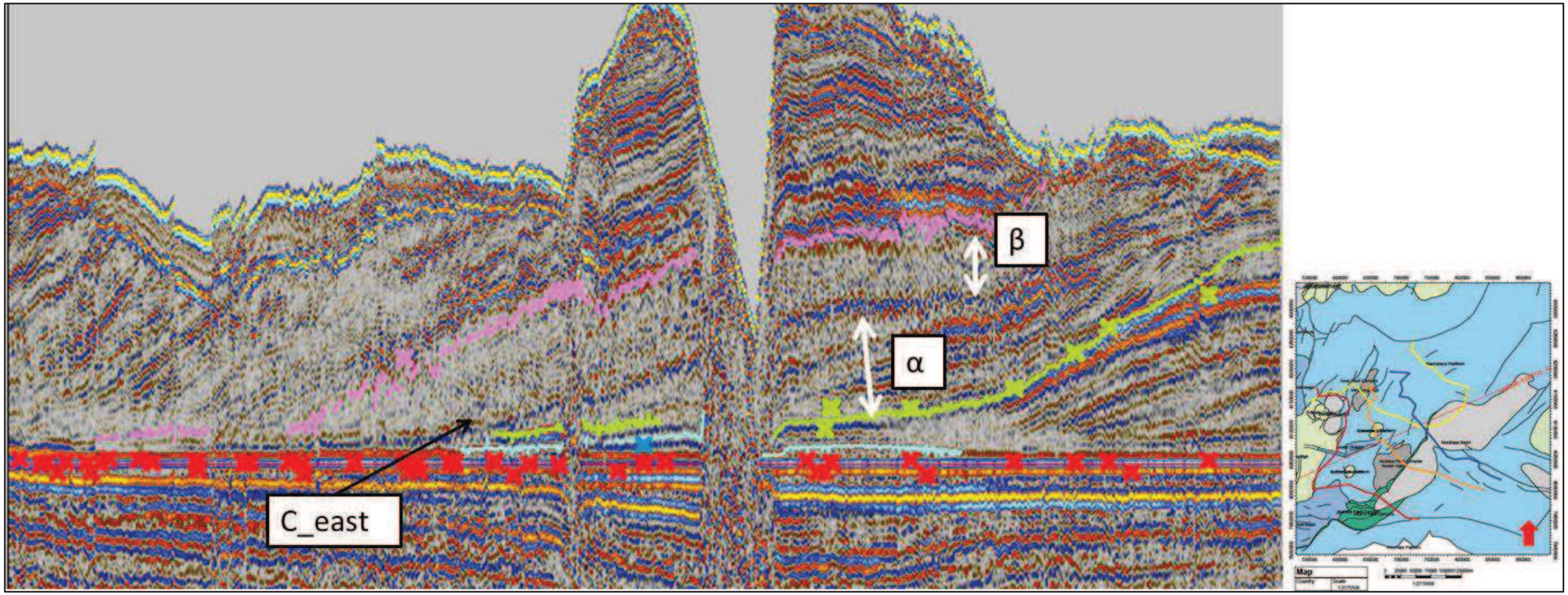

Figure 33 - Package's C_east reflectors amplitude decrease. Notice the difference between area α and β. Map modified from (Directorate, 2014) (seismic line legend fig. 17)

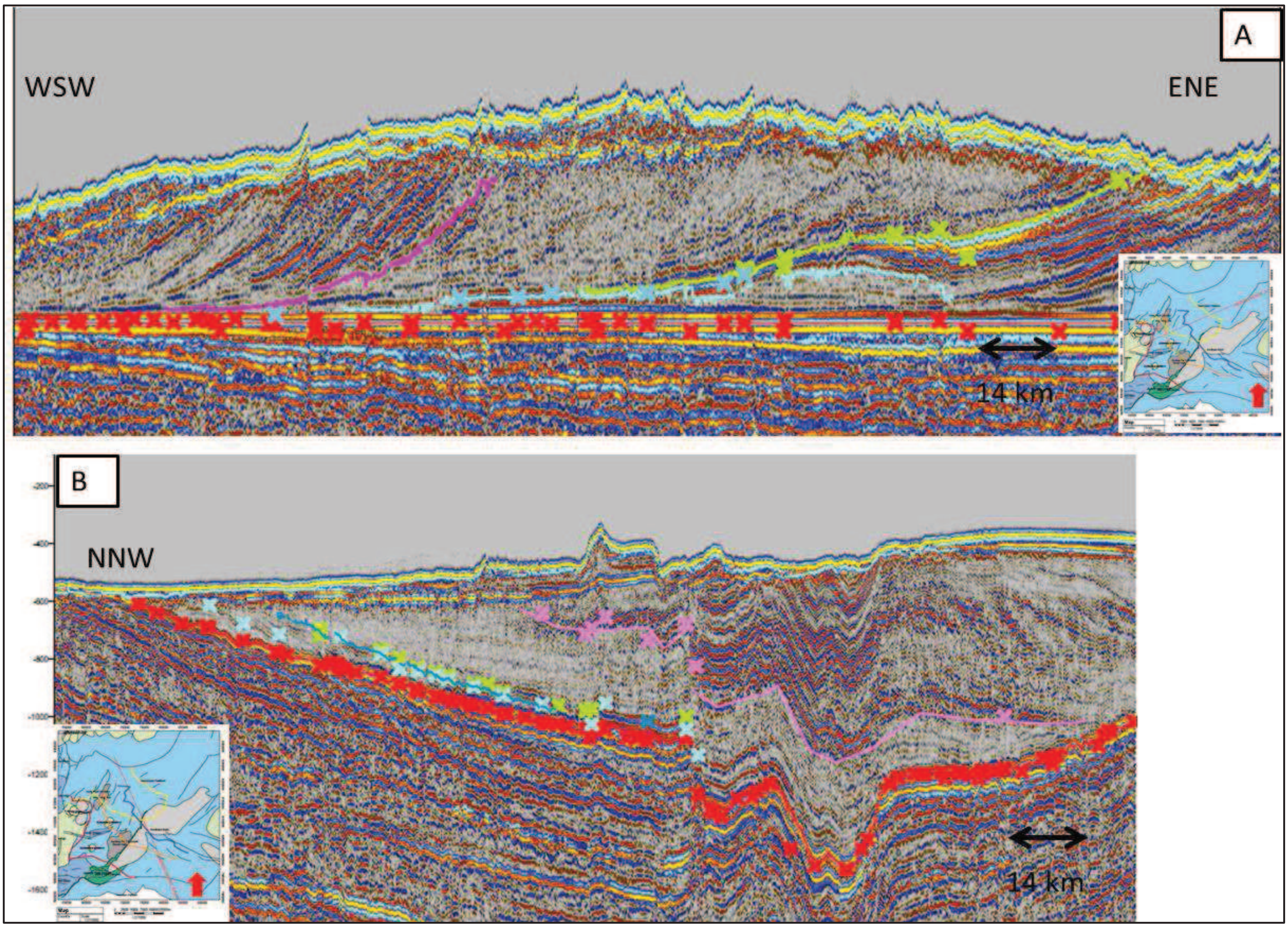

Figure 34 - Package C_east in dip section (A) and transverse section (B). Map modified from (Directorate, 2014) (seismic line legend fig. 17)

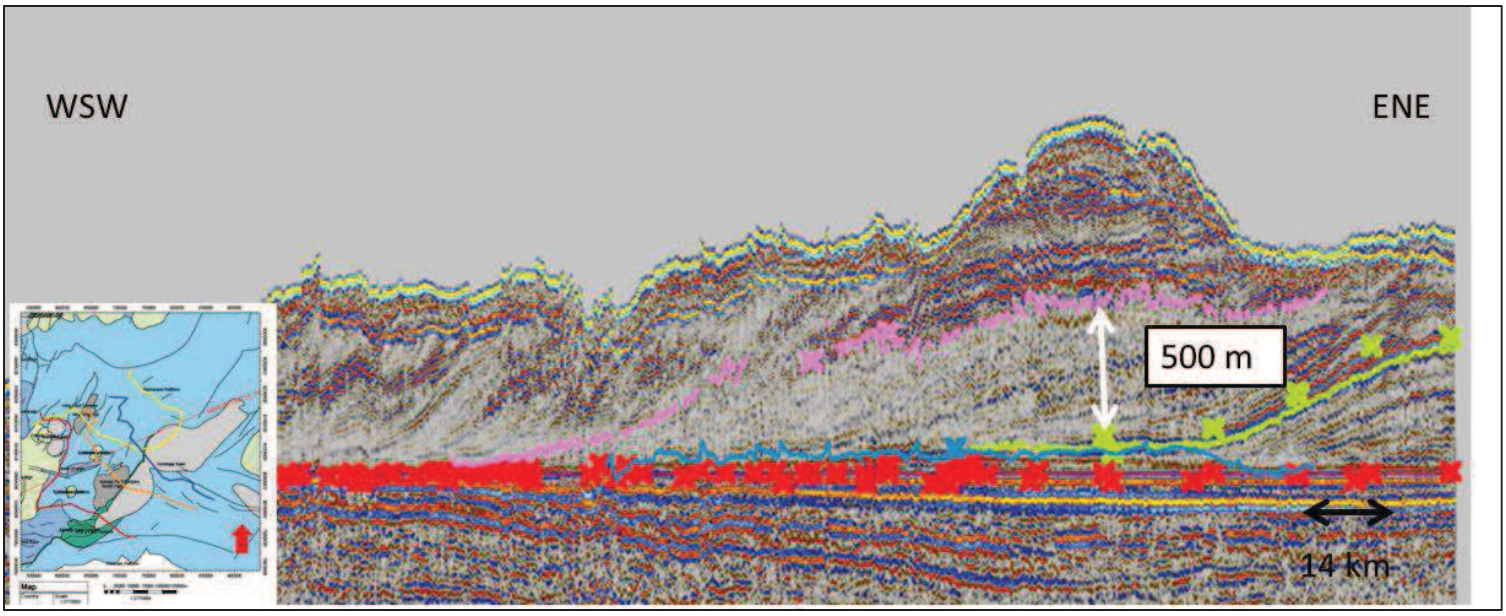

Figure 35 - Package C_east thickness. Map modified from (Directorate, 2014) (seismic line fig. 17)

4.2.2.4 Package D_east

This is the youngest resolved package with a progradation direction from northeast to south-west. It is, also, highly affected by the uplift and erosion the area has undergone. Its limits are shown in Fig. 36 and coincide with the BCU window in the current Loppa High. Southwards, there is an interesting interplay between sediments coming out from the Hammerfest Basin, with a west-east or north-south direction (Fig. 38). D_east is terminating by onlapping onto a package prograding from the Hammerfest Basin; and another package, higher stratigraphically, is terminating by onlapping onto D_east (Fig. 38). The boundary between C_east and D_east is where the reflectors are showing higher amplitudes, with good continuity and higher angles (Fig. 37). The upper boundary is marked by an erosional truncation and the lower one by downlaps, with increasing length, in MFS_1 (Fig. 37). An interesting feature, traced along a number of seismic lines and more pronounced south of Nordkapp Basin, is an alteration of subpackages with higher and lower amplitudes (Fig. 39). Although the level of erosion does not allow a clear distinction between sigmoid or oblique infill patterns, the high angles and the elongated bottomsets imply an oblique tangential pattern (Fig. 11 & 38) (Mitchum Jr et al., 1977). In the transverse section a prograded fill describes the reflectors configuration (Fig 41).

Package D_east has a preserved average thickness of 900 m, with the maximum thickness observed being 1300 m and the minimum 500 m (Fig. 40).

Interpretation

This is the only package interpreted to been deposited in a higher energy regime, if the oblique infill pattern is correct. The steeper dipping reflectors with thinner bottomsets observed are in accordance with the “Oblique Progradational reflection configuration” described by Mitchum Jr et al. (1977), especially with the tangential one. A difference in sedimentation can already be inferred by the change in seismic facies between C_east and D_east. The good continuity and high amplitudes of the reflectors imply stable and widespread sedimentation. The subpackages with the alternating reflector strength are interpreted to correspond to interfingering lobes; depositional lobes that were changing direction during propagation. A point for discussion is whether the package termination in the current Loppa High is apparent or real. It must be determined if, in Cretaceous times, there was a high in the area where the Loppa High is located today, which halted the clinothem propagation and hence the observed termination, is the actual one, or not. Had the package prograded further and been eroded away because of the inversion that created Loppa High, so that the observed termination would not be the original. In this case, there would have been some erosional products observed around the Loppa High; which could be the case, but they have, also, been eroded. A third possibility is an interplay between the two scenarios; with the inversion happening while the clinothem prograded. According to (Gabrielsen et al., 1990), the Loppa High was an island in the Cretaceous which makes the first scenario the most probable one; something that is supported by the seismic data. A closer examination of the seismic lines revealed a surface where the reflectors are onlaping (Fig. 42), indicating that the strata were deposited towards an inclined surface. Further southwards, D_east is onlapping onto a package prograding from the Hammerfest Basin and marks its termination point (Fig. 38). The package that onlaps onto D_east postdates it. Their interaction is further discussed in the Hammerfest Basin subchapter. As far as D_east is concerned, it terminated onto the Paleo-Loppa High in the north and onto a sedimentary package that was prograding from the Hammerfest Basin in the south.

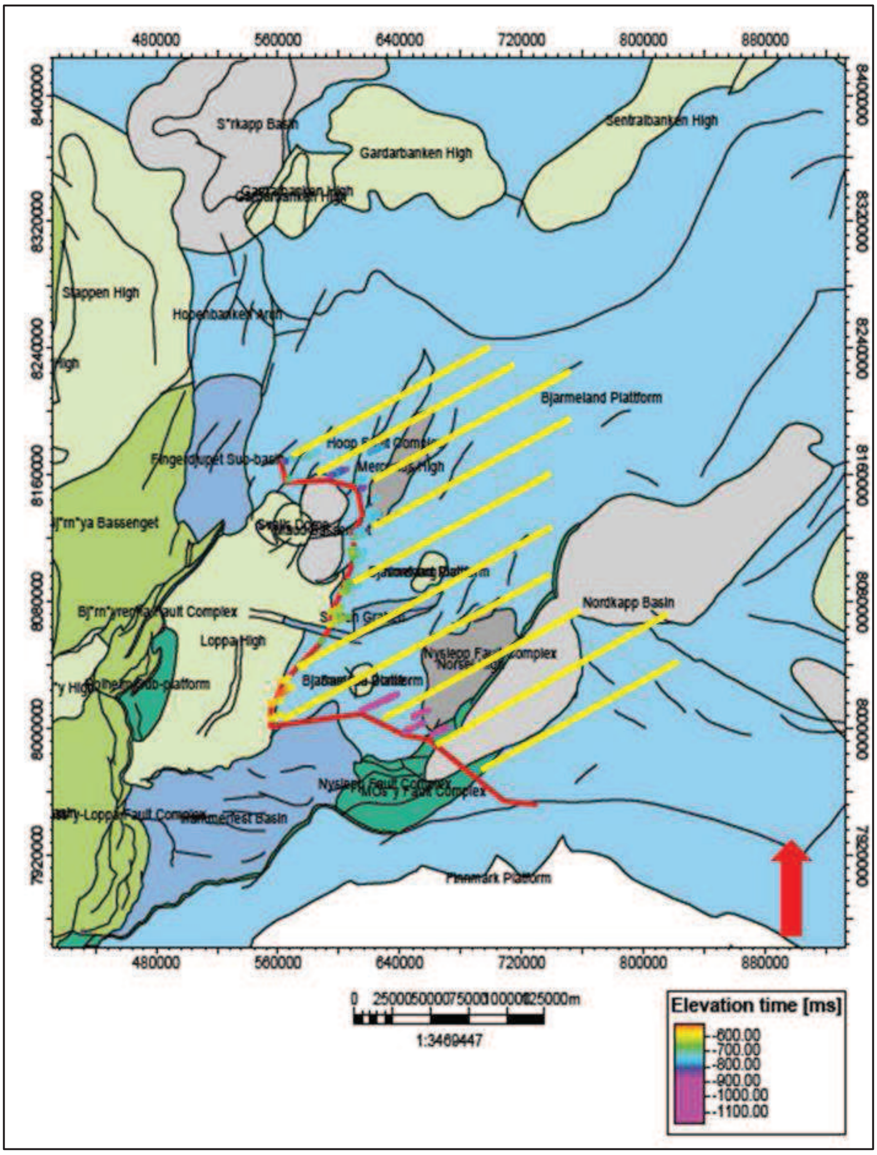

Figure 36 - Package D_east areal distribution, the yellow lines are an approximation of the distribution. Map modified from (Directorate, 2014) (legend fig. 18)

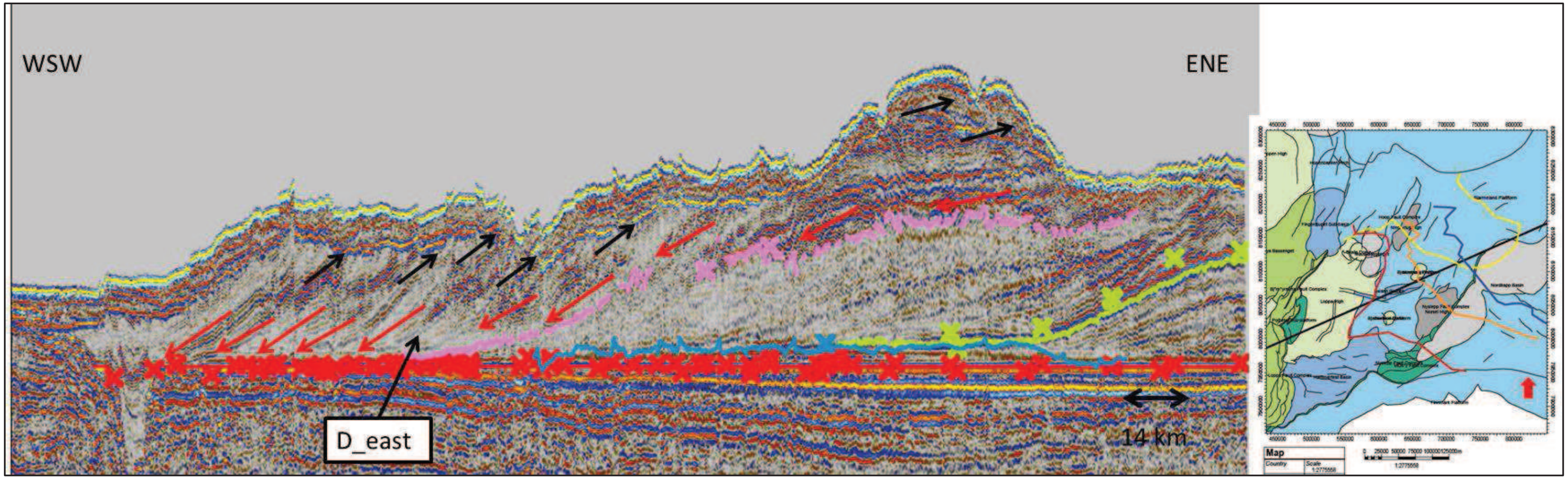

Figure 37 - Package D_east reflection terminations and boundaries. Map modified from (Directorate, 2014) (seismic line legend fig. 17)

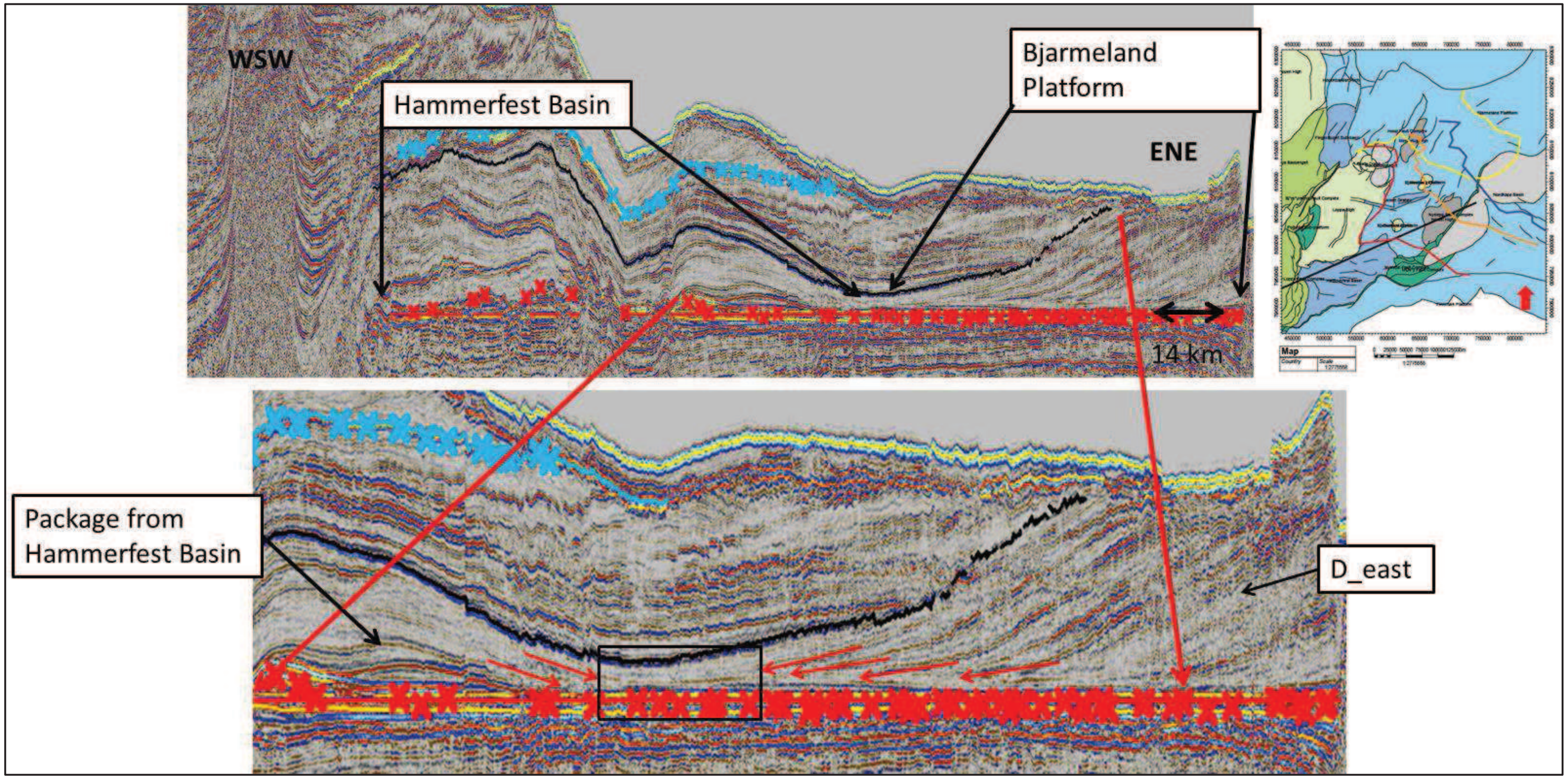

Figure 38 - Interplay between sediments from D_east and Hammerfest Basin. Map modified from (Directorate, 2014) (seismic line legend fig. 17, plus blue line: Base Cenozoic)

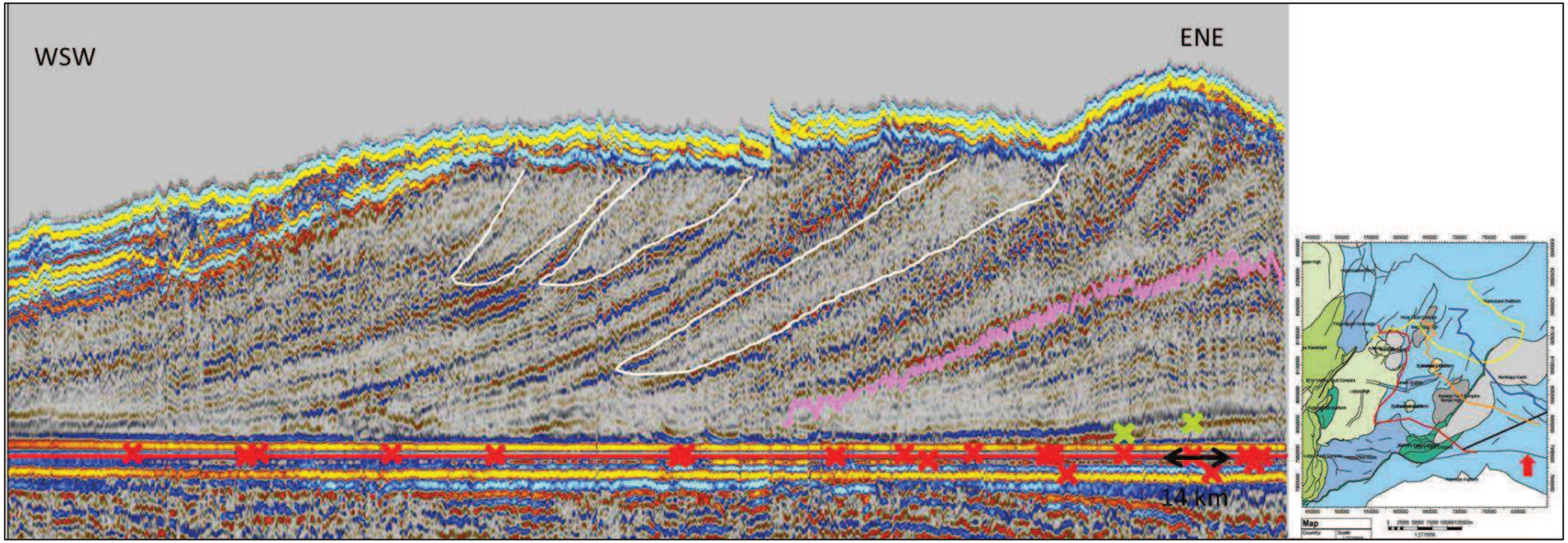

Figure 39 - Package D_east subpackages with lower amplitudes, defined by the white lines. Map modified from (Directorate, 2014) (seismic line legend fig. 17)

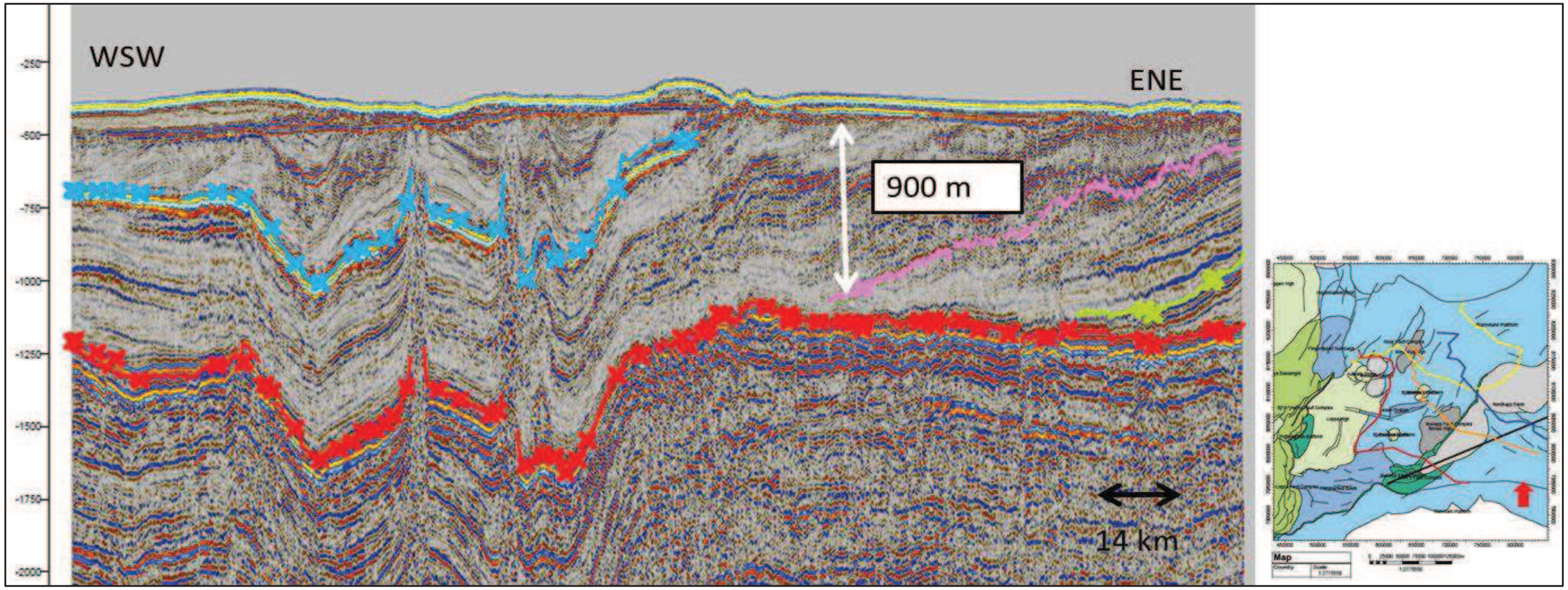

Figure 40 - Package D_east thickness. Map modified from (Directorate, 2014) (seismic line legend fig. 17, plus blue line: Base Cenozoic)

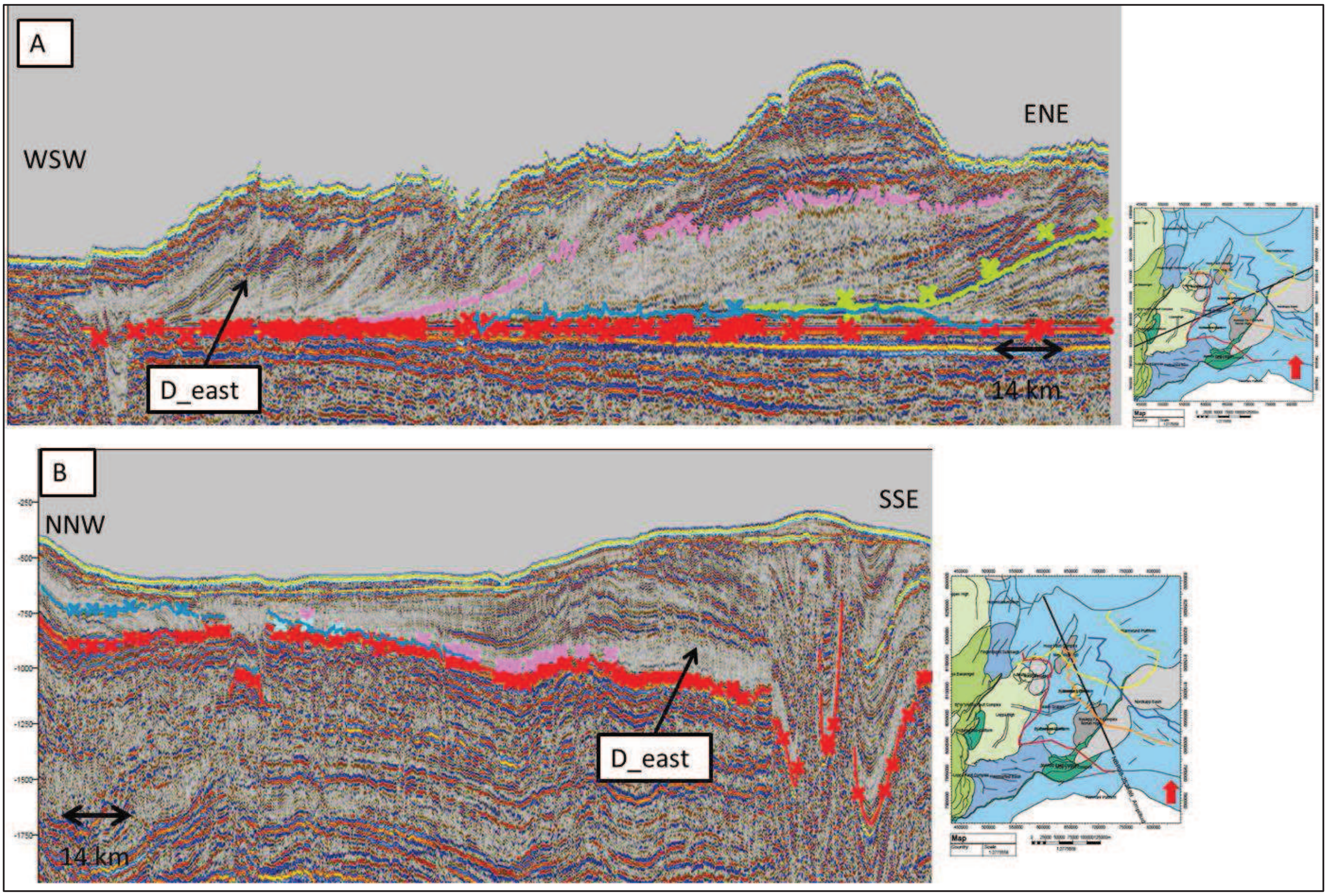

Figure 41 - Package D_east in dip section (A) and in transverse section (B). Map modified from (Directorate, 2014) (seismic line legend fig. 17)

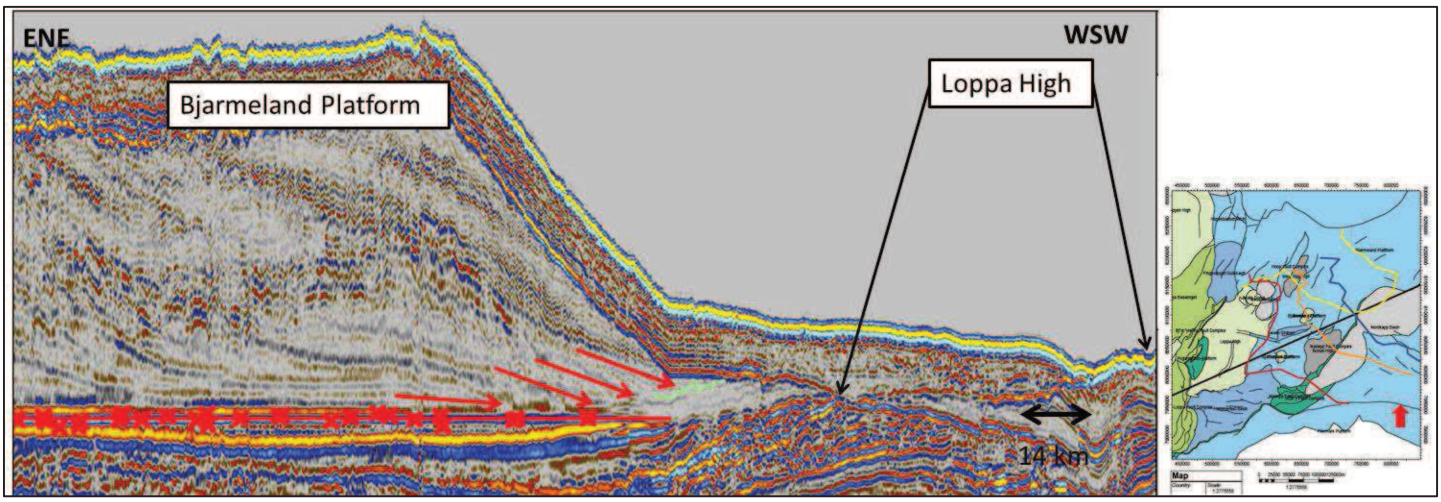

Figure 42 - Package D_east, onlapps onto Loppa High. Map modified from (Directorate, 2014) (seismic line legend fig. 17)

4.2.2.5 Unresolved/unmapable packages

Above Package A_north, there is a package of reflectors that, although no pattern or reflection configuration can be resolved, indications (Fig. 43) suggest that it prograded from the north. Extensive erosion removed it, and only a small part of it is preserved and resolved. Neither its lateral extent nor its boundaries can be mapped. Regardless, it has to be taken into account that there were more strata deposited on top of A_north with possibly the same progradation direction. A time frame between that unresolved package and C, D_east is difficult to be determined. A number of questions arise: had that package the same source as A_north, is it older, younger or synchronous with C, D_east, what was its configuration, was it actually prograding or is that a reflection artefact created by the uplift and erosion, and what was its thickness? If it is not a prograding unit, this means that the basin setting changed to a stable one and the sea level rose. If it is a prograding unit, how far did it prograde and did it prograde in a low or high energy regime? Was that the last prograding package from the north or were there more? Unfortunately, due to later uplift and erosion, those questions will most likely never be answered.

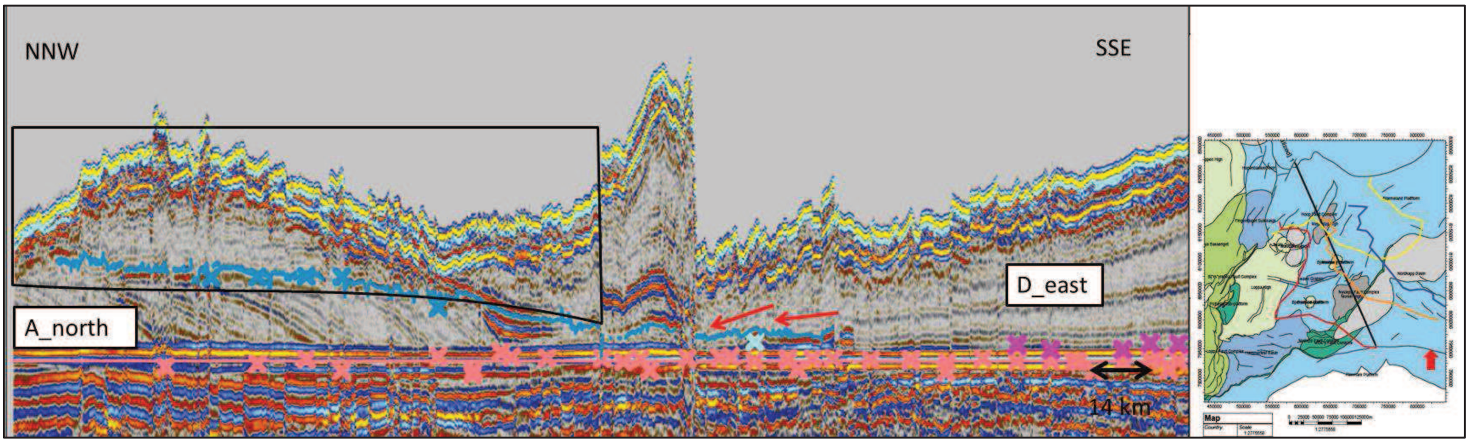

Figure 43 - Unmappable package above A_north (within black box). Map modified from (Directorate, 2014) (seismic line legend fig. 17)

4.2.2.6 Nordkapp Basin

Most lines crossing the Nordkapp Basin contain clinothem packages distorted by the salt structures. There are two lines that cross the basin from northwest to southeast, approximately perpendicular to the B, C, D_east packages, that do not cross any salt structures (Fig. 44). In these lines there are reflectors that, although are affected by subsidence and faults, can be traced from the northwest of the area to southeast with excellent continuity (Fig. 44). Even along lines where salt structures are present (Fig. X), the reflectors show a continuity before and after the diapirs (Fig. 44).

Interpretation

The fact that the reflectors are continuous, hence not affected, in syndepositional terms, by the salt diapirs, agrees with what (Nilsen et al., 1995) have stated. The diapirs were not active when the clinothems were propagating into the basin, thus they prograded unaffected. The current deformation is due to salt reactivation in the L. Cretaceous – M. Tertiary (Nilsen et al., 1995).

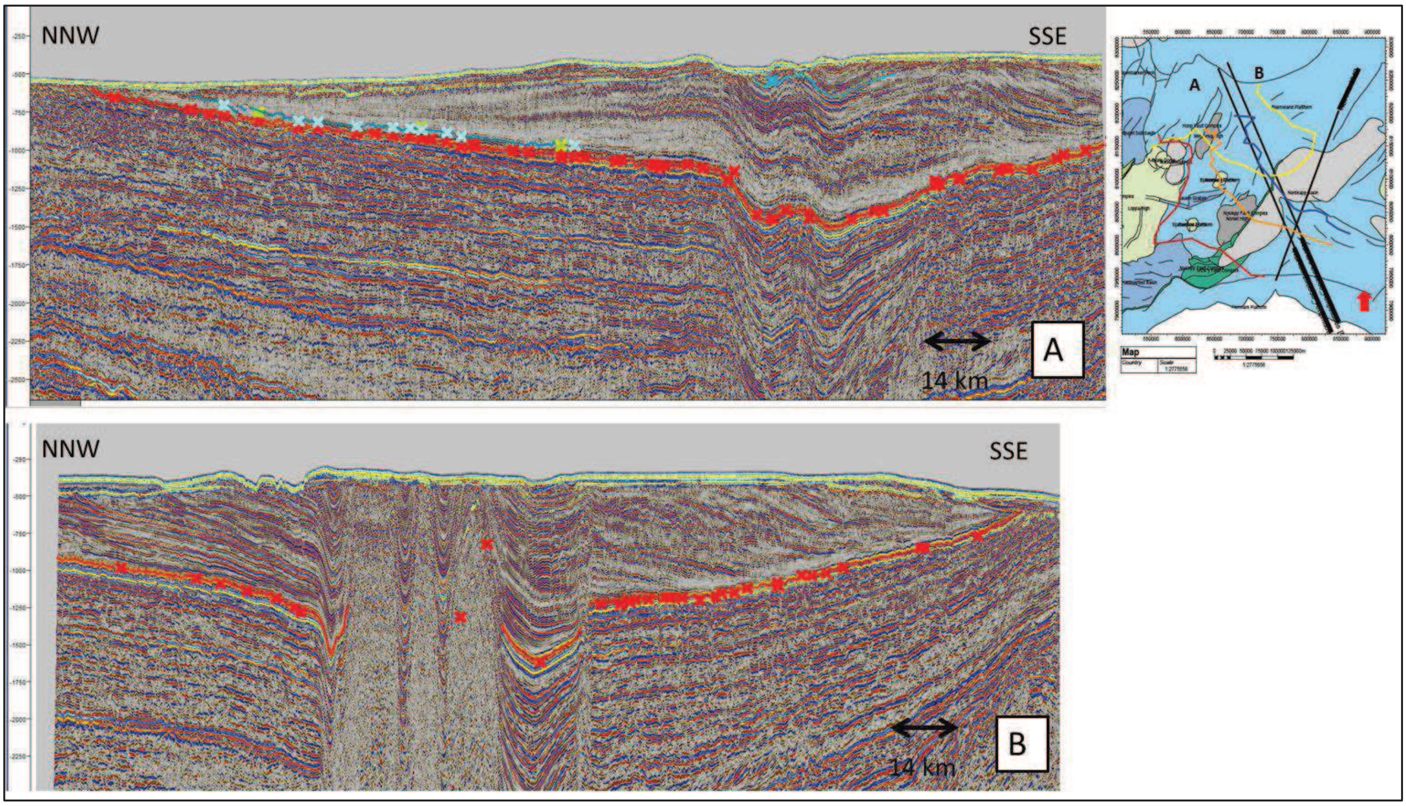

Figure 44 - Seismic line crossing the Nordkapp Basin. Notice the packages' continuity even when salt structures are present. Map modified from (Directorate, 2014) (seismic line legend fig. 17, plus blue line: Base Cenozoic)

4.2.2.7 Hammerfest Basin

The Hammerfest Basin is the only part of the study area where Cretaceous strata are better preserved, overlain by Cenozoic successions, and are not as extensively affected by later uplift and erosion (Fig. 45). In Figure 46 an interesting interplay between sedimentary packages is shown. Package D_east is terminating where sediments are prograding from the Hammerfest Basin in a west-east direction (Fig. X). These sediments form a package that is referred to as H_α. Overlying both of them, is a succession, H_β, which onlaps onto D_east in the east and thins towards the west with the reflectors either terminating at Base Tertiary or continuing in the deep basins further west (Fig. 46).

Interpretation

From the seismic interpretation, it is evident that the infill history of the Hammerfest Basin during the Cretaceous was complex with many source areas contributing to its formation. Package D_east did not prograde into the basin, with the lapout points migrating eastwards after reaching the Hammerfest Basin (Fig. 36). The interaction between D_east and H_α is shown in Fig. 46 and is marked by their downlaps in MFS_1 and their possibly unresolvable interfingering (Fig. 46). It is hard to distinguish their relative time relationship. The most probable scenario is that they were synchronous, but a short time difference, with one halting the other's progradation, is also plausible. H_α's source is located either somewhere west of the Ringvassøy-Loppa Fault Complex, outside the study area, or south; from the present day Finnmark Platform (Fig. 47 & 48). The first case is supported by what is shown in Fig. 47. The profile runs from southwest to northeast of the basin, in that H_α seems to be sourced from the west (Fig. 47). However, on the seismic line which is perpendicular to the previous one and has a N-S direction, H_a seems to be propagating from the southeast (Fig. 48). Further investigation of the available seismic lines, encountered the same double pattern, without revealing the sediment's source. The possibility that sediments from the Loppa High were, also, contributing to the basin fill, cannot be excluded. H_β source was as well difficult to determine. The reflectors do not show a prograding reflection configuration (Fig. 49 & 50) and they are onlapping onto D_east. When near-BCU is flattened, a parallel reflection configuration is revealed (Fig. 50) (Mitchum Jr et al., 1977). On account of this, H_β is interpreted to be deposited in a stable basin setting with constant and homogenous deposition (Mitchum Jr et al., 1977, Sangree and Widmier, 1979). The onlapping reflector corresponds to a sequence boundary (Fig. 46). Whether that boundary was produced by sea level rise, leading to flooding of the area and termination of H_α's and D_east's further development, or sea level fall, or from a depositional hiatus, cannot be determined from the data available.

The complex, multidimensional history of the Hammerfest Basin, characterized by the interplay between structural elements and sedimentary processes, at local and regional scales constitutes an extensive study, by itself. Integration between well and 2D/3D seismic data will provide an insight to the basin evolution, based in what has been presented here.

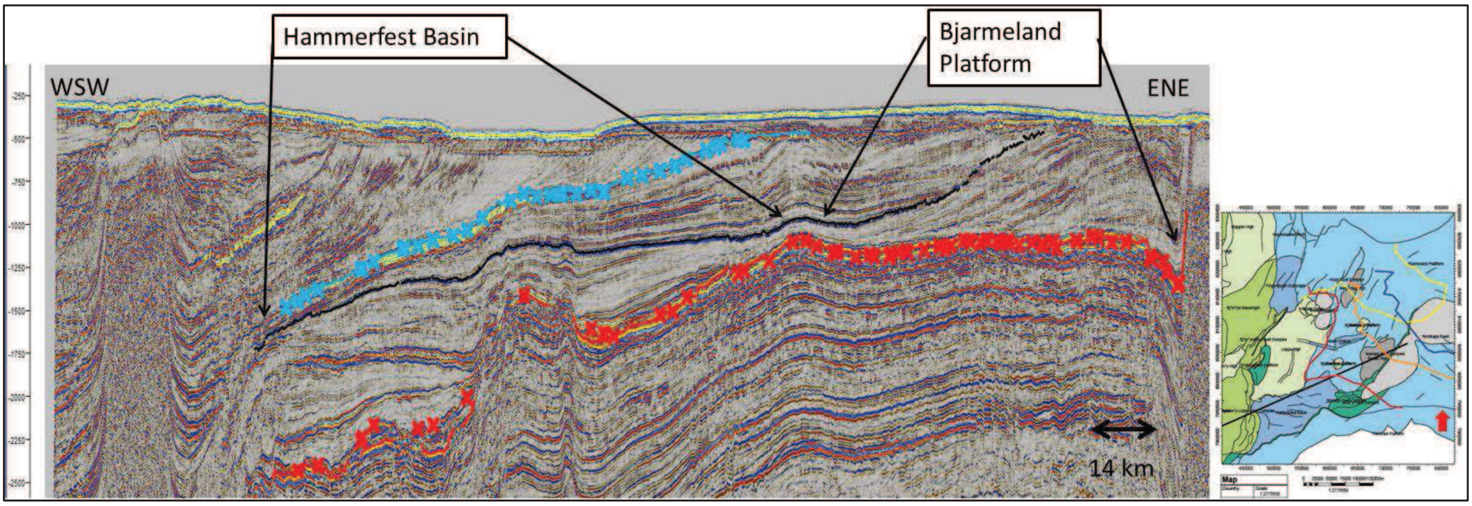

Figure 45 - Seismic line crossing Hammerfest Basin and Bjarmeland platform. Map modified from (Directorate, 2014) (seismic line legend fig. 17, plus blue line Base Cenozoic)

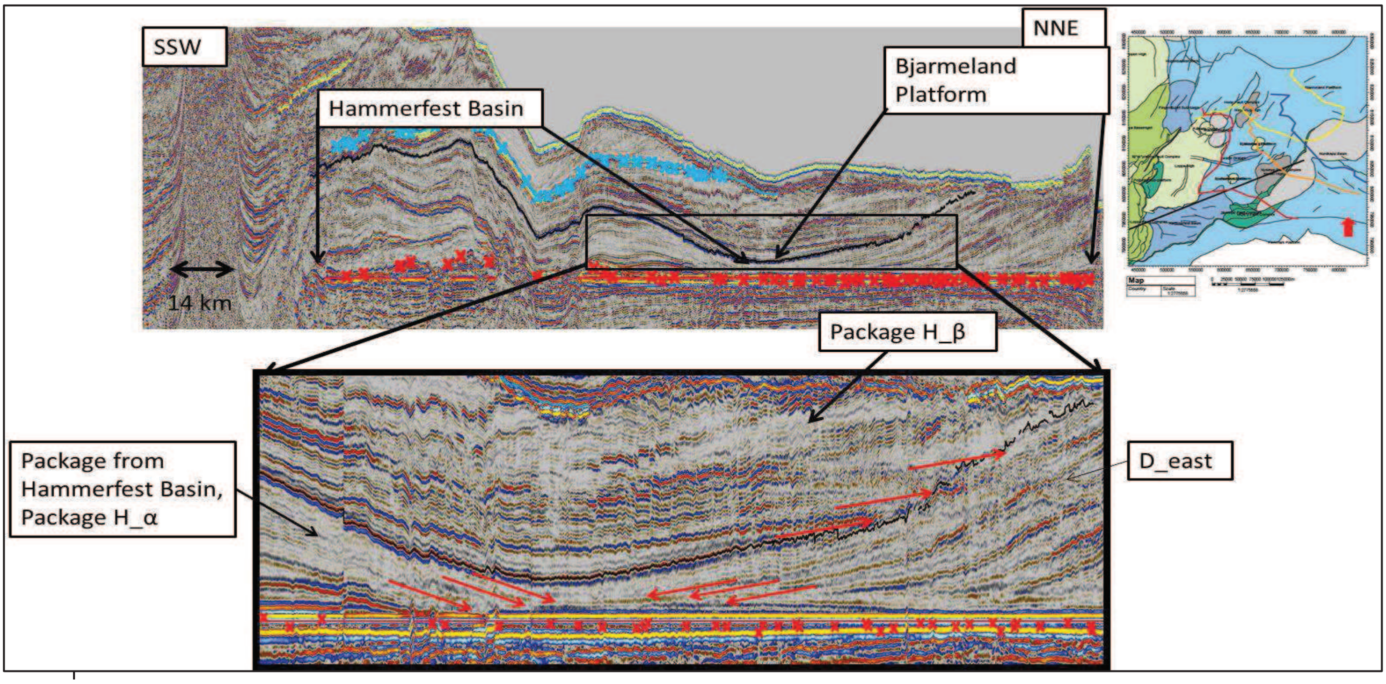

Figure 46 - Zoom in imge of the interplay between sediments from D_east, H_α and H_β. Map modified from (Directorate, 2014) (seismic line legend fig. 17, plus blue line: Base Cenozoic)

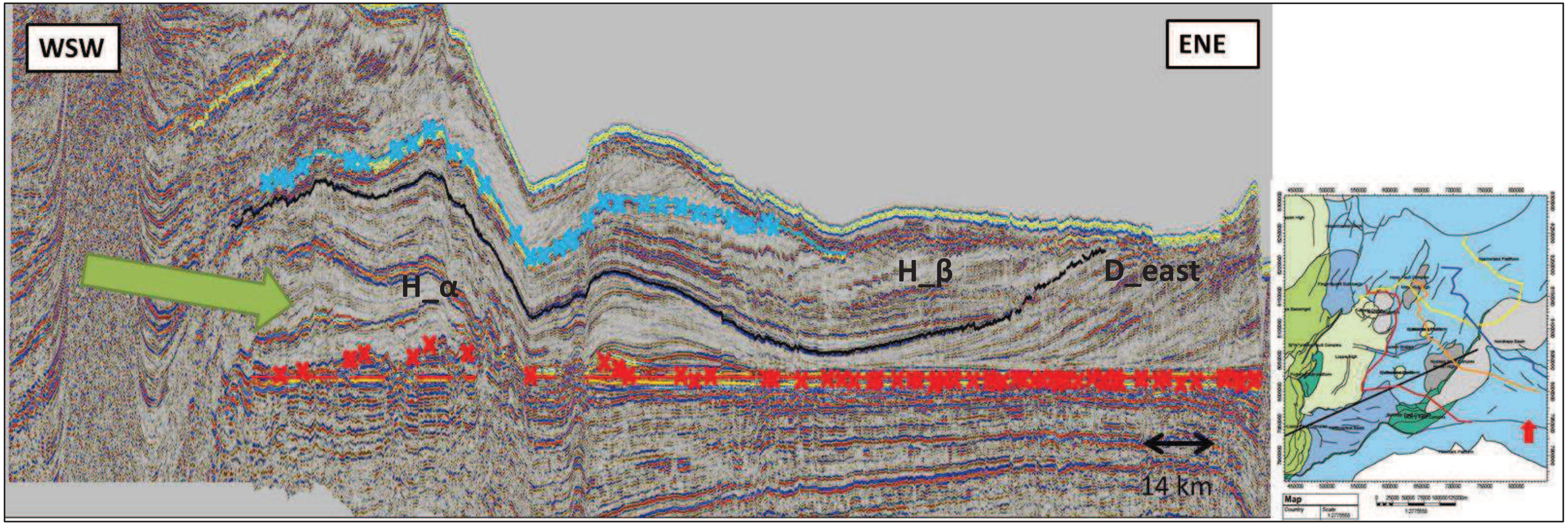

Figure 47 - One possible progradation direction for Package H_α. Map modified from (Directorate, 2014) (seismic line legend fig. 17, plus blue line: Base Cenozoic)

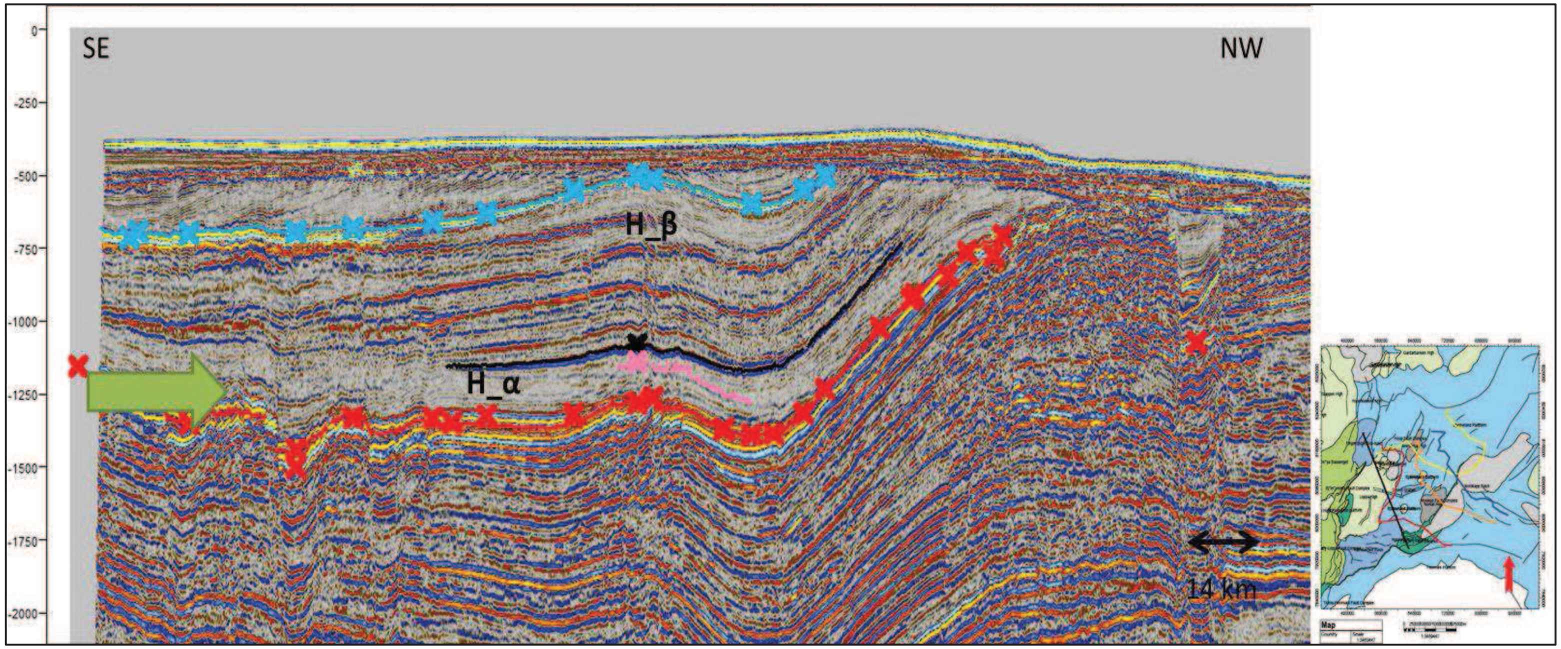

Figure 48 - One possible progradation direction of Package H_α. Map modified from (Directorate, 2014) (seismic line legend fig. 17, plus blue line: Base Cenozoic)

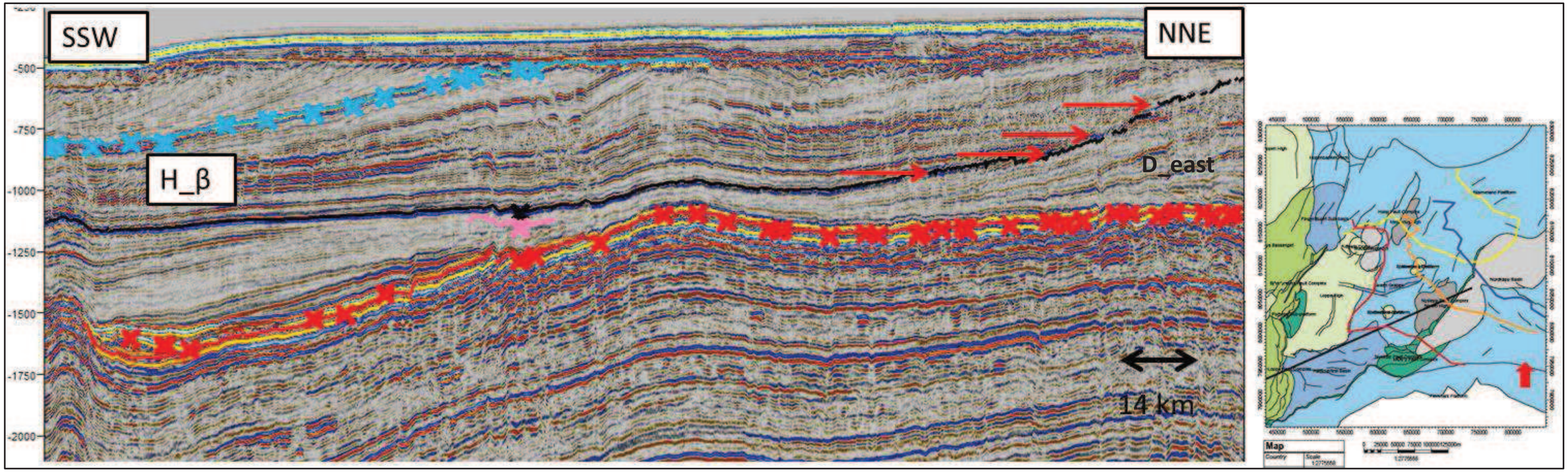

Figure 49 - H_β onlaps onto D_east. Map modified from (Directorate, 2014) (seismic line legend fig. 17, plus blue line: Base Cenozoic)

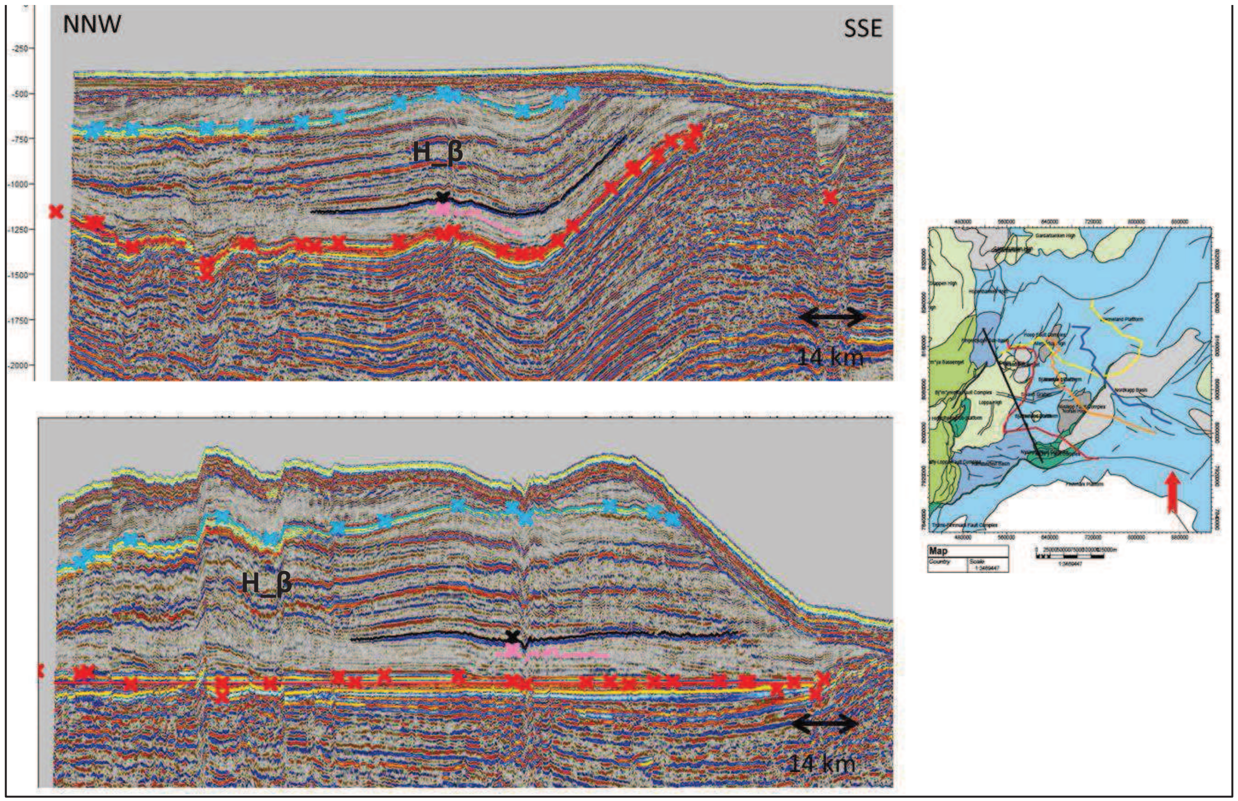

Figure 50 - Package H_β parallel reflection configuration where the near Base Cretaceous is flattened. Map modified from (Directorate, 2014) (seismic line legend fig. 17, plus blue line: Base Cenozoic)

4.2.2.8 Relative age of deposition

The simplified age relationship between the four clinothem packages is presented above; A_north predates B,C and D_east (Fig. 17). However, further southward and close to the eastern limit of the study area (Fig. 51), an interaction between the reflectors from A_β_north and B_east is observed. Although B_east is onlapping onto A_β_north on the majority of the seismic lines, on one line they terminate onto each other (Fig. 51). The feature is observed on all the available lines that extend to the eastern limits of A_β_north. This indicates that although, generally, A_north predates B_east, when the first sediments of A_β_north reached the northern parts of the Bjarmeland Platform, the first sedimentary successions of B_east also reached the area. The subsequent parts of B_east onlap onto A_β_north (Fig. 51). This means that either A_β_north was prograding faster than B_east, or that B_east was deposited in various time phases; something that is supported by what was described in the "Package B_east" subchapter. Since, there are no biostratigraphy data available, a definite time relationship cannot be established here. 3D or high resolution seismic data would also be useful in determining the two packages age and space relations. For the time being, the fact that the initial interplay between these two packages is more complicated, is acknowledged and taken into consideration.

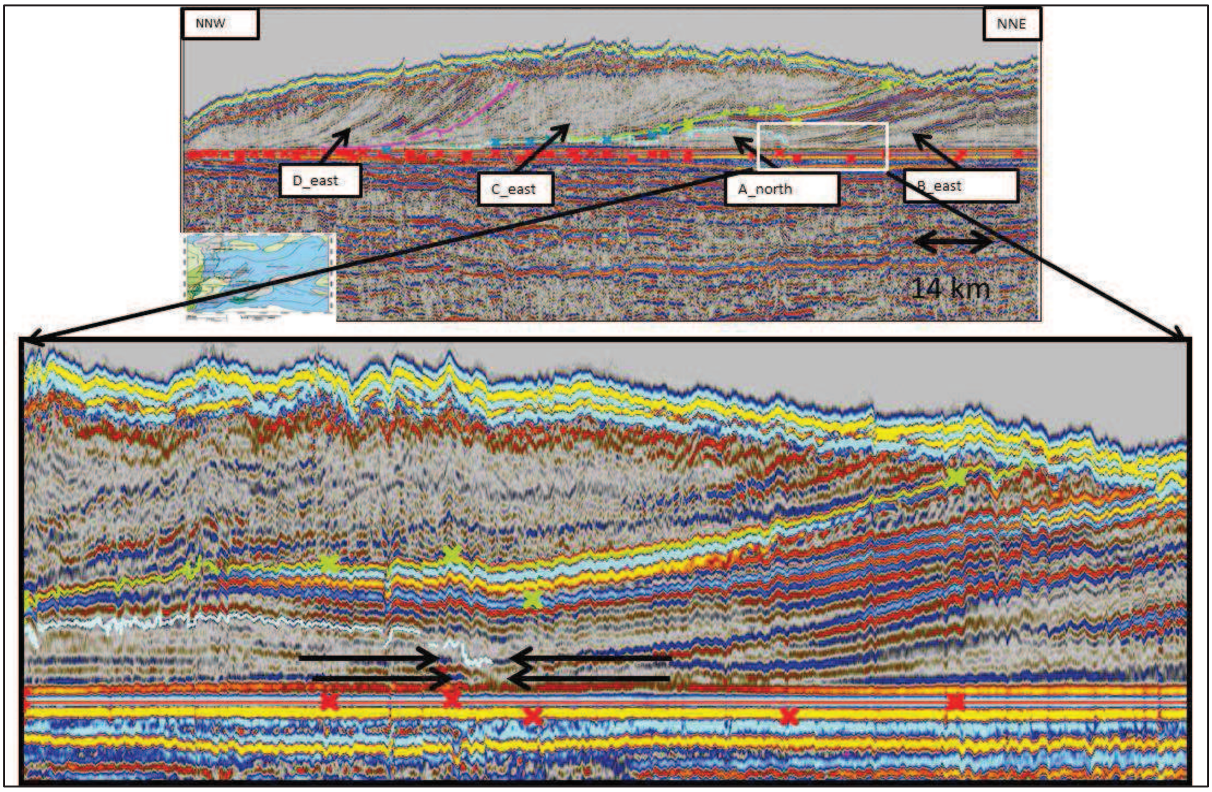

Figure 51 - Packages A_north and B_east reflection interfingering. Map modified from (Directorate, 2014) (seismic line legend fig. 17)

4.2.3 Well data examination – part two

In the second phase, after the seismic interpretation was completed, and a primary insight on the basin's infill dynamics and clinoform packages distribution was established; certain wells that penetrated strata corresponding to the examined successions were chosen for further analysis. These are shown in Fig. 52 and Table 3. The well data were imported into Petrel and their gamma-ray response was examined, together with which formation corresponds to which clinothem package, so a preliminary relative time frame could be established. The wells imported, penetrate only Package D_east (Fig. 53). The Kolje Formation is not present in any of them; the Knurr Formation has a maximum thickness of 34 m and Kolmule varies between 220-821 m. The greatest thicknesses are observed in the wells located at the southern limits of Nordkapp Basin and into the Nysleppen Fault Complex (Fig. 52). Although the available wells are broadly spaced, and are located only at the southern part of the study area, it is indicative that apart from a thin Knurr Formation interval, below seismic resolution, the Kolmule Formation lies above the Hekkingen Formation. Relative time wise, from Valanginian to early Barremian, it appears that only a condensed section developed in the area, with the main deposition time being Barremian-Aptian. This implies that at least Package D_east is of Barremian-Aptian age. No wells penetrate any of the other clinothem packages. Three (7224/6-1, 7226/2-1, 7225/3-1) out of the four available gamma-ray readings show clear clay readings (Table 3, Fig. 55), indicative of fine grained sediments. Well 7228/9-1, which is the eastern-most one, located south of the Nordkapp Basin (Fig. 52) has the lowest gamma-ray readings, 40-70 API (Table 3, Fig. 55). The possible significance of this and the gamma-ray readings relationship with the seismic facies observed are further examined in the discussion chapter.

Table 3 - Formation thickness and Gamma-ray readings of the wells examined in phase two.

Wells	Knurr Fm thickness	Kolje Fm thickness	Kolmule Fm thickness	Knurr Fm API	Kolje Fm API	Kolmule Fm API	Clinoform Package penetrating
7225/3-1	34 m	-	220 m	60-100	-	60-100	D_east
7226/2-1	27 m	-	273m	170-200	-	170-200	D_east
7224/6-1	16 m	-	471 m	70-100	-	70-100	D_east
7228/7-1	-	-	722 m	40-70	-	40-70	D_east

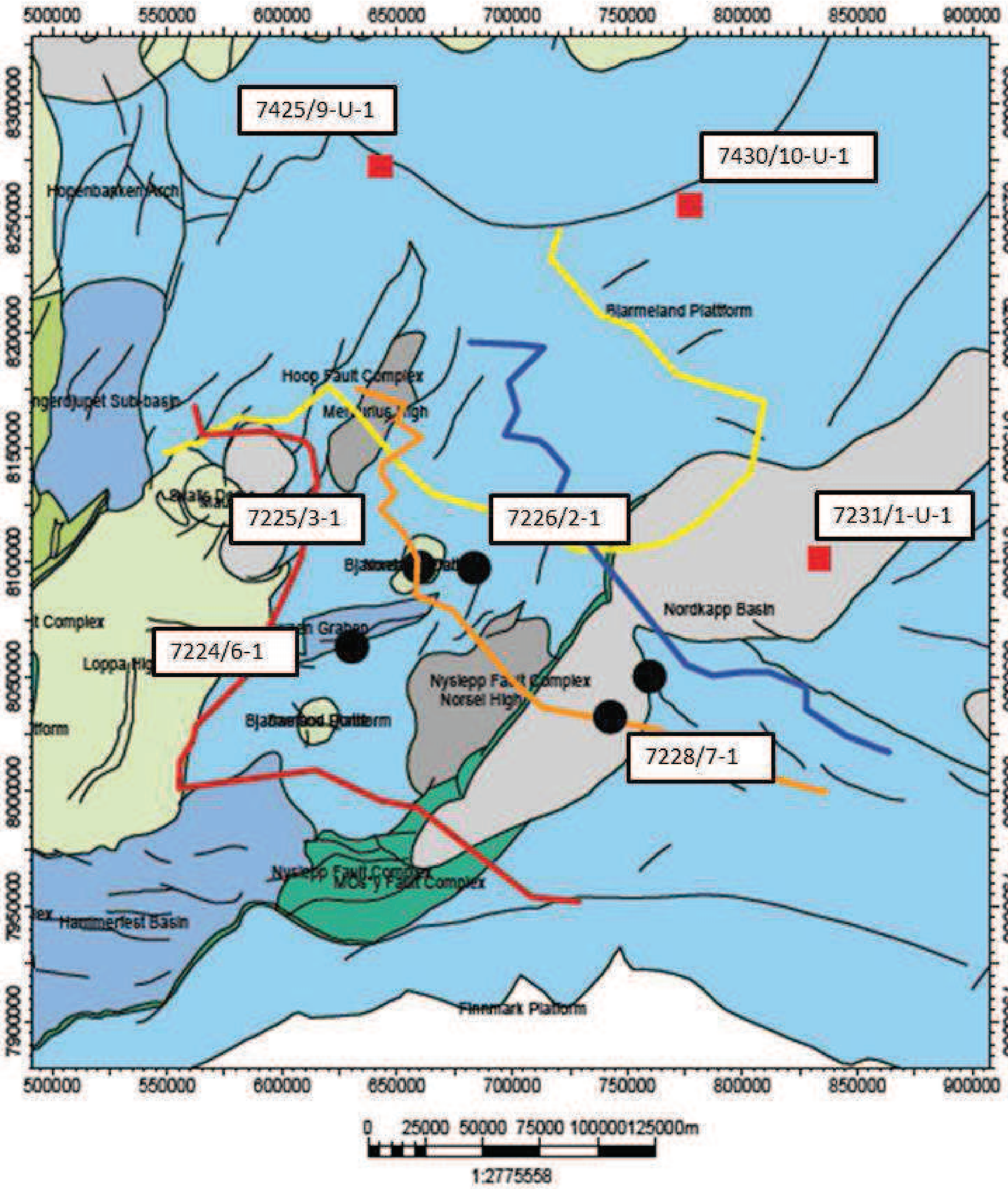

Figure 52 - Black circles: location of the wells examined in phase two; Red squares: location of the shallow boreholes examined in phase three. Map modified from (Directorate, 2014) (legend fig. 18)

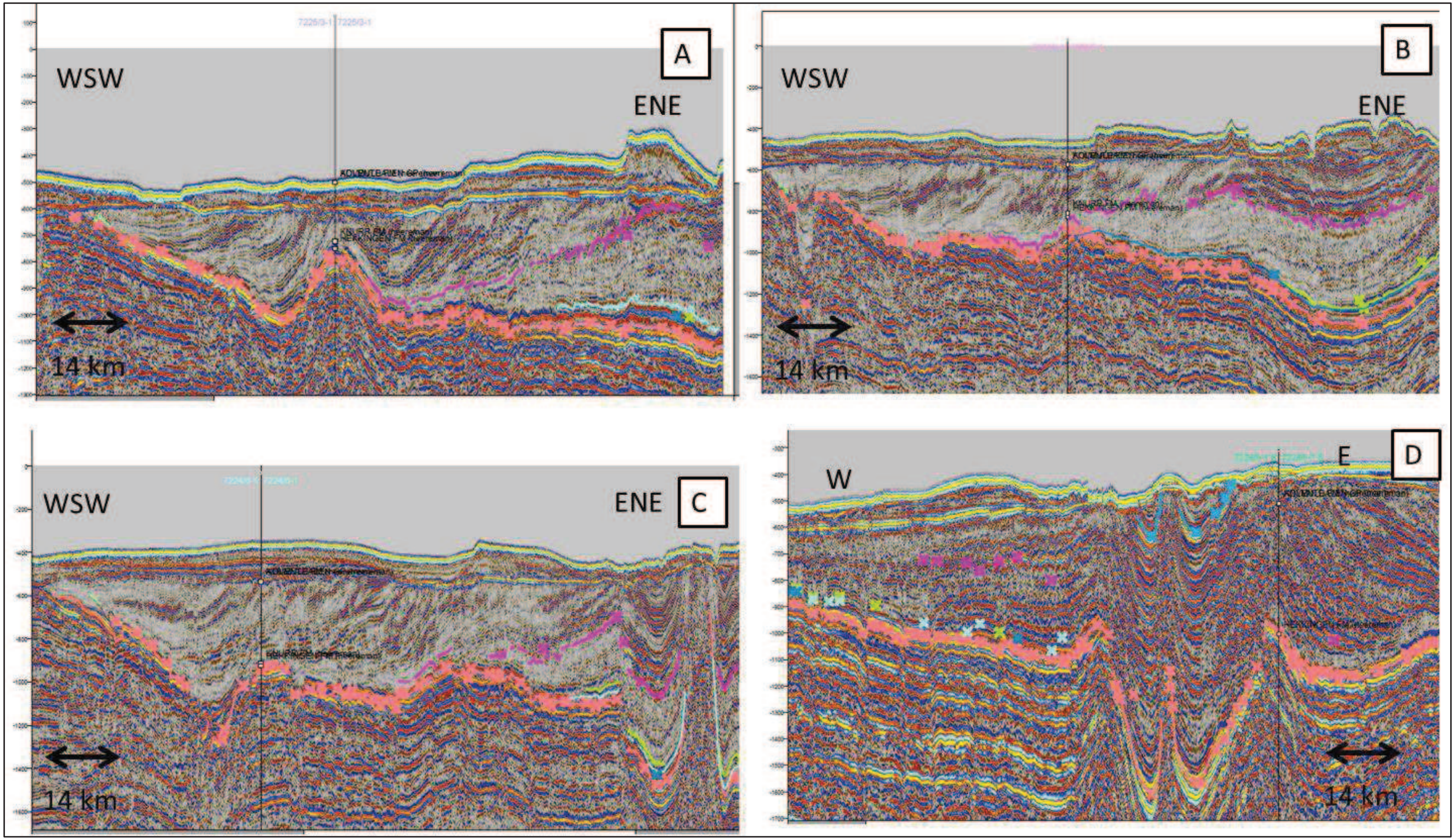

Figure 53 - Wells with corresponding seismic lines (wells and lines position seen in Fig. 54) (seismic lines legend fig. 17, plus blue line: Base Cenozoic)

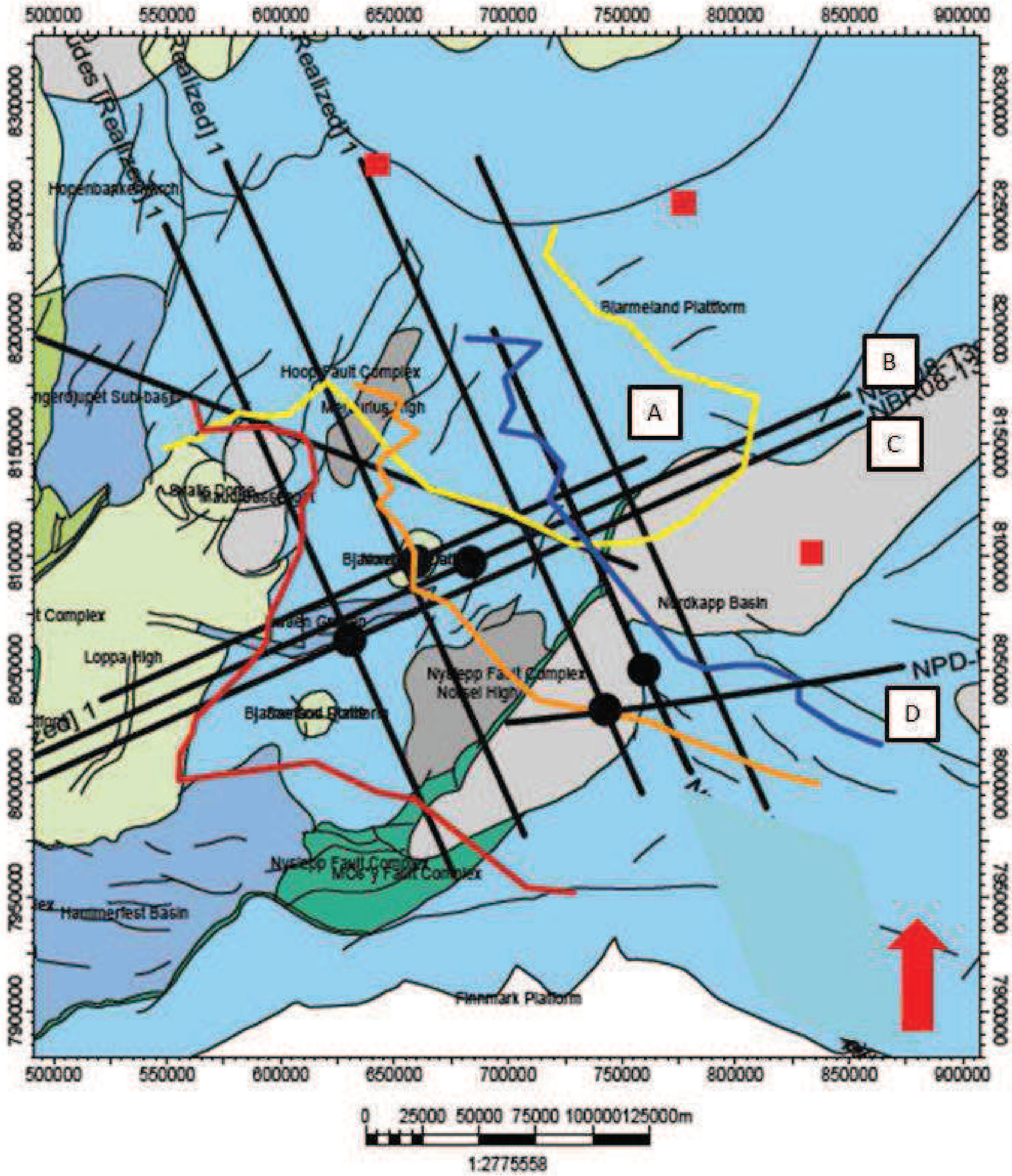

Figure 54 - Lines and wells used in phase two superimposed. Map modified from (Directorate, 2014) (legend fig. 18 & 52)

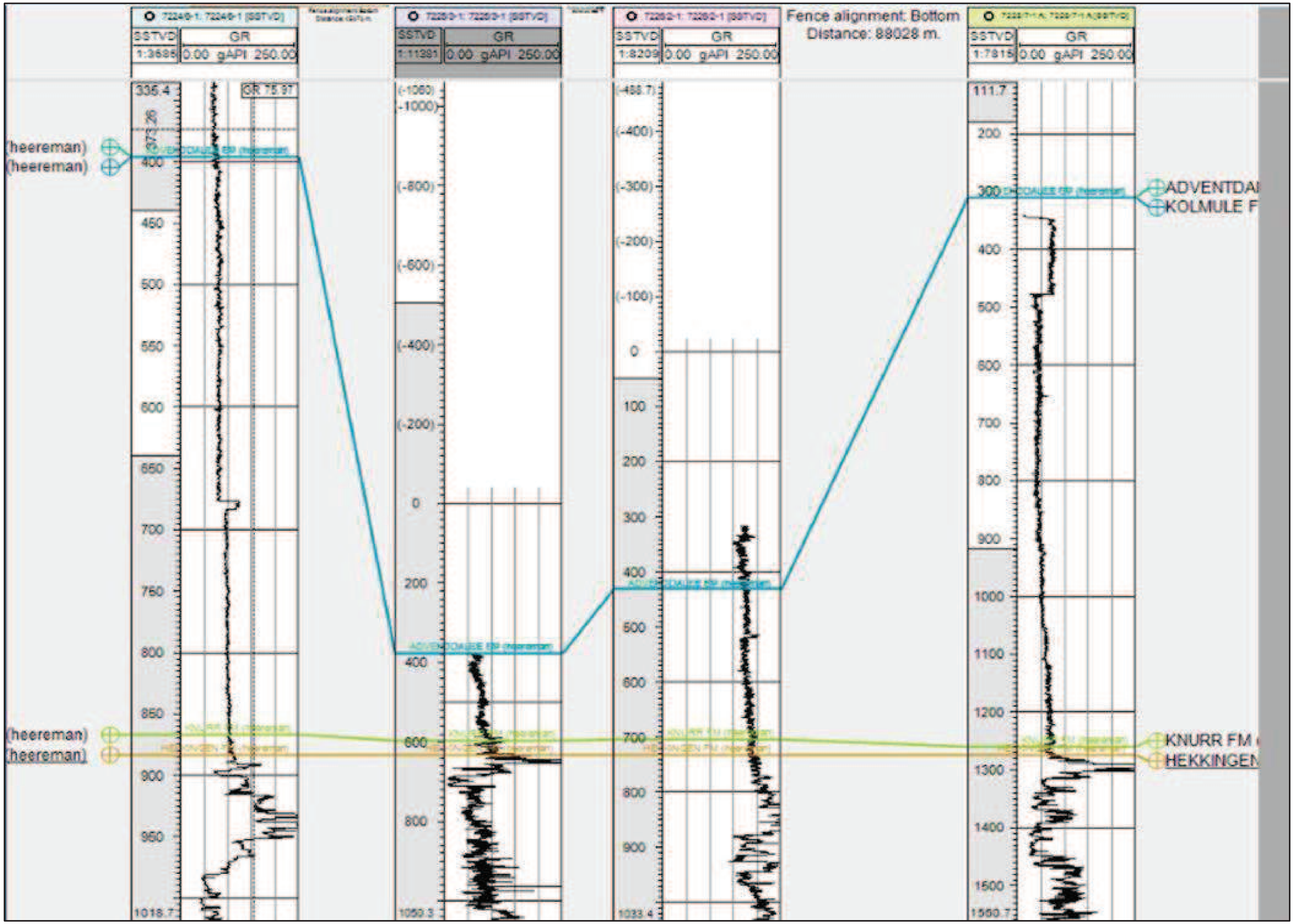

Figure 55 - Gamma-ray logs for the four wells in phase two.

4.2.4 Well data examination – part three

In the third phase, three shallow boreholes drilled in the area, between 1985 and 1988, as part of IKU's shallow drilling program, where the observed clinothem packages develop, were integrated to gain more information on the Jurassic-Cretaceous boundary and the downlapping surface's age and lithology. The boreholes are 7425/9-U-1, 7430/10-U-1 and 7231/1-U-1 (Fig. 54 and 56). In Fig. 54 their position relatively to the packages distribution is shown. Extended lithostratigraphic and biostratigraphic analyses have been performed to all three of them and presented in (Århus (1991), Århus et al. (1990), Bugge et al. (2001)).

In the two northernmost boreholes (7425/9-U-1, 7430/10-U-1), a 5 m thick succession of Boreal Berriasian black mudstone is found at the base of the cores (Fig. 56). Above them, 5 m of marls and carbonates of Valanginian- Early Barremian age are present in all three wells (Fig. 56). The fact that the carbonates are present in all three wells, which are distributed over such a large area, suggests a widespread deposition of the succession. In the southernmost well (7231/1-U-1), this succession lies directly above Volgian mudstones. Then an abrupt change of deposition occurs. Early Barremian dark claystone beds are deposited directly above them (Fig. 56). Summarising, a condensed but widespread section of marls and carbonates was deposited during Valanginian-Early Barremian in the study area, overlain by dark claystones of Early - Middle Barremian age. That abrupt change in lithologies, points to an abrupt change in depositional environment; from shallow water carbonate and marl sedimentation to deeper water dark claystones.

Smelror et al. (1998) introduced, named and extensively described the marl/carbonate section, formally known as the Klippfisk Formation. It is subdivided in two members: the Kutling Member, which corresponds to the sections found in the shallow cores from Bjarmeland Platform, and the Tordenskjoldberget Member, from Kong Karls Land. These two members are contemporary and the successions distribution appears to be broad, reaching from the eastern part of the south-western Barents Sea platform areas to Kong Karls Land. It corresponds to a condensed section of Berriasian to early Barremian age, overlying, usually uncomfortably, Hekkingen or Agardhfjellet formations. It was deposited in a shallow marine environment and it marks a transgression that occurred at that time period over the area. It passes laterally westwards and eastwards into the Knurr Formation.

Integrating what is known from the data available, it can be inferred that the dark claystones, observed in the shallow boreholes, correspond to what is currently referred to as the Kolmule Formation, in the deep wells, and the clinothem packages, from the seismic. Also, the downlapping surface is neither the Hekkingen or Knurr formations, but a carbonate/marl condensed section of Valanginian-Early Barremian age, the Kutling Member of the Klippfisk Formation. This condensed section is below seismic resolution, and that is why the clinothem packages appear to downlap onto Jurassic strata in the seismic data. Finally, what has been referred to as Early Cretaceous prograding units, is not strictly speaking of lowest Early Cretaceous age, but the units must have developed during the Barremian-Aptian, so is latest Early Cretaceous. This is also supported by what has been observed in the Fingerdjupet Subbasin. Package A_north does not onlap onto Jurassic strata, but 267 ms above the Upper Jurassic surface (Dahlberg, 2014), which means a thick succession was deposited before the older clinothem package was deposited in the area. Relative dating in the Fingerdjupet Subbasin has yielded a lower Barremian age to Package A_north (Dahlberg, 2014). The relative timing issues is further treated in the discussion section.

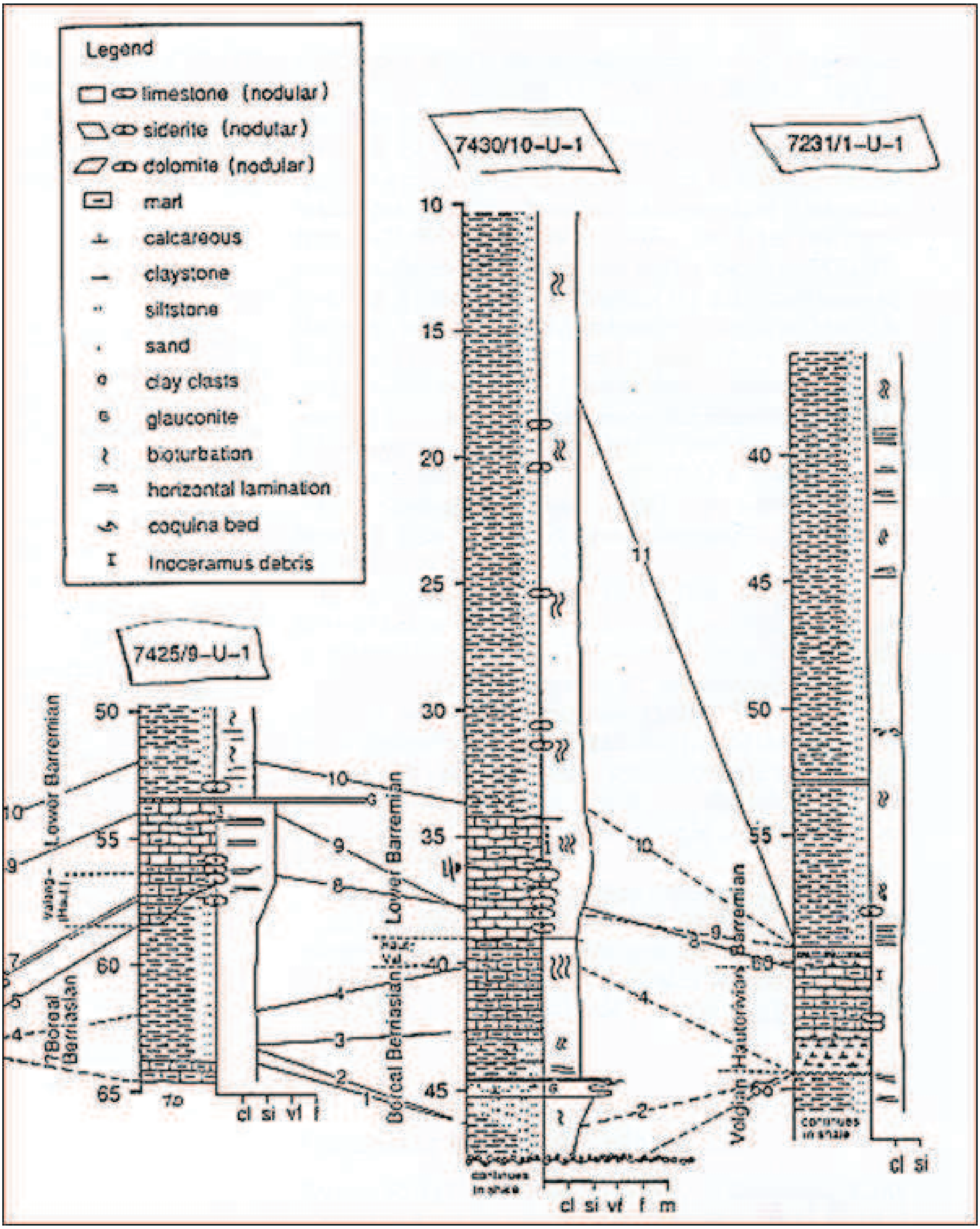

Figure 56 - Shallow boreholes' stratigraphy, used in Well data examination phase three. Modified from Århus (1991).

5 Discussion

5.1 Basin Infill History

The seismic patterns show that a progressive infill of the basin took place during the Early Cretaceous. At least four discrete phases of basin infill are recognized through the four clinothem packages. The first phase corresponds to the deposition of Package A_north. The prograding direction is towards the south-southeast. The second, third and fourth phases correspond to the deposition of Package B_east, C_east and D_east, respectively. Their prograding direction is from northeast towards southwest. The foreset of Package A_north filled up the accommodation space available in the northwest of the paleo-basin, while the bottomset prograded southwards until the Nordkapp Basin (Fig. 18). The progradational potential of the sedimentary system was significant, as evidenced by the 230 km pinchout distance from Spitsbergen onto the Bjarmeland Platform. It must have been a large system with the ability to transport significant amounts of sediment. Whether that system was drained, after the deposition of Package A_north, or there was more sediment transported through it will be discussed in a separate subchapter.

The second package recorded in this part of the basin is B_east. This marks a major shift in infill direction as a vast amount of sediments came in from the northeast, in three distinct phases (Fig. 57). The relative time of deposition of the two first packages is not fully constrained. The most probable scenario is that they are penecontemporaneous, but A_north reached the basin earlier than B_east, due to its proximity to the source area. Package B_east had a greater distance to travel before it reached the same area. This means that while A_north was deposited in the northwestern part of the Bjarmeland Platform, B_east was prograding in the northeastern part. The longer distance from the source led to the onlap of B_east onto the bottomset of A_north. A correlation between seismic and biostratigraphic data might further resolve the timing of these events.

The offlap breaks observed (Fig. 27) shows the position of the platform edge, at the time of B_east deposition (Fig. 58). Uplift and erosion have removed any evidence of whether the platform edge was migrating north-eastwards or south-westwards, during the deposition of C and D_east. The probability of another package, predating B_east, further east cannot be excluded, in connection with the potential position of the platform-edge through time. All packages appear to have had source areas located to the northeast. Local sources, such as the Loppa High or the horst area between the Fingerdjupet Subbasin and Leirdjupet Fault Complex, could have contributed to the infill of the basin, but to a significantly lower extent. The infill timing is of importance and is discussed below.

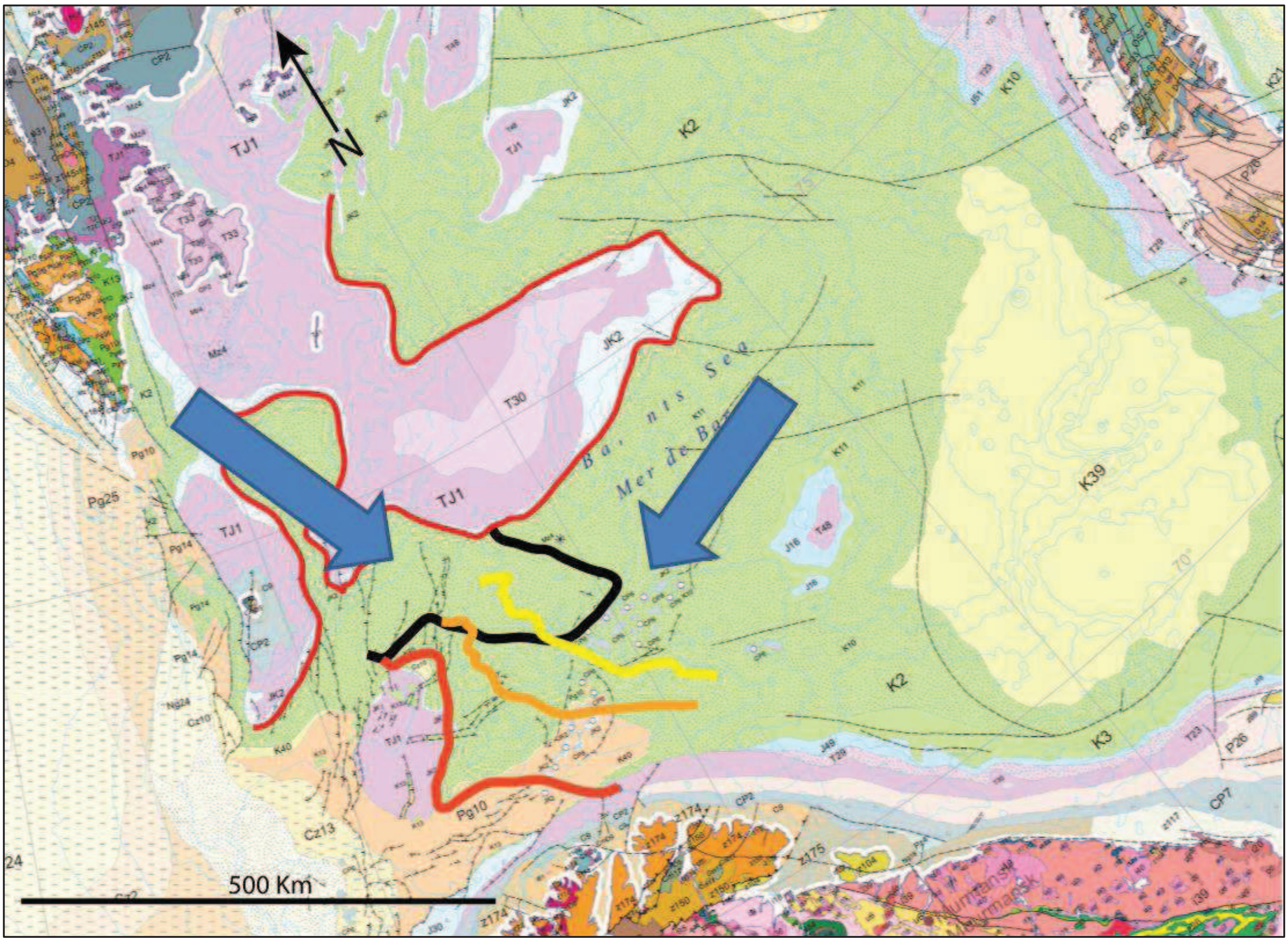

Figure 57 - Basin infill; arrows indicating general progradation directions; black line: Package A_north boundary; yellow line: Package B_east boundary; orange line: Package C_east boundary; red line: Package D_east boundary. Modified from (Harrison et al., 2011)

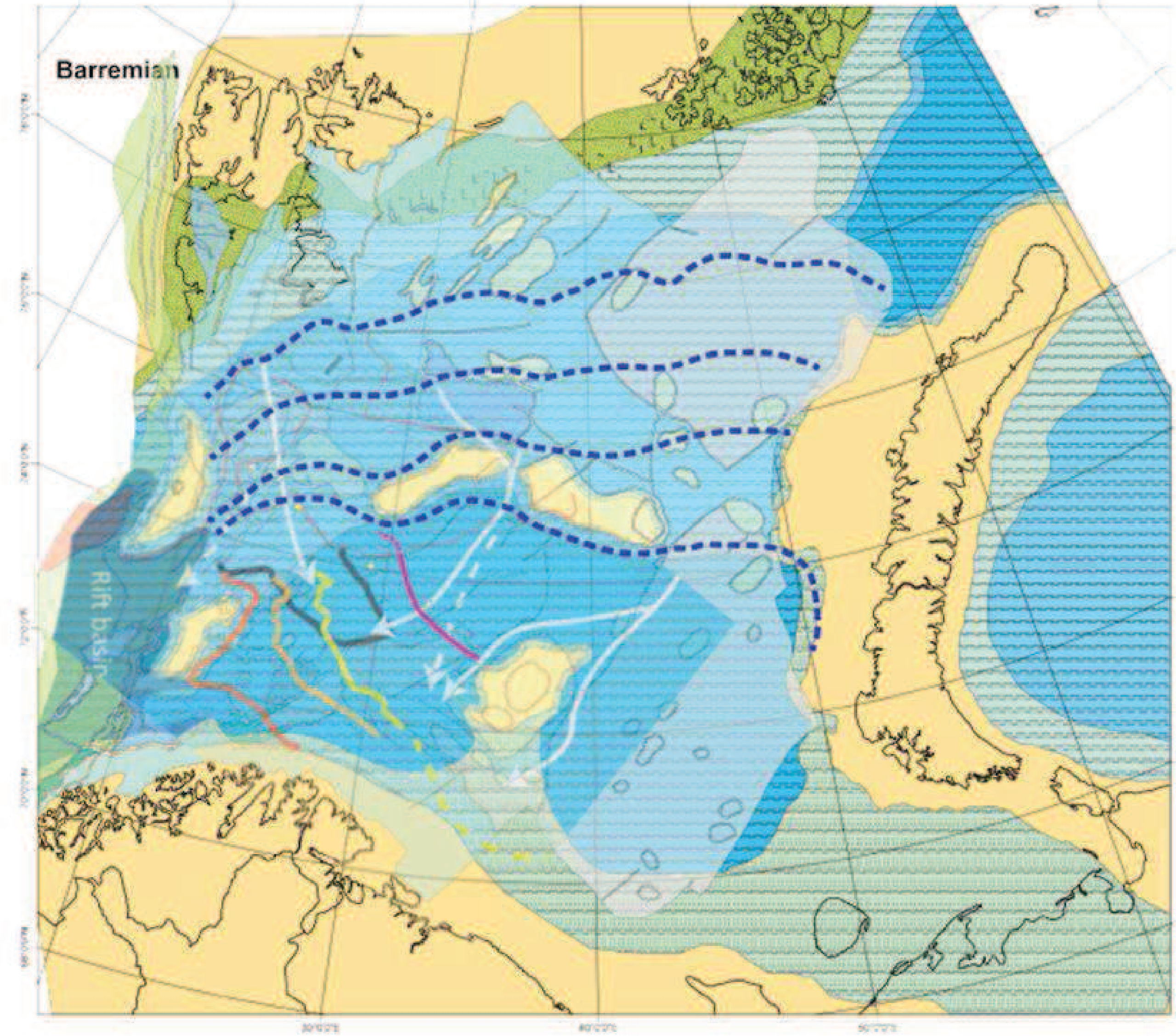

Figure 58 - Superimposed map of interpreted packages, prograding directions, platform-edge, possible shoreline positions and palaioenvironment. Same legend as Fig. 57 plus magenta line: platform edge, blue doted lines: possible shoreline positions. Map modified from (Smelror et al., 2009)

5.2 Source area

The progradational directions of the clinothem packages, as they have been presented in Chapter 4 and 5.1 , indicate that the predominant sediment source was located northerly of the basin. A distinctive uplift of the northern margin of the Barents shelf in Early Cretaceous, related to the HALIP (see Chapter 2.5), produced and acted as the source for the fluvial, coastal plain and marginal marine system of the Helvetiafjellet Formation in Svalbard. The lateral extent of that paralic/deltaic system, as has been suggested by (Smelror et al. (2009), Worsley (2008)) is shown on Fig. 5 & 58. The HALIP system has acted as a source for sediments also in the Canadian Arctic Archipelago and northern Greenland (Maher, 2001). It can be suggested that the HALIP province acted as the source, also for the clinothem packages discussed here. The local sources, such as the inferred highs to the north of the Bjarmeland Platform and the present day Stappen, Gardarbanken, Sentralbanken and Polarrev/Persey highs, could not have produced the amount of sediments that generated the clinothem packages described above. The aforementioned highs could have contributed locally to the basin infill, but their contribution was negligible compared to the source area to the north. Furthermore, no such evidence has been found in the seismic data.

It is suggested here that the two parts, the Helvetiafjellet Formation in Svalbard and the four clinothem packages in the south-eastern part of the western Barents Sea are part of the same progradational system, sourced from the greater HALIP area in the Arctic (Midtkandal et al., 2014). Package A_north could be more closely connected to the Helvetiafjellet Formation in Spitsbergen, with their combined architecture forming what is shown on Fig. 60, while Packages B, C and D_east were sourced from HALIP areas east of present day Spitsbergen. This is supported not only from Package A_north's prograding direction, but, also, from the Helvetiafjellet Formation's NW to SE general palaeocurrent direction (Midtkandal et al., 2007, Gjelberg and Steel, 1995). Packages B, C and D_east could be more closely connected, with the same relationship shown in Fig. 60, as an eastward continuation of the aforementioned system (Fig. 60).

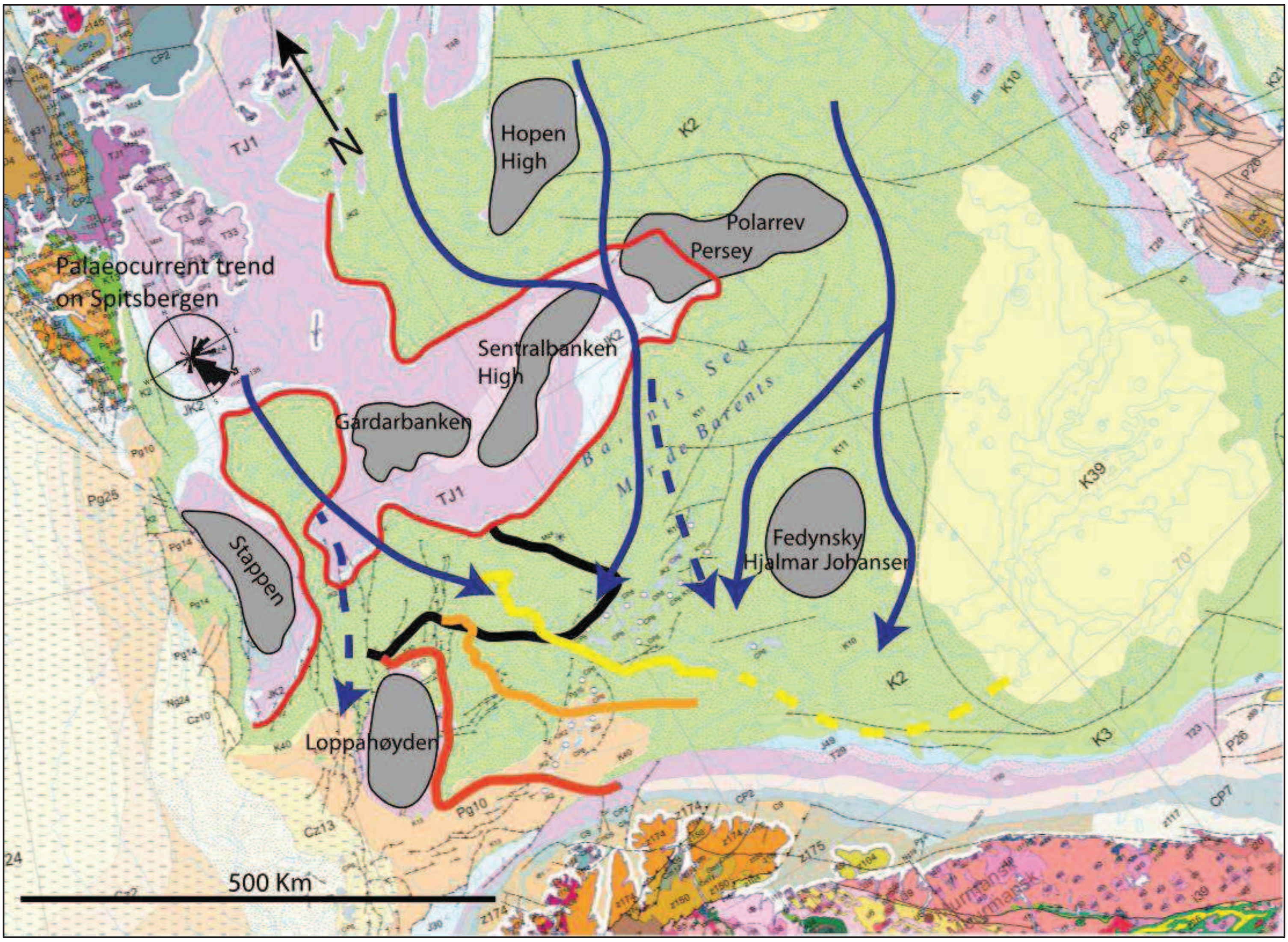

Figure 59 - Packages boundaries (color defined on Fig. 57), potential progradational directions (blue lines) with entry points. Map modified from (Harrison et al., 2011)

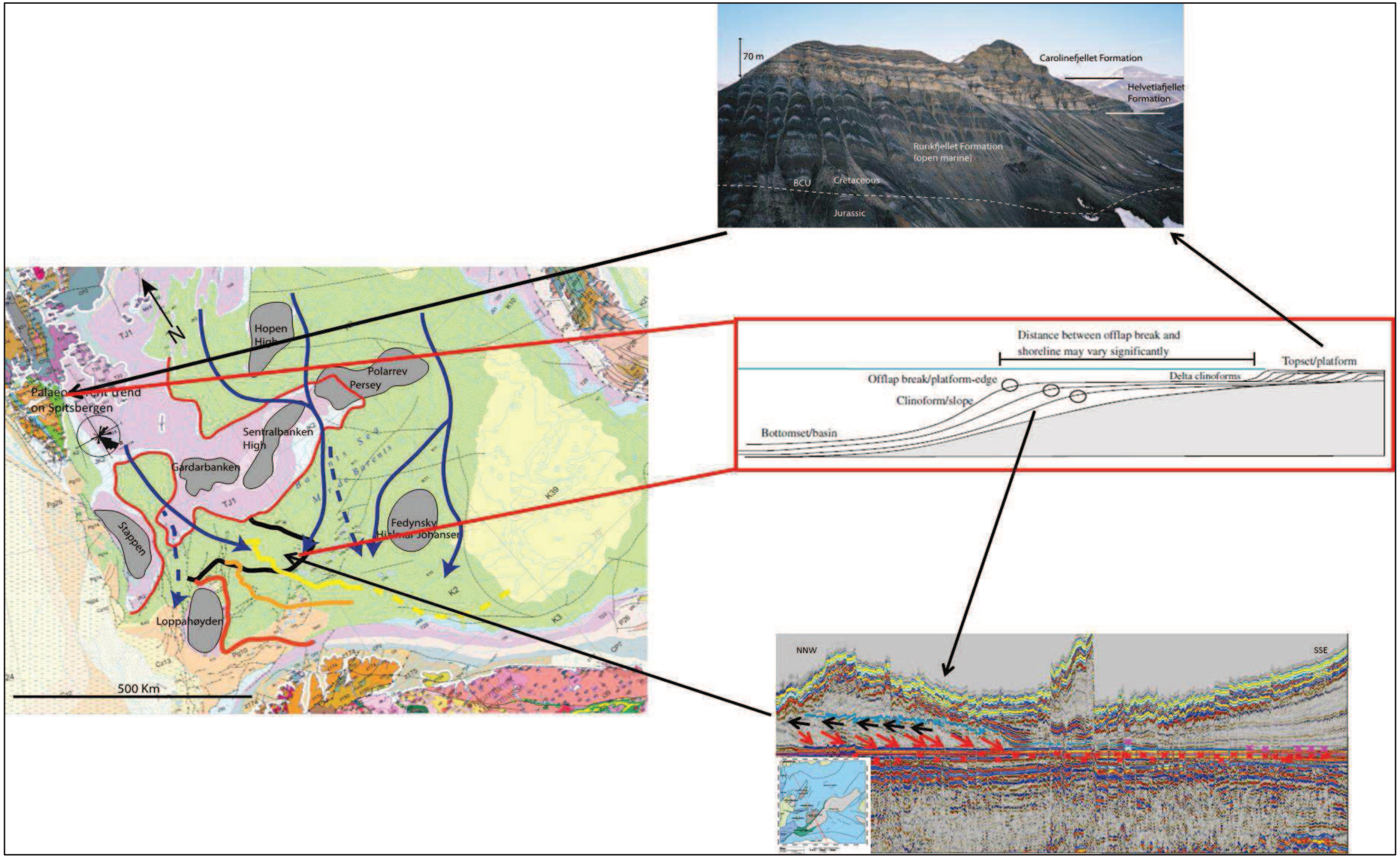

Figure 60 - Possible connection geometry between the Helvetiafjellet Formation on Svalbard and Package A_north. (Map modified from Harrison et al. (2011), figure from Glørstad-Clark et al. (2010), photo Louiseberget, SW Spitsbergen by Midtkandal et al. (2014)).

5.3 Entry points

An important question and discussion is from where the sediments comprising the clinothem packages entered the basinal area. The Stappen, Gardarbanken, Sentralbanken and Polarrev/Persey highs, although were not as pronounced as they are today, were positive features in the Early Cretaceous (Gabrielsen et al., 1990). From the seismic data and as the prograding directions suggested, the most likely scenario is that Package A_north entered the basin between the present day Stappen and Gardarbanken highs (Fig. 59). The possibility that sediments prograded between the Gardarbanken and Sentralbanken highs (Fig. 59) and contributed to Package A_north's infill cannot be excluded, since a definite progradational direction could not be obtained from the seismic imagery. However, the proximity to the fluvial/deltaic system of the Helvetiafjellet Formation in Svalbard (Fig. 60) indicates that the major sediment progradation occurred between the Stappen and Gardarbanken highs. 3D mapping of the clinothem package in the area might further resolve this issue. Packages B, C and D_east entered the basin either between the present day Sentralbanken and Polarrev/Persey highs (Fig. 59) or around the Polarrev/Persey High (Fig. 59). While, seismic mapping was equivocal, the more pronounced south-western, rather purely western, trend of progradation of the packages, suggests that the first entry point was the main one. However, during the three clinothem packages' deposition, sediments could have been entering the basin from different positions. The interfingering lobes observed in Package D_east, south of the Nordkapp Basin (Fig. 39), could be an indication of that. Unless, both 2D and 3D seismic data, further east are integrated, no answer can be obtained.

The possibility that the aforementioned highs were insignificant topographic features, or that they were at proximal positions, relative to the shoreline, at the time of deposition was also taken into consideration. The shoreline position will be further discussed, but it is likely that it was affected by the location of the highs (Fig. 59). If the highs were above sea level, then they were not islands acting as barriers, but onshore highs, directing the fluvial/deltaic systems to the basin area and maybe even acting as local source areas. If the highs were less pronounced, then the prograding directions were more widespread and less focused through entry points (Fig. 61), than in the first scenario. Careful examination of seismic data, around the highs might provide further insight into this issue, but this problem was beyond the scope and time limitations of this thesis. The subsequent uplift and erosion may have removed any evidence that could provide a definite answer.

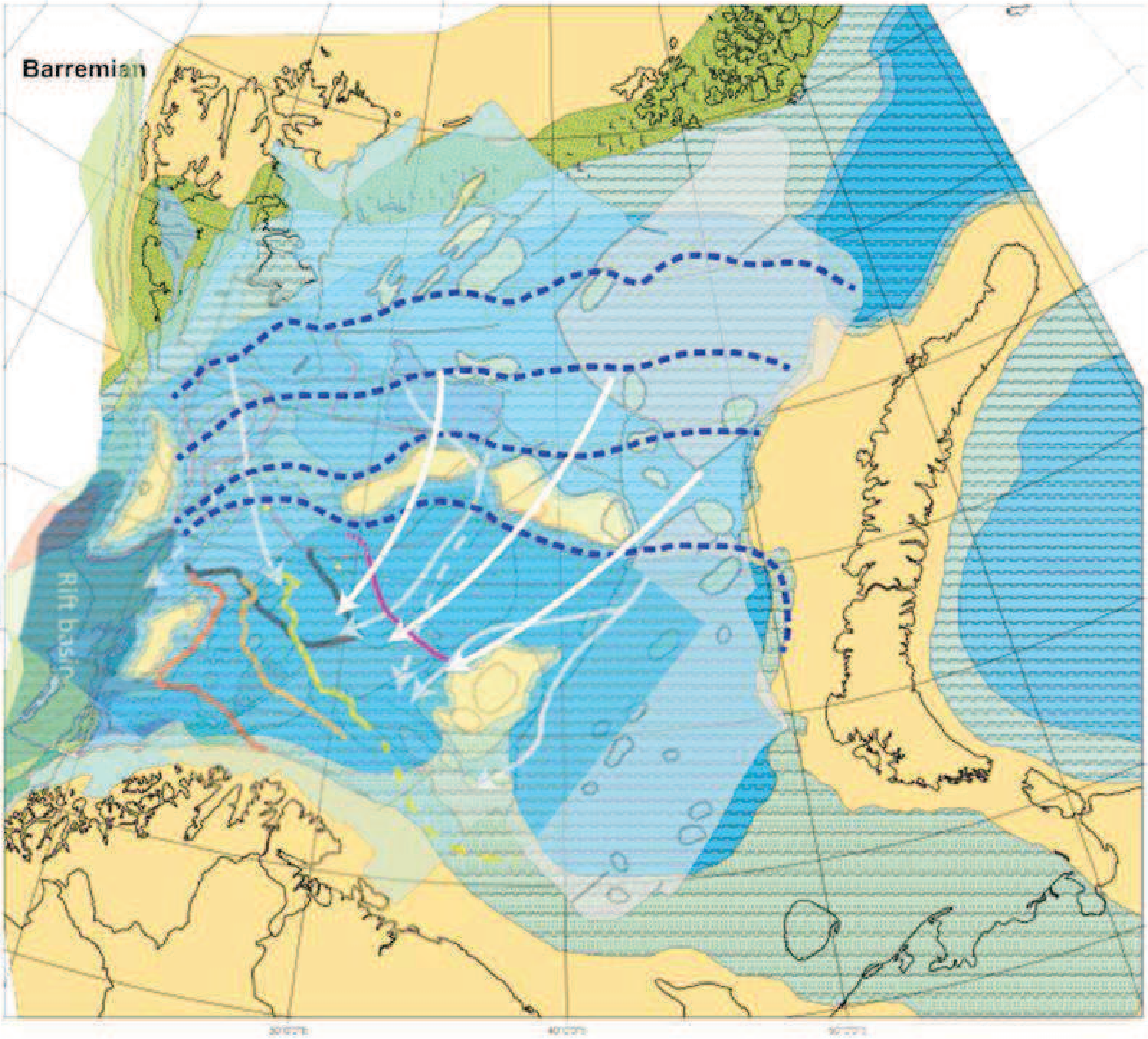

Figure 61 - Progradation without specific entry points, modified from (Smelror et al., 2009)

5.4 Shoreline-Platform Edge

The platform edge is an important feature that can provide valuable information about basin infill dynamics. It provides an insight into progradation directions; by positioning the platform, to sea level changes (Myers and Milton, 1996); through trajectory analysis, and to the possibility of deep water sands (Johannessen and Steel, 2005, Steel and Olsen, 2002, Helland-Hansen and Hampson, 2009). The platform edge is preserved in only one line within the available seismic data in this study (Fig. 27). The position of the platform edge for Package B_east, as revealed on this line, is shown in Fig. 58. For all the other clinothem packages, the platform edge has been eroded. The imaged offlap-breaks, show an aggradational architecture of the stacked clinoforms (Fig. 27). However, the information obtained from only one line cannot be decisive, and could only be an indication for further examination of the vicinity and eastwards of this line.

The shoreline position is also of great importance. The closer the shoreline is to the platform, the greater the potential for coarser grained sediments in the clinothem packages. Furthermore, the construction of the paleogeography, with the land, coast line, platform, platform edge and basin areas defined, is of great importance in reconstructing the geological history of the region. (Smelror et al. (2009), Worsley (2008), Steel and Worsley, 1984, Gjelberg and Steel, 1995) positioned the shoreline and maximum delta progradation south of, but in close proximity to Svalbard and Franz Josef Land (Fig. 5). At some time interval during the system's evolution, the shoreline and maximum transgression point must have been positioned there. From the new information that was acquired via the mapping of the Lower Cretaceous strata in south-western Barents Sea, and what has been documented in Midtkandal and Nystuen (2009), the shoreline could have migrated further into the basin (Fig. 58). Fluvial sediments, of such great thicknesses (20 m), as those mapped in southern Spitsbergen (Midtkandal and Nystuen, 2009), have the ability to build out and reposition the shoreline and push the point of maximum regression further southwards than Fig. 5 suggests.

Furthermore, the clinothem packages, mapped in this study, indicate a large system with the ability to transport significant amounts of sediment several tens to some hundreds of kilometres along a low gradient basin floor. The combination of such a large fluvial and marine clinoform system indicates that a proportionally large and far-reaching deltaic system was present, with the capacity to migrate the shoreline considerable distances into the basin. The most likely scenario is that the shoreline was migrating through time southwards and northwards (Fig. 58), influenced by sea level changes and/or tectonic movements, at a regional and local scale, with plausible positions shown in Fig. 58. Where exactly it was positioned relative to the platform-edge that created the clinothem packages has yet to be pinpointed, with certainty. With the available seismic data and due to the limitations of the BCU window on the Norwegian side of the Barents Sea, the chances of finding evidence of the shoreline position are greater on the Russian side of the Barents Sea.

5.5 Package A_north system distribution

Package A_north is the poorest imaged one (see Chapter 4.2.2.1). Its position close to the BCU window, in an area extensively affected by later fault movement, made it hard to map and almost unresolvable, without flattening on the near BCU reflector. As it has already been mentioned in Chapter 4.2.2.5, there are seismic reflectors preserved above Package A_north, and the different possibilities for the sediments source are presented. One remaining question is whether a system with the energy capable of transporting sediments to the Nordkapp Basin, 230 km from the resolvable first clinoform to the north and down to the possible lap-out point (Fig. 18), was exhausted or there were more sediments transported through it.

The most plausible scenario, if there were more sediments transported through the NW-SE trending system, is that the sediments deposited above Package A_north were redirected to the western deep rift basins, because C's and D_east's deposition made it impossible for them to prograde further in a south-easterly direction. This scenario's feasibility could be further examined in the Fingerdjupet Subbasin, because if sediments were to be redirected from the north-western part of the Bjarmeland Platform to the deep basins in the west, they must have passed the Fingerdjupet Subbasin (Fig. 1 & 2). Although Package A_north clinoforms are found in the Fingerdjupet Subbasin, there are no north-trending clinoforms found above them (Dahlberg, 2014). On the contrary, all the overlying successions that form the post-Package A_north infill of the basin show an aggradational architecture. Package A_north's sediments do not prograde into the Fingerdjupet Subbasin after the Barremian. However, it is possible that the redirection of the sediments' transport occurred before they reached the Fingerdjupet Subbasin (Fig. 2). An examination of the Lower Cretaceous strata west of the Leirdjupet Fault Complex could provide the answer.

If there are no more sediments prograding with the same direction as Package A_north, a remaining question is why that system was exhausted or lost its ability to transport sediments. No definite answer is possible with the data available in this study.

Another possibility is that the prograding system, after A_north's deposition was redirected before it reached the area between the Stappen and Gardarbanken highs, and was added to the system supplying sediments to Packages C and D_east (Fig. 59). The reason for this could be various barriers created in the area of the Sørkapp Basin. Anell et al. (2014a) found a different depocenter, west of the main Sørkapp Basin, filled in with Middle Jurassic – Lower Cretaceous sediments. That could have been the bypass area of Package A_north. Although, uplift and erosion has removed Cretaceous strata from the area, examination of seismic data in the Sørkapp Basin might provide the answer.

5.6 Lithologies prediction

Definite lithological evidence can only be obtained through wells and wireline logging or cores. The information acquired through seismic facies could only act as a lithology prediction tool. An amalgamation between the two can provide a lithology estimation.

All the available wells drilled in the area where the clinothem packages developed, penetrate Package D_east in its south-western most extent (Fig. 53, Chapter 4.2.3). Three out of four wells show clear shale readings (60-200 API, Table 3) (Rider, 1996), with the corresponding seismic character shown in Fig. 54; Low Amplitude/Low Continuity (Sangree and Widmier, 1979), but better defined reflectors than those seen in Package C_east. From this it can be deducted that the areas of Package D_east with the same seismic character, consist of fine grained sediments, possibly clay or mudstones, with shale readings in gamma-ray logs. The areas where this seismic character is observed are shown in Fig. 54. Also, since Package C_east shows the poorest amplitude/continuity relationship, with disturbances by a large number of syn-sedimentary faults (Fig. 31 & 32), it can be deducted that it consists of even finer grained sediments. However, since no wells penetrate this package, this can only be an estimation.

An interesting feature is observed in the eastern-most well, 7228/9-1 (Fig. 54, Table 3), which shows the lower gamma-ray readings, 40-70 API. Although, the readings are not in the clear sand interval (Rider, 1996), the penetrated sediments, of Package D_east, definitely contain less clay minerals than wells 7224/6-1, 7226/2-1, 7225/3-1 (Chapter 4.2.3). This is an indication of silty-sandier material present in the well. Furthermore, the seismic character of the reflectors change into high amplitude/high continuity (Sangree and Widmier, 1979) (Fig. 54). The clear difference between the two seismic characters is shown in Fig. 54. From that, it can be inferred that Package D_east contains more sandy/silty sediments further eastwards. However, the evidence of only one well cannot be decisive. More well data need to be incorporated for the hypothesis to be verified. No wells penetrate Packages

A_north and B_east. But, those two Packages are the ones with the best amplitude/continuity relationship, and through what has been mentioned before, a higher percentage of sandier material might be expected. Package B_east is located closer to the platform-edge (Fig. 58), where coarser grained material is expected to be deposited. Steeply dipping clinoforms, such as the ones observed in Package A_north (Fig. 34), are usually observed in coarser grained successions. Considering no wells are drilled through Packages A_north, B_east and C_east, any lithology estimation is a prediction in theory, until more evidence is obtained.

5.7 Thickness - Erosion - Water depth/Accommodation

The thickness obtained through the average velocity measured in the Cretaceous strata in the Barents Sea, has been presented in the Results chapter. This thickness corresponds to the preserved, after uplift and erosion strata. Package A_north has an average preserved thickness of 160 m, Package B_east 400 m, Package C_east 500 m and Package D_east 900 m. From the above, a number of questions arise, concerning matters of initial thicknesses, erosion levels and water depths/accommodation available.

If the aforementioned thicknesses are the preserved values, a number of assumptions could be made for the initial volume deposited. How much was deposited in relation to how much has been preserved? Equal, half, double, a few meters more? The possibilities are endless and they may, as well, vary throughout the area. For example, Package D_east shows a maximum preserved thickness of 1.300 m, it could be estimated that the original deposited volume was not far from this. And since 1.300 m is the maximum thickness observed, could it be deducted that the other packages were of the same maximum thickness? The suggestion that more than 3000 m of sediments were deposited is a far-reached possibility. The most realistic scenario is that since the clinothem packages were originally stacked on top of each other, a summation of their preserved thicknesses, which gives a thickness of 1500 m, is closer to the initial one. Again, that could have varied along the area, with sediments, of Package D_east for example, bypassing the platform and deposited in more subsided areas, such as the Nordkapp Basin or around the Loppa High, where the maximum thicknesses are observed. The only observed thickness, which could be proposed as an initial thickness, is that of Package A_β_north, 100 m (Fig. 23). Nevertheless, a proposed combined thickness of the four clinothem packages, in the Bjarmeland Platform area, exceeding 1000 – 1.500 m, accounts for a vast amount of sediments transported through the system.

If the 1.500 m initially deposited sediments assumption, is correct, together with the measured preserved thickness, it means that at least 1000-1.500 m of sediments were eroded during the Upper Cretaceous-Cenozoic. This is a significant level of erosion. The most probable positions for these erosional products to be deposited are in the Hammerfest Basin, the deep southwest rift basins and the basins in the eastern Barents Sea (Fig. 1 & 2). Further examination in these areas might provide the answer of whether the erosion was that pronounced and if the 1.500 m estimated thickness is correct.

Furthermore, if the presumed thickness is accepted, an accommodation space that could hold that amount of sediments must have been available. A combination of water and basin depths exceeding 2000 m must have been present.

It has to be pointed out that a basin's water depth cannot be directly calculated from accumulated thickness. Accommodation space is created by synsedimentary subsidence, from tectonics and compaction, in addition to initial water depth (Myers and Milton, 1996). For initial water depth to be calculated from progradational successions having clinoform geometry, the height of sigmoidal clinoforms can be used (Glørstad-Clark et al., 2010, Helland-Hansen and Hampson, 2009, Anell et al., 2014b). In this study, since no full clinoform profile is preserved, an estimation of water depth cannot be performed.

5.8 Creation of accommodation

An accommodation of 2 km must have been available for the described clinothem packages to be deposited. Accommodation is created either by sea level rise or subsidence of the area or a combination of both (Myers and Milton, 1996).

From the information obtained by the shallow boreholes, the depositional environment, during the Early Cretaceous, changed, rather abruptly, from shallow water carbonates to deeper water dark claystones, (Århus, 1991, Smelror et al., 1998). This suggests a rather rapid basin deepening accompanied by the drowning of the carbonate platform and the predominance of siliciclastic sedimentation. However, no large-scale fault movements that could produce such an abrupt subsidence are documented in the region. Furthermore, a rise in sea level, alone, could not have produced such an effect.

During the same time period in Svalbard, the depositional environment changed, rather rapidly, from the open marine shelf mudstones and thin sandstone units of the Rurikfjellet Formation to the fluvial and marginal marine sandstone units of the Helvetiafjellet Formation e.g. (Mørk et al., 1999).

Thus, while on the eastern parts of the western Barents Sea, the depositional environment was changing from shallow water to deeper water, on Svalbard it was changing from deeper water to fluvial/paralic. The abrupt change in Svalbard has been regarded to be a result of the formation of the proto-Amerasian basin in connection with the HALIP formed in the Early Cretaceous (Grogan et al., 2000, Maher, 2001, Midtkandal and Nystuen, 2009). It is suggested that the HALIP, which caused the pronounced and abrupt uplift on Svalbard, induced the rapid subsidence that created the accommodation needed for the clinothem packages to develop. So, while Svalbard and the whole Arctic region were uplifted, the south-western Barents Sea was subsiding with a rise in relative sea level. That is a hypothesis formed based on the fact that for the equilibrium profile to be achieved, where an area is so profoundly uplifted the areas around it have to subside. The HALIP was created due to mantle movements (Maher, 2001), which could also be the deeper source of the study area's subsidence, since no large scale fault movements have been documented. It has to be emphasized that the above are only a hypothesis formed based on several indications. Firstly, there are no fault movements recorded in the area that could accommodate the abrupt creation of accommodation, indicated by the abrupt change in depositional environments (see Chapter 4.2.5). And secondly, the timing of the HALIP matches the timing of the subsidence recorded in the area, and since the mantle processes are linked with the HALIP (Maher, 2001), the subsidence could as well.

5.9 Time

The time factor was initially approached in a relative way in this study. The prograding units studied were deposited during the Early Cretaceous, since they downlap onto the regional known BCU above the Hekkingen Formation, after the deposition of the Helvetiafjellet Formation in Svalbard. It is suggested that they comprise the same large scale system with the same source, with their relative age relationship being, older to younger, Package A_north, B_east, C_east and D_east.

Information obtained through shallow boreholes (Chapter 4.2.4) and the Fingerdjupet Subbasin (Dahlberg, 2014) provided further insight to the timing of deposition. The prograding units do not downlap onto BCU above the Hekkingen Formation, but on a condensed carbonate section of Valanginian – Early Barremian age (Århus, 1991) in the greater Bjarmeland Platform area. Through biostratigraphy data, the shift is estimated, to have taken place in the Early Barremian, from shallow borehole 7430/10-U-1, which penetrates Package B_east. This reveals that the clay deposition started there relatively earlier than in borehole 7425/9-U-1, which penetrates Package A_north (Århus, 1991) (Fig. 52). The same has been documented in the Fingerdjupet Subbasin (chapter X, (Dahlberg, 2014)).

The evidence of the complexity of the timing of deposition between Package A_north and B_east is described in Chapter X. With the new information from the shallow boreholes it appears that the initial progradation of Package B_east predates slightly that of Package A_north, at least in the area of the borehole. Package B_east entered the basin some short geological time before A_north, but probably due to A_north's proximity to the source and potentially higher energy regime, the end result was that B_east onlaps onto A_north. An almost synchronous and complex progradation, with initial interfingering deposition, below seismic resolution, of the two packages is the most plausible scenario.

Packages C and D_east are definitely younger than A_north and B_east, with a probable middle/upper Barremian to Aptian age. The younger age limit of progradation in the study area is not able to be defined with the available data. The evidence of whether it continued during the Albian or even Upper Cretaceous or stopped in the Aptian, is lost due to the uplift and erosion of the area.

6 Conclusion

Seismic sequence analysis of the Lower Cretaceous successions of the eastern part of the south-western Barents Sea region revealed a progressive infill of the basin through four distinct prograding units, all characterized by internal clinoform reflections; Package A_north, B_east, C_east and D_east. The two major progradational directions are NW to SE (Package A_north) and NE to SW (Packages B, C and D_east). All the packages are bounded on the bottom by a Maximum Flooding Surface (MFS_1) and by erosional truncation on the top. Package A_north and B_east were the first deposited in the basin, with their relative time of deposition being rather complicated; almost synchronous in the beginning, with A_north prevailing with time. Packages C_east and D_east are respectively younger.

The main source area was located north of the Barents Shelf limits, associated with the High Arctic Large Igneous Province (HALIP) uplift which initiated the fluviodeltaic and paralic system of the Helvetiafjellet Formation on Svalbard and its likely eastern equivalent chronostratigraphic units on Franz Josef Land. Potential entry points and progradation routes are between the Stappen and Gardarbanken highs for Package A_north, and between the Sentralbanken and Polarrev/Persey highs for Packages B, C and D_east. Specific shoreline/platform edge positions have been impossible to pinpoint, due to erosion, in part, but also lack of time to integrate data from the basin further east.

The time of initiation of deposition of the clinothem packages in the area is set to early-middle Barremian, based on biostratigraphic data from shallow boreholes. A 5 m condensed section of marls and carbonates, Valanginian to Early Barremian in age, comprises the downlap surface of the prograding units. An abrupt change of depositional environments, from shallow water to deeper water, is revealed through the shift in sedimentation. The time limit for the termination of the progradation has not been resolved.

No indications of significant sand or coarser grained material were found from the well and seismic facies investigations. Fine grained sedimentation is considered to have prevailed in the area at the time of deposition.

Conclusion

Estimated thicknesses of the originally deposited sediments approach 2000 m. Erosion has led to preserved thicknesses of 400 to 1000 m. A proportionally deep accommodation space must have been available. A combination of subsidence and sea level rise provided the space needed for the clinothem packages to be deposited. The mechanism proposed here for the abrupt change in depositional environments and creation of accommodation is associated with mantle processes, connected with the HALIP development.

7 Outlook

After the seismic interpretation was finished, and all the available information was utilized and an attempt was made to determine how various factors, affecting the depositional history of the region, acted during Early Cretaceous times, it became obvious that more questions than answers arose. Below are some proposals for further studies in an attempt to answer those questions. The following were not executed due to either the time constraints on the thesis to be completed or unavailability of data.

- Examination of 3D/High Resolution seismic data, when they become available, in the same local study area as this thesis and further east, north and west, within the Norwegian sector, so the exact progradation directions and space relationship of the clinothem packages can be determined.
- Examination of seismic data (2D/3D/High Resolution) a) further north of the study area, where potential Cretaceous strata are preserved, and b) at the areas around the Stappen, Gardarbanken, Sentralbanken and Polarrev Persey highs, to determine the packages' entry points and find indications of the shoreline and platform-edge movements.
- Integration of data (seismic/well) on Early Cretaceous successions from the eastern part of the Barents Sea, within the Russian sector, that could provide further insight on the depositional environment, architecture and history of the region.
- Examination of seismic data (2D/3D/High Resolution) on the western part of the south-western Barents Sea, within the deep rift basins. Information on Package's A_north's further progradation and on the presence of the expected erosional products could be obtained.
- An attempt to more closely link the clinoform system observed in this study with the Helvetiafjellet Formation on Svalbard and its eastward continuation until Franz Josef Land has to be made. This could be done through study of mineralogical and biostratigraphic data.
- Integration of the well data, which are currently not published, or data from wells that will be drilled in the future, to further constrain the estimated lithologies of the clinothem packages. A possible well position is already being suggested in the discussion part.

Outlook

- Further investigation of the available cores from the shallow boreholes, to determine the depositional environment of the clinothem packages.
- A large geophysical/geological survey to determine the possible connections of the prograding system with the HALIP; to provide further evidence on the hypothesis of creation of accommodation in the Barents Sea, simultaneously with doming above the rising HALIP as a sediment source in the Arctic. A survey extending to the whole Arctic region could provide further information on the extent and position of the HALIP, together with the creation of an accurate depositional model for the Arctic region during the Early Cretaceous.

References

ANELL, I., BRAATHEN, A. & OLAUSSEN, S. 2014a. Regional constraints of the Sørkapp Basin: A Carboniferous relic or a Cretaceous depression? *Marine and Petroleum Geology,* 54**,** 123-138.

ANELL, I., MIDTKANDAL, I. & BRAATHEN, A. 2014b. Trajectory analysis and inferences on geometric relationships of an Early Triassic prograding clinoform succession on the northern Barents Shelf. *Marine and Petroleum Geology,* 54**,** 167-179.

ÅRHUS, N. 1991. The transition from deposition of condensed carbonates to dark claystones in the Lower Cretaceous succession of the southwestern Barents Sea. *Norsk Geologisk Tidsskrift,* 71**,** 259-263.

ÅRHUS, N., KELLY, S. R. A., COLLINS, J. S. H. & SANDY, M. R. 1990. Systematic palaeontology and biostratigraphy of two early Cretaceous condensed sections from the Barents Sea. *Polar Research,* 8**,** 165-194.

BERGLUND, L., AUGUSTSON, J., FAERSETH, R., GJELBERG, J. & RAMBERG-MOE, H. 1986. The evolution of the Hammerfest Basin. *Habitat of hydrocarbons on the Norwegian continental shelf***,** 319-338.

BERTRAM, G. & MILTON, N. 1996. Seismic stratigraphy. *In:* EMERY, D. & MYERS, K. J. (eds.) *Sequence Stratigraphy.* UK: Blackwell Pyblishing Ltd.

BUGGE, T., ELVEBAKK, G., FANAVOLL, G., MANGERUD, G., SMELROR, M., WEISS, H. M., GJELBERG, J., KRISTENSEN, S. E. & NILSEN, K. 2001. Shallow stratigraphic drilling applied in hydrocarbon exploration of the Nordkapp Basin, Barents Sea. *Marine and Petroleum Geology***,** 13-37.

COE, A. L. 2003. *The sedimentary record of sea-level change*, Cambridge University Press.

CORFU, F., POLTEAU, S., PLANKE, S., FALEIDE, J. I., SVENSEN, H., ZAYONCHECK, A. & STOLBOV, N. 2013. U–Pb geochronology of Cretaceous magmatism on Svalbard and Franz Josef Land, Barents Sea Large Igneous Province. *Geological Magazine,* 150**,** 1127-1135.

DAHLBERG, M. E. 2014. *Structrural and stratigraphical evolution of the Fingerdjupet Subbasin, SW Barents Sea.* Master University of Oslo.

DALLAND, A., WORSLEY, D. & OFSTAD, K. 1988. *A Lithostratigraphic Scheme for the Mesozoic and Cenozoic and Succession Offshore Mid-and Northern Norway*, Oljedirektoratet.

DALLMANN, W. K. (ed.) 1999. *Lithostratigraphic Lexicon of Svalbard,* Tromsø: Norsk Polarinstitutt.

DIMAKIS, P., BRAATHEN, B. I., FALEIDE, J. I., ELVERHØI, A. & GUDLAUGSSON, S. T. 1998. Cenozoic erosion and the preglacial uplift of the Svalbard–Barents Sea region. *Tectonophysics,* 300**,** 311-327.

References

DIRECTORATE, N. P. 2014. *FactMaps* [Online]. Norway. Available: http://www.npd.no/en/Maps/Fact-maps/ 2014].

DORÉ, A. 1995. Barents Sea geology, petroleum resources and commercial potential. *Arctic,* 48**,** 207-221.

DORÉ, A. & JENSEN, L. 1996. The impact of late Cenozoic uplift and erosion on hydrocarbon exploration: offshore Norway and some other uplifted basins. *Global and Planetary Change,* 12**,** 415-436.

DORÉ, A. G. 1991. The structural foundation and evolution of Mesozoic seaways between Europe and the Arctic. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 87**,** 441-492.

DYPVIK, H., GUDLAUGSSON, S. T., TSIKALAS, F., ATTREP, M., FERRELL, R. E., KRINSLEY, D. H., MØRK, A., FALEIDE, J. I. & NAGY, J. 1996. Mjølnir structure: An impact crater in the Barents Sea. *Geology,* 24**,** 779-782.

FALEIDE, J. I. 2014. *RE: Velocity of Cretaceous sediments in the Barents Sea.*

FALEIDE, J. I., GUDLAUGSSON, S. T. & JACQUART, G. 1984. Evolution of the western Barents Sea. *Marine and Petroleum Geology,* 1**,** 123-150.

FALEIDE, J. I., SOLHEIM, A., FIEDLER, A., HJELSTUEN, B. O., ANDERSEN, E. S. & VANNESTE, K. 1996. Late Cenozoic evolution of the western Barents Sea-Svalbard continental margin. *Global and Planetary Change,* 12**,** 53-74.

FALEIDE, J. I., TSIKALAS, F., BREIVIK, A. J., MJELDE, R., RITZMANN, O., ENGEN, O., WILSON, J. & ELDHOLM, O. 2008. Structure and evolution of the continental margin off Norway and the Barents Sea. *Episodes,* 31**,** 82.

FALEIDE, J. I., VÅGNES, E. & GUDLAUGSSON, S. T. 1993. Late Mesozoic-Cenozoic evolution of the south-western Barents Sea in a regional rift-shear tectonic setting. *Marine and Petroleum Geology,* 10**,** 186-214.

GABRIELSEN, R. 1984. Long-lived fault zones and their influence on the tectonic development of the southwestern Barents Sea. *Journal of the Geological Society,* 141**,** 651-662.

GABRIELSEN, R. H., FAERSETH, R. B. & JENSEN, L. N. 1990. *Structural Elements of the Norwegian Continental Shelf. Pt. 1. The Barents Sea Region*, Norwegian Petroleum Directorate.

GJELBERG, J. & STEEL, R. J. 1995. Helvetiafjellet Formation (Barremian-Aptian), Spitsbergen: characteristics of a transgressive succession. *Norwegian Petroleum Society Special Publications,* 5**,** 571-593.

GLØRSTAD-CLARK, E. 2011. *Basin Analysis in the western Barents Sea area: The interplay between accomodation space and depositional systems.* Philosphiae Doctor Series of dissertations, University of Oslo.

References

GLØRSTAD-CLARK, E., BIRKELAND, E., NYSTUEN, J., FALEIDE, J. & MIDTKANDAL, I. 2011. Triassic platform-margin deltas in the western Barents Sea. *Marine and Petroleum Geology,* 28**,** 1294-1314.

GLØRSTAD-CLARK, E., FALEIDE, J. I., LUNDSCHIEN, B. A. & NYSTUEN, J. P. 2010. Triassic seismic sequence stratigraphy and paleogeography of the western Barents Sea area. *Marine and Petroleum Geology,* 27**,** 1448-1475.

GROGAN, P., NYBERG, K., FOTLAND, B., MYKLEBUST, R., DAHLGREN, S. & RIIS, F. 2000. Cretaceous magmatism south and east of Svalbard: evidence from seismic reflection and magnetic data. *Polarforschung,* 68**,** 25-34.

GROGAN, P., ØSTVEDT-GHAZI, A.-M., LARSSEN, G., FOTLAND, B., NYBERG, K., DAHLGREN, S. & EIDVIN, T. Structural elements and petroleum geology of the Norwegian sector of the northern Barents Sea. Geological Society, London, Petroleum Geology Conference series, 1999. Geological Society of London, 247-259.

GUDLAUGSSON, S., FALEIDE, J., JOHANSEN, S. & BREIVIK, A. 1998. Late Palaeozoic structural development of the south-western Barents Sea. *Marine and Petroleum Geology,* 15**,** 73-102.

HARRISON, J. C., ST-ONGE, M. R., PETROV, O. V., STRELNIKOV, S. I., LOPATIN, B. G., WISLON, F. H., TELLA, S., LYNDS, T., SHOKALSKY, S. P., HULTS, C. K., BERGMAN, S., JEPSEN, H. F. & SOLLI, A. 2011. *Geological Map of the Arctic*, 1:5 000 000. Canada: Geological Survey of Canada.

HELLAND-HANSEN, W. & HAMPSON, G. 2009. Trajectory analysis: concepts and applications. *Basin Research,* 21**,** 454-483.

JAKOBSSON, M., MACNAB, R., MAYER, L., ANDERSON, R., EDWARDS, M., HATZKY, J., SCHENKE, H. W. & JOHNSON, P. 2008. An improved bathymetric portrayal of the Arctic Ocean: Implications for ocean modeling and geological, geophysical and oceanographic analyses. *Geophysical Research Letters,* 35.

JOHANNESSEN, E. P. & STEEL, R. J. 2005. Shelf-margin clinoforms and prediction of deepwater sands. *Basin Research,* 17**,** 521-550.

MAHER, H. D. J. 2001. Manifestations of the Cretaceous High Arctic large igneous province in Svalbard. *The Journal of Geology,* 109**,** 91-104.

MIDTKANDAL, I., FALEIDE, J. I., PLANKE, S., DAHLBERG, M. E., DIMITRIOU, M. & NYSTUEN, J. P. 2014. The Lower Cretaceous strata in Svalbard and the Barents Sea; basin infill dynamics and palaeobathymetry. *EGU 2014.* Vienna.

MIDTKANDAL, I. & NYSTUEN, J. 2009. Depositional architecture of a low-gradient ramp shelf in an epicontinental sea: the lower Cretaceous of Svalbard. *Basin Research,* 21**,** 655-675.

References

MIDTKANDAL, I., NYSTUEN, J. P. & NAGY, J. 2007. Paralic sedimentation on an epicontinental ramp shelf during a full cycle of relative sea-level fluctuation; the Helvetiafjellet formation in Nordenskiold land, Spitsbergen. *NORSK GEOLOGISK TIDSSKRIFT,* 87**,** 343.

MITCHUM JR, R., VAIL, P. & SANGREE, J. 1977. Seismic stratigraphy and global changes of sea level: Part 6. Stratigraphic interpretation of seismic reflection patterns in depositional sequences: Section 2. Application of seismic reflection configuration to stratigraphic interpretation.

MØRK, A., DALLMANN, W., DYPVIK, H., JOHANNESSEN, E., LARSSEN, G., NAGY, J., NØTTVEDT, A., OLAUSSEN, S., PCHELINA, T. & WORSLEY, D. 1999. Mesozoic lithostratigraphy. *In:* DALLMANN, W. K. (ed.) *Lithostratigraphic lexicon of Svalbard. Upper Palaeozoic to Quaternary bedrock. Review and recommendations for nomenclature use.* Tromso: Norsk Polarinstitutt.

MØRK, A. & WORSLEY, D. 2006. Triassic of Svalbard and the Barents shelf. *Boreal Triassic***,** 23-29.

MYERS, K. J. & MILTON, N. J. 1996. Concepts and Principles of Sequence Stratigraphy. *In:* EMERY, D. & MYERS, K. J. (eds.) *Sequence Stratigraphy.* UK: Blackwell Science Ltd.

NEJBERT, K., KRAJEWSKI, K. P. & PÉCSKAY, Z. 2011. Dolerites of Svalbard, north-west Barents Sea Shelf: age, tectonic setting and significance for geotectonic interpretation of the High-Arctic Large Igneous Province. *Polar Research,* 30.

NILSEN, K. T., VENDEVILLE, B. C. & JOHANSEN, J.-T. 1995. Influence of regional tectonics on halokinesis in the Nordkapp Basin, Barents Sea.

NØTTVEDT, A., CECCHI, M., GJELBERG, J. G., KRISTENSEN, S. E., LØNØY, A., RASMUSSEN, A., RASMUSSEN, E., SKOTT, P. H. & VAN VEEN, P. M. 1993. Svalbards - Barents Sea correlation: a short review. *In:* VORREN, T. O., BERGSAGE, R. E., HOLTER, E., JOHANSEN, B., LIE, E., LUND, T. B. & (eds.) *Arctic Geology and Petroleum Potential.* Amsterdam: Elsevier.

NYSTUEN, J. P. 1998. History and development of sequence stratigraphy. *In:* GRADSTEIN, F. M., SANDVIK, K. O. & MILTON, N. (eds.) *Sequence Stratigraphy—Concepts and Application. Norwegian Petroleum Society Special Publication.* Netherlands Elsevier Science B. V. .

PIEPJOHN, K., STANGE, R., JOCHMANN, M. & HUBNER, C. 2012. *The Geology of Longyearbyen,* Longyearbyen, Longyearbyen feltbiologiske forening (LoFF).

RIDER, M. H. 1996. The gamma ray and spectral gamma ray logs. *The geological interpretation of well logs.* Second ed. Scotland: Rider-French Consulting Ltd. .

RIIS, F., LUNDSCHIEN, B. A., HØY, T., MØRK, A. & MØRK, M. B. E. 2008. Evolution of the Triassic shelf in the northern Barents Sea region. *Polar Research,* 27**,** 318-338.

References

SAMUELSBERG, T. 100 Exploration Wells and thousands of miles of seismic lines in the Barents Sea; the key is finally found? *In:* CARSTENS, H., ed. Hydrocarbon Habitats, Play Models in the Barents Sea, 02.04.2014 2014 Oslo. NGF/GeoPublishing AS.

SANGREE, J. & WIDMIER, J. 1978. Seismic stratigraphy and global changes of sea level, part 9: seismic interpretation of clastic depositional facies. *AAPG Bulletin,* 62**,** 752-771.

SANGREE, J. & WIDMIER, J. 1979. Interpretation of depositional facies from seismic data. *Geophysics,* 44**,** 131-160.

SIGMOND, E. M. O. 2002. *Geological map, Land and Sea Areas of Northern Europe*, 1:4 000 000. Norway: Geological Survey of Norway.

SIGMOND, E. M. O. & ROBERTS, D. (eds.) 2007. *Geology of the Land and Sea areas of Northern Europe.,* Norway: Norges geologiske undersøkelse.

SMELROR, M. 1994. Jurassic stratigraphy of the western Barents Sea region: A review. *Geobios,* 27**,** 441-451.

SMELROR, M., MØRK, A., MONTEIL, E., RUTLEDGE, D. & LEEREVELD, H. 1998. The Klippfisk Formation—a new lithostratigraphic unit of Lower Cretaceous platform carbonates on the Western Barents Shelf. *Polar Research,* 17**,** 181-202.

SMELROR, M., PETROV, O. V., BIRGER LARSSEN, G. & WERNER, S. (eds.) 2009. *Atlas: Geological History of the Barents Sea,* Trondheim: Norges geologiske undersøkelse.

STEEL, R. & OLSEN, T. 2002. Clinoforms, clinoform trajectories and deepwater sands. *Sequence stratigraphic models for exploration and production: Evolving methodology, emerging models and application histories***,** 367-381.

STEEL, R. J. & WORSLEY, D. 1984. Svalbard's post-Caledonian strata—an atlas of sedimentational patterns and palaeogeographic evolution. *Petroleum geology of the North European margin.* Springer.

STEMMERIK, L. & WORSLEY, D. 2005. 30 years on: Arctic Upper Palaeozoic stratigraphy, depositional evolution and hydrocarbon prospectivity. *Norsk Geologisk Tidsskrift,* 85.

VÅGNES, E., FALEIDE, J. I. & GUDLAUGSSON, S. T. 1992. Glacial erosion and tectonic uplift in the Barents Sea. *Norsk geologisk tidsskrift. Supplement,* 72**,** 333-338.

VAIL, P. R., TODD, R. & SANGREE, J. 1977. Chronostratigraphic significance of seismic reflections. *Seismic stratigraphy—Applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir,* 26**,** 99-116.

References

WORSLEY, D. 2008. The post-Caledonian development of Svalbard and the western Barents Sea. *Polar Research,* 27**,** 298-317.