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Key Points:
- The Bjørnøyrenna Drift records the high north ocean circulation that influenced climate deterioration after the Mid Miocene Climatic Optimum
- The drift accumulated on the slope until Quaternary glacigenic sediments buried it, resulting in a submarine failure
- The drift sedimentation rates compare to deep-sea input from the Amazon/Mississippi rivers, but are less than from continental ice caps

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An Early Neogene—Early Quaternary Contourite Drift System on the SW Barents Sea Continental Margin, Norwegian Arctic

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Abstract The onset and evolution of the middle to late Cenozoic "icehouse" world was influenced by the development of the global ocean circulation linking the Norwegian–Greenland Sea-Arctic Ocean to the Atlantic Ocean. The evolution of the early Neogene to early Quaternary Bjørnøyrenna Drift, located at the SW Barents Sea continental margin, shed new light on this important hydrological event. By analyzing seismic data and exploration wellbores, it is found that the drift likely started to form in the early/middle Miocene, probably as a result of an ocean circulation reorganization following the opening of the Fram Strait gateway (c. 17 Ma) and subsidence of the Greenland–Scotland Ridge (c. 12 Ma). Thus, the onset of drift growth is considered to have happened close in time to the Mid Miocene Climatic Optimum at 16–14 Ma, and was part of a regional onset of large-scale ocean circulation in the Norwegian–Greenland Sea that influenced the subsequent climate cooling. The drift continued to grow under the influence of early Quaternary glacimarine sedimentation, and later overtopping of the drift mound by downslope transfer of glacigenic sediments during full-glacial conditions resulted in a submarine failure. For the first time, minimum average sedimentation rates of a Neogene to Quaternary drift in this area is calculated, giving rates of 0.020–0.031 m/Kyr. These values are comparable to average deep-sea sedimentation rates from modern low-latitude river systems such as the Amazon and Mississippi, but lower than the Quaternary glacial sedimentation rates from the Barents Sea and Fennoscandian continental margins.

Plain Language Summary The ocean water masses are constantly moving through the thermohaline circulation, which both distribute heat from low to high latitudes, as well as cold water in the opposite direction. This is crucial for maintaining the global climate, and the start and evolution of ocean currents can be decrypted from marine sedimentary deposits known as contourite drifts. This study outlines the evolution of a drift that likely started building up in the SW Barents Sea when the Gulf Stream first extended into the Arctic Ocean. This likely happened as important ocean passages such as the Fram Strait gateway west of Svalbard opened up, which occurred during a global temperature highpoint in the mid Miocene (16–14 Ma). The global temperatures dropped following this, possibly partly because of the establishment of this ocean circulation, allowing for precipitation and growth of larger ice caps on the northern hemisphere. The drift accumulated by 0.020–0.031 m per 1,000 years, before it was later rapidly buried (at a rate of 0.18–0.64 m per 1,000 years) by glacigenic sediments during the last 2.7 Ma. The weight of these overlying sediments likely caused parts of the drift to fail, resulting in a large submarine slide.

1. Introduction

Alongslope flowing ocean currents are important sediment transport agents on high-latitude continental margins at present as well as during past glacials and interglacials (e.g., Campbell & Mosher, 2016; Rebesco et al., 2014). Such currents, spatially and temporally variable, are both eroding the continental slope in areas of persistent flow strength and direction, often creating widespread unconformities, and leading to the deposition of extensive mound-shaped, elongated contourite drifts (Figure 1a) (Faugères et al., 1999; Stow et al., 1996). These sedimentary processes, however, have so far attracted less attention compared to subglacial transport and subsequent downslope processes such as debris flows and turbidity flows, from

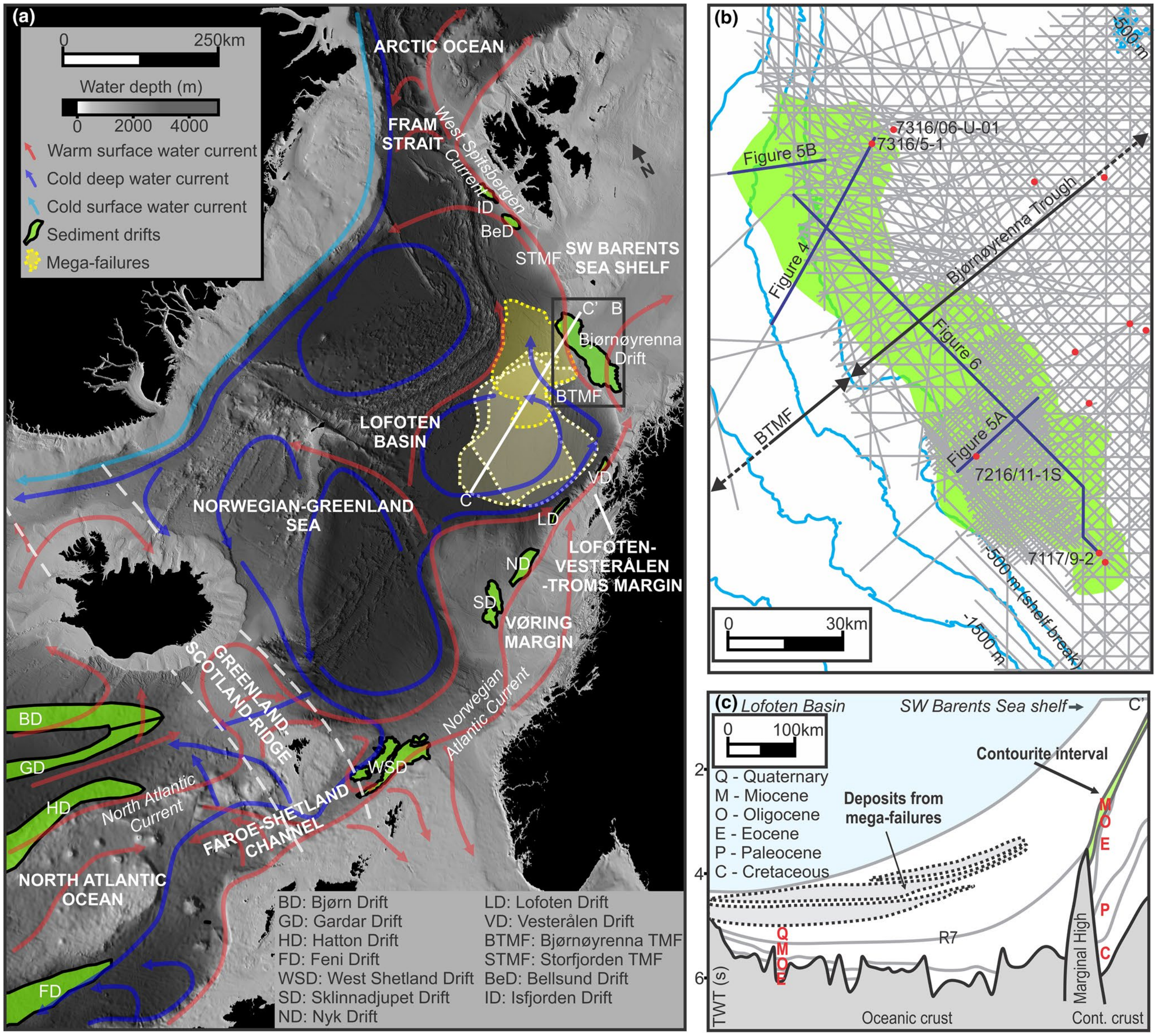

Figure 1. (a) Modern ocean currents and locations of sediment drifts in the Atlantic Ocean and along the Norwegian-Barents Sea margin. Deposits from mega-failures originating on the Bjørnøyrenna Trough-Mouth Fan is also indicated. The circulation is modified from Hansen and Østerhus (2000), Orvik and Niiler (2002), and Beszczynska-Möller et al. (2012). The bathymetric map is generated from the International Bathymetric Chart of the Arctic Ocean Version 4.0 (Jakobsson et al., 2020) and the ETOPO11 Arc-Minute Global Relief Model (Amante & Eakins, 2009). TMF, trough-mouth fan. (b) Study area with outline of the Bjørnøyrenna Drift (green). Seismic data are shown in gray lines, water depths in blue lines, and exploration wellbores and the 7316/06-U-01 shallow borehole in red circles. Seismic data courtesy of TGS and NPD. (c) Geoseismic profile across the SW Barents Sea continental shelf extending into the Lofoten Basin. The contourite interval and deposits from mega-failures (Hjelstuen et al., 2007) are indicated. R7 marks the base of the Quaternary deposits (Faleide et al., 1996; Laberg et al., 2012). The seismic horizons are from Lasabuda et al. (2018b).

whose deposits are well-known building blocks of trough-mouth fans (Clausen, 1998; Dowdeswell et al., 2010; Hiscott & Aksu, 1994; King et al., 1996, 1998; Laberg & Vorren, 1995; Rydningen et al., 2015; Vorren et al., 1989, 1998).

Contourite drift growth along the NW European Atlantic glaciated margin has been related to intensified paleo-circulation controlled by tectonic events such as the opening of the Fram Strait gateway and the subsidence of the Greenland–Scotland Ridge (Jakobsson et al., 2007; Kristoffersen, 1990; Laberg et al., 1999; Rebesco et al., 2013). These events occurred in a period of important fluctuations in the global climate including the "Mid-Miocene Climatic Optimum," its abrupt termination and the following climatic cooling (Zachos et al., 2001).

Contourite drifts cover large areas of the eastern North Atlantic continental margin, from west of the British Isles to the Fram Strait (Figure 1) (Laberg et al., 2005). However, details on the nature and influence of the circulation system responsible for forming this pattern on the SW Barents Sea continental margin, the southern entrance to the Fram Strait, are still lacking. Little is also known about the potential influence of drift deposits on the release of some of the submarine landslides identified along this margin (Figure 1), estimated to be one order of magnitude larger in volume than the giant Storegga Slide (Hjelstuen et al., 2007; Kuvaas & Kristoffersen, 1996). Similar mega-slides in the glacial part of the slope succession further north on the Barents Sea margin were identified and inferred to be preconditioned by contourite drifts by Safronova et al. (2017).

We present the first study of a contourite drift within the Neogene to Quaternary succession on the continental slope of the SW Barents Sea, the Bjørnøyrenna Drift (Figure 1). The drift is stratigraphically located beneath the Bjørnøyrenna Trough-Mouth Fan, a fan that built out during the Quaternary glaciations (Figure 1c). The age and development of the drift are addressed, as well as the drift influence on the later evolution of the trough-mouth fan. Furthermore, implications of the onset of large-scale ocean circulation in the Norwegian–Greenland Sea are discussed, and related to the history of global climate shifts during the Neogene to Quaternary. Finally, we estimate the sedimentation rates for this major Neogene to Quaternary sediment drift in the Norwegian–Greenland Sea, in order to better constrain the growth rate of high-latitude passive continental margins as a response to the climatic and oceanographic changes through time.

2. Database and Methods

The seismic data base consists of multichannel 2-D seismic surveys provided by the Norwegian Petroleum Directorate (NPD) through the Diskos data base (publicly available surveys; NPD-BJVI-86, GBW-88, HB-96, and NH9702 collected in 1986, 1988, 1996, and 1997, respectively), and TGS (NBR06-12 collected between 2006 and 2012). The data from TGS were collected using air guns with volumes between 2,000 and ~4,000 cubic inches, streamer lengths of usually ~8,000 m, and between 324 and 960 channels. For details on the older seismic surveys the reader is referred to the NPD.

The distance between 2-D seismic lines is generally between 2 and 5 km on the upper slope down to ~500 m water depth. Very few seismic lines are acquired on the lower slope, and the line spacing is here between 10 and 40 km within the study area (Figure 1b). The seismic data are generally of good quality, and the vertical resolution in the studied interval is ~30–50 m in the vicinity of well 7216/11-1S.

Three exploration wellbores located on the SW Barents Sea continental margin are used in this study (Figure 1b; downloaded from the Diskos data base). Formation tops from these wells, together with the established stratigraphy from Eidvin et al. (1993, 2013), Ryseth et al. (2003), and Eidvin et al. (1998, 2013, 2014), form the basis for the seismic stratigraphy for wells 7117/9-2, 7216/11-1S, and 7316/5-1, respectively.

An estimated average velocity value of ~2,500 m/s is extracted for the studied interval, based on visual inspection of the velocity log from well 7216/11-1S between depths of ~2,100 and 2,300 m measured depth, that is, corresponding to the depths of the top and base horizon for the studied interval from the seismic data (see NPD, 2020 for wellbore logs). This is used to convert the isopach map (generated from seismic data) from depth in two-way traveltime to meters.

The data interpretation, gridding, and depth conversion was done in the Petrel software®. The plate reconstruction shown in Figure 2 is created from the GPlates 2.0 software® (Matthews et al., 2016; Müller et al., 2016).

3. Physiographic, Geologic, and Oceanographic Setting

Near the Paleocene-Eocene transition (55–54 Ma), lithospheric breakup between the Eurasian and North American plates culminated in a northward propagating seafloor spreading forming the early Norwegian–Greenland Sea. Transform movements characterized the SW Barents Sea up until the Oligocene, from which a passive margin with regional subsidence evolved. Extension, breakup, and subsequent seafloor spreading

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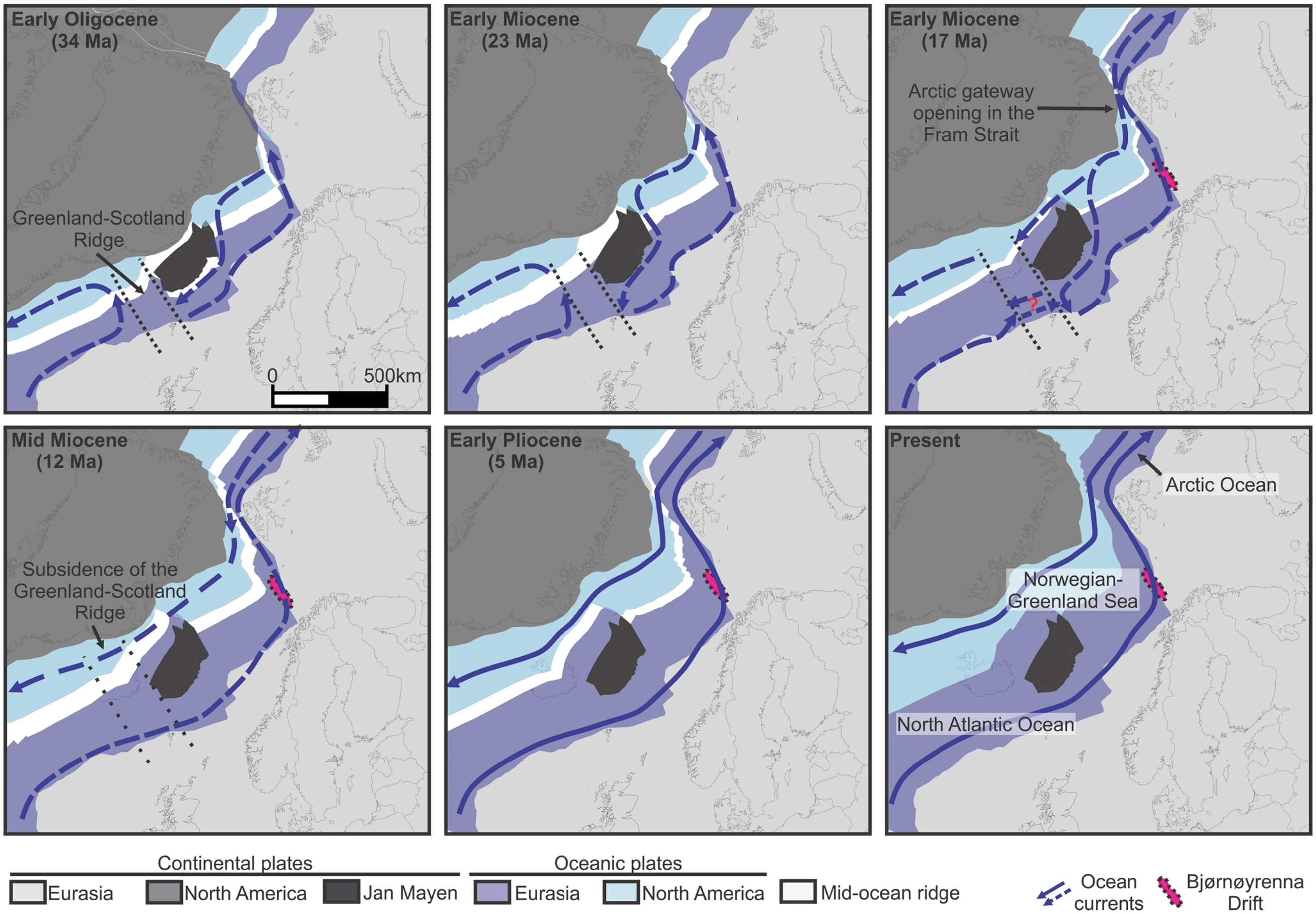

Figure 2. Opening history of the Norwegian–Greenland Sea reconstructed using the GPlates 2.0 software (Matthews et al., 2016; Müller et al., 2016). The Bjørnøyrenna Drift likely started to form during the early/middle Miocene, following the opening of the Arctic Ocean gateway in the Fram Strait.

eventually also propagated to the northern part of the ocean basin west of Svalbard (Eldholm et al., 1987; Faleide et al., 2008, 2015; Talwani & Eldholm, 1977). To the southeast, the Barents Sea-Thetys sea-way is interpreted to have been closed in the middle to late Eocene (Akhmetiev et al., 2012).

During the Eocene, erosion of uplifted areas in the east and north resulted in sediment transport south and westwards, with clastic deposition including sandy turbidites in the structural basins along the SW Barents Sea continental margin (Lasabuda et al., 2018b, 2018c; Safronova et al., 2012, 2014). As a result, a gradual shallowing into a more shallow water shelf is inferred during the Oligocene through Miocene (Eidvin et al., 2014; Ryseth et al., 2003).

The Norwegian–Greenland Sea and Arctic Ocean were probably oceanographically isolated basins from sometime in the Eocene to the early Miocene (Figure 2) (Hutchinson et al., 2019; Moran et al., 2006). To the north, the opening of the Fram Strait gateway allowed for full ventilation between the ocean basins with deep-water exchange suggested from c. 17.5 Ma (Jakobsson et al., 2007). Paleobathymetric modeling predicts water depths in the strait deeper than 2,000 m since at least 17 Ma (Ehlers & Jokat, 2013; Knies & Gaina, 2008). However, coring gaps and hiatuses in the available Arctic Ocean sediment cores make the exact timing uncertain (Backman & Moran, 2009; Thiede & Myhre, 1996). Therefore, the established circulation between the basins is reconstructed with confidence from c. 6.0 Ma (Knies et al., 2014a). A much earlier inception of marine conditions, that is, a marine inflow event resulting from an opening of the Fram Strait west of Svalbard already at 36 Ma has been suggested by Poirier and Hillaire-Marcel (2011) from an alternate Osmium-isotope stratigraphy of sediments cored during the Arctic Ocean Expedition. However, other studies have shown that the late Paleocene to early Oligocene was the period of the West Spitsbergen orogeny on Svalbard (e.g., Steel et al., 1985) allowing for little or no water exchange as there was no gateway in this area at that time (Lasabuda et al., 2018c). In the southern part of the Norwegian–Greenland Sea, the Greenland–Scotland Ridge prevented free passage of warm North Atlantic water into the Norwegian–Greenland Sea up until the middle Miocene (c. 12 Ma) (Bohrmann et al., 1990; Laberg et al., 2005; Wright, 1998), after which subsidence of the ridge allowed for an increased circulation in the northern ocean basins (Figure 2).

During the Miocene, warm Atlantic water started to flow northwards along the British-Norwegian–Barents Sea continental shelf and slope. At the same time, cold and high-density water (North Atlantic Deep Water) flowed southwards along the Greenland margin, as a result of the formation of a ventilated North Atlantic Ocean—Norwegian–Greenland Sea—Arctic Ocean (Majoran & Dingle, 2001; Piotrowski et al., 2000). As a response to this oceanographic setting, contourite drift growth accelerated along the continental margins since c. 17–12 Ma in the Faroe-Shetland Channel, on the Vøring margin, and on the Lofoten-Vesterålen continental slope (Figure 1) (Davies et al., 2001; Laberg et al., 1999, 2001, 2005). The onset of drift growth in the Fram Strait is inferred to be younger, that is, between 10 and 3 Ma, implying that these started to accumulate at a time when the gateway was well established (Eiken & Hinz, 1993).

Following the Pliocene-Quaternary climate deterioration, ice sheets started to expand onto the SW Barents Sea shelf at c. 2.7 Ma (Knies et al., 2009, 2014b), and repeated advances of grounded glaciers reaching the shelf break are inferred since c. 1.5 Ma, eroding the substratum and transporting vast amount of debris to the outer shelf and upper slope (Andreassen et al., 2007; Eidvin et al., 1993, 1998; Faleide et al., 1996; Laberg et al., 2010, 2012; Vorren et al., 1991). These glacigenic sediments later remobilized downslope as debris flows and turbidity flows with long run-out distances, forming the present shape of the trough-mouth fans in the SW Barents Sea (Laberg & Vorren, 1995, 1996; Vorren et al., 1998). Contemporaneous to trough-mouth fan development, contourite drift onset on the West Svalbard margin just south of the Fram Strait gateway is inferred to be related to enhanced sediment supply to the margin following glacial expansion onto the shelf in the early Pleistocene (Rebesco et al., 2013).

From other parts of the Norwegian continental margin, it is also known that the development of contourite drifts influenced on the continental margin stability, and thus also sediment transfer to the deep sea. Sediment failures, including the Storegga, Nyk, Trænadjupet, and Andøya submarine landslides, are related to rapid burial of contouritic interglacial/interstadial sediments by glacigenic sediments during peak glacials, resulting in the build-up of excess pore pressure, thereby forming planes of weakness within contouritic sediments in which the initial failure presumably occurred (Bryn et al., 2005; Haflidason et al., 2005; Laberg & Camerlenghi, 2008; Laberg et al., 2003). Large submarine landslides are also described from the Bjørnøyrenna Trough-Mouth Fan on the SW Barents Sea continental margin (Figure 1), with areal extents and volumes up to 120,000 km^2 and 24,500 km^3, respectively. In previous studies, these slides have not been linked to contouritic sediments, although they are related to rapidly deposited glacigenic sediments on a softer substratum in a continental slope setting (Hjelstuen et al., 2007).

Warm and saline surface waters are presently flowing north-eastward along the slope on the eastern side of the North Atlantic and Norwegian–Greenland seas as the North Atlantic Current (Figure 1). This current passes through the narrow Faroe-Shetland Channel and continues as the Norwegian Atlantic Current along the Norwegian shelf edge and upper slope (Beszczynska-Möller et al., 2012; Hansen & Østerhus, 2000; Orvik & Niiler, 2002). When reaching the Barents Sea, this current splits into two branches: one branching off into the southern Barents Sea, and the other continuing northwards along the SW Barents Sea slope (Hansen & Østerhus, 2000). The latter current continues into the Fram Strait as the West Spitsbergen Current west of the Svalbard archipelago (Figure 1) (Aagaard et al., 1973; Jónsson et al., 1992). A profound winnowing along the Norwegian–Barents Sea-Svalbard shelf and upper slope is documented due to this inflow of Atlantic water. The winnowed sediments are deposited as contourite drifts in lower slope embayments and in slide scars along the Norwegian margin (Laberg et al., 2005).

4. Seismic Stratigraphic Framework—The Nordland Group

The studied interval belongs to the Cenozoic Nordland Group (Dalland et al., 1988) (Figure 3). Most of the literature dealing with the Cenozoic stratigraphy of the SW Barents Sea follows the geological timescale of Berggren et al. (1995). These ages have been updated following Cohen et al. (2016).

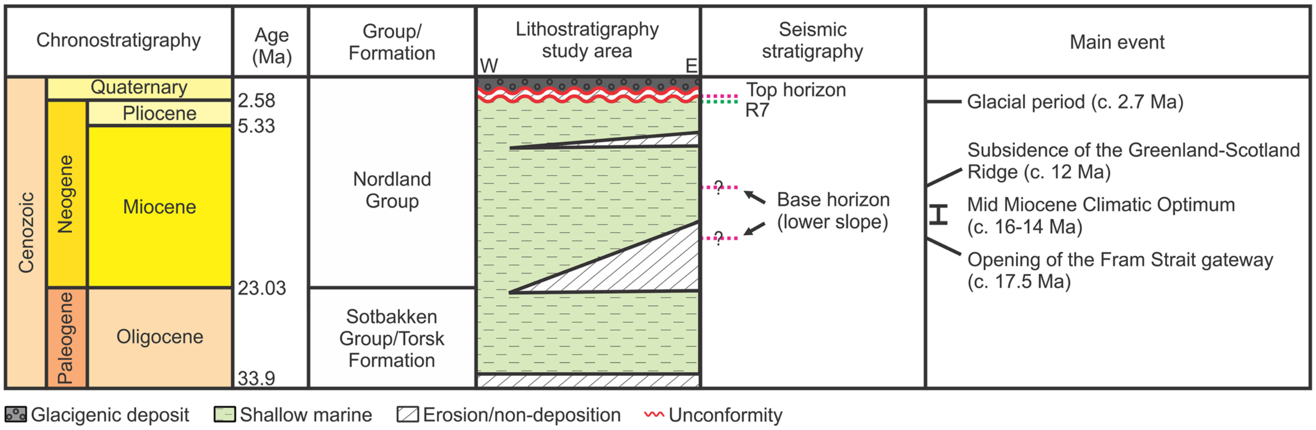

Figure 3. Chronostratigraphic and lithostratigraphic chart of the study area, with seismic horizons and main geological events. The generalized lithostratigraphy is modified from Lasabuda et al. (2018b), and the geologic timescale follows Cohen et al. (2016).

The Eocene to Pliocene interval consists of shallow to deep marine shale-dominated deposits in the major structural basins along the SW Barents Sea continental margin, while it is generally eroded or not deposited further east (Eidvin et al., 1998, 2014; Lasabuda et al., 2018b) (Figures 1c and 3). The Quaternary interval mainly consists of reworked glacigenic sediments deposited along the SW Barents Sea slope in trough-mouth fans (Figure 1c).

The regional Cenozoic stratigraphy of the area with age correlations based on well control is presented by Lasabuda et al. (2018b), and only key horizons are shown on the seismic profiles in this study (Figures 4–6). Furthermore, the glacigenic Quaternary interval is subdivided in three subunits, that is, TeC/GI, TeD/GII, and TeE/GIII following interpretations of Vorren et al. (1991) and Faleide et al. (1996). The regionally correlatable horizon R7 marks the base of the subunit TeC/GI and, therefore, the base of the Quaternary deposits (Figure 3) (Faleide et al., 1996; Laberg et al., 2012; Vorren et al., 1991).

5. Results

5.1. Description of Seismic Stratigraphy

An overall along-slope oriented sediment accumulation is mapped beneath the Bjørnøyrenna Trough-Mouth Fan on the SW Barents Sea continental margin (Figures 4–7). The top and base horizons delimiting the sediment accumulation are high amplitude, continuous to semi-continuous reflections. The base horizon truncates underlying strata, making it a basal unconformity. The top horizon marks a change in reflection configuration from overall divergent reflections (within the sediment accumulation) to prograding clinoforms in the overlying strata (Figures 4 and 5).

The base horizon dips southwestwards in the southern sector of the study area and toward the west in the northern sector (Figure 7a). The slope angles generally vary from less than 1°–3°, with local slope angles up to 6°. A distinct escarpment with a gently sloping area downslope is located in the southern sector (Figures 5a and 7a), and two subdued ridges extend down the paleo-slope in the northern sector (Figure 7a).

The mapped sediment accumulation is ~300 km long, between 30 and 90 km wide, and up to 1,380 m thick (Figure 7c), corresponding to an area of ~1.8×10^4 km^2 and a sediment volume of ~5,000 km^3. Data limitations make the westward extension of the sediment accumulation uncertain. The sediment accumulation is characterized by (i) two SSE-NNW-elongated mound-shaped forms filling both bathymetric lows and smooth and gently sloping areas of the base horizon and (ii) sheet drapes that follow the underlying morphology (Figures 7a and 7c).

The largest mound in the southern sector of the study area is up to ~20 km wide and extends for ~120 km on flat parts of the base horizon. Further downslope, the unit has an external sheet-drape form, with a

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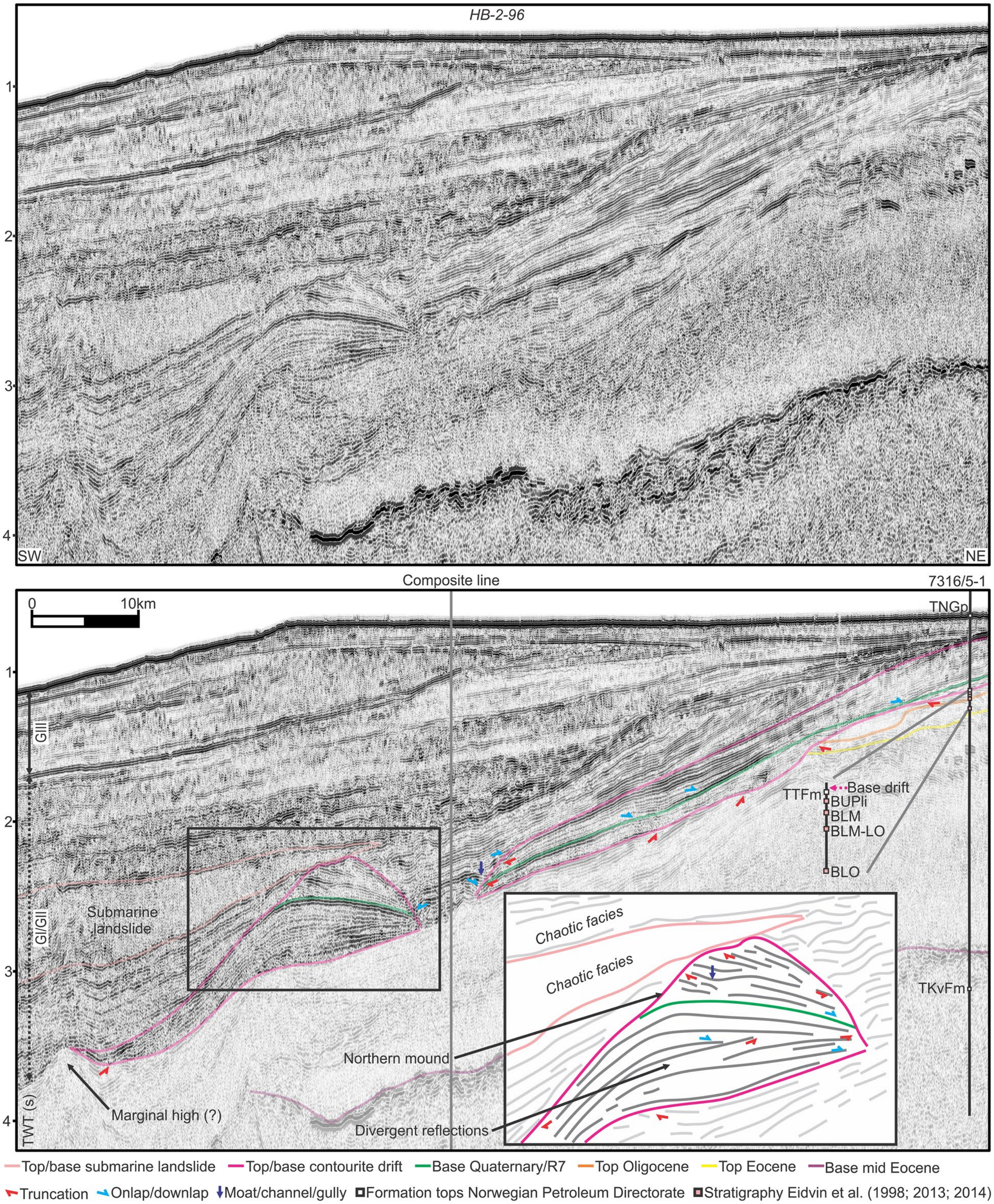

Figure 4. Seismic dip profile in the the northern sector of the Bjørnøyrenna Drift. The base horizon overlies upper Pliocene strata on the upper slope (in the area of well 7316/5-1). The northern mound is characterized by a divergent reflection configuration with progressive upslope onlapping reflections, and the top horizon truncates internal reflections. BLM, Base lower Miocene; BLM-LO, Base lower Miocene-lower Oligocene; BLO, Base lower Oligocene; BUPli, Base upper Pliocene; TKvFm, Top Kveite Formation; TNGp, Top Nordland Group; TTFm, Top Torsk Formation. See Figures 1b and 7 for location of seismic profile. Seismic data courtesy of NPD.

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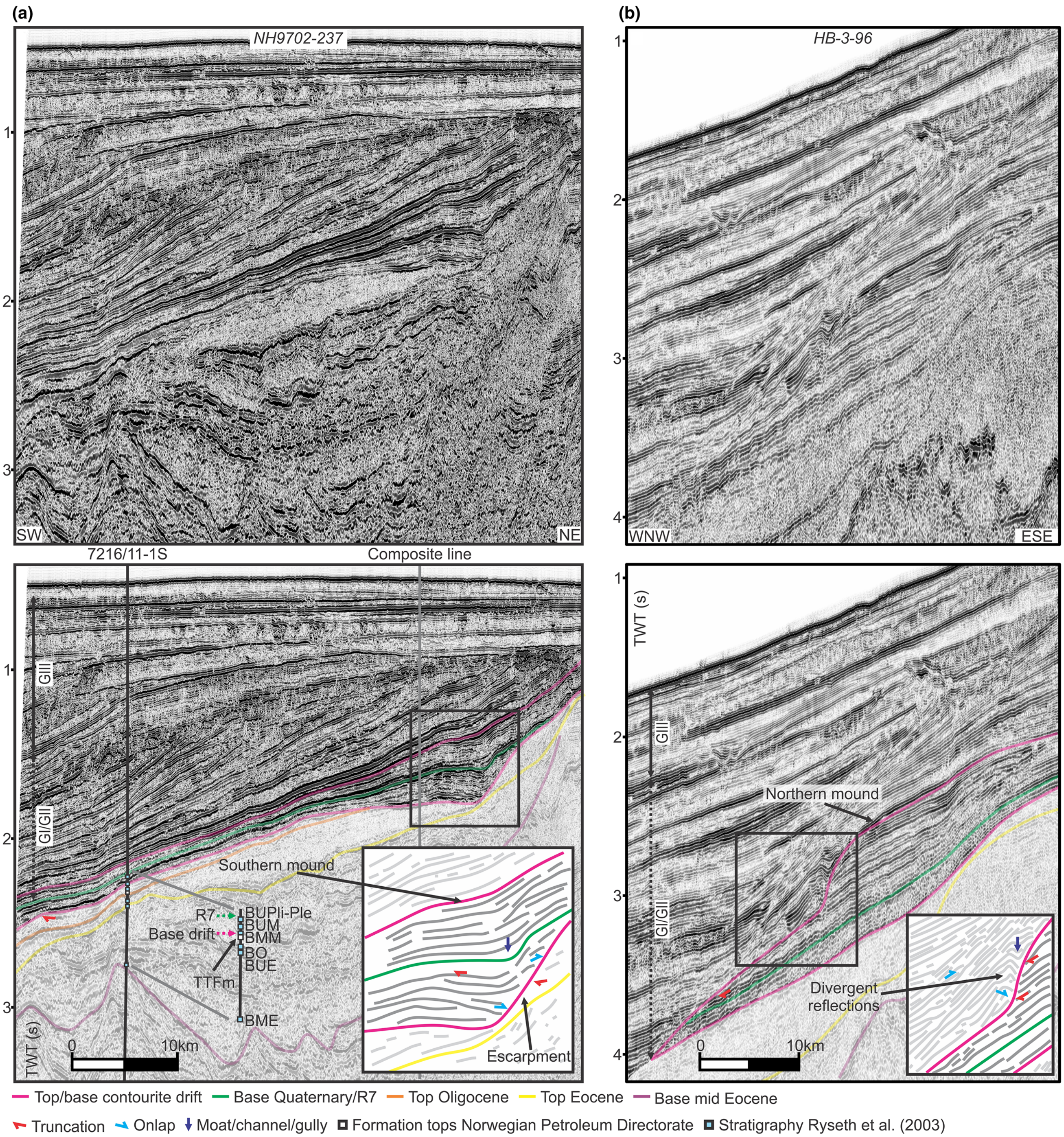

Figure 5. (a) Seismic dip profile in the southern sector of the Bjørnøyrenna Drift, crossing the southern mound. The base horizon overlies Miocene strata on the lower to middle part of the slope (in the area of well 7216/11-1S). Internal reflections within the drift onlap a distinct escarpment on the base horizon. (b) Seismic dip profile crossing the northern drift mound. Internal reflections within the drift are truncated by the top horizon. Divergent reflections with onlapping terminations are observed also in the overlying glacigenic strata (GI/GII). BME, Base middle Eocene; BMM, Base middle Miocene; BO, Base Oligocene; BUE, Base upper Eocene; BUM, Base upper Miocene; BUPli-Ple, Base upper Pliocene-Pleistocene; TTFm, Top Torsk Formation. See Figures 1b and 7 for location of seismic profiles. Seismic data courtesy of NPD.

shorter (~30 km) elongated mound at the lower and steeper part of the paleo-slope (Figure 7c). An up to 50 km wide elongated mound extends for more than 150 km in the northern sector. This has an irregular shape, where its southern part is generally characterized by an uniform thickness between 600 and 700 m,

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locally more than 1,100 m. An area of thinner sediments (down to less than 100 m) separates the southern and northern part of the mound. The mound is thickest in the confinement between the two ridges on the base horizon in the northern sector of the study area (Figure 7c).

The sediment accumulation is composed of medium-high amplitude reflections that are continuous to semi-continuous; the more continuous reflections are located where the drift thickness is larger, that is, within the elongated mounds (Figures 4 and 5). A divergent reflection configuration characterizes the sediment accumulation, and progressive upslope onlap characterizes the reflection terminations. The onlaps are more pronounced in the northern and southern elongated mounds, where upward-thickness increase is more rapid. Incisions are often observed in connection with the upslope onlap (Figures 4 and 5). Internal horizons truncate underlying seismic reflections within the sediment accumulation (Figure 4), including also the inferred base Quaternary horizon (from Laberg et al., 2012) (Figures 5a and 6). The eastern and western parts of the sediment accumulation are truncated by horizons within the overlying glacigenic deposits (Figures 4–6).

The internal reflections within the upper parts of the northern mound are truncated by the top horizon (Figure 4); this is particularly evident in the area between the northern and southern part of the mound, and where narrow incisions on the top horizons extend down into the upper part of the sediment accumulation (Figure 6). As such, the top horizon is an unconformity surface in the area of the northern mound.

The overlying strata is generally characterized by prograding clinoforms, as well as intervals with a chaotic seismic reflection configuration, particularly evident in the northern sector of the study area (Figure 4). The clinoforms downlap and onlap the northern sediment accumulation, thus filling in the accommodation space between the northern and southern part of this mound (Figures 4 and 7c). Furthermore, a divergent internal seismic configuration consisting of reflections with onlapping terminations, including also internal incisions, is observed stratigraphically above the northern part of the sediment accumulation (Figure 5b). Similar narrow incisions also occur elsewhere within the overlying glacigenic TeC-TeE/GI-GIII units (Figure 6).

The base horizon overlies various levels of the Nordland Group (Figures 4–6). On the lower to middle part of the slope, the base horizon overlies Miocene strata (well 7216/11-1S) (Ryseth et al., 2003) (Figure 5a), while it overlies upper Pliocene strata on the upper slope (wells 7117/9-2 and 7316/5-1) (Figures 4 and 6) (Eidvin et al., 1993, 1998, 2013, 2014). Furthermore, the base horizon is overlain by Quaternary strata on the upper part of the slope in the northern and southern sectors (Figures 4 and 6) and middle to upper Miocene strata on the lower part of the slope in the central part of the study area (Figure 5a) (Eidvin et al., 1993, 1998, 2013, 2014; Ryseth et al., 2003). It is difficult to determine the relative age of deposition between the north and south, given the southward thinning of the studied interval and the low continuity between internal reflections in strike direction (Figure 6). The top reflection of the studied interval is interpreted within the Pleistocene glacigenic unit TeC/GI (Faleide et al., 1996; Laberg et al., 2012; Vorren et al., 1991) (Figures 4–6).

5.2. Lithology from Exploration Wellbores

The lithology of the interval covering the sediment accumulation is described in the completion reports from wells 7316/5-1 and 7117/9-2. Ditch cuttings and sidewall cores in well 7316/5-1 show that the studied interval contains ~300 m of claystones interbedded with sands (Eidvin et al., 1994, 1998; NPD, 1993). Similarly, a ~200 m interval of claystone with stringers of sand, limestone and traces of dolomite is described for the interval in well 7117/9-2 in the southern sector of the study area (Eidvin & Riis, 1989; Eidvin et al., 1993; NPD, 1984). Furthermore, Ryseth et al. (2003) identified mudstones interbedded with sandstones and limestones in the middle-upper Miocene to lower Pliocene interval in well 7216/11-1S. East of the northern part of the sediment accumulation, a lower Miocene sandstone interval including minor glauconite was penetrated by shallow borehole 7316/06-U-01 (see Figure 1 for location of the borehole). Here, the age was tentatively suggested to be between 19 and 17 Ma (Sættem et al., 1994).

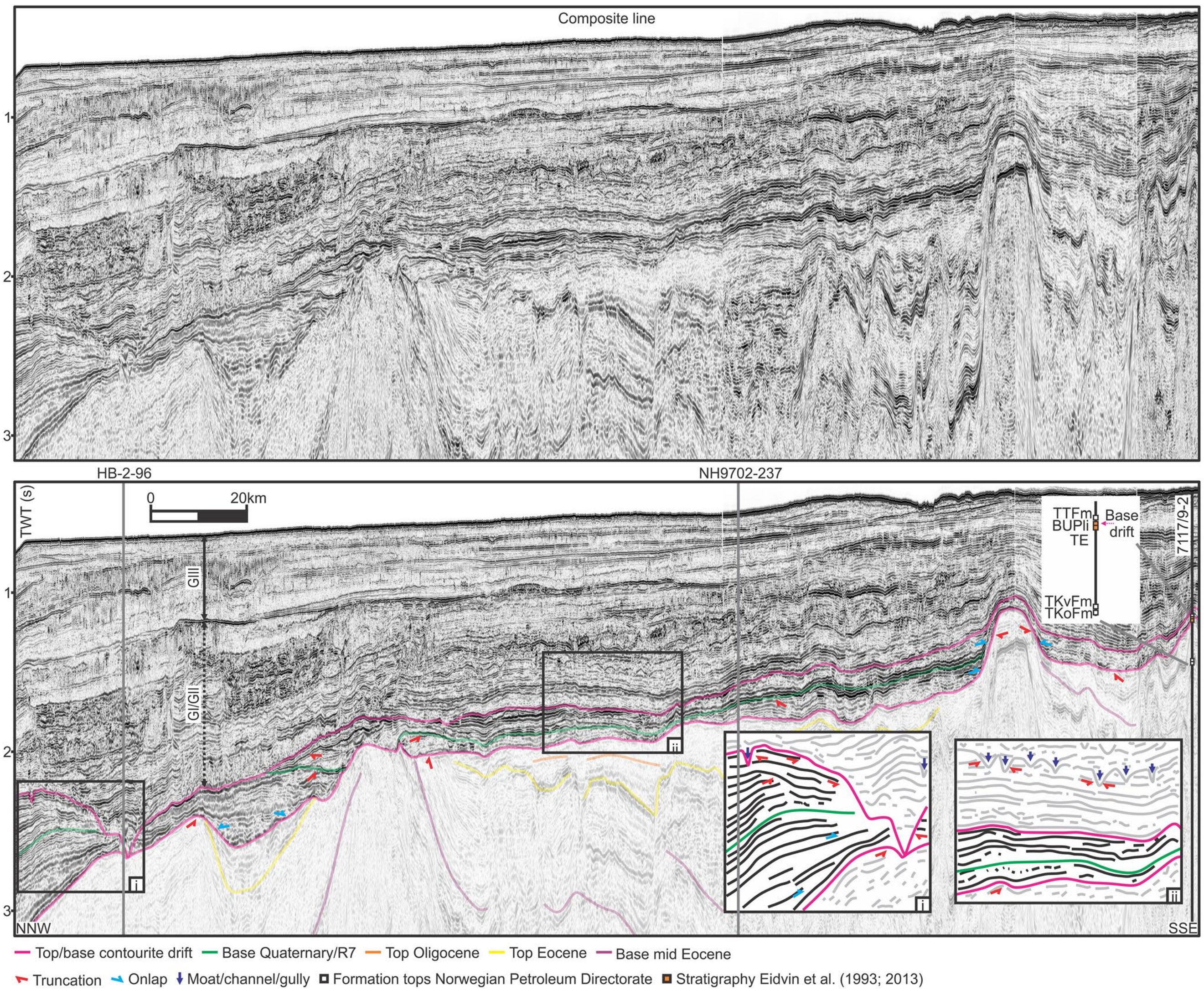

Figure 6. Seismic strike profile across the study area, showing that the lower horizon overlies upper Pliocene strata on the upper slope in the south (in the area of well 7117/9-2). Internal horizons within the Bjørnøyrenna Drift truncate underlying internal seismic reflections. Narrow incisions occur both on the top horizon and within the overlying glacigenic strata (GI/GII). BUPli, Base upper Pliocene; TE, Top Eocene; TKoFm, Top Kolmule Formation; TKvFm, Top Kveite Formation; TTFm, Top Torsk Formation. Seismic data courtesy of TGS. See Figures 1b and 7 for location of seismic profile.

6. Interpretation and Discussion

6.1. Origin of the Sediment Accumulation—The Bjørnøyrenna Drift

Based on the location and size of the mapped sediment accumulation, its thickness, and mounded, elongated character along the slope, we interpret it to be a contourite drift, and we name it the Bjørnøyrenna Drift. A slope-parallel orientation is common to contourite drifts as they are formed by alongslope flowing contour currents (Faugères & Stow, 2008; Faugères et al., 1999; Laberg et al., 1999, 2001; Rebesco et al., 2014). The Bjørnøyrenna Drift can be classified as a giant elongated drift, *sensu* Faugères and Stow (2008).

The main drift body has accumulated on smooth and gently sloping parts of the base horizon (Figures 7a and 7c), and a consistent upslope migration is observed, typical of separated drifts (Faugères & Stow, 2008; Faugères et al., 1999). The internal incisions truncating underlying seismic reflections are likely areas of higher flow velocities where the ocean currents eroded underlying strata, resulting in moats. Similar characteristics of modern drifts are documented on the Norwegian–Barents Sea-Svalbard margin, that is, the Nyk, Lofoten, and Vesterålen drifts to the south (Laberg et al., 1999, 2001, 2005) and the Isfjorden and

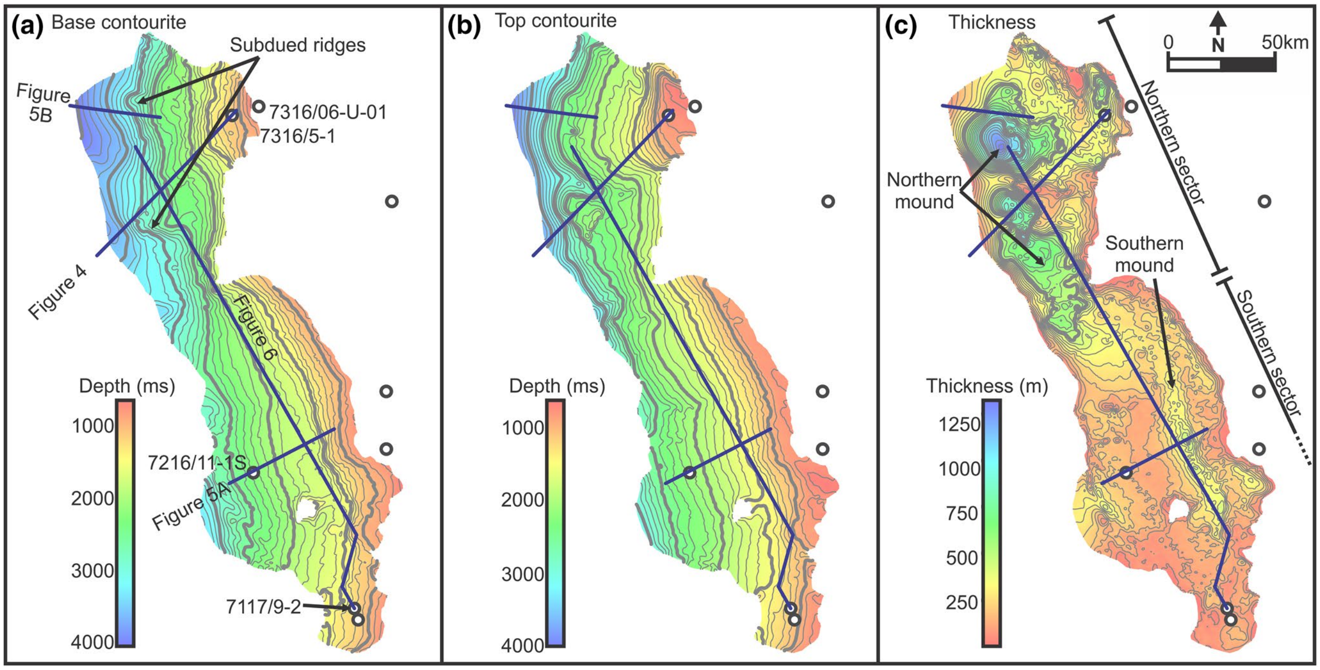

Figure 7. (a and b) Isochrone maps in two-way traveltime of the top (a) and base (b) of the Bjørnøyrenna Drift. Contour intervals are 100 ms (bold every 500 ms). (c) Isopach map of the drift. Contour intervals are 50 m (bold every 500 m). Seismic data courtesy of TGS and NPD.

Bellsund drifts to the north (Rebesco et al., 2013). A contourite drift origin is also interpreted for the divergent reflections with onlapping terminations observed stratigraphically above the Bjørnøyrenna Drift (Figure 5b).

The clay-dominated lithology within the Bjørnøyrenna Drift is also consistent with a contourite drift origin of the sediment accumulation. The sand-dominated intervals likely originate from turbidity flows, as ocean currents mainly transport grain sizes below the sand fraction (Faugères & Stow, 2008; Rebesco et al., 2014). Still, some of the sands may originate from ocean currents, as shown from studies of modern contour current driven sandwaves from the SW Barents Sea continental margin (King et al., 2014).

The contourite drift origin of the sediment accumulation suggested in this study differs from the shallow marine depositional environment interpreted by Ryseth et al. (2003) for the Oligocene–Miocene section in the area of the 7216/11-1S well. Nonetheless, the consistent upslope migration and alongslope orientation of the sediment accumulation observed in the seismic data in our view clearly points to a continental slope setting (e.g., Figures 4 and 7).

The area of thinner sediments in the northern mound, where internal reflections are truncated by the top horizon (Figures 4 and 7c), is interpreted to represent a failed part of the drift. The narrow incisions that truncate the top of the drift and internal reflections of the glacigenic sediments stratigraphically above (Figure 6), are interpreted to represent erosive channels. These likely formed by turbidity flows, thought to originate from the marine continuation of a glacifluvial system characterizing a subaerial SW Barents Sea at this time. These erosive channels, as described by Laberg et al. (2010), mark the onset of glacial intensification on the SW Barents Sea shelf. The chaotic seismic reflection configuration within the TeC-TeE/GI-GIII units above the drift is interpreted to be a mass-transport deposit.

6.2. Age Estimate of the Bjørnøyrenna Drift

6.2.1. Age Estimate from Available Wells

The unconformity defining the base of the drift is overlain by (i) Quaternary deposits on the upper part of the slope in the northern and southern sectors (Eidvin et al., 1993, 1998, 2013, 2014), and (ii) middle—upper

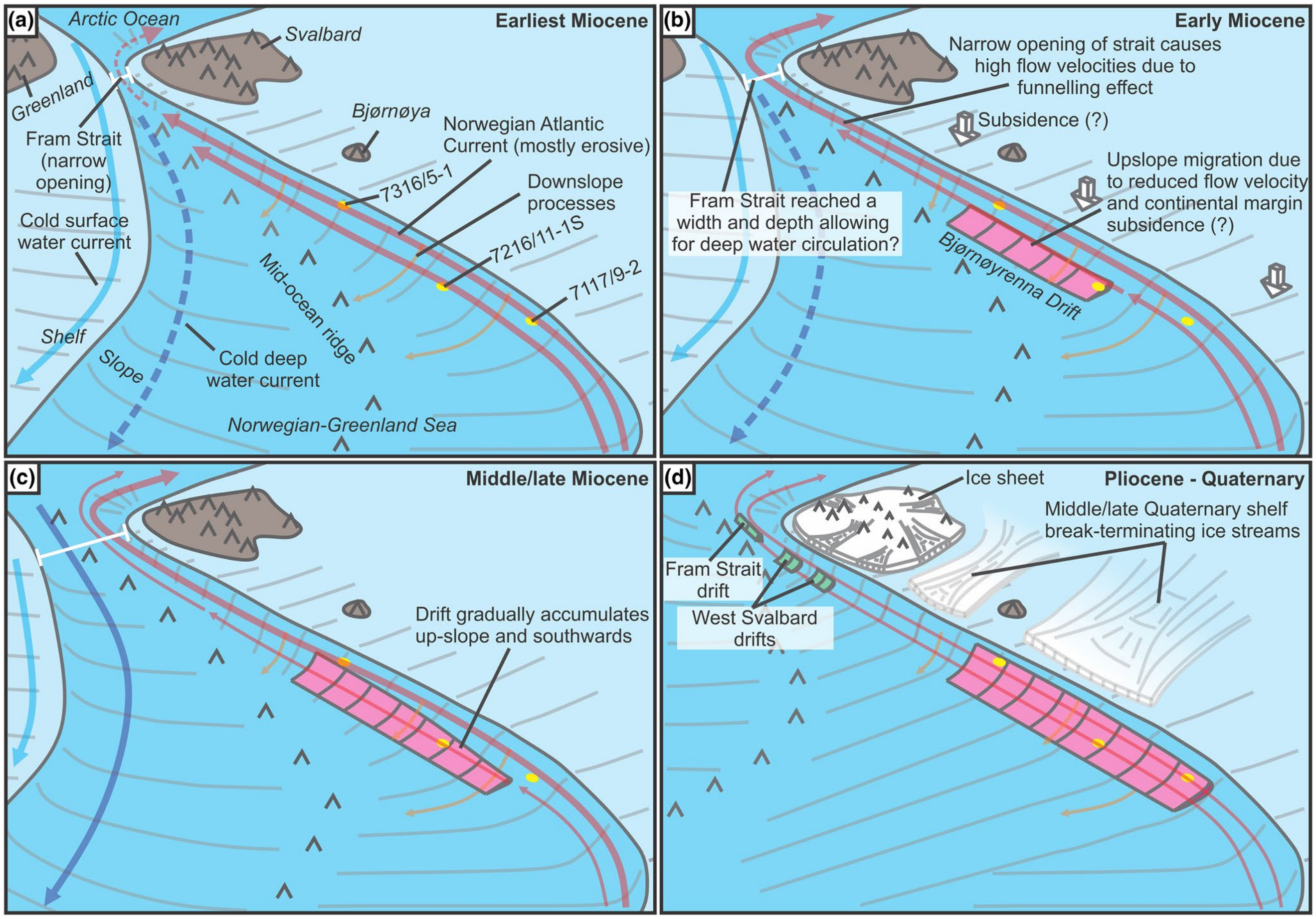

Figure 8. Neogene to Quaternary evolution of the Bjørnøyrenna Drift. (a) Ocean current erosion dominated in the early phase of alongslope influence, (b) before the drift started to build up on the lower slope in the northern sector of the study area. (c and d) The drift later progressively migrated upslope and southwards. See text for further details.

Miocene deposits on the lower slope in the central part of the study area (Ryseth et al., 2003). From this, and the consistent upslope migration of the drift, we infer that it started accumulating on the lower part of the slope in the Miocene, before it gradually progressed upslope until the early Quaternary (Figures 8a–8d).

6.2.2. Correlation to Regional Tectonic Events and Comparison to Other Drifts

The most pronounced oceanographic changes in the North Atlantic during the Neogene resulted from the establishment of deep-water circulation through the Fram Strait gateway at c. 17 Ma (Jakobsson et al., 2007), and the re-organization of the ocean-circulation pattern resulting from the subsidence of the Greenland–Scotland Ridge estimated to c. 12 Ma (Bohrmann et al., 1990; Wright et al., 1998). These ages correspond well with the ages from the available exploration wells, and we therefore infer a maximum age of early Miocene (17 Ma) and a minimum age of middle Miocene (12 Ma) for the onset of drift growth along the SW Barents Sea continental margin (Figures 2 and 8). A similar age estimate of drift onset is inferred for the Lofoten–Vesterålen margin (Laberg et al., 1999, 2001, 2005) and the Gardar and Bjørn drifts further south in the North Atlantic Ocean (Figure 1) (Wold, 1994). Moreover, the drift growth accelerated in the Faroe-Shetland Channel and on the Vøring margin from the early Neogene (Laberg et al., 2005). As such, these drifts demonstrate the initiation of a regional hydrological event in the North Atlantic during the Miocene.

To the north of the study area, the lower part of the contourite sequence in the Fram Strait is assumed to be deposited at a time when the gateway was well established, that is, between 10 and 3 Ma (Eiken & Hinz, 1993). However, as this age estimate was based on limited data, it remains an open question as to whether

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these contourites deposited from the same water mass as the Bjørnøyrenna Drift, but started accumulating later, or if they initiated at the same time as the Bjørnøyrenna Drift and thus are older than originally inferred by Eiken and Hinz (1993). The drifts on the West Svalbard margin are inferred to coincide with the early Quaternary glacial intensification and thereby following increased sediment supply to the shelf edge (Rebesco et al., 2013). Thus, the onset of the Bjørnøyrenna Drift growth may have preceded that of the drift systems to the north (Figure 8). This age discrepancy, if correct, could be related to the geometry of the initial, narrow Fram Strait gateway, causing a funneling effect for ocean currents flowing northwards along the slope. It is possible that this resulted in higher flow velocity west and north of Svalbard, and thus nondeposition of drift sediments until the gateway widened and deepened, and/or the sediment supply increased in the early stages of glacial intensification (Figure 8).

6.3. The Bjørnøyrenna Drift Evolution

The contourite drift stretches for several hundred kilometers along the paleo-slope, and it most likely continues both northwards and westwards of the area of data coverage. The margin-wide coverage of this contourite drift suggests an efficient ocean circulation system in the basin, where alongslope sedimentation prevailed over downslope processes. This interpretation is supported by the internal reflection configuration of the drift, showing upslope drift migration rather than margin progradation. The latter is a configuration that dominates the postdrift glacigenic TeC-TeE/GI-GIII units deposited during the Quaternary (Faleide et al., 1996; Laberg et al., 2012; Vorren et al., 1991). As such, the drift likely started to form as the northward-flowing North Atlantic Current commenced, which is a persistent alongslope flow of Atlantic water moving northwards along the SW Barents Sea continental margin at present (Figure 1) (Beszczynska-Möller et al., 2012; Hansen & Østerhus, 2000; Orvik & Niiler, 2002).

The base of the drift truncates underlying strata, which demonstrates widespread ocean current erosion in the early phase of alongslope influence (Figure 8a). The thickness of the accumulated sediments increases northwards, with the drift mainly consisting of a thin blanket (sheeted drift) in the southern sector (Figures 6 and 7c). This indicates a higher degree of sediment bypass and/or erosion in the south. In the nature of ocean currents, there is an interplay between erosion and deposition (e.g. Rebesco et al., 2014). Contourite drift build-ups during the Miocene on the Lofoten–Vesterålen margin to the south of the study area testify to a regional ocean circulation pattern with water masses moving from south to north along the continental margin, and these sediments originated from south of Lofoten (Laberg et al., 1999, 2001, 2005). Similarly, the source area for parts of the sediments of the Bjørnøyrenna Drift were south of the SW Barents Sea, likely between the Vesterålen Margin and the southern sector of the mapped area in this study. The change from a southwest to westward dipping slope in the northern part of the study area (Figure 7a) likely facilitated accumulation of sediments. The early drift build-up here possibly occurred as the current swerved past the change in slope direction on its way northwards. In addition, there was available accumulation space between the subdued ridges on the base of the contourite in the northern sector of the study area (Figure 7a).

There was also an upslope time-transgressive transition from erosion to deposition on the continental slope, caused by a reduction in ocean current velocity from the upper to the lower slope, possibly due to subsidence of the continental margin. This is inferred from the progressive build-up of the contourite, initiating on the lower slope at the same time as ocean current erosion prevailed on the upper slope (Figures 8b–8d). This internal configuration is particularly evident in the bathymetric low in the northern sector (Figures 4 and 7a), as well as where the base horizon is gently sloping in the southern sector (Figures 5a and 7a). Contourites are also observed to fill in bathymetric lows in other areas where ocean currents slow down, such as in slide scars and submarine canyons on the mid- and north-Norwegian margin (e.g. Bryn et al., 2005; Laberg et al., 1999; Rise et al., 2013; Rydningen et al., 2016) and on the NW Barents Sea margin (Safronova et al., 2017).

Overall, the Bjørnøyrenna Drift testifies to predominantly alongslope sedimentation, that is, there is little influence of downslope sediment transport from the Barents Sea shelf in the period of drift accumulation and prior to the Quaternary (see below). The reason for this remains unknown. However, we suggest that it may be related to a relative rise in sea level. A relative rise in sea-level could explain the transition on the upper slope from erosion and formation of the basal unconformity, to later deposition and drift growth (Figure 8). A relative sea-level rise was possibly a response to a higher rate of regional subsidence of this part of the

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margin compared to the global eustatic sea-level fall, controlled by ice growth in Antarctica and Greenland (Haq et al., 1988; Miller et al., 2020; Thiede et al., 2011; Zachos et al., 2001). This subsidence could have been enhanced by the increased load on the slope following the onset of the Bjørnøyrenna Drift growth. If correct, this differs from the interpretation of Ryseth et al. (2003) and Eidvin et al. (2014) who inferred a declining relative sea-level in the Oligocene through Miocene in this area.

6.4. Paleoclimatic Implications of the Onset of Ocean Circulation

Prior to the opening of the Fram Strait gateway, cold intermediate and deep-water masses were confined to the Arctic Ocean. It was first from the time of the opening of the gateway at c. 17 Ma that Arctic water could pass over this threshold and flow southwards along the western part of the Norwegian–Greenland Sea (Jakobsson et al., 2007). The Norwegian–Greenland Sea was probably at this time still isolated from the North Atlantic Ocean by the Greenland–Scotland Ridge, thus limiting the onset of transfer of cold water masses to lower latitudes to c. 12 Ma (Bohrmann et al., 1990; Wright, 1998).

The inferred onset of this North Atlantic-Arctic Ocean connection is concurrent in time with the Mid Miocene Climatic Optimum, where global temperatures peaked at c. 16–14 Ma. Following this, there was a climate deterioration where the temperatures dropped ~2°C during a few million years, and the global cooling trend continued through the remainder of the Neogene (Zachos et al., 2001). We suggest that this cooling trend may have been influenced by the reorganization of the large-scale circulation of water masses on the northern hemisphere. The low-and high-latitude sectors of the Atlantic Ocean became connected following the opening of the Fram Strait and the subsidence of the Greenland–Scotland Ridge, allowing for transfer of heat and moisture to high latitudes (Smith & Pickering, 2003) and transfer of cold North Atlantic Deep Water southwards, which likely played an important role in lowering the global temperature.

This event represented the beginning of a more dynamic northern hemisphere climate, where heat and moisture from lower latitudes were spread northwards, facilitating necessary preconditions for the establishment of larger ice caps of this area (Bohrmann et al., 1990), that formed on northern Svalbard at c. 15–14 Ma (Knies & Gaina, 2008). On the other side of the Norwegian–Greenland sea, ice caps reached the continental margin on SE Greenland from c. 11 Ma (Helland & Holmes, 1997) or c. 7 Ma (Larsen et al., 1994), although smaller inland ice caps were established here already in late Eocene-early Oligocene (Eldrett et al., 2007).

6.5. Average Sedimentation Rate for the Bjørnøyrenna Drift

As the volume, extent, and approximate age of the Bjørnøyrenna Drift are known, we can—for the first time—calculate average sedimentation rates for a Neogene drift in the Norwegian–Greenland Sea. However, some precautions need to be considered. First, the full extent of the contourite drift remains unknown due to a limited coverage of the available data set. Second, the sedimentation rate has varied across the depositional area, as evidenced by the varying thickness of the drift with more accumulated sediments in the northern sector compared to the south (Figure 7c). In addition, parts of the drift have failed in the northern sector, that is, an unknown volume of the drift has been transferred downslope; our numbers are, therefore, minimum average estimates across the mapped area. Third, we assume that the calculated average sedimentation rates are exclusively from ocean currents, that is, excluding the influence of downslope processes. Some downslope influence is indicated by the sand-dominated parts identified in the wells. However, this is considered to be of minor relevance. Finally, the exact age of the contourite drift onset remains to be defined. We assume that an early to middle Miocene age between 17 and 12 Ma is likely. The upper boundary of the drift with the transition from alongslope- to downslope-dominated deposition is better constrained, with a proposed date close to the onset of Quaternary glaciations, that is, slightly after 2.7 Ma (Knies et al., 2009; Laberg et al., 2012).

A minimum and a maximum sedimentation rate is calculated to compensate for the uncertainty of the onset of the contourite-drift deposition (Figure 9), coinciding with the inferred opening of the Fram Strait gateway and the subsidence of the Greenland–Scotland Ridge, respectively. The total volume of the drift (5,000 km^3) is divided by the area of deposition (1.8×10^4 km^2), giving a minimum average sediment thickness

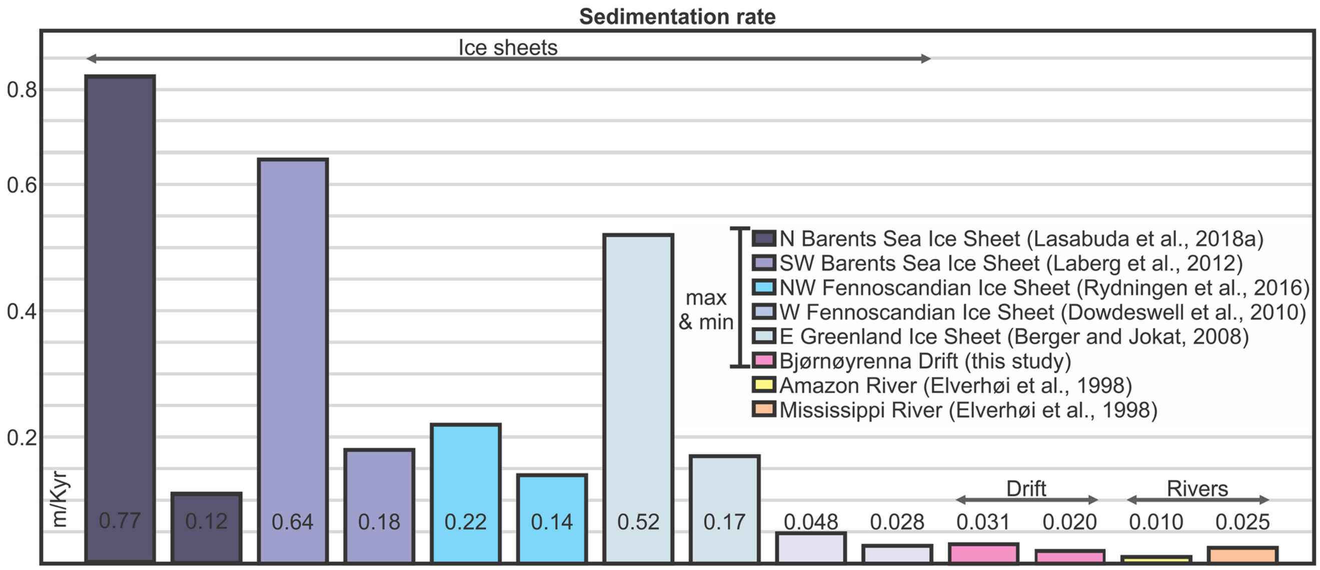

Figure 9. Estimates of average sedimentation rate in m/Kyr for the Bjørnøyrenna Drift compared to ice sheets and low-latitude rivers.

across the study area of 280 m. Divided by the age estimates, this gives sedimentation rates of 0.020 and 0.031 m/Kyr for the time spans of c. 14 and c. 9 Ma, respectively (Figure 9).

These first-order estimates allow us to compare different sediment sources and their relative influences on ocean basin sedimentation. The calculated sedimentation rates for this ocean current system are one order of magnitude lower than the average rates calculated for the subsequent deposits from the Quaternary Barents Sea Ice Sheet (Laberg et al., 2012) in the same area and on the Northern Barents Sea margin (Figure 9) (Lasabuda et al., 2018a). These numbers therefore support the finding of Lasabuda et al. (2018b), that is, that there was a pronounced increase in sedimentation rate on the SW Barents Sea continental margin following the establishment of Northern Hemisphere Glaciations in the Quaternary. The sedimentation rate for the Quaternary glaciations to the south are also one order of magnitude higher than for the Bjørnøyrenna Drift (Dowdeswell et al., 2010; Rydningen et al., 2016). Estimates of sediment input to deep-sea fans from ice sheets elsewhere are sparse, and the only well-documented sedimentation rates are late Quaternary input from the East Greenland Ice Sheet (Figure 9; 0.028–0.048 m/Kyr) (Berger & Jokat, 2008). These numbers are comparable to the sedimentation rates presented in this study, showing that the sediment distribution capability of ocean currents in ocean basins can be of the same magnitude as continental ice sheets elsewhere in the Arctic. Still, the calculated rates for the Bjørnøyrenna Drift are lower than the younger glacial systems on the NW part of the Norwegian–Greenland Sea (Figure 9).

Estimates of modern sedimentation rates in deep-sea fans from major river systems such as Amazon and Mississippi (Elverhøi et al., 1998) are also comparable to our results for the Bjørnøyrenna Drift (Figure 9). This further emphasizes that ocean currents are important agents in ocean basins, where they both can erode underlying strata over large areas creating regional unconformities and add sediments to the continental margin at rates comparable to large river system input to the ocean basin.

6.6. Failure of the Bjørnøyrenna Drift

The Bjørnøyrenna Drift influenced the continental slope morphology, especially in the northern part, giving it an alongslope oriented and positive relief in its middle to upper reaches prior to the onset of glacial sedimentation and trough-mouth fan growth (Figure 10a). During the early Quaternary glacial cycles, glacimarine (hemipelagic) and glacifluvial sedimentation, as well as reworked material from the shelf and upper slope, increased the downslope component of sediment input, while alongslope sedimentation and contourite drift growth continued (Figure 10b). Subsequently, grounded glaciers extended to the shelf break in the middle-late Quaternary, depositing subglacial till at high sedimentation rates at the ice sheet

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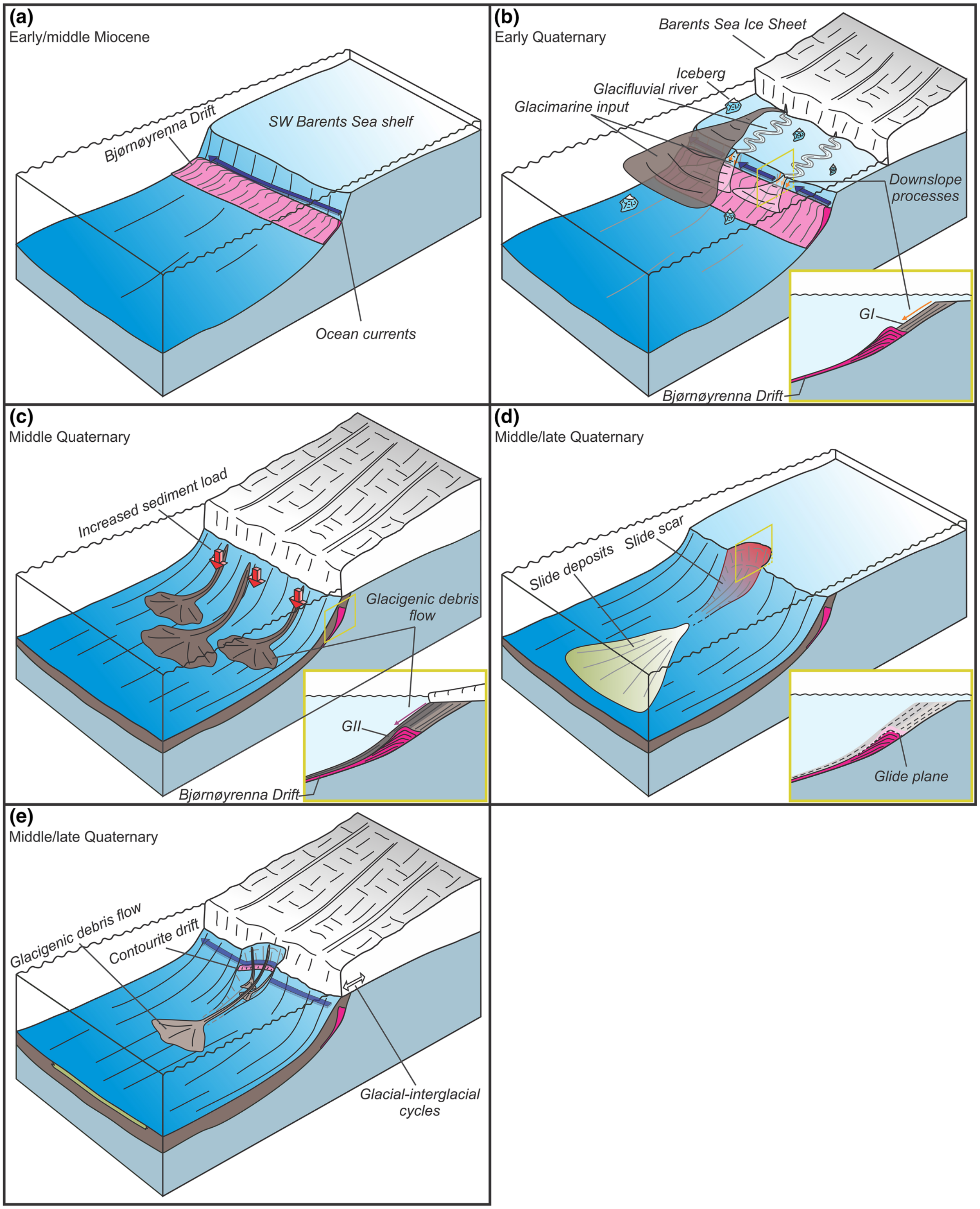

Figure 10. Conceptual model illustrating the Neogene to Quaternary evolution of the SW Barents Sea continental margin. (a) Alongslope flowing ocean currents dominate on the SW Barents Sea continental slope from early/middle Miocene. (b) The build-up of glaciers in the early Quaternary increases the sediment supply to the slope. (c) During glacial maxima in the middle to late Quaternary, glacigenic debris flows dominate on the slope. The debris flows are initially blocked by the relief of the Bjørnøyrenna Drift, before they overtop it, increasing the stress on the drift. (d) Parts of the drift fail, resulting in a submarine slide. (e) The slide scar is later filled in by sediments deposited from alongslope and downslope processes.

termini (Figure 10c). These sediments were later remobilized downslope as debris flows (Laberg & Vorren, 1995; Vorren et al., 1998). Some of these debris flows were probably blocked by the positive relief of the Bjørnøyrenna Drift and, thus, prevented from moving further downslope (Figure 10c).

Repeated episodes of downslope flow of glacigenic debris flows likely led to overtopping of the drift mound, allowing for transport of sediments further into the deep-ocean basin. The stress exerted by the upflank accumulation of glacigenic sediments is interpreted to have caused part of the drift sediments in the northern mound and overlying debris flow deposits to become unstable and fail (Figure 10d), resulting in downslope transport of the drift masses. Large parts of the drift were evacuated close to the thickest accumulation in the northern mound (Figures 4 and 5b).

Contourite drift sediments—together with debris flows—filled the slide scar (Figure 10e), as shown by the onlapping and downlapping reflections within the evacuated area (Figure 4). Moreover, observations further up in the stratigraphy show that alongslope processes deposited contourites postdating the main sediment drift body (Figure 5b). Such drifts therefore likely preconditioned repeated slope failures on the trough-mouth fan, and it is likely that also other later mega-slides along the western Barents Sea margin occurred along contouritic layers, as described by Hjelstuen et al. (2007) for the Bjørnøyrenna Trough-Mouth Fan, and by Safronova et al. (2017) for the Storfjorden Trough-Mouth Fan, north of the study area. Failures along contouritic "weak zones" are also well known from the mid-Norwegian margin, resulting in big submarine landslides such as the Storegga and Trænadjupet slides (Bryn et al., 2005; Haflidason et al., 2005). This demonstrates the influence of contouritic sediments on the stability of continental margins at high latitudes, and thereby also their impact on margin morphology and sediment distribution (Laberg & Camerlenghi, 2008).

7. Conclusions

1. A contourite drift deposit, here named the Bjørnøyrenna Drift, is identified on the SW Barents Sea continental margin. Based on mapping from available multichannel 2-D seismic data, the drift covers a minimum of $\sim 1.8 \times 10^4$ km^2 of the upper, middle and lower paleo-slope, and it has a minimum total volume of $\sim 5{,}000$ km^3. The maximum thickness of the deposit is ∼1,380 m. Exploration wellbores show that the drift mainly consists of claystones, likely deposited from ocean currents. Interbedded sandstone stringers within the drift likely originate mainly from turbidity flows.
2. The Bjørnøyrenna Drift started to form in the early to middle Miocene, similar to other drift systems along the British-Norwegian margin and in the southern part of the Norwegian–Greenland Sea, and prior to drifts on the Svalbard margin and in the Fram Strait gateway. The erosive character of the base of the Bjørnøyrenna Drift, as well as the later build-up of contourites to the north is possibly related to strong ocean currents during the initial narrow opening of the Fram Strait gateway. This possibly caused a funneling effect for the ocean currents, and thereby higher flow velocities and nondeposition of drift sediments until the gateway deepened and widened. The margin-wide occurrence of drifts in the North Atlantic testifies to the later establishment of an efficient deep-water circulation following the opening of the Fram Strait gateway between Svalbard and Greenland at c. 17 Ma and the subsidence of the Greenland–Scotland Ridge at c. 12 Ma.
3. The onset of the large-scale circulation system identified through the Bjørnøyrenna Drift, and the general regional distribution of contourite drifts in the Norwegian–Greenland Sea is suggested to be concurrent in time with the climate deterioration following the Mid Miocene Climatic Optimum at c. 16–14 Ma where global temperatures dropped ∼2°C. Thus, this global cooling trend was possibly influenced by the coupling of the circulation systems in the North Atlantic and the Norwegian–Greenland Sea, allowing for cold North Atlantic deep water to be transported southwards and warm North Atlantic water northwards across the Greenland–Scotland Ridge. This marks the beginning of a more dynamic northern hemisphere climate, where the overall global temperature decreased.
4. For the first time, sedimentation rates for an early Neogene drift in the North Atlantic have been calculated, showing that minimum rates are between 0.020 and 0.031 m/Kyr. This is one order of magnitude lower than the subsequent glacial sedimentation rates related to the action of the Barents Sea and Fennoscandian ice sheets. However, they are within the same range as sedimentation rates offshore the NE

sector of the Greenland Ice Sheet. The rates are also comparable to the rates of sediment transport to deep-sea fans for major river systems such as the Mississippi and Amazon. The results from this study underline that ocean currents are important agents in the evolution of ocean basins, where they both can erode underlying strata over large areas and distribute sediments at rates comparable to large river systems.

5. The mounded and elongated drift started to accumulate on the SW Barents Sea continental slope prior to increased sedimentation during the Quaternary glaciations. Continued drift growth, combined with glacimarine to glacifluvial sedimentation on the slope, was followed by downslope-influenced sedimentation from glacigenic debris flows. Middle to late Quaternary overtopping of the drift by glacigenic debris flows likely increased the stress on the contouritic deposits, making them unstable and resulting in a submarine landslide.

Data Availability Statement

We are grateful to TGS for providing the NBR seismic data and the Norwegian Petroleum Directorate for the public seismic data from the Diskos data base. The readers will have to contact these institutions for a permission to access the seismic data (contact info can be found at www.tgs.com and www.npd.no/en/diskos/).

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