Norwegian Sea Oceanic Basin and Prograded Margins Composite Tectono-Sedimentary Element

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Abstract

The Norwegian Sea oceanic basins and prograded margins developed since NE Atlantic breakup in the earliest Eocene. Significant amounts of sediments were fed to the regionally subsiding and widening Norwegian Sea during the Cenozoic as a result of several phases of uplift and erosion of the bounding shelves and their hinterland. Despite an overall passive margin evolution, the area experienced tectonic events and associated processes that interrupted the regional subsidence causing contraction/inversion and tilting. The post-breakup depositional history of the mid-Norwegian margin comprises two main stages: (1) middle Eocene-Pliocene margin subsidence and relatively modest sedimentation during a period of climatic decline; and (2) latest Pliocene-Pleistocene full-scale Northern Hemisphere glaciations resulting in deep erosion of shelves and hinterlands, and very high sedimentation rates and large-scale continental margin progradation. Slope failures within rapidly deposited glacial sediments affected both prograded margins releasing large slides travelling down-slope into the oceanic Norway and Lofoten basins. Despite a long exploration history for prospects in deeper waters and large amounts of data acquisition, no significant discovery has been made.

Introduction (no heading)

The present paper reviews the geology of the Norwegian Sea Oceanic Basin and Prograded Margins Composite Tectono-Sedimentary Element (NSOBPM CTSE; Fig. 1), which has developed since NE Atlantic breakup in the earliest Eocene (e.g. Brekke 2000; Eldholm *et al.* 2002; Faleide *et al.* 2008). The mid-Norwegian (62-69°N) and western Barents Sea-Svalbard (69-78°N) continental margins (Fig. 1) experienced regional subsidence in response to thermal cooling and sediment loading during the Cenozoic widening and deepening of the Norwegian-Greenland Sea. Significant amounts of sediments were fed to the Norwegian Sea during the Cenozoic post-breakup stage as a result of several phases of uplift and erosion of the bounding shelves and their hinterland. The sedimentary record of the prograded margin provides the best age constraints on the Cenozoic exhumation of the adjacent areas (e.g. Vorren *et al.* 1991; Richardsen *et al.* 1991; Faleide *et al.* 1996; Hjelstuen *et al.* 1996, 1999; Stuevold and Eldholm 1996; Laberg *et al.* 2005a; Henriksen *et al.* 2011; Baig *et al.* 2016; Ktenas *et al.* 2017, 2019, 2023; Lasabuda *et al.* 2021; Eidvin *et al.* 2022). In addition, sediment input by ocean currents contributed (Rebesco *et al.* 2014; Rydningen *et al.* 2020; Bjordal-Olsen *et al.* 2023). Despite an overall passive margin evolution, the area experienced tectonic events and associated processes that interrupted the regional subsidence causing contraction/inversion and tilting (e.g. Doré and Lundin 1996; Lundin and Doré 2002; Mosar *et al.* 2002; Praeg *et al.* 2005; Stoker *et al.* 2005a).

The post-breakup depositional history of the mid-Norwegian margin (Møre-Vøring margins; Fig. 1B) comprises two main stages (e.g. Vorren *et al.* 1998; Hjelstuen *et al.* 1999; Laberg *et al.* 2005a; Stoker *et al.* 2005b,c): (1) middle Eocene-Pliocene margin subsidence and variable sedimentation rates during a period of climatic decline from greenhouse towards icehouse conditions; and (2) latest Pliocene-Pleistocene Northern Hemisphere glaciations resulting in deep continental erosion, very high sedimentation rates and large-scale glacial sedimentary fan construction, and continued margin subsidence and progradation (Dahlgren *et al.* 2005). In Eocene to early Pliocene times, the Møre and Vøring margins (Fig. 1B) were located in a distal position relative to sediment supply from Scandinavia, and biogenic ooze makes up a significant part of the succession. Clay-rich sediments were deposited on more proximal parts of the mid-Norwegian margin in this period (Laberg *et al.* 2005b; Eidvin *et al.* 2022). The margin setting was changed at the Pliocene-Pleistocene transition (~2.7 Ma) when the Northern Hemisphere glaciations led to rapid progradation gradually forming a huge, regional depocentre near the shelf edge along the entire Vøring margin (Rise *et al*. 2005; Ottesen *et al*. 2009, 2012; Bjordal-Olsen *et al.* 2023) and the North Sea Trough Mouth Fan (TMF) at the northern North Sea-Møre margin (King *et al*. 1996; Nygård *et al*. 2005; Batchelor *et al*. 2017).

Along the western Barents Sea-Svalbard margin (Fig. 1B) the passive margin evolution started later due to ongoing basin formation/development on the shear margin during Eocene-?Oligocene time (Faleide *et al*. 2024b). Major margin progradation occurred in response to regional uplift and glacial erosion of the Barents Sea shelf during latest Pliocene-Pleistocene time (Faleide *et al*. 1996; Hjelstuen *et al*. 1996; Solheim *et al*. 1998; Vorren *et al*. 1998; Henriksen *et al.* 2011). The links between uplift/erosion of the shelf and deposition in the prograded margin offer a unique source-to-sink system where mass balance can be carried out (e.g. Dimakis *et al*. 1998; Lasabuda *et al*. 2021; Medvedev *et al.* 2022). Glacial erosion by ice streams shaped the Barents Sea shelf and large sediment volumes were transported to the margin and deposited as km-thick trough mouth fans (Faleide *et al*. 1996; Hjelstuen *et al*. 1996; Solheim *et al*. 1998; Vorren *et al*. 1998; Andreassen *et al*. 2004; Andreassen and Winsborrow 2009; Laberg *et al*. 2010).

Slope failure within rapidly deposited glacial sediments affected both prograded margins releasing large slides travelling down-slope into the oceanic Norway and Lofoten basins (Laberg and Vorren 1993, 2000; Laberg et al. 2002; Haflidason *et al*. 2004; Bryn *et al*. 2005; Evans *et al*. 2005; Hjelstuen *et al*. 2005, 2007; Kvalstad *et al*. 2005a,b; Riis *et al*. 2005; Solheim *et al*. 2005; Rise *et al*. 2006).

Age

The Norwegian Sea Oceanic Basin and Prograded Margins CTSE (NSOBPM CTSE) comprises strata of Eocene to recent age deposited since continental breakup and onset of seafloor spreading in the earliest Eocene.

Geographic location and dimensions

The NSOBPM CTSE comprises most of the continental margin between 62° and 80°N (Fig. 1) covering an area of approximately 745 000 km^2. On the mid-Norwegian margin (62-69°N), it covers the underlying pre-breakup CTSE's (Bunkholt *et al*. 2021; Tsikalas *et al.* 2022; Faleide *et al*. 2024a) and extends further into the oceanic domain (Figs. 1 and 2). Along the western Barents Sea-Svalbard margin (69-78°N), it covers the marginal basins of the West Barents Shear Margin CTSE (Faleide *et al*. 2024b).

Principal data sets

The principal data sets comprise exploration wells and scientific boreholes tied to 2D/3D seismic reflection data (Fig. 3).

Wells

More than 400 exploration wells have been completed within the NSOBPM CTSE area (Norwegian Offshore Directorate FactPages; https://factpages.sodir.no/en), most of them in proximal parts of the Vøring margin (Fig. 3A) where they also reach the underlying CTSE (Bunkholt *et al*. 2021). In the SW Barents Sea, only 11 wells cover the prograded margin. In the exploration wells the shallowest stratigraphy is seldom sampled since most of them are drilled with a return to seabed for the upper part. Key wells used for definition of the main Cenozoic lithostratigraphic units are highlighted and labelled in Figure 3 (see description of these units below). Scientific (DSDP, ODP, IODP; Talwani *et al.* 1976; Eldholm *et al.* 1989; Planke *et al.* 2023) and shallow stratigraphic boreholes (e.g. Rise and Sættem 1994; Sættem *et al.* 1994; Grogan *et al.* 1998) provide continuous cores of the shallow stratigraphy, in particular at the outer margin (Fig. 3A).

Seismic data

The mid-Norwegian margin is extensively covered by a dense grid of 2D seismic lines complemented by 3D seismic in large parts (Fig. 3B). For regional mapping the main 2D data set is the reprocessed CFI_MNR (Mid Norway Renaissance) survey by TGS. The outer margin is covered by several extensive 3D cubes (Atlantic Margin North/South) and these were used to identify drilling targets for the recent IODP Expedition 396 (Planke *et al.* 2023). In the SW Barents Sea, proximal parts of the prograded margin is also covered by a dense grid of 2D seismic lines and a few 3D seismic cubes. Here, the CFI-NBR (Norwegian Barents Sea Renaissance) of TGS is the most important 2D set, while SWB17 and Carlsen represent extensive 3D cubes. The 2D and 3D seismic datasets mentioned above are all of very good quality contributing to consistent and well-constrained regional mapping results. However, in the oceanic parts, the seismic data coverage is generally poor (Fig. 3B). Important 2D data sets covering the outer margin and the oceanic Norway and Lofoten basins (NPD-HB-96, NPD-HV-96, NPD-LOS-99) were acquired by Norwegian authorities in relation to the United Nations Convention on the Law of the Sea (UNCLOS) to support Norway's claims with respect to an extended continental shelf into the Norwegian Sea.

Other data

Complementary data include bathymetry (IBCAO 4.0; Jakobsson *et al.* 2020), gravity (Skilbrei *et al.* 2000; Olesen *et al.* 2010) and magnetic (Verhoef *et al.* 1996; Maus *et al.* 2009; Olesen *et al.* 2010; Nasuti and Olesen 2014) data. Heat flow data are generally sparse (Fig. 3A) but some exist that will be discussed in a later section.

Tectonic setting, TSE boundaries, and main tectonic /erosional/ depositional phases

Tectonic setting and boundaries

The NSOBPM CTSE developed in response to the final breakup and subsequent sea floor spreading in the Norwegian-Greenland Sea since the earliest Eocene (Fig. 4; e.g. Eldholm *et al.* 2002; Faleide *et al.* 2008; Gaina *et al.* 2009). The mid-Norwegian rifted margin can be subdivided into three segments (Møre, Vøring and Lofoten-Vesterålen; Fig. 1) having different margin architectures that reflect different styles of margin progradation. The western Barents Sea-Svalbard shear margin bounds a broad shelf area in the Barents Sea that sourced widespread margin progradation.

The outline of the CTSE is shown in Figure 1B. The eastern (landward) extent is defined by the subcrop of the near base Eocene at the seabed close to the coast. Towards west, the

Eocene and younger sedimentary succession belonging to the NSOBPM CTSE extends into and cover oceanic crust in the Norwegian-Greenland Sea. The Norway Basin opened during Eocene before the Ægir Ridge became extinct (Breivik *et al*. 2006, 2012) and spreading moved to the Kolbeinsey Ridge (west of the Jan Mayen Microcontinent; Fig. 1A). The prograded margin associated with the North Sea TMF (King *et al*. 1996; Nygård *et al*. 2005; Batchelor *et al*. 2017) reached parts of the Norway Basin east of the Ægir Ridge (Hjelstuen and Andreassen 2015; Hjelstuen and Sejrup 2021). The CTSE boundary is drawn at the mouth of the Norwegian Channel that sourced this fan (Fig. 1B).

In the Lofoten Basin, formed by seafloor spreading along the Mohns Ridge (Fig. 1B), most of the CTSE belong to the Bjørnøya TMF that was sourced from the Barents Sea shelf (Fiedler and Faleide 1996; Faleide *et al*. 1996; Hjelstuen and Sejrup 2021). To the north, the Storfjorden TMF occupies the area between the Barents Sea shelf and the Knipovich Ridge (Faleide *et al*. 1996; Hjelstuen *et al*. 1996; Lasabuda *et al*. 2018a). The CTSE narrows further northwards (Fig. 1B) and is filled with minor fans outside fjords in western Svalbard (Spitsbergen) (Solheim *et al*. 1998; Forsberg *et al*. 1999; Butt *et al*. 2000a,b).

The boundary between the Prograded Margin and Oceanic Basin TSE's reflects a facies transition zone separating dominantly prograding sediments (delivered from the continents) and dominantly aggrading sediments in the deep oceanic basin. However, it is difficult to delineate this as a distinct boundary since the two facies interfinger in distal parts of the prograded margin. Furthermore, the data coverage is generally poor in deeper parts of the oceanic basin. The distal boundary of the Prograded Margin TSE (Fig. 1B) is guided by the thickness distribution within the huge sedimentary fans reflecting major outbuilding of sediments into the oceanic basins.

Main tectonic, erosional and depositional phases

Breakup occurred in the earliest Eocene (Fig. 4) and was associated with massive magmatism within the North Atlantic Igneous Province (Skogseid *et al*. 2000; Eldholm *et al*. 2002; Faleide *et al*. 2008; Planke *et al*. 2023). Initial spreading occurred subaerially forming the Møre and Vøring marginal highs covered by thick piles of lava flows (Fig. 2; Planke *et al*. 2000, 2017; Berndt *et al*. 2001; Abdelmalak *et al*. 2016). Regional Eocene-Oligocene subsidence by cooling and sediment loading caused burial of the marginal highs so that the margin could prograde further into the Norwegian Sea oceanic basins.

The passive margin development started later along the western Barents Sea margin (Faleide *et al.* 2024b). Here, Eocene-Oligocene basins formed in a shear-dominated setting before passive margin development was established in Oligocene-Miocene time when the Barents Sea shelf was source area for sediments building out westwards.

Mid-Cenozoic compressional deformation including domes/anticlines, reverse faults, and broad-scale inversion is well documented on the Vøring margin (Fig. 2), but its timing and significance are debated (Doré and Lundin 1996; Vågnes *et al.* 1998; Lundin and Doré, 2002; Løseth and Henriksen, 2005; Stoker *et al.* 2005a; Doré *et al.* 2008; Lundin *et al.* 2013). The main phase of deformation is likely Miocene in age but some of the structures were apparently initiated earlier in late Eocene–Oligocene times. A multi-phase growth history is suggested for the domes based on seismic onlap patterns (Fig. 2): late Eocene-early Oligocene for the Ormen Lange Dome, late Eocene-early Miocene for the Helland Hansen Arch, and Early-Middle Miocene for the Naglfar Dome by Doré *et al.* (1999), whereas Hjelstuen *et al.* (1997) suggested a Late Oligocene-Miocene age for both Vema and Naglfar domes. On the other hand, Vågnes *et al.* (1998) reported a surprisingly constant growth rate for the Ormen Lange Dome from Eocene to present, while Lundin and Doré (2002) documented episodic activity. Miocene compression is also recorded on the western Barents Sea margin (Richardsen *et al.* 1991; Gac *et al.* 2016; Gabrielsen *et al.* 2023).

There is increasing evidence on the mid-Norwegian margin for late Miocene outbuilding on the inner shelf (Molo Formation; Eidvin *et al.* 2007) indicating a regional, moderate uplift of Fennoscandia (e.g. Eidvin *et al.* 2000, 2007; Faleide *et al.* 2002; Løseth and Henriksen, 2005; Lidmar-Bergström *et al.* 2007). Pre-glacial uplift also affected the NW Barents Sea shelf including Svalbard and a late Miocene age is indicated by observed tilting of the Vestbakken Volcanic Province (Fig. 2; Jebsen and Faleide 1998). A late Miocene exhumation event is also reported based on apatite fission track analysis (AFTA) of samples from several wells in the Barents Sea (Green and Duddy 2010).

The Miocene succession preserves a record of deep-water sedimentation that indicates an expansion of contourite sediment drifts (Fig. 2; Eiken and Hinz, 1993; Laberg *et al*., 2005a,b; Stoker *et al*., 2005b; Rebesco *et al*. 2014; Rydningen *et al*. 2020; Bjordal-Olsen *et al*. 2023).

A marked shift in prograding style occurred when latest Pliocene-Pleistocene glacial sediments prograded westward as continental ice sheets expanded onto the shelf (Henriksen *et al*. 2005; Hjelstuen and Sejrup 2021; Lien *et al*. 2022). Large Pleistocene depocenters formed fans in front of bathymetric throughs sourced by ice streams eroding the shelf (Faleide *et al*. 1996; Laberg and Vorren 1996; Vorren *et al*. 1989; Sejrup *et al*. 2003; Andreassen *et al*. 2004; Dahlgren *et al*. 2005; Nygård *et al*. 2005; Ottesen *et al*. 2002, 2005; Rise *et al*. 2005; Andreassen and Winsborrow 2009; Patton *et al*. 2022). Pleistocene uplift and glacial erosion of the Barents Sea shelf and deposition of large volumes of glacial deposits in submarine fans along the margin resulted in a regional tilt of the margin (Dimakis *et al*. 1998). In terms of post-opening sediments, the glacial component constitutes more than half of the total volume deposited on the mid-Norwegian and western Barents Sea margins (Lasabuda *et al*. 2021). The greatly enhanced Pleistocene deposition rates within the fans induced excess pore pressure and sediment instability resulting in a series of submarine slides of various sizes and timing (Kuvaas and Kristoffersen 1996; Haflidason *et al*. 2004; Bryn *et al*. 2005; Evans *et al*. 2005; Solheim *et al*. 2005; Hjelstuen *et al*. 2005, 2007; Rise *et al*. 2006; Safronova *et al*. 2017; Rydningen *et al*. 2020).

Underlying and overlying rock assemblages

Age of youngest underlying sedimentary unit

On the mid-Norwegian margin, the youngest underlying sedimentary unit is of late Paleocene (-earliest Eocene?) age represented by the Tare Fm containing tuff related to volcanic activity during breakup. On the western Barents Sea margin, the youngest sedimentary unit underlying the prograded margin TSE is of Oligocene-Miocene age (Fig. 4).

Age of oldest overlying sedimentary unit

The NSOBPM CTSE comprises sedimentary strata from Eocene to recent sediments at the present seafloor.

Subdivision and internal structure

The overall prograded margin TSE can be subdivided into three main systems (Fig. 1): (1) Northern North Sea-Møre Margin, (2) Vøring Margin and (3) Western Barents Sea margin. For the Møre and Vøring margins there are a lower part bounded by the Møre and Vøring marginal highs respectively, which represented restrictions to Eocene-Oligocene margin progradation (Fig. 5). Eocene-Oligocene depocenters are located landward of the escarpments bounding the marginal highs (Fig. 6A). The marginal highs were gradually buried and the Neogene units were able to prograde farther out into the oceanic basin in the Norwegian Sea.

A variety of mechanisms have been suggested for the initiation and growth of the compressional structures which are widespread in the Vøring Basin and the adjacent Jan Mayen Corridor (Fig. 2). These include (1) plate-driving forces (ridge push, slab pull, mantle drag), (2) differences in spreading rates, (3) asymmetric spreading, (4) changes in absolute plate motion, (5) far-field transmission of orogenic stress, (6) reactivation of basement structures/lineaments, and (7) differential sedimentary loading and compaction. Several of these mechanisms have likely interacted during the complex evolution of the structures (see discussion in Mosar *et al*. 2002 and Doré *et al*. 2008). The distinct compressional episode in the middle Miocene causing major growth of many dome structures, coincided in time with the formation of Iceland and its surrounding pedestal and body forces related to this elevated bathymetry/topography may have increased the compressional stresses affecting the dome structures (Doré *et al*. 2008). It also coincides with an increase in spreading rate and a change in absolute plate motion (Mosar *et al*. 2002). The relief of many domes was amplified by differential loading and compaction during margin progradation. The most prominent domes are the *Helland-Hansen Arch*, *Modgun Arch*, *Vema Dome* and *Naglfar Dome* (Figs. 2 and 5). The mid-Cenozoic domes also formed temporary barriers to progradation, in particular during the Miocene when the compressional deformation was strongest. In contrast, within the central and southern Møre Basin compressional structures are less common (Fig. 2), which could be the result of strain partitioning along the Jan Mayen Fracture Zone (Doré *et al*. 2008).

The main prograding units on the mid-Norwegian margin are associated with the North Sea TMF on the northern North Sea-Møre Margin and the Naust depocenter on the outer shelf of the Vøring Margin (Figs. 5 and 6B). The North Sea TMF is located at the mouth of the Norwegian Channel and was fed by the ice stream shaping the channel, which was linked to the Scandinavian ice sheet (King *et al*. 1996; Sejrup *et al*. 2003). The fan is divided into two provinces by the Møre Marginal High (Fig. 5A,B; Nygård et al. 2005). On the seaward side of the high the data coverage is sparse and the stratigraphy is poorly constrained in the Norway Basin (see profiles A and B in Fig. 5).

The northern North Sea-Møre margin comprises several slides related to slope failure (Fig. 7). The most recent and exposed slide is the prominent Storegga Slide, which was studied in large detail in relation to development of the Ormen Lange Field that is located in the scar of the slide (Haflidason *et al*. 2004; Berg *et al*. 2005; Bryn *et al*. 2005; Kvalstad *et al*. 2005a,b; Solheim *et al*. 2005). The Storegga Slide occurred 8200 years ago (Haflidason *et al*. 2005) soon after the last deglaciation of the Norwegian margin. Rapid loading from glacial deposits generated excess pore pressure and reduced the effective shear strength of the underlying clays and oozes. Failure and sliding of the unstable sediments were likely triggered by a strong earthquake located downslope from Ormen Lange (Haflidason *et al*. 2004; Bryn *et al*. 2005). Similar mechanisms were likely involved in earlier slide events on the northern North Sea-Møre margin during the last ~1.1 m.y. Three mass transport deposits are identified corresponding to the Tampen (~130 ka), Møre (~300 ka) and Stad (~400 ka) slides (Nygård *et al*. 2005; Hjelstuen and Grinde 2016). The Pleistocene depocenter on the outer shelf of the Vøring margin comprises prograding wedges of glacial sediments belonging to the Naust Fm (Fig. 5C-E; Rise *et al*. 2005; Ottesen *et al*. 2009, 2012; Bjordal-Olsen *et al*. 2023). A system of craters and mounds are found at the base of the glacially influenced sediments along the mid-Norwegian margin. Rapid sedimentation by low-permeable glacial muds caused overpressure in oozes, which were remobilized from the evacuation craters into the associated mounds (Riis *et al*. 2005; Bellwald *et al*. 2024).

The western Barents Sea progaded margin can be further subdivided into a series of trough mouth fans (TMFs) that developed in front of cross-shelf troughs formed by glacial erosion, mainly by ice streams (e.g. Faleide *et al*. 1996; Sejrup *et al*. 2003; Laberg *et al*. 2010, 2012; Alexandropoulou *et al*. 2021; Hjelstuen and Sejrup 2021; Patton *et al*. 2022). The Bjørnøya

TMF is the largest when considering areal extent, and cover most of the oceanic Lofoten Basin (Figs. 6B and 8A-C). The Storfjorden TMF is smaller in areal extent but has the thickest sedimentary succession (Figs. 6B and 8D; Hjelstuen *et al*. 1996; Lasabuda *et al*. 2018a). To the north, several smaller fans are found outside fjords of western Svalbard (Spitsbergen) (Fig. 8E; Solheim *et al*. 1998; Forsberg *et al*. 1999; Butt *et al*. 2000a,b). On the Bjørnøya TMF, several buried megaslides 1.0 to 0.2 Ma old have been identified (Figs. 7 and 8C). The two largest of these involved one order of magnitude more sediment than the Storegga Slide (Hjelstuen *et al*. 2007). Megaslides have also been identified on the Storfjorden TMF within the lowermost glacial unit GI (Figs. 7 and 8D; Safronova *et al*. 2017).

Sedimentary fill

Total thickness

The total sedimentary thickness from seabed to the top Paleocene typically ranges between 3-6 km within the prograded margins, thinning westwards into the oceanic basin (Figs. 5, 6 and 8).

Stratigraphy (lithostratigraphy, seismic stratigraphy)

The lithostratigraphy was originally defined by Dalland *et al*. (1988) for the mid-Norwegian shelf (Haltenbanken at inner part of the Vøring margin). In a recent paper, Eidvin *et al*. (2022) made some revisions/updates. The Cenozoic succession making up the prograded margin TSE comprises four formations (from oldest to youngest): Brygge, Kai, Molo and Naust (Fig. 4).

The *Brygge Formation* is of early Eocene to early Miocene age (Fig. 4). At Haltenbanken (e.g. in type well 6407/1-3; Fig. 3A), it consists of mainly claystone with stringers of sandstone, siltstone, limestone and marl (Dalland *et al*. 1988; Eidvin *et al*. 2022). Westwards, in the Vøring and Møre basins, siliceous ooze becomes common (Dalland *et al*. 1988; Bellwald *et al*. 2024).

The *Kai Formation* of middle Miocene to early Pliocene age (Fig. 4) is dominated by ooze-rich claystones alternating with siltstone and sandstone in some areas. Limestone stringers, glauconite and pyrite are also recorded (Dalland *et al*. 1988; Eidvin *et al*. 2022). Key wells for the Kai Formation include 6407/1-2, 6507/5-1, 6609/11–1, 6508/5–1, 6507/12–1 and 6305/5-1 (Fig. 3A). After deposition of the ooze-rich, stratified sediments, Opal A-CT conversion, polygonal faulting and fluid-flow processes have altered the sediments (Chand *et al*. 2011; Millett *et al*. 2022).

The *Molo Formation* (type well 6407/9-5; Fig. 3A) represents a set of steep clinoforms extending about 500 km from the coast off Møre to Lofoten. In proximal parts (e.g. wells 6610/3-1 and 6510/2-1; Fig. 3A), the unit consists of sand and some pebbles, while in more distal parts it contains sand, silt and clay (Eidvin *et al*. 2022). It has been challenging to date the formation and its age has been discussed extensively. According to Løseth and Henriksen (2005) and Løseth *et al*. (2017) the Molo Formation is of early Pliocene age making it younger than the Kai Formation (Fig. 4). Recent dating efforts (well 6610/3-1; Fig. 3A) gave a late Miocene to early Pliocene age (Grøsfjeld *et al*. 2019; Dybkjær *et al*. 2021) supporting the view of Eidvin *et al*. (2007, 2014, 2019) based on studies of ditch cuttings samples in wells 6407/9–5, 6407/9–2 and 6407/9–1 (Fig. 3A) that the southern part of the Molo Fm corresponds to the middle/upper part of the Kai Fm.

The *Naust Formation* is of latest Pliocene-Pleistocene age (< 2.75 Ma; Eidvin et al. 2020, 2022) (Fig. 4), and consists of interbedded claystone, siltstone and sand, occasionally with very coarse clastics in the upper part. On the mid-Norwegian margin the type and reference sections for the Naust Formation come from wells 6507/12-1 and 6507/5-1 (Fig. 3A) respectively.

A formal lithostratigraphy has not been established for the western Barents Sea margin but Eidvin *et al*. (2022) introduced a lithostratigraphic scheme for parts of the margin (Fig. 4). The Naust Formation is extended into the SW Barents Sea with a type section in well 7117/9-1 (Fig. 3A). Below they defined the new Tiskjegg Formation of Miocene age (Fig. 4) based on a type section in well 7216/11-1 S (Fig. 3A). Within the underlying Torsk Formation of Eocene-Oligocene age (Fig. 4) Eidvin *et al*. (2022) defined the middle Eocene Tobis Member consisting of sandy fan deposits penetrated in wells 7216/11-1 S and 7316/5-1 (Fig. 3A; Ryseth *et al*. 2003).

Regionally along the western Sea margin we mainly build on a well-established seismic stratigraphy (Fig. 4) first presented by Faleide *et al*. (1996). They subdivided the post-breakup sedimentary succession of the prograded margin into four units. G0 represents pre-glacial sediments that were further subdivided into four sub-units Te1-4 and tentative ages were assigned based on the age of the oceanic basement where they pinch out (Fiedler and Faleide 1996). Seven seismic reflectors (R1-R7) were interpreted in the glacial sediments and these formed the basis for identifying three units; GI (R7-R5), GII (R5-R1) and GIII (R1-seabed) (Fig. 4). The boundaries of these units were tied to exploration wells 7117/9-1 and 7117/9-2 (Fig. 3A) at the Senja Ridge in the SW Barents Sea showing that they were of glacial origin and of late Pliocene-Pleistocene age (Eidvin *et al*. 1993). R1-R7 were interpreted/correlated along the entire margin and tied to DSDP Site 344, drilled at the flank of the Knipovich Ridge (Fig. 3A). Later drilling at ODP Site 986 in a similar setting farther north (Fig. 3A) largely confirmed the stratigraphic framework of Faleide *et al*. (1996) (Forsberg *et al*. 1999; Butt *et al*. 2000b). Following reanalyzes of ODP Site 986 the age of R7, corresponding to the base of the glacial sediments, was changed from 2.3 to 2.7 Ma (Knies *et al*. 2009; Alexandropoulou *et al*. 2021).

Depositional environment and provenance

The Cenozoic NE Atlantic-Arctic plate tectonic evolution had large impact on the paleoceanography and sedimentation in the Norwegian-Greenland Sea and its continental margins (e.g. Thiede *et al*. 1989; Eldholm *et al*. 1994, 2002). Ocean basin segmentation caused by offsets in the initial plate boundary, local migration of the mid-ocean ridge axis and changes in relative plate motion created along-margin barriers affecting watermass circulation and depositional processes. The most important of such barriers were the Greenland-Iceland-Faroe Ridge bounding the Norwegian-Greenland Sea towards south, and the Fram Strait Gateway between the NE Atlantic and Arctic Eurasia Basin (Fig. 1A; Laberg et al. 2005a; Jakobsson *et al*. 2007; Engen *et al*. 2008; Parnell-Turner *et al*. 2015; Straume *et al*. 2020). Across-margin barriers also existed, in particular in the Paleogene. Regional uplift along the initial plate boundary and the subsequent formation of emerged marginal highs like the Møre and Vøring marginal highs (Fig. 5) had large impact on depositional processes during progradation of the mid-Norwegian margin.

The early Eocene to early Miocene sediments of the Brygge Formation on the mid-Norwegian (Møre-Vøring) margin are marine, mainly deposited in deep water in a distal environment (Dalland *et al*. 1988). During much of the Eocene-Oligocene the Møre and Vøring marginal highs were emerged and acted as sediment source area, and hindered margin progradation into the developing Norwegian Sea oceanic basin. The oceanic Lofoten Basin was mainly filled from the Barents Sea shelf (Fiedler and Faleide 1996; Faleide *et al*. 1996), but sediments were also routed through a number of canyons along the Lofoten-Vesterålen margin (Rise *et al*. 2013).

The middle Miocene to early Pliocene marine sediments of the Kai Formation were deposited on the outer and middle parts of the mid-Norwegian margin. On the outer shelf and slope down to the deeper Møre and Vøring basins, the Kai Formation is overall rich in clay and siliceous and calcareous microfossil-bearing pelagic ooze. The sediments of the Kai Formation have largely been redistributed by contour currents (Bryn *et al*. 2005; Laberg *et al*. 2005a; Bjordal-Olsen *et al*. 2023). These were related to the opening of the Fram Strait Gateway sometime between 20 and 15 Ma (Jakobsson *et al*. 2007; Engen *et al*. 2008) when extensive deep-water circulation was established between the North Atlantic and Arctic. However, in the Vøring Basin, evidence exist for older contourites, interpreted to originate from ocean circulation also prior to the mid-Miocene (Laberg *et al*. 2005b).The vertical motion history of the Greenland-Iceland-Faroe Ridge (Parnell-Turner *et al*. 2015; Straume *et al*. 2020) also had large impact on the ocean circulation in the Norwegian-Greenland Sea and associated depositional processes.

The new ocean circulation also affected the SW Barents Sea margin where the Bjørnøyrenna Drift (Fig. 2) started to form in the early/middle Miocene (Rydningen *et al*. 2020). The drift is located on the slope and consists of primarily shale with some interfingering sandstones. The sand, however, was probably deposited through turbiditic currents reflecting a complex interplay between down-slope and along-slope sedimentary processes (Rydningen *et al*. 2020). The development of this drift was concurrent with Mid-Miocene Climate Optimum (c. 16-14 Ma) suggesting a link between ocean circulation and global cooling (Rydningen *et al*. 2020).

During deposition the seafloor bathymetry was affected by large domes and depressions formed during the mid-Miocene compressional tectonic phase, and redistribution of fine-grained sediments commonly took place along the flanks of the domes (Eidvin *et al.* 2014).

The late Miocene-early Pliocene Molo Formation, characterized by steep clinoforms (Eidvin *et al.* 1998, 2007), was deposited in a coastal shallow marine to prograding deltaic environment, probably formed in a wave-dominated environment with extensive long-shore drift. It is situated on the middle/inner part of the shelf extending about 100 km from the coast off Møre (63°15'N) and north to Lofoten (67°50'N). Based on the recent dates (Grøsfjeld *et al.* 2019; Dybkjær *et al.* 2021) and regional seismic mapping (Bjordal-Olsen *et al.* 2023) the Molo Formation is now interpreted to be the proximal equivalent to the deeper marine Kai Formation, deposited as a result of the compression and uplift of mainland Norway in mid-Miocene time (Eidvin *et al.* 2022).

The main source area for the current-influenced sediments was probably located in the northeast (Lofoten/Vestfjorden area). Significant Neogene uplift and erosion, starting in the Miocene, is reported here (Hendriks and Andriessen 2002; Bjørnseth *et al.* 2003; Redfield *et al.* 2005).

A significant shift in sedimentary processes and depositional environments took place at the Pliocene-Pleistocene transition. Major shelf edge progradation can be linked to grounding of ice sheets on the continental shelf (Andreassen *et al.* 2004, 2008; Dahlgren *et al.* 2005; Andreassen and Winsborrow 2009; Ottesen *et al.* 2009, 2012; Newton and Huuse 2017). The deposition and major progradation of glacial sediments in the North Sea TMF and the trough mouth fans along the western Barents Sea margin were closely linked to the processes shaping the shelves of the North Sea and Barents Sea respectively. Large volumes of glacial sediments were deposited in the Norwegian Sea (and the Nansen Basin in the Arctic) as large fans in front of the bathymetric troughs on the shelf formed by glacial erosion (e.g. Faleide *et al.* 1996; Lasabuda *et al.* 2018a; Hjelstuen and Sejrup 2021; Lien *et al.* 2022).

Over large parts of the Barents Sea shelf there is a distinct composite upper regional unconformity (URU; e.g. Faleide *et al.* 1996). In some areas we observe several unconformities formed in response to individual ice sheets that was grounded and eroded on the shelf. This is more clear on the inner part of the mid-Norwegian (Vøring) margin where upper parts of the Naust Formation reveal several sub-horizontal unconformities (Ottesen *et al*. 2009). On the slope, a downlap surface for huge prograding wedges sourced on the mainland and the shelf marks the transition to glacial sediment deposition during the Northern Hemisphere Glaciation since about 2.7 Ma. In terms of total post-breakup sediment volume the glacial component constitutes as much as about 50% on the mid-Norwegian and western Barents Sea margins (Lasabuda *et al*. 2021). The abrupt change in sedimentation rate at the beginning of the Quaternary, increasing by an order of magnitude, cannot be explained by tectonic uplift of landmasses as the main cause. More likely, it reflects climatic change causing effective and significant glacial erosion (Hjelstuen and Sejrup 2021; Patton *et al*. 2022).

The Scandinavian Ice Sheet repeatedly advanced to the shelf edge throughout the Pleistocene (Dahlgren *et al*. 2002; Sejrup *et al*. 2005), and loaded the slopes with thick packages of glacial sediment. Glaciations were initiated a bit earlier (~4 Ma) in the northern Barents Sea/Svalbard area but the first large-scale glaciation reaching the shelf edge did not occur before ~2.75 Ma (Knies et al. 2014).

Continental slope mass failures affected both the North Sea TMF (Nygård *et al*. 2005; Hjelstuen and Andreassen 2015) and Bjørnøya TMF (Hjelstuen *et al*. 2007) and large volumes of slide deposits were transported into the oceanic Norway Basin and Lofoten Basin, respectively (Fig.7). The rapid deposition of glacigenic sediments at the outer shelf and upper slope contributed to conditions favorable for failure (Hjelstuen *et al*. 2005).

On the Vøring margin, the latest Pliocene-Pleistocene Naust Formation comprises large quantities of glacially derived material that were transported westwards from the Norwegian mainland and inner shelf and deposited in a basin of intermediate depth as prograding sediment wedges (Dahlgren *et al*. 2002; Rise *et al*. 2005; Ottesen *et al*. 2009, 2012; Newton and Huuse 2017). In this basin, the Helland–Hansen Arch (Fig. 2) acted as a prominent north–south-trending topographic element and affected the deposition of glaciogenic, hemipelagic and contouritic deposits in the early Naust period (Fig. 5; Rise *et al*. 2010; Millett *et al*. 2022).

Magmatism

Voluminous Paleogene volcanism affected the mid-Norwegian margin prior to and during NE Atlantic breakup and initial seafloor spreading between Greenland and Europe and thick piles of extrusive volcanic rocks were emplaced (Planke *et al*. 2000, 2017; Berndt et al. 2001; Abdelmalak *et al.* 2016). However, these are not considered part of the prograded margin TSE but form its substrate at the outer margin.

Heat flow

The Møre and Vøring margins have heat flow measurements (both at seabed and in deep exploration wells; Fig. 3A) around 60-65 mW/m^2, which are typical for "normal" continental areas with no recent tectonic activity. Some lateral variation likely reflects structural complexity (Ritter *et al.* 2004; Pascal 2015).

The heat flow values at the western Barents Sea margin are generally low except for the abnormally high values (exceeding 1000 mW/m^2) associated with the Håkon Mosby mud volcano (Hjelstuen *et al*. 1999; Eldholm *et al*. 1999).

Petroleum geology

The petroleum geology of the pre-breakup CTSE's on the mid-Norwegian margin is well covered by Bunkholt *et al*. (2021) and Faleide *et al*. (2024a), while Ryseth *et al*. (2021) and Faleide *et al*. (2024b) do the same for the western Barents Sea margin. An important source of information is the FactPages of the Norwegian Offshore Directorate (https://factpages.sodir.no/en) which is continuously updated with respect to wellbores, discoveries, fields etc. They also present play models for different parts of the Norwegian Continental Shelf (https://www.sodir.no/en/facts/geology/plays/).

Discovered HC potential

No discoveries are yet made within the prograded margins TSE.

Current exploration status

Exploration activities in the area covered by the Norwegian Sea prograded margins TSE have so far not targeted plays within the prograding sedimentary sequences.

Hydrocarbon systems and plays

The hydrocarbon systems and plays described for the underlying CTSE's (Bunkholt *et al.* 2021; Ryseth *et al.* 2021; Faleide *et al.* 2024a,b) are not applicable to the prograded margins.

The Norwegian Offshore Directorate has only two potential plays covering the prograded margins (https://www.sodir.no/en/facts/geology/plays/). One is unconfirmed and located at the Møre-Vøring marginal highs where fractured volcanic and volcaniclastic rocks could work as reservoir rock. The other builds on the Peon gas field (well 35/2-1; Fig. 3A) found above a prominent angular unconformity within the Norwegian Channel in the northeastern North Sea (Fig. 1B; Bellwald *et al.* 2022). Here, Quaternary glaciofluvial sands forms the reservoir which is sealed by fine-grained glaciomarine sediments and till units (Ottesen *et al.* 2012). Similar rocks in a similar setting may exist in the Naust Formation on the mid-Norwegian (Vøring) margin but such a play is not confirmed here.

In addition, based on studies of recent 3D seismic data covering the outer Vøring and Møre margins (Fig. 3B), Millett *et al.* (2022) presented a range of less conventional plays in Neogene to Quaternary sequences including sand injectites, glacial sands and plays associated with shallow gas hydrates. These are poorly constrained with respect to age, making them difficult to place in the summary chart (Fig. 4).

Source rocks. Mesozoic (Jurassic and Cretaceous) source rocks are present below the mid-Norwegian prograded margin but these are deeply buried and was likely exhausted of any hydrocarbon generation potential at the time of Cenozoic margin progradation. A younger source rock may exist at the outer margin associated with the early Eocene Azolla event (Brinkhuis *et al*. 2006). This may be the source for hydrocarbons generated within the Bjørnøya TMF and methane-venting seep at the seabed of the Håkon Mosby Mud Volcano (Fig. 2) (Hjelstuen *et al*. 1999, Damm and Budéus 2003; Niemann *et al*. 2006; Pape *et al.* 2011). Widespread methane seepages are reported along the margin farther north from

Bjørnøya to Kongsfjorden on Svalbard (Fig. 1B; Mau *et al*. 2017; Weniger *et al*. 2019) indicating working petroleum system(s).

Reservoirs. Sand injectites are widespread within the Kai/Brygge formations on the mid-Norwegian (Vøring) margin (Millett et al. 2022). Their geometry varies from isolated mounds and saucer-shaped sills to more laterally extensive sills, and these may have reservoir properties. Contourites are interpreted to be present in deeper parts of the North Sea TMF. Some of these may contain sand that could provide reservoir rocks. Quaternary glacial sands may represent shallower exploration targets within the prograded margin (Millett *et al*. 2022).

Seals. Fine-grained glacigenic sediments may have considerable sealing potential related to the plays described above. The thick wedges of glacigenic debris flows contain large volumes of such sediments that could trap potential reservoir sands mentioned above.

Traps. The Cenozoic compressive anticlines that are widespread on the mid-Norwegian (Vøring) margin form both structural traps with four-way dip closure and combined structural-stratigraphic traps related to their effect on depositional patterns (Doré and Lundin 1996). However, drilling on some of the domes has so far not been successful. The plays mentioned above related to sand injectites and contourites are eventually associated with stratigraphic traps.

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References

Abdelmalak, M.M., Planke, S., Faleide, J., *et al*. 2016. The development of volcanic sequences at rifted margins: New insights from the structure and morphology of the Vøring Escarpment, mid-Norwegian Margin. *Journal of Geophysical Research: Solid Earth*, **121**, 5212–5236. https://doi.org/10.1002/2015JB012788

Abdelmalak, M.M., Gac, S., Faleide, J.I., *et al*. 2023. Quantification and restoration of the pre-drift extension across the NE Atlantic conjugate margins during the mid-Permian-early Cenozoic multi-rifting phases. *Tectonics*, **42**, e2022TC007386, https://doi.org/10.1029/2022TC007386

Alexandropoulou, N., Winsborrow, M., Andreassen, K., et al. 2021. A Continuous Seismostratigraphic Framework for the Western Svalbard-Barents Sea Margin Over the Last 2.7 Ma: Implications for the Late Cenozoic Glacial History of the Svalbard-Barents Sea Ice Sheet. Front. Earth Sci. 9:656732. doi: 10.3389/feart.2021.656732

Andreassen, K. and Winsborrow, M. 2009. Signature of ice streaming in Bjørnøyrenna, Polar North Atlantic, through the Pleistocene and implications for ice-stream dynamics. *Annals of Glaciology*, **50**,

Andreassen, K., Nilssen, L.C., Rafaelsen, B. and Kuilman, L. 2004. Three-dimensional seismic data from the Barents Sea margin reveal evidence of past ice streams and their dynamics. *Geology*, **32**, 729-732. doi: 10.1130/G20497.1

Andreassen, K., Laberg, J.S. and Vorren, T.O. 2008. Seafloor geomorphology of the SW Barents Sea and its glaci-dynamic implications. *Geomorphology*, **97**, 157–177. https://doi.org/10.1016/j.geomorph.2007.02.050

Baig, I., Faleide, J.I., Jahren, J. and Mondol, N.H. 2016. Cenozoic exhumation on the southwestern Barents Shelf: Estimates and uncertainties constrained from compaction and thermal maturity analyses. *Marine and Petroleum Geology*, **73**, 105-130.

Batchelor, C.L., Ottesen, D. and Dowdeswell, J.A. 2017. Quaternary evolution of the northern North Sea margin through glacigenic debris-flow and contourite deposition. *Journal of Quaternary Science*, **32**, 416–426. DOI: 10.1002/jqs.2934

Bellwald, B., Planke, S., Vadakkepuliyambatta, S., et al. 2022. Quaternary and Neogene Reservoirs of the Norwegian Continental Shelf and the Faroe-Shetland Basin. *First Break*, **40**, 33-44.

Bellwald, B., Manton, B., Lebedeva-Ivanova, N., et al. 2024. Rapid glacial sedimentation and overpressure in oozes causing large craters on the mid-Norwegian margin: integrated interpretation of the Naust, Kai and Brygge formations. Geological Society, London, Special Publications, **525**, SP525-2023.

Berg, K., Solheim, A., Bryn, P. 2005. The Pleistocene to recent geological development of the Ormen Lange area. *Marine and Petroleum Geology*, **22**, 45–56. doi:10.1016/j.marpetgeo.2004.10.009

Berndt, C., Planke, S., Alvestad, E., et al. 2001. Seismic volcanostratigraphy of the Norwegian Margin: constraints on tectonomagmatic break-up processes. *Journal of the Geological Society of London*, **158**, 413–426, https://doi.org/10.1144/jgs.158.3.413

Bjordal-Olsen, S., Rydningen, T.A., Laberg, J.S., et al. 2023. Contrasting Neogene–Quaternary continental margin evolution offshore mid-north Norway: Implications for source-to-sink systems. *Marine Geology*, **456**, 106974. https://doi.org/10.1016/j.margeo.2022.106974

Bjørnseth, H.M., Grant, S.M., Hansen, E.K., et al. 1997. Structural evolution of the Vøring Basin, Norway, during the Late Cretaceous and Paleogene. *Journal of the Geological Society of London*, **154**, 559–563. https://doi.org/10.1144/gsjgs.154.3.0559

Breivik, A.J., Mjelde, R., Faleide, J.I. and Murai, Y. 2006. Rates of continental breakup magmatism and seafloor spreading in the Norway Basin-Iceland plume interaction. *Journal of Geophysical Research*, **111** (B07102)

Breivik, A.J., Mjelde, R., Faleide, J.I. and Murai, Y. 2012. The eastern Jan Mayen microcontinent volcanic margin. *Geophysical Journal International*, **188**, 798-818.

Brekke, H. 2000. The tectonic evolution of the Norwegian Sea Continental Margin with emphasis on the Vøring and Møre Basins. *Geological Society, London, Special Publications*, **167**, 327–378, https://doi.org/10.1144/GSL.SP.2000.167.01.13

Brinkhuis, H., Schouten, S., Collinson, M. E., et al. 2006. Episodic fresh surface waters in the Eocene Arctic Ocean. *Nature*, **441**, 7093, 606-609.

Bryn, P., Berg, K., Forsberg, C.F., *et al*. 2005. Explaining the Storegga Slide. *Marine and Petroleum Geology*, **22**, 11–19. https://doi.org/10.1016/j.marpetgeo.2004.12.003

Bunkholt, H.S.S., Oftedal, B.T., Hansen, J.A., *et al*. 2021. Trøndelag Platform and Halten-Dønna terraces Composite Tectono-Sedimentary Element, Norwegian Sea Rifted Continental Margin. *Geological Society, London, Memoirs*, **57**, https://10.1144/M57-???

Butt, F.A., Drange, H., Elverhøi, A., *et al*. 2000a. Modelling Late Cenozoic isostatic elevation changes in the Barents Sea and their implications for oceanic and climatic regimes: preliminary results. *Quaternary Science Reviews*, **21**, 1643–1660.

Butt, F.A., Elverhøi, A., Solheim, A. and Forsberg, C.F. 2000b. Deciphering late Cenozoic evolution of the western Svalbard Margin based of ODP Site 986 results. *Marine Geology*, **169**, 373–390.

Cohen, K.M., Finney, S.C., Gibbard, P.L. and Fan, J.-X. (2013; updated). The ICS International Chronostratigraphic Chart. *Episodes*, **36**, 199-204.

Chand, S., Rise, L., Knies, J., *et al*. 2011. Stratigraphic development of the south Vøring margin (Mid-Norway) since early Cenozoic time and its influence on subsurface fluid flow. *Marine and Petroleum Geology*, **28**, 1350-1363. doi:10.1016/j.marpetgeo.2011.01.005

Damm, E. and Budéus, G. 2003. Fate of vent-derived methane in seawater above the Håkon Mosby mud volcano (Norwegian Sea). *Marine chemistry*, **82**, 1-11 . doi: 10.1016/S0304-4203(03)00031-8

Dalland, A., Worsley, D. and Ofstad, K. 1988. A Lithostratigraphical Scheme for the Mesozoic and Cenozoic Succession Offshore Mid- and Northern Norway. *Norwegian Petroleum Directorate Bulletin*, **4**.

Dahlgren, K.I.T., Vorren, T.O. and Laberg, J.S. 2002. The role of grounding-line sediment supply in ice-sheet advances and growth on continental shelves: An example from the mid-Norwegian sector of the Fennoscandian ice sheet during the Saalian and Weichselian. *Quaternary International*, **95-96**, 25-33.

Dahlgren, K.I.T., Vorren, T.O., Stoker, M.S., *et al*. 2005. Late Cenozoic prograding wedges on the NW European continental margin: their formation and relationship to tectonics and climate. *Marine and Petroleum Geology*, **22**, 1089–1110. doi:10.1016/j.marpetgeo.2004.12.008

Dimakis, P., Braathen, B.I., Faleide, J.I., et al. 1998. Cenozoic erosion and the preglacial uplift of the Svalbard–Barents Sea region. *Tectonophysics*, **300**, 311-327.

Doré, A.G. and Lundin, E.R. 1996. Cenozoic compressional structures on the NE Atlantic margin: nature, origin and potential significance for hydrocarbon exploration. *Petroleum Geoscience*, **2**, 299-311.

Doré, A.G., Lundin, E., Jensen, L.N., *et al*. 1999. Principal tectonic events in the evolution of the northwest European Atlantic margin. *Petroleum Geology Conference Proceedings*, **5**, 41-61.

Doré, A.G., Lundin, E.R., Kusznir, N.J. and Pascal, C. 2008. Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: pros, cons and some new ideas. *Geological Society Special Publications*, **306**, 1–26. DOI: 10.1144/SP306.1

Dybkjær, K., Rasmussen, E.S., Eidvin, T., *et al*. 2020. A new stratigraphic framework for the Miocene – Lower Pliocene deposits offshore Scandinavia: A multiscale approach. *Geological Journal*, **56**, 1699–1725.

DOI: 10.1002/gj.3982

Eidvin, T., Jansen, E. and Riis, F. 1993. Chronology of Tertiary fan deposits off the western Barents Sea: Implications for the uplift and erosion history of the Barents Shelf. *Marine Geology*, **112**, 109-131.

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

Eidvin, T., Jansen, E., Rundberg, Y., *et al*. 2000. The upper Cainozoic of the Norwegian continental shelf correlated with the deep-sea record of the Norwegian Sea and North Atlantic. *Marine and Petroleum Geology*, **17**, 579–600. https://doi.org/10.1016/S0264-8172(00)00008-8.

Eidvin, T., Bugge, T. and Smelror, M. 2007. The Molo Formation, deposited by coastal progradation on the inner Mid-Norwegian continental shelf, coeval with the Kai Formation to the west and the Utsira Formation in the North Sea. *Norwegian Journal of Geology*, **87**, 75–142.

Eidvin, T., Riis, F. and Rasmussen, E.S. 2014. Correlation of Upper Oligocene to Lower Pliocene deposits of the Norwegian continental shelf, Norwegian Sea, Svalbard, Denmark and their relation to the uplift of Fennoscandia: a synthesis. *Marine and Petroleum Geology*, **56**, 184–221. https://doi.org/10.1016/j.marpetgeo.2014.04.006.

Eidvin, T., Ottesen, D., Dybkjær, K., Rasmussen, E.S. & Riis, F. 2020: The use of Sr isotope stratigraphy to date the Pleistocene sediments of the Norwegian continental shelf – a review. Norwegian Journal of Gelogy 100, 202013. https://dx.doi.org/10.17850/njg100-3-1.

Eidvin T., Riis, F., Brekke, H. and Smelror, M. 2022. A revised lithostratigraphic scheme for the Eocene to Pleistocene succession on the Norwegian continental shelf. *Norwegian Journal of Geology, Special Publication*, **1**, 1–132, https://dx.doi.ord/10.17850/njgsp1

Eiken, O. and Hinz, K. 1993. Contourites in the Fram Strait. *Sedimentary Geology*, **82**, 15–32. https://doi.org/10.1016/0037-0738(93)90110-Q

Eldholm, O., Thiede, J. and Taylor, B. 1989: Evolution of the Vøring volcanic margin. In: *Proceedings of the Ocean Drilling Program, Scientific Results*, **104** 21, College Station, TX (Ocean Drilling Program), 1033–1065. https://doi.org/10.2973/ODP.PROC.SR.104.191.1989

Eldholm, O., Myhre, A.M. and Thiede, J. 1994. Cenozoic tectono-magmatic events in the North Atlantic: potential paleoenvironmental implications. In: Boulter, M.C. & Fischer, H.C. (eds) Cenozoic Plants and Climates of the Arctic, NA TO ASI Series, 127. Springer-Verlag, Heidelberg, 35-55.

Eldholm, O., Sundvor, E., Vogt, P.R., *et al*. 1999. SW Barents Sea continental margin heat flow and Hakon Mosby Mud Volcano. *Geo-Marine Letters*, **19**, 29-37.

Eldholm, O., Tsikalas, F. and Faleide, J.I. 2002. The continental margin off Norway 62-75oN: Palaeogene tectono-magmatic segmentation and sedimentation. *Geological Society Special Publications*, **197**, 39-68.

Engen, Ø., Faleide, J.I. and Dyreng, T.K. 2008. Opening of the Fram Strait gateway: A review of plate tectonic constraints. *Tectonophysics*, **450**, 51-69.

Evans, D., Harrison, Z., Shannon, P.M., *et al*. 2005. Palaeoslides and other mass failures of Pliocene to Pleistocene age along the Atlantic continental margin of NW Europe. *Marine and Petroleum Geology*, **22**, 1131–1148. doi:10.1016/j.marpetgeo.2005.01.010

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

Faleide, J.I., Solheim, A., Fiedler, A., Hjelstuen, B.O., *et al*. 1996. Late Cenozoic evolution of the western Barents Sea-Svalbard continental margin. *Global and Planetary Change*, **12**, 53-74.

Faleide, J.I., Kyrkjebø, R., Kjennerud, T., Gabrielsen, R.H., et al. 2002. Tectonic impact on sedimentary processes during Cenozoic evolution of the northern North Sea and surrounding areas. *Geological Society Special Publications*, **196**, 235-269.

Faleide, J.I., Tsikalas, F., Breivik, A.J., *et al*. 2008. Structure and evolution of the continental margin off Norway and the Barents Sea. *Episodes*, **31**, 82–91. http://dx.doi.org/10.18814/epiiugs/2008/v31i1/012

Faleide, J.I., Zastrozhnov, D., Abdelmalak, M.M., et al. 2024a. Møre–Vøring Composite Tectono-Sedimentary Element, Norwegian rifted margin, Norwegian Sea. *Geological Society, London, Memoirs*, **57**,

Faleide, J.I., Wong, P.W., Hassaan, M., et al. 2024b. West Barents Shear Margin Composite Tectono-Sedimentary Element. *Geological Society, London, Memoirs*, **57**,

Fiedler, A. and Faleide, J.I. 1996. Cenozoic sedimentation along the southwestern Barents Sea margin in relation to uplift and erosion of the shelf. *Global and Planetary Change*, **12**, 75-93.

Forsberg, C.F., Solheim, A., Elverhøi, A., *et al.* 1999. The depositional environment of the western Svalbard margin during the late Pliocene and the Pleistocene: Sedimentary facies changes at Site 986. *Proceedings of the Ocean Drilling Program: Scientific Results*, **162**, 233-246.

Funck, T., Geissler, W.H., Kimbell, G.S., *et al*. 2017, Moho and basement depth in the NE Atlantic Ocean based on seismic refraction data and receiver functions. Geological Society, London, Special Publications, **447**, 207-231.

Gabrielsen, R.H., Giannenas, P.A., Sokoutis, D., *et al*. 2023. Analogue experiments on releasing and restraining bends and their application to the study of the Barents Shear Margin. *Solid Earth*, **14**, 961–983.

Gac, S., Klitzke, P., Minakov, A., Faleide, J.I. and Scheck-Wenderoth, M. (2016) Lithospheric strength and elastic thickness of the Barents Sea and Kara Sea region. *Tectonophysics*, **691**, 120-132.

Gaina, C., Gernigon, L. and Ball, P. 2009. Palaeocene–Recent plate boundaries in the NE Atlantic and the formation of the Jan Mayen microcontinent. *Journal of the Geological Society, London*, **166**, 601–616. doi: 10.1144/0016-76492008-112.

Gernigon, L., Zastrozhnov, D., Planke, S., *et al*. 2021. A digital compilation of structural and magmatic elements of the Mid-Norwegian continental margin (version 1.0). *Norwegian Journal of Geology*, **101**.

Green, P.F. and Duddy, I.R. 2010. Synchronous exhumation events around the Arctic including examples fromBarents Sea and Alaska North Slope. *Petroleum Geology Conference Proceedings*, **7**, 633-644.

Grogan, P., Østvedt-Ghazi, A.-M., Larsen, G.B., *et al*. 1999. Structural elements and petroleum geology of the Norwegian sector of the northern Barents Sea. *Geological Society Petroleum Geology Conference Series,* **5**, 247-259.

Grøsfjeld, K., Dybkjær, K., and Eidvin, T., *et al*. 2019. A Miocene age for the Molo Formation, Norwegian Sea shelf off Vestfjorden, based on marine palynology. *Norwegian Journal of Geology*, **99**,

Haflidason, H., Sejrup, H.P., Nygård, A., *et al*. 2004. The Storegga Slide: architecture, geometry and slide development. Marine Geology, **213**, 201–234. doi:10.1016/j.margeo.2004.10.007

Haflidason, H., Lien, R., Sejrup, H.P., *et al*. 2005. The dating and morphometry of the Storegga Slide. *Marine and Petroleum Geology*, **22**, 123-136. https://doi.org/10.1016/j.marpetgeo.2004.10.008

Hendriks, B., Andriessen, P., Huigen, Y., *et al.* 2007. A fission track data compilation for Fennoscandia *Norwegian Journal of Geology*, **87**, 143-155.

Henriksen, S., Fichler, C., Grønlie, A., *et al*. 2005. The Norwegian Sea during the Cenozoic. *NPF Special Publication*, **12**, 111-133.

Henriksen, E., Bjørnseth, H.M., Hals, T.K., *et al*. 2011. Chapter 17: Uplift and erosion of the greater Barents Sea: impact on prospectivity and petroleum systems. Geological Society, London, Memoirs, 35, 271-281.

Hjelstuen, B.O. and Andreassen, E.V. 2015. North Atlantic Ocean deep-water processes and depositional environments: A study of the Cenozoic Norway Basin. *Marine and Petroleum Geology*, **59**, 429-441. http://dx.doi.org/10.1016/j.marpetgeo.2014.09.011

Hjelstuen, B.O. and Grinde, S. 2016. 3D Seismic Investigations of Pleistocene Mass Transport Deposits and Glacigenic Debris Flows on the North Sea Fan, NE Atlantic Margin. In: G. Lamarche et al. (eds.), Submarine Mass Movements and their Consequences, *Advances in Natural and Technological Hazards Research*, **41**, DOI 10.1007/978-3-319-20979-1_26

Hjelstuen, B.O. and Sejrup, H.P. 2021. Latitudinal variability in the Quaternary development of the Eurasian ice sheets - Evidence from the marine domain. *Geology*, **49**, 346-351.

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

Hjelstuen, B.O., Eldholm O. and Skogseid, J. 1997. Vøring Plateau diapir fields and their structural and depositional settings. *Marine Geology*, **144**, 33-57.

Hjelstuen, B.O., Eldholm, O. and Skogseid, J. 1999. Cenozoic evolution of the northern Vøring margin. *Geological Society of America Bulletin*, **111**, 1792–1807, https://doi.org/10.1130/0016-7606(1999)111%3C1792:CEOTNV%3E2.3.CO;2

Hjelstuen, B., Eldholm, O., Faleide, J.I. and Vogt, P. 1999. Regional setting of the Håkon Mosby Mud Volcano, SW Barents Sea Margin. *Geo-Marine Letters*, **19**, 22-28.

Hjelstuen, B.O., Sejrup, H.P., Haflidason, H., *et al*. 2005. Late Cenozoic glacial history and evolution of the Storegga Slide area and adjacent slide flank regions, Norwegian continental margin. *Marine and Petroleum Geology*, **22**, 57–69. doi:10.1016/j.marpetgeo.2004.10.002

Hjelstuen, B.O., Eldholm, O. and Faleide, J.I. 2007. Recurrent Pleistocene mega-failures on the SW Barents Sea margin. *Earth and Planetary Science Letters*, **258**, 605-618.

Jakobsson, M., Backman, J., Rudels, B., *et al*. 2007. The early Miocene onset of a ventilated circulation regime in the Arctic Ocean. *Nature*, **447**, 986-990.

Jakobsson, M., Mayer, L. A., *et al.* 2020. The International Bathymetric Chart of the Arctic Ocean Version 4.0. *Scientific Data*, **7**, 1, 176.

Jebsen, C. and Faleide, J.I. 1998. Tertiary rifting and magmatism at the western Barents Sea margin (Vestbakken Volcanic Province). Third Int. Conf. on Arctic Margins, Celle, Germany, 12-16.10, 1998.

King, E.L., Sejrup, H.P., Haflidason, H., Elverhøi, A. and Aarseth, I., 1996, Quaternary seismic stratigraphy of the North Sea Fan: glacially-fed gravity flow aprons, hemipelagic sediments and large submarine slides. *Marine Geology*, **130**, 295-315. https://doi.org/10.1016/0025-3227(95)00168-9

Knies, J., Matthiessen, J., Vogt, C., et al. 2009. The Plio-Pleistocene glaciation of the Barents Sea–Svalbard region: A new model based on revised chronostratigraphy. *Quaternary Science Reviews*, **28**, 812–829. https://doi.org/10.1016/j.quascirev.2008.12.002

Knies, J., Mattingsdal, R., Fabian, K., *et al*. 2014. Effect of early Pliocene uplift on late Pliocene cooling in the Arctic–Atlantic gateway. *Earth and Planetary Science Letters*, **387**, 132–144. https://doi.org/10.1016/j.epsl.2013.11.007

Ktenas, D., Henriksen, E., Meisingset, I., *et al*. 2017. Quantification of the magnitude of net erosion in the Southwest Barents Sea using sonic velocities and compaction trends in shales and sandstones. *Marine and Petroleum Geology*, **88**, 826–844.

Ktenas, D., Meisingset, I., Henriksen, E. and Nielsen, J.K., 2019. Estimation of net apparent erosion in the SW Barents Sea by applying velocity inversion analysis. *Petroleum Geoscience*, **25**, 169–187.

Ktenas, D., Nielsen, J.K., Henriksen, E., *et al*. 2023. The effects of uplift and erosion on the petroleum systems in the southwestern Barents Sea: Insights from seismic data and 2D petroleum systems modelling. *Marine and Petroleum Geology*, **158**, 106535.

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

Kvalstad, T.J., Andresen, L., Forsberg, C.F., *et al*. 2005a. The Storegga slide: evaluation of triggering sources and slide mechanics. *Marine and Petroleum Geology*, **22**, 245–256. doi:10.1016/j.marpetgeo.2004.10.019

Kvalstad, T.J., Nadim, F., Kaynia, A.M., *et al*. 2005b. Soil conditions and slope stability in the Ormen Lange area. *Marine and Petroleum Geology*, **22**, 299–310. doi:10.1016/j.marpetgeo.2004.10.021

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

Laberg, J.S. and Vorren, T.O. 1996. The middle and late Pleistocene evolution of the Bear Island Trough Mouth Fan. *Global and Planetary Change*, **12**, 309-330.

Laberg, J.S. and Vorren, T.O. 2000. Flow behaviour of the submarine glacigenic debris flows on the Bear Island Trough Mouth Fan, western Barents Sea. *Sedimentology*, **47**, 1105-1117.

Laberg, J.S., Vorren, T.O., Mienert, J., *et al*. 2002. Late Quaternary palaeoenvironment and chronology in the Trænadjupet Slide area offshore Norway. *Marine Geology*, **188**, 35-60.

Laberg, J.S., Stoker, M.S., Dahlgren, K.I.T., *et al*. 2005a. Cenozoic alongslope processes and sedimentation on the NW European Atlantic margin. *Marine and Petroleum Geology*, **22**, 1069–1088. doi:10.1016/j.marpetgeo.2005.01.008

Laberg, J.S., Dahlgren, K.I.T. and Vorren, T.O. 2005b. The Eocene–late Pliocene paleoenvironment in the Vøring Plateau area, Norwegian Sea - paleoceanographic implications. *Marine Geology*, **214**, 269-285.

Laberg, J.S., Andreassen, K., Knies, J., et al. 2010. Late Pliocene–Pleistocene development of the Barents Sea ice sheet. *Geology*, **38**, 107–110. https://doi.org/10.1130/G30193.1

Laberg, J.S., Andreassen, K. and Tore O. Vorren, T.O. 2012. Late Cenozoic erosion of the high-latitude southwestern Barents Sea shelf revisited. *GSA Bulletin*, **124**, 77–88; doi: 10.1130/B30340.1

Lasabuda, A., Laberg, J.S., Knutsen, S.-M. and Safronova, P.A. 2018a. Cenozoic tectonostratigraphy and pre-glacial erosion: a mass-balance study of the northwestern Barents Sea margin, Norwegian Arctic. *Journal of Geodynamics*, **119**, 149-166, https://doi.org/10.1016/j.jog.2018.03.004

Lasabuda, A., Laberg, J.S., Knutsen, S.-M. and Høgseth, G. 2018b. Early to middle Cenozoic paleoenvironment and erosion estimates of the southwestern Barents Sea: Insights from a regional mass-balance approach. *Mar. Pet. Geol.*, **96**, 501–521, https://doi.org/10.1016/j.marpetgeo.2018.05.039.

Lasabuda, A.P., Johansen, N.S., Laberg, J.S., Faleide, J.I., *et al.* 2021 Cenozoic uplift and erosion of the Norwegian Barents Shelf–a review. *Earth-Science Reviews*, **217**, 103609.

Lidmar-Bergström, K., Näslund, J.-O., Ebert, K., *et al.* 2007 Cenozoic landscape development in northern Scandinavia. *Norwegian Journal of Geology*, **87**, 181-196.

Lien, Ø.F., Hjelstuen, B.O., Zhang, X. and Sejrup, H.P. 2022. Late Plio-Pleistocene evolution of the Eurasian Ice Sheets inferred from sediment input along the northeastern Atlantic continental margin. *Quaternary Science Reviews*, **282**, 107433. https://doi.org/10.1016/j.quascirev.2022.107433

Ljones, F., Kuwano, A., Mjelde, R., *et al*. 2004. Crustal transect from the North Atlantic Knipovich Ridge to the Svalbard Margin west of Hornsund. *Tectonophysics*, **378**, 17-41.

Lundin, E.R. and Doré, A.G. 2002. Mid-Cenozoic post-breakup deformation in the 'passive' margins bordering the Norwegian- Greenland Sea. *Marine and Petroleum Geology*, **19**, 79–93.

Lundin, E.R., Doré, A.G., Rønning, K. and Kyrkjebø, R. 2013. Repeated inversion and collapse in the Late Cretaceous–Cenozoic northern Vøring Basin, offshore Norway. *Petroleum Geoscience*, **19**, 329–341. doi: 10.1144/petgeo2012-022

Løseth, H., Kyrkjebø, R., Hilde, E., *et al*. 2017. 500 m of rapid base level rise along an inner passive margin–Seismic observations from the Pliocene Molo Formation, mid Norway. *Marine and Petroleum Geology*, **86**, 268–287. https://doi.org/10.1016/j.marpetgeo.2017.05.039.

Martinsen, O.J., Bøen, F., Charnock, M.A., *et al*. 1999. Cenozoic development of the Norwegian margin 60-64°N: sequences and sedimentary response to variable basin physiography and tectonic setting. *Geological Society Petroleum Geology Conference Series*, **5**, 293-304.

Mau, S., Römer, M., Torres, M.E., et al. 2017. Widespread methane seepage along the continental margin off Svalbard - from Bjørnøya to Kongsfjorden. *Nature Scientific Reports*, 7:42997. DOI: 10.1038/srep42997

Maus, S., Barckhausen, U., Berkenbosch, H., *et al*. 2009. EMAG2: A 2-arc min resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne, and marine magnetic measurements. *Geochemistry, Geophysics, Geosystems*, **10**, Q08005.

Maystrenko, Y.P., Olesen, O., Gernigon, L. and Gradmann, S. 2017. Deep structure of the Lofoten-Vesterålen segment of the Mid-Norwegian continental margin and adjacent areas derived from 3-D density modeling: *Journal of Geophysical Research: Solid Earth*, **122**, 1402-1433.

Medvedev, S., Faleide, J.I. and Hartz, E. 2022. Cenozoic reshaping of the Barents-Kara Shelf: Influence of erosion, sedimentation, and glaciation. *Geomorphology*, **420**, 108500

Meza-Cala, J.C., Tsikalas, F., Faleide, J.I. and Abdelmalak, M.M. 2021. New insights into the late Mesozoic-Cenozoic tectono-stratigraphic evolution of the northern Lofoten-Vesterålen margin, offshore Norway. *Marine and Petroleum Geology*, **134**, 105370.

Millett, J.M., Manton, B.M., Zastrozhnov, D., *et al*. 2022. Basin Structure and Prospectivity of the NE Atlantic Volcanic Rifted Margin: Cross-border examples from the Faroe-Shetland, Møre and Southern Vøring Basins. *Geological Society of London, Special Publications*, **495**, 99–138, https://doi.org/10.1144/SP495-2019-12

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

Nasuti, A. and Olesen, O. 2014. Magnetic data. In: Hopper, J.R., Funck, T., Stoker, M.S., et al. (eds) Tectonostratigraphic Atlas of the North-East Atlantic Region. GEUS, Copenhagen, Denmark, 41-52.

Newton, A.M.W. and Huuse, M. 2017. Late Cenozoic environmental changes along the Norwegian margin. *Marine Geology*, **393**, 216-244. http://dx.doi.org/10.1016/j.margeo.2017.05.004

Niemann, H., Lösekann, T., de Beer, D., et al. 2006. Novel microbial communities of the Haakon Mosby mud volcano and their role as a methane sink. Nature, 443, 19 October 2006. Doi:10.1038/nature05227

Nygård, A., Sejrup, H.P., Haflidason, H. and Bryn, P. 2005. The glacial North Sea Fan, southern Norwegian Margin: architecture and evolution from the upper continental slope to the deep-sea basin. *Marine and Petroleum Geology*, **22**, 71–84. doi:10.1016/j.marpetgeo.2004.12.001

Olesen, O., Brönner, M. et al. 2010. New aeromagnetic and gravity compilations from Norway and adjacent areas: methods and applications. *Geological Society, London, Petroleum Geology Conference Series*, **7**, 559–586, https://doi.org/10.1144/0070559

Ottesen, D., Dowdeswell, J.A., Rise, L., *et al*. 2002. Large-scale morphological evidence for past ice-stream flow on the mid-Norwegian continental margin. *Geological Society Special Publications*, **203**, 245-258.

Ottesen, D., Dowdeswell, J. A. and Rise, L. 2005. Submarine landforms and the reconstruction of fastflowing ice streams within a large Quaternary ice sheet: the 2500 km-long Norwegian–Svalbard margin (57 to 80 N). *Geological Society of America Bulletin*, **117**, 1033–1050.

Ottesen, D., Rise, L., Andersen, E. S., Bugge, T. and Eidvin, T. 2009. Geological evolution of the Norwegian continental shelf between 61N and 68N during the last 3 million years. *Norwegian Journal of Geology*, **89**, 251–265.

Ottesen, D., Dowdeswell, J.A., Rise, L. and Bugge, T. 2012. Large-scale development of the mid-Norwegian shelf over the last three million years and potential for hydrocarbon reservoirs in glacial sediments. *Geological Society Special Publications*, **368**, doi 10.1144/SP368.6

Pape, T., Feseker, T., Kasten, S., *et al*. 2011. Distribution and abundance of gas hydrates in near-surface deposits of the Håkon Mosby Mud Volcano, SW Barents Sea. *G-cube*, **12**. doi:10.1029/2011GC003575

Parnell-Turner, R., White, N.J., McCave, I.N., *et al*. 2015. Architecture of North Atlantic contourite drifts modified by transient circulation of the Icelandic mantle plume. *Geochemistry, Geophysics, Geosystems*, **16**, 3414-3435.

Pascal, C. 2015. Heat flow of Norway and its continental shelf. *Marine and Petroleum Geology*, **66**, 956-969, http://dx.doi.org/10.1016/j.marpetgeo.2015.08.006

Patton, H., Hubbard, A., Heyman, J., *et al*. 2022. The extreme yet transient nature of glacial erosion. *Nature Communications*, **13**:7377. https://doi.org/10.1038/s41467-022-35072-0

Planke, S., Symonds, P.A., Alvestad, E. and Skogseid, J. 2000. Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins. *Journal of Geophysical Research - Solid Earth*, **105**, 19335–19351. https://doi.org/10.1029/1999JB900005

Planke, S., Millett, J.M., Maharjan, D., *et al*. 2017. Igneous seismic geomorphology of buried lava fields and coastal escarpments on the Vøring volcanic rifted margin. *Interpretation*, **5**, 1–42.

Planke, S., Berndt, C., Alvarez Zarikian, C.A., and the Expedition 396 Scientists 2023. Expedition 396 summary. *Proceedings of the International Ocean Discovery Program*, Volume **396**, publications.iodp.org

Praeg, D., Stoker, M.S., Shannon, P.M., *et al*. 2005. Episodic Cenozoic tectonism and the development of the NW European 'passive' continental margin. *Marine and Petroleum Geology*, **22**, 1007–1030. doi:10.1016/j.marpetgeo.2005.03.014

Rebesco, M., Hernández-Molina, F.J., Van Rooij, D. and Wåhlin, A. 2014. Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations. *Marine Geology*, **352**, 11-154.

Redfield, T. and Osmundsen, P.T. 2013. The long-term topographic response of a continent adjacent to a hyperextended margin: A case study from Scandinavia. *GSA Bulletin*, **125**, 184–200. doi:10.1130/B30691.1

Richardsen, G., Henriksen, E. and Vorren, T.O. 1991. Evolution of the Cenozoic sedimentary wedge during rifting and seafloor spreading west of the Stappen High, western Barents Sea. *Marine Geology*, **101**, 11-30.

Riis, F., Berg, K., Cartwright, J., *et al*. 2005. Formation of large, crater-like evacuation structures in ooze sediments in the Norwegian Sea. Possible implications for the development of the Storegga Slide. *Marine and Petroleum Geology*, **22**, 257–273. doi:10.1016/j.marpetgeo.2004.10.023

Rise, L. and Sættem, J. 1994. Shallow stratigraphic wireline coring in bedrock offshore Norway. *Scientific Drilling*, **4**, 243-257.

Rise, L., Ottesen, D., Berg, K. and Lundin, E. 2005. Large-scale development of the mid-Norwegian margin during the last 3 million years. *Marine and Petroleum Geology*, **22**, 33–44.

Rise, L., Ottesen, D., Longva, O., *et al*. 2006. The Sklinnadjupet slide and its relation to the Elsterian glaciation on the mid-Norwegian margin. *Marine and Petroleum Geology*, **23**, 569–583.

Rise, L., Chand, S., Hjelstuen, B.O., *et al*. 2010. Late Cenozoic geological development of the south Vøring margin, mid-Norway. *Marine and Petroleum Geology*, **27**, 1789-1803. doi:10.1016/j.marpetgeo.2010.09.001

Rise, L., Bøe, R., Riis, F., *et al*. 2013. The Lofoten-Vesterålen continental margin, North Norway: Canyons and mass-movement activity. *Marine and Petroleum Geology*, **45**, 134-149.

Ritter, U., Zielinski, G.R., Weiss, H.M., *et al*. 2004. Heat flow in the Vøring Basin, Mid-Norwegian Shelf. *Petroleum Geoscience*, **10**, 353–365, https://doi.org/10.1144/1354-079303-616

Rydningen, T.A., Høgseth, G.V., Lasabuda, A.P.E., Laberg, J.S., *et al*. 2020. An early Neogene—Early Quaternary contourite drift system on the SW Barents Sea continental margin, Norwegian Arctic. *G-cube*, **21**, e2020GC009142. https://doi.org/10.1029/2020GC009142

Ryseth, A.E., Augustson, J.H., Charnock, M., *et al*. 2003. Cenozoic stratigraphy and evolution of the Sørvestsnaget Basin, southwest Barents Sea. *Norwegian Journal of Geology*, 83, 107–130.

Ryseth, A.E., Similox-Tohon, D. and Thieβen, O. 2021. Tromsø–Bjørnøya Composite Tectono-Sedimentary Element, Barents Sea. Geological Society, London, Memoirs, 57, https://doi.org/10.1144/M57-2018-19

Safronova, P.A., Laberg, J.S., Andreassen, K., *et al*. 2017. Late Pliocene–early Pleistocene deep-sea basin sedimentation at high-latitudes:mega-scale submarine slides of the north-western Barents Sea margin prior to the shelf-edge glaciations. *Basin Research*, **29**, 537-555.

Sejrup, H.P., Larsen, E., Haflidason, H., *et al*. 2003. Configuration, history and impact of the Norwegian Channel Ice Stream. *Boreas*, **32**, 18–36. https://doi.org/10.1080/03009480310001029

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., *et al*. 2005. Pleistocene glacial history of the NW European continental margin. *Marine and Petroleum Geology*, **22**, 1111–1129. doi:10.1016/j.marpetgeo.2004.09.007

Skilbrei, J.R., Kihle, O., Olesen, O., *et al*. 2000.Gravity anomaly map Norway and adjacent ocean areas, scale 1:3 Million,Geological Survey of Norway, Trondheim.

Skogseid, J., Planke, S., Faleide, J.I., *et al*. 2000. NE Atlantic continental rifting and volcanic margin formation. *Geological Society Special Publications*, **167**, 295–326, https://doi.org/10.1144/GSL.SP.2000.167.01.12

Solheim, A., Faleide, J.I., Andersen, E.S., *et al.* 1998. Late Cenozoic seismic stratigraphy and glacial geological development of the East Greenland and Svalbard–Barents Sea continental margins. *Quat. Sci. Rev.* 17, 155–184.

Solheim, A., Berg, K., Forsberg, C.F. and Bryn, P. 2005. The Storegga Slide complex: repetitive large scale sliding with similar cause and development. *Marine and Petroleum Geology*, **22**, 97–107. doi:10.1016/j.marpetgeo.2004.10.013

Stoker, M.S., Praeg, D., Shannon, P.M., *et al*. 2005a. Neogene evolution of the Atlantic continental margin of NW Europe (Lofoten Islands to SW Ireland): anything but passive. *Geological Society, London, Petroleum Geology Conference Series*, **6**, 1057–1076.

Stoker, M.S., Hoult, R.J., Nielsen, T., *et al*. 2005b. Sedimentary and oceanographic responses to early Neogene compression on the NW European margin. *Marine and Petroleum Geology*, 22. doi: 10.1016/j.marpetgeo.2005.01.009.

Stoker, M.S., Praeg, D., Hjelstuen, B.O., Laberg, J.S., *et al*. 2005c. Neogene stratigraphy and the sedimentary and oceanographic development of the NW European Atlantic margin. *Marine and Petroleum Geology*, **22**, 977–1005. doi:10.1016/j.marpetgeo.2004.11.007

Straume, E.O., Gaina, C., Medvedev, S. and Nisancioglu, K.H. 2020. Global Cenozoic Paleobathymetry with a focus on the Northern Hemisphere Oceanic Gateways. *Gondwana Research*, **86**, 126–143. https://doi.org/10.1016/j.gr.2020.05.011

Stuevold, L.M. and Eldholm, O. 1996. Cenozoic uplift of Fennoscandia inferred from a study of the mid-Norwegian margin. *Global and Planetary Change*, **12**, 359-386.

Sættem, J., Bugge, T., Fanavoll, S., *et al*. 1994. Cenozoic margin development and erosion of the Barents Sea: Core evidence from southwest of Bjørnøya. *Marine Geology*, **118**, 257-281.

Talwani, M., Udintsev, G. and White S.M. 1976. Introduction and Explanatory Notes, Leg 38, Deep Sea Drilling Project. doi:10.2973/dsdp.proc.38.101.1976.

Thiede, J., Eldholm, O. and Taylor, E. 1989. Variability of Cenozoic Norwegian-Greenland Sea paleoceanography and northern hemisphere paleoclimate. Proceedings of the Ocean Drilling Program, Scientific Results, 104, 1067-118.

Tsikalas, F., Meza-Cala, J.C., Abdelmalak, M.M., *et al*. 2022. Lofoten Composite Tectono-Sedimentary Element, Norwegian Rifted Margin, Norwegian Sea. *Geological Society of London, Memoirs*, **57**,

Verhoef, J., Roest, W. R., MacNab, R., *et al*. 1996. Magnetic anomalies of the Arctic and North Atlantic Oceans and adjacent land areas. Geological Survey Canada Open File 3125a.

Vorren, T.O., Lebesbye, E., Andreassen, K. and Larsen, K.-B. 1989. Glacigenic sediments on a passive continental margin as exemplified by the Barents Sea. *Marine Geology*, **85**, 251-272.

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

Vorren, T.O., Laberg, J.S., Blaume, F., *et al.* 1998, The Norwegian-Greenland Sea continental margins: Morphology and Late Quaternary Sedimentary processes and environment: Quaternary Science Reviews, v. 17, p. 273-302, https://doi.org/10.1016/S0277-3791(97)00072-3.

Vågnes, E., Gabrielsen, R.H. and Haremo, P. 1998. Late Cretaceous–Cenozoic intraplate contractional deformation at the Norwegian continental shelf: timing, magnitude and regional implications. *Tectonophysics*, **300**, 29–46.

Weniger, P., Blumenberg, M., Berglar, K., *et al*. 2019. Origin of near-surface hydrocarbon gases bound in northern Barents Sea sediments. *Marine and Petroleum Geology*, **102**, 455-476.

Zastrozhnov, D., Gernigon, L., Gogin, I., *et al*. 2020, Regional structure and polyphased Cretaceous-Paleocene rift and basin development of the mid-Norwegian volcanic passive margin. *Marine and Petroleum Geology*, **115**, 104269.

Figure captions

Figure 1: (A) Regional North Atlantic-Arctic setting and location of study area. (B) Study area with outline of the Norwegian Sea Oceanic Basin and Prograded Margins Composite Tectono-Sedimentary Element. Outline of other CTSE's also shown. Topography and bathymetry from IBCAO (Jakobsson et al. 2020) and oceanic structure based on Abdelmalak et al. (2023). Bj, Bjørnøya; FS, Fram Strait; EGFZ, East Greenland Fracture Zone; GIFR, Greenland-Iceland-Faroe Ridge; KB, Kolbeinsey Ridge; Kfj, Kongsfjorden; KR, Knipovich Ridge; LVM, Lofoten-Vesterålen Margin; NC, Norwegian Channel; ÆR, Ægir Ridge.

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Figure 5: Regional profiles across the Møre-Vøring margins highlighting the post-breakup succession. Profile A based on Martinsen *et al*. (1999) and Nygård *et al*. (2005). Profile B based on Gernigon *et al*. (2021) and Hjelstuen and Andreassen (2015). Profiles C-E based on Gernigon *et al*. (2021). Profile locations shown in Figs. 2, 6 and 7.

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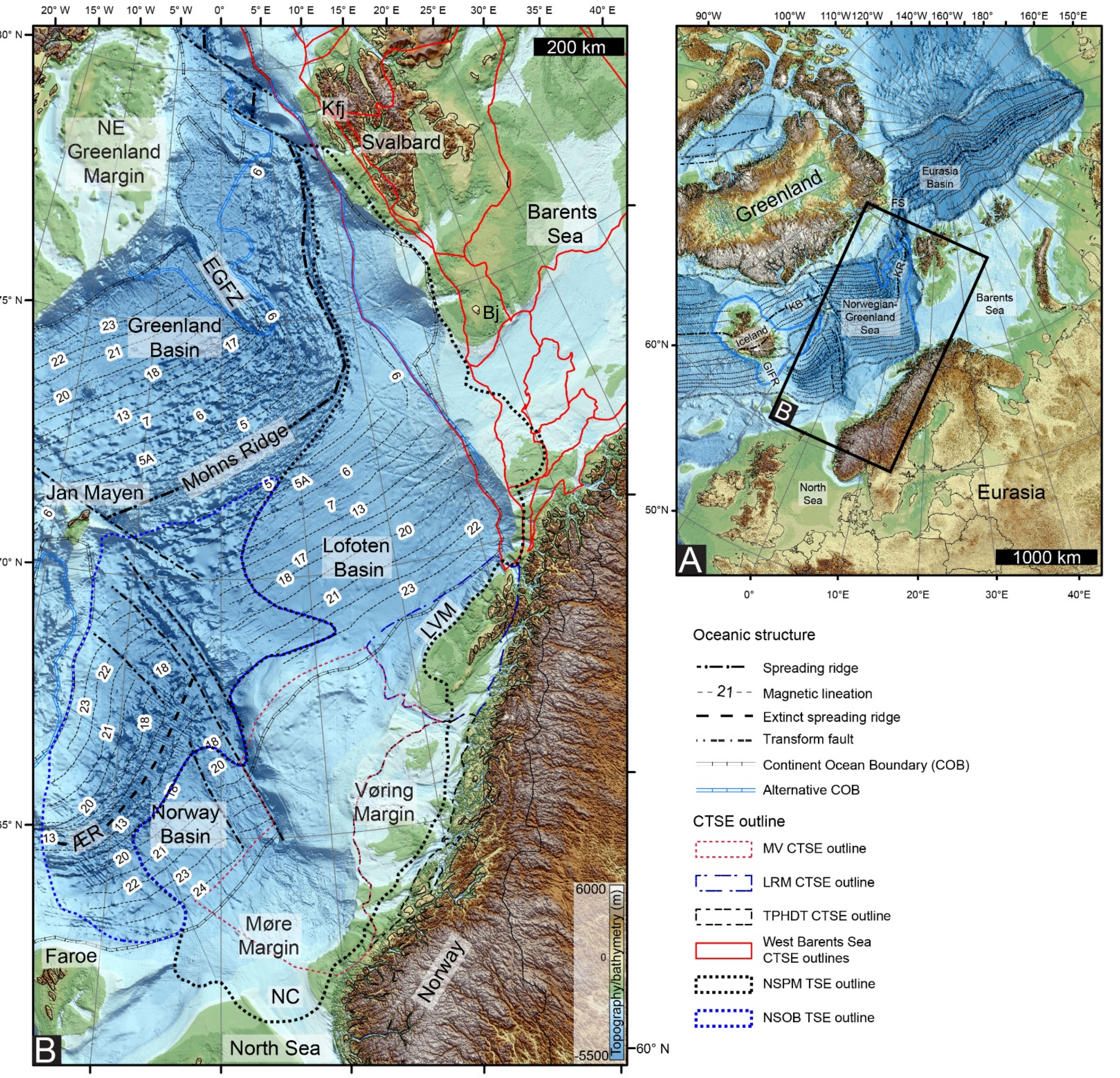

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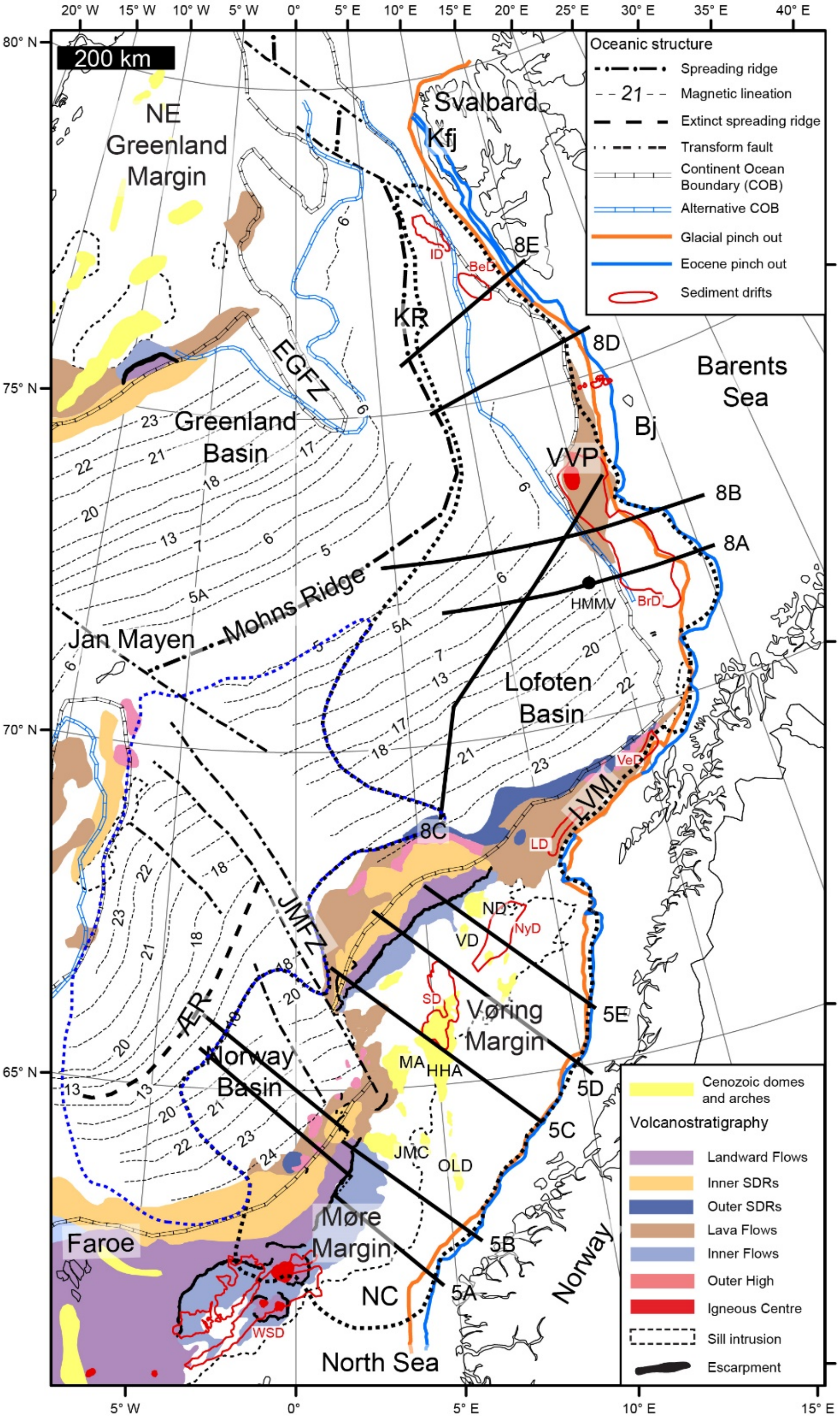

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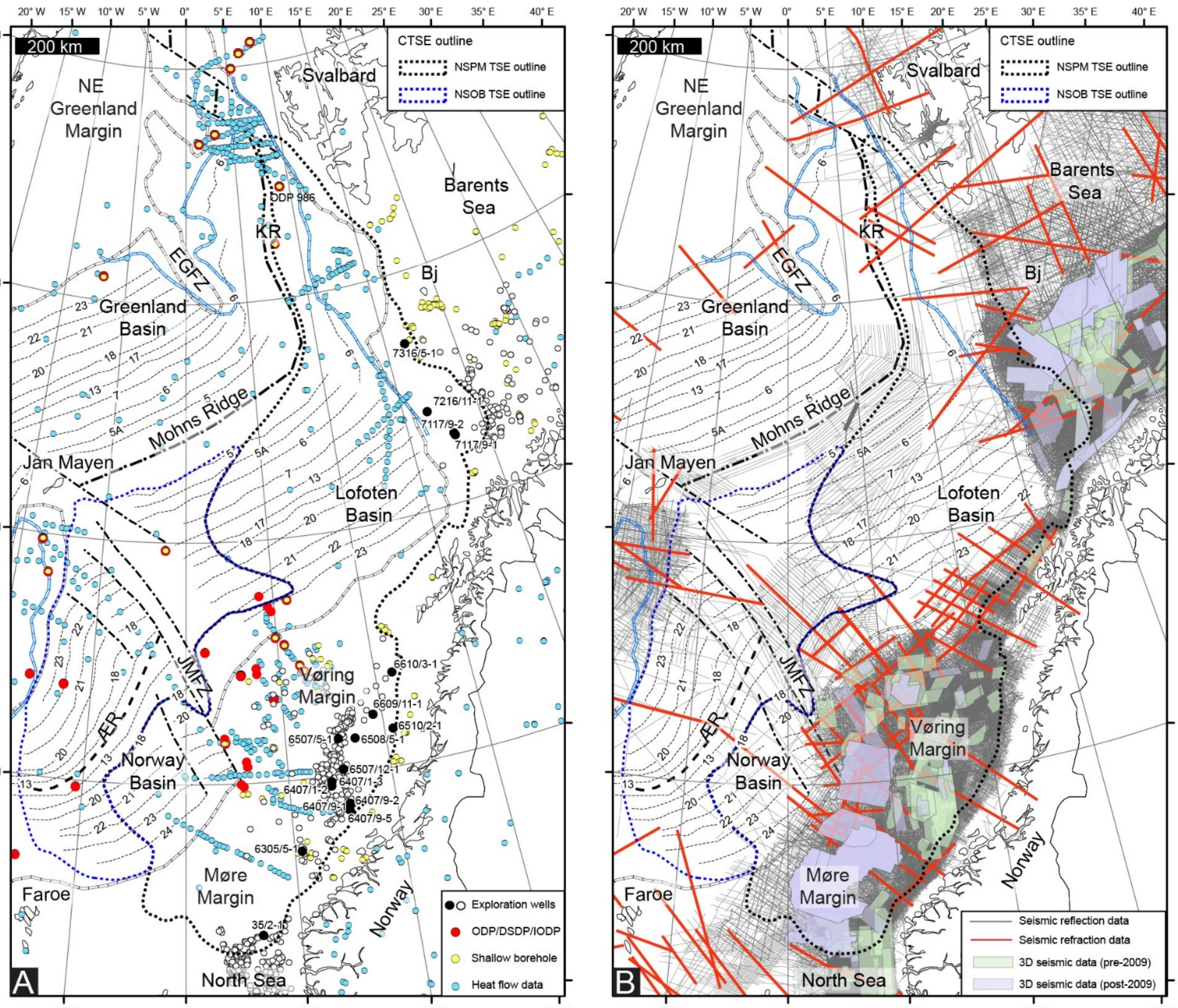

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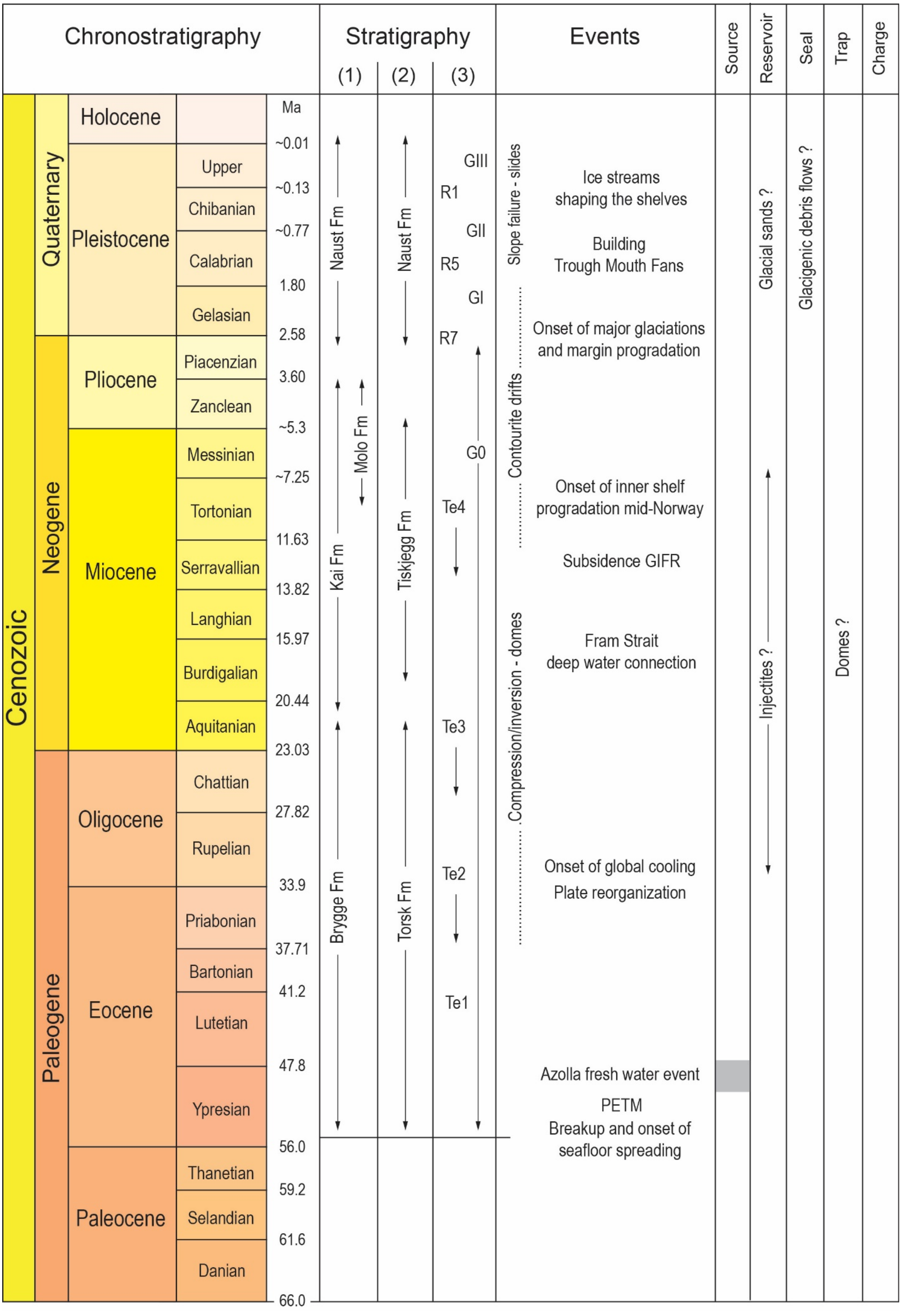

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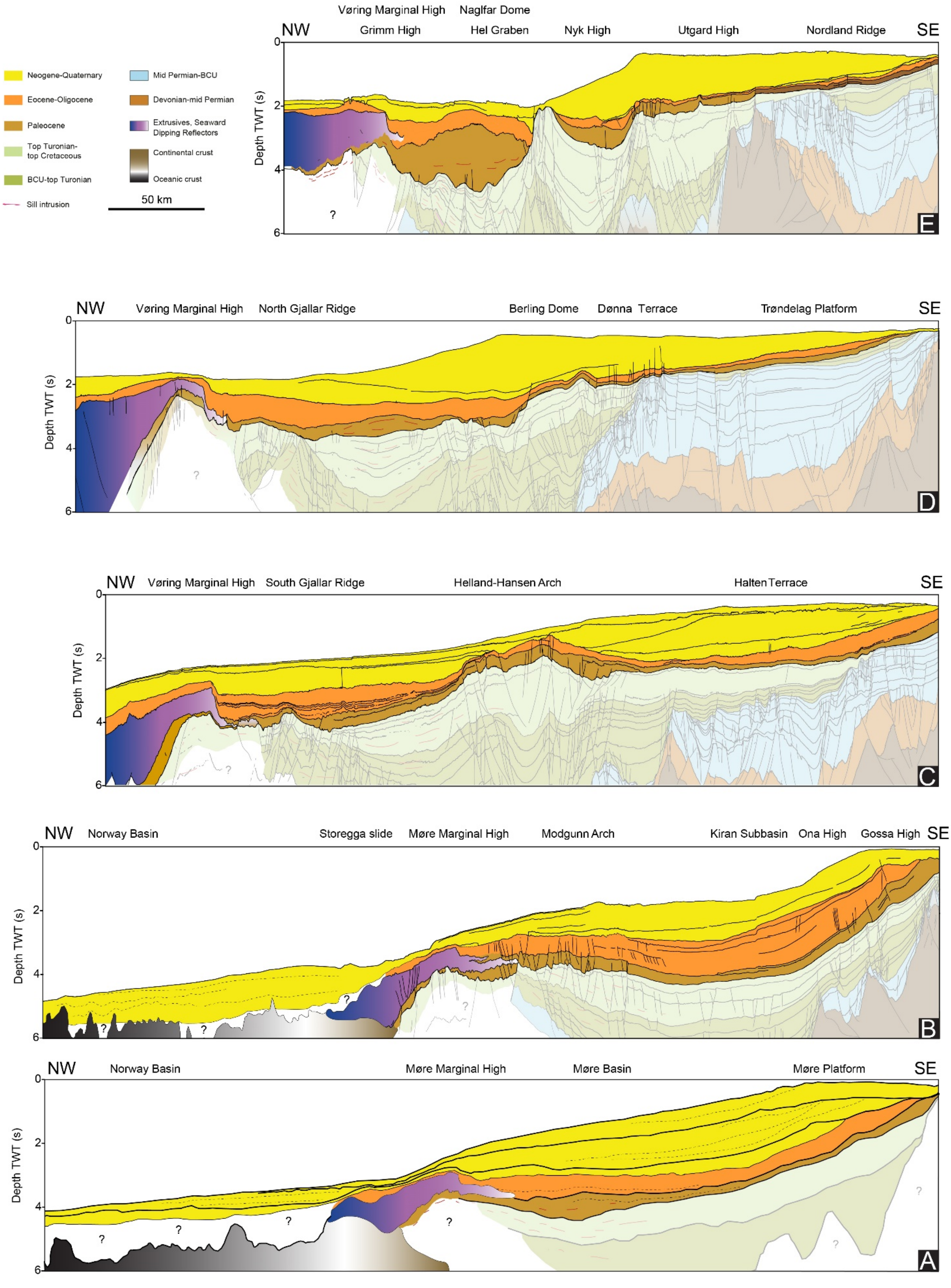

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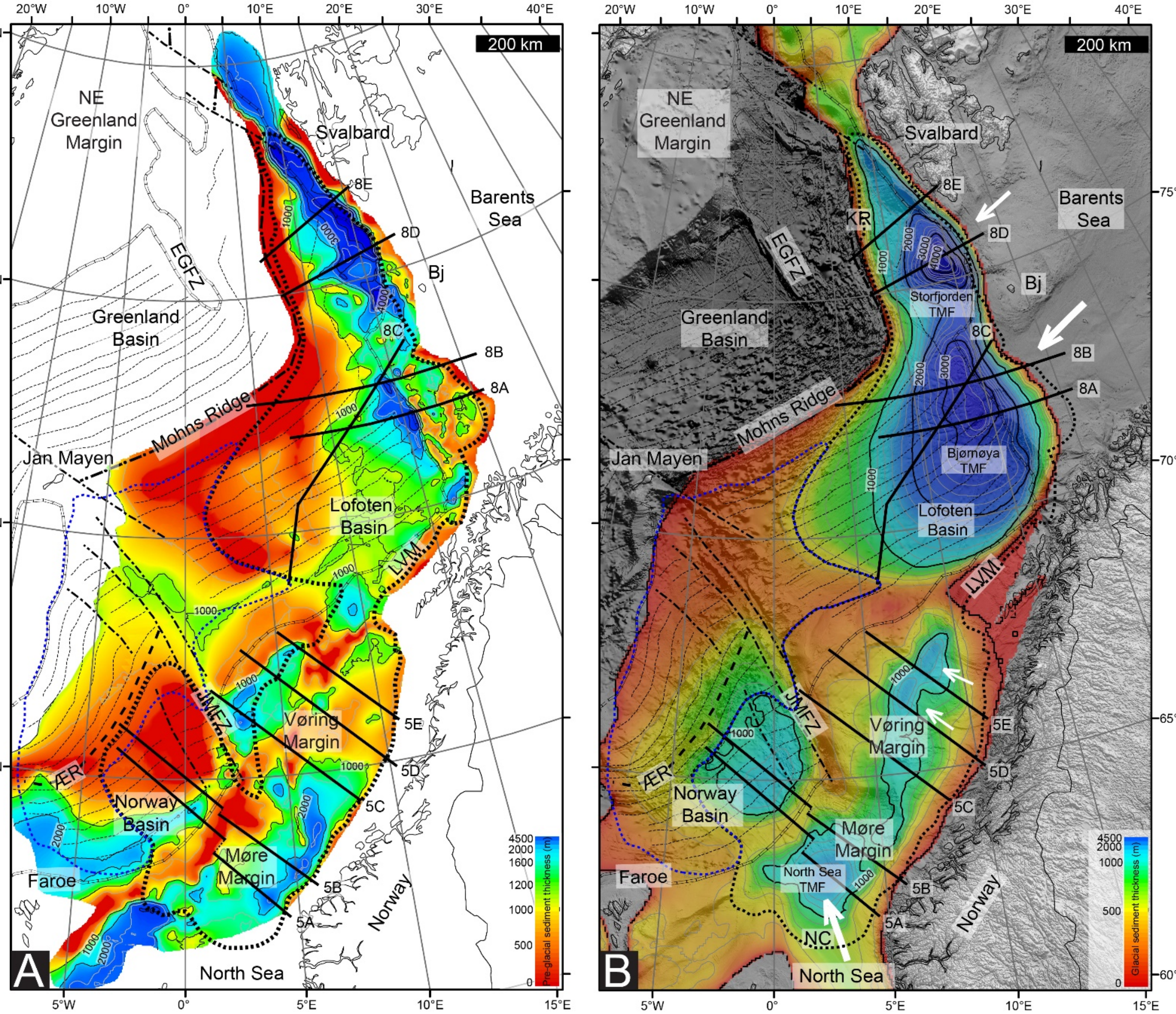

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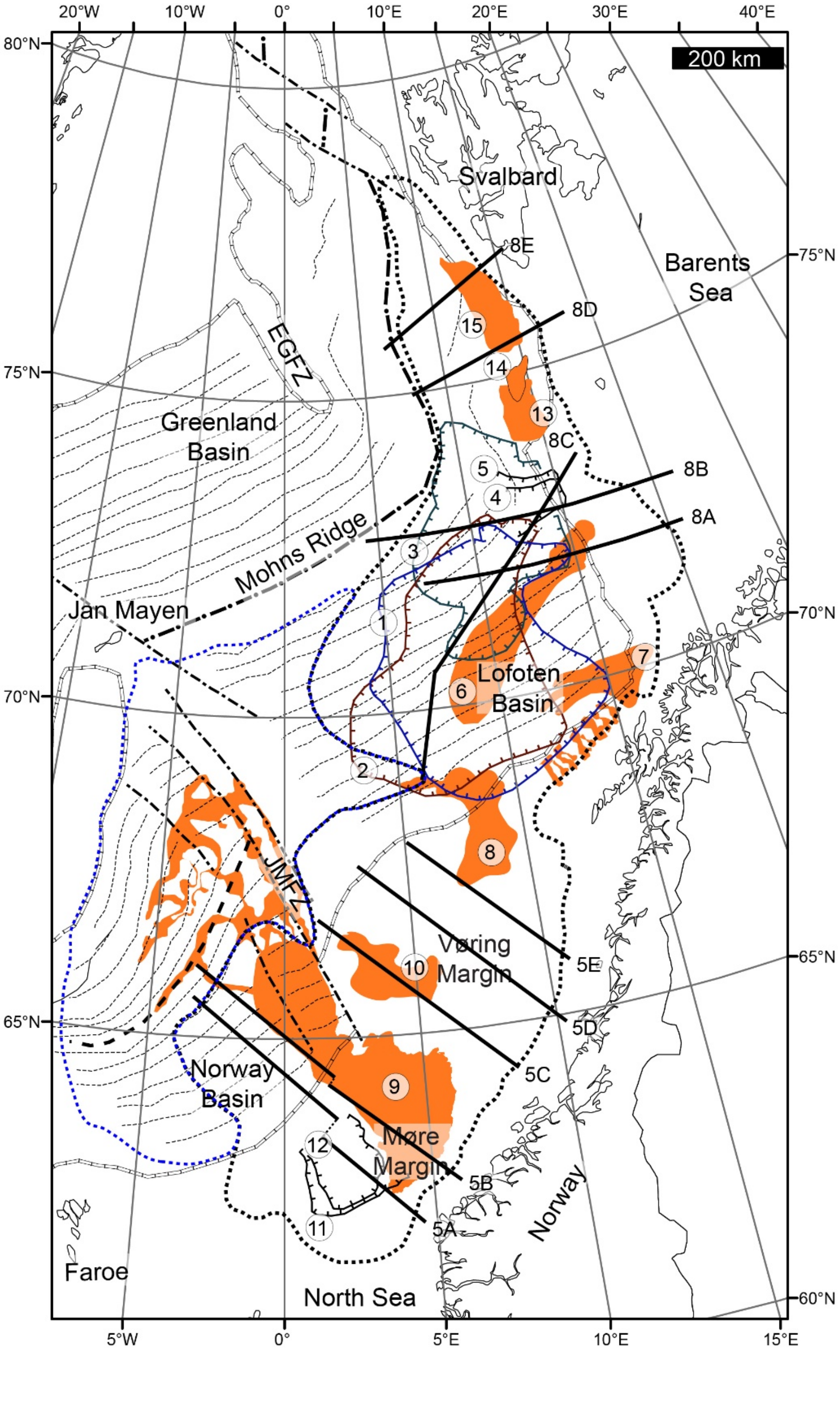

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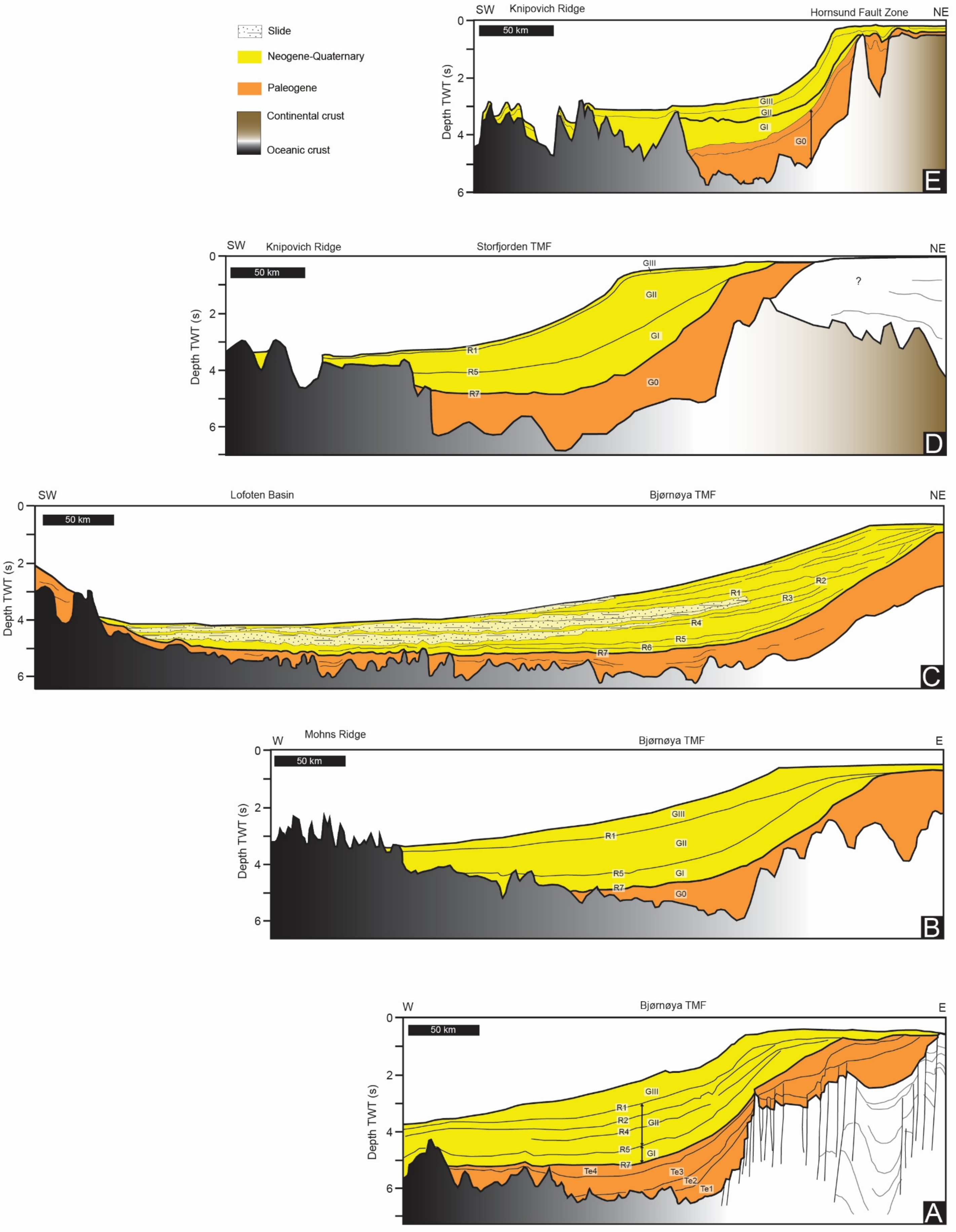

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