Mesozoic and Cenozoic basin development and sediment infill in the North Sea region – shifting depocenters associated with regional structural development

Erlend Morisbak Jarsve

Faculty of Mathematics and Natural Science

Department of Geosciences

University of Oslo

Norway

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Preface

This thesis entitled “Mesozoic and Cenozoic basin development and sediment infill in the North Sea region - shifting depocenters associated with regional structural development” has been submitted to the Department of Geosciences at the University of Oslo in agreement with the requirements for the degree of Philosophiae Doctor (Ph.D). The study was initiated September 2009 and the study area was focused on both the North Sea region and onshore southern Norway. The study area is an excellent laboratory for studying the relation between regional structural development and sediment infill, because the region is influenced by multiple tectonic events, such as Paleozoic compression, Late Paleozoic-Mesozoic rifting and Cenozoic uplift. In addition, the North Sea region is a successful and mature hydrocarbon province with long-term (>50 years) hydrocarbon exploration, which has generated extensive data coverage including both seismic data and well data across the region.

The research in this thesis is mainly based on interpretation of long offset reflection seismic data integrated with well data, such as petrophysical log, biostratigraphy and core log information, and remote-sensing techniques and field-work. Field studies in southern Norway were carried out during three field seasons, with a focus on mapping and describing the sub-Cambrian peneplain.

The study was carried out under supervision of Professor Roy Helge Gabrielsen, Professor Jan Inge Faleide, Professor Johan Petter Nystuen and Professor Bernd Etzelmüller.

The thesis includes an introduction, which summarizes the main findings and observations and interpretations which may form the basis of future work. The thesis furthermore includes five thematic papers, of which three are published in international journals. The main results from these papers have also been presented to the scientific community of several conferences, both nationally and internationally.

Acknowledgment

First and foremost I want to thank my main supervisor Roy H. Gabrielsen for his laudable supervision, and for his help and correction of my papers, for the good times in the field, and for always having the door open for questions and chatting. The research, and the papers presenting it, benefitted significantly from his vast experience and many thoughtful advices.

I extend my sincere gratitude to my co-supervisors Prof. Jan Inge Faleide, Prof. Johan Petter Nystuen and Prof. Bernd Etzelmüller. I thank Jan Inge and Johan Petter for their support and scientific guidance troughout this study. Their in-depth knowledge of the study area was key to the success of this thesis. I also thank Prof. Bernd Etzelmüller for his contributions in the study of the sub-Cambrian peneplain.

I will sincerely thank Idar Horstad and Stein Aasheim, together with all my colleagues at Fugro Multi Client Services (or CGG as it is now) who encouraged me and supported me throughout this study. I thank you all.

I am indepted to Brit Thyberg, who first welcomed me to the department of Geoscience, and later became my colleague and friend. I thank you for the good times and many interesting discussions.

I want to thank all of my colleagues at the department of Geoscience. In particular, I want to thank Dr. Caroline Sassier, Dr. Mattias Lundmark and Dr. Tom Erik Maast for our many insightful discussions and simple chatting.

Finally, I want to thank my fantastic family, who have supported me throughout these years, and in particular my dear wife Marianne and our two children. I would never manage to do this without you and your encouragement.

List of papers

Paper 1: Jarsve, E.M., Maast, T.E., Gabrielsen, R.H., Faleide, J.I., Nystuen, J.P. & Sassier, C. (2014). Seismic stratigraphic subdivision of the Triassic succession in the Central North Sea; integrating seismic reflection and well data. *Journal of the Geological Society, London*, 171, 353-374.

Paper 2: Jarsve, E.M., Faleide, J.I., Gabrielsen, R.H. & Nystuen, J.P. (In press). Mesozoic and Cenozoic basin configurations in the North Sea. *IAS Special Publications*, 46.

Paper 3: Jarsve, E.M., Eidvin, T., Nystuen, J.P., Faleide, J.I., Gabrielsen, R.H. & Thyberg, B.I. (In revision (minor)). The Oligocene succession in the eastern North Sea – basin development and depositional systems. *Geological Magazine,*

Paper 4: Jarsve E.M., Krøgli, S.O., Etzelmüller, B. & Gabrielsen, R.H. (2014). Automatic identification of topographic surfaces related to the sub-Cambrian peneplain (SCP) in southern Norway – Surface generation algorithms and implications. *Geomorphology*. 211, 89-99.

Paper 5: Gabrielsen, R.H., Nystuen, J.P., Jarsve, E.M. & Lundmark, A.M. (submitted). The SubCambrian Peneplain in southern Norway: Its geological significance and its implication for the Caledonian deformation and the post-Caledonian faulting, exhumation and denudation.

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1. Introduction

Motivation and scope of study

Major interest in North Sea geology and geological evolution followed the first successful exploration wells in the 1960s (Balder Field and Ekofisk Field), which proved the hydrocarbon potential in the region. During the 1970s, 1980s and 1990s, fundamental findings were published with emphasis on the Mesozoic basin evolution (e.g. Ziegler, 1975, 1990; Gabrielsen et al., 1990; Nøttvedt et al,. 1995, 2000; Roberts et al., 1990; Evans et al., 2003). Increased focus on the Cenozoic basin evolution initiated in the 1990s (Michelsen, 1994; Michelsen et al., 1995; Jordt et al., 1995, 2000; Faleide et al., 2002), and are still debated (Huuse, 2002; Nielsen et al., 2009, 2010; Anell et al., 2010, 2011, 2012; Gabrielsen et al., 2010a & b; Goledowski et al., 2012, 2014; Rasmussen & Dybkjær, 2014). Increased interest the recent years have been on the onshore-offshore relationship to study the relation between tectonic processes along passive continental margins in time and space (e.g. Riis, 1996; Dawes, 1997; Gabrielsen et al., 2005 2010a; Stoker et al., 2005; Japsen et al., 2006; Nielsen et al., 2009; Miller et al., 2013; Medvedev et al., 2013; Redfield & Osmundsen, 2013).

Recent studies demonstrate the complexity of areas subject to repeated vertical movements and that structures related to lithospheric processes, such as rifting and collision, are long-lived (Odinsen et al., 2000; Van Wees & Beekman, 2000; Ziegler et al., 2002; Gabrielsen et al., 2010; Japsen et al., 2006; Redfield & Osmundsen, 2013). When analyzing pattern of vertical displacements, several geodynamic processes, such as uplift-subsidence and erosion-deposition patterns, must be evaluated. Tectonic vertical movements can be analyzed from studying the creation and infill of sedimentary basins in a source-to-sink context (Gabrielsen et al., 2005; Cloetingh & Burov, 2011; Sømme & Jackson, 2013; Sømme et al., 2013).

The general scope of this thesis is to study the evolution and infill of sedimentary basins in the North Sea and its relation to southern Norway as sediment source area. The emphasis has been on understanding the migration and shifting positions of depocenters in time and space, related to repeated vertical movements. By studying reflection seismic data at different scales it is possible to interpret regional variations in seismic stacking patterns, sedimentation and facies distributions. Such variations, combined with migration of depocenters, reveal the basin configuration at different times. This thesis provides three studies (papers I, II and III) of seismic successions in the central and northern North Sea, with emphasize on discussing basin development, sediment transportation and distribution, as well as potential source areas. The intention was also to establish an erosional model for southern Norway, but the understanding of the paleic surface is controversial (e.g. Steer et al., 2012). It is therefore important to constrain the tectonic influence on southern Norway, focusing on the sub-Cambrian peneplain as a reference surface. Time was not sufficient to extend this into a total erosional model for southern Norway. The thesis therefore includes two studies from onshore southern Norway, with focus on mapping and describing the sub-Cambrian peneplain, where particular emphasize was on discussing tectonic influence on that surface.

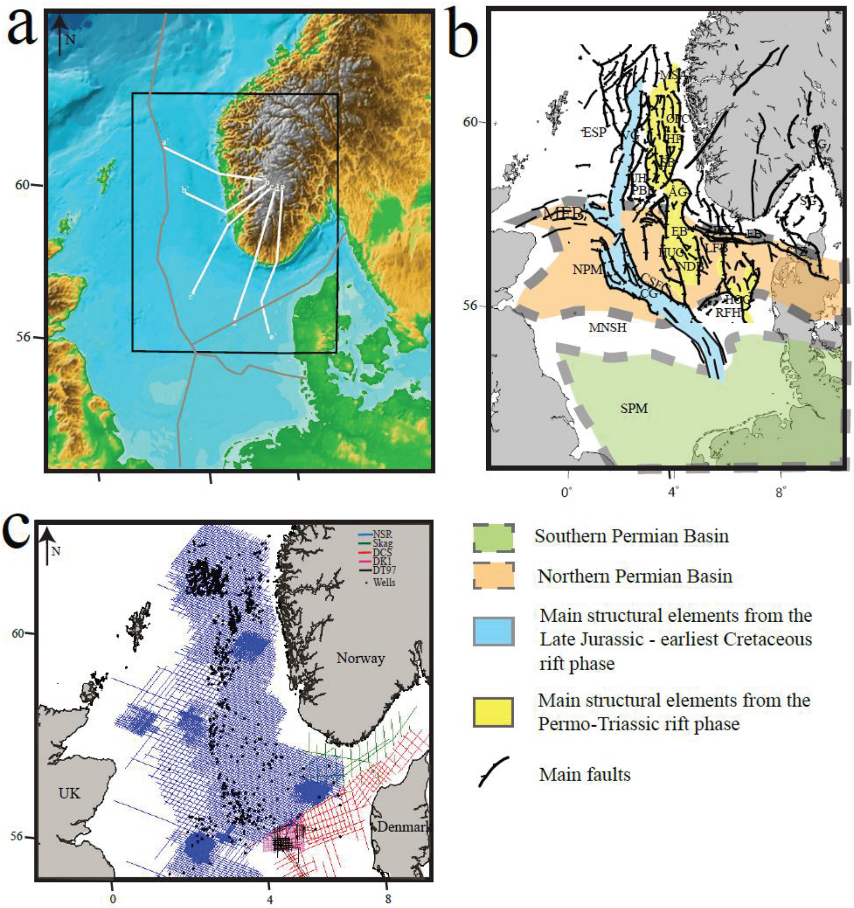

Figure 1: Map of the North Sea region (a), structural map (b) and the available reflection seismic and well data (c). The black square in (a) indicates the location of the main study area. The white lines indicate location of onshore-offshore profiles in Fig. 4.

Data base

The database included commercial reflection seismic data (the North Sea Renaissance dataset; NSR), kindly made available for the project by Fugro and TGS. The NSR dataset is a regional seismic grid covering the entire North Sea area. It was acquired in the period from 2004 to 2009 (NSR data have also been acquired after 2009, mainly outside the study area). In addition to the NSR seismic data set, selected 2D public domain available seismic data were studied during the work with this thesis. The seismic data were tied to key wells on the Norwegian continental shelf (NCS), and to several key wells on the Danish continental shelf (DCS; Fig. 1). The wells provide biostratigraphic, petrographic and lithostratigraphic information, and were used to calibrate the seismic sequences/successions interpreted.

Field data were acquired onshore southern Norway, with focus on the location and characterization of the sub-Cambrian peneplain.

Methods and approach

Seismic sequence stratigraphy

Seismic sequence stratigraphy has become an important tool to predict facies distribution and depositional environments, and is commonly used to predict the formation and infill patterns of sedimentary basins which generally reflect basin morphology and physiography (e.g. Vail et al., 1977ab; Mitchum et al., 1977; Embry, 1993, 1995; Emery & Myers, 1996; Reading, 1996; Glørstad-Clark, 2011). Seismic sequence stratigraphy is therefore a powerful tool in studying the basin formation and configuration.

The use of sequence stratigraphic methods when studying the basin evolution in a sedimentary basin has the advantage of that the basin dynamics can be inferred directly from observations, and can be defined as a model independent approach (Glørstad-Clark, 2011). Creation of accommodation spaces are in seismic sections commonly reflected by progradational wedges with internal clinoforms downlapping on marine conformable surfaces. Prograding successions of the highstand systems tract (HST) downlap onto the maximum flooding surface (MFS). A MFS is commonly reflected from high-gamma peaks in well logs, which separates an upward-fining trend (retrogradation) from an overlying upward-coarsening trend (progradation) in electric well logs (e.g. Galloway, 1989). Where the TST is non-accretionary, prograding strata may be located directly on top of a subaerial unconformity

(SU) (or a shallow-marine unconformity), thus forming a combined seismic stratigraphic surface, including subaerial exposure, transgression and maximum flooding (SU/TS/MFS-surface). Such a combined surface indicates rapid increase in rate of creation of accommodation space versus rate in sedimentation.

Sequence stratigraphy in continental basins

Continental sedimentary basins are known from all continents and many continental margins worldwide, (e.g. May et al., 1999; Glørstad-Clark, 2010; Weissmann et al., 2010). In order to assess the relative importance of tectonics, climate and base-level fluctuations in continental basins, it is crucial to have a detailed understanding of the sedimentary facies changes in time and space (May et al., 1999). Continental basins are characterized by the deposition of alluvial and fluvial plains, lacustrine and playa basins. This implies that rocks of different sedimentary facies can be deposited across limited areas, down to meter scale.

Sequence stratigraphic sub-division of sedimentary successions of continental origin has been a topic of discussion the recent years, because the sequence stratigraphic concepts, as proposed by e.g. Mitchum *et al.* (1977) and Galloway (1989), relate mainly to marine sedimentation. However, changes in sea level have limited influence on continental deposition in the interior of continents (e.g. Shanley & McCabe, 1994; Blum & Törnqvist, 2000). For this reason, recent studies have suggested using palaeosols as sequence boundaries (e.g. Atchley *et al.* 2004; Catuneanu, 2006; Prochnow *et al.* 2006; Ruskin & Jordan, 2007), since these surfaces indicate stable tectonic and climatic conditions, and they tend to have a regional distribution. Although palaeosols are adequate candidates as sequence boundaries in continental basins at outcrop scale, these are not identified in the reflection seismic record due to limited vertical resolution (tens of metres). It is therefore challenging to correlate sequence boundaries on a regional scale with only reflection seismic data and limited well data available. In this thesis, a seismic stratigraphic sub-division of continental deposits is based on changes in rock properties and changing sedimentary facies distribution on seismic scale vertically through the seismic succession.

Onshore data sampling and analyses

It is important to study earth surface morphology in understanding both regional and local tectothermal-isostatic processes (e.g. Bonow et al., 2006; Minàr and Evans, 2008; Green et al., 2013). Along passive continental margins such as Norway, there has been special focus on the connection between the onshore and offshore geological evolution (e.g. Riis, 1996; Gabrielsen et al., 2005, 2010). Active tectonics significantly affects the morphology of the hinterlands and the basinal realms of affiliated continental margins, and it is important to understand this in terms of both marginal and intraplate tectonics and source-to-sink systems on passive continental margins. Detailed geological mapping of hinterlands relative to sedimentary basins, such as onshore Norway, often requires extensive field work to comprehend the necessary understanding, both with emphasize on tectonics and the onshore as a source area. Although increased interest the recent years has been on generating digital solutions for help with geological mapping and predictions (e.g. Krøgli & Dypvik, 2010), limited attempts has been on digitally identifying and mapping geological surfaces which are smooth, levelled and/or mildly inclined. Such surfaces are often difficult to identify and correlate in the field, though they are important to understand in a source-to-sink context as they may represent erosional surfaces and reference surfaces relative to tectonic displacements. To study tectonic influence in the hinterlands, field work was carried out in southern Norway, with focus on the sub-Cambrian peneplain.

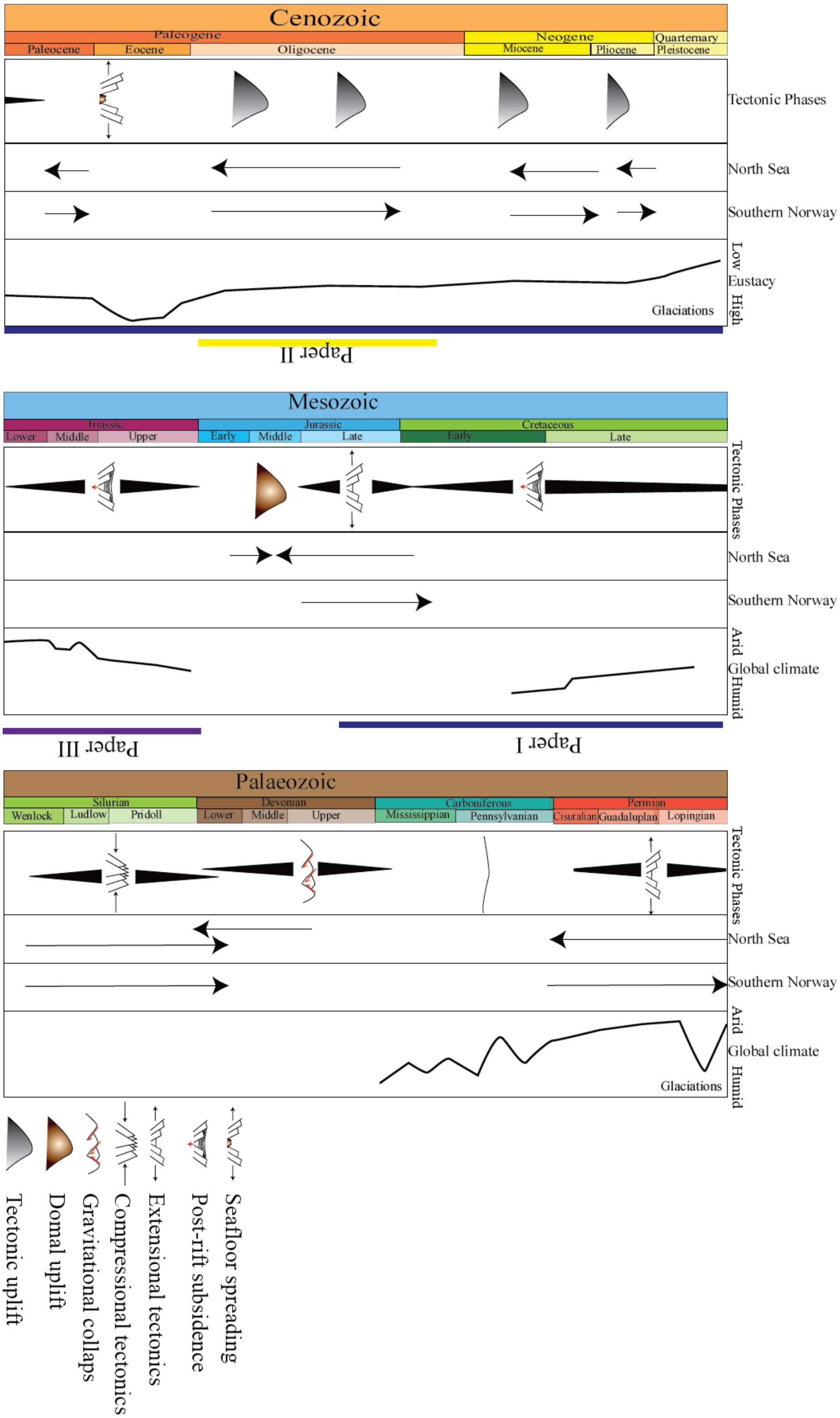

Figure 2: Stratigraphic chart showing tectonic phases which have influenced the North Sea region throughout the Phanerozoic. Global climate records and eustacy are from Miller et al., 2005, Korte et al., 2005

Evolution of the North Sea Region – historical overview integrated with main results from the present study

Research on North Sea geology the recent 50 years and onshore geology the recent 150 years has revealed several geological processes, which have had significant influence on the evolution of the North Sea Basin and its hinterlands (Fig. 2); including (1) creation of the sub-Cambrian peneplain (SCP) during the precambrian-Cambrian (e.g. Rekstad, 1903; papers IV & V), (2) Late Silurian – Early Devonian contraction, creating the Caledonian Mountains (e.g. Gee, 1975; Roberts, 2003; Ramberg et al., 2008), (3) Late Paleozoic and Mesozoic rift phases (e.g. Ziegler, 1975, 1990; Gabrielsen et al., 1990; Færseth et al., 1995; Gowers et al., 1993; Gowers, 1995; Andersen et al., 1999; Fraser et al., 2002; Glennie et al., 2003; Heeremans et al., 2004; papers I, III, IV & V), (4) opening of the NE Atlantic (e.g. Jordt et al., 1995, 2000; Faleide et al., 2002; paper II), and (5) Late Palaeogene – Neogene differential uplift of southern Norway (e.g. Gabrielsen et al., 2005, 2010; Anell et al., 2009, 2010; papers II & III). These processes occurred simultaneously with (6) global climate changes (e.g. Abbink et al., 2001; Miller et al., 2005) associated with rise and fall of eustatic sea level (e.g. Haq et al., 1987; Miller et al., 2005), inducing increase/decrease in erosion rate, vegetation and weathering (e.g. Nielsen et al., 2009). These processes are also associated with (7) development of palaeo-surfaces and peneplains onshore western Scandinavia (Riis, 1996; Lidmar-Bergstrøm et al., 2013; Green et al. 2013). Following is a description of the geological evolution during the Mesozoic and Cenozoic.

Mesozoic and Cenozoic basin configuration and depositional setting

The north-western Europe was affected by an extensional stress regime during the Late Carboniferous – Early Triassic, related to reorganization of the Laurentia and Baltic plate configuration (Ziegler, 1975, 1990; Glennie et al., 2003; Pharaoh et al., 2010). The rifting created several N-S trending horst and graben structures in the North Sea area, both in the southern and northern Permian basins (e.g. Glennie et al., 2003; Pharaoe et al., 2010). Rifting also affected southern Norway by the creation of the Oslo Graben (Ro et al., 1990; Heeremans & Faleide, 2004). Also, several N-S and NE-SW trending lineaments in southern Norway may have developed during the Paleozoic (Gabrielsen et al., 2002), of which may have acted as sediment pathways during the Triassic (paper I). The Permian climate was arid, with mostly continental aeolian deposition, including the Rotliegendes sandstones, in the central and eastern North Sea areas (e.g. Taylor, 1998; Pharaoh et al., 2010). The Late Permian is characterized with marine incursion in the North Sea region and deposition of the Zechstein evaporates (Tucker, 1991; Taylor, 1998).

The Triassic period was characterized by post-rift thermal subsidence in the central North Sea, except from rifting in the Horn Graben (e.g. Vejbæk, 1997; Stemmerik, 2001) and minor renewed faulting in parts of the Norwegian-Danish Basin (e.g. Gabrielsen et al., 1990; paper I). The Permian basin configuration most likely affected the Triassic sedimentation patterns, particularly during the Early Triassic (paper I), including sediment thicknesses exceeding 2 s. TWT (two-way-traveltime)(Fig. 3a). During the Middle and Late Triassic, sediment distribution and creation of accommodation spaces were mostly controlled by mobilization and re-mobilization of Zechstein salt (Goldsmith et al., 2003; paper I). The North Sea was characterized by arid to semi-arid climate, and the depositional environments encompassed continental playa, alluvial fans, alluvial plains, aeolian dune fields and temporal shallow-water lakes (Ziegler, 1975; Steel & Ryseth, 1990; Goldsmith et al., 2003; Lervik, 2006; McKie & Williams, 2009; Nystuen et al., in press). During the Late Triassic to Early Jurassic the European plate moved northwards (Evans et al. 2003), and the climate changed accordingly from dominantly hot and warm arid and semiarid to warm semihumid and humid (Müller et al. 2004; Nystuen et al. in press). The southern Permian Basin was periodically flooded in the Middle Triassic (Ziegler 1975; Geluk 2005; McKie & Williams 2009), though the transgression has not been documented to have reached the Norwegian Danish Basin (NDB). On the other hand, NDB was the site of continental deposition throughout the Triassic (Goldsmith et al., 1995, 2003; Geluk, 2005; McKie & Williams, 2009). The exclusively continental nature of the Triassic sedimentary succession in the central North Sea area has traditionally restrained sequence sub-division of the Triassic succession in the region. It is showed in paper that the Triassic succession in the Norwegian Danish Basin is characterized by variable seismic facies distribution and petrophysical properties, which correlates with changing sedimentary facies distribution following a typical terminal fan model (*sensu* Tunbridge, 1984). The correlation between seismic stratigraphy and sedimentary facies from well data (petrophysical data and core data) of the Triassic succession is demonstrated in paper I.

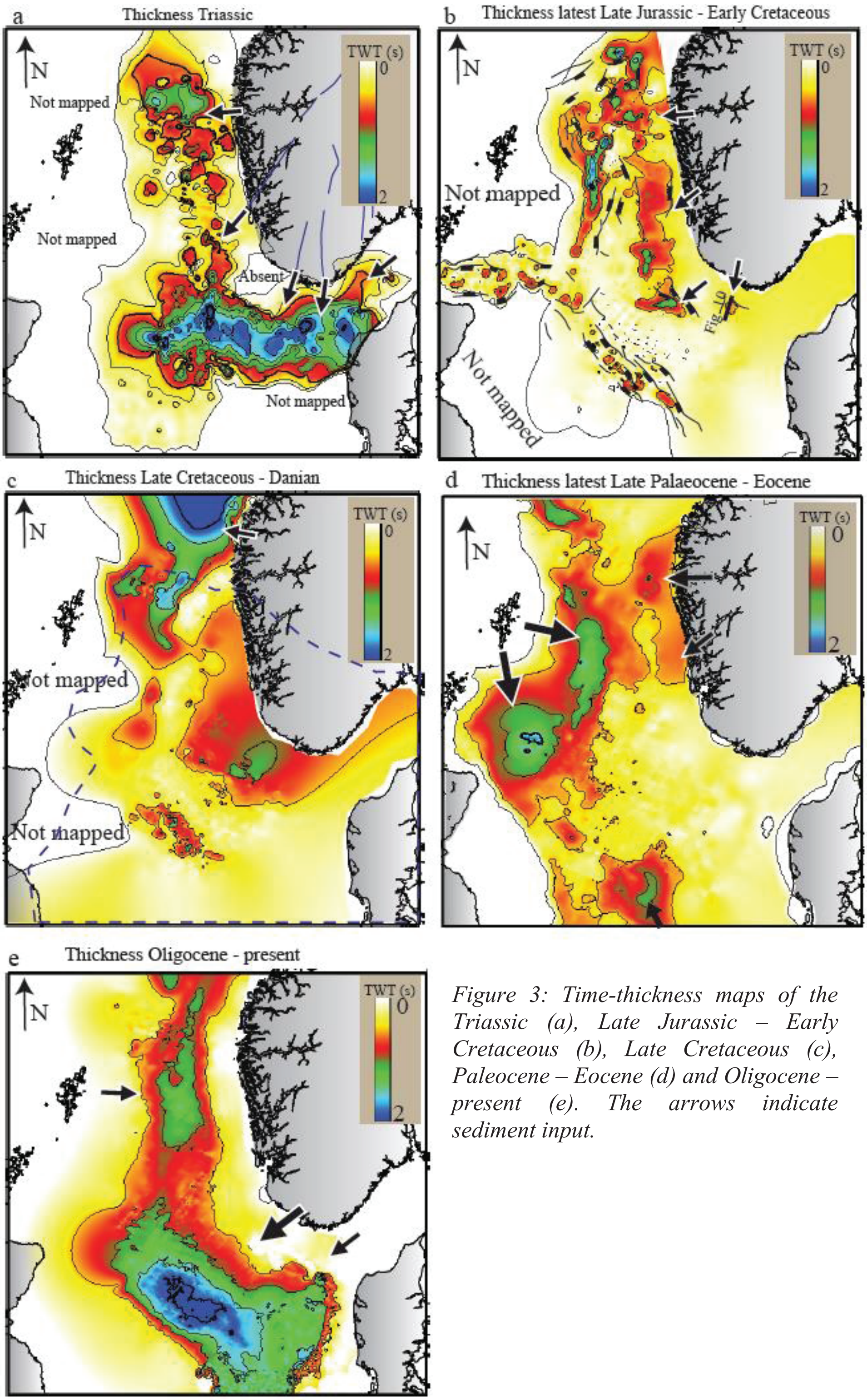

Figure 3: Time-thickness maps of the Triassic (a), Late Jurassic – Early Cretaceous (b), Late Cretaceous (c), Paleocene – Eocene (d) and Oligocene – present (e). The arrows indicate sediment input.

The Late Mesozoic and Cenozoic succession in the central and northern North Sea can be sub-divided into four main basin configurations, as shown in paper II (Fig. 3b-3e). Each basin configuration are characterized with creation and infill of new accommodation spaces, related to tectonic phases, and the creation of and destruction of intra-basinal topographies and, potential relief in the hinterlands (paper II). In the northern North Sea, E-W oriented extension initiated in Middle Jurassic, though the principal tensional stress presumably changed to more NE-SW in Late Jurassic (Færseth et al., 1997), where the crests of rotated fault blocks represented the main topographies (Kyrkjebø et al., 2001; Kjennerud et al., 2001). Jurassic, clastic sedimentation took place as far east as the Bergen area (Fossen et al., 1998). In the central North Sea, Gowers et al. (1993) showed that the Central Graben was formed by several tectonic pulses, though with a principal NNE-SSW and NE-SW orientation of the extension (Gowers et al., 1993; Møller and Rasmussen, 2003). Sedimentary basins with water depths up to 200-300 m also developed along the present day coast of southern Norway, including Stord Basin/Åsta Graben, Egersund Basin and Farsund Basin, with sediment progradation towards the W and SW (Gabrielsen et al., 2010; paper II). The directions of sediment progradation indicate uplift and creation of source areas in parts of southern Norway, and are in support of that Caledonian lineaments, such as the Hardangerfjord Fault Zone and Lærdal Gjende Fault Zone, were tectonically active and acted as sediment pathways also during the Late Jurassic and Early Cretaceous. The Early Cretaceous was characterized by post-rift thermal subsidence in the North Sea area, though the transition from syn –to post rift was gradual (Gabrielsen et al., 2001). The intra-basinal relief inherited from the syn-rift stage became gradually drowned during the Early Cretaceous, including SW oriented sediment progradation sourced from relief in southern Norway (paper II). The syn-rift basin configuration persisted throughout the Early Cretaceous (paper II), corresponding to the early post-rift phase (Nøttvedt et al., 1995; Gabrielsen et al., 2001).

The North Sea area was characterized by a different basin configuration in Late Cretaceous (paper II), which was accompanied by the shift from mainly siliciclastic sediment input in the Jurassic and Early Cretaceous to mainly chalk deposition in Late Cretaceous, in the central North Sea area (Surlyk et al., 2003). The intra-basinal relief in the central North Sea was eroded and draped by Late Cretaceous calcareous material. Siliciclastic sediment input from the north and east continued in the northern North Sea and the Norwegian Sea

(Surlyk et al. 2003; Sømme et al., 2013; Fig. 3). The Chalk Group sediments were deposited in an epicontinental sea, locally affected by ocean bottom currents (Esmerode et al., 2008; Gennaro et al., 2013). The basal boundary of the Chalk Group is believed to correlate with the paleic surface onshore southern Norway and Sweden (Fig. 5; Riis, 1996; Lidmar-Bergström et al., 2013), which is presently uplifted to approximately 1300-1400 meters above sea level in Hardangervidda and 800-1200 meters in eastern parts of southern Norway (Nystuen et al., 2014). Thickening of the Chalk Group in the central North Sea, northwards from the Coffee-Soil Fault Complex towards southern Norway, indicates that parts of southern Norway were transgressed during the Late Cretaceous with potential chalk deposition (Fig. 3; paper II).

In Paleocene and Eocene, uplift of the East Shetland Platform took place, with subsequent siliciclastic sediment input in a rapidly deepening North Sea basin (e.g. Jordt et al., 1995, 2000; Faleide et al., 2002; Gabrielsen et al., 2005, 2010a; Anell et al., 2011; Goledowski et al., 2012; paper II). Tectonic uplift and subsidence in the North Sea area gave rise to a new basin configuration, compared to that during the Late Cretaceous (basin configuration 3 in paper II). Tectonic uplift of East Shetland Platform corresponds in time with major igneous activity in the North Atlantic Igneous Province, northwest of the study area (e.g. Knox & Morton, 1988) and an overall change from shallow marine conditions in the Viking Graben area during Late Cretaceous to deep marine during Early Paleogene (Michelsen, 1994; Kyrkjebø et al., 2001). Uplift of parts of southern Norway is inferred from the creation and sediment infill of accommodation spaces offshore the major fjords in southern Norway, such as the Sognefjord and Hardangerfjord (Jordt et al., 1995, 2000; Clausen et al., 1999; Faleide et al., 2002; paper II). The uplift is likely to have been most severe in the northwestern parts of southern Norway, as onshore-offshore profiles indicates that parts of southern Norway was parts of the sedimentary basin during the Paleogene (Fig. 4). This is also suggested in paper III, where a uniform thickness of the late Early Oligocene seismic sequence towards the north (southern Norway) indicates that parts of southern Norway was part of a shallow marine basin in the Oligocene. The presence of depocenters at the offshore continuation of major lineaments during the Paleocene and Eocene indicates that vertical displacements and sediment transportation were influenced by the underlying structural grain. This was also the case in the Viking Graben area, where tectonic subsidence corresponded with the main Jurassic graben structure.

The North Sea area was subject to an increasing supply of coarse-clastic material in the Early Oligocene time, caused by a combination of renewed uplift/subsidence relationship and climatic change (Jordt et al., 1995, 2000; Huuse & Clausen, 2001; Faleide et al., 2002; Huuse, 2002; papers II & III). This gave rise to a different basin infill pattern than that prevailed during the Paleocene and Eocene times (annotated basin configuration 4 in paper II). The main sediment transport direction changed, from eastwards during Paleocene and Eocene to southwest –and westwards during the Neogene (Jordt et al., 1995; Fig. 3). Paper III focuses on a study of the basin evolution in the eastern North Sea during the Oligocene, with emphasize on regional vertical displacements. It is showed here that rapid rises in sea level of up to 300 m are out-of-phase relative to known eustatic sea level changes. This probably reflects initial tectonic subsidence of the eastern North Sea area, which most likely continued in phases also during the Miocene and Pliocene (e.g. Japsen & Chalmers, 2000; Faleide et al., 2002; Rasmussen, 2004; Stoker et al., 2005; paper II). The tectonic subsidence is most likely related to tectonic uplift of southern Norway, though potential mechanisms are still debated (Faleide et al., 2002; Anell et al., 2009).

Global cooling in the Quaternary resulted in major glaciations of the northern hemisphere. The consequence of this was glacial erosion and major glacial incision in southern Norway, including major glacial incision along the structural lineaments, such as the Sognefjord and Hardangerfjord (e.g. Nesje et al., 1994). Also, truncation along the Norwegian Trench removed significant portions of the Cenozoic and Mesozoic successions adjacent to present-day southern Norway (e.g. Riis, 1996).

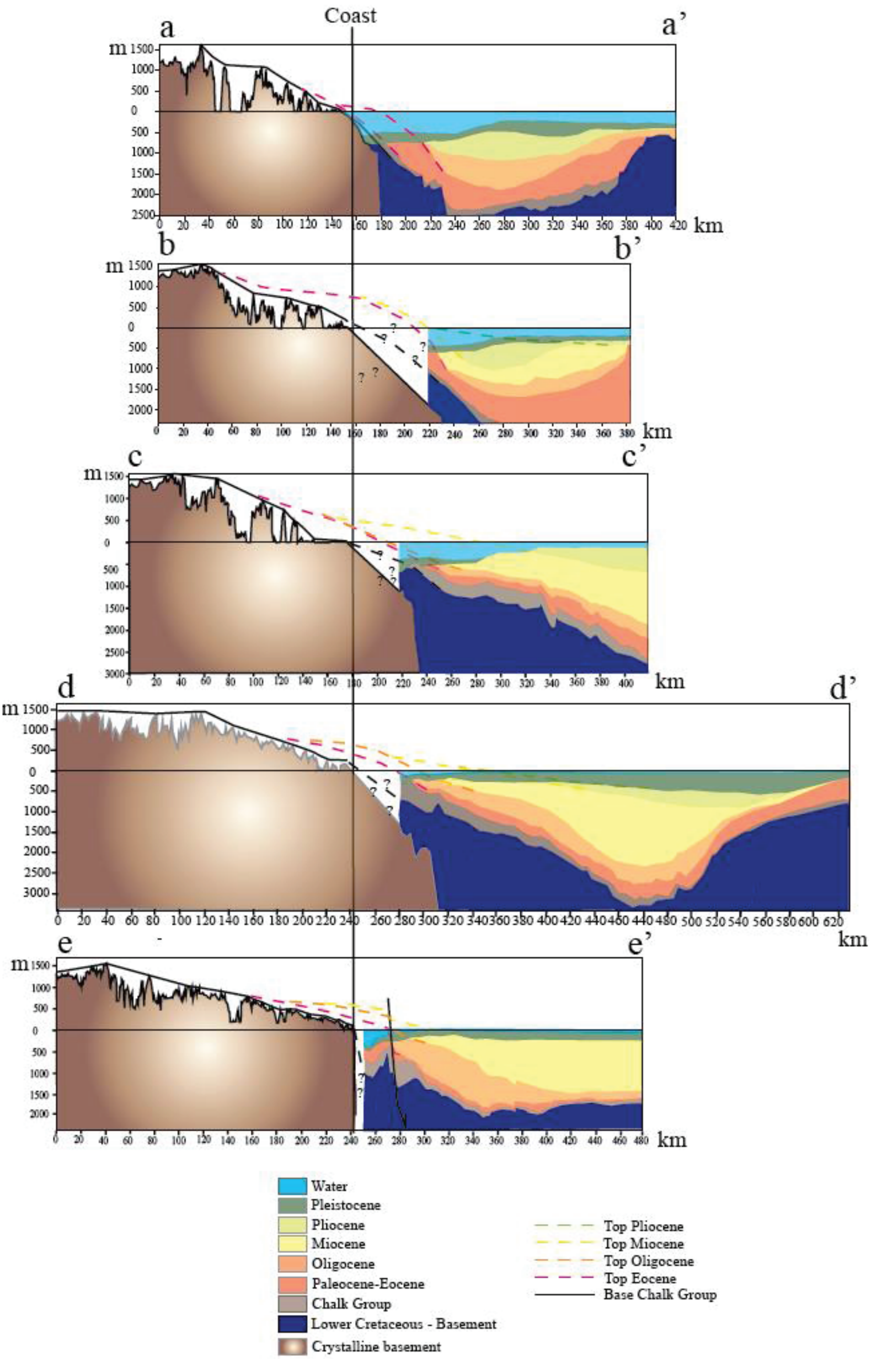

Figure 4: Onshore-offshore profiles. See Fig. 1 for location of the profiles. The initial tectonic uplift was most likely in the northwestern parts of southern Norway, as indicated by onlap of Cenozoic strata close to present sea level (a-b). Note the onshore extrapolation of to the south (c-e), which indicates sediment deposition onshore present day southern Norway.

Onshore geology

Geology and geomorphology onshore southern Norway has fascinated geoscientist for more than a century (Kjærulf, 1879; Brøgger, 1888; Reusch, 1901; Rekstad, 1903; Strøm, 1948). Already in the 19th and early 20th centuries, geoscientists proposed that southern Norway has been eroded to base level at least twice, with subsequent uplift; from identification of the sub-Cambrian peneplain and the paleic surface (Brøgger, 1893; Reusch, 1903; Ahlmann, 1919). Unfortunately, no Mesozoic or Cenozoic sedimentary rocks are presently known to be preserved onshore southern Norway. These facts challenge the onshore-offshore correlation, as no direct tie between offshore deposits of Mesozoic and Cenozoic ages can be associated to equivalent deposition onshore. Despite this, studies show that the present onshore landscape is influenced by the Paleozoic and Mesozoic extensional phases, which is evident from Apatite Fission Track (AFT) studies (e.g. Andersen et al., 1999; Ksienzyk et al., 2014). However, the lack of Mesozoic and Cenozoic sedimentary rocks onshore southern Norway means that the most important and correlable surfaces are erosional surfaces, such as the sub-Cambrian peneplain (SCP) and the paleic surface.

The sub-Cambrian peneplain (SCP) most probably developed across most of the Baltic shield, and is an important tectono-morphological element in Norway (Rekstad, 1903; Ahlmann, 1919; Strøm, 1948; Holtedahl, 1960; Gjessing, 1967; Lidmar-Bergström et al., 2013; papers IV & V), Sweden (Lidmar-Bergström, 1993) and Finland (Kohonen and Rämö, 2005). The SCP represents a significant break in the stratigraphic record of southern Norway, with Proterozoic bedrock being discordantly overlain by regolith grading into conglomerate, sandstone and Cambrian black shale and phyllite (e.g. Reusch, 1901; paper V). The sediments are preserved in isolated pockets in the weathered surface of the Proterozoic autochthonous basement, and can reach considerable thicknesses as identified for the Vangsås Formation north of the Oslo Region (Nystuen, 1987) and in Baltica (Nielsen & Schovbo, 2011). The SCP displays different modes of development including (paper V): (1) local, tectonically mobilized basement underlain by slivers of mylonites; (2) basement consisting of Proterozoic gneisses, intrusives and tectonites, weathered to varying extent producing an altered zone between 1 and 200 cm thick, coated by a mineralized surface containing Mn, Cu and Pb; (3) weathered surface altered to a 1–10 cm thick layer of regolith; (4) conglomerate, referred to as the 'basal conglomerate' by Brøgger (1888) and Rekstad (1903); and (5) gravel and sandstone of latest NeoProterozoic to Cambrian age, overlain by alum shale (e.g. Holtedahl, 1960). The SCP can presently be identified at different altitudes in southern Norway, although the surface tends to be surprisingly flat over great distances in some parts of it (papers IV & V). In the southwestern part, it is elevated up to c. 1400 m, whereas the same surface is identified below c. 1100 m in the northeastern part of Hardangervidda, southern Norway. The SCP is furthermore downfaulted to c. 700 m above sea level to the east of Hardangervidda, southern Norway, and furthermore to sea level at the Oslo Fjord (Paper V). On regional scale, the in-situ deposits affiliated with the SCP are thin and the base of the phyllite can be used as a proxy for the peneplain when its characteristics have been confirmed by field survey. Digital mapping of the SCP in the Hardangervidda area is presented in paper IV, whereas a more extensive study of the tectonic influence on the SCP across southern Norway is discussed in paper V. These studies show that the southern Norway is a fault-bounded plateau area, which may reflect that the southern Norway is likely to have been influenced by uplift/subsidence, possibly related to rifting.

Summary of the papers

i) Paper 1 – Seismic stratigraphic subdivision of the Triassic succession in the central North Sea – integrating reflection seismic data and well data

Journal of the Geological Society, London, 2014

The focus in this study was the Triassic succession in the central North Sea. The Triassic succession in the North Sea was deposited in a continental environment. Since sequence stratigraphy is dependent on marine influence and changes in relative/eustatic sea level, no earlier published attempts have been made on sub-dividing the Triassic succession in the North Sea into seismic sequences. In this paper, we show that there is a close relationship between seismic facies and sedimentary facies within well sections. Well-to-seismic correlation combined with observation and mapping of regional amplitude anomalies, allowed us to sub-divide the Triassic succession into four seismic units. The seismic units correlate across the central North Sea with published biostratigraphy. We also used the well-to-seismic correlation to propose the gross palaeoenvironment for the four seismic units in the central North Sea during the Triassic, and the basin morphology relative to basin subsidence and halokinesis. We discuss the source-to-sink system based on this seismic sub-division with emphasize on climate changes and basin formation.

Main conclusions from this study:

- The Triassic succession can be subdivided into four seismic units. The subdivision was based on changing seismic facies which correlates with changing sedimentary facies within the well sections, and regional mappable amplitude anomalies which reflect changing rock properties. This study shows that sedimentary basins consisting exclusively of continental deposits can be sub-divided into seismic units based on seismic facies changes and amplitude anomalies.

- The net accumulation rate was greatest during the Early Triassic, which is surprising considering the warm and arid climate at the time. This was an important finding regarding the source-to-sink relationship, as this favor an establishment of topography at the Permian-Triassic boundary.

- In this study we also propose the palaeoenvironment across the Norwegian-Danish Basin throughout the Triassic. We also show the great influence from halokinesis on the basin morphologies an sediment dispersal patterns.

ii) Paper 2 – Mesozoic and Cenozoic basin configurations in the North Sea

International Association of Sedimentologists, Special Publication, 2014.

This paper focuses on the Late Mesozoic and Cenozoic succession in the North Sea region, with emphasize on changing basin configurations on the basis of sediment patterns and distribution of accommodation spaces. Four basin configurations were identified; (1) latest syn-rift and early post-rift stage, (2) late post-rift stage, (3) initial opening of the NE Atlantic, and (4) migration of depocenters related to uplift of southern Norway. The early post-rift phase share the same basin configuration as the late syn-rift phase, including the same accommodation spaces which developed during rifting. The rift basins were mostly infilled at the initiation of the late post-rift phase, including burial of intra-basinal reliefs and the onset of basin configuration 2. Basin configuration 3 developed due to creation of deep accommodation spaces in the Viking Graben area in the Palaeocene and Eocene times, during initial opening of the NE Atlantic. The basin configuation 4 was defined from the shift in main sediment source area, from a dominantly western source area in Paleocene and Eocene to a dominantly eastern and northeastern source area in the Oligocene and Neogene, combined with migration of depocenters within the North Sea area. Basin configuration 4 reflects the interplay between tectonic uplift of southern Norway and global cooling which initiated at the Eocene-Oligocene boundary.

Main conclusions from this study:

- In this study we sub-divide the Late Mesozoic and Cenozoic successions in the North Sea region into four basin configurations of which indicates changing basin morphologies and main source areas. The various basin configurations reflect different tectonic phases and sediment infill patterns.
- The basin configuration which was established during the Late Jurassic – earliest Cretaceous syn-rift phase extended to mid-Cretaceous, where all structural elements became draped by the Upper Cretaceous Chalk Group. During the Late Cretaceous the central and eastern North Sea then represented an epicontinental shallow sea, of which most likely extended northwards across parts of southern Norway and Sweden.
- Several depocenters developed along the Norwegian coast, including the Horda Platform area, Stord Basin/Åsta Graben and Egersund Basin, with subsequent

sediment progradation via old structures from source area(s) along present-day southern Norway.

- There are distinct relationships between tectonic activity and sediment progradation during the Late Mesozoic and Cenozoic, which favor a strong tectonic control on basin formation and development. Although the main depocenters shifted position during the Late Mesozoic and Cenozoic, older, underlying structural elements influenced the positions of repeated vertical movements within the North Sea region.

iii) Paper 3 – The Oligocene succession in the eastern North Sea – basin development and depositional systems

Geological Magazine, in revision (minor)

In Paper 3 we did a re-interpretation of the Oligocene succession in the eastern North Sea, by applying the regional reflection seismic data on the Norwegian Continental shelf integrated with biostratigraphy and Sr-stratigraphy in selected wells, which constrains the age of the various seismic sequences deposited during the Oligocene. The Oligocene sediments represent the first major sediment input from southern Norway since the Early Cretaceous times. Also, since the onset of the Oligocene was characterized by major glaciation on the Antarctica and major lithospheric re-organizations, the Oligocene succession is relevant for studying the effects of potential tectonic uplift/subsidence and climate changes on the source-to-sink system. The Oligocene succession in the eastern North Sea was here sub-divided into four seismic sequences. The sequences were characterized as transgressive-regressive sequences, where the transgressive systems tract were either accretionary or non-accretionary.

Main conclusions from this study:

- Accommodation space developed rapidly during the Oligocene, leaving non-accretionary transgressive systems tracts during increase of water depths of several 100s m.

- The basin subsidence is likely to have accompanied tectonic rise of the southern Norwegian landmass, where the eastern part of the North Sea basin experienced subsidence forced by differential vertical movements of the lithosphere. These vertical movements gave rise to rapid changes in palaeowaterdepth and accompanying changes from potential subaerial exposure of basin platforms to marine flooding and water depths up to about 300 m.
- Climate changes occurred simultaneously with tectonic uplift of southern Norway, which had an effect on the source-to-sink relationship in terms of changing erosion rates and rise and fall in eustatic sea level. This is particularly the case in the Late Oligocene, where increased sedimentation rates correlates with periods with global cooling, and potential growth of wet-based alpine glaciers in the hinterland.

- Within the basin, halokinesis influenced sediment progradation locally throughout Rupelian and Early Chattian times. The halokinesis was most likely caused by differential sediment loading in adjacent areas of the depositional basin. However, the actual sizes of the salt diapirs are considered too limited to have influenced basin subsidence.

iv) Paper 4 – Automatic identification of topographic surfaces related to the sub-Cambrian peneplain (SCP) in southern Norway – surface generation algorithms and implications

Geomorphology, 2014

In this paper, we apply surface generating algorithms to identify the sub-Cambrian peneplain (SCP) on the Hardangervidda, in southern Norway. This paper is part of a larger study of the sub-Cambrian peneplain, where we applied computer assessments to identify the surface of interest, both for help in regional interpretation of geological implications of the presence of the SCP and to limit the amount of field work. We applied two algorithms; *Region Grow* and *Surface fit* to create digital surfaces representing the SCP.

Main conclusions from this study:

- The algorithms identified the known SCP segments from map sheets and segments we observed during field work, and hence are considered to be successful in identifying and calibrating horizontal and subhorizontal surfaces in the field. This indicates that the algorithms and their applications are beneficial in reducing the amount of necessary field work.

- We observed candidates for down-faulted and, potentially, thrusted segments of the SCP. This indicates that the applied methods can identify deformation of the surface of interest.

- Faulting of the SCP identified in this study indicates that the extensional stress regime during the Paleozoic and Mesozoic may have influenced the central parts of southern Norway of greater degree than previously shown.

v) Paper 5 – The SubCambrian Peneplain in southern Norway: Its geological significance and its implication for the Caledonian deformation and the post-Caledonian faulting, exhumation and denudation

Submitted to Geological Society of London

In this paper, we study the sub-Cambrian peneplain, with emphasize on conditions of preservation of the surface and present morphology across southern Norway. During field work, several modes of preservation of the SCP have been identified, including (1) angular unconformity, (2) in-situ, weathered surface, (3) weathered and mineralized surface, (4) undisturbed regolith, (5) undisturbed primary deposits, such as conglomerate, sandstone and shale, (6) reworked primary sediments, (7) mildly tectonized contacts and (8) faulted contacts.

Main conclusions from this study:

- The sub-Cambrian peneplain is surprisingly flat across the central part of southern Norway. This observation does not support "domal uplift" of southern Norway, which is repeatedly reported, rather that the central part of southern Norway is a fault-bounded plateau.
- The south-central Norway (including the Hardangervidda mountain plateau) was subject to mechanical and chemical subaerial weathering during the Precambrian and Early Cambrian, with mostly fluvial deposition ontop of the SCP.
- Albitization seems to be the most common process associated with weathering of the SCP in the Hardangervidda region, where plagioclase is transformed to albite in the weathered zones. The weathered zones have thicknesses of up to a couple of meters, which requires significant time to develop. This indicates that marine transgression in Cambrian times covered an area that was already deeply weathered and where fluvial processes, and potentially glacial processes, have been active for an extended period.

General conclusions

Understanding the interplay between basin formation, sediment supply and sediment transport direction/migration and hinterland geomorphology and climate, are critical to achieve an understanding of the evolution of a geological province. This thesis has been focused on study the changing depocenter locations relative to various tectothermal-isostatic events during the Mesozoic and Cenozoic. The focus has been on understanding depocenter formation, migration and infill, and the interaction between regional and local tectonics, basin morphologies, global climate changes as well as eustacy. This thesis has provided new information based on interpretation of seismic data integrated with inter-disciplinary geological methods which shed new lights into the relationship between depocenter formation and migration relative to repeated vertical displacements in the North Sea region during the Mesozoic and Cenozoic.

The work in this thesis reveals a close relationship between the creation and infill of accommodation spaces with regional tectonothermal events and climate changes in the North Sea region and associated hinterlands, during the Mesozoic and Cenozoic. This is shown from both regional studies (papers I and II), from integrated studies of well data and seismic data of the Oligocene succession in the eastern North Sea (paper III) and from field studies and remote sensing techniques onshore southern Norway (papers IV and V).

Repeated uplift of parts of southern Norway is associated with subsidence and to creation of accommodation space in the North Sea region. Older lineaments have influenced the structural evolution of the region also during the Mesozoic and Cenozoic, as indicated by depocenter formation and sediment transportation associated with the larger fjord systems onshore southern Norway. The Late Mesozoic and Cenozoic succession in the North Sea area is sub-divided in four basin configurations which are bounded by tectothermal-isostatic events reflected by creation and infill of accommodation spaces combined with uplift/denudation of the hinterlands. That the tectonic events also affected the hinterlands is evident from the study of the subcambrian peneplain, which shows that southern Norway is a fault-bounded plateau (papers IV and V). However, this thesis also highlights the climatic effects on the source-to-sink systems during the Mesozoic and Cenozoic, as shown in paper III, where the Oligocene succession in the eastern North Sea was affected by rapid subsidence associated with the interplay between tectonic uplift of southern Norway combined with rise and fall in eustatic sea level.

Variations in seismic facies are associated with variations in sedimentary facies in the Triassic succession in the central North Sea, which furthermore reflects regional climate changes (paper I). The creation of accommodation space is regionally controlled by the interplay between thermal cooling succeeding Paleozoic rifting, sediment compaction and flexural isostatic effects, though locally controlled by halokinesis.

2. Future work

Looking forward, there are still many unresolved issues related to the Mesozoic and Cenozoic basin evolution of the region. As shown in this thesis, it is clear that parts of southern Norway were transgressed during the Late Cretaceous and Palaeogene (Paper II), with the potential of a more widespread chalk sea than earlier assumed. To further investigate this hypothesis, a detailed study of Palaeogene and, in particular, Neogene successions in wells offshore Norway should reveal re-worked chalk fragments and Palaeogene sediments. This is already observed by Thyberg et al. (2000), though a more systematic study of the well sections is necessary. This may be part of a more extensive study of the paleic surface to establish an erosional model for southern Norway. The paleic surface may be investigated by the same procedures and methods as presented in papers IV and V in this thesis, combined with more geomorphological considerations concerning erosional incision. An erosional model for southern Norway is crucial for establishing complete understanding of the source-to-sink systems in the North Sea during the Cenozoic.

In paper I, we propose a seismic sub-division of the Triassic succession in the central North Sea area, based on changes in rock properties and facies. Similar sub-division should also be applicable in the northern North Sea and, potentially also for the Permian seismic succession. This can, and should, be combined with mineralogical studies, which may increase the understanding of potential reservoir intervals in the Triassic succession. Recent studies (Maast, 2013) demonstrate that grain coatings, which are critical for preservations of porosities at greater depths, are facies dependent, which, combined with seismic stratigraphy, may de-risk exploration in parts of the North Sea region.

As shown in this thesis, repeated vertical movements occurred along old lineaments. There is a need to study the Paleozoic succession in the North Sea region, to improve the understanding of inherited structures and theire influence on younger tectonic phases. I have started the work with mapping and interpreting the Paleozoic succession in the North Sea, though the results of the work are not incorporated in any of the enclosed papers. The main findings and conclusions can be considered to be fundamental for future work of the Paleozoic succession in the region. The main observations and interpretations are presented below.

Observations of Paleozoic structural evolution

Seismic interpretation of three seismic horizons was achieved for the Paleozoic succession, assumed to represent top basement (basal boundary of the Paleozoic succession), top Devonian-Carboniferous and top Permian. The top basement reflector is penetrated by wells on structural highs, such as the Utsira High, in the Måløy Slope area and on the Mandal High, and is identified in the Stord Basin area as a high seismic amplitude reflection (Fig. 5). The upper bounding seismic reflection of a seismic succession overlying the top basement reflector is characterized by an amplitude anomaly, which is highly faulted both in the central North Sea area and in the Stord Basin/Horda Platform area (Fig. 5). The seismic succession is here interpreted to consist of Devonian – Carboniferous sedimentary rocks, based on the stratigraphic position below the Permian-Triassic succession and the character of the upper bounding amplitude anomaly, which indicates a significant contrast in acoustic impedance. Thicknesses of the Devonian-Carboniferous seismic succession indicate the presence of several depocenters, which are bounded by basement highs (Fig. 6b). The basement highs are located in the offshore elongation of major Caledonian lineaments onshore southern Norway, such as the Hardangerfjord Fault Zone and Nordfjord Sogn Detachment (Fig. 6). It is suggested here that the depocenters in the northern North Sea most likely developed as intra-mountain sedimentary basins which developed during gravitational collapse in the late phase of Caledonian compression. This interpretation is supported by the presence of similar sedimentary basins onshore southern Norway (Steel, 1976; Roberts, 1983;) and offshore UK (Coward et al., 1989; Marshall, 1998). Basement relief in the offshore continuation of the major Caledonian lineaments were also proposed by Fossen and Hurich (2005), based on gravity, magnetics and deep seismic. Basement relief is also observed in the central North Sea area, close to the Norwegian-Danish border, which correlates with where the Devonian-Carboniferous, Permian and Triassic seismic successions are inverted (Fig. 6c). However, despite of potential basement structures in the central North Sea, most of the Devonian-Carboniferous sedimentary succession seems to have been deposited in a more laterally extensive sedimentary basin here compared to in the northern North Sea, based on the time-thickness map in Fig. 6.

The central and eastern North Sea may have been a foreland basin relative to the Caledonian Orogeny and, possibly, the Variscan Orogeny in the south, during the Devonian and Carboniferous, including vast sediment deposition exceeding 4 s. TWT. The observed inversion along the Norwegian-Danish border may rather be related to thermal doming relative to the Late Jurassic – earliest Cretaceous rift phase, which further indicates that the Jurassic doming event was more complex compared to that proposed by Underhill & Partington (1993). Furthermore, it shows that the domal uplift may have been influenced by established basement structures. However, detailed seismic interpretations of the overlying Jurassic succession, combined with detailed well studies, including facies and biostratigraphy, are necessary for a more comprehensive study of the Jurassic thermal doming event. This is likely to be of great interest for the oil and gas industry, since it may enhance the prospectivity in the central and eastern North Sea, as locally-derived sandstones may be more widespread than previously known.

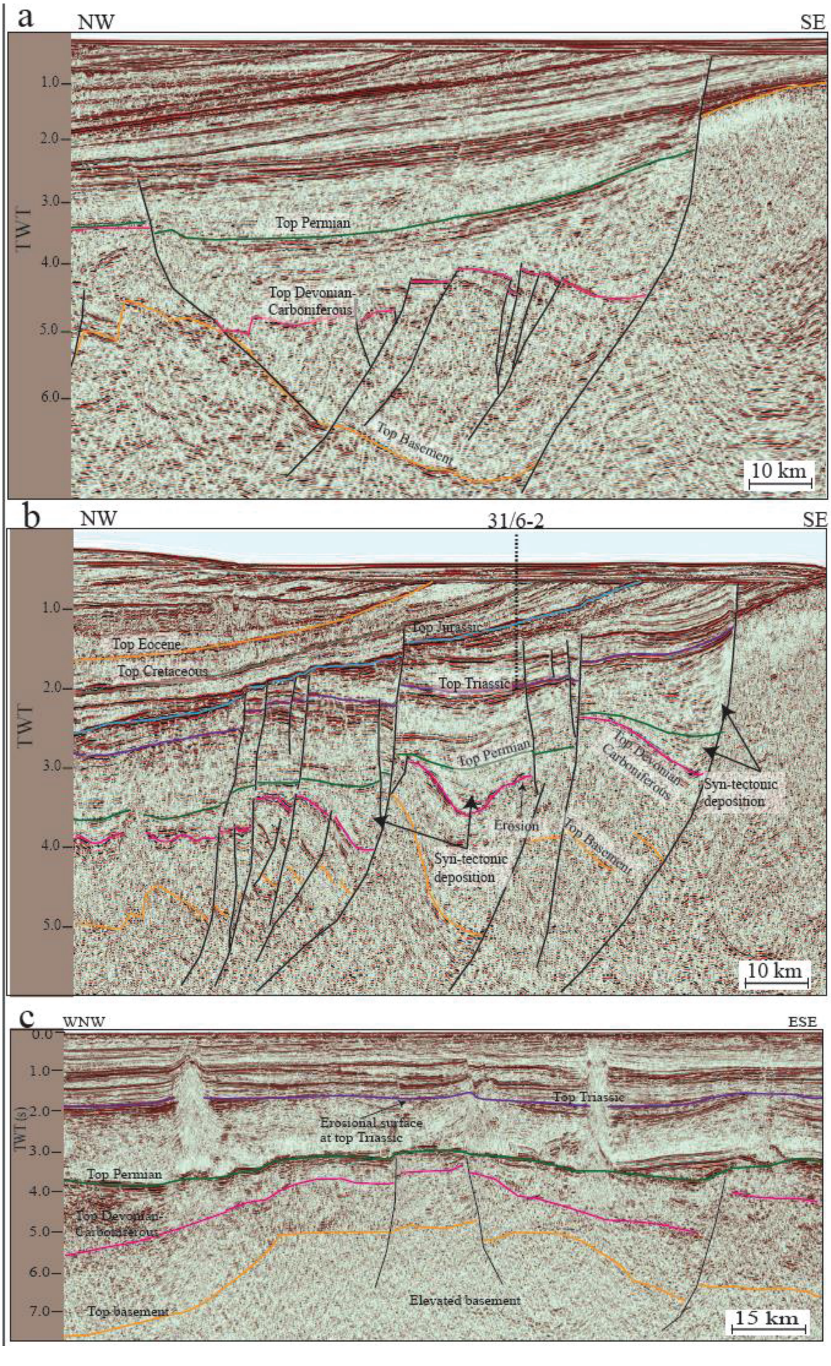

Figure 5: Seismic examples of Devonian-Carboniferous basins, Permian rifting and Jurassic inversion. Seismic sections are courtesy of Fugro and TGS.

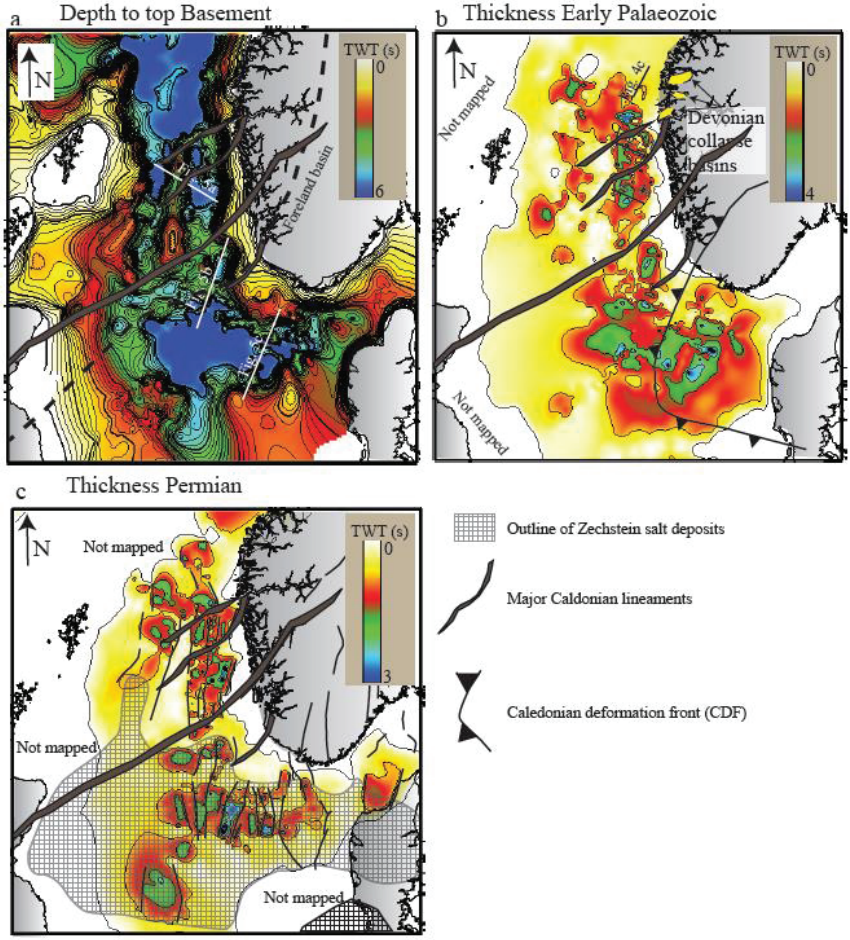

Figure 6: Depth to top basement (in TWT) (a), time thickness map of the Early Paleozoic (b), time-thickness of the Permian succession (c).

Seismic interpretation of the top Permian seismic reflection reveals sediment thicknesses greater than 3 s TWT, located within N-S trending graben structures, both in the central and northern North Sea (Fig. 6c). The upper bounding seismic reflection is characterized by a strong amplitude anomaly in the central North Sea, correlative with Zechstein evaporates in well sections. Seismic interpretation of the upper bounding seismic reflection is also feasible in the northern North Sea, where it correlates with a set of high seismic amplitude anomalies (Fig. 5). Extensional tectonics during the latest Carboniferous - Triassic is well constrained in the southern North Sea, central North Sea and in the Skagerrak and Oslo grabens (e.g. Heeremans et al., 2004; Heeremans & Faleide, 2004; Torsvik et al., 2008; Lundmark et al., 2012). However, the extensional phase is less explored in the Stord Basin area and northwards, where the main controversy is the age of the rifting itself. Since no wells penetrate the upper seismic reflector corresponding to the top syn-rift phase in the Stord Basin area, the exact age of the rift phase has been difficult to constrain, though often considered as Triassic or Permo-Triassic (e.g. Steel & Ryseth, 1990; Roberts et al. 1995; Færseth, 1996; Heeremans & Faleide, 2004). However, observations and seismic interpretation in this study indicates that the extensional stress regime most likely ended in late Permian in the southern Stord Basin area, though probably sustained until the Early Triassic in the Horda Platform area and, potentially, further northwards. The main Permian graben structures in the northern North Sea are located in the same areas as identified for the Devonian-Carboniferous basins, and the Caledonian lineaments may have had an impact on offsets/transfer zones in the Permian rift system, as indicated in the thickness distribution map in Fig. 6c. This indicates that extension in the northern North Sea was influenced by the same Caledonian lineaments as during the Devonian-Carboniferous. Also shown in this thesis, depocenter formations and drainage systems have been associated with the same lineaments during the Mesozoic and Cenozoic, which indicates that Caledonian structures have been important in basin development and the overall structural evolution of the North Sea region until today.

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Conference abstracts

i) **Abstract 1:** Jarsve, E. M., Faleide, J. I. & Gabrielsen, R. H., 2009. The Cenozoic balance between shelf sedimentation and uplift of southern Norway. NGF Winter meeting, Oslo.

ii) **Abstract 2:** Jarsve, E. M., Faleide, J. I. & Gabrielsen, R. H., 2009. Mesozoic and Cenozoic asymmetrical depositional systems in the North Sea. In relation to uplift of southern Norway ("source-to-sink"). NPF, Stavanger.

iii) **Abstract 3:** Jarsve, E. M., Gabrielsen, R. H. & Krøgli, S. O., 2012. Generating digital surfaces – mapping the sub-Cambrian peneplain in southern Norway. NGF winter meeting, Reykjavik.

iv) **Abstract 4:** Jarsve, E. M, Maast, T. E. & Faleide, J. I., 2013. Seismic stratigraphic sub-division of the Triassic succession in the central North Sea – integrating seismic reflections and well data. NGF winter meeting, Oslo.

Papers

Paper 1

Seismic stratigraphic subdivision of the Triassic succession in the Central North Sea; integrating seismic reflection and well data

By:

Erlend Morisbak Jarsve, Tom Erik Maast, Roy Helge Gabrielsen, Jan Inge Faleide, Johan Petter Nystuen and Caroline Sassier.

Journal of the Geological Society. 2014, **171**, 353-374

Paper 2

Mesozoic and Cenozoic basin configurations in the North Sea

By:

Erlend Morisbak Jarsve, Jan Inge Faleide, Roy Helge Gabrielsen and Johan Petter Nystuen.

Int. Assoc. Sedimentol. Spec. Publ. **46**, 417–452

Paper 3

The Oligocene succession in the eastern North Sea – basin development and depositional systems

By:

Erlend Morisbak Jarsve, Tor Eidvin, Johan Petter Nystuen, Jan Inge Faleide, Roy Helge Gabrielsen and Brit Inger Thyberg

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The Oligocene succession in the eastern North Sea – basin development and depositional systems

Jarsve, E. M.[1], Eidvin, T.[2], Nystuen, J. P.[1], Faleide, J. I.[1], Gabrielsen, R. H.[1] and Thyberg, B. I.[3]

[1]Department of Geosciences, University of Oslo, PO Box 1047 Blindern, N-0316 Oslo, Norway

[2]Norwegian Petroleum Directorate, PO Box 600, NO 4003 Stavanger, Norway

[3]CGG Multi Client Scandinavia and Russia, PO Box 490 Skøyen, 0213 Oslo, Norway

Abstract - The Oligocene sedimentary succession in the eastern North Sea is revised and re-interpreted, by applying new state-of-the-art reflection seismic data integrated with new bio- and Sr-stratigraphy from three key wells in the study area. The Oligocene succession in the eastern North Sea is divided into four transgressive-regressive (T-R) sequences, characterised by non-accretional and/or aggradational transgressive systems tracts and prograding regressive systems tracts. Detailed studies of three wells, including biostratigraphy and Sr-analysis, constrain the age-relationships between the transgressive-regressive (T-R) sequences. Internal clinoform geometry indicates that the sediments were sourced from the present southern Norwegian mainland to the north of the depositional area. The direction of progradation shifted from being southeast directed in the earliest Rupelian (early Oligocene) to the south and southwest during Chattian times (late Oligocene). Rapid basin subsidence is indicated by the development of non-accretionary transgressive systems tracts, with subsequent progradation into water depths of hundreds of metres. The creation of accommodation space was out-of-phase relative to eustatic sea-level changes, and mainly controlled by regional-scale differential vertical movements where uplift and exposure of landmasses of the hinterland (southern Norway) occurred concurrently with basin subsidence. Halokinesis had an intra-basinal influence on the main sediment transport direction, although probably did not contribute much in creation of accommodation space.

1. Introduction

To understand the source to sink relationships in sedimentary basin is crucial to comprehend the coupling between regional and local tectonics, together with climate changes and hinterland geomorphology. Increased interest have therefore been on the onshore-offshore relationship to study the relation between climate and tectonics (e.g. Riis, 1996; Gabrielsen et al., 2005, 2010a; Stoker et al., 2005; Japsen et al., 2006; Nielsen et al., 2009; Miller et al., 2013; Medvedev et al., 2013; Redfield & Osmundsen, 2013).

It is evident from observations of siliciclastic wedges in the eastern North Sea basin that the source area of terrigenous detritus changed from being situated to the west in the Paleocene and Eocene times to becoming mainly situated to the north (i.e. southern Norway) in the Oligocene time (e.g. Jordt *et al.* 1995, 2000; Michelsen *et al.* 1995; Faleide *et al.* 2002). It has previously been proposed that observed changes in the sedimentary pattern at the Eocene-Oligocene boundary of North Europe was due to tectonic uplift of Scandinavia and associated subsidence in the adjacent North Sea basin. (e.g. Jordt *et al.* 1995; Michelsen *et al.* 1995; Faleide *et al.* 2002; Gabrielsen *et al.* 2010). The same authors suggested that tectonic increase in relief was the triggering mechanism of changes in climatic conditions and associated switches in erosion and drainage systems. However, in a series of recent studies this view has been challenged by the interpretation of that the recorded changes in sedimentary trends can be ascribed solely to major climatic cooling at the Eocene – Oligocene boundary (e.g. Clausen et al. 1999; Huuse & Clausen, 2001; Huuse *et al.* 2001; Nielsen *et al.* 2009; 2010; Goledowski *et al.* 2012). Nielsen *et al.* (2009, 2010) suggest that the topography of southern Norway has been significant since the establishment of the Caledonian Orogeny in Silurian-Devonian time and mainly changed through the combined effects of erosion due to climatically forced weathering/erosion and associated isostatic response and extensional collapse. Hence, this view excludes the effect of increased relief from tectonic uplift of Scandinavia in Oligocene time.

In our view, several aspects of the tectono-dynamic and climatic changes that influenced Cenozoic sedimentation of eastern North Sea are not yet fully understood, such as the relationship between creation of accommodation space and global climate changes and basin subsidence. In this context, the Oligocene succession studied provides relevant and new information on sediment transport directions, sedimentation rates and migration of depocentres, and is a good candidate for studying the relationship between tectonic and climatic influence in a source to sink system. In particular, we would emphasise the development of accommodation space in the basinal area and its possible linkage to development of relief in the hinterland area and/or climate changes in Oligocene time by integrated studies of bio –and Sr-stratigraphy, seismic sequence stratigraphic techniques and

published climate data. Hence, the present work aims at re-evaluating the Oligocene sedimentary succession in the eastern North Sea area, based on improved age control and enhanced seismic coverage in the Norwegian sector (Fig. 1). These data are complementary to the data set used in previous studies (Michelsen & Danielsen, 1996; Danielsen *et al.* 1997), which had their main focus on the Oligocene sequences in the Danish sector. Our study includes an analysis of any relative influence of tectonic uplift and climate changes to the development of relief and rate of erosion in the hinterland and sedimentary flux to the basin, as well as a discussion of the processes influencing the accommodation space in the basin, such as basin subsidence, eustasy and halokinesis. We will furthermore discuss the interplay between climate changes and tectonics from seismic sequence stratigraphic analyses.
The study area is situated between longitudes 3^{o}E – 8^{o}E and latitudes 55^{o}N – 58^{o}N (Fig. 1).

2. Regional Geology

The main structural element in the study area is the Norwegian-Danish Basin, which is a major, NW-SE oriented basin of Mesozoic age in the central and eastern North Sea. It is bounded to the south by the Ringkøbing-Fyn High and the Coffee-Soil Fault Complex and to the north by the Fjerritslev Fault Zone and Farsund Basin (Fig. 1). The Fjerritslev Fault Zone and Farsund Basin are closely associated with the Sorgenfrei-Tornquist Zone, as known from Denmark and further southeastwards, and are often considered as the Fennoscandian Border Zone (Ziegler, 1990; Berthelsen, 1998; Fredriksen *et al.* 2001; Heeremans & Faleide, 2004; Heeremans *et al.* 2004).

One of the most striking events in the North Sea basin during the Cenozoic was the marked change in sediment provenance at the Eocene – Oligocene boundary in the eastern North Sea area (e.g. Jordt *et al.* 1995, 2000; Huuse, 2002; Faleide *et al.* 2002; Anell *et al.* 2010). In the latest Paleocene – Eocene, sediments of the North Sea basin were primarily derived from the East Shetland Platform and the British Isles to the west (Galloway *et al.* 1993; Jordt *et al.* 1995; Rohrman *et al.* 1995; Faleide *et al.* 2002; Anell *et al.* 2010, 2012). This was related to tectonic uplift of the East Shetland Platform in Late Paleocene during break-up of the northeast Atlantic (e.g. Jordt *et al.* 1995; Faleide *et al.* 2002). Minor sediment influx from the north in Paleocene time in the eastern North Sea area (e.g. Hamberg *et al.* 2005) may indicate a tectonic uplift of parts of southern Norway as well during break-up of the NE Atlantic

(Jordt *et al.* 1995, 2000; Martinsen *et al.* 1999; Huuse, 2001; Faleide *et al.* 2002; Dmitrieva *et al.* 2012). The main sediment transport was focused towards the eastern North Sea in the Early Oligocene, reflecting a shift from a mainly western source area during the Paleocene and Eocene to a mainly northern source area in the Oligocene (e.g. Jordt *et al.* 1995, 2000; Michelsen *et al.* 1995; Clausen *et al.* 1999; Japsen *et al.* 2002, 2007; Faleide *et al.* 2002; Gabrielsen *et al.* 2005, 2010; Schiøler *et al.* 2007; Anell *et al.* 2009, 2010, 2012). The same authors ascribe this shift in main provenance area to be linked to a tectonic uplift of southern Norway in Late Palaeogene - Neogene times. A second tectonic phase was proposed to have occurred in the mid-Miocene time (e.g. Japsen & Chalmers, 2000; Stoker *et al.* 2005; Japsen *et al.* 2007; Rasmussen, 2009). However, other authors have suggested that the Oligocene siliciclastic wedges and mid-Miocene unconformity are related to climatic changes, reflected by increased erosion and sediment transport (e.g. Huuse *et al.* 2001; Huuse, 2002; Goledowski *et al.* 2012). These authors suggest that only isostasy, climate and eustatic changes influenced erosion and sediment transport on an already established topography. Nielsen *et al.* (2009, 2010) also believe that the then existing topography in southern Norway was a remnant of the Caledonian orogeny; the ICE-hypothesis.

In the Pliocene – Pleistocene, glaciations in Scandinavia gave rise to increased erosion rates of the Norwegian mainland, with subsequent isostatic response and basinward tilting (i.e. dip-direction to the SW) of the Mesozoic and Cenozoic sedimentary successions in the eastern North Sea (e.g. Riis, 1996; Huuse *et al.* 2001; Faleide *et al.* 2002; Huuse, 2002; Gabrielsen *et al.* 2005, 2010; Nielsen *et al.* 2009). However, Stoker *et al.* (2005) showed that the onset of major progradation was initiated about 4 Ma, which pre-dates the growth of glaciation by at least 1 My, implying a potential tectonic phase in the Pliocene (Japsen *et al.* 2007).

3. Seismic Sequence Stratigraphy

Data

The present study utilizes more than 20 000 km of long-offset 2D data (NSR survey), combined with detailed studies of three key wells: 11/10-1, 9/12-1 and 2/2-2 in the Norwegian sector (Fig. 1). The NSR seismic survey was acquired by Fugro and TGS Nopec in the period 2003 – 2009 on the Norwegian continental shelf. The NSR seismic survey is a high-quality uniform data set with a vertical resolution of approximately 10-20 metres, which offers seismic coverage beyond that seen in previous studies. In addition to the NSR survey, the surveys NDT and UG in the Norwegian sector and DCS, DK1, DK2, DT97, SP82 and UCGE97 in the Danish sector were utilized to achieve a complete updated coverage of the study area and to obtain full comparison with previous studies.

Previous applied seismic stratigraphic sequences

The Cenozoic succession in the northern and eastern North Sea area has been subdived into depositional sequences *sensu* Mitchum *et al.* (1977) and Vail (1987) (Exxon Model), by Jordt *et al.* (1995, 2000), Michelsen & Danielsen (1996), Danielsen *et al.* (1997), Michelsen *et al.* (1998), Martinsen *et al.* (1999) and Faleide *et al.* (2002). However, these authors pointed out the challenges in identifying the system tracts that ought to be present according to the depositional sequence model of Exxon, particularly the lowstand and transgressive systems tracts (Michelsen *et al.* 1995; Michelsen & Danielsen, 1996; Danielsen *et al.* 1997; Michelsen *et al.* 1998; Martinsen *et al.* 1999). Michelsen & Danielsen (1996) and Danielsen *et al*. (1997) documented that downlap surfaces correlated with high-gamma peaks and interpreted these surfaces as maximum flooding surfaces. However, they were also able to indentify the sequence boundary (*sensu* Exxon depositional model) on the basis of both seismic downlaps and onlaps, which appears contradictional as downlap presumes the presence of accommodation space above the surface. If the boundaries of the sequences defined by Michelsen *et al*. (1995, 1998), and in the other studies referred to above that followed the same systematics, were formed as subaerial unconformities in accordance with the Exxon depositional sequence model (*sensu* Van Wagoner *et al.* 1987; 1988; 1990; Posamentier *et al.* 1988; Posamentier & Vail, 1988), there would not be any marine accommodation space above these surfaces except in the deeper parts of the basins, and then above conformable surfaces correlative to the subaerial unconformity. Nevertheless, above some of these sequence boundaries there are downlapping prograding successions, implying that marine accommodation had formed.

Seismic sequence stratigraphic model applied in the present study

The challenges related to the identification of bounding surfaces between possible lowstand and transgressive deposits on seismic sections in Cenozoic successions in the North Sea area make it difficult to apply the lowstand, transgressive and highstand systems tracts of the Exxon depositional sequence model. However, as also pointed out by Michelsen *et al*. (1998), several of the Cenozoic successions display distinct transgressive-regressive trends, demonstrated by seismic facies, clinoform geometry and well-log trends. Transgressive-regressive trends reflect the interplay between creation and/or destruction of accommodation space (A) and the rate of sedimentation (S), which are the controlling factors in basin infill dynamics, irrespective of types of allogenic driving factors such as tectonics, eustasy, climate and geomorphology. Thus, in our sequence stratigraphic analysis we apply the T-R sequence stratigraphic model (Embry, 1988, 1993, 1995; Embry & Johannessen, 1992; Fig. 2).

The transgressive systems tract (TST) can be non-accretionary, implying lacking sediments deposited during rise in relative sea-level, or consisting of sediments thicknesses less than the seismic resolution (Helland-Hansen, 1995). Accretionary TST consist of marine successions with aggrading stacking geometry (Fig. 2). The underlying bounding transgressive surface, TS, coincides with a regional unconformity, defined by toplap and/or toplap truncation. The part of the surface characterised by toplap truncation is interpreted as a subaerial unconformity (SU), whereas the toplap part of the surface is a candidate for the marine conformable part of the SU. Alternatively, this part of the regional unconformity may represent subaerial exposure without marked erosion, or a shallow-marine omission, bypass or ravinement surface. Onlap on the regional unconformity implies creation of accommodation space, and hence the establishment of the TS, accompanied by sedimentation, as marine and/or coastal onlap. The combined subaerial unconformity and the transgressive surface are termed a SU/TS surface.

The transgressive systems tract is bounded at the top by a regional surface characterised by downlap. This is the maximum flooding surface (MFS), forming the lower bounding surface of the regressive systems tract (RST). In cases where a transgressive systems tract is absent, the MFS may coincides with both the regional unconformity and the transgressive surface, forming a combined SU/TS/MFS surface. The regressive systems tracts are distinguished by progradational successions with internal clinoform geometry. In this system, eventual deposits formed during a fall in relative sea level will be included in the regressive systems tract.

Nomenclature

In this study, we introduce an adjusted nomenclature for the Oligocene seismic sequences (herein referred to as the 'Oligocene seismic sequences' (OSS; Figs. 2 & 3), compared to previous studies (Jordt *et al.* 1995; Michelsen & Danielsen, 1995 and Danielsen *et al.* 1997).

The need of a new nomenclature is due to the T-R systematic subdivision employed in this study compared to previous studies which applied the 'Exxon' systematics. We divide the Oligocene succession in four seismic sequences, where two of the sequences are of Early Oligocene age (OSS-1 and OSS-2) and the two later sequences are of Late Oligocene age (OSS-3 and OSS-4). The sequence boundaries are compared to previous studies and summarised in figure 3.

4. Methods

Well correlation

The seismic data were tied to available wells, including key wells 11/10-1, 9/12-1 and 2/2-2 in the Norwegian sector (Figs. 4 & 5) and wells F-1, Inez-1, D-1, Nini-1 and Ibenholt-1 in the Danish sector. Extensive studies, including biostratigraphy and Sr-stratigraphy, were only pursued on material from the Norwegian wells. More comprehensive studies of the Norwegian wells are presented in Eidvin et al. (2013). In combination with the new stratigraphic information obtained from the biostratigraphical and chemostratigraphical studies, the seismic geometries were used to establish a depositional model for the study area with a particular emphasis on recognising progradation direction and transgressions as well as maximum flooding surfaces.

Biostratigraphy and Strontium Isotope Stratigraphy (SIS)

For this study, new micropalaeontological and Sr-isotope analyses from well 2/2-2, 9/12-1 and 11/10-1 are used to obtain a better age control on the Oligocene sequence in the eastern North Sea. Altogether 66 ditch cutting samples and two conventional core samples (well 2/2-2) were analysed (Table 1, Fig. 4).

Micropalaeontological analyses

The micropalaeontological investigations are based on analyses for planktonic and benthic foraminifera and pyritised diatoms. The fossil assemblages are correlated with the biozonation of King (1989), who outlines a micropalaeontological zonation for Cenozoic sediments in the North Sea. Gradstein and Bäckström's (1996) faunal zonation from the North Sea and Haltenbanken is also used.

Strontium isotope analyses

Strontium isotope stratigraphy is used as an additional control on the biostratigraphic correlations. The $^{87}Sr/^{86}Sr$ ratio of seawater is very uniform on a global scale, which is a reflection of the long oceanic residence time of strontium (2-4 My), combined with a relative short (≤2000 years) oceanic mixing rate. Sr isotope stratigraphy is an effective tool particularly for dating of Miocene and Oligocene sections. It has best resolution in sediments older than 15 Ma. The reason for this is that seawater Sr isotopic composition changed rapidly during this period (e.g. Howard & McArthur 1997).

23 samples were investigated for their Sr isotopic compositions with a total of 41 analyses (Table 1, Fig. 4). The majority (26 analyses) were conducted on tests of calcareous index foraminifera, the remainder on mollusc fragments (15 analyses, from sandy sections). Sr values were converted to age estimates using the strontium isotope stratigraphy look-up table of Howard & McArthur (1997). This table is based on the time scale compiled by Berggren *et al.* (1995), which for the Oligocene does not deviate significantly from the new time scale of the International Commission on Stratigraphy (ICS, 2013). See McArthur *et al*. (2001), Howard & McArthur (1997) and Eidvin & Rundberg (2001, 2007) for details about the precision of the method. Also note that the micropalaeontological zonation of King (1989) is based on the time scale of Berggren *et al*. (1985), but we have converted the ages to the time scale of Berggren *et al*. (1995). The micropalaeontological zonation of Gradstein and Bäckström (1996) is based on the time scale of Cande & Kent (1992) in which the absolute ages are identical to those of Berggren *et al*. (1995).

Volume estimates and water depths

The sound wave velocity is set to 2000 m/s for the combined Cenozoic succession, as measured in the studied wells (check shot; 11/10-1, 9/12-1 and 2/2-2). 2000 m/s was also applied by Jordt *et al*. (2000). Volumes of sediments are calculated for each of the sequences within the 100 m (100 ms TWT) contours (Fig. 6). The volumes are calculated between the upper and lower bounding surfaces for each sequence, hence including both the TST and the RST. However, note that these estimates give minimum volumes, because no allowance has been made for compaction and post-depositional erosion. In addition, there may be undetected sediment volumes deposited beyond the study area.

The estimated water depths are based on the heights of clinoforms for each sequence as calculated after correcting for later tilting of the corresponding downlap surface, assuming that the clinoform height also represents the palaeo water depth.

5. Description and analysis of the seismic sequences

The Oligocene seismic succession was subdivided into four 2nd. order seismic sequences, all of which are characterised as T-R sequences (Fig. 2). The following is a description of the Oligocene seismic sequences (OSSs).

5.a. Oligocene seismic sequence 1 (OSS–1)

The lower boundary of OSS-1 is defined by a downlap surface (Fig. 7). This surface is characterised by a strong and continuous reflector, mapable across the entire study area. It represents sedimentary strata which drape a surface that shows erosional truncation into underlying Eocene and Paleocene strata to the east and southeast of Norwegian well 9/12-1 (Fig. 8). OSS-1 is identified mainly in the Norwegian sector and is upward bounded by toplap truncation and succeeded by OSS-2 (Fig. 7). The upper sequence unconformity corresponds with the Oi1a global cooling event (Pekar et al. 2002), which in well 11/10-1 also corresponds with a section including the dinoflagella cyst *Svalbardella* (Sliwinska and Heilmann-Clausen, 2011).

The main depocentre of OSS-1 is located in the area west and southwest of Norwegian well-site 11/10-1 (Fig. 7). Here the sequence reaches a maximum thickness of 300 m (Fig. 7) and the estimated net depositional volume rate is 866 km^3 My^{-1}. This is a minimum estimate as volume loss from mechanical compaction, and sediments transported beyond the study area, are not included. The sequence thins eastward to less than 50 m at the Danish well F-1, and also thins towards the west and southwest (Fig. 7).

In the central part of the depocentre, OSS-1 is strongly influenced by a salt structure (Fig. 9). This corresponds with the area where the sequence reveals its maximum thickness. OSS-1 strata thin across this salt structure and onlap its flanks (Fig. 9). Similarly, the sequence onlaps a salt structure southeast of well 11/10-1, on the Norwegian-Danish border, and further to the east its thickness is reduced to less than that detectable within the seismic resolution. OSS-1 is not seen in the Inez-1 well area. Towards the north, OSS-1 onlaps

Eocene strata along the NW-SE striking Fjerritslev Fault Zone (Figs. 10 & 11a). It is noteworthy that in contrast to OSS-1, the Eocene and Palaeocene sequences thickens northwards, indicating that the Fjerritslev Fault Zone area represented parts of the depositional area in Early Palaeogene time.

OSS-1 contains seismic geometries that are characterised by clinoforms prograding SSE, which is perpendicular to the basin axis during deposition (NE–SW; Fig. 7). The clinoforms have a complex, sigmoidal/oblique geometry, with dips between 0.5^{o} - 1^{o}. The clinoform heights are approximately 100 m, and the prograding succession is upwards bounded by clinoform toplap truncation (SU). The clinoforms shift to a more sigmoidal geometry in the southwestern part of the depositional area, where the clinoform topsets are preserved (Fig. 11b). Well 11/10-1, which penetrates the prograding clinoforms, reveals gamma log readings consistent with fine-grained sediments throughout OSS-1 (Fig. 4). The gamma log also reveals upward-decreasing gamma ray response of individual packages, interpreted as upward-coarsening parasequences, typical for prograding, regressive depositional systems.

Interpretation

Based on the downlapping of the internal clinoforms onto the basal bounding reflector of OSS-1, and the strong and regional character, this basal reflector is interpreted as a MFS. The Eocene – Oligocene boundary at the base of OSS-1 resembles a marine erosional surface, representing either a ravinement surface (>20 m water depth) or the action of deep marine currents (in up to hundreds of metres water depth, e.g. Nichols, 2009). However, as the TST at the base of OSS-1 is non-accretionary, the lower bounding surface of OSS-1 is a combined SU/TS/MFS surface, at least in the platform margin areas of the basin. This is supported by well data offshore Denmark (Danielsen *et al.* 1997) and by observations onshore Denmark, which reveal that the base of the Viborg Formation contains glauconite, supporting the presence of a well developed hiatus (Christensen & Ulleberg, 1973) that may represent a non-accretionary TST.

The clinoform heights indicate water depths of approximately 100 m in the earliest Rupelian time. The shale lithology, as recorded in well 11/10-1, is consistent with a parallel and sigmoidal clinoform geometry together with gentle clinoform dips (0.5^{o}-1^{o}), typical where fine-grained material dominates (e.g. Mitchum *et al.* 1977; Veeken, 2007). Such depositional systems are also often characterised by low energy in the basin, where limited reworking of the sediments takes place.

The thinning of OSS-1 and its onlapping pattern against the salt diapir located within the central part of the OSS-1 depocentre (Fig. 9) is taken to indicate diapirism during deposition of the sequence in Early Rupelian time. Similarly, halokinesis is interpreted to have controlled the eastern extent of the main depositional area of OSS-1, as seen from the onlap contact and thinning of OSS-1 onto salt diapirs at the Norwegian-Danish border, thus reflecting bathymetric relief here in earliest Rupelian time. Salt mobilization is also known from onshore Denmark during the Oligocene (Japsen *et al.* 2007)

5.b. Oligocene seismic sequence 2 (OSS-2)

The lower boundary of OSS-2 corresponds to the erosional surface representing the SU at top OSS-1. OSS-2 also contains an internal downlap surface, represented by a strong continuous seismic reflector which is recorded across most of the study area (Fig. 7). The upper boundary of OSS-2 is characterised by toplap truncation and severe incision (Fig. 12), and is considered equivalent to the upper boundary of unit 4.2 in Michelsen and Danielsen (1996; Fig. 3).

OSS-2 displays a maximum thickness of approximately 550 m south of wells 11/10-1 and F-1, and thins south –and westwards to less than 100 m (Fig. 12). Unlike OSS-1, OSS-2 maintains a uniform thickness northwards, with no observed onlap or marked thinning in the Fjerritslev Fault Zone area (Fig. 10). Based on the recorded thicknesses, the bulk sediment volume rate is calculated to approximately 616 km^3 My^{-1} (Fig. 6).

In well 11/10-1 and southwards, the lower part of OSS-2 is characterised by seismic geometries showing southeasterly dipping clinoforms with off-lap breaks defining a near-vertical trajectory, thus showing an aggrading depositional geometry of about 100 m (Fig. 10). The gamma ray log trend in well 11/10-1 indicates the presence of slightly upward-coarsening parasequences (Fig. 4). The gamma response culminates in the middle part of OSS-2 in a strong peak (Fig. 4) which in stratigraphic position coincides with a strong and continuous seismic reflection (Fig. 5). This continuous character of the seismic reflection likely reflects strata that drape the aggrading clinoforms and acts as a downlap surface for the upper part of OSS-2.

The upper part of OSS-2 is characterised by a seismic succession with prograding clinoforms dipping towards the south and southwest. The clinoforms have a tangential oblique geometry, with clinoform heights of approximately 200 – 250 m and clinoform dips from 1.5^{o} to 5.5^{o}. The upper boundary suggests erosion as evidenced by truncation and incision of the clinoform topsets (Fig 12). The incision of the clinoform topsets are up to 20-30 meters vertical depths (Fig. 12), indicating channel deposition. The clinoforms shift westwards to more complex sigmoidal/oblique geometry (Fig. 11b). Onlap from sediments belonging to OSS-3 is recorded against the upper SU of OSS-2, indicating coastal onlap (Fig. 12).

Internally, the clinoform system in the upper part of OSS-2 is highly complex with lensoidal subunits bounded by unconformities and onlap surfaces (Fig. 12), indicating internal clinoform reflectors dipping in various directions.

In the frontal part of the prograding clinoforms (i.e. basinwards), OSS-2 is characterised by a 150 m interval with strong seismic amplitude reflectors (Figs. 10 and 11a). These seismic reflectors downlap onto the bottom-bounding reflector relative to the succession of SSW prograding clinoforms of the same sequence as well as onlapping the frontal part of the prograding clinoforms towards the NNE (Fig. 10).

At the position of Norwegian wells 11/10-1, 9/12-1 and northwards, OSS-2 is characterized by parallel seismic reflectors. The gamma ray log in the well 11/10-1 reveals an upward-coarsening succession, as indicated by the upward decrease in gamma readings (Fig. 4).

Interpretation

The lower bounding surface for this sequence represents a sequence boundary separating OSS-1 and OSS-2. As indicated by the aggrading depositional pattern, the lowermost part of OSS-2 is interpreted as a TST where sediment input closely balanced the rate of creation of accommodation space during the transgression. The strong and continuous character of the reflector, its downlap pattern and the gamma ray peak of the reflector defining the top of the TST, are interpreted to represent the MFS. As indicated by the clinoform heights, the water depth during transgression is assumed to have reached approximately 250 m during maximum transgression.

The prograding part of OSS-2 is interpreted to constitute the RST. The oblique geometry of the clinoforms is typical for coarse-grained clastic debris (Hansen and Rasmussen, 1998; Bullimore *et al.* 2005). However, the internal architecture of the upper part of OSS-2, with its shifting lensoid geometry and erosional surfaces (Fig. 12), probably represents various depositional lobes, shifting in position and progradational direction through time. Lateral shifts in sediment accumulation are typical for delta lobes and can be explained by avulsion and shifting transport directions of the fluvial system in the hinterland, as seen with modern deltas (e.g. the Mississippi delta; Coleman, 1988). However, as halokinesis is recorded at the time of deposition of OSS-2, local doming within the basin is likely to have created local barriers for the sediments and thereby also influenced the pattern of sedimentation laterally through time.

The sediments belonging to the TST of OSS-2 entered the basin from the north-northwest, following similar sediment routing as OSS-1. The shift in direction of progradation, from SE for OSS-1 and the lower part of OSS-2 to S and SW for the upper part of OSS-2, may indicate that the entry point of the sediment influx to the basin shifted or that depocentres of depositional lobes changed position. The parallel, subhorizontal seismic reflectors in the northern part of the study area are interpreted as shallow marine shelf deposits.

Based on the downlap onto the maximum flooding surface and onlap onto the RST of OSS-2, the uppermost part of OSS-2 is interpreted as lowstand fan deposits. These are likely to contain gravity flow facies derived as erosional material from the shelf (Posamentier & Vail, 1988).

The depositional evolution of OSS-2 was terminated by toplap truncation and major incision, creating an erosional surface interpreted as a sequence unconformity and a sequence boundary (Fig. 12). The upper sequence unconformity is probably of subaerial or shallow marine origin, supported by fossil assemblages typical for the upper shoreface in well 11/10-1 (Fig. 4), and potential fluvial incision (Fig. 12).

5.c. Oligocene seismic sequence 3 (OSS-3)

South of the 11/9-1 well area, the lower boundary of OSS-3 bears the characteristics of a marine flooding surface, which in the area just south of well 11/10-1 coincides with the erosional SU bounding OSS-2. Here, downlap of seismic reflectors is recorded in the distal part of the depocentre and the same reflectors onlap the RST of OSS-2 in the more proximal part of the depocenter (Fig. 10). The upper boundary of OSS-3 is also characterised by toplap truncation (Fig. 13), and corresponds to the top of unit 4.3 in Michelsen & Danielsen (1997, Fig. 3). The main depocentre of OSS-3 was located south of the depocentre of OSS-2, where a maximum thickness of about 200 m (Fig. 13) is recorded. In the southern parts of the study area the lower part of OSS-3 thins across salt diapirs and onlaps against them (Fig. 9b). The thickness and duration of sedimentation are consistent with a sediment volume rate of approximately 796 km^3 My^{-1}. The sequence thins to less than 100 m to the south and west, including the 9/12-1 well area (Fig. 13).

In the lower part of OSS-3, seismic reflectors with an aggradational geometry are dipping towards south-southwest. These onlap the prograding clinoforms related to OSS-2, including the erosional surface (SU) which towards the north truncates the OSS-2 clinoform succession (Figs. 10 & 13).

A strong continuous reflector, which extends across the entire study area, represents sedimentary draping of the aggrading clinoform set. This reflector represents a stratigraphic surface with prograding clinoforms downlapping onto it (Fig. 13). The prograding clinoforms above this surface dip towards the SSW with an oblique geometry, with clinoform toplap truncation below offlap break (Fig. 13). These prograding clinoforms are restricted to the area of maximum thickness of the sequence (>200 m; Fig. 13) and hence only identified in the Danish sector, NNE of the Nini-1 well (Fig. 13). The clinoform height is approximately 100 m, with clinoform dips of between 2^o and 3^o. Outside this area, the clinoforms shift to a more aggradational style, accompanied by a gradual thinning of the seismic successions to below seismic resolution west and southwest of the Nini-1 well, where the sequence boundary combines with the MFS within the T-R sequence.

In the northern part of the study area, at well 11/10-1 and northwards, sequence OSS-3 consists of parallel, subhorizontal reflectors. The OSS-3 consists mostly of sandstone, with abundant fragments of limestone and molluscs (Fig. 4**).** Sandstone also dominates the lithology of this sequence in the Danish wells F-1, Inez-1, Ibenholt-1 and D-1 (Danielsen *et al.* 1997). At the Norwegian well sites 2/2-2 and 9/12-1, which are positioned distally to the main depocentre, OSS-3 consists of shale (Fig. 4).

Interpretation

The upper sequence unconformity (SU) of OSS-2 was transgressed and the TS overlain by strata having an internal aggradational geometry of clinoforms. This aggradational succession is interpreted as representing the TST, in which the rate of sedimentation mostly equalled creation of accommodation space (like the lower part of OSS-2). The lower boundary of OSS-3 reflects first a shift from lowering of relative sea level with subaerial erosion to still stand or sediment bypass, succeeded by marine flooding and rise in relative sea level. The southwestern dip of the clinoforms indicates main progradational direction from the northeast, which is perpendicular to the orientation of the basin axis (Fig. 13).

As OSS-3 thins across salt structures in the southern parts of the depositional area, halokinesis appears to have influenced the depositional pattern, and acted as barriers in various parts of the basin during deposition of the sequence.

The progradational succession above the MFS within OSS-3 is interpreted to be the RST of OSS-3. The oblique geometry, in addition to the steepness of the clinoforms, is typical for systems deposited in a high-energy environment, where the coarser material may be trapped in the foresets (Bullimore *et al.* 2005; Veeken, 2007). The thickness map and the direction of clinoform dips may indicate that the sequence was sourced from the NNE (Fig. 13). The salt structures which developed simultaneously with deposition of OSS-3 likely influenced the continued southwestward progradation of the succeeding RST, by creating a narrow depositional basin for the prograding RST. This is supported by the oblique clinoform geometry, which are often characteristic for narrow depocentres (cf. Bullimore *et al.* 2005). The upper erosional surface that terminates the prograding clinoforms most probably formed as a subaerial unconformity (SU).

5.d. Oligocene seismic sequence 4 (OSS-4)

The lower boundary of OSS-4 is characterised as a downlap surface, where reflectors downlap onto a continuous high amplitude reflector which extends across the study area. In the eastern parts of the depocentre, onlap patterns are recorded against the frontal parts of the RST of OSS-3 (Fig. 10). However, this is not observed elsewhere in the depocentre. The clinoforms which onlap the frontal parts of the RST of OSS-3 share the same downlap surface as the overall OSS-4. The upper boundary of OSS-4 is a seismic surface characterised by toplap truncation (Fig. 14) and correlates with the upper boundary of unit 4.4 in Michelsen & Danielsen (1996) and sequence CSS-4 in Jordt *et al.* (1995). OSS-4 has a maximum thickness of 500 m and a sediment volume rate of approximately 2546 km^3 My^{-1}.

The main depocentre of OSS-4 is situated in the Norwegian-Danish Basin and is oriented NW-SE, as seen in the thickness map (Fig. 14). The sequence thins to less than 100 m to the south, southwest and to the west.

In OSS-4, seismic clinoforms dip towards the southwest and indicate progradation in this direction. The seismic geometry in the lower part of the sequence shifts towards the east, from progradational to aggradational, although with the same direction of dip.

The prograding clinoforms have a sigmoidal geometry, with internal onlap surfaces and erosional surfaces recorded within the succession. However, these are less pronounced and the clinoforms are downlapping the same downlap surface as the overall prograding succession (Fig. 14). The clinoform heights of sequence OSS-4 are between 200 to 300 m, with clinoform dips between 1^o and 2^o.

Interpretation

Based on the downlap pattern of the lowermost surface of OSS-4, this is interpreted as a maximum flooding surface (MFS), which within the seismic resolution coincides with a transgressive surface (TS). The TS succeeds a likely subaerial unconformity reflected by fossil assemblages in well 11/10-1 indicating shallow marine environment and the toplap truncation that terminates the underlying OSS-3 sequence in the platform areas of the basin. Although the onlap pattern at the frontal part of OSS-3 may represent a thin TST in the eastern part of the study area, the clinoforms share the same downlap surface as the overall sequence. This suggests that the sediment input may have been focused in another part of the basin during progradation. This is supported by the internal onlap surfaces recorded throughout the sequence, which indicate lobe switching and hence change in direction of main sediment input.

As the transgressive system tracts is only identified by the MFS at the base of OSS-4 (non-accretionary systems tract), and the maximum flooding surface appears to coincide with the toplap truncation surface cutting the underlying OSS-3, the transgression and resulting increase in accommodation space must have taken place quickly.

The prograding succession above this maximum flooding surface is interpreted to be the RST in OSS-4. The sigmoidal geometry, in addition to the steepness of the clinoforms, is typical for muddy systems, with sediments deposited in a low-energy system with substantial accommodation space (Mitchum *et al.* 1977; Bullimore *et al.* 2005). The thickness map and the direction of clinoform dips indicate that the sequence was deposited into the basin from the northeast (Fig. 14).

6. Discussion

The Cenozoic succession in the North Sea area has been the subject of numerous publications in recent years. These publications have been mainly concerned with relating late Palaeogene and Neogene sedimentation variations and depocentre migration to either a "tectonic model" or "climatic model". The "tectonic model" suggests tectonic uplift of southern Norway (e.g. Jordt *et al.* 1995, 2000; Danielsen *et al.* 1997; Michelsen & Danielsen, 1998; Michelsen *et al.* 1998; Faleide *et al.* 2002; Anell *et al.* 2010, 2012). The 'climatic model', mainly invokes climatic changes and isostatic adjustments as the controlling factors regarding sediment dispersal and depocentre migration in the eastern North Sea (e.g. Huuse & Clausen, 2001; Huuse *et al.* 2001; Nielsen *et al.* 2009, 2010; Goledowski *et al.* 2012). However, that both regional tectonics and climate changes have influenced the western Scandinavia in the Cenozoic is supported by more regional studies. These studies show that the prograding successions described in this study correlate to a period of substantial lithospheric reorganisation in the north Atlantic (e.g. Gaina *et al.* 2009), including alpine compression in southern Europe (e.g. Coward & Dietrich, 1989 and references therein), and the global cooling event at the Eocene – Oligocene boundary (e.g. Haq *et al.* 1987; Abreu & Anderson, 1998; Miller *et al.* 2005; DeConto *et al.* 2008; Pekar & Christie Blick, 2008; Scher *et al.* 2011). The aim of this paper is to discuss the creation of accommodation space and sediment infill according to the observations presented earlier, with emphasis on both regional tectonics and climate changes.

6.a. Creation of accommodation space, climate and shifting depocentres

This section discusses the development and migration of depocentres correlated to well-known eustatic sea level changes.

The base Oligocene unconformity (Fig. 8) corresponds in time with the eustatic fall in sea level at the Eocene – Oligocene boundary (e.g. Haq *et al.* 1987; Miller *et al.* 2005; Van Simaeys *et al.* 2005; Fig. 15), concurrent with major glaciation in Antarctica (e.g. Lear *et al.* 2004; Tripati *et al.* 2005; Pekar & Christie-Blick, 2008), and furthermore correlates with the regional O1 unconformity in the eastern North Sea (Huuse & Clausen, 2001; Huuse, 2002; Stoker *et al.* 2005; Japsen *et al.* 2007). Marine origin for the unconformity is suggested here, based on the shape of the erosional surface which resembles marine incision, possibly from ocean currents. Marine incision at the Eocene – Oligocene boundary has also been proposed by Clausen *et al.* (1999) and Huuse & Clausen (2001) offshore Denmark, to the east of the study area.

The sea level rise associated with deposition of the TST at the base of OSS-1 is correlative with a rise in eustatic sea level of about 30 m in the early phase of deposition of OSS-1 (Kominz & Pekar, 2001, Miller *et al.* 2005; Fig. 15). However, when considering that water depth was c. 100 m during deposition of the RST of the same sequence; additional basin subsidence is required. In particular one salt structure shows re-activation and diapir growth in the central part of the OSS-1 depocentre. Subsidence from salt removal in the sub-surface may have given additional basin subsidence in Early Rupelian time (halokinesis is discussed in more detail later in the paper). This reflects that the accommodation space related to OSS-1 developed mainly during marine erosion at the Eocene-Oligocene boundary, combined with halokinesis and rise in eustatic sea-level in the early Rupelian.

Succeeding progradation and deposition of the RST of OSS-1, erosion of the clinoform topsets indicates that the accommodation space created in Early Rupelian time was infilled by the RST of the same sequence. The erosional character of the upper bounding surface of OSS-1 (Fig. 7) may reflect either (1) subaerial exposure and continental incision, (2) erosion and truncation from deep marine currents or (3) a shallow marine ravinement surface. Both subaerial and deep marine erosion are often recognised by incision, parallel and/or perpendicular with direction of progradation. Also, deep marine erosion/incision often occurs basinward of the clinoform break point, of which has previously been documented to have occurred during the Cenozoic in the North Sea Basin (Clausen *et al.* 1999; Huuse & Clausen, 2001). The SU at top OSS-1 signifies clinoform toplap truncation (Fig. 7). Incised valleys that may reflect deep marine or continental incision have not been observed at the top of OSS-1 wherever in the study area. Hence, we propose that shallow marine erosion formed the SU at the top of OSS-1. This is also strengthened by the observation of shallow water fossil assemblages in well 11/10-1, indicating deposition in the middle neritic zone (Fig. 4). Although seismic resolution of the data set should be adequate to identify channel incision, of which is also observed at the SU at the top of OSS-2 (Fig. 12), it is noteworthy that similar features may be present but below seismic resolution at the top sequence OSS-1. However, based on the character of the erosional surface at top OSS-1, it is suggested here that the accommodation space available in Early Rupelian time was infilled by OSS-1 sediments. However, as the upper sequence unconformity corresponds with the Oi1a global cooling event (Pekar et al. 2002; Sliwinska and Heilmann-Clausen, 2011), it is also likely that a drop in eustatic sealevel took place at the later phase of deposition of OSS-1.

Following maximum regression and toplap truncation in early Rupelian (top OSS-1), aggradation and subsequent flooding of the RST of sequence OSS-1 indicates rise in relative sea level and creation of new accommodation space. The aggrading TST in the lower part of OSS-2 corresponds with a period with increased eustatic sea level (Kominz & Pekar, 2001; Fig. 15). This was followed by lowering of the eustatic sea level of the same magnitude, which indicates that global sea level changes cannot alone explain the development of new accommodation space involving an increase in water depth of minimum 250 m (Fig. 15). In general, isostatic flexuring due to denudation of the hinterland and sediment loading are important factors regarding subsidence in a sedimentary basin (Watts *et al.* 1982; Reynolds *et al.* 1991), and probably also during the late Palaeogene and Neogene in the North Sea (e.g. Huuse, 2002; Goledowski *et al.* 2009). These processes are considered to be slow, which may explain subsidence patterns over longer periods on the scale of first order sequences (e.g. the complete Oligocene sedimentary succession in the North Sea; Watts *et al.* 1982; Cloetingh *et al.* 1990). Exceptions are when isostatic rejuvenations are related to glacial meltdown, where isostatic adjustments of 100's of metres may take place within only some thousand years, as revealed during post-glacial rebound in Scandinavia during the Quaternary (e.g. Riis, 1996). The northern hemisphere were most likely barren for continental glaciers during the Oligocene (e.g. DeConto *et al.* 2008), and hence isostatic rejuvenations may hardly explain basin subsidence and rapid creation of accommodation space over short time periods of the Oligocene seismic sequences in the eastern North Sea. Creation of accommodation space of approximately 250 m during late Early Oligocene time cannot be solely explained by isostatic flexuring effects caused by increased erosion and sedimentation rates in the hinterland. This is supported by the low volume rates (accumulation rates) in the Late Rupelian (Fig. 15), which indicate drier climatic conditions and lower erosion rates in the hinterland. It is therefore proposed here that the accommodation space related to the RST of sequence OSS-2 was created during tectonic uplift of southern Norway and corresponding basin subsidence in the eastern North Sea. That sequence OSS-2 has a uniform thickness across the Fjerritslev Fault Zone area indicates that the northernmost parts of the study area are also likely to have been influenced by basin subsidence. This implies that the sedimentary basin extended northwards, potentially across parts of the present southern Norwegian mainland.

The deposition of OSS-3 and OSS-4 reflect continued creation of accommodation space due to relative rise of sea level in the Chattian time. Lowering of the eustatic sea level took place during deposition of OSS-3 (Fig. 15; Kominz & Pekar, 2001), which may reflect that the creation of accommodation space within the study area had a more local origin. However, the accretionary TST in the lower part of the sequence, combined with the basinward shift in progradation compared to the RST of OSS-2, support that the creation of accommodation space may have been related to a combination of long-term flexural isostatic effects and sediment compaction. The accommodation space relative to sequence OSS-3 was completely infilled by the RST of the same sequence, based on clinoform topset truncation at the upper bounding sequence unconformity (Fig. 13). A period with global cooling in early Chattian (Kominz & Pekar, 2001) may explain the increase in accumulated sediment volumes, compared to the Rupelian OSS-1 and OSS-2 sequences, due to that wet-based alpine glaciers may have developed in the hinterland (DeConto *et al.* 2008; Nielsen *et al.* 2009). This is supported by the SU of OSS-3 corresponding to a period with forced regression in the North

Sea area during maximum regression (Clausen *et al.* 2012). The lowering of the sea level was related to a global cooling event, of which appear to have been synchronous with the Oi2 cooling event (Miller *et al.* 1998; Clausen *et al*. 2012).

Following exposure of the shelf corresponding to the SU at top OSS-3, new accommodation space, with water depth of approximately 300 m were created (Fig. 6). The eustatic sea-level fluctuated by ten's of metres during the Late Chattian, although with an overall rise of only approximately 20 m (Fig. 15; Kominz & Pekar, 2001). This indicates that additional basin subsidence is required to explain the remaining accommodation space available during infill of the RST of OSS-4. The accumulation rate of OSS-4 is three times higher relative to sequence OSS-3 (Fig. 15) implying that the erosion rate during deposition of OSS-4 must have been significantly higher than during the Early Chattian time (OSS-3). This may relate to that the lower part of sequence OSS-4 corresponds in time with the Oi-2b cooling phase (Van Simaeys *et al.* 2005; Sliwinska *et al.* 2010), dated at approximately 27,1 Ma (Miller *et al.* 1998), inducing the potential of build-up of alpine glaciers in the hinterlands. However, when considering that global cooling also affected the OSS-3 sequence, similar accumulation rates for OSS-3 and OSS-4 would have been expected. The creation of accommodation space related to OSS-4 was rapid, considering the non-accretionary TST at the base of the sequence. Since isostatic rejuvenation related to glacial meltdown is unlikely to have occurred in the Oligocene (DeConto *et al.* 2008), rapid creation of accommodation space is most likely related to tectonic subsidence. The tectonic subsidence may have taken place in conjunction with tectonic uplift of the hinterland, which may further explain the threefold increase in accumulation rate during OSS-4 relative to OSS-3.

Mechanisms causing basin subsidence

The exact mechanism responsible for creation of accommodation space in Oligocene time is still debated (Faleide et al., 2002; Anell et al., 2010). However, observations from this study indicate that basin subsidence is related to regional tectonic processes. This implies that processes in the hinterland and in the basinal realm acted simultaneously, and that the same mechanism created simultaneously both uplift in the hinterland and subsidence in the eastern North Sea area. No indications of major tectonic displacement of local origin are observed within the basin. This reflects that basin subsidence relates to large scale lithospheric processes, such as differential vertical movements during compression of the lithosphere (lithospheric folding) or mantle processes. Both processes may cause long-wavelength deformation of the lithosphere of up to 100s of kilometres, and the depocentres are characterised by accelerated basin subsidence (Vågnes *et al.* 1998; Bourgeois *et al.* 2007; Cloetingh & Burov, 2011) that triggered potential non-accretionary TSTs. However, the exact mechanism is still debated, and the reader is referred to Faleide *et al.* (2002) and Anell *et al.* (2010) and references therein for an overview of the discussion.

Shifting depocentres and drainage system

Although progradation direction may be influenced by several basinal processes, such as wave and tidal currents, with longshore transport, changes in direction of progradation may reflect changes in the drainage system along with basin subsidence (Fig. 16). However, the gradual shift in progradation, from NNW-SSE in earliest Chattian (OSS-1) to NE-SW in Rupelian (OSS-3 & OSS-4), may reflect a dynamic fluvial drainage system in the hinterland. The first progradational sequence into the eastern North Sea in Early Oligocene (OSS-1) represents the most severe shift in sediment transportation during the Cenozoic times. Tranportation of only minor amount of erosional material being transported into the eastern North Sea during the Palaeocene and Eocene, indicates that the Oligocene sequences represent sediment deposition reltated to the the initial tectonic uplift phase of southern Norway in Late Palaeogene and Neogene times.

The structural high along the Fjerritslev Fault Zone may have acted as a barrier during deposition of OSS-1 and the lower part of OSS-2, forcing the sediment input to the west with subsequent southeastward dispersal (Fig. 15).

It is interpreted here that the drainage system shifted further eastwards during deposition of the upper part of OSS-2 and in OSS-3 and OSS-4, allowing fluvial drainage systems deliver detritus to the basin more from the north and northeast. Only minor proportions of the Oligocene sedimentary succession in the northern North Sea have been sourced from southern Norway (e.g. Galloway *et al.* 1993; Jordt *et al.* 1995, 2000; Faleide *et al.* 2002; Anell *et al.* 2009), the watershed is likely to have been located far to the west, thus causing most of the erosional material to be transported south and southeastwards. We believe the uplift of southern Norway has influenced the drainage pattern, as reflected by the shift in sediment transport direction and subsequent direction of progradation. As uplift continued, gradually more landmasses were exposed, forcing the drainage system to follow established N-S and NE-SW striking lineaments on present day eastern and southern Norway. This probably continued in the Miocene, were Lower Miocene deposits onshore Denmark were sourced from southern Norway (Olivarius, 2009), and continued southwestward sediment dispersal and depocentre migration into the Central Graben area (e.g. Jarsve *et al.* 2014).

6.b. Halokinesis

In general, the prime mechanism for halokinesis in the study area appears to be related to differential loading, which often developed in sedimentary basins as prograding successions created greater loading in some parts of the depositional area compared to elsewhere (e.g. Trusheim, 1960; Seni & Jackson, 1983; Hughes & Davison, 1993; Kossow *et al.* 2000; Steward, 2007). However, we cannot exclude the effect of active tectonism on salt mobilization in the study area, which was the prime mechanism regarding salt mobilization onshore Denmark during the Early Oligocene (Japsen *et al.* 2007).

The emphasis for this study is the intrinsic control on sedimentation caused by the salt diapirism. In particular one salt diapir was influensing the main depocentre of OSS-1. The actual size of the salt diapir appears, however, to be too limited in size relative to the size of the depocentre for it to have influenced basin development. We therefore believe halokinesis was insignificant in respect to creation of accommodation space during the Early Oligocene time (OSS-1). However, halokinesis does seem to have influenced maximum progradation for OSS-1, OSS-2 and OSS-3 in parts of the depocentres, indicated by the thinning of all the seismic sequences across salt diapirs at the margins of the depocentres. Parts of the main depocentre infilled by OSS-1 are located around a salt structure located west-southwest of well 11/10-1 (Figs. 7 & 9) onlapping against the salt structure. These observation shows that the salt diapirs form intra-basinal topography affecting sediment progradation. This effect is also influencing the OSS-2 and OSS-3 progradation (Fig. 9). Sediment progradation is observed on either side of salt diapirs supporting that halokinesis had an intrinsic control on sediment progradation. These observations indicate that halokinesis controlled the extension of maximum progradation and exerted an internal control of progradation within the main depocentres.

7. Conclusions

In this study, we have shown that renewed interpretation of the Oligocene succession, combining seismic sequence stratigraphic techniques, biostratigraphy and Sr-isotope stratigraphy and published climate data, gives additional contributions in understanding the coupling between tectonic and climatic influence on the Oligocene source to sink system in the eastern North Sea area.

Each of the four seismic sequences described above are characterised as T-R sequences, with a transgressive systems tract (TST) overlain by a regressive systems tract (RST). In OSS-1 and OSS-4 the TST are non-accretionary, while in OSS-2 and OSS-3 they are aggradational. Accommodation space developed simultaneously with initial sediment progradation from N-NW. The main findings from this study are:

- New age-constraints from this study show that the sediment progradation from southern Norway was initiated in the earliest Oligocene, and slightly post-dates the global cooling event at the Eocene-Oligocene boundary.

- It is documented here that the vast increases in water depths during deposition of the Oligocene seismic sequences were related to basin subsidence that outpaced a generally shallowing fall in eustatic sea level. It is also shown that creation of accommodation spaces were out-of-phase relative to intra-Oligocene eustatic sea level fluctuations.

- The basin subsidence is likely to have accompanied tectonic rise of the southern Norwegian landmass, where the eastern part of the North Sea basin experienced subsidence forced by differential vertical movements of the lithosphere. These vertical movements gave rise to rapid changes in palaeo water depth and accompanying changes from potential subaerial exposure of basin platforms to marine flooding and water depths up to about 300 m.

- The shift in direction of progradation from southeast in the earliest Rupelian to south and southwest in the Late Rupelian and Chattian was a response to tectonic uplift in the western part of southern Norway which gradually may have forced the drainage system eastwards.

- Within the basin, halokinesis influenced lateral extension of sediment progradation throughout Rupelian and Early Chattian times. The halokinesis was caused by differential sediment loading in adjacent areas of the depositional basin. However, the actual sizes of the salt diapirs are considered too limited to have influenced basin subsidence.

We have demonstrated that the creation and infill of accommodation spaces during the Oligocene in the eastern North Sea are related to both tectonic processes and climate changes. This study further shows the importance in studying the interplay between tectonics and climate to understand the source to sink relationship.

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Well 11/10-1

Litho. Unit	Sample (DC)	Corrected $^{87/86}$Sr	2S error	Age (Ma)	Comments	Analysed fossils
Vade Fm	304.8 m	0.708177	0.000007	25.26		Nine large tests of *Elphidium subnodosum*
Vade Fm	304.8 m	0.708118	0.000008	26.48		Ten large tests of *E. subnodosum, Astigerina guerichi gue*richi and *Guttulina* sp.
Vade Fm	365.8 m	0.708091	0.000008	27.23		One mollusc fragment
Vade Fm	365.8 m	0.708101	0.000007	26.93		One mollusc fragment
Vade Fm	426.7 m	0.708008	0.000009	29.39		One mollusc fragment
Vade Fm	426.7 m	0.708227	0.000009	24.48	Caved?	One mollusc fragment
Vade Fm	457.2 m	0.707979	0.000008	30.11		Approximately 30 fragments of *Bryozoa* and *Echinoderma*
Vade Fm	472.4 m	0.708039	0.000012	28.61		50 small tests of *Pararotalia canui, G. angustiumbilicata* and *G. Praebulloides*
Hordal. Gr	487.7 m	0.708015	0.000008	29.22		One mollusc fragment
Hordal. Gr	487.7 m	0.707991	0.000007	29.81		One mollusc fragment
Hordaland Gr	502.9 m	0.707991	0.000008	29.81		One mollusc fragment
Hordal. Gr	502.9 m	0.707973	0.000007	30.27		One mollusc fragment
Hordal. Gr	518.2 m	0.707951	0.000008	30.87		One mollusc fragment
Hordal. Gr	518.2 m	0.707937	0.000008	31.24		One mollusc fragment
Hordal. Gr	640.1 m	0.707938	0.000007	31.22		Nine large tests of *G. soldanii girardana, Nodosaria* sp. A (King, 1989), *Lagena* sp., *Alabamina scitula*
Hordal. Gr	640.1 m	0.708077	0.000008	27.69	Caved?	One mollusc fragment
Hordal. Gr	640.1 m	0.708250	0.000008	24.10	Caved?	One mollusc fragment
Hordal. Gr	823.0 m	0.707875	0.000008	32.59		19 tests of *Stilostomella* spp., *T. alsatica, R. bulimoides, Ceratobulimina contraria, G. soldanii girardana*, *Cibicides mexicanus*
Hordal. Gr	853.4-883.9 m	0.707871	0.000008	32.66		26 tests of *Stilostomella* spp., *Bolivina* cf. *antique*, *T. alsatica, R. bulimoides, Hoeglundina elegans, G. soldanii girardana, Cibicides mexicanus*
Hordal. Gr	914.4 m	0.707871	0.000008	32.66		Twelve tests of *G. soldanii mamillata, H. elegans, G. soldanii girardana, Stilostomella* spp., *G. subglobosa*, *Frondicularia budensis, T. alsatica, C. contraria*, *G. praebulloides*

Well 9/12-1

Litho. Unit	Sample (DC)	Corrected $^{87/86}$Sr	2S error	Age (Ma)	Comments	Analysed fossils
Hordal. Gr	463.3 m	0.708135	0.000008	26.10		One mollusc fragment
Hordal. Gr	463.3 m	0.708150	0.000008	25.79		One mollusc fragment
Hordaland Gr	475.5 m	0.708152	0.000008	25.75		One mollusc fragment
Hordal. Gr	475.5 m	0.708145	0.000008	25.89		One small mollusc
Hordal. Gr	475.5 m	0.708140	0.000007	25.99		One mollusc fragment
Hordal. Gr	487.6 m	0.708103	0.000008	26.87		One mollusc fragment
Hordal. Gr	487.6 m	0.708159	0.000008	25.61		Approximately 20 tests of *A. guerichi guerichi, A. guerichi staeschei*
Hordal. Gr	499.9 m	0.708080	0.000008	27.55		One mollusc fragment
Hordal. Gr	499.9 m	0.708128	0.000009	26.25		One mollusc fragment
Hordal. Gr	499.9 m	0.708111	0.000008	26.65		One mollusc fragment
Hordal. Gr	512.1 m	0.708231	0.000008	24.42		Approximately 15 tests of *A. guerichi guerichi, A. guerichi staeschei*
Hordal. Gr	512.1 m	0.708136	0.000008	26.08		One mollusc fragment
Hordal. Gr	512.1 m	0.708113	0.000007	26.60		One mollusc fragment
Hordal. Gr	512.1 m	0.708114	0.000008	26.57		One mollusc fragment
Hordal. Gr	524.3 m	0.708092	0.000008	27.20		Approximately 35 tests of *A. guerichi guerichi, A. guerichi staeschei*
Hordal. Gr	536.5 m	0.708075	0.000008	27.69		Approximately 23 tests of *A. guerichi guerichi, A. guerichi staeschei*
Hordal. Gr	548.6 m	0.708103	0.000007	26.87		Approximately 55 tests of *A. guerichi guerichi, A. guerichi staeschei*
Hordal. Gr	573.0 m	0.708042	0.000007	28.53	Reworked?	Approximately 40 tests of *A. guerichi guerichi, A. guerichi staeschei*
Hordal. Gr	609.6 m	0.708037	0.000007	28.66		Ten tests of *Siphonina reticulate*

Well 2/2-2

Litho. Unit	Sample (Core)	Corrected $^{87/86}$Sr	2S error	Age (Ma)	Analysed fossils
Vade Fm	1984.5 m	0.708127	0.000009	26.3	Fragment of one large *Bivalve*
Vade Fm	1984.5 m	0.708127	0.000009	26.0	Fragment of one large *Bivalve*

Table 1: Strontium isotope data from well 11/10-1, 9/12-1 and 2/2-2. The samples are analysed at the University in Bergen. Sr ratios were corrected to NIST 987 = 0.710248. The numerical ages were derived from the SIS Look-up Table Version 3:10/99 of Howard and McArthur (1997).
NIST = National Institute for Standard and Technology.

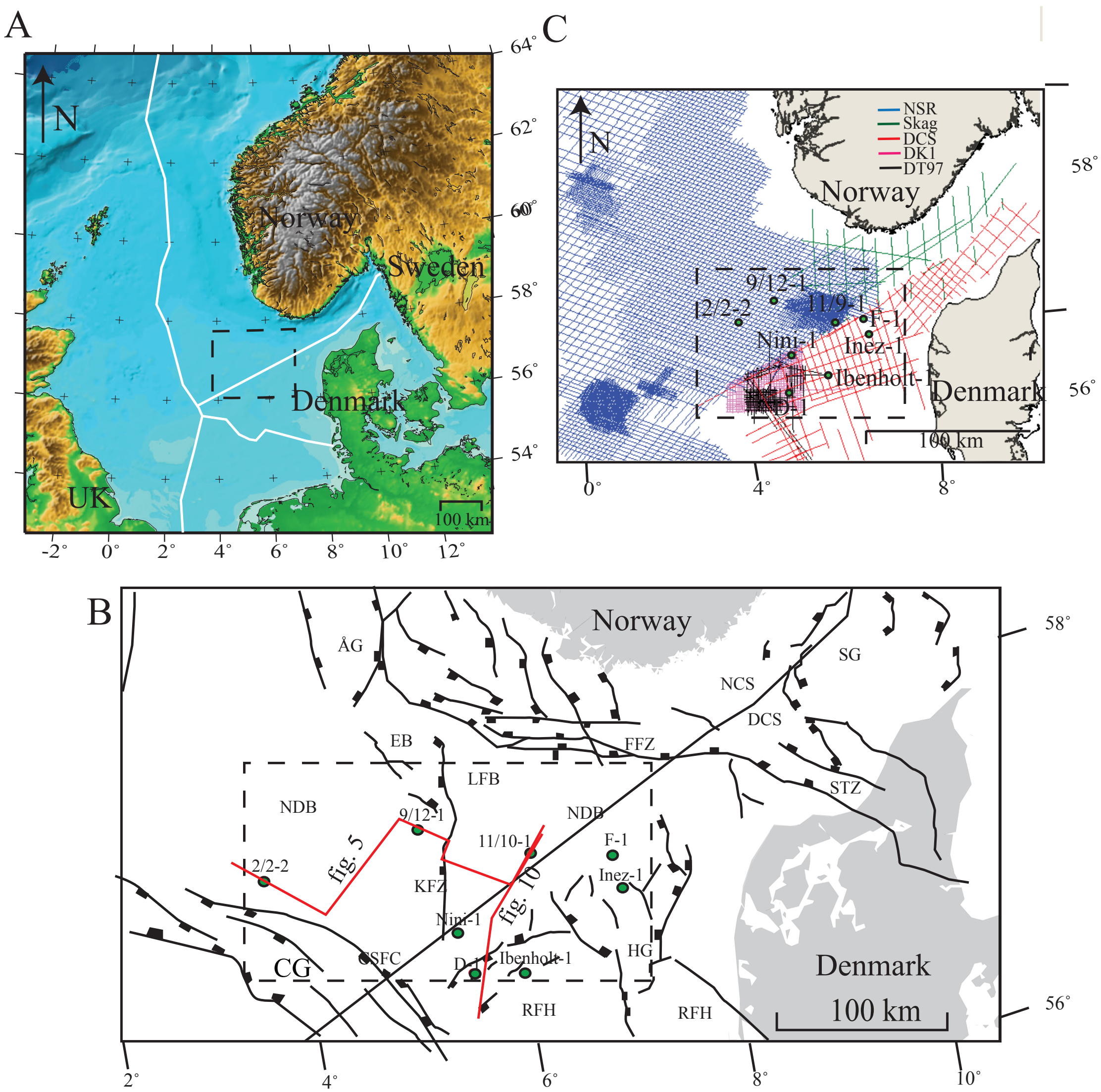

Figure 1: A) Location of the study area. B) Structural elements within the study area, including wells applied in this study (CG=Central Graben, DCS=Danish Continental Shelf, CSFC=Coffee-Soil Fault Complex, EB=Egersund Basin, FFZ=Fjerrislev Fault Zone, HG=Horn Graben, KFZ=Kreps Fault Zone, LFB=Lista Fault Blocks, NCS=Norwegian Continental Shelf, NDB=Norwegian Danish Basin, RFH=Ringkøbing Fyn High, SG=Skagerrak Graben, STZ=Sorgenfrei Torquist Zone, ÅG=Åsta Graben). See correlation between Norwegian wells 11/10-1, 9/12-1 and 2/2-2 in figure 4. C) Seismic data coverage available for this study (courtesy of Fugro and TGS).

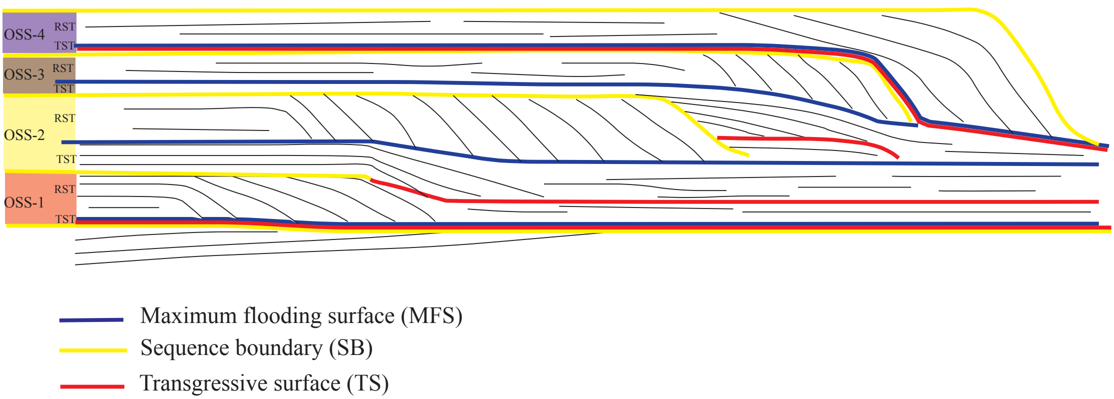

Figure 2: Sketch summarising the four T-R sequences described in this study and the corresponding sequence boundaries (SB), transgressive surfaces (TS) and maximum flooding surfaces (MFS). Note the non-accretionary nature of the TST of OSS-1 and OSS-4, while the TST in OSS-2 and OSS-3 are aggradational. The sketch is out of scale.

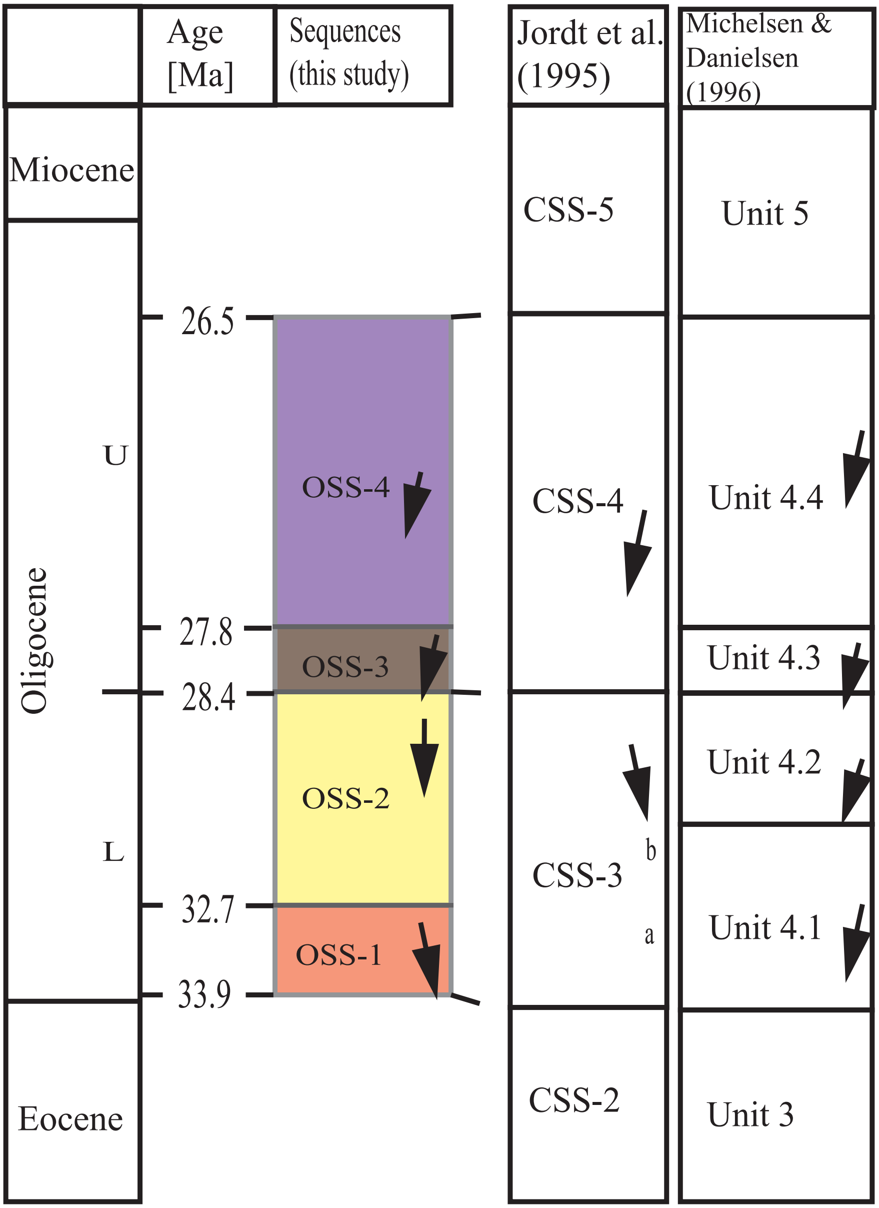

Figure 3: Seismic stratigraphic sequences correlation with the NSA zonation of King (1989) and Gradstein & Bäckström (1996), and the work by Jordt et al. (2000) and Michelsen & Danielsen (1996). Arrows indicate direction of sediment progradation.

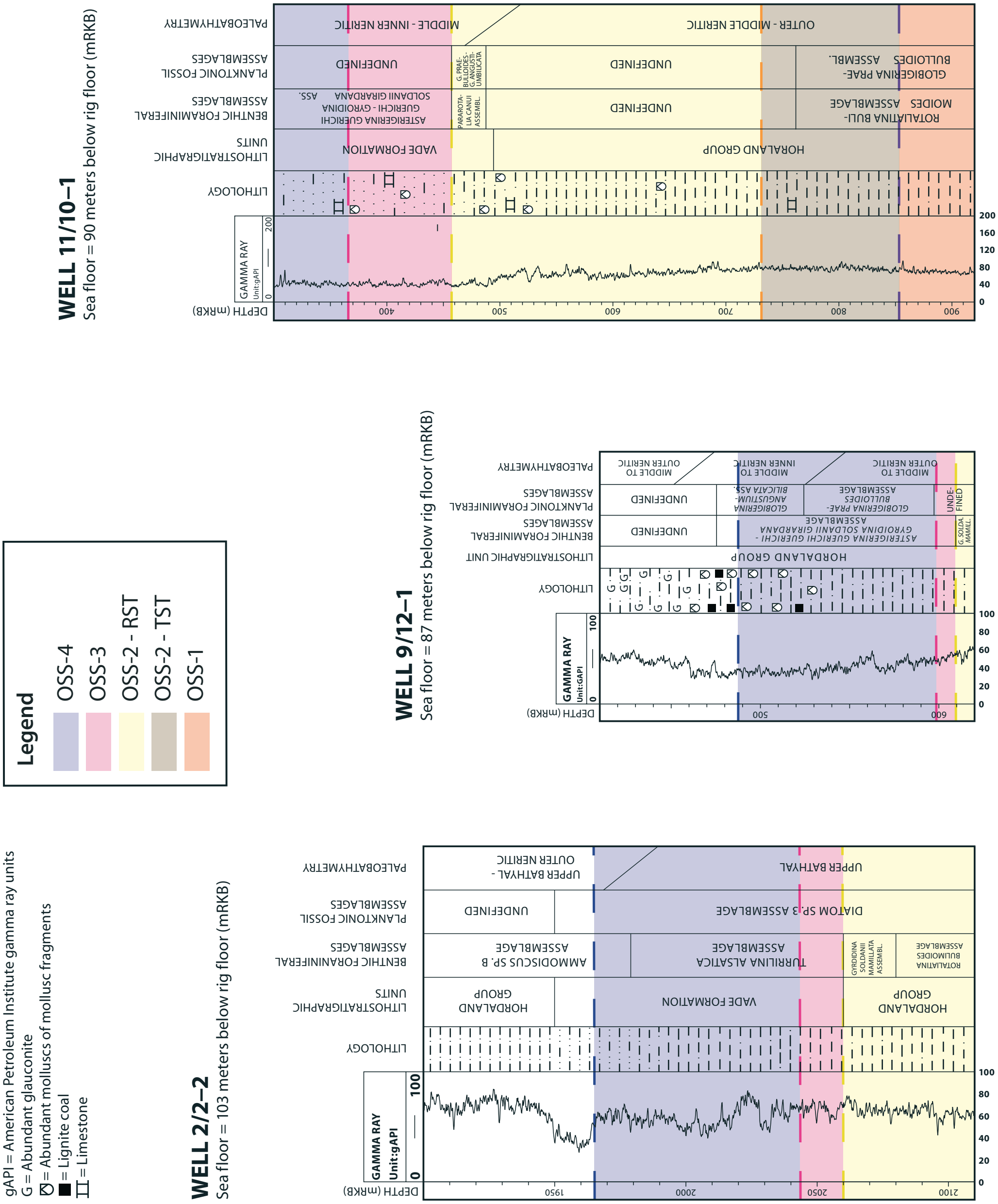

Figure 4: Correlation between the three wells on the Norwegian Continental Shelf applied to this study for Sr-stratigraphy and biostratigraphic analysis.

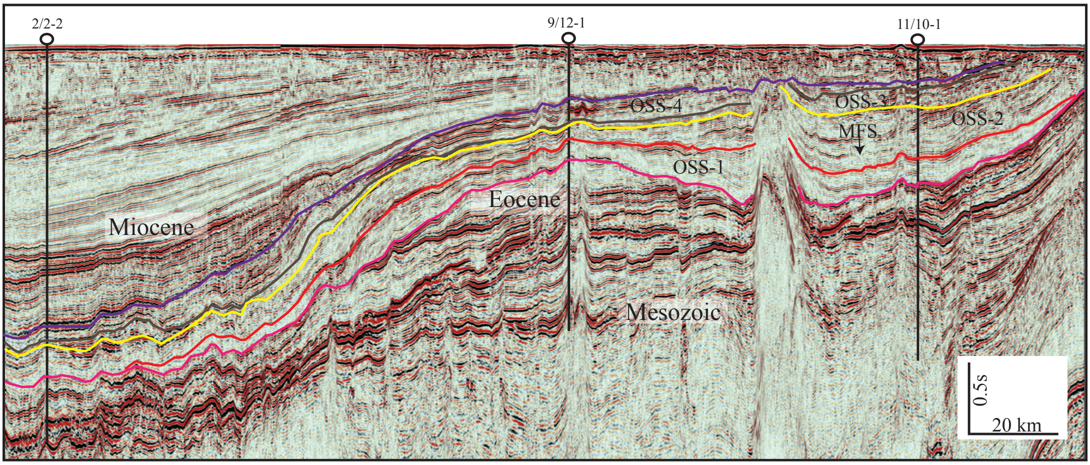

Figure 5: Seismic correlation between the three key wells 11/10-1, 9/12-1 and 2/2-2 in this study. Seismic section courtesy of Fugro and TGS.

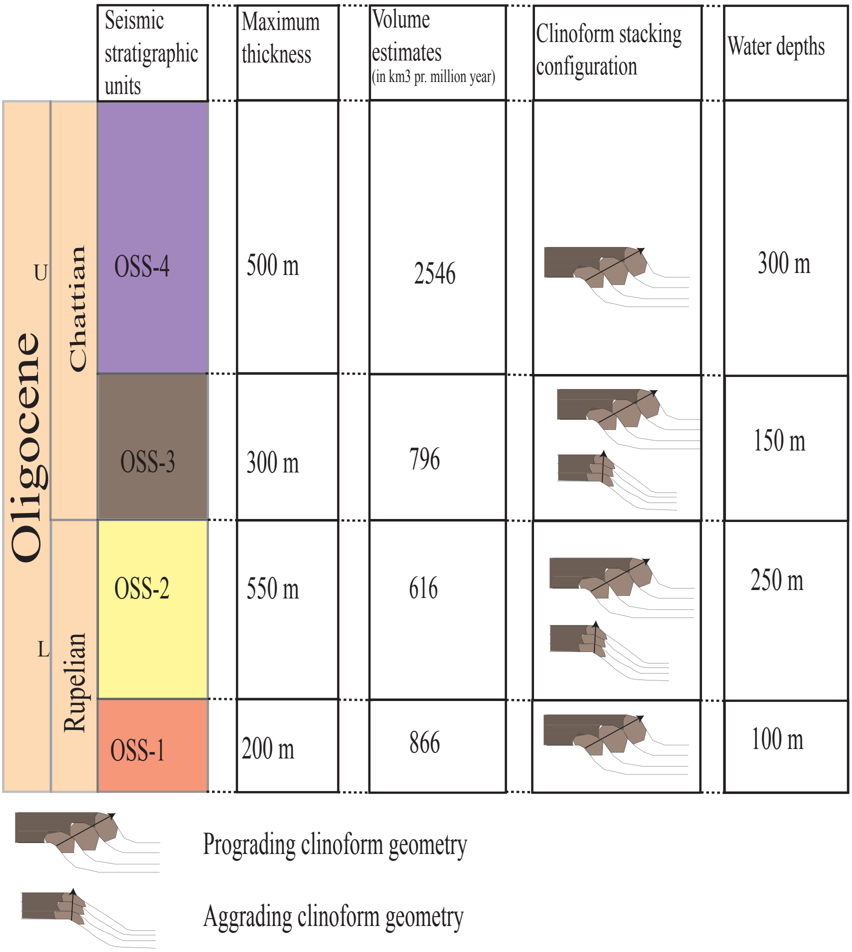

Figure 6: Seismic stratigraphic subdivision from this study, with characteristic features for each sequence. Note that water depth is calculated from clinoform heights.

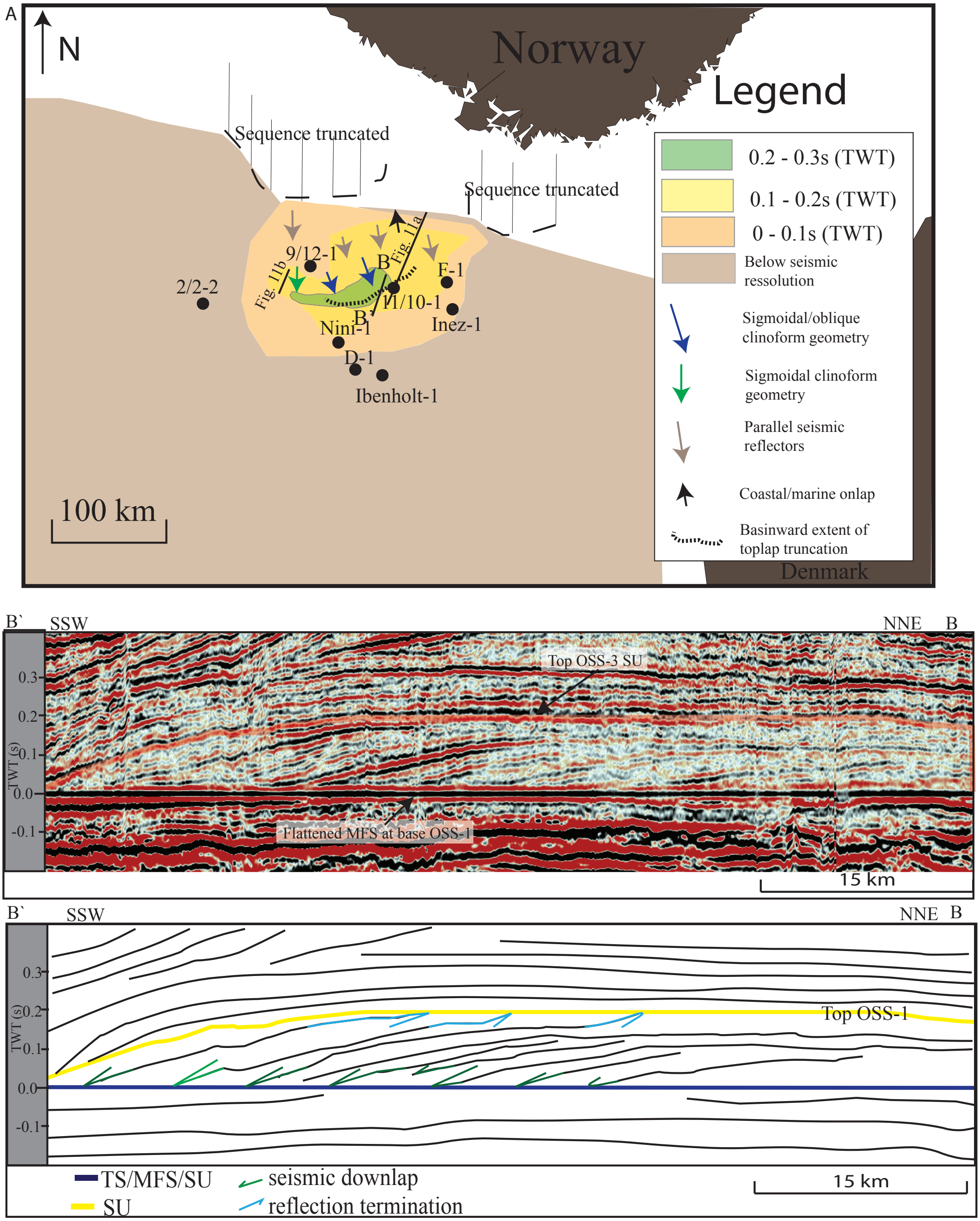

Figure 7: Time-thickness map (a) of OSS-1. The clinoform facies for the various units represents the highstand systems tract and also the main depocentre at the time of deposition. The upper surface of OSS-1 is marked in red in the seismic section (B-B'). Seismic termination above offlap break, indicating clinoform toplap truncation. Seismic section courtesy of Fugro and TGS.

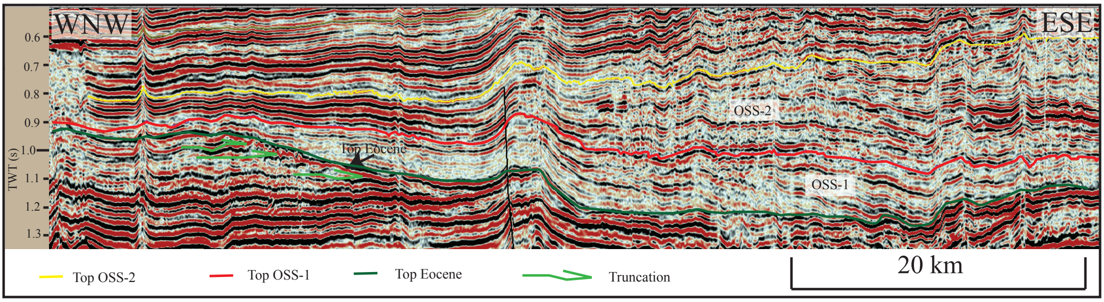

Figure 8: Seismic terminations indicating erosion of Eocene strata at base OSS-1 (termination indicated by green arrows). Note the strong seismic amplitude directly above the unconformity, corresponding with the downlap surface of OSS-1.
Seismic section courtesy of Fugro and TGS.

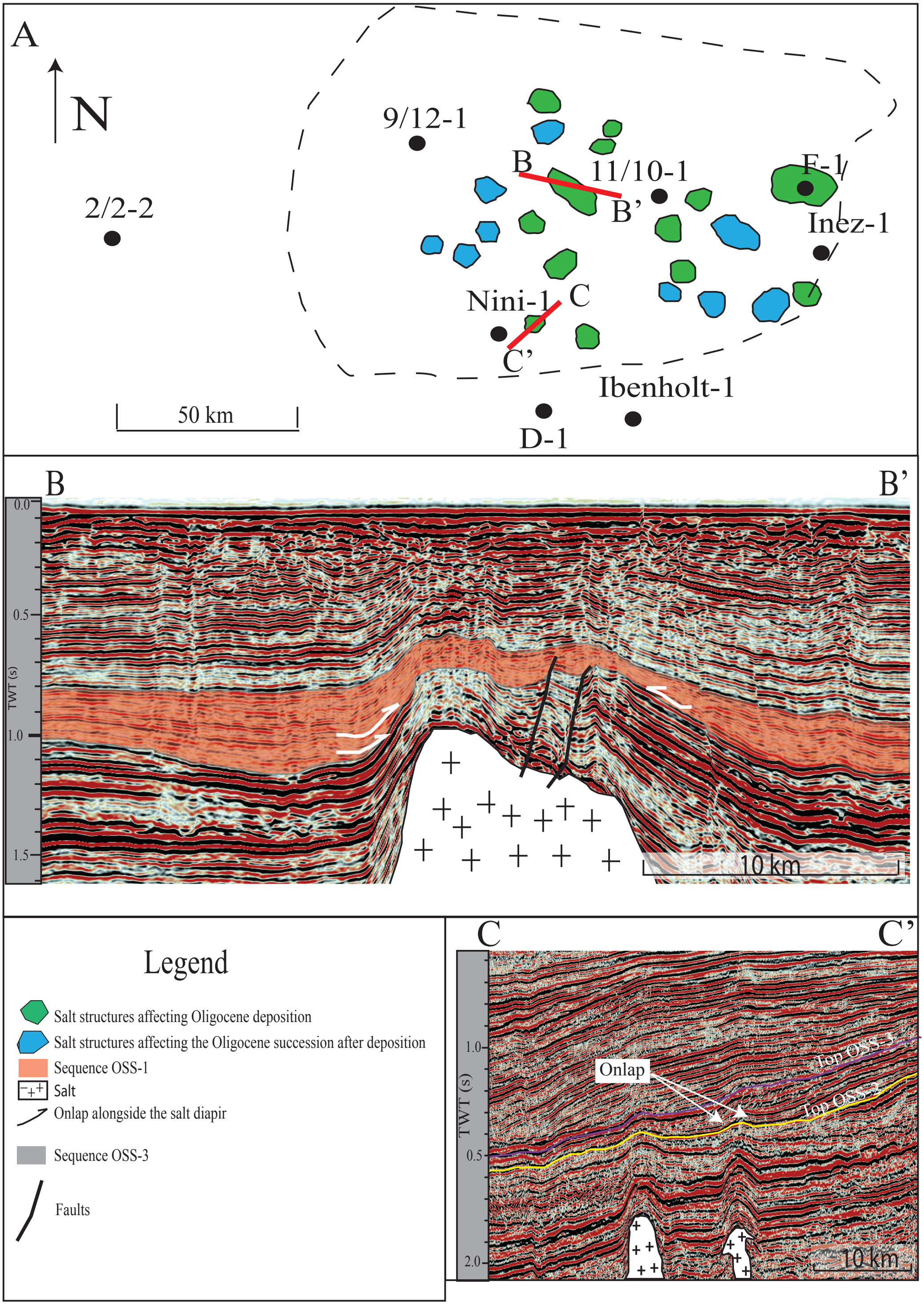

Figure 9: a) Base map showing salt structures in the study area penetrating and/or affecting the Oligocene sequences. Seismic sections showing deposition during halokinesis during deposition of OSS-1 (b) and during deposition of OSS-3 (c). White arrows in b and c mark seismic onlap against the salt structures.

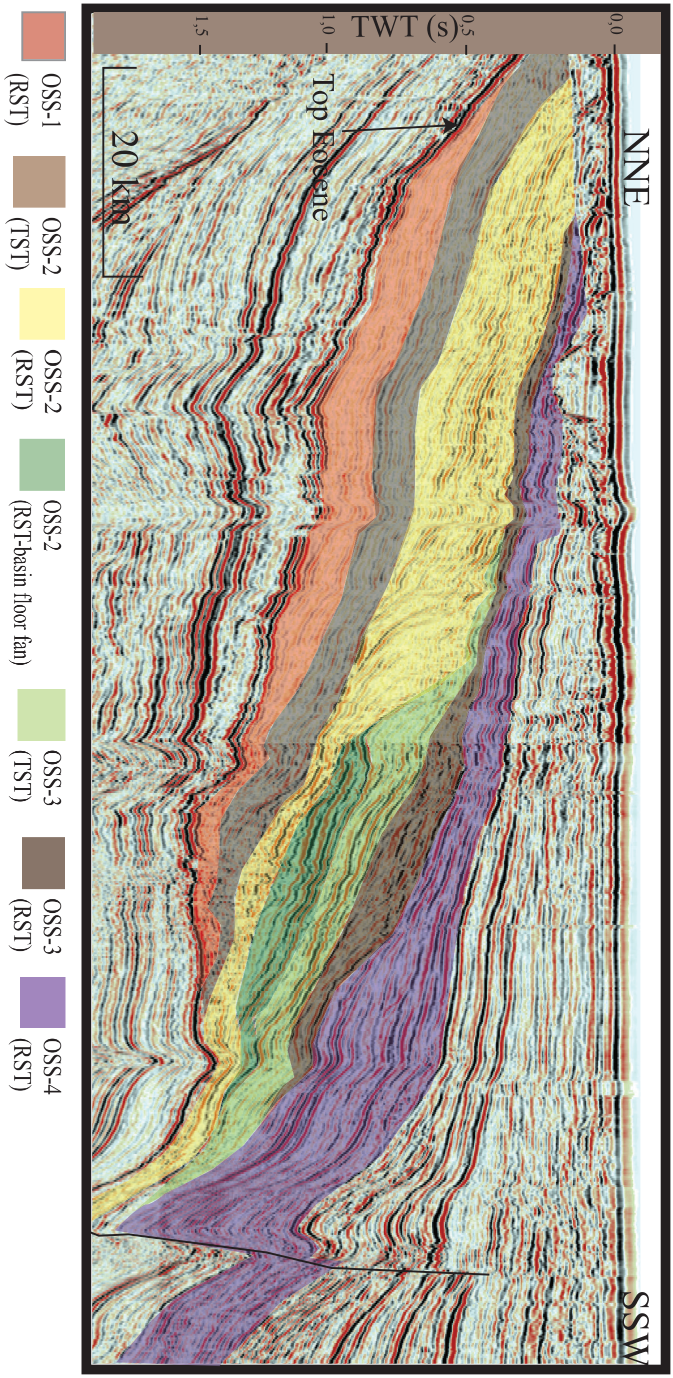

Figure 10: Seismic sections illustrating the various systems tracts of the Oligocene sequences. It is an arbitrary line, although striking NNE-SSW. Note the onlap pattern of OSS-1 against Eocene strata in the northeastern part. See figure 1 for location of the seismic lines. Seismic section courtesy of Fugro and TGS.

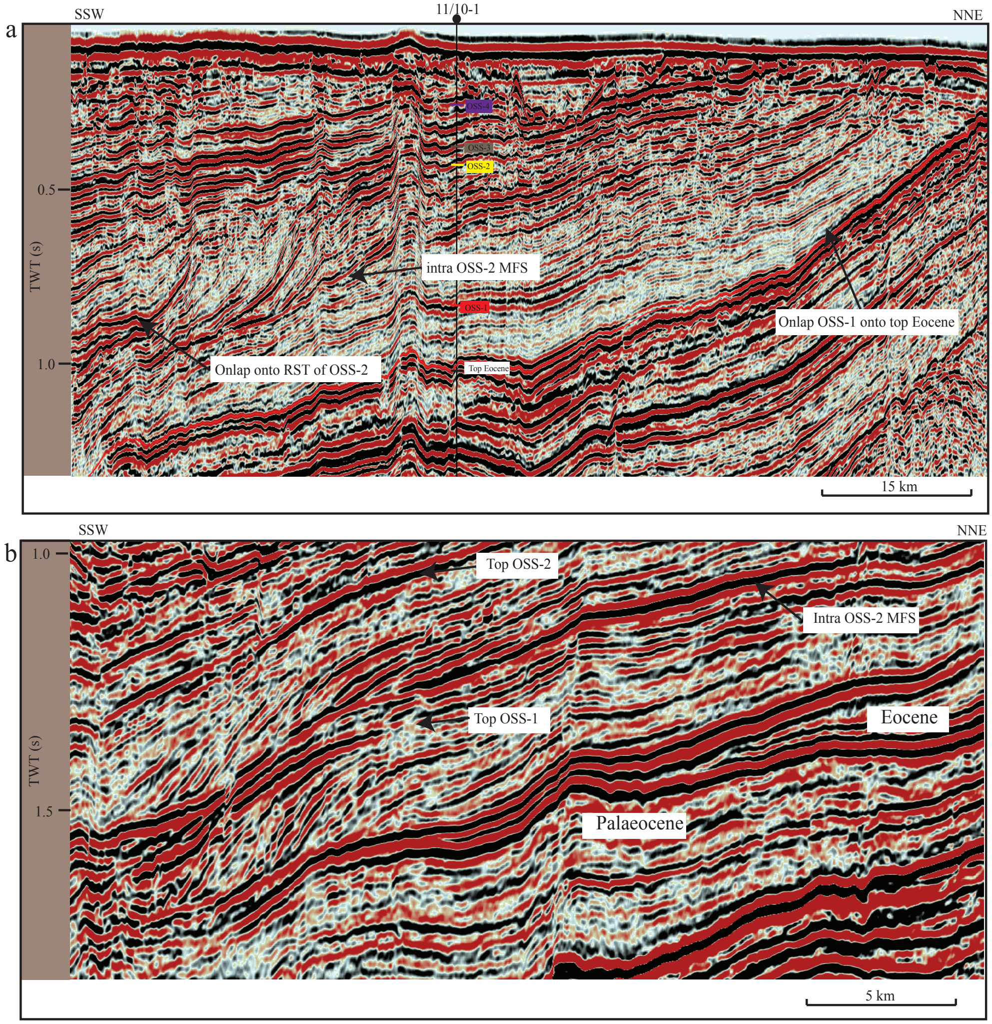

Figure 11: Seismic examples including well tie to well 11/10-1 (a) and the prograding RST's in the western part of the main depocentre relative to sequence OSS-1 and OSS-2 (b). See figure 7 for line locations. Note that OSS-1 onlap Eocene strata towards the north in a, whereas OSS-2 has a more uniform thickness northwards.
Seismic section courtesy of Fugro and TGS.

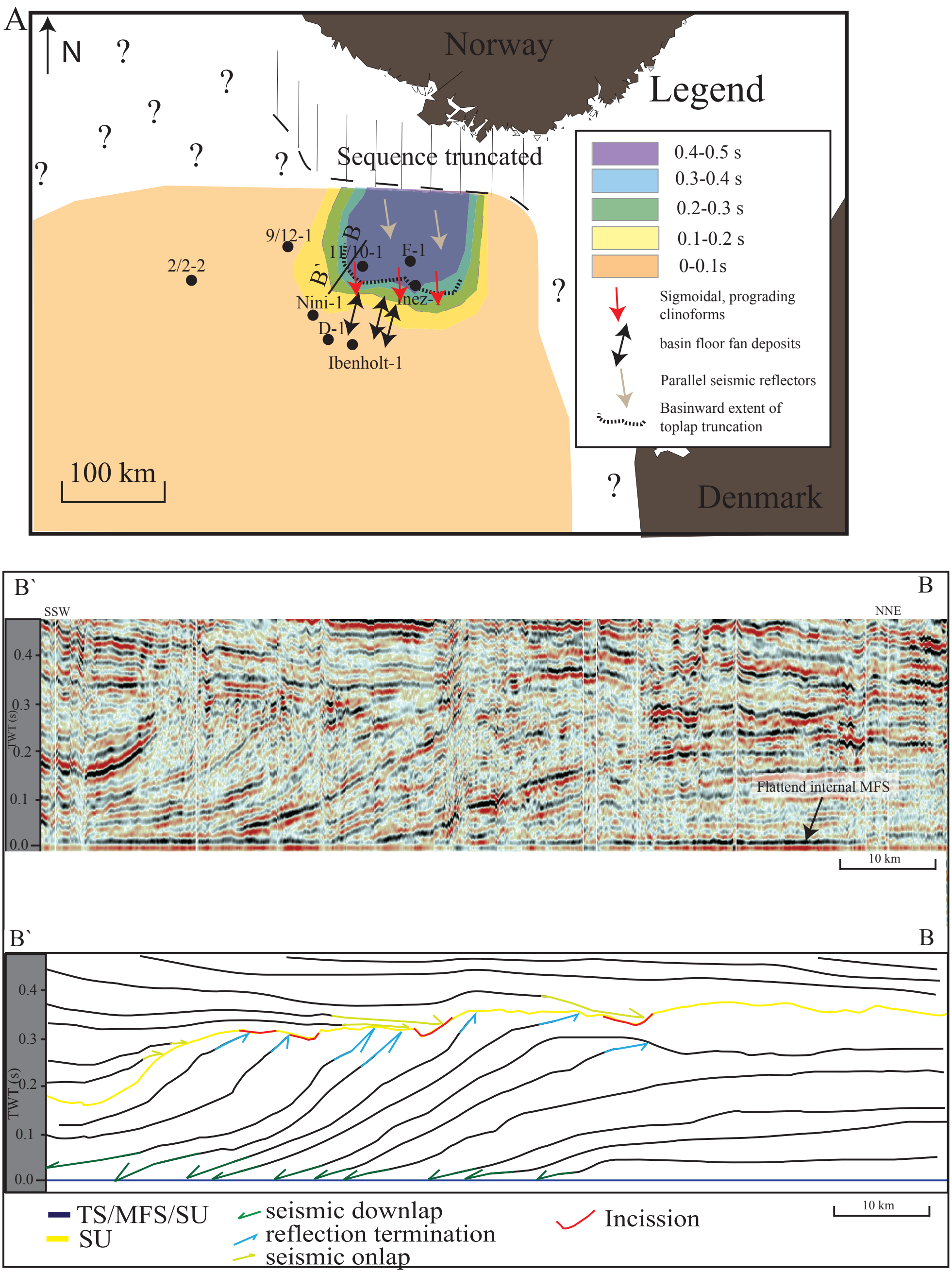

Figure 12: Time-thickness map (a) of OSS-2. The clinoform facies for the sequence represents the highstand systems tract and is coherent with the main depocentre at the time of deposition. Note the internal erosional surfaces in the seismic section in c-c’, and incision at the upper SU (marked in red).
Seismic section courtesy of Fugro and TGS.

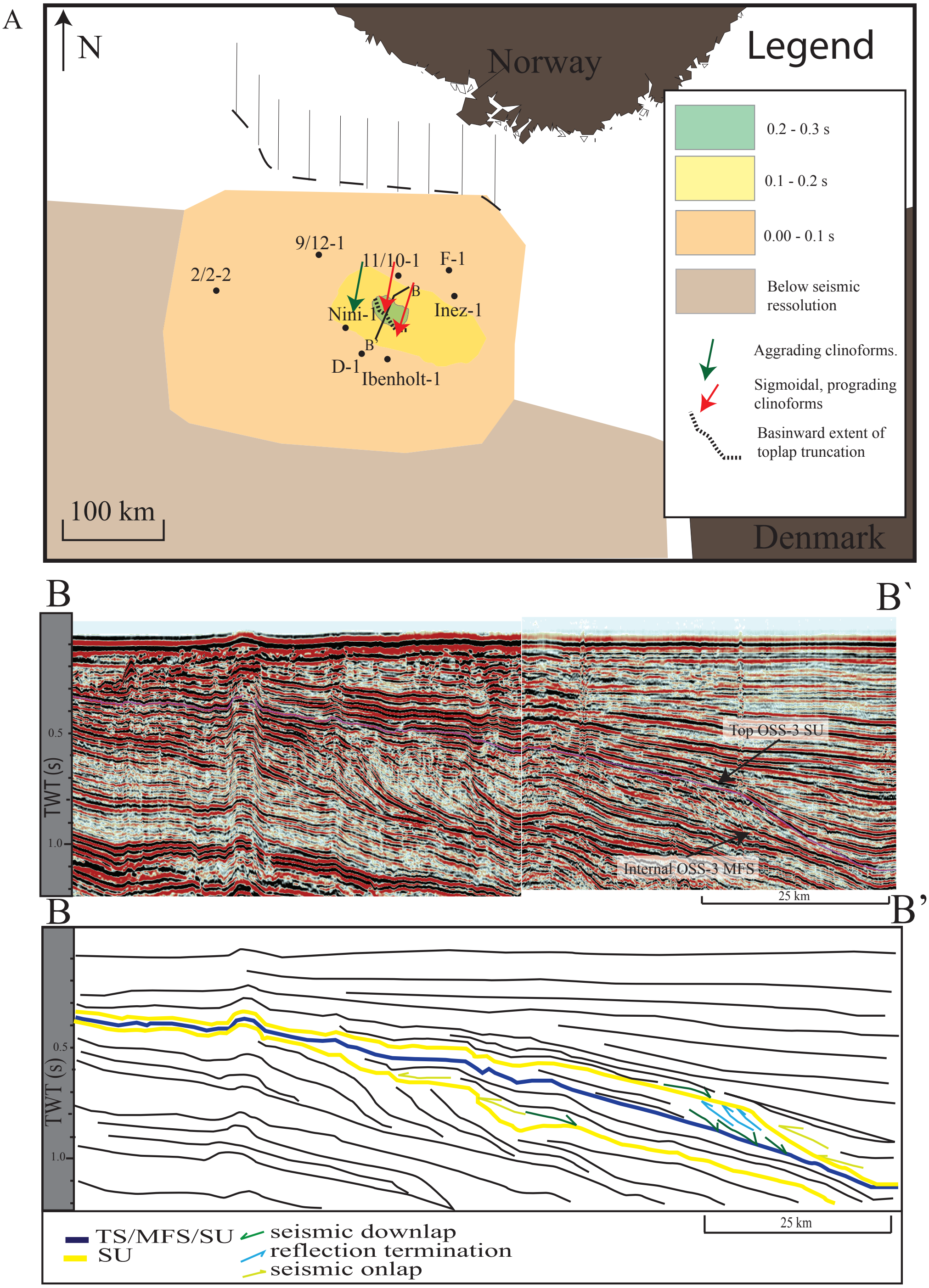

Figure 13: Time-thickness map (a) of OSS-3. The clinoform facies for the sequence represents the highstand systems tract and also the main depocentre at the time of deposition. The TST and RST are separated by a MFS in c-c`. Seismic sections courtesy of Fugro and TGS.

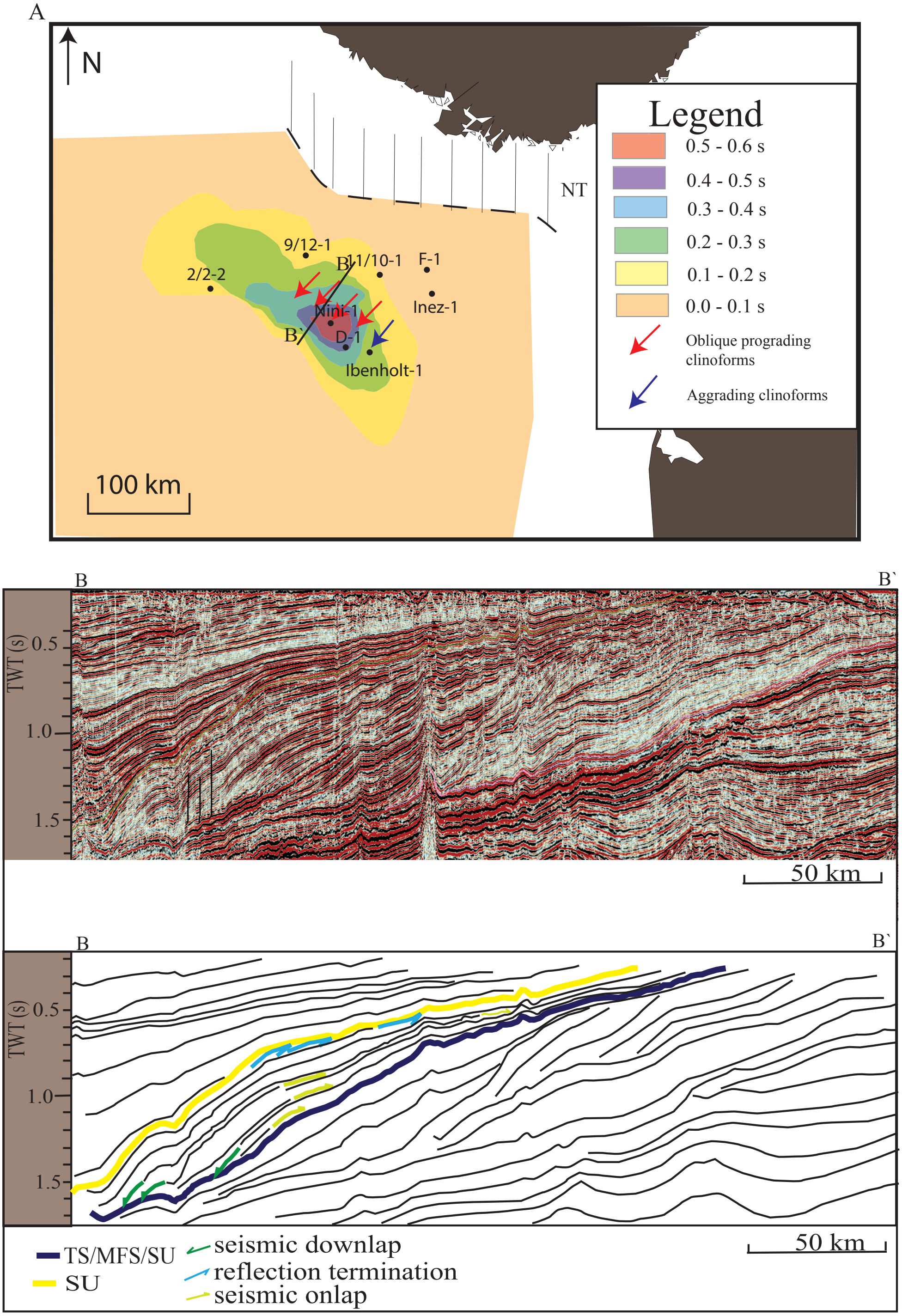

Figure 14: Time-thickness map (a) of OSS-4. Note the internal onlap surfaces, indicating lobe shifting during deposition of the RST of the sequence. Seismic section courtesy of Fugro and TGS.

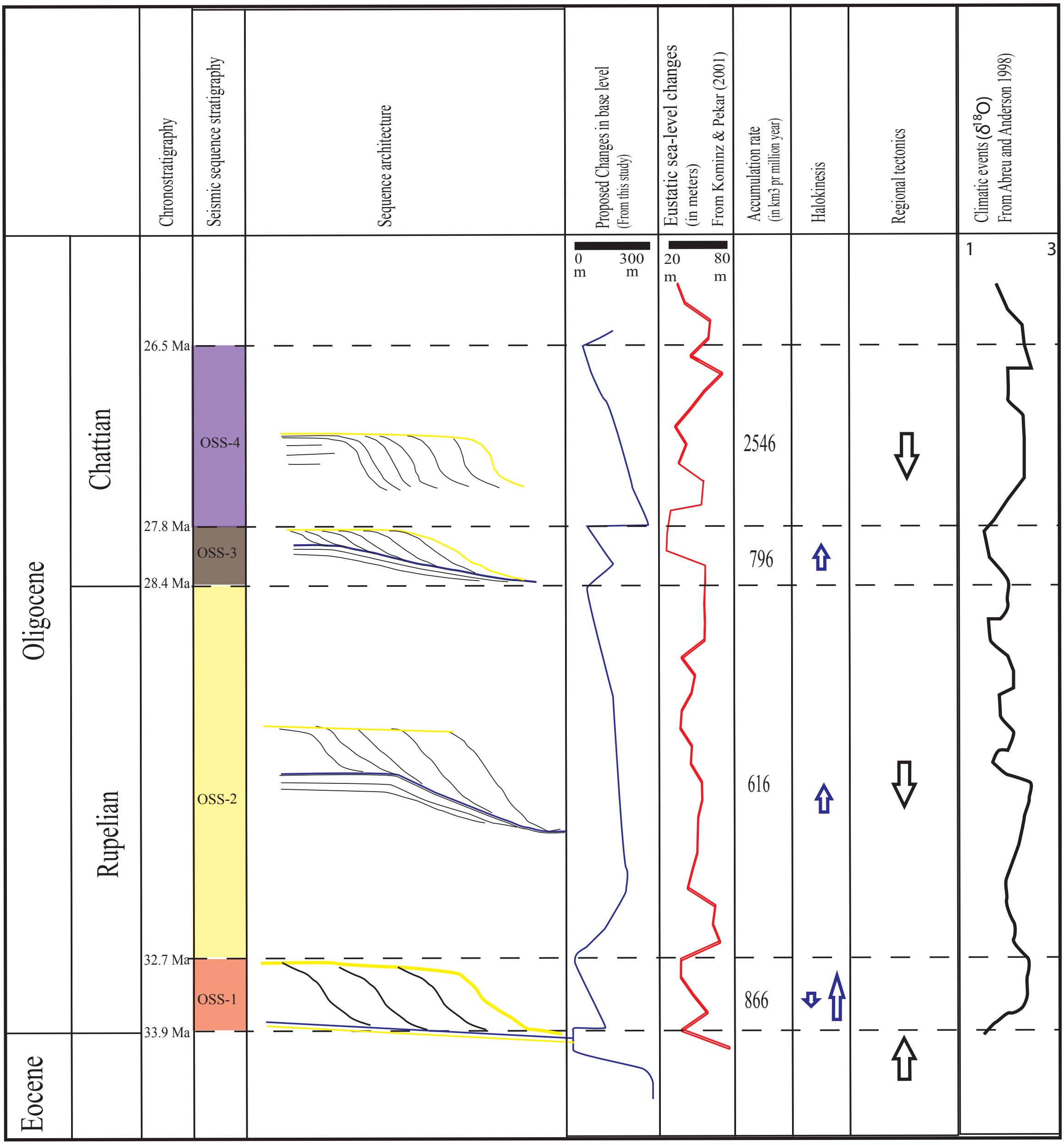

Figure 15: Summary of sea level changes and regional subsidence during deposition of the individual sequences from this study compared to the eustatic sea level changes proposed by Pekar & Kominz (2001). Note the vast sediment volume rate in OSS-4.

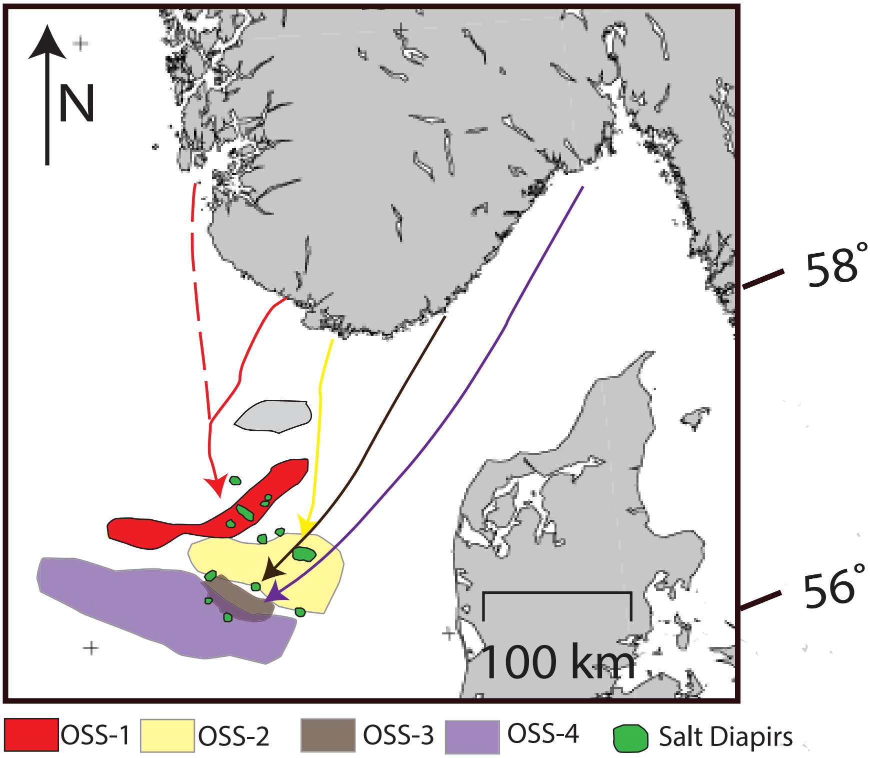

Figure 16: Position of the main depocentres of the OSS-sequences and illustration of drainage pattern during the Oligocene. Uplift of southern Norway may have forced the drainage system eastwards, with the result of sediment transportation mainly from the NNW and N in the Early Oligocene and from the NE in Late Oligocene.

Paper 4

Automatic identification of topographic surfaces related to the sub-Cambrian peneplain (SCP) in southern Norway — Surface generation algorithms and implications

By:

Erlend Morisbak Jarsve, Svein Olav Krøgli, Bernd Etzelmüller and Roy Helge Gabrielsen

Geomorphology. 2014, **211**, 89-99

Paper 5

The SubCambrian Peneplain in southern Norway: Its geological significance and its implication for the Caledonian deformation and the post-Caledonian faulting, exhumation and denudation

By:

Roy Helge Gabrielsen, Johan Petter Nystuen, Erlend Morisbak Jarsve, and Anders Mattias Lundmark

Submitted to Geological Society of London