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Distribution, depositional environment and post-depositional deformation of Cenozoic gravity-induced deposits along the western Barents Sea continental margin

Polina Alekseevna Safronova

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Department of Geology, Faculty of Science and Technology,

University of Tromsø, Norway

“Learning never exhausts the mind”

- Leonardo da Vinci -

“No one knows what he can do till he tries”

- Publilius Syrus -

Preface

This PhD thesis was carried out at the Department of Geology, University of Tromsø from May 2007 to June 2013, including a total of two years of maternity leaves (09.2008-10.2009; 04.2012-04.2013). The main supervisor was Professor Karin Andreassen, and co-supervisors were Associated Professor Jan Sverre Laberg and Professor Tore O. Vorren who passed away during the final stage of this PhD work. All the supervisors are from the University of Tromsø. The four-year PhD work was financially supported by the Research Council of Norway (Petromaks project DEMOCEN), Statoil and the University of Tromsø. The main objective of the DEMOCEN project is to develop depositional model for Cenozoic sandy systems on the Barents Sea margin in order to better identify and quantify factors critical to reservoir rock occurrence and distribution.

A two weeks stay at Marine Arctic Geological Expedition in Murmansk (Russia) in summer 2010 and several research visits to Statoil Harstad and the Statoil Research Centre in Trondheim were undertaken within the working period, including two months leave for a summer internship at Statoil Harstad in summer 2011. Several obligatory courses, one scientific cruise and a number of software courses (ArcGIS and Schlumberger's Petrel interpretation software) were completed. 25% of the PhD time was devoted to work at the University of Tromsø, mainly as a teaching assistant in the "Introduction to Geology" course and as a part-time lecturer in the "Petroleum Geology" course, in addition to participation in the National Science Week in Norway in September 2010.

The three and two-dimensional seismic and well data used in this PhD thesis are from the Diskos PetroBank database, which is managed by the Norwegian Petroleum Directorate. The Marine Arctic Geological Expedition (Russia) also provided extensive two-dimensional seismic data. The results of this work have been presented at several international conferences and workshops in the form of posters and talks.

List of papers

Paper I

P.A. Safronova, K. Andreassen, J.S. Laberg and T.O. Vorren, 2012. **Development and post-depositional deformation of a Middle Eocene deep-water sandy depositional system in the Sørvestsnaget Basin, SW Barents Sea.** Marine and Petroleum Geology 36, 83-99.

Paper II

P.A. Safronova, S. Henriksen, K. Andreassen, J.S. Laberg and T.O. Vorren. **Evolution of shelf-margin clinoforms and basin-floor fans during the Middle Eocene in the Sørvestsnaget Basin, SW Barents Sea.** (Accepted with revisions to AAPG Bulletin; submitted).

Paper III

P.A. Safronova, J.S. Laberg, K. Andreassen, R. Mattingsdal, V. Shlykova T.O. Vorren, and S. Chernikov. **Large-scale submarine slides affecting the north-western Barents Sea margin during the Late Pliocene – Early Pleistocene.** (manuscript to be submitted to Basin Research).

Table of contents

Acknowledgments

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I would like to thank everyone at the Department of Geology and the Head of the Department Prof. Jurgen Mienert for wonderful working conditions and enjoyable social environment. I am thankful to the Research Council of Norway, Statoil and the University of Tromsø which sponsored my PhD work and allowed me to participate in different international conferences, workshops and courses that significantly extended my knowledge and circle of contacts. I would like to express my gratitude to my supervisor Prof. Karin Andreassen who supported and guided me through my PhD study. Thank you for giving me a scientific freedom, possibility to think independently and to believe in me and my scientific ideas. I would like to thank my co-adviser Associated Prof. Jan Sverre Laberg for always being helpful and quick in providing feedback on my work. Your calm, reasonable and consistent way of giving presentations and holding a discussion is so inspiring. Every time I teach someone or give a talk, I try to achieve this level. Special thanks to my second co-adviser Prof. Tore O. Vorren who was an outstanding person and always shared his extensive knowledge. I am thankful to all my supervisors for their patience while reading and correcting my long and complicated sentences in the manuscripts. If I have succeeded to some extent in my scientific style of writing, way of presenting and discussing the results - that is because of all of you.

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Finally, I am forever grateful to my husband Denis for his love, endless support, patience and encouragement. You have done an impressive amount of work with our two small children, allowing me to focus on my dissertation. Without you I would never manage to finish the PhD thesis. There are no words to say how much I'm thankful to my wonderful daughter Alla and son Artyom for their love and keeping me smiling during these years.

1. Introduction

The Arctic is one of the few remaining geologically underinvestigated areas of the world, where the Barents Sea is of current exploration and scientific interest (Figure 1). Exploration activity in the Norwegian part of the Barents Sea (Figure 1) started in 1979 (Larsen et al., 1993). Since then more than 80 wells have been drilled and numerous two- and three-dimensional seismic datasets have been acquired (Glørstad-Clark et al., 2011) forming the basis for our present understanding of the evolution of the area (Henriksen et al., 2011b). The wells have documented reservoirs within the Permian, Triassic, Jurassic and Cretaceous successions (e.g. Larsen et al., 1993; Dore, 1995; Henriksen et al., 2011b; Stoupakova et al., 2011). However, many of the discoveries are non-commercial or only marginally commercial, at least partly, due to the Late Cenozoic regional tectonic uplift and subsequent fluvial-glaciofluvial erosion of up to 500 - 3000 m of sediments from the Barents Sea area. These processes have affected the maturity of the source rocks, reservoir quality and caused leakage of former hydrocarbon accumulations (Vorren et al., 1991; Riis and Fjeldskar, 1992; Dore and Jensen, 1996; Ryseth et al., 2003; Henriksen et al., 2011a; Laberg et al., 2012). The Late Cenozoic uplift and subsequent erosion of much of the Cenozoic strata resulted in re-deposition of eroded material along the contemporary subsiding western Barents Sea margin (Faleide et al., 1993b; Martinsen and Nøttvedt, 2008; Henriksen et al., 2011a; 2011b).

A thick and relatively complete Cenozoic succession, dominated by the Late Pliocene-Pleistocene predominantly glaciogenic sediments, is present along the western Barents Sea margin, particularly in the Sørvestsnaget Basin (Ryseth et al., 2003; Andreassen et al., 2007; Laberg et al., 2010), the Vestbakken Volcanic Province (Rasmussen et al., 1995; Eidvin et al., 1998; Knutsen et al., 2000) and along the Hornsund Fault Zone, from the Stappen High to the north of Svalbard (Faleide et al., 1996; Grogan et al., 1999) (Figure 2). Previous studies of the Cenozoic interval have mainly focused on the Early Cenozoic tectonic history related to the opening of the Norwegian-Greenland Sea (Talwani and Eldholm, 1977; Spencer et al., 1984; Faleide et al., 1988; 1993b; 2008; Breivik et al., 1998; Dore et al., 1999; Lundin, 2002; Lundin and Dore, 2002; Mosar et al., 2002). Many studies have also been devoted to the Late Pliocene-Pleistocene depositional processes and paleoenvironment and its relation to the glacial history of the region (e.g. Vorren et al., 1991; Sættem et al., 1992; 1994; Laberg and Vorren, 1993; 1996; Faleide et al., 1996; Hjelstuen et al., 1996; Solheim et al., 1998).

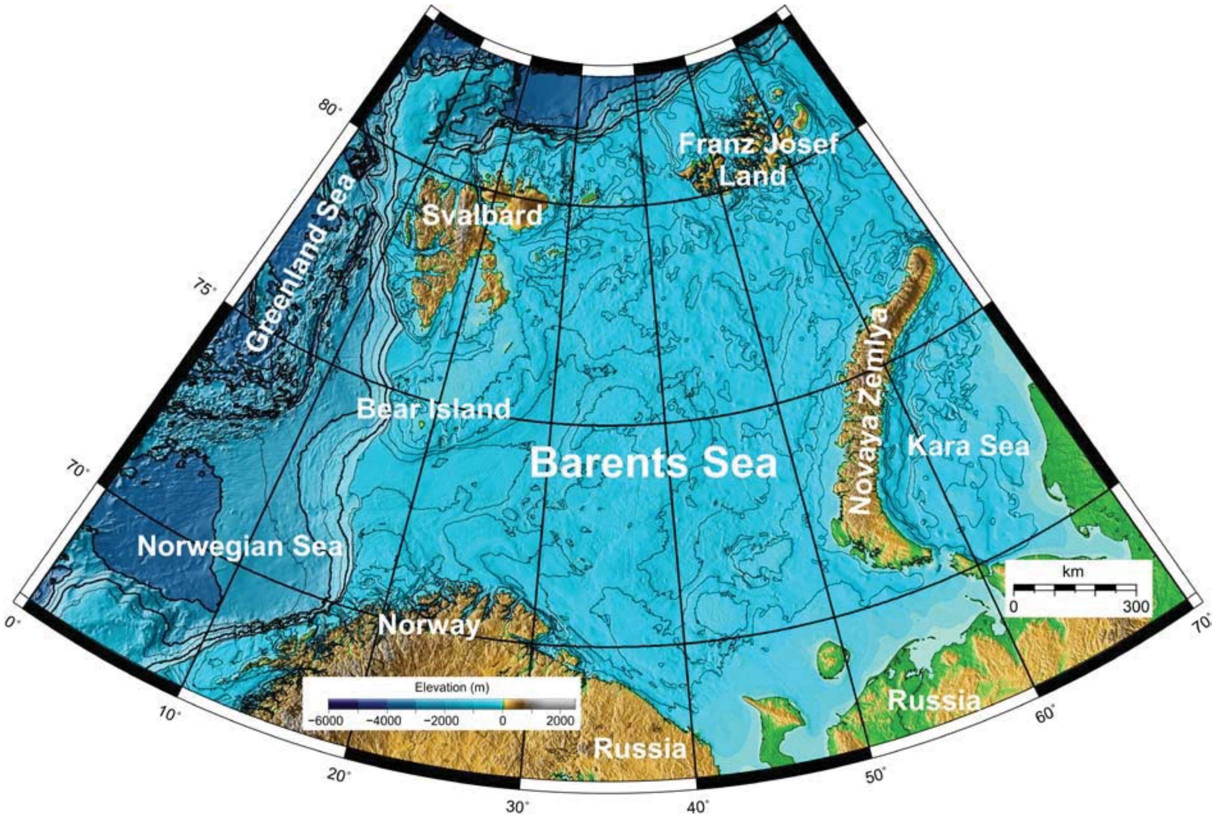


Figure 1. Bathymetric map of the Barents Sea area. The map was made in the Generic Mapping Tool (GMT) based on the data from IBCAO (International Bathymetric Chart of the Arctic Ocean) v. 3.0.

Very little, however, has been published on the buried Cenozoic deep-water gravity-induced deposits along the western Barents Sea margin. A vast range of deposits fall into the category of gravity-induced deposits, where major ones include slumps, slides, debris flows and turbidites (Dott, 1963; Nardin et al., 1979; Moscardelli et al., 2006; Moscardelli and Wood, 2008; Mulder, 2011) (Figure 3). It is important to study these processes as they play an important role in the transfer of sediment into the deep-water environment and consequently deliver an important part of the sedimentary fill of basins along the continental margins worldwide (Moscardelli and Wood, 2008). A better understanding of deep-water gravity-induced deposits and factors controlling their deposition and distribution are of key importance both for hydrocarbons exploration and for protection of offshore infrastructure (cables, pipelines and platforms) against natural hazards (Mulder and Cochonat, 1996).

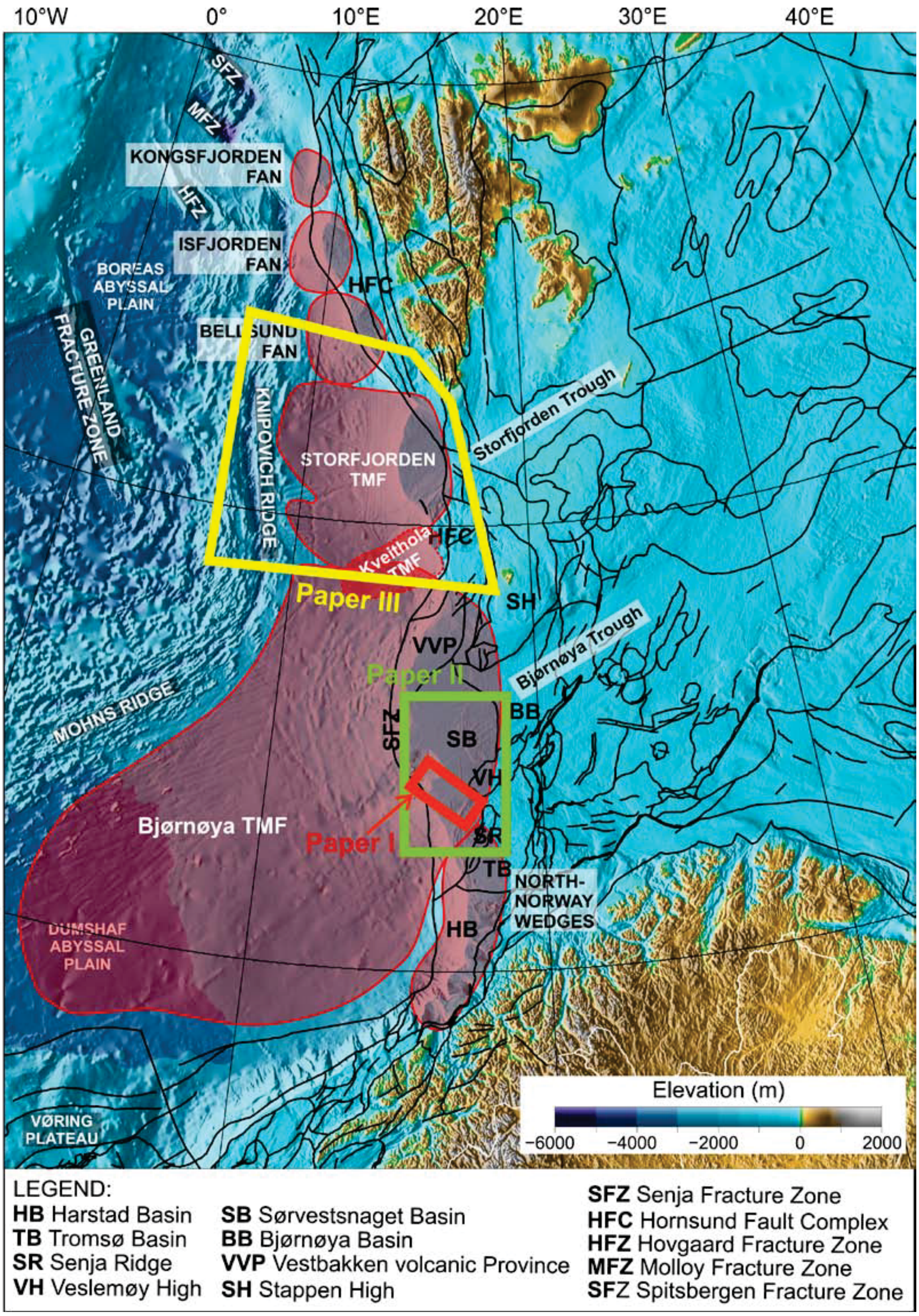


Figure 2. Bathymetric map of the western Barents Sea with the main structural elements indicated by black lines. The structural elements are from a map made by Norwegian Petroleum Directorate. The map was made in the Generic Mapping Tool (GMT) based on the data from IBCAO (International Bathymetric Chart of the Arctic Ocean) v. 3.0 (2012). Red shaded zones indicate the distribution of the Late Pliocene-Pleistocene Trough Mouth Fans (TMFs). Red rectangle indicates the study area of Paper I. Green rectangle indicates the study area of Paper II. Yellow polygon indicates the study area of Paper III.

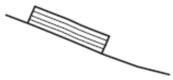
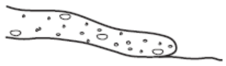
GRAVITY INDUCED DEPOSITS			Genetic Classification Transport Mechanism	Descriptive Classification Sedimentary Structures	Seismically Recognizable Features (Moscardelli et al., 2006; this work)
Mass Transport Complex	Slide		Shear failure along discrete shear planes with little or no internal deformation or rotation	Essentially undeformed, continuous bedding	Continuous blocks without apparent internal deformation. High-amplitude, continuous reflections.
	Slump		Shear failure accompanied by rotation along discrete shear surfaces with various degrees of internal deformation	Plastic deformation particularly at the toe or base. Plow structures, folds, tension faults, joints, slickensides, grooves, rotational blocks	Compressional ridges, imbricate slides, irregular upper bedding contacts, duplex structures, contorted layers. Low- and high-amplitude reflections geometrically arranged as though deformed through compressive stresses.
	Debris Flow		Shear distributed throughout the sediment mass. Strength is principally from cohesion due to clay content. Additional matrix support may come from buoyancy. Plastic rheology and laminar state.	Matrix supported, random fabric, clast size variable, matrix variable. Rip ups, rafts, inverse grading and flow structures possible.	Mega rafted and/or detached blocks, irregular upper bedding contacts, lateral pinch-out geometries, oriented ridges and scours. Low-amplitude, semitransparent chaotic reflections.
Turbidity Current	Turbidite		Supported by fluid turbulence (newtonian rheology)	Normal size grading, sharp basal contacts, gradational upper contacts.	Lobate features Laterally continuous

Figure 3. Classification of gravity-induced deposits. Compiled from Dott (1963), Nardin et al., (1979) and Moscardelli et al. (2006). (Reprinted with permission from Moscardelli and Wood, (2008)).

The aim of this PhD thesis is to get a better understanding of internal and external characteristics, distribution in space and time, depositional environments and degree of deformation of Cenozoic deep-water gravity-induced deposits along the western Barents Sea passive continental margin based on two- and three-dimensional seismic data calibrated with available well data (Figure 4). The scientific results are presented in three papers. Papers I and II provide an insight into, and contribute to, a better understanding of the Early Cenozoic deep-water gravity-induced sandy (turbidite) deposits along the south-western Barents Sea margin - Sørvestsnaget Basin, which can be considered as potential reservoirs for hydrocarbon accumulations. A better understanding of factors controlling the deposition and preservation of the deep-water gravity-induced reservoir deposits in the study area is of key importance as it will help to improve future exploration of the Barents Sea margin. Potentially, it can also help to predict stratigraphic and geographic distribution of deep-water reservoirs worldwide (Lien, 2006).

Paper III focuses on Late Cenozoic buried submarine slides along the NW Barents Sea margin, timing of the events and factors promoting their failure. It is important to study submarine slides as they can illuminate the evolution of a margin, depositional processes on the margin and slope instability (Mulder and Cochonat, 1996; Evans et al., 2005). A sudden displacement of the sea-floor through catastrophic sediment failure can affect offshore infrastructure and disrupt the water column above the failure generating a tsunami that could affect coastal areas causing loss of human life (Canals et al., 2004; e.g. Dawson et al., 2004; Fryer et al., 2004; Lee et al., 2007; Leynaud et al., 2009).

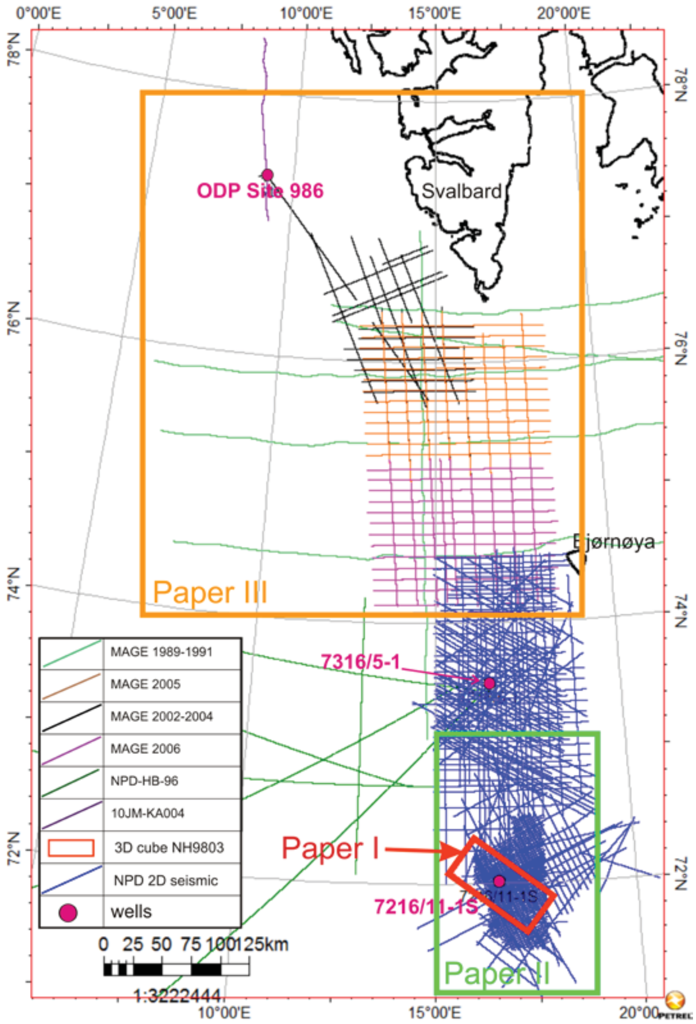


Figure 4. Seismic data used in Paper I (red rectangle = 3D seismic dataset NH9803), Paper II (green rectangle = NPD 2D seismic data (blue lines) + 3D seismic data) and Paper III (orange rectangle includes MAGE data, NPD data and 10JM-KA004 acquired by the University of Tromsø).

Below, subchapter 1.1 provides a general overview of the current knowledge about Cenozoic deep-water gravity-induced turbidite deposits, potential for hydrocarbons accumulation along the Western Barents Sea margin and other passive margins. Subchapter 1.2 focuses on our present knowledge about Late Cenozoic submarine slides along the western Barents Sea margin and other passive margins.

1.1. Deep-water turbidites and their distribution along passive continental margins

Turbidites represent one of the most attractive reservoir types among the deep-water gravity-induced deposits (Pettingill, 1998b). Turbidites are sediments deposited from turbidity currents i.e. gravity-driven dilute (non-cohesive) flows of poorly sorted sediments in which fluid turbulence maintains grain dispersion in the main part of the flow (Mulder and Cochonat, 1996; Parsons et al., 2007) and are characterized by graded bedding, moderate sorting and well-developed primary structures, i.e. part of or the complete Bouma cycle (Neuendorf et al., 2005). Turbidite systems are often named as deep-water depositional systems, in spite of the fact that deep-water depositional systems may be composed of a continuum of sediment gravity-induced deposits (Stelting et al., 2000). Individual unconformity-bounded turbidite systems have been called 'fan lobes' (Bouma et al., 1985) and stacked turbidite systems and their bounding basinal shales are called turbidite complex or submarine fan (Stelting et al., 2000).

More than 1300 oil and gas fields, including both discoveries and producing fields, are known to be related primarily to deep-water turbidites (Stow and Mayall, 2000). A steep worldwide cumulative reserves growth indicates that deep-water turbidite systems, in particularly Cenozoic reservoirs at passive margins, will play a significant role in the future of hydrocarbon exploration, taking into account that they are at an immature exploration stage globally (Pettingill, 1998a). Cenozoic deep-water sandy turbidites along passive continental margins worldwide form one such potential hydrocarbon-producing reservoirs, and are found in the Norwegian Sea (Martinsen et al., 2005; Lien et al., 2006), North Sea (Ahmadi et al., 2003; Jones et al., 2003), offshore West Africa (Stow and Johansson, 2000; Beglinger et al., 2012), offshore Brazil (Guardado et al., 1990; Bruhn and Walker, 1997), west of Shetlands (Stow and Johansson, 2000) and in the Gulf of Mexico (Apps et al., 1994; McGee et al., 1994; Dutton and Loucks, 2010; Crawford et al., 2011).

Very little is currently known about the Cenozoic deep-water hydrocarbon reservoirs along the western Barents Sea margin. Exploration drilling of the western Barents Sea margin has failed to prove economic Cenozoic hydrocarbons reservoirs (Henriksen et al., 2011b). A small dry gas discovery in Middle Eocene sandstones was made by exploration well 7316/5-1 in the Vestbakken Volcanic Province (Knutsen et al., 2000) (Figures 2 and 4). Well 7216/11-

1S penetrated a significant 214 m thick Middle Eocene (Intra Lutetian) sandstone-bearing interval (with an average porosity of 25.8 %; Henriksen et al. (2011b)) in the central part of the Sørvestsnaget Basin, SW Barents Sea (Ryseth et al., 2003) (Figures 2 and 4). Based mainly on the core and well data interpretation, and to lesser degree on seismic mapping, the Intra Lutetian interval has been interpreted as a submarine fan deposited from high-density turbidity currents (Ryseth et al., 2003). The sediment source area was inferred to be the Stappen High (Ryseth et al., 2003), which was uplifted at that time due to Early Eocene tectonism (Gabrielsen et al., 1990). Considering a paucity of current knowledge about the deep-water turbidite systems in the Sørvestsnaget Basin, a better overview of this system and other potential systems, and their depositional environment is needed, and this is the overall aim of Papers I and II.

Deep-water depositional systems often show indications of having undergone post-depositional sand remobilization and injection (e.g. Lonergan et al., 2000; Hurst et al., 2003b; Briedis et al., 2007; Huuse et al., 2007; Jackson et al., 2011). Hydrocarbon fields subjected to sand re-mobilization can be a challenge during exploration, field development and production (e.g. Lonergan et al., 2000) and individual sandstone injections can be large enough to form hydrocarbon reservoirs (Huuse et al., 2005a). Understanding the origin of sandstone intrusions and factors that primes and triggers their formation is important and can add to our understanding of fluid flow and sediment mobilization in sedimentary basins and have important implications for the pre-drill prediction of reservoir presence and quality, and seal risk (Szarawarska et al., 2010).

Examples of remobilized and injected sand have been documented at core- and seismic-scales, in both outcrops worldwide, for example, in California (Vigorito et al., 2008; Vetel and Cartwright, 2010), Northern England (Kane, 2010), East Greenland (Surlyk et al., 2007) and on seismic data, mainly within the Early Cenozoic interval from the North Sea (Molyneux et al., 2002; Hurst et al., 2003a; Shoulders and Cartwright, 2004; Huuse et al., 2005a; Huuse et al., 2007) (Figure 5). Core-scale sandstone injections have also been indicated for the Middle Eocene deep-water turbidite system in the Sørvestsnaget Basin, but so far, no seismic-scale studies have been published. Therefore, Papers I and II also aim to identify and understand the regional distribution of post-depositional sand deformation and injection of the Middle Eocene deep-water depositional systems and to gain better insight into the processes that prime and trigger their deformation.

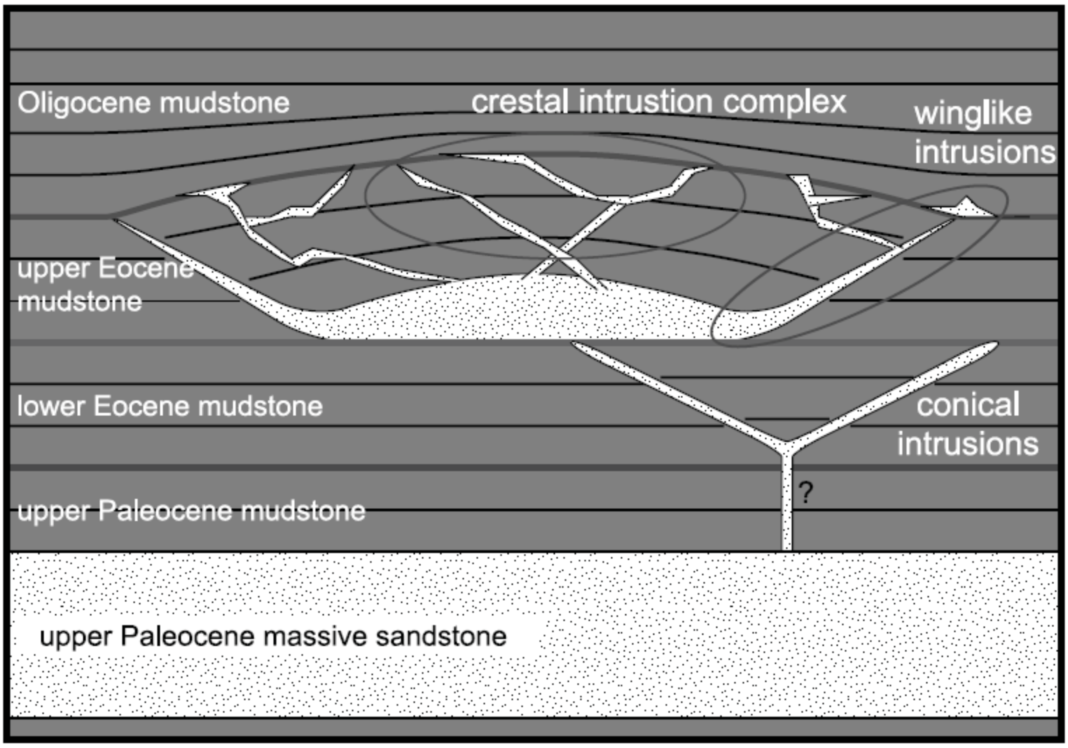


Figure 5. Three types of sandstone intrusions detected by 3-D seismic data in the North Sea Paleogene. Schematic based on data from the outer Moray Firth (Huuse et al., (2005b)) shows type 1 = winglike intrusions adjacent to and above concordant parent sand bodies; type 2 = conical intrusions some distance above their parent sands; type 3 = crestal intrusion complex above more massive sand bodies. (from Huuse et al., (2007), reprinted by permission of the AAPG whose permission is required for further use).

1.2. Submarine slides and their distribution along passive continental margins

Submarine slides or slope failures are defined as movements of coherent, internally undeformed masses of sediments are bounded on all sides by distinct failure planes, which usually following the stratification of the underlying strata (Mulder and Cochonat, 1996; Masson et al., 2006; Lee et al., 2007) (Figure 3). The term slide is commonly used for both the process and the deposit of that process (e.g. Mulder, 2011). A slide can be differentiated from a slump based on the value of the Skempton ratio (h/l; maximum depth of the slip surface to length of the slump/failure), where slumps are rotational with Skempton ratios >0.33 and slides are translational with ratios <0.15 (Skempton and Hutchinson, 1969). Slumps have also been suggested to be a type of slide in which blocks of failed material rotate along a curved lip surface (Lee et al., 2007), and therefore rotational slides are called slumps (Mulder,

2011) (see Figure 3 for more information). The majority of submarine slides appear to be translational (Prior and Coleman, 1984). Submarine slides can become, for example, a debris flow or turbidite current as the failed material progressively disintegrates and continuous downslope movement occurs (Morgenstern, 1967; Hampton, 1972; Lee et al., 2007).

Submarine slides are common features along passive continental margins worldwide (Lee, 2009), for example, along the southeast Canadian margin (Piper et al., 2003), the area off West Africa and surrounding the Canary Islands (Urgeles et al., 1977; Masson, 1996; Urgeles et al., 1999) and the eastern US margin (Prior et al., 1986; Lee, 2009). Large-scale submarine slides have influenced and still influence the sea-floor morphology on the northern Svalbard margin (Vanneste et al., 2006) and the Norwegian continental margin, including the Andøya Slide (Laberg et al., 2000), the Trænadjupet Slide (Laberg and Vorren, 2000; Laberg et al., 2002) and the Storegga Slide - the world's largest exposed submarine slide (Bugge, 1983; Haflidason et al., 2004). Submarine slides of various sizes have also been instrumental in shaping the Late Pliocene-Pleistocene south-western Barents Sea passive continental margin, among them the 1.0-0.2 Ma old mega-scale Bjørnøya Fan Slide Complex (Hjelstuen et al., 2007), the large-scale 0.2-0.3 Ma old Bjørnøyrenna Slide (Laberg and Vorren, 1993; 1996) and several Pliocene-Pleistocene (?) smaller and large-scaled submarine slides (Knutsen et al., 1992; Kuvaas and Kristoffersen, 1996). Each of the two largest slides of the Bjørnøya Fan Slide Complex remobilized approximately 25×10^3 km^3 of sediments; that is one order of magnitude greater than the worlds' largest exposed submarine slide, the Storegga, which remobilized < 3.2×10^3 km^3 of sediments (Hjelstuen et al., 2007). Small- and large-scale submarine landslides (younger than 1.0 Ma) covering an area of ca. 50 km^2 to more than 1100 km^2 have been documented on the continental slope of the NW Barents Sea margin (Lucchi et al., 2012; Rebesco et al., 2012).

Several preconditioning factors which act as an early stimulus before the final triggering mechanism occurs (Ireland et al., 2011) has been considered: rapid sedimentation, gas charging and/or gas hydrate dissociation, groundwater flow, cyclic loading of sediments and the presence of a generally weak layer (e.g. Laberg and Vorren, 2000; Lindberg et al., 2004; Evans et al., 2005; Lee et al., 2007). The triggering mechanism is an external stimulus that initiates slope instability (Sultan et al., 2004). Among the important triggers are earthquakes, localized erosion by moving water or sediment flows, sediment accumulation, volcanoes, storm waves, dissociation of gas hydrates resulting from environmental changes (i.e. sea-level fall destabilizes the base of the gas-hydrate zone), groundwater seepage, diapirism and human activity (e.g. Laberg and Vorren, 1993; 2000; Imbo et al., 2003; Lee et al., 2007). However, glaciations are inferred to be one of the dominant factors that influence the timing of significant submarine slides occurrence (Lee, 2009). For example, all the submarine slides along the western Barents Sea are inferred to have been related to the Late Pliocene-Pleistocene Northern Hemisphere Glaciations due to increased loads of rapidly deposited glaciogenic sediments on a softer substratum, oversteepening of the margin by glacial-marine sedimentation processes and earthquakes (Laberg and Vorren, 1993; 1996; Kuvaas and Kristoffersen, 1996; Hjelstuen et al., 2007; Lucchi et al., 2012).

Many studies have been devoted to Late Pleistocene-Holocene submarine slides along the Norwegian - Barents Sea – Svalbard margin, little is, however, known about the older and buried large-scale submarine slides on the western Barents Sea margin and factors promoting their failure. The presence of extensive mass movement deposits (broadly defined as gravity-induced deposits (e.g. Nardin et al., 1979; Hampton and Lee, 1996; Lee et al., 2007), characterized by a discontinuous seismic reflection pattern, has been indicated in the Late Pliocene-Early Pleistocene succession along the NW Barents Sea margin (Faleide et al., 1996; Hjelstuen et al., 1996). Similar seismic facies within the same interval have also been observed along the south-western Svalbard margin (in the Bellsund Fan) (Amundsen et al., 2011). They have been inferred to represent the most northern rim of extensive slide deposits covering the largest part of the NW Barents Sea margin and part of the SW offshore Svalbard. In paper III, new high-resolution two-dimensional seismic data from the Russian Marine Arctic Geological Expedition are used, together with results from Ocean Drilling Program Site 986 west of Svalbard (Figure 4), to present the first detailed description and to discuss potential precondition factors and triggering mechanisms for these buried gravity-induced deposits - submarine slides on the NW part of the Barents Sea margin. Establishing the ages of individual large-scale submarine slides would help to understand the timing of failure relative to glacial cycles (Evans et al., 2005) and potentially suggest triggering mechanism irrespective of the glacial history.

2. Study area and geological background

Two areas along the western Barents Sea continental margin are studied in this thesis. Papers I and II focus on the Early Cenozoic (Middle Eocene) succession in the Sørvestsnaget Basin, SW Barents margin (Figures 2 and 4). Paper III focuses on Late Cenozoic interval along the NW Barents Sea margin and south-western rim offshore of Svalbard (Figures 2 and 4). Since these papers cover together the entire Cenozoic interval, a brief introduction on the overall development of the western Barents Sea margin during the Cenozoic is given below.

The Barents Sea is one of the largest continental shelves in the world and covers an area of approximately 1.3×10^6 km^2 (Dore, 1995; Vorren et al., 1998). It is bordered by the islands of Novaya Zemlya and Franz Josef Land in the east and northeast, the Svalbard archipelagos in the northwest, by the northwest Russian and Norwegian costs in the southeast and southwest, respectively, and Cenozoic passive continental margins to the north and west (Figure 1). The Barents Sea area experienced a long history of post-Caledonian extension (since the Devonian) followed by (1) Late Devonian - Middle Carboniferous rifting, (2) Late Carboniferous - Permian carbonate platform development with deposition of thick evaporates, (3) Triassic - Cretaceous siliciclastic shelf development, (4) Late Cretaceous-Paleocene rifting, (5) Early Eocene continental breakup started at the magnetic anomaly 24 (ca. 54-55 Ma) and gradual northward opening of the Norwegian-Greenland Sea along the regional De Geer Zone megashear system, and (6) Late Cenozoic passive margin development (Nøttvedt et al., 1992; Mosar et al., 2002; Ryseth et al., 2003; Faleide et al., 2008).

The present Barents Sea - Svalbard passive continental margin developed along the De Geer Zone megashear system comprising three main structural segments, which differ in their crustal, magmatic and structural properties and their Norwegian-Greenland post-opening history: (1) a southern sheared margin segment (70°–72°30’N) marked by the Senja Fracture Zone; (2) a central rifted margin segment (72°30’–74°30’N) located southwest of Bjørnøya and mainly marked by the Vestbakken Volcanic Province associated with breakup-related volcanism and; (3) a northern initially sheared and later rifted continental margin along the Horsund Fault Zone (74°30’–81°N) (e.g. Faleide et al., 1993b, a; Faleide et al., 1996; Faleide et al., 2008) (Figure 2). The northern segment is subdivided into three sub-segments: (1) a sheared margin sub-segment from Bjørnøya to Sørkapp at the southern tip of Spitsbergen (74°30'–76°N); (2) an initially sheared and later rifted margin between Sørkapp and

Kongsfjorden (76°–79°N); and (3) a complex sheared and rifted margin along NW Svalbard and SW Yermak Plateau associated with volcanism (79°–81°N) (Faleide et al., 2008).

The evolution of the western Barents Sea - Svalbard margin is closely linked to the gradual northward opening of the Norwegian-Greenland Sea. The SW Barents Sea margin formed during the Eocene along the Senja Fracture Zone, starting (1) as continent-continent shear during Early Eocene (ca. 54-55 Ma) when the eastern boundary of the northeast Greenland continental shelf was located along the western margin of the Harstad Basin and Sørvestsnaget Basin, (2) followed by continent-ocean shear and, (3) has been passive since earliest Oligocene (Skogseid et al., 2000; Mosar et al., 2002; Faleide et al., 2008). During the Paleocene-Eocene, widespread deep-marine conditions persisted in the SW Barents Sea (Sørvestsnaget Basin) with deposition of mainly fine-grained mudrocks with episodes of sand deposition in the Intra Lutetian (Ryseth et al., 2003).

The Vestbakken Volcanic Province was characterized by breakup-related magmatism during the Eocene (Ryseth et al., 2003; Faleide et al., 2008). The north-western Barents Sea - Svalbard margin experienced oblique continent-continent and partly continent-ocean shear with both transpressional and transtentional components during that time (Grogan et al., 1999; Bergh and Grogan, 2003; Faleide et al., 2008). Sea-floor spreading reached the margin off southern Spitsbergen at the end of Eocene, and a narrow oceanic basin existed between the NE Greenland and western Barents Sea continental margins (Faleide et al., 2008).

A significant shallowing of the Sørvestsnaget Basin took place from the end-Eocene, due to plate tectonic reorganization in the earliest Oligocene (Ryseth et al., 2003) when Greenland moved in a more westerly direction related to Eurasia (Faleide et al., 2008). Early Oligocene rifting reactivated primarily NE-trending faults and renewed volcanism in the Vestbakken Volcanic Provenance (Jebsen and Faleide, 1998; Faleide et al., 2008). It also resulted in a northward opening of the Greenland Sea between Greenland and Svalbard, first by continent extension, followed by incipient sea-floor spreading along the Knipovich Ridge (Lundin and Dore, 2002; Mosar et al., 2002). Since the Oligocene, oceanic crust developed along the entire western Barents Sea margin and after breakup the margin evolved in response to subsidence and high sediment loading during widening and deepening of the Norwegian-Greenland Sea (Ryseth et al., 2003; Faleide et al., 2008).

The Late Cenozoic depositional environment of the western Barents Sea margin was strongly influenced by tectonically induced uplift and Late Pliocene to Pleistocene climate deterioration and onset of Northern Hemisphere Glaciations (3.6-2.4 Ma) (e.g. Vorren et al., 1991; Dahlgren et al., 2005; Knies et al., 2009). Relative sea-level fall during the Middle Miocene led to erosion of the shelf areas and formation of lowstand deposits in the Late Miocene-Early Pliocene (Vorren et al., 1991; Knutsen et al., 1992). The established fluvial-glaciofluvial erosional regime during the Late Pliocene-Pleistocene greatly increased sedimentation rates and led to formation of prominent westward prograding wedges - Trough Mouth Fans (TMFs) near the shelf edge in front of bathymetric troughs in the western Barents Sea - Svalbard area (e.g. Faleide et al., 1996; Hjelstuen et al., 1996; Laberg and Vorren, 1996; Vorren et al., 1998) (Figure 2). Climate is regarded as the main factor controlling the wedge growth and glacially derived sediments comprise a significant proportion of the TMFs, in some areas, however, it is still unclear if the initial stage of fans growth occurred during a fluvial phase in response to uplift, with glaciations a later consequence (Butt, 2000; Dahlgren et al., 2005; Praeg et al., 2005; Stoker et al., 2005; Andreassen et al., 2007).

The Plio-Pleistocene succession along the western Barents Sea margin is subdivided into three seismic units GI, GII and GII, which are separated by the regionally correlatable reflectors R7, R5 and R1 (Faleide et al., 1996) (Figure 6). There is widespread agreement that glacial ice reached the shelf edge in the SW Barents Sea margin around 1.5 Ma (R5) (Faleide et al., 1996; Andreassen et al., 2004; Sejrup et al., 2005). However, it is still unclear when the NW Barents Sea margin started to be affected by shelf-edge glaciation. The reflector R7, corresponding to the time period of 2.7. Ma (Knies et al., 2009), has been suggested to mark an onset of continental shelf glaciations west off Svalbard and along the Storfjorden TMF area (Faleide et al., 1996). However, sedimentological data from the ODP Site 986 (Figure 4) indicate that the NW Barents Sea margin was free of major ice sheets at this time, with the first evidence for shelf-edge glaciation only appearing from reflector R5 i.e. 1.5 Ma and onwards (Butt et al., 2000). According to this revised chronology, large-scale glaciations in the NW Barents Sea, with repeated advances to the shelf edge, took place from 1.0 Ma (Knies et al., 2009). A new correlation of seismic data with the ODP Site 986 (Figure 2) suggests that onset of Storfjorden TMF growth took place at time 1.3 Ma (Rebesco et al., in review).

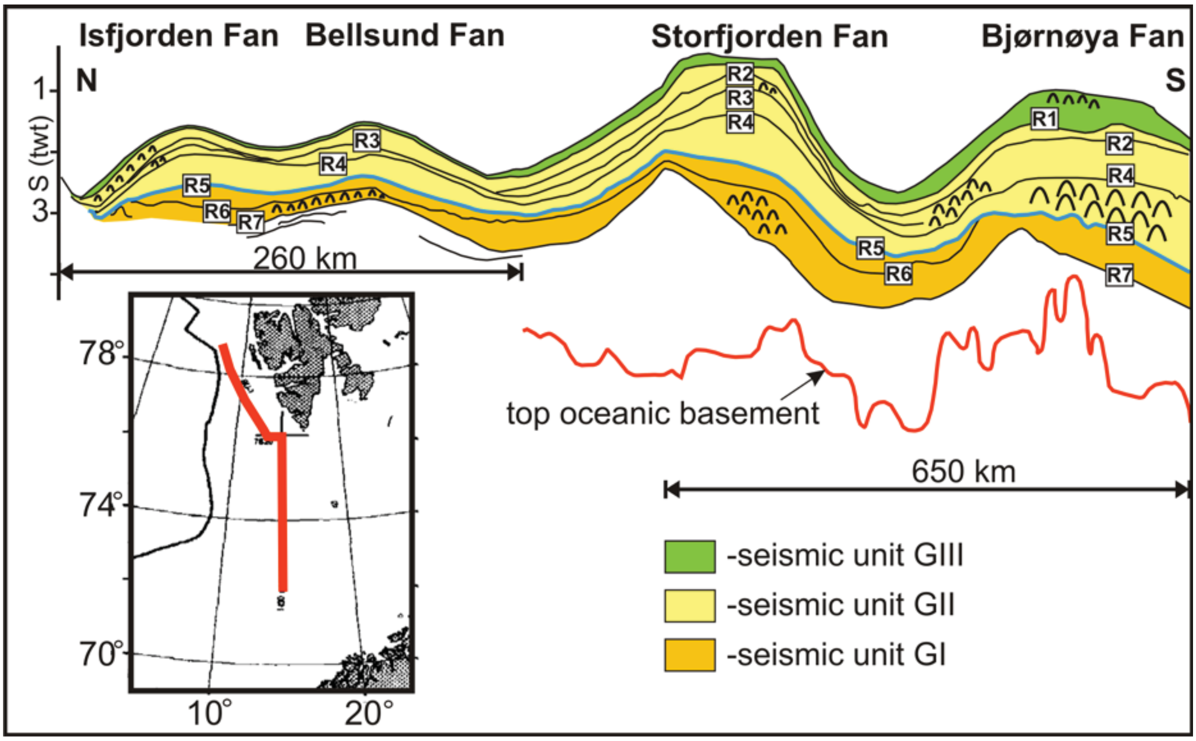


Figure 6. Composite regional profile covering Bjørnøya, Storfjorden, Bellsund and Isfjorden TMF. The lateral and vertical distribution of three main seismic units with chaotic reflection pattern is indicated. Modified from Faleide et al., 1996.

3. Aims of the study

The overall aim of the PhD study is to increase our understanding of the distribution and depositional environment of the Cenozoic deep-water gravity-induced deposits in the western Barents Sea margin.

In more detail the objectives are to:

- Elucidate overall architecture of the Middle Eocene, deep-water sandy depositional system penetrated by well 7216/11-1S in the Sørvestsnaget Basin based on three-dimensional seismic data analysis integrated with well data (Paper I).
- Obtain an understanding of the potential link between seismic facies architecture of the Middle Eocene deep-water depositional system and its degree of deformation (Paper I).
- Document and discuss seismic-scale sandstone intrusions and their origin (Paper I and partly Paper II).
- Identify priming and triggering mechanisms causing post-depositional sand remobilization and formation of sandstone intrusions (Paper I).
- Investigate the variation in shelf-margin spatial scale clinoform geometries and their shelf-edge trajectory trends. This will help to reveal the depositional environments of the Middle Eocene sediments in the Sørvestsnaget Basin in the context of long-term shelf evolution, source area and prediction of potential reservoir sandstones from seismic data without well control (Paper II).
- To understand the importance of tectonic control on the accommodation development and stratigraphic pattern in the Sørvestsnaget Basin during the Middle Eocene (Paper II).
- Present the first detailed description and discuss potential precondition factors and triggering mechanisms for buried submarine slides in the north-western part of the Barents Sea margin (Paper III).
- Understand the timing and depositional environment during the formation of the buried submarine slides along the north-western Barents Sea margin (Paper III).

4. Database and methods

4.1. Seismic data

The three-dimensional seismic data set (NH9803) and extensive two-dimensional seismic surveys used to investigate a Middle Eocene sedimentary succession in the Sørvestsnaget Basin are from the Diskos PetroBank database provided by the Norwegian Petroleum Directorate (Papers I and II) (Figures 2 and 4). The 2D seismic data, covering an area of ca. 18820 km^2, are of medium to poor quality at the target interval. The 3D seismic data covers an area of approximately 2000 km^2. They have a generally good vertical resolution at the depth of interest, which is approximately 26 m assuming a seismic P-wave velocity (V) of ca. 2000 m/s and a dominant frequency (f) of 20 Hz. In practice, the horizontal resolution of 3D migrated seismic data is defined by a Fresnel zone diameter (1/2 wavelength) (Brown, 1999) and is ca. 52 m.

Large-scale submarine slides on the NW Barents Sea margin (Paper III) are interpreted using high-resolution seismic data acquired in 2002 - 2006 and a series of regional lines acquired in 1989-1991 by the Russian Joint Stock Company “Marine Arctic Geological Expedition”. The high-resolution seismic line 10JM-KA004 collected by the University of Tromsø in 2010 was integrated in order to tie seismic data to the ODP Site 986 and to identify the stratigraphic position of the slides. A set of 2D multichannel seismic reflection profiles provided by Norwegian Petroleum Directorate (Diskos PetroBank database) were used to do a seismic tie from the south of the study area to the established seismostratigraphy along the SW Barents Sea margin (e.g. Faleide et al., 1996; Hjelstuen et al., 2007) (Figure 4).

4.2. Well data

Wireline log data from the well 7216/11-1S are used to define the upper and lower limits of the Middle Eocene (Intra Lutetian) deep-water sandy depositional system (Paper I) (Figure 4). The top and base of the Middle Eocene sand-bearing interval are interpreted from the gamma ray log, which records the radioactivity of the formation (Rider, 2002). The sandy beds correspond to decreased values of gamma ray measured in API (American Petroleum Institute), due to their low radioactivity compared with shale. To correlate the seismic response with the lithology interpreted from the well, a synthetic seismogram is generated from the sonic log, which was calibrated with check shots and the density log data from the interval of interest using Schlumberger's Petrel interpretation software. The seismic wavelet was extracted from the 3D seismic cube (NH9803).

Information from Ocean Drilling Program Site 986 (Jansen et al., 1996; Forsberg et al., 1999; Butt et al., 2000) west of Svalbard is used in paper III to identify the stratigraphic position of the studied submarine slides, and reveal lithological description and depositional environments of the enclosing strata (Figure 4).

4.3. Seismic facies analysis

Papers I, II and III attempt to reveal strata terminations and seismic facies variations within the intervals of interest. Seismic facies units are groups of seismic reflections, which are distinguished through a series of characteristics such as reflection configuration, continuity, amplitude and frequency, internal geometrical relationship and external three-dimensional form (Mitchum et al., 1977a; Miall, 2010) (Figure 7). Seismic facies analysis helps to interpret lithofacies distribution, their depositional environmental, energy and sediment source from seismic data (Mitchum et al., 1977a; Veeken, 2007). On two-dimensional seismic sections, reflection terminations are defined by the geometric relationship between the reflection (strata) and the seismic surface against which it terminates (Emery and Myers, 1996). The terms 'toplap, onlap, downlap, truncation, lapout and baselap' were introduced by Mitchum et al. (Mitchum et al., 1977b) in order to describe reflection termination styles (Emery and Myers, 1996).

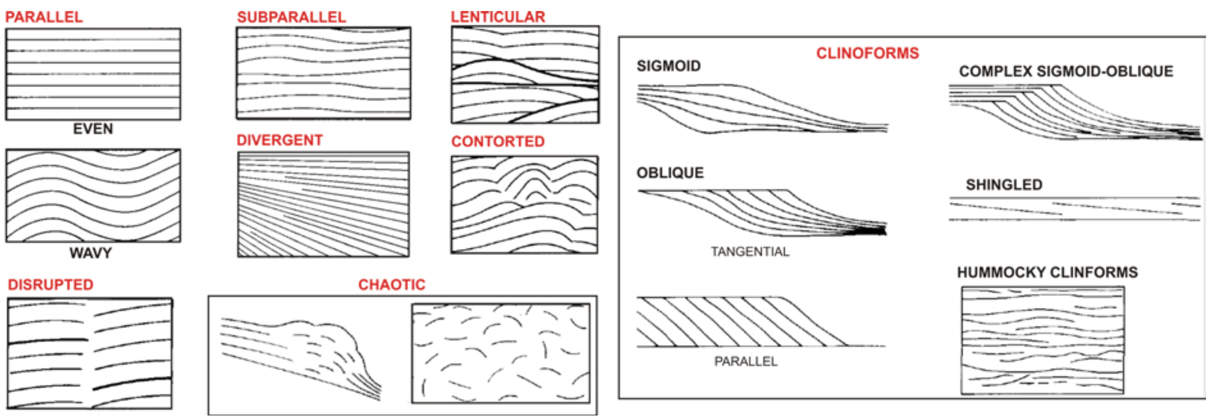


Figure 7. Various reflection configurations. Modified from Mitchum et al., 1977a.

4.4. Shelf-edge trajectory analysis

The sedimentary infill of the Sørvestsnaget Basin during the Middle Eocene is analyzed through a series of seismically defined clinoforms at different stratigraphic levels and with a shelf-margin spatial scale according to Steel and Olsen (2002) (Paper II). The term "clinoform" is applied during this study to the entire sigmoidal-shaped surfaces ('topset-foreset-bottomset') on a wide range of spatial scales where the topset of the clinoforms is interpreted as a morphological "shelf", the upper rollover referred to as the "shelf-slope break" and "slope" is the deeper water surface below (Steel and Olsen, 2002). Helland-Hansen and Hampson (2009) stated: "Trajectory analysis is the study of the lateral and vertical migration of geomorphological features and associated sedimentary environments, with emphasis on the paths and direction of migrations". Trajectories can be studied at different scales: ripple migration, point-bar accretion, shoreface (10s of meter relief) and shelf-edge (100s of meter) progradation to continental margin progradation (500-1000s of meter relief) (Larue and Martinez, 1989; Helland-Hansen and Hampson, 2009; Henriksen et al., 2011c) (Figure 8). During this study, this method is applied to 2D studies of the Middle Eocene depositional dip-oriented succession at shelf-margin spatial scale. Investigation of variation in shelf-margin clinoform geometries and their shelf-edge trajectory trends, defined by successive positions of the shelf-slope breaks in a stratigraphic succession, is a relatively new method helping to reveal the depositional environment of the succession in the context of long-term shelf evolution and to predict lithology on the shelf, slope and basin floor from seismic data in areas without well control (Bullimore et al., 2005; Johannessen and Steel, 2005; e.g. Helland-Hansen and Hampson, 2009). A shelf-edge trajectory analysis represents a relatively new interpretative tool and analytical approach that complements and extends conventional sequence stratigraphic methods and models (Helland-Hansen and Martinsen, 1996; Helland-Hansen and Hampson, 2009; Henriksen et al., 2011c). It considers the sum of a long-term response to combined changes in rates of relative sea-level (eustasy plus subsidence/uplift) and sedimentation rate (e.g. Helland-Hansen and Hampson, 2009).

4.5. Three-dimensional seismic attribute maps

Different 3D seismic attribute maps were produced in Schlumberger's Petrel software to identify lithological changes and specific characteristics in the zone of interest within the Middle Eocene succession in the Sørvestsnaget Basin (Papers I and II). Seismic attributes are a powerful tool in seismic interpretation enabling enhancement of a desired geological feature, reservoir property of interest and definition of the depositional environment and structural features (Chopra and Marfurt, 2007). Attribute maps can be generated along a single mapped horizon, for a volume between two horizons and for a specific time or time interval. The Instantaneous seismic amplitude attribute and the Extract Amplitude Value surface attribute extracting amplitude values along a single horizon are commonly used in this thesis. A volume-based attribute - the root-mean-squared (RMS) amplitude is used during this study. It squares all the amplitudes within the window of interest, calculates the average of squared amplitude values, and eventually the square root of that number.

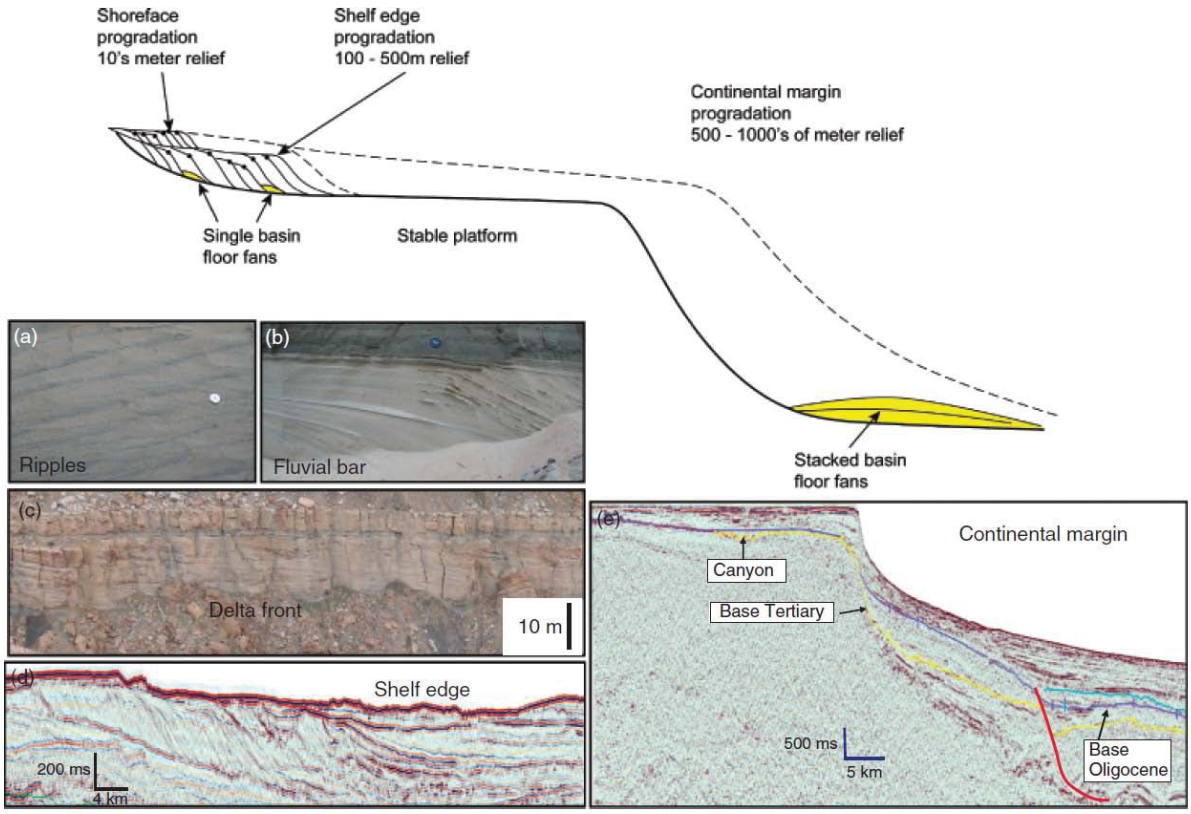


Figure 8. Scales of progradation, ranging from ripples to continental margin clinoforms. (a) Climbing ripples and (b) aggrading fluvial bar from Tana River, Northern Norway. (c) Prograding delta front clinoforms from Cretaceous Ferron Sandstone, Utah, USA. (d) Shelf edge progradation from Neogene of the Norwegian Sea. (e) High relief continental margin from offshore Brazil (Courtesy of Fugro). Figure reprinted with permission from Henriksen et al., (2009).

5. Summary of papers

Paper I: **Development and post-depositional deformation of a Middle Eocene deep-water sandy depositional system in the Sørvestsnaget Basin, SW Barents Sea**

Polina Alekseevna Safronova, Karin Andreassen, Jan Sverre Laberg and Tore Ola Vorren

3D seismic data from the Sørvestsnaget Basin are used to investigate a Middle Eocene deep-water sandy depositional system penetrated by well 7216/11-1S. The system is spatially defined by a NNW-SSE-oriented sediment accumulation having an abrupt western termination and thickens northwards up to 200 ms (twt). A volume based root-mean-square amplitude map images amplitudes variation along the system. Areas with highest amplitudes are interpreted to reflect a higher sand content, while areas with lower amplitudes are interpreted to reflect lack of sandstone or the sandy interval being too thin to be resolved.

The depositional system has a very complex geometry as the result of synsedimentary faulting and post-depositional sand remobilization and injection. In the east, the system is characterized by isolated, several kilometers wide, sub-circular, sediment blocks, which are suggested to represent either small sandstone lobes or to be remnants of the main sand deposit, disturbed by post-depositional sand remobilization and injection. In the north and north-east, the deepwater depositional system was deformed by wing-like sandstone intrusions, extending 200-400 m upwards from the margins of the parent sand bodies. The intrusions have polygonal or broadly circular plan view geometries. Overpressure in the sand bodies is inferred to be caused by (1) rapid burial, (2) fluid migration into the sealed sand bodies from deeper sources via synsedimentary faults and (3) fluid drainage from the surrounding mud during early compaction. The mechanism that finally triggered sand remobilization and injection may have been fault-induced earthquakes, and/or differential compaction and associated fracturing adjacent to the buried sand bodies.

<u>Contribution of authors:</u> P. Safronova was responsible for seismic data interpretation and analysis, calibration of seismic data with well information, making of all the figures and the writing of the paper. The co-authors contributed to the discussions of the data interpretation, structuring of the paper and gave valuable input throughout the writing of the paper.

Paper II: **Evolution of shelf-margin clinoforms and basin-floor fans during the Middle Eocene in the Sørvestsnaget Basin, SW Barents Sea**

Polina Alekseevna Safronova, Sverre Henriksen, Karin Andreassen, Jan Sverre Laberg and Tore Ola Vorren

This paper presents 3D and 2D seismic data analysis that aims to understand the Sørvestsnaget Basin development during the Middle Eocene, sediment source area and location of potential deep-water sandstone fans. During the Middle Eocene, a gradual basin infilling was generated by southward stepping clinoforms, indicating a sediment source area in the north, presumably, the Stappen High. Tectonic movements were important driving mechanisms for the accommodation development, and the variable basin physiography exerted a major control on the succession development. During this time, the Sørvestsnaget margin shows transformation from an initially high relief margin, due to the presence of an intra-basinal high in the north, to a progradational in the final stage.

Generally oblique clinoform shifts creating a flat shelf-edge trajectory were established during the early stage of basin development. This implies a gentle falling or stable relative sea-level, with no significant coeval coastal plain and delta plain deposits on the shelf, and significant sediment bypass and accumulation into the downslope deep-water areas. The basin is characterized by accumulation of thick and aerially extensive deep-water sandy fans, which likely result from a combination of factors: high relief margin, narrow shelf, high rate of sediment supply, relative sea-level fall or stillstand and seismicity. Taking into account the relatively narrow shelf and the inferred high sediment supply, part of the sand could have been dislocated from the shelf and onto the basin floor during a later stage of basin development marked by relative sea-level rise.

A fully progradational margin developed during the later stage of basin development when the shelf-to-basin profile became less steep, probably, due to increased subsidence of the northern part of the basin. This stage of basin development is characterized mainly by sigmoid clinoforms shifts, which create an overall low angle ascending shelf-edge trajectory, suggesting a relative sea-level rise during a deposition. The accommodation-to-sediment supply ratio is >1 implying sand accumulation on the shelf. A series of sandy channel-lobe complexes are however inferred to be present at the toe of clinoform slopes.

Contribution of authors: P. Safronova was responsible for seismic data analysis and interpretation, all the figures and writing the paper. S. Henriksen provided the main input to the analysis of the shelf-margin spatial scale clinoforms and their trajectory trend. All the co-authors participated in discussions of the results and review of the manuscript.

Paper III: **Large-scale submarine slides affecting the north-western Barents Sea margin during the Late Pliocene – Early Pleistocene**

Polina Alekseevna Safronova, Jan Sverre Laberg, Karin Andreassen, Rune Mattingsdal, Valentina Shlykova, Tore Ola Vorren and Sergey Chernikov

This paper presents the first detailed description of the 2.7-2.1 Ma old buried submarine slide debrites in the NW Barents Sea margin by using high-resolution two-dimensional seismic data integrated with ODP Site 986 data. The largest of them - submarine slide debrite 1 is located in the north of the study area and partly associated with a paleo-scar. It has a maximum thickness of 870 m, covers an area of more than 10.7×10^3 km^2 and volume of sediments within the failure is > 4.1×10^3 km^3. It involved more sediments than the largest modern Storegga Slide in the northern Norwegian margin. In the south of the NW Barents Sea margin at least four large-scale submarine slides are identified. These slide debrites lack clearly defined scars and are smaller than the northern slide 1. Each of them is ca. 295 m thick, covers an area of at least 7.04×10^3 km^2 and involved $1{,}1\times10^3$ km^3 of sediments.

This study shows that high latitude passive continental margins may be affected by large-scale slides prior to the first shelf edge glaciation. Intervals of weak contouritic sediments and presence of gas/gas hydrates were likely a preconditioning factor for submarine slide generation in this area. Failures were likely triggered by earthquakes due to proximity of the Knipovich spreading ridge and tectonic lineaments.

Contribution of authors: P. Safronova was responsible for seismic data interpretation and analysis, most of the figures and writing the paper. R. Mattingsdal and V. Shlykova identified the main regional reflectors on two seismic lines crossing the ODP Site 986. J.S. Laberg provided valuable input to the structuring of the manuscript and discussion of the results. The co-authors participated in discussions of the results and review of the manuscript.

6. Synthesis

This chapter presents a synthesis of the results from the three papers within the context of the western Barents Sea margin development during the Early Cenozoic and Late Cenozoic time.

6.1. Early Cenozoic evolution of the western Barents Sea margin

The Early Cenozoic development and depositional environment of the Sørvestsnaget Basin as well as the entire western Barents Sea margin, was affected by tectonic activity related to the opening of the Norwegian-Greenland Sea since the Early Eocene (e.g. Faleide et al., 2008). Sedimentation mainly took place along the newly established western Barents Sea continental margin (within the Sørvestsnaget-, Harstad-, Tromsø Basins, Vestbakken Volcanic Province and the areas west of Hornsund Fault Zone) (Figure 2), which continued to subside due to spreading and received a large amount of clastic sediments from uplifted eastern and northern parts of the Barents Sea shelf (Vorren et al., 1991; Smelror et al., 2009).

The results from Paper II demonstrate that during the Middle Eocene, the Sørvestsnaget Basin experienced a continued accommodation development due to differential subsidence, caused not only by active sea-floor spreading, but also by differential or synchronous activity of the synthetic and antithetic faults in the basin, salt movement in the south-east and different tectonic activity between the Sørvestsnaget Basin and Veslemøy High in the north-east (Ryseth et al., 2003). The influence of eustasy on the space available for sediment accumulation cannot be ruled out because the Sørvestsnaget Basin was not isolated from the Norwegian-Greenland Sea during that time. Differential subsidence caused changes in margin style through the Middle Eocene, from an initial high relief to a progradational margin i.e. transition from an 'under-filled' stage of basin development to an 'over-filled' in a sense of Handler-Jacobsen et al. (2005). The results from Paper II also demonstrate gradual basin infilling during the Middle Eocene from the north, generated by southward prograding shelf-margin spatial scale clinoforms. The presence of clinoforms supports Ryseth et al. (2003) inference that the majority of the Middle Eocene sediments were most likely sourced from the Stappen High, which was uplifted in the Paleogene (Gabrielsen et al., 1990).

- **Formation of Middle Eocene deep-water fans (or depositional systems)**

Papers I and II provide an improved understanding of the Cenozoic (Middle Eocene) potential for deep-water gravity-induced sandstone deposits in the Sørvestsnaget Basin and their depositional environments. During the early Middle Eocene, the Sørvestsnaget Basin was characterized by (1) a significant high relief margin, (2) narrow shelf, (3) mainly oblique clinoforms forming a flat shelf-edge trajectory trend that implies a gentle falling or stable relative sea-level and (4) apparently high sedimentation rate. All these factors could contribute to an effective long-term sediment bypass across the shelf into a deep-water environment by sediment gravity-flow processes (turbidite currents and/or debris flows?) (cf. Bullimore et al., 2005; Henriksen et al., 2005; Johannessen and Steel, 2005; Helland-Hansen and Hampson, 2009). It therefore led to formation of thick and areally extensive deep-water fans on the basin floor, which had a large run-out distance. Sandstones are likely to be laterally discontinuous and interbedded with mudstones, and underwent post-depositional deformation and injection. Fault-induced earthquakes or earthquakes due to active spreading of the Mohns Ridge (Figure 2) could cause excess pore pressure and as a result, increased instability of slope sediments (Bugge et al., 1988; Ryan et al., 2009). This is consistent with the large number of earthquakes of magnitude ≥ 6, which have been detected since 1970 associated with the Mohns rifts valley and old fault systems, in particular, the Senja Fracture Zone (Avetisov, 1996) (Figure 2). Note that some sand may have been dislocated from the shelf and onto the basin floor during early stage of relative sea-level rise. This ‘exception to the rule’ may be attributed to the presence of narrow shelf accompanied by high sedimentation rate (cf. Henriksen et al., 2005; 2009; Carvajal and Steel, 2006).

The presence of extensive sigmoid clinoform shifts, giving an overall low angle ascending shelf-edge trajectory during the later Middle Eocene fully progradational stage of Sørvestsnaget Basin development, implies sand storage on the continental shelf and coastal plain (e.g. Bullimore et al., 2005) and presence of mainly muddy slopes and basin floors (Johannessen and Steel, 2005). Shelf-edge deposits may be of intermediate to good reservoir quality, but sand will probably be thinner than those associated with the high angle positive shelf-edge trajectory (Bullimore et al., 2005). However, a series of sandy channel-lobe complexes are also inferred to be present during this stage at the toe of clinoform slopes due to the inferred narrow shelf accompanied by high sedimentation rate.

- **Sandstone intrusions and their origin**

Middle Eocene deep-water fans (or depositional systems) are highly deformed by post-depositional sand remobilization and injection. Paper I presents the first documentation of seismic-scale sandstone injections in the Barents Sea. It describes 'bowl- and W-shaped' sandstone bodies deforming the lowermost Middle Eocene deep-water sandy fan 1. The bases of these features, being generally concordant to the sedimentary bedding, are inferred to be in situ depositional sandstone bodies. Discordant wing-like parts are inferred to be sandstone injections, sourced from the margins of the concordant sandstone bodies. Low- to moderate amplitude folds underlying these features are interpreted to result from differential compaction of the sandstone bodies and surrounding mudstone. Deep-water depositional systems tendency to undergo post-depositional sand remobilization and injection is mainly due to a presence of good seal (low permeable mudstones) and a volumetrically significant, well sorted, unconsolidated sand in which an excess-fluid pressure has built up (e.g. Lonergan et al., 2000; Huuse, 2008). In the Sørvestsnaget Basin, pore fluid overpressure in the buried Middle Eocene sand bodies is suggested to be result from (1) rapid burial, (2) fluid migration into the sealed sand bodies from deeper sources via synsedimentary faults and (3) fluid drainage from the surrounding mud during early compaction. The following mechanisms are suggested to have triggered seal failure and subsequent sand remobilization and injections: (1) fault-induced earthquakes, and/or (2) differential compaction and associated fracturing adjacent to the buried sand bodies. Earthquakes associated with the Mohns spreading ridge might also have been involved.

Paper II shows that the overlying Middle Eocene deep-water fan 2 is also deformed by similar 'bowl-like' features as deep-water fan 1. Some of these can be completely intrusive based on criteria such as (1) the presence of generally non-erosional bases; (2) equally thick layers of encasing mudstones; (3) 'jack-up' of the overburden equal to the thickness of an underlying sandstone body (cf. Szarawarska et al., 2010). Folding above the intrusions can be explained by folding of the sedimentary cover due to forceful intrusion of sand just below the depositional surface (Trude et al., 2003; Shoulders and Cartwright, 2004). Several sources for sand are considered: (1) the underlying deep-water sandy fan 1 penetrated by well 7216/11-1S can be a source for the sandstone intrusions of the deep-water fan 2; (2) the deep-water fan 2 could originally have contained sandstone bodies, which could have acted as a source for the wing-like sandstone intrusions being entirely remobilized and, therefore, forming 'bowl- or saucer-shaped' fully intrusive sandstone bodies. Sand migration hundreds of meters away from the potential parent sand body has been suggested by several authors (e.g. Huuse et al., 2004; Shoulders and Cartwright, 2004; Huuse et al., 2007). Sand migration in the study area from the deeper sources seems unlikely for two reasons: (1) the underlying stratigraphic succession down to Early Palaeocene is interpreted to be mudstone dominated (Ryseth et al., 2003) and (2) there is no evidence for regionally extensive sandy systems below the Paleocene. Even if we assume the presence of sand below the Paleocene, it is unlikely that it could act as source for the intrusions as it had already been deeply buried (>500 m) and most likely had been lithified before the deep-water fans formation (cf. Dmitrieva et al., 2012).

In conclusion, papers I and II contribute to a better understanding of deep-water fans (depositional systems) in the Sørvestsnaget Basin, their distribution and depositional environment. This may potentially help to improve future exploration in the Barents Sea and the general ideas can be applicable for similar basins worldwide.

6.2. Late Cenozoic evolution of the western Barents Sea margin

The established fluvial-glaciofluvial erosional regime during the Late Cenozoic time due to tectonically induced uplift and the late Pliocene to Pleistocene climate deterioration and onset of Northern Hemisphere Glaciations (3.6-2.4 Ma; Knies et al. (2009)) greatly increased sedimentation rates and led to formation of thick succession of Late Cenozoic sediments along the western Barents Sea margin (e.g. Vorren et al., 1991; Dahlgren et al., 2005; Laberg et al., 2010). Pleistocene-Holocene submarine slides of various sizes have been instrumental in shaping the Late Cenozoic western Barents Sea continental margin, and these were directly related to the dynamics of the ice sheet during the Pliocene-Pleistocene Northern Hemisphere Glaciations (Hjelstuen et al., 2007; Laberg and Vorren, 1993; 1996; Lucchi et al., 2012; Kuvaas and Kristoffersen, 1996).

However, the results from Paper III demonstrate the presence of five older large-scale submarine slide debrites characterized by chaotic- to reflections-free seismic facies along the north-western Barents Sea margin within the time period from 2.7 to 2.1 Ma i.e. Late Pliocene-Early Pleistocene between the seismic reflectors R7 and R6 (Figure 6) (Knies et al., 2009). The chaotic to reflection-free seismic facies within the interval R7-R6 have previously been inferred to represent mass movement deposits (Faleide et al., 1996; Hjelstuen et al., 1996). During this study it is suggested that these submarine slides were likely formed before glacial ice reached the shelf edge in this area based on (1) ODP Site 986 analysis (Butt et al., 2000), revised chronology (Knies et al., 2009) and a new correlation of seismic data with the ODP Site 986 (Rebesco et al., in review) (see the chapter 2 "Study area and its geological background" for more information). Moreover, the results from paper III may also support later (Pleistocene) onset of glaciation in the NW Barents Sea margin. This is based on observations that the sediment depocenters had changed through time. The thickest part of the seismic unit GI (Figure 6), corresponding to the period of time from 2.7 to 1.5 Ma (Knies et al., 2009), is seen close to 75°N - south of the present Storfjorden Trough. Then there is a northward shift in the depocenter of sequence GII (Figure 6) (time period from 1.5 to 0.2 Ma), where its thickest part correlates with the mouth of the Storfjorden Trough.

Therefore, paper III demonstrates that large scale sliding can happen before the shelf-edge glaciation and that one of the slides could even have remobilized more sediments than the Storegga Slide in the Norwegian Sea, the largest exposed submarine slides in the world. Several preconditioning factors and final triggering mechanisms considered to generate sliding in the study area, irrespective of the glacial history, are suggested. Preconditioning factors are (1) the presence of gas and/or gas hydrates and (2) the presence of regionally extensive weak layer (contouritic sediments). Earthquakes associated with the Knipovich spreading ridge and tectonic activity along older tectonic features could finally also trigger submarine sliding in the study area.

7. Ideas for future research

- The internal and external characteristics, distribution in space and time, and the depositional environment of the Middle Eocene deep-water sandy turbidites in the Sørvestsnaget Basin are highlighted in this work. It is important also to get a better overview of the age-equivalent sandstone interval penetrated by an exploration well 7316/5-1 in the Vestbakken Volcanic Province (Knutsen et al., 2000) (Figure 4). Knowing the potential of deep-water depositional systems to experience post-depositional sand remobilization and injections, it would also be interesting to evaluate this interval for post-depositional deformation.

- Considering the availability of new two-dimensional seismic data from the MAGE, it is important to update regional correlation of major Late Pliocene-Pleistocene seismic units (GI, GII and GIII), their thickness variations in space and time, and internal seismic facies changes laterally and vertically along the north-western Barents Sea and Svalbard margin. It will potentially improve our understanding of the onset of glaciations in this region and reveal their palaeoclimatic and sedimentological evolution. Updated estimation of erosional and depositional rates, their spatial and temporal variations are needed in order to gain better understanding of the glacial history of the Barents Sea - Svalbard area.

- Paper I highlighted the distribution of thick and regionally extensive submarine slides debrites within the lower part of the seismic unit GI between reflectors R7 and R6 (Figure 6). However, high-resolution two-dimensional seismic data from the Russian Marine Arctic Geological Expedition also indicate the presence of numerous smaller-scaled slope submarine slides within the seismic unit GII in the south of the NW Barents Sea margin (Figure 9). It would be interesting to (1) make a detailed description of these failures, (2) discuss potential preconditioning factors and triggering mechanisms, (3) establish the ages of these failures and (4) compare them with submarine slide debrites from the Paper III. In addition, Figure 10 demonstrates the presence of potential debris flow deposits within the seismic unit GI (above reflector R1), which can be of special interest. Debris flow deposits have a potential of causing massive damage due to their ability of entraining material and reaching long run-outs, and therefore they represent a major threat to human life and properties (Hedda, 2005).

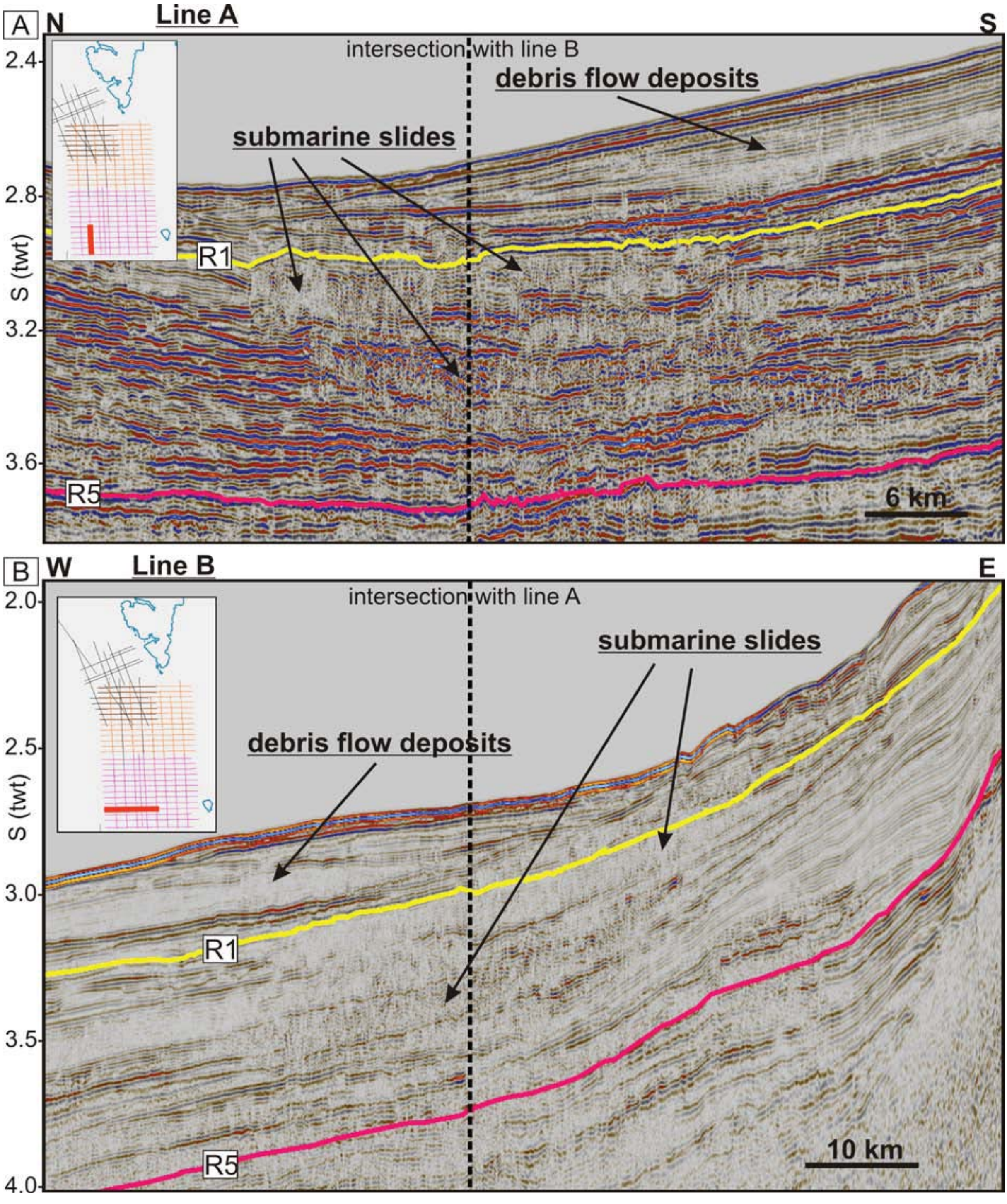


Figure 9 (A-B) Vertical seismic sections indicate presence of submarine slides within the seismic unit GII between the reflectors R5 and R1, and extensive debris flow deposits within the seismic unit GIII above the reflector R1 and sea-floor.

References

Ahmadi, Z., M. Sawyers, S. Kenyon-Roberts, B. Stanworth, K. Kugler, J. Kristensen, and E. Fugelli, 2003, Paleocene, *in* D. Evans, C. Graham, A. Armour, and P. Bathurst, eds., The Millennium Atlas: Petroleum geology of the central and northern North Sea, Geological Society of London, p. 236-261.

Amundsen, I. M., M. Blinova, B. O. Hjelstuen, R. Mjelde, and H. Haflidason, 2011, The Cenozoic western Svalbard margin: sediment geometry and sedimentary processes in an area of ultraslow oceanic spreading: Marine Geophysical Researches, v. 32, p. 441-453.

Andreassen, K., E. G. Nilssen, and C. M. Odegaard, 2007, Analysis of shallow gas and fluid migration within the Plio-Pleistocene sedimentary succession of the SW Barents Sea continental margin using 3D seismic data: Geo-Marine Letters, v. 27, p. 155-171.

Andreassen, K., L. C. Nilssen, B. Rafaelsen, and L. Kuilman, 2004, Three-dimensional seismic data from the Barents Sea margin reveal evidence of past ice streams and their dynamics: Geology, v. 32, p. 729-732.

Apps, G. M., F. J. Peel, C. J. Travis, and C. A. Yeilding, 1994, Structural controls on Tertiary deep water deposition in the northern Gulf of Mexico: Submarine fans and turbidite systems, sequence stratigraphy, reservoir architecture and production characteristics, Gulf of Mexico and international, GCS-SEPM Foundation 15th annual research conference, p. 1-7.

Avetisov, G. P., 1996, Seismically active zones of the Arctic, Saint Petersburg VNIIOkeangeologia.

Beglinger, S. E., H. Doust, and S. Cloeting, 2012, Relating petroleum system and play development to basin evolution: West African South Atlantic basins: Marine and Petroleum Geology, v. 30, p. 1-25.

Bergh, S., and P. Grogan, 2003, Tertiary structure of the Sorkapp-Hornsund region, south Spitsbergen, and implications for the offshore southern extension of the fold-thrust belt: Norwegian Journal of Geology, v. 83, p. 43-60.

Bouma, A. H., C. E. Stelting, and J. M. Coleman, 1985, Mississippi fan, Gulf of Mexico, *in* A. H. Bouma, W. R. Normark, and N. E. Barnes, eds., Submarine fans and related turbidite systems: New-York, Springer-Verlag, p. 143-150.

Breivik, A. J., J. I. Faleide, and S. T. Gudlaugsson, 1998, Southwestern Barents Sea margin: late Mesozoic sedimentary basins and crustal extension: Tectonophysics, v. 293, p. 21-44.

Briedis, N. A., D. Bergslien, A. Hjellbakk, R. E. Hill, and G. J. Moir, 2007, Recognition criteria, significance to field performance, and reservoir modeling of sand injections in the Balder field, North Sea: AAPG Memoir, v. 87, p. 91-102.

Brown, A. R., 1999, Interpretation of three-dimensional seismic data, AAPG Memoir 42, SEG Investigations in Geophysics, No. 9, 514 p.

Bruhn, C. H. L., and R. G. Walker, 1997, Internal architecture and sedimentary evolution of coarse-grained, turbidite channel-levee complexes, Early Eocene Regência Canyon, Espírito Santo Basin, Brazil: Sedimentology, v. 44, p. 17-46.

Bugge, T., 1983, Submarine slides on the Norwegian continental margin, with special emphasis on the Storegga area, v. 110: Trondheim, Norway, Continental Shelf and Petroleum Research Institute Publication.

Bugge, T., R. H. Belderson, and N. H. Kenyon, 1988, The Storegga slide: Philosophical Transactions of the Royal Society of London, v. 325, p. 357-388.

Bullimore, S., S. Henriksen, F. M. Liestøl, and W. Helland-Hansen, 2005, Clinoform stacking patterns, shelf-edge trajectories and facies associations in Tertiary coastal deltas, offshore Norway: Implications for the prediction of lithology in prograding systems: Norwegian Journal of Geology, v. 85, p. 169-187.

Butt, F. A., 2000, Late Cenozoic shifts in climate, topography and depositional environments in the Polar North Atlantic: causes and impacts as evidenced from ODP data and numerical simulations, University of Oslo, Oslo, Norway.

Butt, F. A., A. Elverhøi, A. Solheim, and C. F. Forsberg, 2000, Deciphering Late Cenozoic development of the western Svalbard Margin from ODP Site 986 results: Marine Geology, v. 169, p. 373-390.

Canals, M., G. Lastras, R. Urgeles, J. L. Casamor, J. Mienert, A. Cattaneo, M. D. Batist, H. Haflidason, Y. Imbo, J. S. Laberg, J. Locat, D. Long, O. Longva, D. G. Masson, N. Sultan, F. Trincardi, and P. Bryan, 2004, Slope failure dynamics and impacts from seafloor and shallow sub-seafloor geophysical data: case studies from the COSTA project: Marine Geology, v. 213, p. 9-72.

Carvajal, C. R., and R. J. Steel, 2006, Thick turbidite successions from supply-dominated shelves during sea-level highstand: Geology, v. 34, p. 665-668.

Chopra, S., and K. J. Marfurt, 2007, Overview of Seismic Attributes, *in* S. J. Hill, ed., Seismic Attributes for Prospect Identification and Reservoir Characterization: Tulsa, OK U.S.A., Society of Exploration Geophysicists, p. 1-24.

Crawford, T. G., G. Burgess, S. Haley, Harrison, C. J. Kinler, G. D. Klocek, and N. K. Shepard, 2011, Outer Continental Shelf. Estimated Oil and Gas Reserves Gulf of Mexico OCS Region December 31, 2007 OCS Report New Orleans, U.S. Department of the Interior Bureau of Ocean Energy Managments, Regulation and Enforcement Gulf of Mexico OCS Region, p. 1-78.

Dahlgren, K. I. T., T. Vorren, M. S. Stoker, T. Nielsen, A. Nygård, and H. P. Sejrup, 2005, Late Cenozoic prograding wedges on the NW European continental margin: their formation and relationship to tectonics and climate: Marine and Petroleum Geology, v. 22, p. 1089-1110.

Dawson, A. G., P. Lockett, and S. Shi, 2004, Tsunami hazards in Europe: Environment International, v. 30, p. 577-585.

Dmitrieva, E., C. A. L. Jackson, M. Huuse, and A. McCarthy, 2012, Paleocene deep/water depositional systems in the North Sea Basin: a 3D seismic and well data case study, offshore Norway: Petroleum Geoscience, v. 18, p. 97-114.

Dore, A. G., 1995, Barents Sea Geology, Petroleum Resources and Commercial Potential: Arctic, v. 48, p. 207-221.

Dore, A. G., and L. N. Jensen, 1996, The impact of late Cenozoic uplift and erosion on hydrocarbon exploration: offshore Norway and some other uplifted basins: Global and Planetary Change, v. 12, p. 415-436.

Dore, A. G., E. R. Lundin, L. N. Jensen, Ø. Birkeland, P. E. Eliassen, and C. Fichler, 1999, Principal tectonic events in the evolution of the northwest European Atlantic margin: Petroleum Geology of Northwest Europe: Proceeding of the 5th Conference, p. 41-61.

Dott, R. H., 1963, Dynamics of subaqueous gravity depositional processes: American Association of Petroleum Geologists Bulletin, v. 47, p. 104-128.

Dutton, S. P., and R. G. Loucks, 2010, Reprint of: Diagenetic controls on evolution of porosity and permeability in lower Tertiary Wilcox sandstones from shallow to ultradeep (200–6700 m) burial, Gulf of Mexico Basin, U.S.A.: Marine and Petroleum Geology, v. 27, p. 1775-1787.

Eidvin, T., R. M. Goll, P. Grogan, M. Smelror, and K. Ulleberg, 1998, The Pleistocene to Middle Eocene stratigraphy and geological evolution of the western Barents Sea continental margin at well site 7316/5-1 (Bjørnøya West area): Norwegian Journal of Geology, v. 78, p. 99-123.

Emery, D., and K. J. Myers, 1996, Sequence stratigraphy, Blackwell, Oxford, 297 p.

Evans, D., Z. Harrison, P. M. Shannon, J. S. Laberg, T. Nielsen, S. Ayers, R. Holmes, R. J. Hoult, B. Lindberg, H. Haflidason, D. Long, A. Kuijpers, E. S. Andersen, and P. Bryn, 2005, Palaeoslides and other mass failures of Pliocene to Pleistocene age along the Atlantic continental margin of NW Europe: Marine and Petroleum Geology, v. 22, p. 1131-1148.

Faleide, J. I., A. M. Myhre, and O. Eldholm, 1988, Early Tertiary volcanism at the western Barents Sea margin, *in* A. Morton, and L. M. Parson, eds., Early Tertiary volcanism and the opening of the NE Atlantic, v. 39, Geological Society Special Publications, p. 135-146.

Faleide, J. I., A. Solheim, A. Fiedler, B. O. Hjelstuen, E. S. Andersen, and K. Vanneste, 1996, Late Cenozoic evolution of the western Barents Sea-Svalbard continental margin.: Global and Planetary Change, v. 12, p. 53-74.

Faleide, J. I., F. Tsikalas, A. J. Breivik, R. Mjelde, O. Ritzmann, Ø. Engen, J. Wilson, and O. Eldholm, 2008, Structure and evolution of the continental margin off Norway and the Barents Sea: Episodes, v. 31, p. 1-10.

Faleide, J. I., E. Vågnes, and S. T. Gudlaugsson, 1993a, Late Mesozoic - Cenozoic evolution of the south-western Barents Sea: J.R. Parker (ed), Petroleum Geology of North West Europe: Pro-ceedings of the Fourth Conference. Geological Society, London, p. 933-950.

Faleide, J. I., E. Vågnes, and S. T. Gudlaugsson, 1993b, Late Mesozoic - Cenozoic evolution of the southwestern Barents Sea in a regional rift-shear tectonic setting: Marine and Petroleum Geology, v. 10, p. 186-214.

Forsberg, C. F., A. Solheim, A. Elverhoi, E. Jansen, J. E. T. Channell, and E. S. Andersen, eds., 1999, The depositional environment of the western Svalbard margin during the late Pliocene and the Pleistocene: Sedimentary facies changes at Site 986.: Proceeding

Ocean Drilling Program. Scientific Results, v. 162: College Station, TX, Ocean Drilling Program, 233–246 p.

Fryer, G. J., P. Watts, and L. F. Pratson, 2004, Source of the great tsunami of 1 April 1946: a landslide in the upper Aleutian forearc: Marine Geology, v. 203, p. 201-218.

Gabrielsen, R. H., R. B. Færseth, L. N. Jensen, J. E. Kalheim, and F. Riis, 1990, Structural elements of the Norwegian continental shelf. Part I: The Barents Sea region: Norwegian Petroleum Directorate Bulletin, v. 6, p. 1-33.

Glørstad-Clark, E., E. P. Birkeland, J. P. Nystuen, J. I. Faleide, and I. Midtkandal, 2011, Triassic platform-margin deltas in the western Barents Sea: Marine and Petroleum Geology, v. 28, p. 1294-1314.

Grogan, P., A. M. Østvedt-Ghazi, G. B. Larssen, B. Fotland, K. Nyberg, K. I. T. Dahlgren, and T. Eidvin, 1999, Structural elements and petroleum geology of the Norwegian sector of the northern Barents Sea: Petroleum geology of Northwest Europe; proceedings of the 5th conference, p. 247-259.

Guardado, L. R., L. A. P. Camboa, and C. F. Lucchesi, 1990, Petroleum geology of the Campos basin, a model for a producing Atlantic type basin, *in* J. D. Edwards, and P. A. Santogrossi, eds., Divergent/Passive margin basins, v. 48, AAPG Memoir, p. 3-79.

Hadler-Jacobsen, F., E. P. Johannessen, N. Ashton, S. Henriksen, S. D. Johnson, and J. B. Kristensen, 2005, Submarine fan morphology and lithology distribution: a predictable function sediment delivery, gross shelf-to-basin relief, slope gradient and basin topography: Petroleum Geology: North-West Europe and Global Perspectives-Proceedings of the 6th Petroleum Geology Conference, p. 1121-1145.

Haflidason, H., H. P. Sejrup, A. Nygård, J. Mienert, P. Bryan, R. Lien, C. F. Forsberg, K. Berg, and D. Masson, 2004, The Storegga Slide: architecture, geometry and slide development: Marine Geology, v. 213, p. 201-234.

Hampton, M. A., 1972, The role of subaqueous debris flow in generating turbidity currents: Journal of Sedimentary Petrology, v. 42, p. 775-993.

Hampton, M. A., and H. J. Lee, 1996, Submarine landslides: Reviews of Geophysics, v. 34, p. 33-59.

Hedda, B., 2005, On the dynamics of debris flows : case study Fjærland, Western Norway - a debris flow triggered by a natural dam breach: Master Thesis thesis, University of Olso, Faculty of Mathematics and Natural Sciences, Oslo.

Helland-Hansen, W., and G. J. Hampson, 2009, Trajectory analysis: concepts and applications: Basin Research, v. 21, p. 454-483.

Helland-Hansen, W., and O. J. Martinsen, 1996, Shoreline trajectories and sequences; description of variable depositional-dip scenarious: Journal of Sedimentary Research, v. 66, p. 670-688.

Henriksen, E., H. M. Bjørnseth, T. K. Hals, T. Heide, T. Kiryukhina, O. S. Kløvjan, G. B. Larssen, A. E. Ryseth, K. Rønning, K. Sollid, and A. Stoupakova, 2011a, Uplift and erosion of the greater Barents Sea: impact on prospectivity and petroleum systems, *in* A. M. Spencer, A. F. Enbry, D. L. Gauties, A. Stoupakova, and K. Sørensen, eds., Arctic Petroleum Geology, v. 35: London, Geological Society, p. 283-294.

Henriksen, E., C. Fichler, A. Grønlie, T. Henningsen, I. Laursen, H. Løseth, D. Ottesen, and I. Prince, 2005, The Norwegian Sea during the Cenozoic: Onshore-Offshore Relationships on the North Atlantic Margin, p. 111-133.

Henriksen, E., A. E. Ryseth, G. B. Larssen, T. Heide, K. Rønning, K. Sollid, and A. Stoupakova, 2011b, Tectonostratigraphy of the greater Barents Sea: implications for petroleum systems, *in* A. M. Spencer, A. F. Enbry, D. L. Gauties, A. Stoupakova, and K. Sørensen, eds., Arctic Petroleum Geology, v. 35: London, Geological Society, p. 163-195.

Henriksen, S., G. J. Hampson, W. Helland-Hansen, E. P. Johannessen, and R. J. Steel, 2009, Shelf edge and shoreline trajectories, a dynamic approach to stratigraphic analysis: Basin Research, v. 21, p. 445-453.

Henriksen, S., W. Helland-Hansen, and S. Bullimore, 2011c, Relationships between shelf-edge trajectories and sediment dispersal along depositional dip and strike: a different approach to sequence stratigraphy: Basin Research, v. 23, p. 3-21.

Hjelstuen, B. O., O. Eldholm, and J. I. Faleide, 2007, Recurrent Pleistocene mega-failures on the SW Barents Sea margin: Earth and Planetary Science Letters, p. 605-618.

Hjelstuen, B. O., A. Elverhøi, and J. I. Faleide, 1996, Cenozoic erosion and sediment yield in the drainage area of the Storfjorden Fan: Global and Planetary Change, v. 12, p. 95-117.

Hurst, A., J. Cartwright, and D. Duranti, 2003a, Fluidization structures produced by upward injection of sand through a sealing lithology: Geological Society Special Publications, v. 216, p. 123-138.

Hurst, A., J. Cartwright, M. Huuse, R. Jonk, A. Schwab, D. Duranti, and B. Cronin, 2003b, Significance of large-scale sand injectites as long-term fluid conduits: evidence from seismic data: Geofluids, v. 3, p. 263-274.

Huuse, M., 2008, Sandstone intrusions: implications for exploration and production: World Oil, v. 229.

Huuse, M., J. Cartwright, R. Gras, and A. Hurst, 2005a, Kilometre-scale sandstone intrusions in the Eocene of the Outer Moray Firth (UK North Sea): migration path, reservoirs and potential drilling hazards: Petroleum Geology: North-West Europe and Global Perspectives-Proceedings of the 6th Petroleum Geology Conference, v. 6, p. 1577-1594.

Huuse, M., J. Cartwright, A. Hurst, and N. Steinsland, 2007, Seismic Characterization of large-scale sandstone intrusions: AAPG Memoir, v. 87, p. 21-35.

Huuse, M., J. A. Cartwright, R. Gras, and A. Hurst, 2005b, Giant conical sandstone intrusions in the lower Eocene of the outer Moray Firth (UK North Sea): Migration paths and potential reservoirs Petroleum geology: NW Europe and global perspectives-Proceedings of the 6th Petroleum Geology Conference p. 1577-1594.

Huuse, M., D. Duranti, N. Steinsland, C. G. Guargena, P. Prat, K. Holm, J. A. Cartwright, and A. Hurst, 2004, Seismic characteristics of large-scale sandstone intrusions in the Paleogene of the south Viking Graben, UK and Norwegian North Sea: Geological Society, London, Memoirs, v. 29, p. 263-278.

Imbo, Y., M. D. Batist, M. Canals, M. J. Pieto, and J. Baraza, 2003, The Gebra Slide: a submarine slide on the Trinity Peninsula Margin, Antarctica: Marine Geology, v. 193, p. 235-252.

Ireland, M. T., R. J. Davies, N. R. Goulty, and D. J. Moy, 2011, Thick slides dominated by regular-wavelength folds and thrusts in biosiliceous sediments on the Vema Dome offshore of Norway: Marine Geology, v. 289, p. 34-45.

Jackson, C. A. L., M. Huuse, and G. P. Barber, 2011, Geometry of winglike clastic intrusions adjacent to a deep-water channel complex: Implications for hydrocarbon exploration and production: AAPG Bulletin, v. 95, p. 559-584.

Jansen, E., M. E. Raymo, and P. Blum, 1996, Site 986: Proceeding of the Ocean Drilling Program, Initial Reports, v. 162, p. 287-343.

Jebsen, C., and J. I. Faleide, 1998, Tertiary rifting and magmatism at the western Barents Sea margin (Vestbakken volcanic province): III international conference on Arctic margins, ICAM III, p. 92.

Johannessen, E. P., and R. J. Steel, 2005, Shelf-margin clinoforms and prediction of deepwater sands: Basin Research, v. 17, p. 521-550.

Jones, E., B. Jones, C. Ebdon, D. Even, P. Milner, J. Plunkett, G. Hudson, and P. Slater, 2003, Eocene, *in* D. Evans, C. Graham, A. Armour, and P. Bathurst, eds., The Millennium Atlas: Petroleum geology of the central and northern North Sea, Geological Society of London, p. 261-278.

Kane, I. A., 2010, Development and flow structures of sand injectites: The Hind Sandstone Member injectite complex, Carboniferous, UK: Marine and Petroleum Geology, v. 27, p. 1200-1215.

Knies, J., J. Matthiessen, C. Vogt, J. S. Laberg, B. O. Hjelstuen, M. Smelror, E. Larsen, K. Andreassen, T. Eidvin, and T. O. Vorren, 2009, The Plio-Pleistocene glaciation of the Barents Sea–Svalbard region: a new model based on revised chronostratigraphy: Quaternary Science Reviews., v. 28, p. 812-829.

Knutsen, S. M., J. H. Augustson, and P. Haremo, 2000, Exploring the Norwegian part of the Barents Sea - Norsk Hydro's lessons from nearly 20 years of experience, *in* K. Ofstad, J. E. Kittilsen, and P. Alexander-Marrack, eds., Improving the Exploration Process by Learning from the Past, v. 9: Amsterdam, Norwegian Petroleum Society Special Publications, p. 99-112.

Knutsen, S. M., G. Richardsen, and T. Vorren, 1992, Late Miocene-Pleistocene sequence stratigraphy and mass-movements on the western Barents Sea margin, *in* T. Vorren, E. Bergsager, Ø. A. Dahl-Stamnes, E. Holter, B. Johansen, E. Lie, and T. B. Lund, eds., Arctic Geology and Petroleum Potential: Elsevier, Amsterdam, Norwegian Petroleum Society Special Publication N. 2, p. 573-606.

Kuvaas, B., and Y. Kristoffersen, 1996, Mass movements in glaciomarine sediements on the Barents Sea continental slope: Global and Planetary Change, v. 12, p. 287-307.

Laberg, J. S., K. Andreassen, J. Knies, T. O. Vorren, and M. Winsborrow, 2010, Late Pliocene - Pleistocene development of the Barents Sea Ice Sheet: Geology, v. 38, p. 107-110.

Laberg, J. S., K. Andreassen, and T. O. Vorren, 2012, Late Cenozoic erosion of the high-latitude southwestern Barents Sea shelf revisited: GSA Bulletin, v. 124, p. 77-88.

Laberg, J. S., and T. O. Vorren, 1993, A Late Pleistocene submarine slide on the Bear Island Trough Mouth Fan: Geo-Marine Letters, v. 13, p. 227-234.

Laberg, J. S., and T. O. Vorren, 1996, The Middle and Late Pleistocene evolution of the Bear Island Trough Mouth Fan: Global and Planetary Change, v. 12, p. 309-330.

Laberg, J. S., and T. O. Vorren, 2000, The Trænadjupet Slide, offshore Norway - morphology, evacuation and triggering mechanisms: Marine Geology, v. 171, p. 95-114.

Laberg, J. S., T. O. Vorren, J. A. Dowdeswell, N. H. Kenyon, and J. Taylor, 2000, The Andøya Slide and the Andøya Canyon, north-eastern Norwegian–Greenland Sea: Marine Geology, v. 162, p. 259-275.

Laberg, J. S., T. O. Vorren, J. Mienert, P. Bryan, and R. Lien, 2002, The Trænadjupet Slide: a large slope failure affecting the continental margin of Norway 4,000 years ago: Geo-Marine Letters, v. 22, p. 19-24.

Larsen, R. M., T. Fjæran, and O. Skarpnes, 1993, Hydrocarbon potential of the Norwegian barenst Sea based on recent well results, *in* T. O. Vorren, E. Bergsager, Ø. A. Dahl-Stamnes, E. Holter, B. Johansen, E. Lie, and T. B. Lund, eds., Arctic Geology and Petroleum Potential: Amsterdam, Norwegian Petroleum Society, p. 321-331.

Larue, D. K., and P. A. Martinez, 1989, Use of bed-form models to analyze geometry and preservation potential of clastic facies and erosional surfaces: American Association of Petroleum Geologists Bulletin, v. 73, p. 40-53.

Lee, H. J., 2009, Timing of occurrence of large submarine landslides on the Atlantic Ocean margin: Marine Geology, v. 264, p. 53-64.

Lee, H. J., J. Locat, P. Desgagnes, J. D. Parsons, B. G. McADOO, D. L. Orange, P. Puig, F. L. Wong, P. Dartnell, and E. Boulanger, 2007, Submarine mass movements on continental margins, *in* C. A. Nittrouer, J. A. Austin, M. E. Field, J. H. Kravitz, J. P. M. Syvitski, and P. L. Wiberg, eds., Continental Margin Sedimentation. From Sediment Transport to Sequence Stratigraphy, Special Publication N 37 of the International Association of Sedimentologists, p. 215-274.

Leynaud, D., J. NMienert, and M. Vanneste, 2009, Submarine mass movements on glaciated and non-glaciated Europeancontinental margins: A review of triggering mechanisms and preconditions to failure: Marine and Petroleum Geology, v. 26, p. 618-632.

Lien, T., 2006, Deep-water depositional systems of the Norwegian Sea; understanding the system evolution, depositional geometries and reservoir quality from subsurface data and field outcrops, University of Bergen, Norway.

Lien, T., R. E. Mitdtbø, and O. J. Martinsen, 2006, Depositional facies and reservoir quality of deep-marine sandstones in the Norwegian Sea: Norwegian Journal of Geology, v. 86, p. 71-92.

Lindberg, B., J. S. Laberg, and T. O. Vorren, 2004, The Nyk Slide—morphology, progression, and age of a partly buried submarine slide offshore northern Norway: Marine Geology, v. 213, p. 277-289.

Lonergan, L., N. Lee, H. D. Johnson, J. A. Cartwright, and R. J. H. Jolly, 2000, Remobilization and injection in deepwater depositional systems: implications for reservoir architecture and prediction: GCSSEPM Foundation 20th Annual Research Conference Deep-Water Reservoirs of the World, December 3-6, p. 515-532.

Lucchi, R. G., M. T. Pedrosa, A. Camerlenghi, R. Urgeles, B. D. Mol, and M. Rebesco, 2012, Recent Submarine Landslides on the Continental Slope of Storfjorden and Kveithola Trough-Mouth Fans (North West Barents Sea), *in* Y. Yamada, K. Kawamura, K. Ikehara, Y. Ogava, R. Urgeles, D. Mosher, J. Chaytor, and M. Strasser, eds., Submarine Mass Movements and Their Consequences, v. 31, Springer, p. 735-745.

Lundin, E., 2002, North Atlantic - Arctic: Overview of sea-floor spreading and rifting history, *in* E. A. Eide, ed., Batlas. Mid Norway plate reconstruction atlas with global and Atlantic perspectives: Trondheim, Geological Survey of Norway, p. 40-47.

Lundin, E., and A. G. Dore, 2002, Mid-Cenozoic post-breakup deformation in the 'passive' margins bordering the Norwegian-Greenland Sea: Marine and Petroleum Geology, v. 19, p. 79-93.

Martinsen, O. J., R. Lien, and C. Jackson, 2005, Cretaceous and Palaeogene turbidite systems in the North Sea and Norwegian Sea Basins: source, staging area and basin physiography controls on reservoir development: Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference, p. 1147-1164.

Martinsen, O. J., and A. Nøttvedt, 2008, Norway rises from the sea. Paleogene and Neogene (Cenozoic) the modern continents take shape; 66-2.6 Ma, *in* I. B. Ramberg, I. Bryhni, A. Nøttvedt, and K. Rangnes, eds., The making of a land. Geology of Norway: Trondheim, The Norwegian Geological Association, p. 442-480.

Masson, D., 1996, Catastrophic collapse of the volcanic island of Hierro 15 ka ago and the history of landslides in the Canary Islands: Geology, v. 24, p. 231-234.

Masson, D. G., C. Harbitz, R. Wynn, G. Pedersen, and F. Løvholt, 2006, Submarine landslides: processes, triggers and hazard prediction: Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, v. 364.

McGee, D. T., P. W. Bilinski, P. S. Gary, D. S. Pfeiffer, and J. L. Sheimanan, 1994, Geological models and reservoir geometries of Auger Field, Deepwater Gulf of Mexico: Submarine Fans and Turbidite Systems, Gulf Coast Section of SEPM 15th Annual Research Conference, p. 245-256.

Miall, A. D., 2010, The Geology of Stratigraphic Sequence, Springer.

Mitchum, R. M., P. R. Vail, and J. B. Sangree, 1977a, Seismic Stratigraphy and Global Changes of Sea Level, Part 6: Stratigraphic Interpretation of Seismic Reflection Patterns in Depositional Sequences, *in* C. E. Payton, ed., Seismic Stratigraphy--Applications to Hydrocarbon Exploration, AAPG Memoir 26, p. 117-133.

Mitchum, R. W. J., P. R. Vail, and S. Thompson, 1977b, AAPG Datapages/Archives: Seismic Stratigraphy and Global Changes of Sea Level: Part 2. The Depositional Sequence as a Basic Unit for Stratigraphic Analysis: Section 2. Application of Seismic Reflection Configuration to Stratigraphic Interpretation, *in* C. E. Payton, ed., Seismic

Stratigraphy - Applications to Hydrocarbon Exploration, v. 26, Memoir American Association of Petroleum Geologists, p. 53-62.

Molyneux, S., J. Cartwright, and L. Lonergan, 2002, Conical sandstone injection structures imaged by 3D seismic in the central North Sea, UK: First break, v. 20, p. 383-393.

Morgenstern, N. R., 1967, Submarine slumping and the initiation of turbidity currents, *in* A. F. Richards, ed., Marine Geotechnique: Urbana, Illinois, University of Illinois Press, p. 189-210.

Mosar, J., G. Lewis, and T. H. Torsvik, 2002, North Atlantic sea-floor spreading rates: Implications for the Tertiary development of inversion structures of the Norwegian - Greenland Sea: Journal of the Geological Society, London, v. 159, p. 503-515.

Moscardelli, L., and L. Wood, 2008, Newclassification systemformass transport complexes in offshoreTrinidad: Basin Research, v. 20, p. 73-98.

Moscardelli, L., L. Wood, and P. Mann, 2006, Mass-transport complexes and associated processes in the Offshore Area of Trinidad and Venezuela: American Association of Petroleum Geologists Bulletin, v. 90, p. 1059-1088.

Mulder, T., 2011, Gravity Processes and Deposits on Continental Slope, Rise and Abyssal Plains, *in* H. Huneke, and T. Mulder, eds., Deep-sea sediemnts: amsterdam, Developments in Sedimentology 63. Elsevier, p. 26-83.

Mulder, T., and P. Cochonat, 1996, Classification of offshore mass movements: Journal of Sedimentary Research, v. 66, p. 43-57.

Nardin, T. R., F. J. Hein, D. S. Gorsline, and B. D. Edwards, 1979, A review of mass movement processes sediment and acoustic characteristics and contrasts in slope and base of slope systems versus canyon fan basin floor systems: SEPM Special Plublication, N. 27, p. 61-73.

Neuendorf, K. K. E., J. P. Mehl, and J. A. Jackson, 2005, Glossary of geology. 5 ed., American Geological Institute Alexandria, VA, United States.

Nøttvedt, A., M. Cecchi, J. Gjelberg, S. E. Kristensen, A. Lønøy, A. Rasmussen, E. Rasmussen, P. H. Skott, and P. van Veen, 1992, Svalbard - Barents Sea correlation: a short review, *in* T. O. Vorren, E. Bergsager, Ø. A. Dahl-Stamnes, E. Holter, B. Johnsen, E. Lie, and T. B. Lund, eds., Arctic Geology and Petroleum Potential, Norwegian Petroleum Society Special Publication, v. 2: Amsterdam, Elsevier, p. 362-375.

Parsons, J. D., C. T. Friedrichs, P. A. Traykovski, D. Mohrig, J. Imran, J. P. M. Syvitski, G. Parker, P. Puig, J. L. Buttles, and M. H. Garcia, 2007, The mechanics of marine sediment gravity flows, *in* C. A. Nittrouer, J. A. Austin, M. E. Field, J. H. Kravitz, J. P. M. Syvitski, and P. L. Wiberg, eds., Continental Margin Sedimentation. From Sediment Transport to Sequence Stratigraphy, Special Publication N 37 of the International Association of Sedimentologists
p. 275-337.

Pettingill, H. S., 1998a, Lessons learned from 43 turbidite giant fields, World turbidites -2 Oil & Gas Journal.

Pettingill, H. S., 1998b, Turbidite plays' immaturity means big potential remains. World Turbidites -1: Oil & Gas Journal.

Piper, D. J. W., D. C. Mosher, B. J. Gauley, K. Jenner, and D. C. Campbell, 2003, The chronology and recurrence of submarine mass movements on the continental slope off southeastern Canada, *in* J. Mienert, ed., Submarine Mass Movements and their Consequences: The Netherlands, Kluwer Academic Publishers, p. 299-306.

Praeg, D., M. Stoker, P. M. Shannon, S. Ceramicola, B. O. Hjelstuen, J. S. Laberg, and A. Mathiesen, 2005, Episodic Cenozoic tectonism and the development of the NW European 'passive' continental margin: Marine and Petroleum Geology, v. 22, p. 1007-1030.

Prior, D. B., and J. M. Coleman, 1984, Submarine slope stability, *in* D. Brunsden, and D. B. Prior, eds., Slope Instability, Wiley & Sons, Incorporated, p. 419-455.

Prior, D. B., E. H. Doyle, and T. Neurauter, 1986, The Currituck slide, mid-Atlantic continental slope-revisited: Marine Geology, v. 73, p. 25-45.

Rasmussen, E., P. H. Skott, and K. B. Larsen, 1995, Hydrocarbon potential of the Bjørnøya West Province, western Barents Sea Margin, *in* S. Hanslien, ed., Petroleum Exploration and Exploitation in Norway, v. 4: Amsterdam, Norwegian Petroleum Society Special Publication, p. 277-286.

Rebesco, M., J. S. Laberg, M. T. Pedrosa, A. Camerlenghi, R. G. Lucchi, F. Zgur, and N. Wardell, Onset and growth of Trough-Mouth Fans on the North-Western Barents Sea margin: a stack of extreme events: submitted to Quaternary Science Reviews.

Rebesco, M., M. T. Pedrosa, A. Camerlenghi, R. G. Lucchi, C. Sauli, B. D. Mol, G. Madrussani, R. Urgeles, G. Rossi, and G. Bohm, 2012, One Million Years of Climatic Generated Landslide Events on the Northwestern Barents Sea Continental Margin, *in* Y. Yamada, K. Kawamura, K. Ikehara, Y. Ogava, R. Urgeles, D. Mosher, J. Chaytor, and M. Strasser, eds., Submarine Mass Movements and Their Consequences, v. 31, Springer, p. 747-756.

Rider, M., 2002, The gamma ray and spectral gamma ray logs, *in* M. Rider, ed., The Geological Interpretation of Well Logs: Malta, Rider-French Consulting Ltd, p. 67-86.

Riis, F., and W. Fjeldskar, 1992, On the magnitude of the Late Tertiary and Quarternary erosion and its significance for the uplift of Fennoscandia and the Barents Sea, *in* R. M. Larsen, H. Brekke, B. T. Larsen, and E. Talleraas, eds., Structural and Tectonic Modelling and its Application to Petroleum Geology, v. 1: Amsterdam, Norwegian Petroleum Society Special Publications, p. 163-185.

Ryan, M. C., W. Helland-Hansen, E. P. Johannessen, and R. J. Steel, 2009, Erosional vs. accretionary shelfmargins: the influenceofmargin typeon deepwater sedimentation: an example fromthe Porcupine Basin, offshore western Ireland: Basin Research, v. 21, p. 676-703.

Ryseth, A., J. H. Augustson, M. Charnock, O. Haugerud, S. M. Knutsen, P. S. Midboe, J. G. Opsal, and G. Sundsbo, 2003, Cenozoic stratigraphy and evolution of the Sorvestsnaget Basin, southwestern Barents Sea: Norwegian Journal of Geology, v. 83, p. 107-130.

Sejrup, H. P., B. O. Hjelstuen, K. I. T. Dahlgren, H. Haflidason, A. Kuijpers, E. Nygaard, D. Praeg, M. S. Stoker, and T. O. Vorren, 2005, Pleistocene glacial history of the NW European continental margin: Marine and Petroleum Geology, v. 22, p. 1111-1129.

Shoulders, S. J., and J. Cartwright, 2004, Constraining the depth and timing of large-scale conical sandstone intrusions: Geology (Boulder), v. 32, p. 661-664.

Skempton, A. W., and J. N. Hutchinson, 1969, Stability of natural slopes and embankment foundations: 7th International Conference on Soil Mechanics and Foundation Engineering, p. 291-335.

Skogseid, J., S. Planke, J. I. Faleide, T. Pedersen, O. Eldholm, and F. Neverdal, eds., 2000, NE Atlantic continental rifting and volcanic margin formation.: Dynamics of the Norwegian Margin., v. 167, Geological Society, London, Special Publication, 295-326 p.

Smelror, M., O. V. Petrov, G. B. Larssen, and C. Werner, 2009, Atlas. Geological History of the Barents Sea: Trondheim, Norway, Geological Survey of Norway, 134 p.

Solheim, A., J. I. Faleide, E. S. Andersen, A. Elverhoi, C. F. Forsberg, K. Vanneste, G. Uenzelmann-Neben, and J. E. T. Channell, 1998, Late Cenozoic seismic stratigraphy and glacial geological development of the East Greenland and Svalbard-Barents Sea continental margins: Quaternary Science Reviews, v. 17, p. 155-184.

Spencer, A. M., P. C. Home, and L. T. Berglund, 1984, Tertiary structural development of the western Barenst shelf, *in* A. M. Spencer, ed., Petroleum Geology of the North European Margin: London, Graham and Trotman, p. 199-209.

Steel, R., and T. Olsen, 2002, Clinoforms, clinoform trajectories and deepwater sands: Sequence Stratigraphic Models for Exploration and Production: Evolving Models and Application Histories: Proceedings of the Gulf Coast Section Society for Sedimentary Geology (GCSSEPM) 22nd Research Conference (Ed. by J.M. Armentrout and Rosen), p. 367-381.

Stelting, C. E., A. H. Bouma, and C. G. Stone, 2000, Fine-grained turbidite systems: overview, *in* A. H. Bouma, and C. B. Stone, eds., Fine-grained turbidite systems, AAPG Memoir 72/SEPM Special Publication, p. 1-7.

Stoker, M. S., D. Praeg, B. O. Hjelstuen, J. S. Laberg, T. Nielsen, and T. M. Schannon, 2005, Neogene stratigraphy and the sedimentary and oceanographic development of the NW European Atlantic margin: Marine and Petroleum Geology, v. 22, p. 977-1005.

Stoupakova, A., E. Henriksen, Y. K. Burlin, G. B. Larsen, J. K. Milne, T. A. Kiryukhina, P. O. Golynchik, S. I. Bordunov, M. P. Ograkova, and A. A. Suslova, 2011, The geological evolution and hydrocarbon potential of the Barents and Kara shelves, *in* A. M. Spencer, A. F. Enbry, D. L. Gauties, A. Stoupakova, and K. Sørensen, eds., Arctic Petroleum Geology, v. 35: London, Geological Society, p. 325-344.

Stow, D. A. V., and M. Johansson, 2000, Deep-water massive sands: nature, origin and hydrocarbon implications: Marine and Petroleum Geology, v. 17, p. 145-174.

Stow, D. A. V., and M. Mayall, 2000, Deep-water sedimentary systems: New models for the 21st century: Marine and Petroleum Geology, p. 125-135.

Sultan, N., P. Cochonat, M. Canals, A. Cattaneo, B. Dennielou, H. Haflidason, J. S. Laberg, D. Long, J. Mienert, F. Trincardi, R. Urgeles, T. Vorren, and C. Wilson, 2004, Triggering mechanisms of slope instability processes and sediment failures on continental margins: a geotechnical approach: Marine Geology, v. 213, p. 291-321.

Surlyk, F., J. Gjelberg, and N. Noe-Nygaard, 2007, The Upper Jurassic Hareelv Formation of East Greenland: A Giant Sedimentary Injection Complex: AAPG Memoir, v. 87, p. 141-149.

Szarawarska, E., M. Huuse, A. Hurst, W. De Boer, L. Lu, S. Molyneux, and P. Rawlinson, 2010, Three-dimensional seismic characterisation of large-scale sandstone intrusions in the lower Palaeogene of the North Sea: completely injected vs. in situ remobilised sandbodies: Basin Research, v. 10, p. 517-531.

Sættem, J., T. Bugge, S. Fanavoll, R. M. Goll, A. Mørk, M. B. E. Mørk, M. Smelror, and J. G. Verdenius, 1994, Cenozoic margin development and erosion of the Barents Sea: Core evidence from southwest of Bjørnøya: Marine Geology, v. 118, p. 257-281.

Sættem, J., D. A. R. Poole, K. L. Ellingsen, and H. P. Sejrup, 1992, Glacial geology of outer Bjørnøyrenna, southwestern Barents Sea: Marine Geology, v. 103, p. 15-51.

Talwani, M., and O. Eldholm, 1977, Evolution of the Norwegian-Greenland Sea: Geological Society American Bulletin, v. 88, p. 969-999.

Trude, J., J. Cartwright, R. J. Davies, and J. Smallwood, 2003, New technique for dating igneous sills: Geology, v. 31, p. 813-816.

Urgeles, R., M. Canals, J. Baraza, B. Alonso, and D. Masson, 1977, The most recent megalandslides of the Canary Islands: El Golfo debris avalanche and Canary debris flow, west El Hiero Island: Journal of Geophysical Research, v. 102, p. 20,305-20,323.

Urgeles, R., D. G. Masson, M. Canals, A. B. Watts, and T. Le Bas, 1999, Recurrent largescale landsliding on the west flank of La Palma, Canary Islands: Journal of Geophysical Research, v. 104, p. 25,331-25,348.

Veeken, P. C. H., 2007, Seismic Stratigraphy, Basin Analysis and Reservoir Characterisation: Handbook of Geophysical Exploration: Seismic Exploration, Elsevier Science, 522 p.

Vetel, W., and J. Cartwright, 2010, Emplacement mechanics of sandstone intrusions: insights from the Panoche Giant Injection Complex, California: Basin Research, v. 22, p. 783-807.

Vigorito, M., A. Hurst, J. A. Cartwright, and A. Scott, 2008, Regional-scale subsurface sand remobilization: geometry and architecture: Journal of the Geological Society, London, v. 165, p. 609-612.

Vorren, T., G. Richardsen, S. M. Knutsen, and E. Henriksen, 1991, Cenozoic erosion and sedimentation in the western Barents Sea: Marine and Petroleum Geology, v. 8, p. 317-340.

Vorren, T. O., J. S. Laberg, F. Blaume, J. A. Dowdeswell, N. H. Kenyon, J. Mienert, J. Rumohr, and F. Werner, 1998, The Norwegian-Greenland Sea continental margins; morphology and late Quaternary sedimentary processs and environment.: Quaternary Science Reviews., v. 17, p. 273-302.

Paper I

Paper II

Paper III

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