Faculty Science and Technology, Department of Geosciences

Cenozoic tectonosedimentary development and erosion estimates for the Barents Sea continental margin, Norwegian Arctic

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Front cover photograph: Amando Lasabuda
The photo was taken from sandy beach ridges in Dicksonfjorden, overlooking Heimenfjellet, Svalbard, August 2015. The photo shows present-day erosion of the Kapp Starostin Formation (Permian).

Doing a PhD is not about becoming the smartest person on earth.
The more you learn, the more you realize the complexity of nature.
Be grateful and respectful.

-A. Lasabuda, that morning walk to the university, 2017-

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Preface

This dissertation consists of three scientific papers that were written during my employment at the Research Centre of Arctic Petroleum Exploration (ARCEx), Department of Geosciences, University of Tromsø (UiT), for the period from 1.3 2015 to 1.3 2018. ARCEx itself is funded by the Research Council of Norway (grant 228107) and several industry partners. I also received funding from the 2018 American Association of Petroleum Geologist Foundation Grants-in-Aid Program. This Ph.D was part of ARCEx Work Package 1 - *Basin Analysis,* led by Prof. Jan Inge Faleide (University of Oslo) and its Task 1.3 - *Uplift, erosion, and sedimentation of the Arctic region* led by Prof. Jan Sverre Laberg (UiT) who has been appointed as my primary advisor. The second supervisor during my PhD fellowship was Assoc. Prof. Stig-Morten Knutsen at the Norwegian Petroleum Directorate (NPD) in Harstad where I spent several research visits.

My Ph.D scheme did not include teaching duties at the Department of Geosciences, UiT. However, I am glad to have been part of the group of teaching assistants at two scientific cruises with R/V Helmer Hanssen, in the summer 2016 and spring 2017. During my PhD, I have been in several trainings, such as on geospatial software (ArcGIS by Dr. Monica Winsborrow and GlobalMapper by Dr. Tom Arne Rydningen), presentation skills (by Melissa Marshall), technical drawings, and scientific proposal writings. Technical support from Sri Susilo at Schlumberger Aachen has improved my Petrel software proficiency.

The three papers presented herein are:

Paper 1: Lasabuda, A., Laberg, J. S., Knutsen, S.-M., Høgseth, G., Early to middle Cenozoic paleoenvironment and sediment yield of the southwestern Barents Sea continental margin: Insights from a regional mass-balance approach. *Marine and Petroleum Geology, in review*.

Paper 1 is focused on the southwestern Barents Sea continental margin. The paper highlights the Cenozoic regional development including a basin analysis, with focus on the Sørvestsnaget Basin, to understand the Cenozoic tectonic and sedimentary interaction. The paper also aims to improve the understanding of Cenozoic uplift and erosion by using the mass-balance approach. Erosion estimates from this area are comparable with results from other techniques and represent an important constraint for hydrocarbon exploration in this area. A research visit to NPD, Stavanger in February 2017 was conducted in conjunction with this paper.

Paper 2: Lasabuda, A., Laberg, J. S., Knutsen, S.-M, Safronova, P. A., Cenozoic tectonostratigraphy and pre-glacial erosion: A mass-balance study of the northwestern Barents Sea margin, Norwegian Arctic. *Resubmitted to Journal of Geodynamics, Special Arctic Issue.*

Paper 2 represent a northward continuation of the study of Paper 1, and concentrated on the continental margin between Bjørnøya and Svalbard. A similar study method was implemented for this part of the margin to better understand the Cenozoic tectonosedimentary development. Erosion estimates based on the mass-balance technique revealed a trend of increasing erosion towards the north, which may be linked to the early Cenozoic tectonism of this area. This paper benefited from cooperation with the Marine Arctic Geological Expedition (MAGE), Russian Federation which supplied most of the seismic data used in the study.

Paper 3: Lasabuda, A., Geissler, W. H., Laberg, J. S., Knutsen, S.-M, Rydningen, T. A., Berglar, K., Late Cenozoic glacial sediment input to the Arctic Ocean – quantifying the contribution from the Barents Sea. *in prep., to be submitted*

Paper 3 is focused on the northeastern part of Svalbard/northern part of Barents Sea continental margin. This paper aims to elucidate the late Cenozoic development of this part of the margin in terms of sedimentary processes and architecture by using seismic data. For the first time, average net erosion and erosion rates are estimated from this area by using the mass-balance method, which reflect the sediment input to the Arctic Ocean. This work resulted from an ARCEx initiative and a collaboration with Alfred Wegener Institute for Polar and Marine Research (AWI) represented by Dr. Wolfram Geissler and Federal Institute for Geoscience and Natural Resources (BGR) in Germany represented by Dr. Kai Berglar. Three research visits to Bremerhaven, Germany during December 2015, April 2017, and December 2017 were conducted in relation to this paper.

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Big thanks to Dr. Matthias Forwick, our Head of Department for his support and help. Prof. Alfred Hanssen, our ARCEx director, whom I greatly acknowledge for his leadership and constant motivation. Thanks goes also to our administrative coordinator, Ellen Ingeborg Hætta, for doing a fantastic job taking care of the Ph.D fellows at ARCEx and for organizing many fun activities and trainings for us. Inger Solheim, Kai Mortensen, Margrethe Lindquist, Andre Pedersen, Cecilie Rikstad, and the administration and IT staffs for their sincere help since the very first day I arrived in Tromsø. I am indebted to Dr. Tom Arne Rydningen and Dr. Michael Schreck for many scientific discussions and football analysis. To Ryan Dillon and Thomas Birchall, thanks a lot for proofreading and corrections to the manuscript.

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Also, I send joyful greetings and best of luck to Jean-Baptiste (JB), Kjetil, Ana Sofia, Nathalie, Malte, Babak, Ronny, Terje, Kamaldeen, Ingrid W, Tyler, Tore, Fredrik, Sigrun, Dimitri, Kate, Lina, Mohamed, Andreia, Andrea, Calvin, Mariana, Ingrid O, Daniel, Fabio and the rest of the outstanding scientists in ARCEx, CAGE, and Department of Geosciences, University of Tromsø for the great time inside and outside campus. Helen Dulfer and Rowan Romeyn are

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Amando Lasabuda

1. Introduction

1.1. Background, relevance and significance of the thesis

The High Arctic is one of the few regions in the world that is still underexplored in terms of its geological evolution. The harsh environment appears to be one of the main challenges in data acquisition (Kristoffersen, 2011). Earlier efforts in the 60's – 70's have produced a foundational series of geophysical data (Karasik, 1968; Talwani and Eldholm, 1977; Sundvor and Eldholm, 1979; Vogt et al., 1979) that has been important for our present understanding of Arctic geodynamics. A number of earlier attempts at field mapping were also important to establish the main geological framework (e.g. Harland, 1969; Harland and Horsfield, 1974).

Major advancement in the 90's to early 2000's in the collection of geophysical and geological data, such as seismic data (e.g. Jokat et al., 1992; Eiken, 1994), gravity and magnetic data (e.g. Brozena et al., 2003), bathymetry data (e.g. Jakobsson et al., 2000), and cores from shallow and deep boreholes (e.g. Jansen et al., 1996; Grogan et al., 1999) have highly accelerated the geological understanding of the High Arctic. In the Norwegian Arctic, the geological understanding from the breakup geometry in the early Cenozoic (e.g. Faleide et al., 2008) to the glacial history in the late Cenozoic (e.g. Vorren et al., 2011) has improved considerably.

This Ph.D project is part of the activities of the Research Centre for Arctic Petroleum Exploration (ARCEx), a research group directed towards eco-safe exploration in the High Arctic. A better understanding of the geology in the Norwegian Arctic will ultimately contribute to the successful petroleum exploration of the region. The main contribution of this project is in the area of Cenozoic uplift and erosion that has affected the Barents Sea shelf. Therefore, the key research questions highlighted in this study are summarised by the following points:

- Improve on the pre-glacial tectonostratigraphy of the western Barents Sea that is related to the early Cenozoic breakup and subsequent plate movement of Greenland relative to the Barents Sea shelf.
- Establish the late Cenozoic paleoclimatic history of the northern Barents Sea focusing on the sedimentary processes and architecture of the trough-mouth fans and contourite drifts.
- Estimate the pre-glacial and glacial erosion for the sediment source areas of the western and the northern margin of the Barents Sea, respectively.

Papers 1, 2, and 3 cover southwestern, northwestern, and northern margin of the Barents Sea shelf, respectively (Fig. 1). The stratigraphic target was the lower to middle Cenozoic for both Papers 1 and 2, and the upper Cenozoic for Paper 3. (Fig 1.)

1.2. Geological setting

The Cenozoic history of the NE Atlantic margin is strongly related to the rifting and sea-floor spreading in the Norwegian-Greenland Sea. The onset of spreading has been estimated based on magnetic polar reversals and is correlated to magnetic anomaly Chron 24 or ca. 55 Ma (Talwani and Eldholm, 1977). The western margin of the Barents Sea shelf shows a segmented transform development as part of the broad scale *De Geer Zone* development (Faleide et al., 1993). The development of this mega fracture zone appears to be concurrent with a broader Eurekan deformation which also affects Greenland and the Elsmere Islands (Piepjohn et al., 2016). To the north, in the Arctic Ocean, breakup also occurred (Karasik, 1968; Vogt et al., 1979) and here it has been suggested to have started earlier, which corresponds to magnetic anomaly Chron 25 or ca. 57 Ma (Brozena et al., 2003).

In the early Cenozoic, the western Barents Sea continental margin was governed by transpression, extension, and transtension (Nøttvedt et al., 1988; Faleide et al., 2008). Seismic data from the western margin off Svalbard showed a rather complex development, including the development of the Forlandsundet Graben (Steel et al., 1985; Gabrielsen et al., 1992). This part of the margin is characterized by the shear-dominated Hornsund Fault Zone. The early Cenozoic breakup shows that a transpression-compression component was responsible for the West Spitsbergen Fold-Thrust Belt (WSFTB) development (Braathen et al., 1995; Bergh et al., 1997). The southern part of the margin, the Senja Fracture Zone, is a shear-dominated segment. Between these two segments, the Senja Fracture zone and the Hornsund Fault Zone, the Vestbakken volcanic province appears as a pull-apart basin (Faleide et al., 2008). Meanwhile in the Arctic Ocean, an episode of continuous rifting is indicated, leading to the separation of the Lomonosov Ridge from the Barents Sea margin (Jokat et al., 1992).

From the major plate reorganization in the earliest Oligocene (at magnetic anomaly Chron 13), Greenland moved in the same direction as the north American Plate (Talwani and Eldholm, 1977). This event marked the onset of a major phase of extension along the whole of the western margin of the Barents Sea, still ongoing. To the north, the Yermak Plateau separated from its counterpart, the Morris Jesup Rise sometime in the Oligocene (Jackson et al., 1984).

The Miocene marks the opening of the Fram Strait, allowing deep-water exchange between the Arctic and Atlantic oceans (Kristoffersen, 1990; Jakobsson et al., 2007; Engen et al., 2008). This period is inferred to be tectonically relatively quiet within the western Barents Sea margin (Ryseth et al., 2003). In addition, global sea-level fluctuations (Haq et al., 1987) might have played a role in controlling the sedimentation and/or erosion in the western Barents Sea area.

The Pleistocene is the period of intensified glaciations of the northern hemisphere. Earlier periods of glaciations might have existed in the Svalbard area and the northern Barents Sea (Knies et al., 2009) and east Greenland (Larsen et al., 1994). From the seabed morphology, a series of glacial landforms illustrates the behaviour of the ice sheet of the last glacial (e.g. Andreassen et al., 2008). In the Barents Sea, an ice-sheet has repeatedly reached the shelf edge during the full-glacial conditions (e.g. Vorren et al., 1989; Laberg and Vorren, 1996; Dowdeswell and Cofaigh, 2002). Off the Barents Sea continental margin, a series of trough-mouth fans (TMF) are located comprising the eroded sediments largely from the Barents Sea shelf that has been transported by fast-flowing ice streams (Vorren and Laberg, 1997). The Bjørnøya/Bear Island TMF (Vorren et al., 1991; Faleide et al., 1996) and Storfjorden TMF (Hjelstuen et al., 1996) are the two major TMFs along the western margin of the Barents Sea.

2. Data uncertainties and methods sensitivities

2.1. Interpretation of seismic and well data uncertainty

Analysis based on subsurface data are highly dependent on the data quality and resolution in order to describe the morphology, geometry and inner structures of sedimentary deposits or to perform fault analysis. This study utilized mainly a set of 2D seismic data from different institutions and with various qualities. The Paper 1 data was provided by TGS/Spectrum, the data for Paper 2 by MAGE, and the data for Paper 3 was provided by AWI, NPD, and BGR. Overall, the seismic data quality was good, allowing for a detailed analysis on the seismic facies of the identified units using the data of highest resolution while the data of low resolution was sufficient for a regional study. However, some data related issues remain as further detailed below:

Large gaps between 2D seismic lines is often problematic for a proper fault mapping and interpretation. Fault branches or relay ramps are often difficult to trace in a complex geological setting. Therefore, it is important to understand the regional tectonic regime in order to capture the faulting style and the overall structural pattern.

Seismic data interpretation are also prone to pitfalls when working with frequency-disturbing features (e.g. salt diapirs, shallow gas). From Paper 1, salt diapirs are common in the Sørvestsnaget and Tromsø Basins. Careful fault mapping and seismic interpretation is needed around a salt body. Shallow gas is also widely known in the southwestern Barents Sea (Vadakkepuliyambatta et al., 2013). The apparent high amplitude package from shallow gas accumulations should not be mixed up with high amplitude reflections from sandy sedimentary packages (i.e. turbiditic basin-floor fans). Volcanic deposits such as those discussed in Paper 1 can also result in a high amplitude package. However, by understanding the nature of the deposits, their relative stratigraphic positions, relation to faults and the regional sedimentary pattern, they can be differentiated from other sedimentary features.

In contrast to seismic data, exploration wells and shallow core data are high-resolution data. However, working in a frontier area as in the High Arctic, these data sets are very limited (e.g. in the Lofoten Basin of Paper 1 and Nansen Basin of Paper 3). Therefore, the integration of well data and seismic data is a useful strategy to expand the lithostratigraphic information found in wells to areas where well data is lacking.

2.2. Volumetric mass-balance sensitivity

There are several methods for measuring the amount and timing of uplift and erosion, each with different advantages and limitations. For the utilization of subsurface data, these methods can be classified into two main categories; a seismic-based approach and a well-based approach (Doré et al., 2002; Anell et al., 2009). A well-based approach includes apatite fission track (AFT), vitrinite reflectance (VR), and shale compaction studies, which are commonly used to provide the amount of erosion at a specific location (e.g. Green et al., 2002; Japsen et al., 2005). However, these methods also contain uncertainties and are prone to miscalculations (Dore et al., 2002). Interpolation between wells and extrapolation away from wells is needed for regional studies.

A seismic-based approach includes a seismic stratigraphic interpretation as well as a volumetric mass-balance study. This method generally provides a direct correlation of denudation and sedimentation, quantification of the eroded volume derived from the sedimentary product, and can address large areas (Anell et al., 2009). This method can specify the amount of erosion contribution from each specific periods. However, it is noteworthy that the mass-balance technique only gives average value of erosion estimate in the source area. This implies a limitation in regard to local variation.

In this study, we present erosion estimates using the volumetric mass-balance approach to quantify the amount of erosion. This method is commonly applied for high-latitude margins, including the southwestern Barents Sea (Vorren et al., 1991; Fiedler and Faleide, 1996), the northwestern Barents Sea (Hjelstuen et al., 1996), mid-Norway (Dowdeswell et al., 2010b), the Faroe Platform (Andersen et al., 2002), Scotland (Wilkinson, 2017), and the area around Britain and Ireland (Jones et al., 2002).

In the mass-balance analysis, a series of assumptions needs to be addressed in order to capture the uncertainty and sensitivity of the method. As the mass-balance technique relies on the direct measurement of the deposited sediment volume, the seismic time-depth conversion is crucial for the sediment volume estimates. In the area of Paper 1, the southwestern Barents Sea margin, we rely on few check shot data from sparsely distributed wells. Further north (the area of Papers 2 and 3) this is even more challenging as these areas are not open for hydrocarbon exploration, thus no wells have been drilled. Thus, velocity estimates using sonobuoy (an equipment deployed along the seismic profile during seismic acquisition) data from other studies was used to convert the seismic data from time to depth domain (Hjelstuen et al., 1996; Geissler and Jokat, 2004).

The amount and rate of erosion also depend on a proper delineation of the source area. Identifying the source area for the glacial strata discussed in Paper 3 is considered less complicated as the former glaciated terrain and landforms are still largely preserved in the present bathymetry. However, a careful analysis integrating the glaciation model and ice extent is crucial. For the pre-glacial strata studied in Papers 1 and 2, the paleo-catchment analysis and delineation of source area are more uncertain as most of the source areas have been altered from later profound glacial erosion. The spatial variation of source areas is also likely to be different owing to the dynamics of plate configuration in the western Barents Sea margin. A proper understanding of the regional tectonics, a detailed structural and stratigraphic mapping, and analysis of the sedimentary pattern (e.g. direction of progradation into sedimentary basin) from seismic data is considered crucial to tackle this problem.

There are also several factors that may affect the sediment budget but are generally difficult to quantify. For example, it is important to consider the amount of sediments that were derived from within the basin or outside the source area (e.g. biogenic ooze/silica or sediment derived from contour currents). These sediments should not be included in the volume of sediments derived from the adjacent onshore area and shelf, so a correction factor must be applied. A further correction is related to sediment compaction due to overburden. Sediments may have been compacted due to thick overburden glacigenic TMF in the western margin of the Barents Sea. Finally, a correction is required due to difference in the lithology composition between the source area and the basin area. This is because the erodiblity of crystalline bedrock is low compared to sedimentary bedrock. This correction is determined by assessing the likely lithology of the source area (e.g. Dowdeswell et al., 2010b; Laberg et al., 2012).

3. Summary of papers

3.1. Paper 1

Early to middle Cenozoic paleoenvironment and sediment yield of the southwestern Barents Sea continental margin: Insights from a regional mass-balance approach. *(in review, Marine and Petroleum Geology)*

Amando Lasabuda, Jan Sverre Laberg, Stig-Morten Knutsen, and Gert Høgseth

In Paper 1, the Paleogene–Neogene strata are mapped and analyzed based on 2D and 3D seismic data and results from commercial wells to better understand the uplift and erosion affecting the southwestern Barents Sea during the Cenozoic. To this end, the mass-balance approach was used to estimate erosion. Our results show that the basins of the western margin received a substantial amount of sediments (up to 280,200 km^3) in the Paleogene–Neogene period from the considered source area. There is an apparent northward shift of the sediment depocenter from being located in the Sørvestsnaget Basin in the Paleocene–early Eocene to the Vestbakken volcanic province in middle–late Eocene. The major accumulation of Oligocene–Neogene strata was in the Lofoten Basin. The average sedimentation rates varied from 0.027 – 0.071 m/k.y throughout the Paleogene–Neogene period.

Interpretation of seismic data reveals that most of the structural highs along the western margin (the marginal high, the Senja Ridge, the Veslemøy High, and the Stappen High) were probably uplifted during the Paleocene–Eocene. Our paleoenvironmental reconstructions also show that the Stappen High, the Loppa High, the area of the Bjarmeland Platform possibly extending into the Gardarbanken High, and part of mainland Northern Norway were the main source areas during the Paleogene–Neogene period. The minimum and maximum size of the source area is 184,100 and 334,000 km^2, respectively. Overall, the basin and high development in this period was contemporaneous with and a response to the major tectonic evolution to the west.

The sediment discharge or sediment load for the total Paleogene–Neogene is estimated to have been 8.7 x 10^6 t/y. Our sediment yield estimations (26.2 – 45.7 t/km^2/y) correspond to those from present-day fluvial systems implying that these estimates fall in a realistic range. The greatest erosion occurred in the Eocene (487 m) and the least erosion affecting the source area occurred in the Oligocene (122 m). It furthermore shows that a total of 858 – 1362 m of sediments have been removed from the source area throughout the Paleogene–Neogene period, at average erosion rates of 0.014 – 0.021 m/k.y.

3.2. Paper 2

Cenozoic tectonostratigraphy and pre-glacial erosion: A mass-balance study of the northwestern Barents Sea margin, Norwegian Arctic. *(resubmitted to Journal of Geodynamics, Special Arctic Issue)*

Amando Lasabuda, Jan Sverre Laberg, Stig-Morten Knutsen, and Polina A. Safronova

In Paper 2, Cenozoic pre-glacial strata deposited along the northwestern Barents Sea continental margin was analyzed based on 2D seismics, commercial wells, and shallow drilling core data. The main aim was to quantify the erosion of the source area during the Paleogene–Neogene using the mass-balance approach. In line with this objective, the Cenozoic tectonostratigraphy was also discussed in order to constrain basin formation and the timing and nature of basin filling.

The structural style of the continental margin between Bjørnøya and Svalbard is characterized by a series of highs and grabens as observed from seismic data. In the southern part, rollover structures and listric faulting, potentially detached to a decollement surface are suggested. Negative flower structures are also observed. Taken together, this area was probably dominated by extension and transtension. To the north, the structural style largely mimics the Cenozoic tectonic development of the WSFTB on Svalbard.

The total corrected sediment accumulation of ca. 115,400 km^2 corresponds to an average sedimentation rate of 0.034 m/k.y. There is a general northward sediment thinning towards Svalbard and westward thinning towards the Knipovich Ridge. The Eocene sediment depocenter is located in the Vestbakken volcanic province. During the Oligocene and Neogene, sediments accumulated predominantly in the oceanic basin to the west. The basin configuration of this segment of the western Barents Sea margin was also largely a response to the contemporaneous plate movement between Greenland and Eurasia.

Our reconstructions using the pattern of sediment progradation and the paleogeographical reconstructions of the GPlates v. 2.0 software shows that NE Greenland and the Stappen High were subjected to erosion and supplying sediments into the study area. The most severe erosion occurred in the Eocene with 865 m of eroded strata identified, corresponding to an average erosion rate of 0.039 m/k.y. The source area for the Oligocene–Neogene deposits is interpreted to mainly have been from further east, the Edgeøya platform area. The total Cenozoic pre-glacial erosion is estimated to be ca. 2440 m corresponding to an average erosion rate of 0.038 m/k.y. These numbers are then compared with results from other Cenozoic pre-glacial studies in the Barents Sea.

The average sediment discharge and sediment yield for this margin for the entire Paleogene–Neogene period correspond to ca. 4 x 10^6 t/y and 51.2 t/km^2/y, respectively. These results are of the same order of magnitude as present-day high-relief areas, i.e. upland areas and mountainous High Arctic areas.

3.3. Paper 3

Late Cenozoic glacial sediment input to the Arctic Ocean – quantifying the contribution from the Barents Sea *(in prep., to be submitted)*

Amando Lasabuda, Wolfram H. Geissler, Jan Sverre Laberg, Stig-Morten Knutsen, Tom Arne Rydningen, and Kai Berglar

In Paper 3, the upper Cenozoic strata was mapped and analyzed based on 2D seismic data in order to better understand the mid–late Cenozoic climatic (glacial and paleoceanographic) history of the northeastern Svalbard/northern margin of the Barents Sea. In particular, the Kvitøya, Albertini, and the Nordenskjold Troughs and their trough-mouth fans (TMF) were addressed.

Based on the revised chronology of Knies et al. (2009), the studied succession was divided into three seismic units; unit NB-3A (ca. 3.5–2.4 Ma), NB-3B (ca. 2.4–1.0 Ma), and NB-3C (ca. < 1.0 Ma). Seismic facies analysis shows that these deposits include glacial-related mass-wasting deposits and ocean contour-current related deposits. The margin development shows a dominance of contourites prior to the late Cenozoic. The upper Cenozoic strata suggests predominantly mass-wasting processes to the east (Kvitøya Trough) and contour current processes to the west towards the Nordenskjold Trough.

A total volume of late Cenozoic sediments of about 28,500 km^3 is estimated for the studied margin, corresponding to an average sedimentation rate of 0.18 m/k.y. The delineation of the source area (minimum and maximum alternatives) are based on late Weichselian ice divides (e.g. Lambeck 1995; 1996; Dowdeswell et al. 2010) and late Cenozoic ice extents from Knies et al. (2009). The source area is interpreted to have included the studied troughs, the NE Nordaustlandet, and areas east of Svalbard. For the first time, erosion estimates for this margin segment using the mass-balance approach are presented. Approximately 430 – 680 m of sediments have been removed from the source area with an average erosion rate of 0.12 – 0.2 m/k.y for the late Cenozoic. These numbers reflect the sediment input to the Arctic Ocean from this sector of its surrounding margin.

The estimated average rates are lower compared to the SW and the NW Barents Sea shelf. They are more in line with the rates obtained from western Svalbard, mid-Norway, and the Troms margin. Several potential controlling factors are discussed including the size of the drainage area, the bedrock erodibility, glacial dynamics, and slope gradient. A submarine slide (Body A) with an estimated volume of 6,700 km^3 covering area of ca. 27,000 km^2 is interpreted to have occurred prior to or at the initial phase of the development of the Kvitøya TMF, i.e. prior to or during the onset of the major glaciations that affected the northern margin of the Barents Sea.

4. Synthesis

The synthesis of the papers is organized in a way that the tectonosedimentary development is presented and the corresponding sedimentary processes and architecture are described. The erosion estimates for both pre-glacial and glacial are compared, particularly from the mass-balance viewpoint. Other results from various methods are then compared and discussed in particular for the SW Barents Sea area. Finally, the sediment load from the three papers are plotted against the size of the source area and compared with other results from both glacial, pre-glacial, and outcrop studies.

The structural configuration linked with its tectonic evolution are important components in the mass-balance (source-to-sink) studies. Much of the source areas are later affected by severe erosion, in both the pre-glacial and glacial periods. A proper delineation of the source area before it was affected by glacial erosion can only be achieved through a detailed study of its tectonic evolution through the early and middle Cenozoic. In addition, an expanded seismic database and updated chronology are considered as an improvement for better identification and delineation of the sediments in the sink area.

4.1. Barents Sea continental margin: Cenozoic breakup and its structural configuration

As described in the geological setting, the Cenozoic evolution of the western Barents Sea continental margin has been linked to the continental breakup and subsequent seafloor opening of the Norwegian-Greenland Sea. The broad transform margin in the western Barents Sea margin affected the study area of Papers 1 and 2. Seismic profiles 1 and 2 from Paper 1 show the development of the marginal high associated with the shear-dominated Senja Fracture Zone (Fig. 2). The mechanism for this is attributed to strain partitioning allowing for simultaneous compression and extension in the Harstad Basin and the southern part of the Sørvestsnaget Basin (Kristensen et al., 2017).

Seismic profiles 2 and 3 show a series of normal faults affecting the Eocene unit indicating that the Sørvestsnatget Basin was governed by transtension contemporaneous with the seafloor spreading to the west (Fig. 2). It is tempting to suggest that the 'intra high' as shown in seismic profile 3 is part of the marginal high. However, inspection of the seismic data shows that the intra high was formed later than the marginal high, probably in the late Eocene–Oligocene transition. The mechanism was most likely thermal uplift, associated with the change in plate spreading direction of Greenland moving away from the Barents Sea from Chron 13 time or ca. 33 Ma (Faleide et al., 2015; Blaich et al., 2017).

Structures in Paper 2 as shown in seismic profile 4 display horst and graben structures (Fig. 2). This E-W profile also shows a densely faulted central segment, this may be attributed to strike-slip development due to the movement of the Hornsund Fault Zone. The structural style of the WSFTB in the area of Paper 2 can still be recognized offshore to the south as shown in seismic profile 5 (Bergh and Grogan, 2003; Fig 2). To the north, compression-transpression dominanted in the early Cenozoic that led to the development of the WSFTB as shown in seismic profile 6 (Braathen et al., 1995; Braathen et al., 1999; Fig. 2). The western hinterland zone consists of the Forlandsundet Graben that developed in a dextral transtension followed by extension in the Oligocene (Gabrielsen et al., 1992; Bergh et al., 1997; Blinova et al., 2009; Fig. 2).

For the northern Barents Sea continental margin, the Cenozoic evolution is marked by the separation of the Lomonosov Ridge from the Barents Sea shelf due to the sea-floor spreading along the Gakkel Ridge in the Eurasia Basin (Jokat and Micksch, 2004; Fig. 2). Seismic profile 7 show a series of normal faults that suggest a rifting development of the Nansen Basin (Berglar et al., 2016; Fig. 2). There is a relatively narrow continental to ocean boundary (COB) i.e. abrupt transition, as opposed to a relatively wider transitional zone for both the mid-Norway and NE Greenland continental margins (Tsikalas et al., 2002; 2005). A more gradual configuration is also suggested along the Atlantic rift margins, which is composed of proximal, necking, and distal domains before reaching the oceanic domain (Peron-Pinvidic et al., 2013). In the Atlantic rift system, the key difference is likely due to a gradual development that may involve thinning and stretching processes which resulted in a hyper-extended continental crust, allowing a series of extensional faults to be formed (Peron-Pinvidic et al., 2013). The area of Paper 3 is interpreted to have an abrupt transition from continental to oceanic crust as indicated by gravity and magnetic modelling (Minakov et al., 2012) and is characterized by exhumed and serpentinized mantle with magmatic additions (Lutz et al., 2018).

The extremely sharp continental margin of the Paper 3 area may suggest that the development of this margin was preceded by shear (Lundin and Doré, 2018). Berglar et al. (2016) proposed a rifting episode between the proto Yermak Plateau - Morris Jesup Rise and the western flank of the Lomonosov Ridge prior to the major seafloor opening. The implication of this rifting is that a strike-slip development between the Barents Sea shelf and the Lomonosov Ridge is needed (Minakov et al., 2013). No major inversion structures like in the Ormen Lange area (Lundin and Doré, 2002) or the area of the intra high in Paper 1 was observed along seismic profile 7 (Fig. 2). This may suggests that the crust transition is too narrow to develop mechanisms such as ridge push and/or mantle drag (Mosar et al., 2002).

4.2. Sedimentary processes and architectures along the continental margin of the Barents Sea

The study as presented in the three papers provide an opportunity to examine variation in sedimentary processes and architecture along the Barents Sea continental margin (Fig. 3). In Papers 1 and 2, the paleoenvironment of the Paleocene–Eocene period along the western Barents Sea margin is interpreted to be shallow to deep marine. The Eocene interval of Paper 1 in the Sørvestsnaget Basin shows imbricated sediment wedges that represent sediment progradation of the paleo-shelf. The sediment progradation may represent an interplay of sediment supply, relative sea-level fluctuations, and basin subsidence (Helland-Hansen and Martinsen, 1996).

A stacked succession of high-amplitude reflection packages at the distal part of sediment progradation in the Paper 1 study area is interpreted to be a sandy turbidite fan system (Safronova et al., 2012; 2014), which has been an important target for hydrocarbon exploration in this area. These sedimentary packages are the product of efficient sediment transport through turbidite currents allowing coarse-grained sediments to reach the basin-floor (Fig. 3). Classical fining-upward Bouma sequences are expected for the turbidite fans, commonly found in a compensational stacking pattern (e.g. Straub et al., 2009). A series of sandy packages has been encountered in well 7316/5-1 (Eidvin et al., 1998) and well 7216/11-1S (Ryseth et al., 2003), but is lacking in the area of well 7016/2-1 (Blaich et al., 2017) suggesting that the Stappen High might have been a more prominent sediment source area than mainland Norway for the sandy sediments deposited along the southwestern margin of the Barents Sea.

In the Miocene, the opening of the Fram Strait substantially influenced the ocean circulation through the establishment of the deep-water gateway connecting the Arctic and the Atlantic oceans (Jakobsson et al., 2007). Paper 1 shows evidence of contourites deposited along the slope in the Miocene. The extent and the development of this sedimentary drift, named the Bjørnøyrenna Drift, is recently studied (Rydningen et al., in prep.). There is also a hint of stratified/contorted packages within the Neogene (Miocene) unit in the area of Paper 2 suggesting the presence of contourites on the upper slope. Earlier investigation by Eiken and Hinz (1993) also documented the significances of contourites in the Fram Strait area continuing towards the area of Paper 3. Within the shallower strata, Rebesco et al. (2013) reported sediment drifts along the slope offshore from the western Svalbard margin. These observations show that the western and northern margin were highly influenced by along slope processes from the Miocene and onwards, probably until the present (Fig. 3).

The identification of turbidites and contourites should not be confused, although mixed turbidite-contourite systems is common (Mulder et al., 2008). Turbidity currents are gravity driven flowing downslope, and are often event-based/episodic. In contrast, oceanic contour currents flow parallel to the slope, driven by thermohaline circulation and occur over a longer time span in a condition of equilibrium (Shanmugam, 2008). These sedimentary features are also observed elsewhere on the slope of the Norwegian continental margin (e.g. Laberg et al., 2005). These deposits are more prone to slope failure compared to other sedimentary features due to their typical location on the slope area, their physical properties, and the tendencies to grow on an inclined surface (Laberg and Camerlenghi, 2008).

Another feature observed are submarine slides and associated mass-transport deposits (MTD). Seismic facies analysis of Paper 3 shows a predominantly chaotic and semi-transparent reflection pattern dominating the slope area. Posamentier and Kolla (2003) noted a correlation between seismic amplitude of the reflections and lithology. They documented that higher amplitudes are often associated with coarser-grained MTDs, while semi-transparent seismic reflections dominate muddy MTDs. The MTDs may also include rotated fault blocks and coarse materials (e.g. Safronova et al., 2015). The MTD referred to as “Body A” in Paper 3 would similarly reflect slope instability of the studied part of the northern Barents Sea continental margin.

During the Plio–Pleistocene, the Barents Sea experienced glaciations that have resulted in several glacial sedimentary fans being deposited in the front of the troughs; the trough-mouth fans (TMF) (Vorren et al., 1989). Glacigenic debris flows are the predominant sediment transport processes of the TMFs (e.g. Vorren et al., 1989; King et al., 1996; Laberg and Vorren, 1996; King et al., 1998; Dahlgren et al., 2002; Dowdeswell et al., 2016; Laberg et al., 2017). During full-glacial conditions, ice streams (the fast-flowing parts of the ice sheet) transferred deforming till to the shelf break. The sediments prograding at the grounding line subsequently caused large debris flows upon reaching the shelf break which then continue to flow downslope. Glacigenic sediments on the upper slope are prone to instability due to oversteepening, and build-up of excess pore pressure to eventually cause slope failure and the release of debris flows (Laberg and Vorren, 1995). Debris flows can transfer sediments downslope for 10’s to 100’s km with individual debris lobes of a few km in width and up to 50 m thick (e.g. King et al., 1996; Batchelor et al., 2013).

Along the Barents Sea continental margin, a variation in the TMF progradation style is observed (Fig. 4). There is an apparent similarity in progradation style between the Kvitøya TMF in the northern Barents Sea (Paper 3) and the Troms margin TMFs offshore of northern Norway, but different to the style at the Bjørnøya TMF and Storfjorden TMF (Faleide et al., 1996; Hjelstuen et al., 1996; Laberg et al., 2010; Rydningen et al., 2016; Fig. 4). The explanation for this variation is that the progradation style is largely controlled by ice sheet dynamics, size of the source area, bedrock composition, and gradient of the continental slope (Dowdeswell et al., 2010b; Laberg et al., 2012; Rydningen et al., 2015).

The ice sheet reconstructions, based on the revised chronology by Knies et al. (2009), show that the northern margin of the Barents Sea and Svalbard most likely were covered by ice much earlier than the SW and NW Barents Sea area (Fig. 4). This implies glacigenic debrites to be developed in Kvitøya TMF and Troms margin TMF, in contrast with Bjørnøya and Storfjorden TMF which are dominated by channelize features indicating glacio-fluvial environment (Fig. 4). Intensified glaciations in the second and the last phase of Knies et al. (2009) can be seen as increasing amount of progradation in all of the TMF (Fig. 4).

The source area for the Kvitøya TMF (Paper 3) and the Troms margin TMFs (Rydningen et al., 2016) is interpreted to have been significantly smaller than the other two TMFs (Bjørnøya and Storfjorden) and composed of predominantly crystalline bedrock. These rocks are significantly harder and thus less erodable than the sedimentary rocks that dominate the source area for the Bjornøya TMF and Storfjorden TMF. Thus, bedrock composition affected their erodibility and the amount of deposited sediment in the TMFs.

4.3.Cenozoic erosion estimates (pre-glacial and glacial erosion)

The total Cenozoic net erosion of the Barents Sea shelf not only resulted from the late Cenozoic glacial erosion, but also early–middle Cenozoic fluvial and coastal erosion (pre-glacial). In the early–middle Cenozoic, tectonic uplift as described in Paper 1 is interpreted to mainly have affected the source area. The oceanic sink (e.g. Lofoten Basin) is assumed to have continuously received sediments. The uplift during the pre-glacial period is interpreted to have been concentrated along the margin, being the most pronounced in the area of the Loppa High, the Bjarmeland Platform, and the Stappen High and its inferred extension towards Svalbard as discussed in Paper 2. This observation is supported by the pattern of sediment progradation and deposition as described in Papers 1 and 2.

Uplift and erosion in the late Cenozoic are related to extensive glaciations of the western Barents Sea area eroding and transporting sediment off the continental shelf to be deposited along the margin. These sediment loading-unloading processes, amplified by glacio-isostatic and -eustatic rebound (e.g. Riis and Fjeldskaar, 1992) may have resulted in a change of the uplift pattern, shifting the uplift axis towards the center of the Barents Sea shelf. A recent study by Zieba et al. (2016) identified little glacial erosion in the area towards the shelf edge indicating that there is a boundary or “hinge line” separating the area of net erosion (to the east) and deposition (along the margin to the west). Our erosion estimates in Papers 1 and 2 imply a N-S trend in the uplift during the early–middle Cenozoic as opposed to an E-W trend of uplift during the late Cenozoic.

4.3.1. Early–mid Cenozoic erosion in the western margin of the Barents Sea

The results of Paper 1 show that up to ~40% of the sediments deposited along the western continental margin are pre-glacial sediments. These findings update previous works suggesting that ~33% sediments are Cenozoic pre-glacial (Fiedler and Faleide, 1996). For the northwestern Barents Sea, the results from Paper 2 show agreement with earlier suggestion that half of the Storfjorden TMF consist of pre-glacial deposits (Hjelstuen et al., 1996). However, the pre-glacial erosion estimates as presented in Paper 2 are up to 40% higher than those as presented by Hjelstuen et al. (1996). In Paper 2, a discussion of this discrepancy is included and mainly relates to the different sizes of the estimated source area.

The pre-glacial erosion estimates of Paper 1 must be added to the glacial erosion estimates of Laberg et al. (2012) in order to estimate the total Cenozoic average net erosion (m) for the southwestern Barents Sea area (Fig. 5a). Paper 1 erosion variation assumes minimum and maximum source area based on structural configuration and paleoenvironmental reconstruction from each period to infer the likely extent of the paleo-high. This implies a variation in erosion estimates for each structural elements and also for different period. The key consideration from glacial erosion from Laberg et al. (2012) is that they estimated lower erosion in the banks (500–650 m) and higher erosion in the troughs (1000–1100 m) (Fig. 5a).

Thus, by using the mass-balance approach, the Loppa High is suggested to show a total net average erosion of 1760–2460 m (Fig. 5a). About 1860–2280 m of sediment have been eroded from Bjarmeland Platform. In the area of the Finnmark platform, the areas coinciding with glacial troughs corresponds to an estimated total erosion of 1700–2460 m, while the bank areas may in total have been eroded by 1200–1830 m. Most of the areas of the Hammerfest Basin experienced about 1380–1480 m of erosion. To the north, 1330–1950 m of erosion may have affected the Stappen High area (Fig. 5a). These numbers show the increasing importance of erosion towards the north and east (Fig. 5b).

In the basins area (sinks), the results of Paper 1 have been added with glacial sediment estimates (Vorren et al., 1991; Fiedler and Faleide, 1996; Laberg et al., 2012) in order to estimate the total average deposition (m) (Table 1). In the Lofoten Basin, the total average depositional volume implies an average thickness of ca. 2500 m (Fig. 5a). In the Sørvestsnaget Basin and in Vestbakken volcanic province, the deposits reach an average thickness of ca. 3200 m (Fig. 5a). Taken together, these show that the estimated average erosion in the source area can be balanced with the estimated average deposition in the sink area (Fig. 5b).

					Average deposition (m)		
			Depositional volume (10^3 km^3)	Depositional Area (10^3 km^2)	Sørvestsnaget Basin and Vestbakken volcanic province	Lofoten Basin	
Glacial	Vorren et al. (1991); Laberg et al. (2012)	Pleistocene	464	542	-	2041	-
	Fiedler and Faleide (1996); Laberg et al. (2012)	Pleistocene	395		1638	-	1638
Pre-glacial	Paper1	Neogene	96	171.6	-	559	
		Oligocene	45.3	130.9	-	346	
		Eocene	99.6	119.6	833	-	-
		Paleocene	39.3	55.7	706	-	-
				Total	3177	2946	2543

Table 1. Average deposition (m) derived from volume of sediment divided by depositional area. Note that the depositional area for glacial strata is adapted from Fieldler and Faleide (1996). In this table, the depocenter for Paleocene–Eocene is assumed to be in the Sørvestnaget Basin and Vestbakken volcanic province, while depocenter for Oligocene–Neogene is considered in the Lofoten Basin. This table is presented as the mass-balance schematic diagram at Figure 5. The value of average deposition here is comparable to the value of average erosion (m) at Table 2.

4.3.2. Net Cenozoic erosion comparison with other results in the southwestern Barents Sea

The pre-glacial average net erosion estimates from Paper 1 have been integrated with glacial erosion estimates from the mass-balance study reported by Laberg et al. (2012) (Table 2). These results show that the Stappen High, the Loppa High, the Bjarmeland Platform, the Finnmark Platform, and the Nordkapp Basin suffered a rather high erosion during the Cenozoic (Table 2). Both the results from Paper 1 and Laberg et al. (2012) indicate that the area of the Sørvestnaget Basin and the Vestbakken volcanic province acted as sediment depocenters (continental sink) experiencing very little erosion throughout the Cenozoic (Table 2).

Results from Riis and Fjeldskaar (1992), Ohm et al. (2008), Henriksen et al. (2011), Baig et al. (2016), and Ktenas et al. (2017), which using different methods including shale compaction, thermal maturity, shot gathers, vitrinite reflectance, and apatite fission track data have been incorporated to analyze the severity of erosion within the southwestern Barents Sea highs and basins (Table 2). This compilation can also be used as comparison of different methods.

		Average erosion (m) from different methods							
Structural elements	Well example	Mass-balance Cenozoic pre-glacial	Mass-balance Cenozoic glacial	Mass-balance total Cenozoic	Combined shale compaction, thermal maturity, shot gathers	Shale compaction	Vitrinite data	Vitrinite data	Combined vitritnite data, sandstone diagenesis, AFT, shale compaction
		Paper 1	Laberg et al., 2012	Paper 1 + Laberg et al., 2012	Baig et al., 2016	Ktenas et al., 2017	Riis and Fjeldskaar, 1992	Ohm et al., 2008	Henriksen et al., 2011
Hammerfest Basin	7121/5-1 (Snøhvit)	380	1000-1100	1380-1480	800-1400	1650 - 1750	1000-1500	700-1200	1000-1200
Finnmark Platform (banks area)	7128/4-1 and 7131/4-1	700-1180	500-650	1200 - 1830	1200-1400	1400	800-1400	800-1400	800-1400
Finnmark Platform (troughs area)	7019/1-1	700-1360	1000-1100	1700 - 2460	1700	1800	1500	750	1400
Sørvestsnaget Basin	7216/11-1	0	0	0	0	361	0	250	0
Vestbakken volcanic province	7316/5-1	0	0	0	0	800	500-1000	1500	350
Loppa High	7120/2-1 and 7220/8-1	760-1360	1000-1100	1760-2460	1150-1950	1750-2000	1500-2000	1500-2200	1200-2000
Bjarmeland Platform	7324/10-1, 7228/2-1	860-1180	1000-1100	1860-2280	1250-2400	2000-2250	1400-2500	1400-2500	1400-2500
Stappen High	7128/4-1	760-1360	500-650	1260 - 2000	2100	2000	2500-3000	2000-2500	2200
Nordkapp Basin	7228/2-1 and 7228/9-1	700	500-650	1200-1350	1400	2000-2250	1100	900	1400-1600

Table 2. Comparison of average erosion (m) from Paper 1 to other recently published results that is shown in the Figure 6.

The erosion estimate shows variations, in the order of 1000–1500 m (e.g. Loppa High) to 400–600 m (e.g. Hammerfest Basin) (Fig. 6). This observation may imply varying degree of erosion or uncertainties in the methods applied. The mass-balance technique shows good agreement with other erosion estimation techniques in the Hammerfest Basin, Sørvestsnaget Basin, and Bjarmeland Platform (Fig. 6). However, the mass-balance technique can have a large uncertainty range and can produce estimates that differ from the other techniques e.g. in the Finnmark Platform area (Fig. 6). In the Stappen High, the higher erosion trend from the other techniques is believed to correspond to erosion estimates in Paper 2, which estimated to be ~2440 m (Figs. 5b and 6).

Exhumation may involve different types of tectonic movements, epeirogenic (large-scale of 100s km) or flexure/failure movements (small-scale of 10s km) (Praeg et al., 2005). These variances may result in different order of uplift-subsidence (100s to 1000s m) (Praeg et al., 2005). The overall missing Cenozoic strata to the east may indicate a tilt due to sediment loading–unloading (e.g. Laberg et al., 2012), that may have affected lithospheric flexure (Faleide et al., 2018).

4.3.3. Late Cenozoic erosion in the northern margin of the Barents Sea

For the northern margin of the Barents Sea shelf, there have not been any previous studies addressing the amount of Cenozoic pre-glacial versus glacial erosion. Our results presented in Paper 3 show that ca. 430–680 m of sediments have been removed from the considered source area during the late Cenozoic. According to the erosion map of Henriksen et al. (2011), the area of Paper 3 has undergone 1500–1600 m of total net Cenozoic erosion. If correct, this shows that ~30% of Cenozoic erosion in this segment of the northern Barents Sea margin was of glacial origin (Fig. 7). Further east, a major uncertainty exists, related to the lack of seismic data accessibility, particularly in the Russian sector.

4.4. Sediment load and drainage area: relationship and comparison

Sediment load (10^6 t/y) reflects the amount of sediments to be discharged over a certain time period. The relation between sediment load and the size of drainage area has been shown (e.g. Milliman and Syvitski, 1992). In this sub-chapter, we utilized results from Sømme et al. (2009) where they plot sediment load from a number of present-day systems from various areas against the size and type of drainage area. Our results can then be related to these cross-plot results to test our hypothesis regarding the paleomorphology of the source-to-sink systems during the studied intervals (Fig. 8). The 29 modern source-to-sink systems are classified based on the tectonic setting; (i) tectonically active system – small (e.g. Crati sytem in southern Italy, Redondo system in California), (ii) tectonically active system – large (e.g. Nitinat system in British Columbia), (iii) tectonically passive system (e.g. Amazon and Ebro system), (iv) tectonically mixed system (e.g. Bengal and Indus systems) (Sømme et al., 2009).

The presented systems consist of sub-surface studies and outcrop studies ranging from Triassic to recent (Holocene) (Table 3). Sediment load/discharge data (10^6 t/y) and the maximum drainage area (10^3 km^2) from these systems have been compiled (Table 3). Where sediment load data are not directly provided in the literature, the estimated values are derived by multiplying volume data and density (2.2 gr/cm^3) and dividing by time (e.g. Wilkinson, 2017). In other cases, by multiplying the rate of sediment supply (10^3 km^3/My) and density, the sediment load can be estimated (e.g. Michael et al., 2014). The sediment load can also be derived by multiplying sediment yield (10^3 kg/km^2/y) and drainage area (e.g. Andersen et al., 2002).

The relationship between the sediment load and the drainage area reflect how effectively the source area is being drained. The general pattern is that the larger the size of the drainage area, the higher the sediment load (Fig. 8). Results from California (Covault et al., 2011) and mid-Norway (Sømme et al., 2013) show a similar trend for outcrop studies (Pechlivanidou et al.; Michael et al., 2014) (Fig. 8). They have a similar trend to small tectonically active systems (Fig. 8). Results from the early Cenozoic systems of Paper 2 are in agreement with results from these systems indicating that the paleomorphology may have been similar, which is in accordance with our interpretation.

	Area (references)	Period	Sediment load (10^6 t/y)	Max. drainage area (10^3 km^2)
Glacial subsurface studies	SW Barents Sea (Fiedler and Faleide, 1996)	Pleistocene (GIII)	373	576
		Pleistocene (GII)	543	576
		Pleistocene (GI)	137	576
	NW Barents Sea (Hjelstuen et al., 1996)	Pleistocene (GIII)	29	69
		Pleistocene (GII)	167	69
		Pleistocene (GI)	82.4	69
	N Barents Sea (Paper 3)	Plesitocene (NB-3C)	1.3	63.2
		Pleistocene (NB-3B)	24.1	63.2
		Late Pliocene?–Pleistocene (NB-3A)	17.4	63.2
Pre-glacial subsurface studies	California (Covault et al., 2011)	Holocene	3.5	6.2
		Holocene	1.12	6.2
	SW Barents Sea (Paper 1)	Neogene	9.3	334
		Oligocene	8.3	334
		Eocene	8.8	275.8
		Paleocene	7.7	232.6
	NW Barent Sea (Paper 2)	Neogene	5.3	78.2
		Oligocene	7.1	78.2
		Eocene	2.7	34
		Paleocene	2.2	17
	Scotland* (Wilkinson, 2017)	Miocene	4.9	231
		Oligocene	4	227
		Eocene	6.0	230
		Paleocene	9.9	122

	North Sea* (Liu and Galloway, 1997)	Miocene	4.4	100
		Oligocene	6.6	100
		Eocene	5.5	100
		Paleocene	22	100
	Faroe Platform (Andersen et al., 2002)	Miocene	1.84	46
		Eocene–Oligocene	3.22	46
	mid-Norway (Sømme et al., 2013)	Paleocene	0.7	1.36
		Paleocene	0.42	1.08
		Paleocene	1.19	3.15
		Paleocene	0.92	5.11
		Cretaceous	0.003	0.24
		Cretaceous	0.022	0.39
		Cretaceous	0.211	1.06
		Cretaceous	0.02	0.5
		Cretaceous	0.02	0.36
		Cretaceous	0.015	0.22
		Cretaceous	0.027	0.4
		Cretaceous	0.538	3.59
		Jurassic	0.56	5.95
		Jurassic	2.46	4.08
	SW Barents Sea (Eide et al., 2017)	Triassic	27	80
Outcrop studies	Pyreneese (Michael et al., 2014)	Eocene	1.2	2.1
		Eocene	1.5	3.7
		Eocene	2.3	4.4
	Greece* (Pechlivanidou et al., 2017)	Holocene	2.2	1.4

Table 3. Comparison of sediment load and drainage area for the pre-glacial, glacial, and outcrop studies that is shown in the Figure 8. The studies marked with (*) indicate density of 2.2 gr/cm^3 is applied.

Our comparison of sediment load and drainage area for the Papers 1 & 2 study areas shows a good fit with similar Cenozoic studies from the Faroe Islands (Andersen et al., 2002), the North Sea (Liu and Galloway, 1997), and Scotland (Wilkinson, 2017) (Fig. 8). Results of Paper 1 suggest that the drainage area included uplifted areas such as the Stappen High, the Loppa High, and the Bjarmeland Platform. In Paper 2, the Stappen High, NE Greenland, and Edgeøya platform are considered as the key source area. These structural elements are thought to have been affected by the early Cenozoic tectonism involving transform between Greenland and the western Barents Sea (Faleide et al., 2008; 2015). Our results as presented in Papers 1 and 2 show a positive match with present-day systems in large tectonically active or passive systems (Fig. 8).

The glacial systems, including the area studied for Paper 3, show a generally high sediment load (Fig. 8). However, the NB-3C system of Paper 3 shows low sediment load, probably due to most of the ice in the northern Barents Sea drained towards the Franz Victoria Trough during the LGM (Dowdeswell et al., 2010a). Results from the glacial systems are of the same order of magnitude as results reported from source-to-sink systems in tectonically mixed areas (Sømme et al., 2009). The relatively high value from systems in tectonically mixed settings is likely due to a combination of high sediment flux due to active tectonics and a relatively wide drainage area, typical of a passive tectonic setting (e.g. Bengal Fan system). This may explained the rather high sediment load from the Triassic system of the SW Barents Sea (Eide et al., 2017; Fig. 8).

5. Conclusions

- This thesis and the corresponding papers provide an overview of our mass-balance studies for the Barents Sea area. For the pre-glacial part, the approach includes a tectonostratigraphic analysis to delineate the evolution of the sedimentary basins along the margin (the sink) and the source area, including its evolution and paleo-relief during the periods considered. For the glacial part, the study relies on an integration of seismic stratigraphic analysis and ice-sheet reconstructions to infer the likely source area. This study shows that the mass-balance method gives reliable erosion estimates when correlating offshore deposit and source area.
- The average erosion for the Paleogene–Neogene in the SW Barents Sea is estimated to be 858–1362 m with average erosion rates of 0.014–0.021 m/k.y. For similar periods in the NW Barents Sea area, the average erosion estimate corresponds to ca. 2440 m with average erosion rates of 0.038 m/k.y. The high pre-glacial erosion estimates are in agreement with the interpreted tectonic development of the western Barents Sea margin during the Cenozoic.
- For the first time, the average glacial erosion is estimated for the northeastern Svalbard/northern Barents Sea continental margin. Approximately 430–680 m of sediments has been removed from the interpreted source area with average erosion rates of 0.12–0.2 m/k.y for the last ca. 3.5 Ma. These numbers represent a quantification of the sediment contribution to the Arctic Ocean from this margin sector.
- The ratio between the Cenozoic pre-glacial and glacial sediments for the Papers 1, 2, and 3 areas is estimated to be 40%, 50%, and 70%, respectively. Along the western

margin of the Barents Sea, there is an N-S trend in the uplift during the early–middle Cenozoic, being highest in the north and an E-W trend of uplift during the late Cenozoic, being highest in the east.

- The dominant sedimentary processes for the basins of the western margin of the Barents Sea were also inferred. Sediment progradation and gravity-driven deposits were found to dominate in the Paleogene and contourites became more significant in the early Neogene, prior to the onset of the large-scale glaciations. Moreover, there is a link between progradation styles of the TMFs and the ice-sheet nature and extent.
- Our estimated sediment loads are comparable with results from present-day systems and in agreement with the interpreted tectonic setting of the study area.

6. Research outlook

Some pieces of the overall puzzle are still missing in terms of areal coverage and stratigraphic targets to constrain the total Cenozoic pre-glacial and glacial erosion in the Barents Sea shelf. For the pre-glacial period, the northern and the western Svalbard area are still poorly known. Paper 3 addressed erosion estimates for the late Cenozoic period. The next step is to address the quantification of the Cenozoic pre-glacial erosion for this margin. Determining this by using the volumetric mass-balance approach would improve our current understanding of the uplift and erosion events that have affected the Barents Sea shelf.

For the period dominated by glacial erosion, there is a need to refine the volume of glacial sediments in the NW Barents Sea and along the western Svalbard margin using the expanded seismic database and revised chronostratigraphy (Cohen et al., 2016). Moreover, during the late Cenozoic a large part of the eroded materials in the Barents Sea was transported by the ice sheet to the northeastern Barents Sea continental margin trough the St. Anna Trough (Fig. 1). However, subsurface data from the St. Anna TMF is lacking. Published results largely relate to the last deglaciation using bathymetry data and shallow gravity cores (e.g. Polyak et al., 1997). A collaboration with Russian institutions to investigate St. Anna TMF will broaden our understanding of the evolution of the Barents Sea during the Quaternary.

The SW Barents Sea is a highly active area for hydrocarbon exploration and production. As discussed above, the comparison of erosion estimates from the mass-balance method and from other methods is to be further developed. A statistical approach may help tackling this issue (e.g. Zieba et al., 2016). A map with relative degree of confidence and uncertainty would be useful to show local variation in the erosion estimates.

A numerical modelling study to test the results of Papers 1 and 2 may be useful to provide more constraint on the paleotopography, sediment transport, and basin infilling along the western and northern Barents Sea margin during the Cenozoic. This study will highlight the nature and timing of infilling of the Sørvestnaget Basin, the Vestbakken volcanic province and the Lofoten Basin, the main sinks along the western margin. Higher resolution in sediment routing (Allen, 2017) will ultimately increase the quality of the paleoenvironmental maps.

Erosion estimates from Papers 1 and 2 are beneficial as an input for petroleum system modelling to determine maximum burial depth. The fact that Papers 1 and 2 provided erosion estimates for each periods, this will also be useful for retention studies in association with the timing between petroleum generations and trap formation. A 1-D modelling might be applied to simulate burial history and hydrocarbon maturation.

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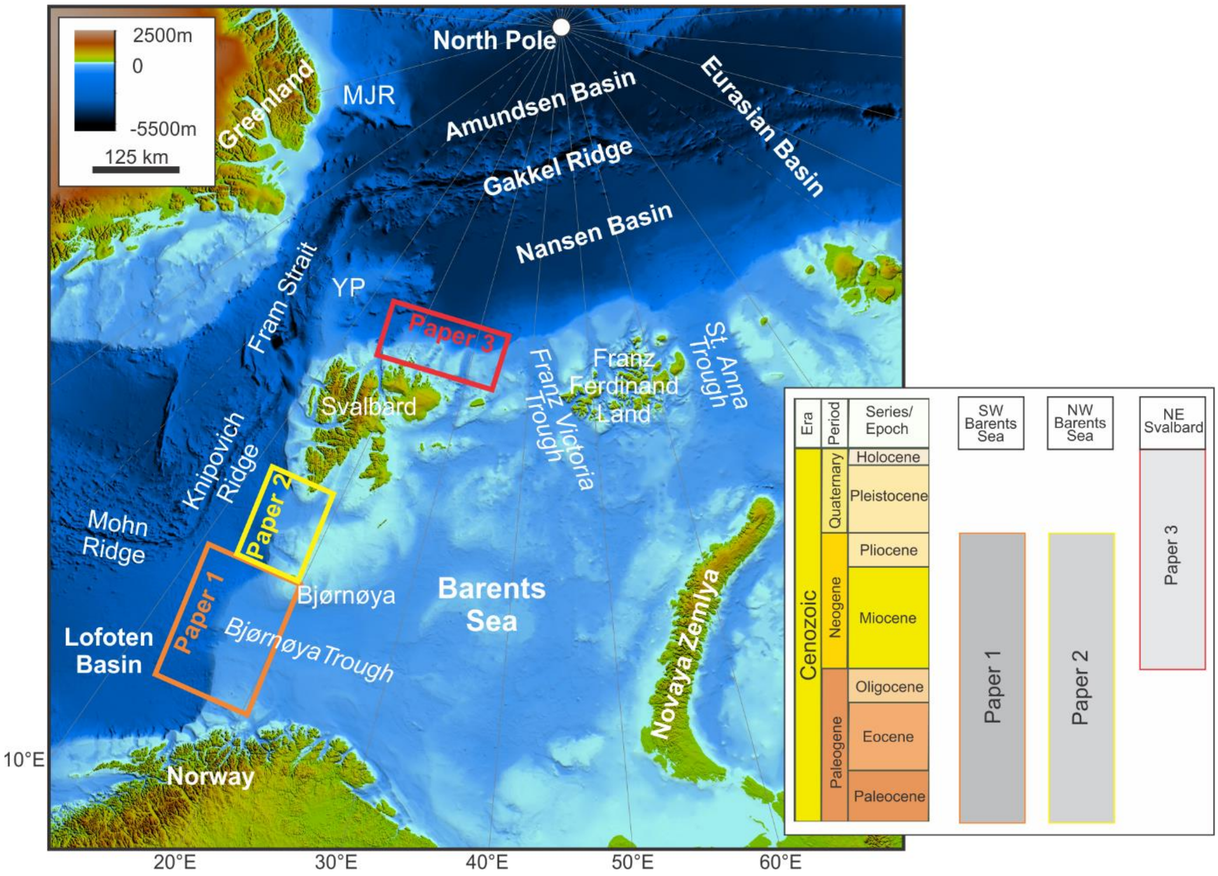


Figure 1. Regional setting of the study area. The relative location for the three papers is indicated. YP=Yermak Plateau; MJR=Morris Jesup Rise. Inset: Stratigraphy target for the three papers. Bathymetry is adapted from International Bathymetric Chart of the Arctic Ocean (IBCAO) v. 3.0 (Jakobsson et al., 2012).

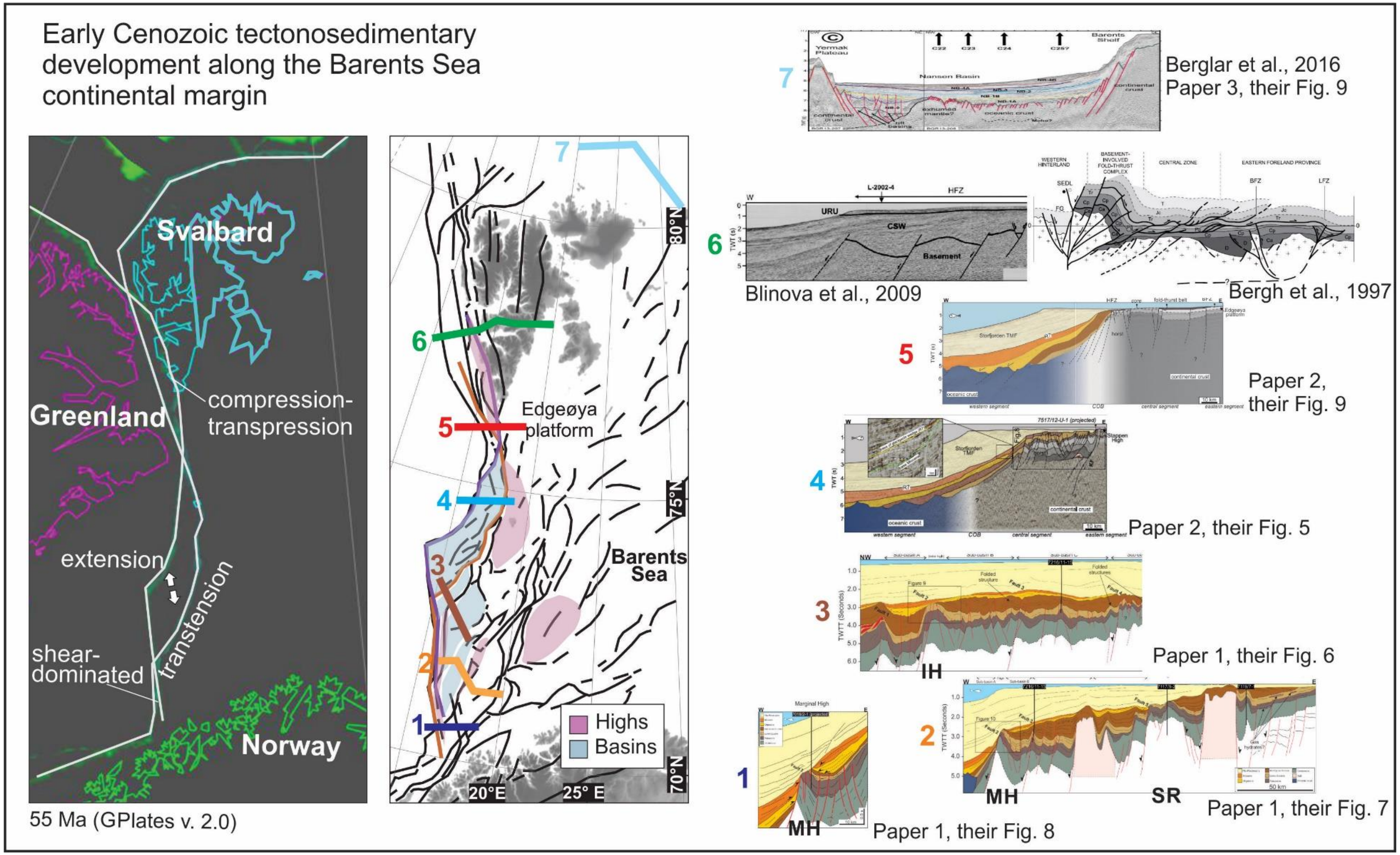


Figure 2. Plate reconstruction from GPlates v. 2.0 (Matthews et al., 2016; Muller et al., 2016) and the relative margin development during the breakup, ca. 55 Ma. The present-day structural elements are characterized by highs and basins. Number 1 to 7 are the key seismic profiles. IH=intra high; MH=marginal high; SR=Senja Ridge. References: Bergh et al. (1997); Blinova et al. (2009); Faleide et al. (2015); Berglar et al. (2016). For higher resolution of each seismic profile, the reader is referred to the original version of each figure in the corresponding paper.

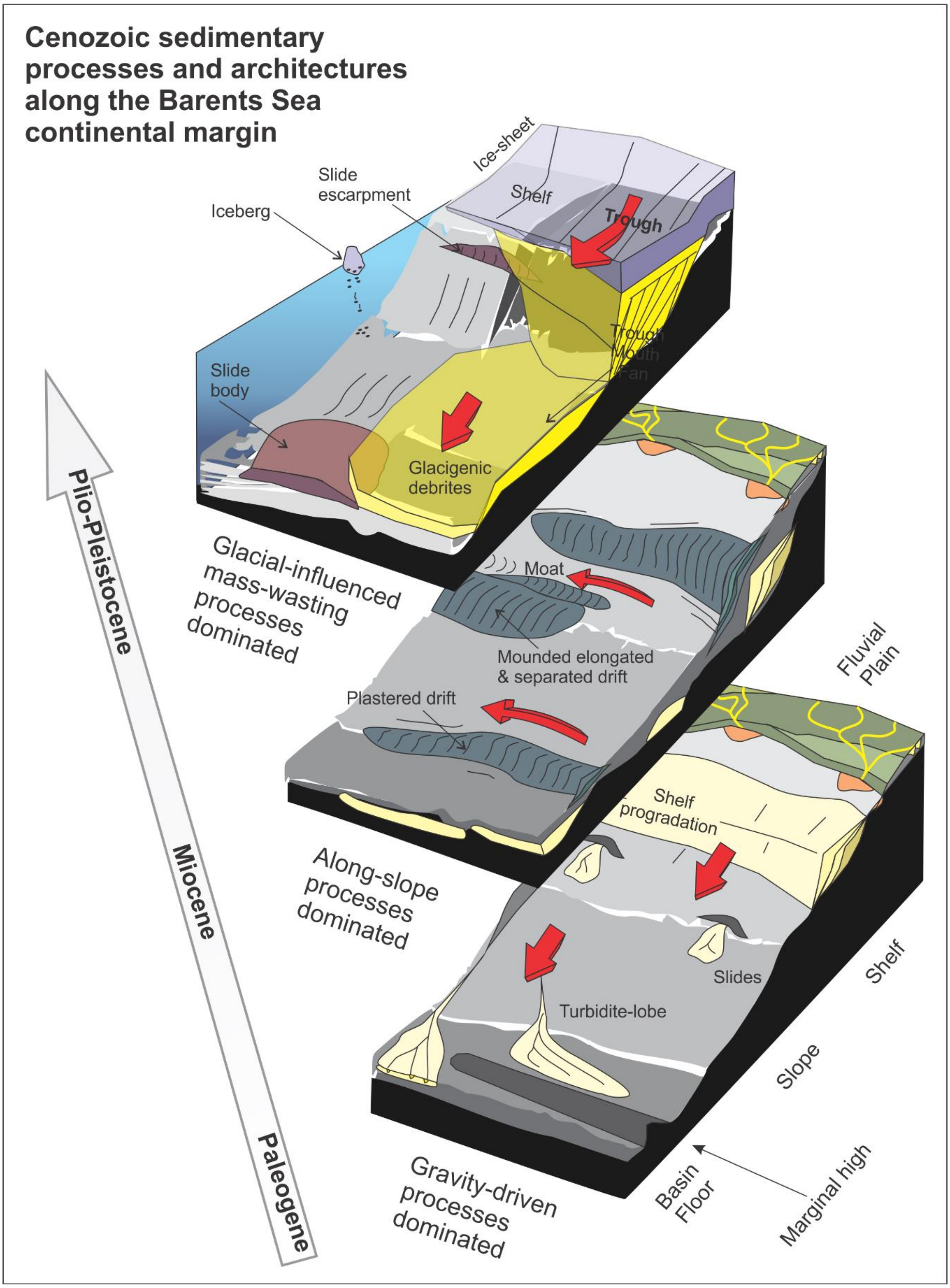


Figure 3. Schematic figures illustrating three key periods in the Cenozoic with the dominant sedimentary processes and major events along the Barents Sea continental margin. Contourite drift conceptual figure is modified from Hernandez-Molina et al. (2008)

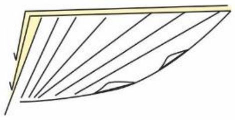
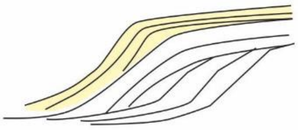
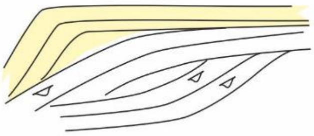
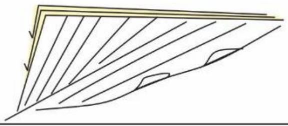
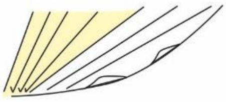
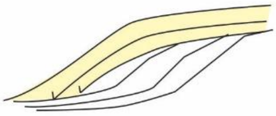
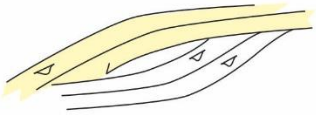
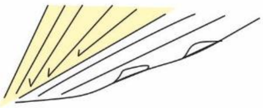
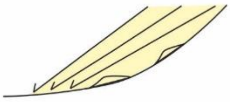
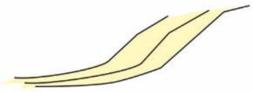
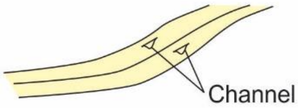
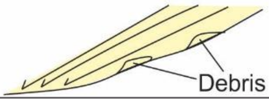
Period (Ma)	Area	Ice reconstruction	Unit	Progradation style (not to scale)
< 1.0	**Norhtern Barents Sea: Kvitøya TMF (Paper 3)**		NB-3C	
< 0.44	NW Barents Sea: Storfjorden TMF		GIII	
< 0.7	SW Barents Sea: Bjørnøya TMF		GIII	
< 0.7	Northern Norway: Troms margin TMF		S4	
2.4 – 1.0	**Norhtern Barents Sea: Kvitøya TMF (Paper 3)**		NB-3B	
1.0 – 0.44	NW Barents Sea: Storfjorden TMF		GII	
1.5 – 0.7	SW Barents Sea: Bjørnøya TMF		GII	
1.5 – 0.7	Northern Norway: Troms margin TMF		S3	
3.5 – 2.4	**Norhtern Barents Sea: Kvitøya TMF (Paper 3)**		NB-3A	
2.3 – 1.0	NW Barents Sea: Storfjorden TMF		GI	
2.7 – 1.5	SW Barents Sea: Bjørnøya TMF		GI	
2.7 – 1.5	Northern Norway: Troms margin TMF		S2	

Figure 4. Sediment progradation style of trough-mouth fans in response of paleoenvironmental/ice sheet development in the Barents Sea during the late Cenozoic. The ice reconstruction model is according to Knies et al. (2009). References: Storfjorden TMF (Hjelstuen et al., 1996; Faleide et al., 1996), Bjørnøya TMF (Faleide et al., 1996; Laberg et al., 2010), Troms margin TMF (Rydningen et al., 2016).

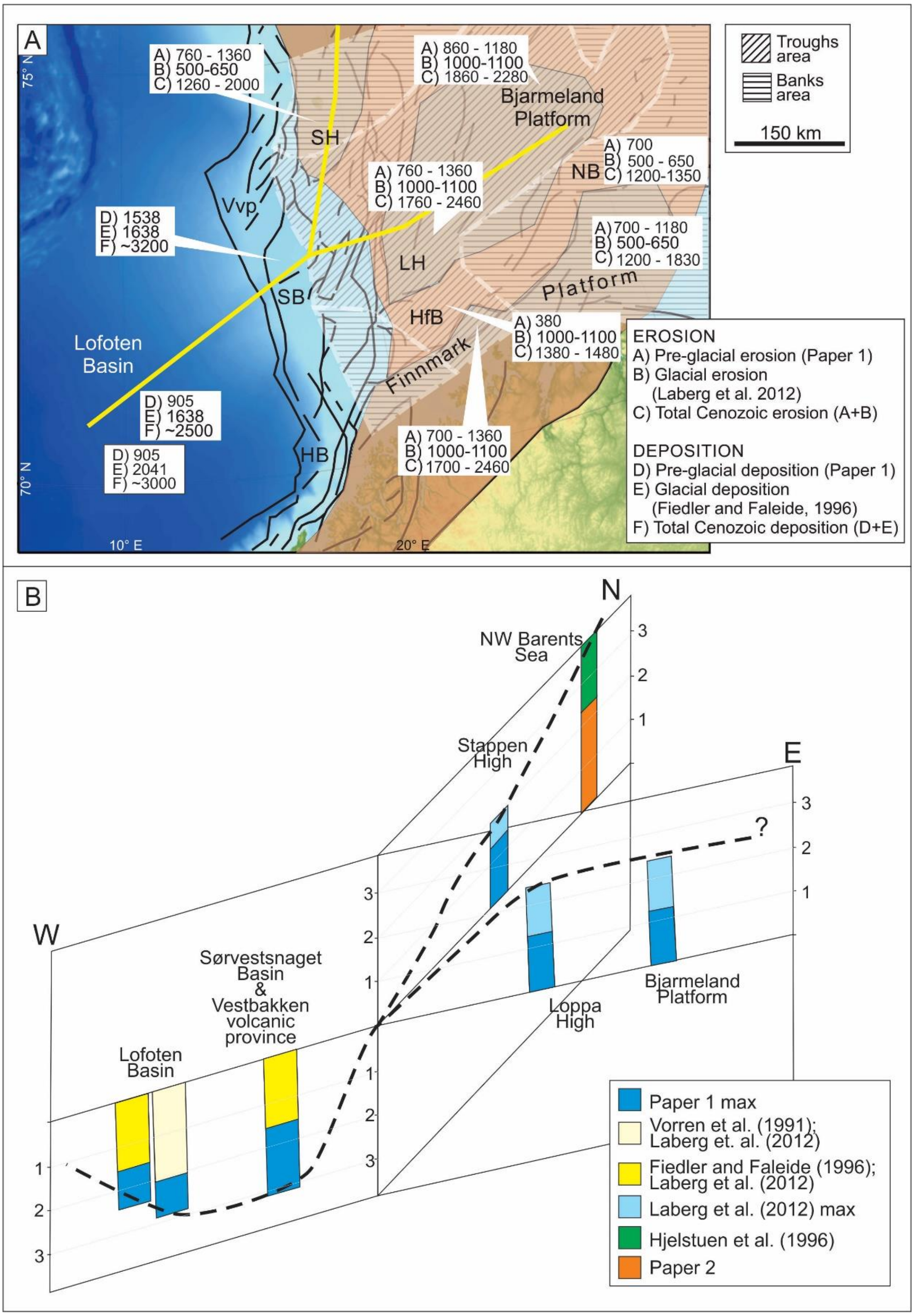


Figure 5. a) Map summarizing the mass-balance approach for the Cenozoic interval in southwestern Barents Sea. The deposition values are taken from Table 1. The erosion values are from Paper 1 and Laberg et al. (2012) in Table 2. b) A 3D diagram following the yellow line in Figure 5a. This diagram shows the significance N-S and E-W trending erosion and deposition. BP= Bjarmeland Platform; HB= Harstad Basin; HfB= Hammerfest Basin; LH= Loppa High; NB= Nordkapp Basin; SB= Sørvestsnaget Basin; SH=Stappen High; Vvp= Vestbakken volcanic province. Structural elements are based on Faleide et al. (2008; 2015). Bathymetry is modified from IBCAO v. 3.0 of Jakobsson et al. (2012).

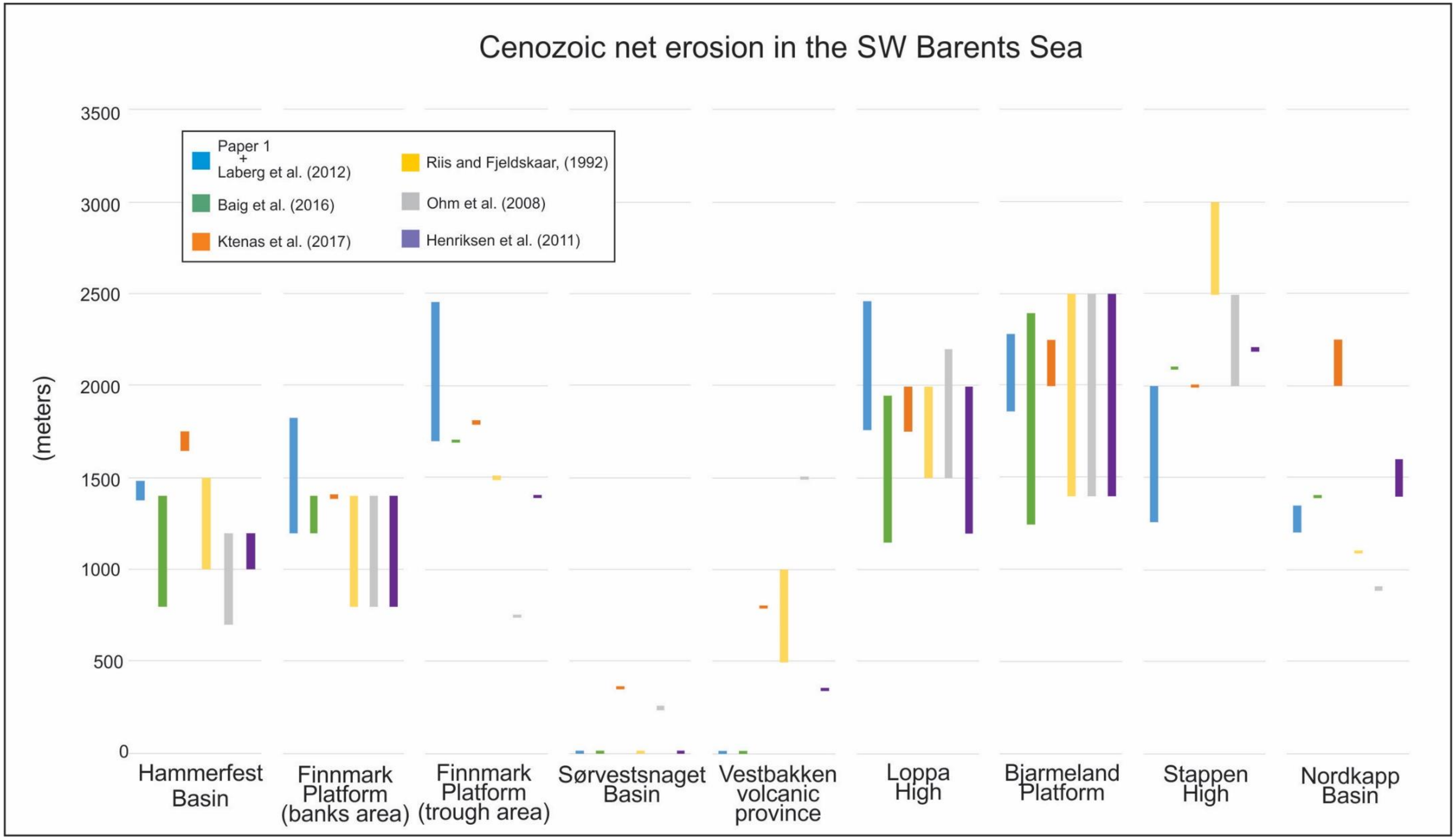


Figure 6. Chart shows Cenozoic net erosion in the southwestern Barents Sea compiled from various references at Table 2.

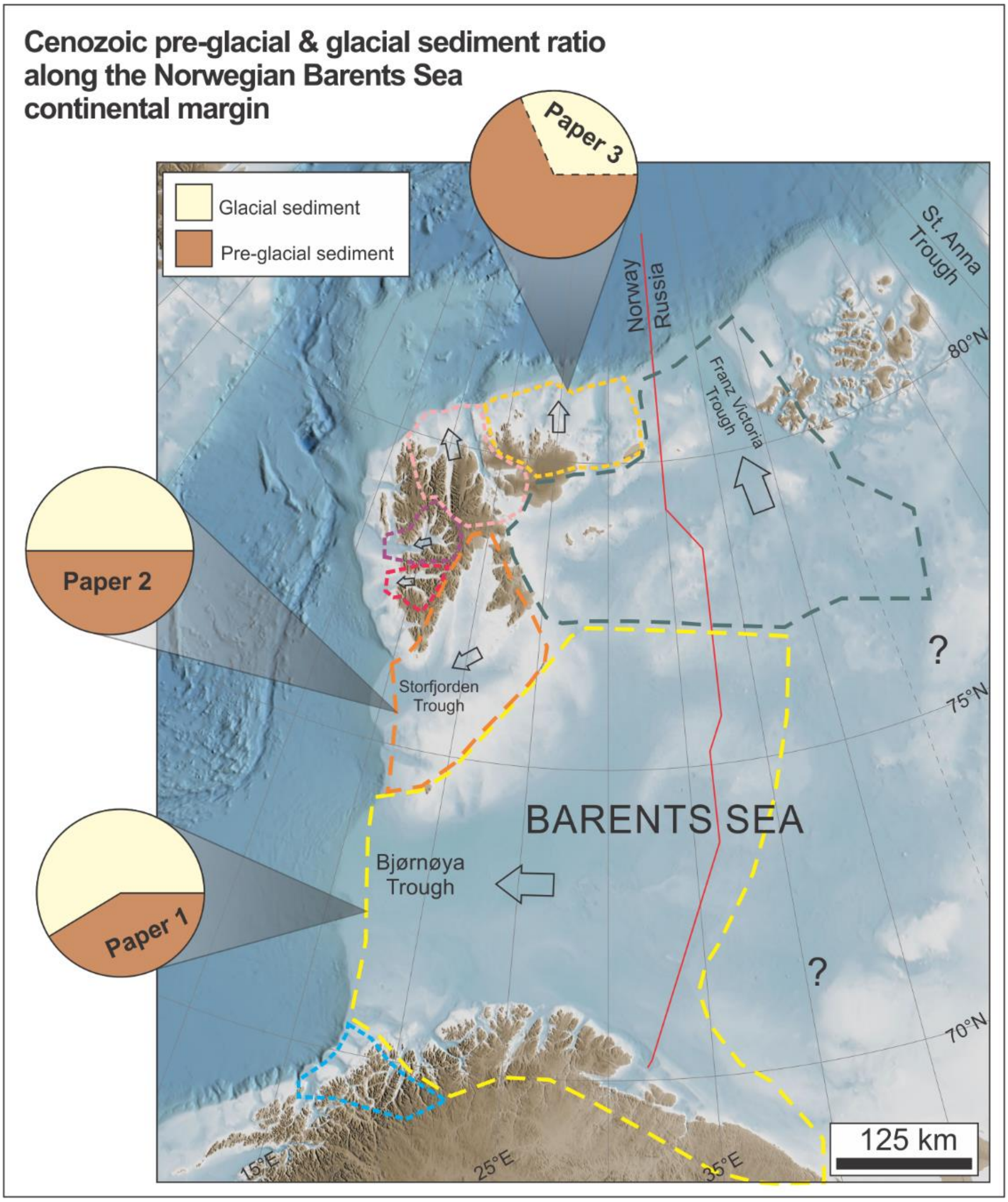


Figure 7. Cenozoic pre-glacial and glacial sediment ratio along the Norwegian Barents Sea continental margin. The dashed lines represent the drainage areas for during the glacial period. The arrows show relative draining direction. The pie charts represent the ratio between the glacial and pre-glacial erosional sediment found in the basins off the continental margin. Please note the pie charts similarity in size does not correspond to similar volume. This map is compiled based on Vorren et al. (1991), Hjelstuen et al. (1996), Fiedler and Faleide, (1996), Elverhøi et al. (1998), Ottesen et al. (2005), Dowdeswell et al. (2010), Laberg et al. (2012), Minakov et al. (2012), and Rydningen et al. (2016). Bathymetry is modified from IBCAO v. 3.0 (Jakobsson et al., 2012).

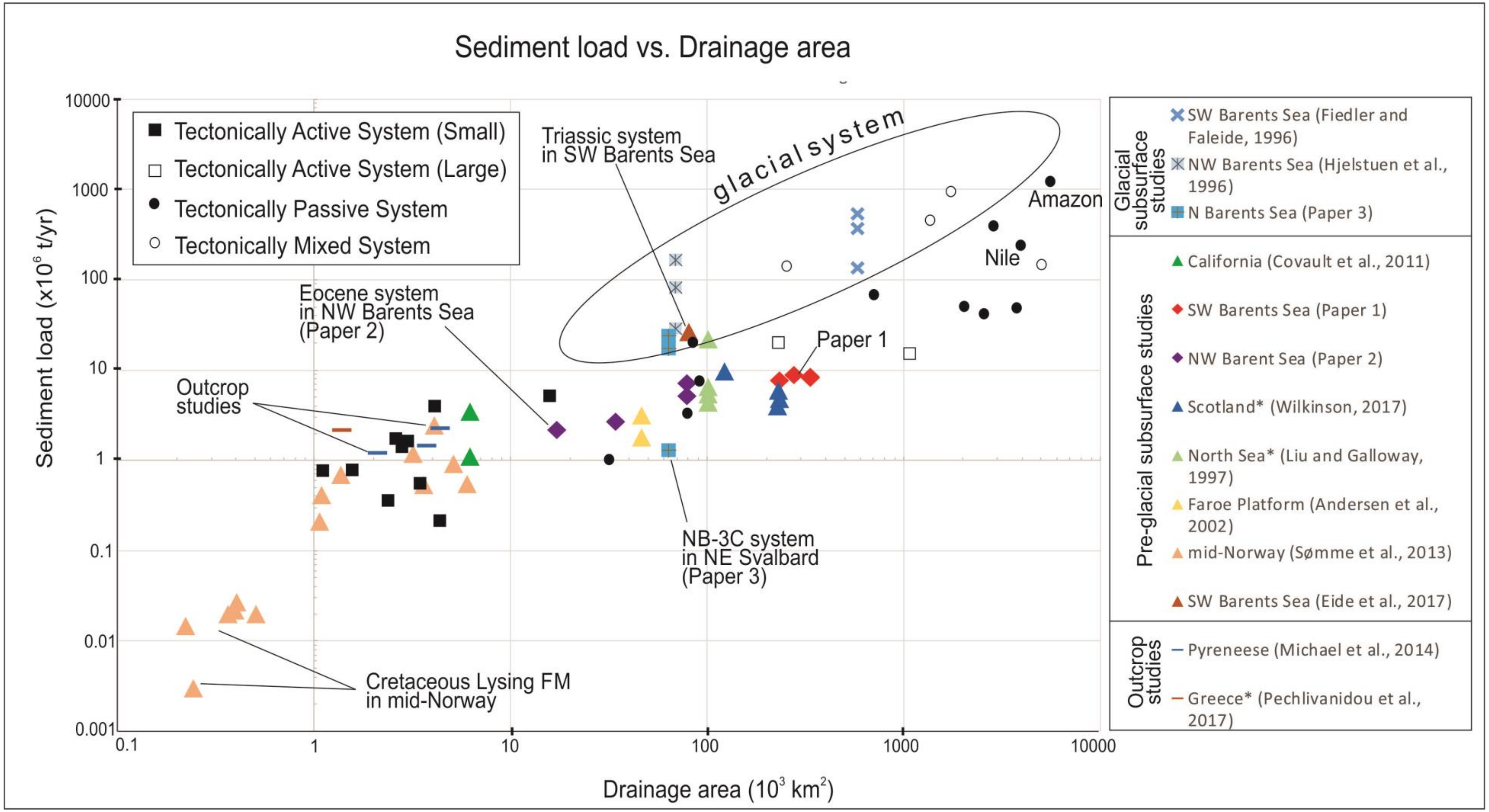


Figure 8. Cross-plot diagram showing sediment load versus drainage area of glacial system, non-glacial system, and outcrop studies. The black and white rectangles and circles are the modern systems from different tectonic settings (Sømme et al., 2009). The colored points are compiled from various areas based on Table 3.

Paper 1

Paper 2

Paper 3

Appendix

Appendix

Conference contributions:

1. **Lasabuda A.**, J.S. Laberg, and S-M. Knutsen (2016), The Early to Middle Cenozoic Paleoenvironment and Sediment Yield of the southwestern Barents Sea – preliminary results: Poster, Nordic geological winter meeting, Helsinki, Finland, 13-15 Jan.
2. **Lasabuda A.**, J.S. Laberg, and S-M. Knutsen (2016), The Early to Middle Cenozoic Paleoenvironment and Sediment Yield of the southwestern Barents Sea: Talk, 2nd ARCEx conference, Tromsø, Norway, 14-16 March.
3. **Lasabuda A.**, J.S. Laberg, and S-M. Knutsen (2016), The Early to Middle Cenozoic Paleoenvironment and Sediment Yield of the southwestern Barents Sea: Talk, AMGG seminar, Tromsø, Norway, 11-12 Apr.
4. **Lasabuda A.**, J.S. Laberg, S-M. Knutsen, and G. Høgseth (2016), The Early to Middle Cenozoic Paleoenvironment and Sediment Yield of the southwestern Barents Sea: Poster, NPF conference, Arctic Exploration, Tromsø, Norway, 31 May-2 June.
5. **Lasabuda A.**, J.S. Laberg, S-M. Knutsen, and G. Høgseth (2016), The Early to Middle Cenozoic Paleoenvironment and Sediment Yield of the southwestern Barents Sea: Talk. NGU conference, Onshore-Offshore Correlation, Trondheim, Norway 18-19 Oct.
6. **Lasabuda A.**, J.S. Laberg, S-M. Knutsen, and G. Høgseth (2016), Cenozoic's pre-glacial tectonostratigraphy and erosion estimates for the southwestern Barents Sea margin: Talk, Uplift and Erosion workshop, ARCEx, Tromsø, Norway, 26 Oct.
7. Laberg, J.S., T.A. Rydningen, and **A. Lasabuda** (2016), On the Late Cenozoic Evolution of the Norwegian Arctic Continental Margin: Invited Talk. American Geophysical Union Fall Meeting, San Francisco, USA, 12-16 Dec.
8. **Lasabuda A.**, J.S. Laberg, S-M. Knutsen, and P. Safronova (2017), Cenozoic pre-glacial tectonostratigraphy and erosion estimates for the northwestern Barents Sea: Poster. EGU Vienna, Austria. 24-28 April.
9. Laberg, J.S., T.A. Rydningen, and **A. Lasabuda** (2017), On the Late Cenozoic Evolution of the Norwegian Arctic Continental Margin: Poster. EGU Vienna, Austria. 24-28 April.
10. **Lasabuda A.** J.S. Laberg, and S-M. Knutsen (2017), Cenozoic pre-glacial tectono-sedimentary development in the western Barents Sea continental margin: Talk. 3rd ARCEx conference, Malangen, Norway. 10-11 May.
11. **Lasabuda A.** J.S. Laberg, and S-M. Knutsen (2017), Cenozoic pre-glacial tectono-sedimentary development in the western Barents Sea continental margin: Talk. Arctic Days. Svolvær, Norway. 29-31 May.
12. Geissler W.H., **A. Lasabuda**, J.S. Laberg, and S-M. Knutsen (2017), The Cenozoic evolution and sedimentary successions of the southwestern Eurasian Basin and the northern Svalbard / Barents Sea continental margin: Keynote Talk. Arctic Days. Svolvær, Norway. 29-31 May.
13. **Lasabuda A**. J.S. Laberg, and T.A. Rydningen (2017), Linking tectonostratigraphy and denudation history: insights from a mass balance approach: Talk. AMGG seminar. Tromsø, Norway, 3 Oct.
14. **Lasabuda A.**, J.S. Laberg, S-M. Knutsen, and P. Safronova (2017), The Early to Middle Cenozoic Paleoenvironment and Erosion Estimates for the northwestern Barents Sea: Talk. AAPG/SEG/3P-Arctic London, UK. 15-18 Oct.
15. **Lasabuda A.**, W.H. Geissler, J.S. Laberg, S-M. Knutsen, T.A. Rydningen, K. Berglar (2018), Late Cenozoic paleoenvironment and erosion estimates for the northeastern Svalbard/northern Barents Sea continental margin, Norwegian Arctic: Talk. Nordic geological winter meeting. Copenhagen, Denmark. 10-12 Jan.
16. Rydningen T.A., G. Høgseth, **A. Lasabuda,** J.S. Laberg and P. Safronova (2018), Origin and sediment budget of an early Neogene - early Quaternary contourite drift system on the SW Barents Sea margin: Poster. Nordic geological winter meeting. Copenhagen, Denmark. 10-12 Jan.