GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G48106.1

Manuscript received 8 July 2020
Revised manuscript received 21 September 2020
Manuscript accepted 22 September 2020

Published online 20 November 2020

Latitudinal variability in the Quaternary development of the Eurasian ice sheets—Evidence from the marine domain

Berit Oline Hjelstuen and Hans Petter Sejrup
Department of Earth Science, University of Bergen, Allegt 41, N-5007 Bergen, Norway

ABSTRACT

Here we present the first compilation of sediment volumes, sedimentation rates, and chronology of Quaternary sediment packages along the entire marine margin of the Eurasian ice sheets (EurIS; British–Irish, Kara–Barents Sea–Svalbard, and Fennoscandian). This compilation allows for a subdivision of the EurIS development into three phases (2.6–1.5 Ma, 1.5–0.78 Ma, and 0.78–0 Ma). At the start of the Quaternary, sedimentation rates increased, relative to pre-Quaternary rates, by an order of magnitude. This abruptness in rate change excludes tectonic raising of landmasses as the main factor, but more likely reflects climate change through increased glacial erosion. The sediment distribution data suggest that the Kara–Barents Sea–Svalbard Ice Sheet (KBSIS) already was quite large at the beginning of the Quaternary, and well before 1.5 Ma it extended to the shelf edge and coalesced with the Fennoscandian Ice Sheet (FIS), which prior to 1.5 Ma most likely was located near the coast. Large ice streams and intense glacial erosion characterized the KBSIS in the 1.5–0.78 Ma time period, whereas the FIS at that time extended farther out on the continental shelf. After 0.78 Ma, a north-south change in EurIS development occurred. In the FIS and the British–Irish Ice Sheet (BIIS), large ice streams developed and shelf-edge glaciations occurred nearly 1 m.y. later compared to the KBSIS. The FIS and BIIS also repetitively coalesced in the North Sea. A significant drop in sediment input along the KBSIS marine margin, to the lowest Quaternary level, suggests a less erosive KBSIS.

INTRODUCTION

At the Pliocene-Pleistocene boundary, the global climate cooled from temperatures 3–4 °C higher than today, transitioning into a 2.6 m.y. period—the Quaternary—characterized by increasingly colder climate, larger climate variability, and extensive glaciations (e.g., Lisiecki and Raymo, 2005; De Schepper et al., 2014). Marine depocenters that formed adjacent to continental ice sheets during the Quaternary reflect climate changes, ice sheet dynamics, the intensity of erosion, and the effect of uplift and subsidence in onshore and offshore catchment areas (Vorren et al., 1998; Nielsen et al., 2005; Fjeldskaar and Amantov, 2017). Volume estimates of such sediment accumulation along the marine margin of the paleo–Eurasian ice sheets (EurIS; British–Irish, Kara–Barents Sea–Svalbard, and Fennoscandian) (Fig. 1) have been essential in detailing the development of glaciations through the Quaternary and in evaluating the role of tectonic uplift versus climate cooling in shaping northwestern European landscapes (Dowdeswell et al., 2010; Steer et al., 2012; Andersen et al., 2018). A challenge, however, has been that studies of the geometry, processes, and geochronology of the Quaternary sedimentary package have focused only on parts of the EurIS marine margin.

Here, we report an inventory of the output of Quaternary erosion products into the oceans from the entire region that was repeatedly glaciated by the EurIS, including an assessment of pre-glacial Paleocene–Pliocene accumulation rates in the same region (Fig. 2). Based on overall trends in sedimentation rates and timing of sediment input, we discuss the variability and extent of the EurIS, glacial erosion, and ice dynamics. The available geochronological control allows for a subdivision of the EurIS development into three phases: the Northern Hemisphere glaciation (NHG) phases I (2.6–1.5 Ma), II (1.5–0.78 Ma), and III (0.78–0 Ma). The 2.6 and 0.78 Ma phase boundaries are linked to paleomagnetic datum levels (Matuyama-Gauss and Brunhes-Matuyama reversals, respectively), identified in a number of deep-sea and continental-shelf cores along the northwestern European margin (Fig. S1 and Table S1 in the Supplemental Material[1]), whereas the 1.5 Ma boundary is based on biostratigraphy and extrapolation between the top Olduvai (1.77 Ma) and base Jaramillo (1.0 Ma) magnetic excursion events.

QUATERNARY DEVELOPMENT OF THE EURIS MARGIN

At the end of the Neogene, the paleo-EurIS marine margin was dominated by fluvial sediment input and nonglacial environments. The Barents Sea, which during the entire Cenozoic was subject to uplift, was at this time subaerially exposed, and it is assumed that rivers followed the incipient track of the large troughs that characterize the present-day bathymetry (Vorren et al., 1991; Fjeldskaar and Amantov, 2017; Zieba et al., 2017). At the mid-Norwegian margin, a 600-km-long and as much as 500-m-thick and 60-km-wide siliciclastic delta, represented by the Molo Formation, was developing (Eidvin et al., 2007), whereas in the southern and central North Sea, which since the Late Cretaceous has undergone subsidence, rivers built out huge deltas in the late Neogene (e.g., Patruno et al., 2020).

It has been suggested that the three individual ice sheets composing the EurIS (Fig. 1) repeatedly coalesced during the Quaternary (e.g., Sejrup et al., 2005). The dominantly marine-based Kara–Barents Sea–Svalbard Ice Sheet (KBSIS) was, during its lifetime, dissected by

[1]Supplemental Material. Overview of published studies included in the present compilation, methods used, calculated sedimentation rates and sediment volumes, uncertainties, and figures of the configuration of the EurIS marine margin and IRD records. Please visit https://doi.org/10.1130/GEOL.S.13150880 to access the supplemental material, and contact editing@geosociety.org with any questions.

CITATION: 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, v. 49, p. 346–351, https://doi.org/10.1130/G48106.1

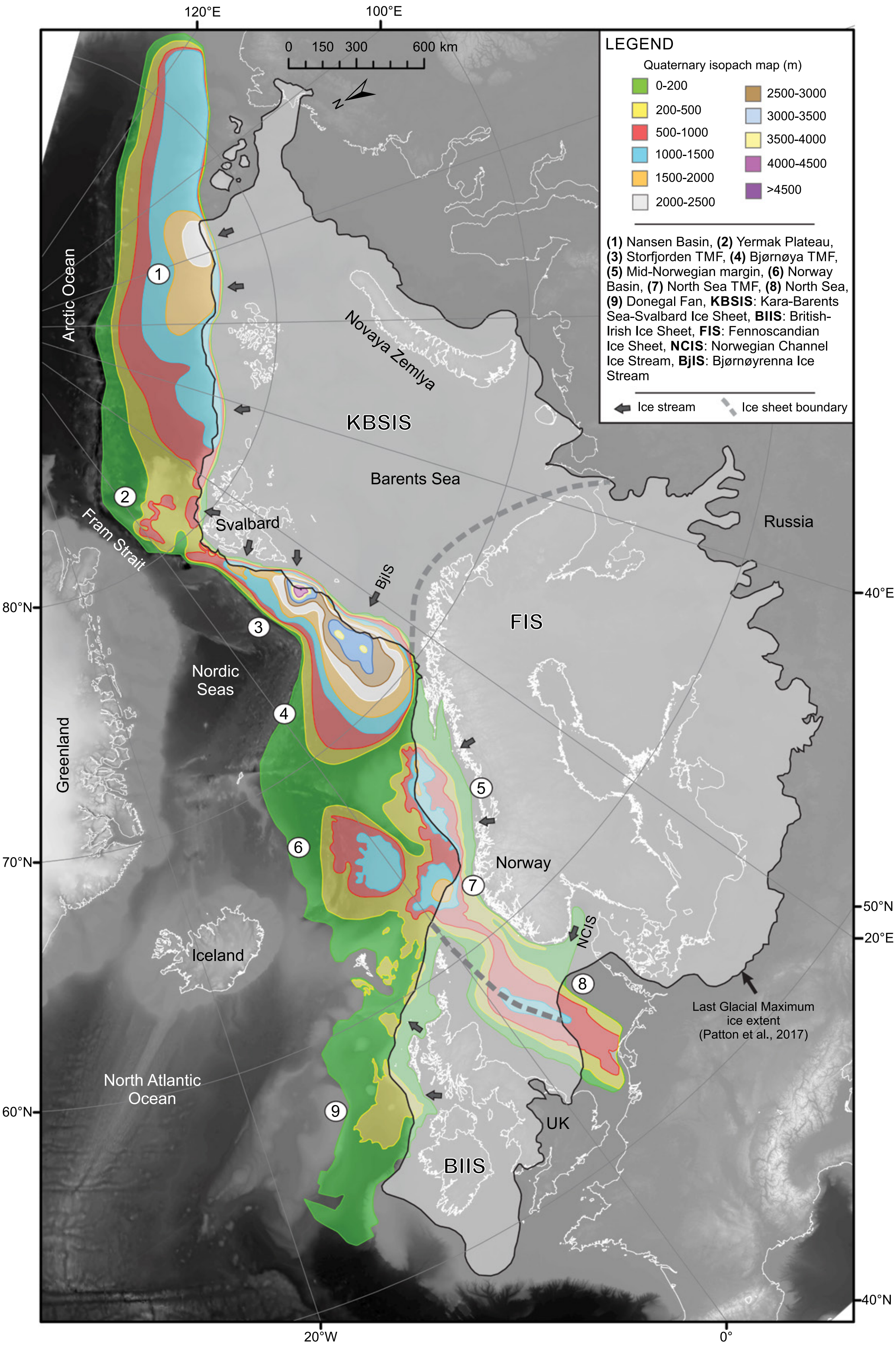

Figure 1. Quaternary isopach map, illustrating the massive amount of sediments delivered to the marine margin of the Eurasian ice sheets (EurIS; British–Irish, Kara–Barents Sea–Svalbard, and Fennoscandian). TMF—trough-mouth fan.

numerous ice streams, evidenced by distinct trough-mouth fans (TMFs) along the margin (Faleide et al., 1996; Vorren et al., 1998). Several ice streams also drained the land based–dominated Fennoscandian Ice Sheet (FIS) (Ottesen et al., 2005). However, the configuration of the mid-Norwegian margin and the North Sea facilitated the development of major prograding wedges, characterized by well-developed clinoforms. The British–Irish margin, along which the dominantly marine-based British–Irish Ice Sheet (BIIS) developed, is characterized by

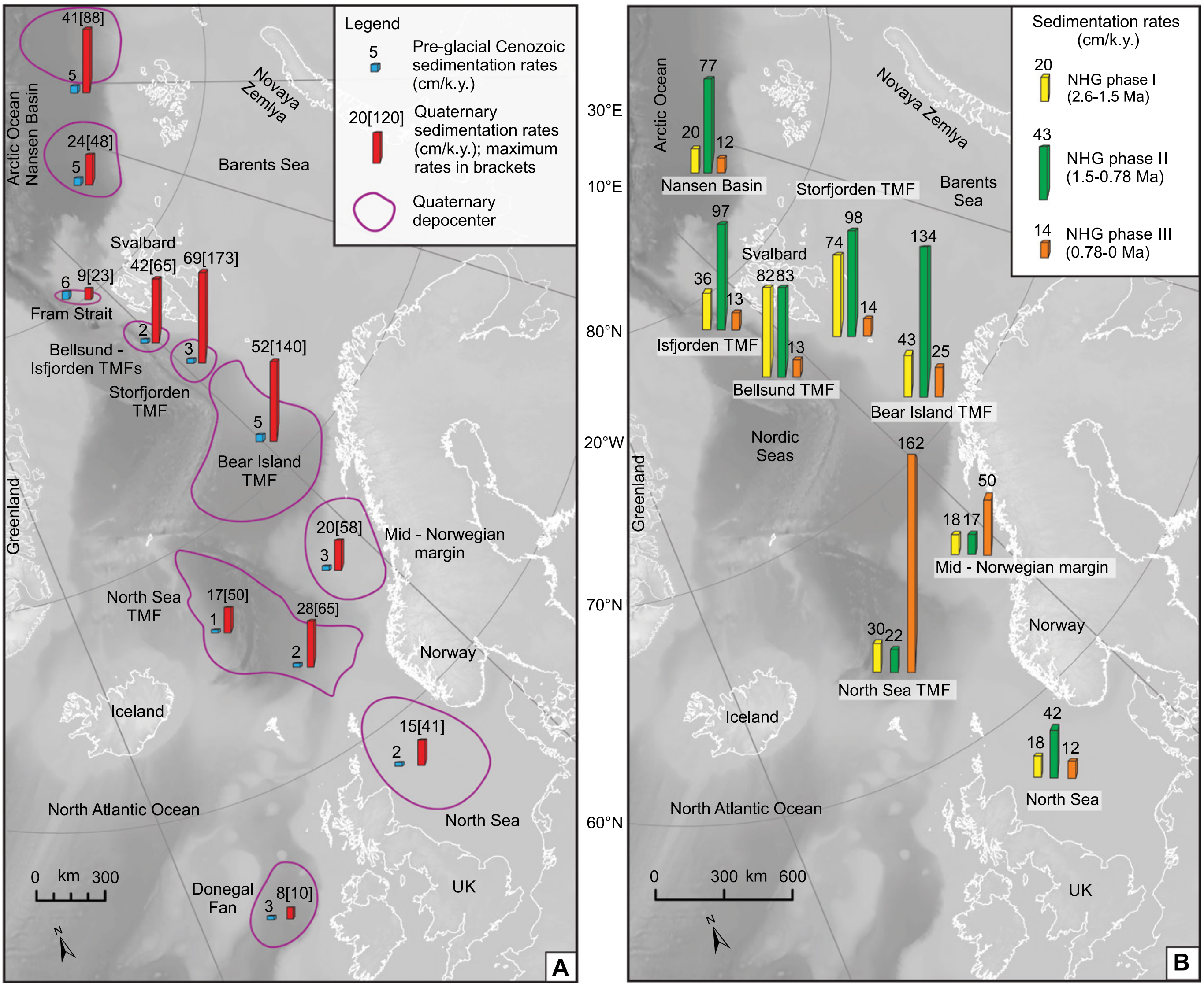

Figure 2. Estimated sedimentation rates for pre-glacial and glacial time periods (A) and Northern Hemisphere glaciation (NHG) phases I–III (B). Note that NHG phase I–III sedimentation rates are only provided in regions with sufficient Quaternary age control. TMF—trough-mouth fan.

relatively smaller-sized TMFs and prograding wedges (Stoker et al., 2005) compared to those found farther north.

The large-scale morphology of the continental shelves of the EurIS marine margin, in addition to glacial landforms such as end moraines, grounding zone wedges, and megascale glacial lineations (MSGLs) (e.g., Ottesen et al., 2005; Sejrup et al., 2005) attest to the existence and extent of former glaciations. Three sedimentary processes are of particular importance when evaluating sedimentation rates on glaciated margins: (1) glacigenic debris flows (GDFs), the building blocks of TMFs, are deposited in periods of shelf-edge glaciations (King et al., 1998; Nygård et al., 2007); (2) submarine slides have occurred frequently in the study area, causing remobilization and transport of slope deposits (Evans et al., 2005); and (3) high-sediment-rate accumulations as contourites (Rebesco et al., 2014) and plumites (Lekens et al., 2005) have been identified along the EurIS margin.

DATA AND METHODS

This study used a compilation of published data on Quaternary sediment volumes, chronostratigraphy, ice-rafted debris (IRD), and glacial landforms in the marine area adjacent to the paleo-EurIS margin (Tables S1–S7 and Figs. S1–S3). It should be emphasized that the amount of data from the Arctic Ocean and British–Irish North Atlantic margin is relatively sparse compared to the western Svalbard–Barents Sea and Norwegian margins, where it is possible to subdivide the Quaternary sediments into three units. The results of our compilation, the methods used, and uncertainties are summarized in the Supplemental Material. Uncertainties related to chronology and sediment-volume estimates are not considered to jeopardize the overall statements on trends and the conclusions of this study.

SEDIMENTATION RATE AND VOLUME ESTIMATES

A total Quaternary sediment volume of ~1.8 × 10^6 km^3 (3.2 × 10^{15} tons) has been deposited in the ~2.8 × 10^6 km^2 EurIS depositional area defined in this study (Fig. 1; Tables S4 and S5). Of this volume, ~75% is eroded from the KBSIS catchment region, ~20% from the FIS region, and ~5% from the BIIS region.

An average sedimentation rate of <7 cm/k.y. was calculated for the pre-Quaternary Cenozoic time span, with the highest rates in the Oligocene and early–middle Miocene (Table S6). The most dramatic change in Cenozoic sedimentation rates took place at the transition to the Quaternary period (Fig. 2A; Tables S6 and S7), when the average sedimentation rate increased by an

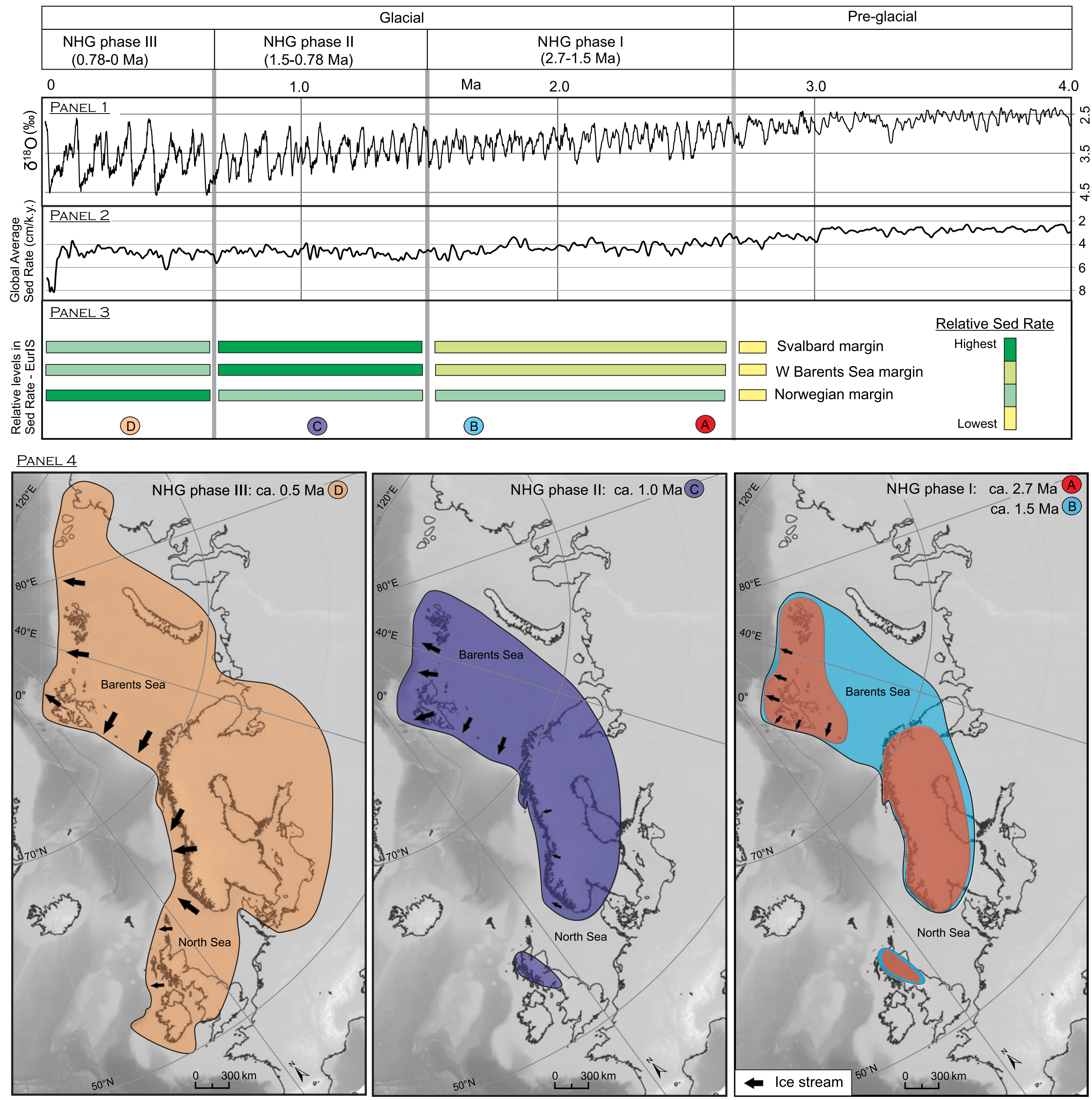

Figure 3. Proposed Quaternary development of Eurasian ice sheets (EurIS; British–Irish, Kara–Barents Sea–Svalbard, and Fennoscandian) (panel 4) in relation to the global marine isotope curve (panel 1) and global sedimentation rates (panel 2) (both from Lisiecki and Raymo, 2005), and relative sedimentation rates (panel 3) from this study. Sed. Rate—sedimentation rate.

order of magnitude along the entire marine border of the paleo-EurIS.

In NHG phase I, the highest sedimentation rates are found along the northwestern Barents Sea and western Svalbard margins (Fig. 2B). Both the western Svalbard–Barents Sea margin and the North Sea experienced a further increase in sedimentation rates in NHG phase II. Indeed, these regions had the highest Quaternary sediment input during NHG phase II, implying that the main Quaternary building of TMFs and prograding wedges in these regions occurred in this ~0.8-m.y.-long time span. During NHG phase III, sedimentation rates dropped significantly in the north as the mid-Norwegian and northern North Sea margins experienced their most massive Quaternary sediment input (Fig. 2B).

EurIS RECONSTRUCTION

The abrupt increase in sedimentation rates at the northwestern European margin close to the Pliocene-Pleistocene boundary (Fig. 2A) coincides with gradual heavier global $\delta^{18}O$ values and an increase in global average sedimentation rates (Lisiecki and Raymo, 2005) (Fig. 3). This also co-occurred with increased input of IRD to the northern North Atlantic Ocean (e.g., Henrich and Baumann, 1994; Knies et al., 2009) (Fig. S3). From this, we infer that the overall change and variability in sedimentation rates in Quaternary depocenters along the northeastern North Atlantic and eastern Arctic Ocean margins are largely controlled by climate through ice sheet expansion and glacial erosion.

During NHG phase I, the sedimentation rates were highest in the incipient depocenters along the northwestern Barents Sea and western Svalbard margins (Fig. 2B), which suggest an extensive ice sheet in this region. This supports the earlier conclusions of Knies et al. (2009) and Lasabuda et al. (2018), who, based on IRD records and identification of GDFs, suggested an ice sheet with active ice streams covering Svalbard and the adjacent continental margins. Identification of glacial-derived sediments in shelf-edge wells (Knies et al., 2009) and the development of a well-defined upper-slope depocenter (Fiedler and Faleide, 1996) at the southwestern Barents Sea margin support the supposition that NHG phase I sedimentation rates (Fig. 2B) are related to glacial erosion in the Bjørnøya TMF (Fig. 1) catchment area. GDFs (indicative of ice stream activity; King et al., 1998), of 2.6–1.5 Ma age have, however, not yet been identified in this region (Laberg et al., 2010). This may explain why the sedimentation rates are lower along the southwestern Barents Sea margin compared to farther north.

The mid-Norwegian margin experienced the lowest Quaternary sediment input during NHG phase I. IRD records from this region (Henrich and Baumann, 1994) may indicate an ice sheet beyond the coastline, providing erosion material to the incipient prograding wedge system. Few observations of ice stream–indicative MSGLs (Montelli et al., 2017; Table S3), and these low sedimentation rates, point toward low ice stream activity along the Norwegian margin. In the southern and central North Sea, the sediment input through river systems continued to dominate, whereas it has been discussed how far the FIS extended beyond the present coastline in western Norway during NHG phase I (Ottesen et al., 2018; Rea et al., 2018).

A dramatic growth of the depocenters around Svalbard and at the western Barents Sea margin took place during NHG phase II (Fig. 2B; Table S7). This suggests a switch-on of numerous KBSIS ice streams, including the prominent Bjørnøyrenna Ice Stream (Fig. 1), as is evidenced by GDFs in the sedimentary record (Laberg et al., 2010; Table S3). Along the Norwegian margin, the sedimentation rates were at the same level as in NHG phase I, suggesting a moderately erosive FIS, where ice streams seem to have been active occasionally (Sejrup et al., 2005; Rea et al., 2018).

The North Sea TMF and the mid-Norwegian prograding wedge had their most significant Quaternary growth during NHG phase III (Figs. 2B and 3). The FIS catchment region is dominantly composed of crystalline bedrock of the Fennoscandian mountains, which is more resistant to glacial erosion than sedimentary bedrock. Thus, the North Sea TMF and mid-Norwegian prograding wedge growth are most likely related to ice sheet growth and an intensification of glacial erosion. At the beginning of NHG phase III, the continental shelf of the mid-Norwegian margin had, for almost 2 m.y., been widening by ~100 km to a width of 150 km (e.g., Dowdeswell et al., 2010). This allowed for ice sheets to erode soft sediments on the continental shelf during the latest parts of the Quaternary, contributing to the estimated high sedimentation rates in this region. Furthermore, the observed change in depositional style on the continental shelf, from prograding to aggrading, at the transition to NHG phase III (Fig. S2) has been taken as an indication of buildup of larger ice sheets (Nielsen et al., 2005).

The decrease in sedimentation rates along the Barents Sea–Svalbard margin in NHG phase III (Fig. 2B) could suggest that the KBSIS did not extend to the shelf edge. However, identification of GDFs (Laberg et al., 2010; Lasabuda et al., 2018) implies that the KBSIS was located at the shelf edge and that ice streams were active also in NHG phase III. Fiedler and Faleide (1996) and Hjelstuen et al. (1996) showed that the character of bedrock exposed to erosion in the catchment areas of the Bjørnøya and Storfjorden TMFs (Fig. 1) was nearly the same during NHG phases II and III, implying a change in KBSIS erosion capacity since 0.78 Ma. This reduced erosion capacity may be a consequence of the fact that the Barents Sea at this time was below current sea level (Zieba et al., 2017) and that the KBSIS became a fully marine-based ice sheet.

IMPLICATIONS AND CONCLUSIONS

The data compilation presented here contributes to our understanding of temporal and spatial variability of the EurIS through the Quaternary. The data suggest that at the beginning of NHG phase I, an incipient KBSIS, with active ice streams, covered Svalbard and the neighboring continental shelves (Fig. 3). Further growth of the KBSIS through NHG phase I gave rise to an ice sheet that also extended to the shelf edge in the southwestern Barents Sea. In this region, the KBSIS probably merged with the FIS no later than 1.5 Ma; i.e., possibly as much as 1 m.y. earlier than previously suggested (e.g., Knies et al., 2009). The FIS is interpreted to have had a relatively restricted extent during the 2.6–0.78 Ma time period, whereas the KBSIS seems to have had its most intensive erosive period, with ice streams forming in every shelf trough in the Barents Sea, between 1.5 and 0.78 Ma. Our compilation suggests a north-south change in the behavior of the EurIS following NHG phase II. The FIS at this time extended to the shelf edge, and it also, most likely regularly, coalesced with the BIIS in the North Sea (Fig. 3). Thus, it seems that it took ~1 m.y. before the southern EurIS had established similar conditions—that is, a position at the shelf edge and comprehensive ice streaming—as the KBSIS already had established at ca. 1.5 Ma. The KBSIS does not seem to have had the powerful erosion capacity during the NHG phase III as during the earlier phases, but seems to have maintained active ice streams and to have been periodically located at the shelf edge.

NHG phase II includes the mid-Pleistocene transition (MPT, ca 1.2–0.8 Ma), characterized by a change from 41 k.y. to 100 k.y. glacial-interglacial cycles. Our compilation suggests more extensive glaciations in the south following the MPT. The buildup of the EurIS has been suggested as a cause of MPT through positive feedback, with a gradual cooling of the oceans allowing for further ice sheet growth (Tziperman and Gildor, 2003). A time lag of ~280 k.y. between onset of 100 k.y. glacial cycles and ice volume buildup has been suggested (Mudelsee and Schulz, 1997; Hughes and Gibbard, 2018) and apparently coincides with the southern growth of the EurIS in NHG phase III. Ice sheet modeling, based on long-term CO_2 decline and regolith removal over land areas surrounding the Atlantic and Arctic Oceans, coupled with orbital variations (Willeit et al., 2019), show a similar trend in EurIS development as suggested in this study.

Low pre-glacial sedimentation rates and the observed dramatic rate increase at the onset of the Quaternary suggest that glacial erosion was a main driver in shaping the Fennoscandian landscape. Taking the sedimentation rates into further consideration, the most significant landscape development in mainland Scandinavia, in the form of glacial erosion, took place during the Middle and Late Pleistocene.

This integrated quantitative study contributes to the understanding of EurIS extension and dynamics through the Quaternary. This understanding may provide a better basis for modeling terrestrial and marine landscape evolution. Such knowledge is essential in order to determine how bathymetric changes could have influenced oceanic circulation, as well as how EurIS and landscape evolution have influenced long-term climate evolution, including events such as the Pliocene-Pleistocene cooling and the MPT.

ACKNOWLEDGMENTS

We thank Eva Bjørseth for help with figures, and acknowledge constructive comments from Philip Hughes and two anonymous reviewers.

REFERENCES CITED

Andersen, J.L., et al., 2018, Widespread erosion on high plateaus during recent glaciations in Scandinavia: Nature Communications, v. 9, 830, https://doi.org/10.1038/s41467-018-03280-2.

De Schepper, S., Gibbard, P.L., Salzmann, U., and Ehlers, J., 2014, A global synthesis of the marine and terrestrial evidence for glaciation during the Pliocene Epoch: Earth-Science Reviews, v. 135, p. 83–102, https://doi.org/10.1016/j.earscirev.2014.04.003.

Dowdeswell, J.A., Ottesen, D., and Rise, L., 2010, Rates of sediment delivery from the Fennoscandian Ice Sheet through an ice age: Geology, v. 38, p. 3–6, https://doi.org/10.1130/G25523.1.

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: Norsk Geologisk Tidsskrift, v. 87, p. 75–142.

Evans, D., 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, v. 22, p. 1131–1148, https://doi.org/10.1016/j.marpetgeo.2005.01.010.

Faleide, J.I., Solheim, A., Fiedler, A., Hjelstuen, B.O., Andersen, E.S., and Vanneste, K., 1996, Late Cenozoic evolution of the western Barents Sea–Svalbard continental margin: Global and Planetary Change, v. 12, p. 53–74, https://doi.org/10.1016/0921-8181(95)00012-7.

Fiedler, A., and Faleide, J.I., 1996, Cenozoic sedimentation along the southwestern Barents Sea margin in relation to erosion and uplift of the shelf: Global and Planetary Change, v. 12, p. 75–93, https://doi.org/10.1016/0921-8181(95)00013-5.

Fjeldskaar, W., and Amantov, A., 2017, Effects of glaciations on sedimentary basins: Journal of Geodynamics, v. 118, p. 66–81, https://doi.org/10.1016/j.jog.2017.10.005.

Henrich, R., and Baumann, K.-H., 1994, Evolution of the Norwegian Current and the Scandinavian Ice Sheets during the past 2.6 m.y.: Evidence from ODP Leg 104 biogenic carbonate and terrigenous records: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 108, p. 75–94, https://doi.org/10.1016/0031-0182(94)90023-X.

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, v. 12, p. 95–117, https://doi.org/10.1016/0921-8181(95)00014-3.

Hughes, P.D., and Gibbard, P.L., 2018, Global glacier dynamics during 100 ka Pleistocene glacial cycles: Quaternary Research, v. 90, p. 222–243, https://doi.org/10.1017/qua.2018.37.

King, E.L., Haflidason, H., Sejrup, H.P., and Løvlie, R., 1998, Glacigenic debris flow on the North Sea Trough Mouth Fan during ice stream maxima: Marine Geology, v. 152, p. 217–246, https://doi.org/10.1016/S0025-3227(98)00072-3.

Knies, J., Matthiessen, J., Vogt, C., Laberg, J.S., Hjelstuen, B.O., Smelror, M., Larsen, E., Andreassen, K., Eidvin, T., and Vorren, T.O., 2009, The Plio-Pleistocene glaciations of the Barents Sea–Svalbard region: A new model based on revised chronostratigraphy: Quaternary Science Reviews, v. 28, p. 812–829, https://doi.org/10.1016/j.quascirev.2008.12.002.

Laberg, J.S., Andreassen, K., Knies, J., Vorren, T.O., and Winsborrow, M., 2010, Late Pliocene–Pleistocene development of the Barents Sea Ice Sheet: Geology, v. 38, p. 107–110, https://doi.org/10.1130/G30193.1.

Lasabuda, A., Geissler, W.H., Laberg, J.S., Knutsen, S.-M., Rydningen, T.A., and Berglar, K., 2018, Late Cenozoic erosion estimates for the northern Barents Sea: Quantifying glacial sediment input to the Arctic Ocean: Geochemistry Geophysics Geosystems, v. 19, p. 4876–4903, https://doi.org/10.1029/2018GC007882.

Lekens, W.A.H., Sejrup, H.P., Haflidason, H., Petersen, G.Ø., Hjelstuen, B., and Knorr, G., 2005, Laminated sediments preceding Heinrich event 1 in the Northern North Sea and Southern Norwegian Sea: Origin, processes and regional linkage: Marine Geology, v. 216, p. 27–50, https://doi.org/10.1016/j.margeo.2004.12.007.

Lisiecki, L.E., and Raymo, M.E., 2005, A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records: Paleoceanography, v. 20, PA1003, https://doi.org/10.1029/2004PA001071.

Montelli, A., Dowdeswell, J.A., Ottesen, D., and Johansen, S.E., 2017, Ice-sheet dynamics through the Quaternary on the mid-Norwegian continental margin inferred from 3D seismic data: Marine and Petroleum Geology, v. 80, p. 228–242, https://doi.org/10.1016/j.marpetgeo.2016.12.002.

Mudelsee, M., and Schulz, M., 1997, The Mid-Pleistocene transition: Onset of 100 ka cycle lags ice volume build-up by 280 ka: Earth and Planetary Science Letters, v. 151, p. 117–123, https://doi.org/10.1016/S0012-821X(97)00114-3.

Nielsen, T., De Santis, L., Dahlgren, K.I.T., Kuijpers, A., Laberg, J.S., Nygård, A., Praeg, D., and Stoker, M.S., 2005, A comparison of the NW European glaciated margin with other glaciated margins: Marine and Petroleum Geology, v. 22, p. 1149–1183, https://doi.org/10.1016/j.marpetgeo.2004.12.007.

Nygård, A., Sejrup, H.P., Haflidason, H., Lekens, W.A.H., Clark, C.D., and Bigg, G.R., 2007, Extreme sediment and ice discharge from marine-based ice streams; New evidence from the North Sea: Geology, v. 35, p. 395–398, https://doi.org/10.1130/G23364A.1.

Ottesen, D., Dowdeswell, J.A., and Rise, L., 2005, Submarine landforms and the reconstruction of fast-flowing ice streams within a large Quaternary ice sheet: The 2500-km-long Norwegian-Svalbard margin (57–80°N): Geological Society of America Bulletin, v. 117, p. 1033–1050, https://doi.org/10.1130/B25577.1.

Ottesen, D., Batchelor, C.L., Dowdeswell, J.A., and Løseth, H., 2018, Morphology and pattern of Quaternary sedimentation in the North Sea Basin (52–62°N): Marine and Petroleum Geology, v. 98, p. 836–859, https://doi.org/10.1016/j.marpetgeo.2018.08.022.

Patruno, S., Scisciani, V., Helland-Hansen, W., D'Intino, N., Reid, W., and Pellegrini, C., 2020, Upslope-climbing shelf-edge clinoforms and the stepwise evolution of the northern European glaciation (lower Pleistocene Eridanos Delta system, U.K. North Sea): When sediment supply overwhelms accommodation: Basin Research, v. 32, p. 224–239, https://doi.org/10.1111/bre.12379.

Patton, H., Hubbard, A., Andreassen, K., Auriac, A., Whitehouse, P.L., Stroeven, A.P., Shackleton, C., Winsborrow, M., Heyman, J., and Hall, A.M., 2017, Deglaciation of the Eurasian ice sheet complex: Quaternary Science Reviews, v. 169, p. 148–172, https://doi.org/10.1016/j.quascirev.2017.05.019.

Rea, B.R., et al., 2018, Extensive marine-terminating ice sheets in Europe from 2.5 million years ago: Science Advances, v. 4, eaar8327, https://doi.org/10.1126/sciadv.aar8327

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, v. 352, p. 111–154, https://doi.org/10.1016/j.margeo.2014.03.011.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason, H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M.S., and Vorren, T.O., 2005, Pleistocene glacial history of the NW European continental margin: Marine and Petroleum Geology, v. 22, p. 1111–1129, https://doi.org/10.1016/j.marpetgeo.2004.09.007.

Steer, P., Huismans, R.S., Valla, P.G., Gac, S., and Herman, F., 2012, Bimodal Plio-Quaternary glacial erosion of fjords and low-relief surfaces in Scandinavia: Nature Geoscience, v. 5, p. 635–639, https://doi.org/10.1038/ngeo1549.

Stoker, M.S., Praeg, D., Hjelstuen, B.O., Laberg, J.S., Nielsen, T., and Shannon, P.M., 2005, Neogene stratigraphy and the sedimentary and oceanographic development of the NW European Atlantic margin: Marine and Petroleum Geology, v. 22, p. 977–1005, https://doi.org/10.1016/j.marpetgeo.2004.11.007.

Tziperman, E., and Gildor, H., 2003, On the mid-Pleistocene transition to 100-kyr glacial cycles and the asymmetry between glaciation and deglaciation times: Paleoceanography, v. 18, 1001, https://doi.org/10.1029/2001PA000627.

Vorren, T.O., Richardsen, G., Knutsen, S.-M., and Henriksen, H., 1991, Cenozoic erosion and sedimentation in the western Barents Sea: Marine and Petroleum Geology, v. 8, p. 317–340, https://doi.org/10.1016/0264-8172(91)90086-G.

Vorren, T.O., Laberg, J.S., Blaume, F., Dowdeswell, J.A., Kenyon, N.H., Mienert, J., Rumohr, J., and Werner, F., 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.

Willeit, M., Ganopolski, A., Calov, R., and Brovkin, V., 2019, Mid-Pleistocene transition in glacial cycles explained by declining CO_2 and regolith removal: Science Advances, v. 5, eaav7337, https://doi.org/10.1126/sciadv.aav7337.

Zieba, K.J., Omosanya, K.O., and Knies, J., 2017, A flexural isostasy model for the Pleistocene evolution of the Barents Sea bathymetry: Norsk Geologisk Tidsskrift, v. 97, p. 1–19, https://doi.org/10.17850/njg97-1-01.

Printed in USA