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A Persistent Norwegian Atlantic Current Through the Pleistocene Glacials

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Key Points:
- 50,000 km^2 of 3-D seismic reflection data are investigated on the mid-Norwegian margin
- Seismic geomorphological analysis shows ~17,500 iceberg scours buried throughout the stratigraphy
- The geomorphological record shows that the Norwegian Atlantic Current persisted through multiple Pleistocene glacial stages

Supporting Information:
- Supporting Information S1

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Abstract Changes in ocean-circulation regimes in the northern North Atlantic and the Nordic Seas may affect not only the Arctic but potentially hemispheric or even global climate. Therefore, unraveling the long-term evolution of the North Atlantic Current-Norwegian Atlantic Current system through the Pleistocene glaciations could yield useful information and climatological context for understanding contemporary changes. In this work, ~50,000 km^2 of 3-D seismic reflection data are used to investigate the Pleistocene stratigraphy for evidence of paleo-oceanographic regimes on the mid-Norwegian margin since 2.58 Ma. Across 33 semicontinuous regional paleo-seafloor surfaces ~17,500 iceberg scours have been mapped. This mapping greatly expands our spatiotemporal understanding of currents and iceberg presence in the eastern Nordic Seas. The scours display a dominant southwest-northeast trend that complements previous sedimentological and numerical modeling studies that suggest northward-flowing currents in the Norwegian Sea during the Pleistocene. This paleo-oceanographic study suggests that through many of the Pleistocene glaciations, the location of surface ocean currents in the Norwegian Sea and, by extension, the eastern North Atlantic, were broadly similar to the present.

Plain Language Summary The bridging location of the northern North Atlantic Ocean and the Nordic Seas between low and high latitudes means that environmental changes in one region can potentially be transmitted on a hemispheric or global scale. The Norwegian Atlantic Current crosses this region, and in the present-day setting, it helps to bring heat up from the tropics and toward the Arctic. This heat exchange helps to keep the climate of NW Europe relatively mild. Over a longer time scale (e.g., the last 2.58 million years) the history of this current is poorly known, not least of all how it behaved through different ice ages. In this work we use evidence of floating icebergs in the Norwegian Sea to reconstruct the ocean currents that controlled the drift directions of the icebergs. This has shown that through many of the glacial periods in the last 2.58 million years, there is evidence for the Norwegian Atlantic Current still reaching high latitudes. This has important implications for understanding the main controls and stability of ocean currents in the region and how they may impact regional and global climate.

1. Introduction

The eastward-flowing North Atlantic Current (NAC) is a warm surface current with two branches that originates from the Gulf Stream (Figure 1a). As the NAC flows across the mid-Atlantic Ridge and turns northward, it crosses the Greenland-Scotland Ridge and advects heat toward the Nordic Seas (Clark et al., 2002; Orvik & Niiler, 2002). Upon entering the Nordic Seas the current is termed the Norwegian Atlantic Current (NwAC) and has two branches: the Norwegian Atlantic Slope and Norwegian Atlantic Front Currents (Figure 1b) (Hansen et al., 2011). The Norwegian Atlantic Slope follows the ~500 m isobath of the Norwegian Sea before continuing east into the Barents Sea and north beyond Svalbard, while the Norwegian Atlantic Front Currents flows northward as an unstable jet between Atlantic and Arctic water in the Nordic Seas (Hansen et al., 2011). On a regional scale, warm and saline (near-)surface waters are transported northward via the NAC-NwAC system and are compensated by the southward-flow of deep water in the Nordic Seas. These flows contribute to North Atlantic Deep Water production and form a crucial component of the Atlantic Meridional Overturning Circulation (Clark et al., 2002). Thus, the strength and flow paths of these currents in the Nordic Seas and the vigor with which convection occurs can potentially impact regional and global climate.

Although the present-day oceanography of the (northern) North Atlantic and the Nordic Seas is well-understood (Figure 1a), the evolution of the NAC and its extension into the Norwegian Sea after the onset of major glaciation at 3.0–2.8 Ma are comparatively poorly known (Naafs et al., 2010). Developing a better

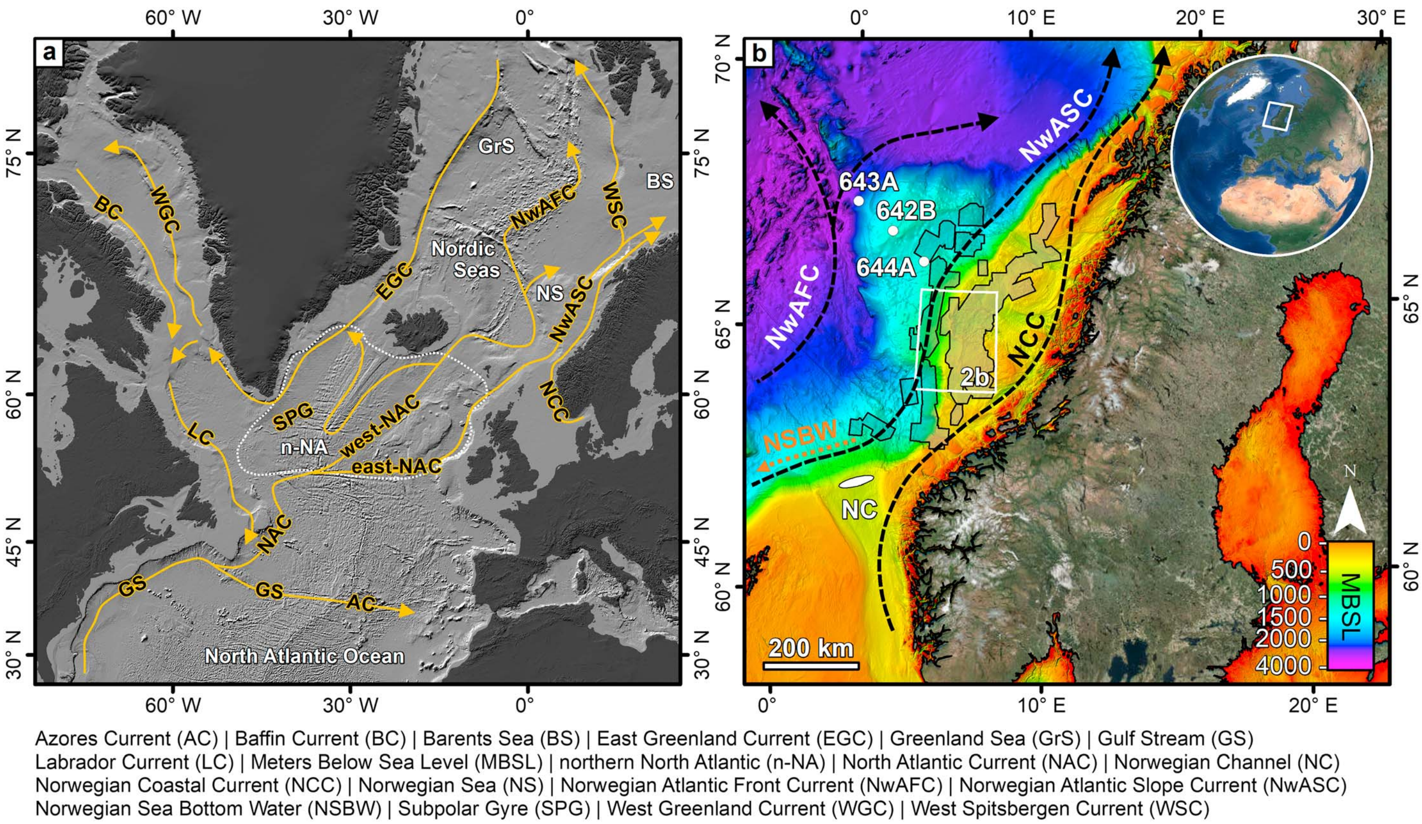

Figure 1. (a) Simplified schematic showing the present-day (near-)surface currents across the North Atlantic and Nordic Seas. The dotted white line shows the area of the (northern) North Atlantic. Abbreviations below the image panels. (b) Study site map showing the regional bathymetry and simplified oceanography of the Norwegian Sea. The black arrows show the present-day (near-)surface currents and the orange arrow the Norwegian Sea Bottom Water (NSBW). The white circles are the Ocean Drilling Program sites shown in Figure 2. Outline of Figure 2b indicated. The semitransparent polygon with black outline shows 3-D seismic reflection data coverage. Note the nonlinear bathymetric color scale to highlight shelf morphology. The white oval shows the general location of contourites formed by the NSBW discussed by Batchelor et al. (2017). Satellite image is from the ArcMap Online World Imagery layer, and the bathymetry is from the General Bathymetric Chart of the Oceans (cf. Weatherall et al., 2015).

understanding of oceanographic changes in the Norwegian Sea across glacial-interglacial time scales is important for putting recent observations into a longer-term perspective (e.g., Berstad et al., 2003) and for calibrating numerical Earth-system models. In this paper, a seismic geomorphological analysis of 50,000 km^2 of 3-D seismic reflection data offshore mid-Norway is presented, providing new insight into the oceanography of the Norwegian Sea since 2.58 Ma.

2. Background

2.1. Oceanography History

Documentation of paleo-oceanographic conditions during the late Pliocene and Early to Middle Pleistocene is limited and somewhat inconsistent. Studies of Nordic Sea borehole cores suggest that deepwater formation from the intrusion of Atlantic waters was effectively blocked off from 2.8 to 1.9 Ma (Henrich et al., 2002). Although a perennial or permanent sea ice cover may have reduced overturning in the region during glacials (Henrich, 1989), limited deepwater renewal may have occurred from brine rejection during sea ice formation (Henrich et al., 2002).

From 1.9 to 1.4 Ma the period was characterized by episodic intrusions of North Atlantic origin that enabled deepwater production in the southeastern Nordic Seas (Henrich et al., 2002). Although it is not clear whether these episodes were a glacial or interglacial feature, it is generally assumed that they were likely an interglacial feature if the present day is a reasonable analogue. However, such an interpretation is contrasted by records from deepwater paths in the (northern) North Atlantic. Raymo et al. (2004) infer that deepwater production in the Nordic Seas seems to have been relatively stable, though volumetrically insignificant in comparison to the present, over glacial-interglacial cycles throughout "much of the Pleistocene" (since 1.8 Ma as they reference the old Plio-Pleistocene boundary). Stable deepwater production is coupled with a persistent (rather than episodic) import of surface waters—e.g., a proto-NwAC. To resolve this contrast requires further insight into paleo-circulation and whether northward-flowing (near-)surface currents were persistent during glacials and interglacials, or whether they were episodic and perhaps confined to interglacials.

The Mid-Pleistocene Transition (MPT), from ~1.2 to 0.7 Ma, is characterized by increasing amplitudes in ice-rafted debris (IRD) input and carbonate shell production records from the Nordic Seas. This indicates an intensification of contrast between glacials and interglacials, potentially reflecting a strengthening of the proto-NwAC (Baumann et al., 1996; Henrich, 1989; Jansen et al., 1988).

During the Middle and Late Pleistocene, North Atlantic Deep Water was, in general, produced almost continuously, with variations in the depth, degree, and location of deepwater production and the strength of the NwAC (Levine & Bigg, 2008; Newton et al., 2016; Seidov et al., 1996). Only during Heinrich events is deepwater production thought to have reduced or possibly stopped (Levine & Bigg, 2008; Seidov et al., 1996). The mid-Brunhes Event is the most pronounced climatic shift during this period, indicating a stepwise increase in interglacial temperatures from marine isotope stage 13 and 11 (Candy & McClymont, 2013). Although there is a basic understanding of the Pleistocene oceanography of the North Atlantic, it is based on limited geological data from widely spaced boreholes. These data also tend to be heavily biased to two specific intervals, the first and last glacial cycles of the Pleistocene. Thus, much of the Pleistocene oceanography and whether there was a northward flow of Atlantic Waters into the Norwegian Sea is poorly resolved (Henrich & Baumann, 1994; Laberg et al., 2005; Newton & Huuse, 2017).

2.2. Glacial History

Offshore mid-Norway, the Naust Formation contains a late Pliocene and Pleistocene record of glacial-interglacial fluctuations (Ottesen et al., 2009). The onset of deposition of the Naust Formation is correlated with observations of increased IRD at ~2.8 Ma on the Vøring Plateau (Figure 2a; Jansen & Sjøholm, 1991). The formation is divided into five units; N, A, U, S, and T, from oldest to youngest (Figures 2a and 2b; Rise et al., 2010). The boundaries of the T and S units are well-constrained, but those for the older three units are tentative (Dahlgren et al., 2002; Rise et al., 2010). It was previously thought that during the earliest Pleistocene, ice cover was restricted to ice caps and mountain glaciers that may have only reached the coast, rather than extended significantly beyond it (Hjelstuen et al., 1999; Mangerud et al., 1996). The first evidence for major marine-based glaciation occurred at ~1.1 Ma (Sejrup et al., 1995) when increased IRD during the MPT suggests more extensive marine-based glaciation in the region (Jansen et al., 2000). Recent observations of buried glacial landforms from 3-D seismic reflection data on the mid-Norwegian margin suggest progressive intensification of glaciation and provide evidence for floating and grounded ice intermittently through the Early Pleistocene (Montelli et al., 2017; Newton & Huuse, 2017), before repeated observations of grounded ice since ~0.5 Ma (Dahlgren et al., 2002).

3. Methods

Over 50,000 km^2 of merged 3-D seismic reflection data were used with a dense grid of 2-D seismic data in a seismic geomorphological analysis (Posamentier, 2004). The vertical seismic resolution for the glacial succession is ~10–20 m (based on frequencies of ~30–60 Hz and sound velocities of 1.8–2.2 km s^{-1}), and the horizontal resolution is ~10–40 m. Using the 3-D seismic volumes, a large number of reflections were manually picked to create paleo-seafloor surfaces. The criteria for picking reflections included those with strong and continuous reflection amplitudes and reflections which, when cut by 3-D seismic time slices, contained evidence of glacial landforms. A semiautomatic approach using Paleoscan generated supplementary paleo-seafloor surfaces of every single reflection for a detailed whole-section analysis (cf. Daynac et al., 2016; Figure S1 in the supporting information). This software creates a geomodel composed of all reflections can can be modified to ensure that reflections are geologically accurate and plausible.

Surfaces were investigated as two-way-time surface maps in 3-D space under a variable light source. Seismic attributes (e.g., Variance and RMS Amplitude) were extracted across the surfaces to provide multiple visualizations of the data. Iceberg scours are typically v- or u-shaped furrows in cross section that are occasionally accompanied by adjacent berms (Brown et al., 2017). In planform the scours are linear and curvilinear and

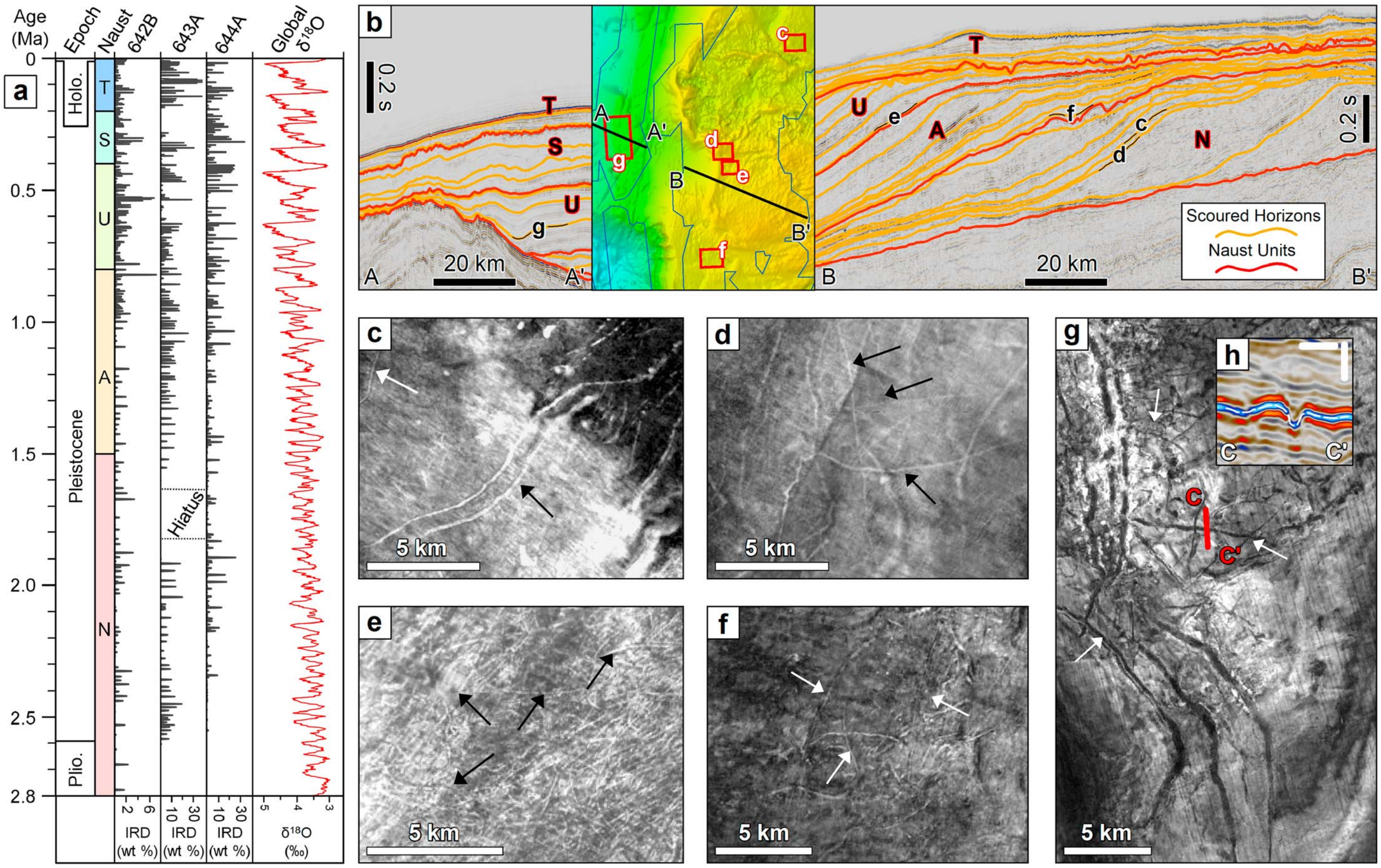

Figure 2. (a) Composite figure showing the ice-rafted debris record from Ocean Drilling Program Sites 642–644 on the Vøring Plateau (Henrich & Baumann, 1994; Krissek, 1989) and the global δ^{18}O record (Lisiecki & Raymo, 2005). (b) Seismic dip line showing the scoured horizons (orange lines) present within the Naust Formation units (red lines). The stratigraphic surfaces (c–g) with iceberg scour examples also labeled. The inset map (location shown on Figure 1b) shows the geographic location of panels (c)–(g) and the two seismic lines from the 3-D seismic survey. Note that due to the semicontinuous nature of the picked surfaces, not all are imaged on these profiles. (c–g) Examples of iceberg-scoured surfaces within the stratigraphy. The arrows point to examples of scours. (h) Seismic cross section of an iceberg scour located on panel (g). The white vertical and horizontal rectangles are scales of 50 ms and 500 m, respectively. The full spatial extent of the scours within each Naust Formation unit is shown on Figure S2.

are primarily the result of ocean currents moving grounded icebergs (Newton et al., 2016; Todd et al., 1988; Woodworth-Lynas et al., 1985). This morphological description was used with other examples (e.g., Dowdeswell et al., 2016) to guide interpretation of geomorphological features from the 3-D seismic data. Using a top-down approach, scours were digitized through the stratigraphy when they were first observed (deep scours can cut surfaces beneath) and correlated across different, time-equivalent, surfaces to provide an estimate for the minimum number of iceberg-scouring episodes. Each episode was then dated relatively using the chronostratigraphic scheme of the Naust Formation (Rise et al., 2010).

The trajectory of each iceberg scour was taken as a compass bearing of a vector connecting the scour start and end points. Rayleigh's test was used to test for the significance of a mean direction (cf. Trauth, 2006). This follows equation (1):

$$\overline{R} = \frac{1}{n}\sqrt{\left(\sum \sin \theta_i\right)^2 + \left(\sum \cos \theta_i\right)^2} \tag{1}$$

where $\overline{R}$ is the length of the mean resultant (which increases with significant preferred direction), n is the number of samples, and θ_i is the bearing of each scour. Circular variance (σ_0), which can be used as the equivalent of coefficient of variation for nondirectional data, was used as a measure of data spread (with zero indicating only one direction) using equation (2):

$$\sigma_0 = 1 - \overline{R} \tag{2}$$

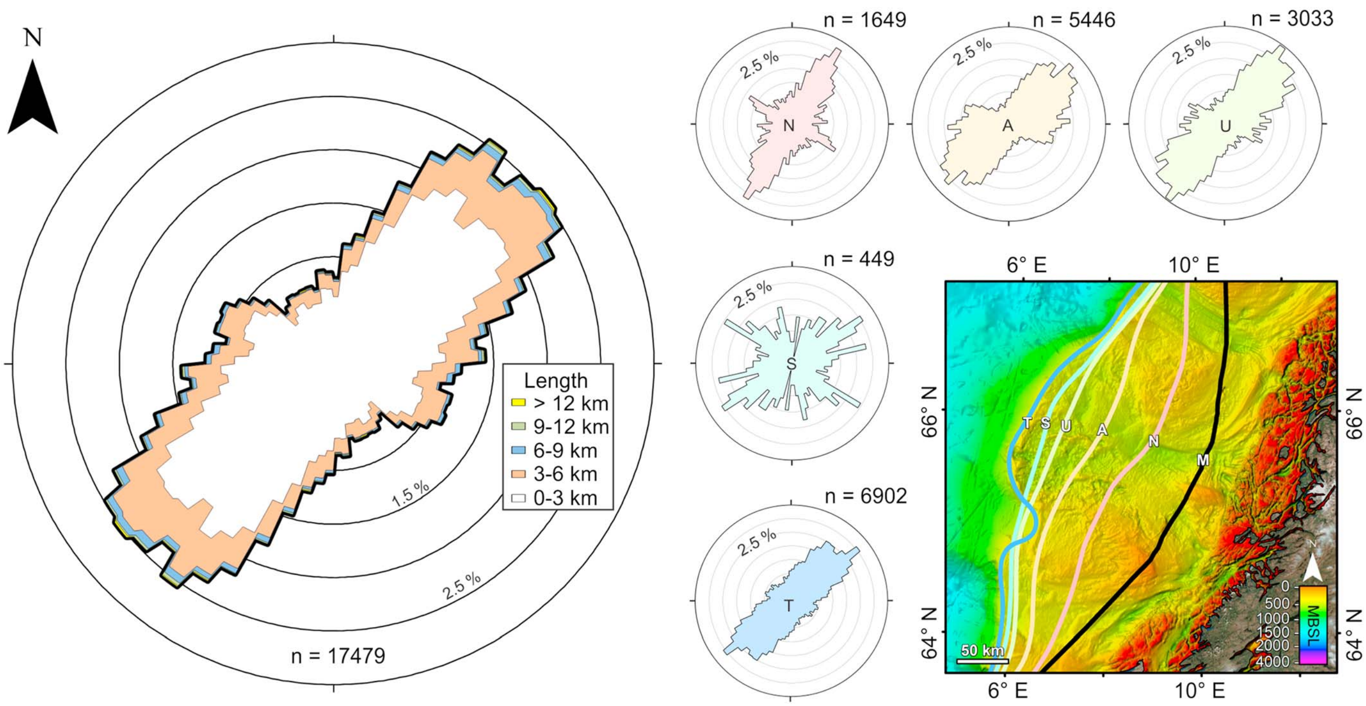

Figure 3. Summary rose chart showing dominant iceberg trajectories and lengths measured from all the iceberg scours. This shows a dominant southwest-northeast trend with the majority of scours <6 km long. Smaller rose charts are for scours observed in each individual Naust Formation unit. The inset map shows the location of the shelf break at the end of deposition of each unit. The black line is for the Molo Formation (M) which marks the location of the shelf edge prior to the deposition of the Naust Formation.

4. Results and Discussion: Pleistocene Oceanography in the Norwegian Sea

4.1. Iceberg Scouring Record

This study identified and mapped 17,479 linear and curvilinear iceberg scours across 33 semicontinuous regional surfaces within a 50,000 km^2 3-D seismic data set (Figures 2c–2g). Maximum widths were 400–500 m, while typical widths were 100–200 m. The mean scour length was 2.5 km (σ = 1.8 km) with the longest features up to 50 km long. It is difficult to determine scour depth because their shallow but long geometry means they are most visible in planform, rather than cross section. A number of the largest scours show they extend for ~10–30 ms (~10–30 m) below the paleo-seafloor. The scours are typically observed on the outer-most paleo-shelves and on the upper and middle parts of the slope. If contemporary water depths (minus glacial sea level fall) are a reasonable estimation of shelf and slope depths during other glacial stages, then this would suggest that iceberg drafts were frequently 200–500 m through the Pleistocene. Such a range in draft size sits well with observations of icebergs calved off Antarctica (Dowdeswell & Bamber, 2007).

Although scours frequently cross-cut each other, their orientations on individual surfaces are similar and show a dominant southwest-northeast orientation, with a secondary perpendicular northwest-southeast component (Figure 3). Rayleigh's test shows that for the combined orientation data the null hypothesis (that there is a uniform distribution—i.e., that there is no dominant current) can be confidently rejected ($p < 0.001$). A circular variance (σ_0) value of 0.28 also strongly suggests that there is a preferred orientation in the scour vectors that have been recorded. Taken together, this suggests that the dominant southwest-northeast pattern visible in most of the rose charts is real and representative of the effective forces driving iceberg motion (Figure 3). Although the rose chart for the Naust Formation S unit demonstrates a similar southwest-northeast pattern to other units, the secondary northwest-southeast orientation provides a larger component of the overall orientations (Figure 3).

4.2. Reconstructing Ocean Currents

It is commonly asserted that surface currents (both tidal and geostrophic) provide the fundamental control on iceberg trajectory (Watkins et al., 2007), and other factors like wind and waves provide only a minor control during storms (Woodworth-Lynas et al., 1985). Iceberg scours have previously been used to investigate ocean currents (Newton et al., 2016; Todd et al., 1988), and we use them here as a proxy for surface paleo-currents in the study area through the Pleistocene. Reconstructed iceberg trajectories show a dominant southwest-northeast or northeast-southwest orientation, which is essentially parallel to the contemporary and paleo-shelf edge throughout the deposition of each Naust Formation unit (Figure 3). When scour orientations are considered for each individual surface, the same trend dominates, albeit to a lesser extent for the Naust Formation S unit.

Any insights on whether the icebergs were floating from northeast to southwest, or from southwest to northeast, are important for reconstructing the Pleistocene oceanography of the Norwegian Sea and whether Atlantic Waters were, more broadly, penetrating to higher latitudes. The clearest support for current direction comes from observations of iceberg scours that have been influenced by the Coriolis Effect in the Norwegian Sea. These show that in order to generate the observed scour pattern, the surface currents (the dominant control on iceberg trajectory) must have been northward-flowing (Newton et al., 2016). Similar patterns are observed on several surfaces, and this lends support to a northward-flowing current (proto-NwAC) being captured in the iceberg scour patterns presented here. The shelf progrades linearly during this time so that the mid-Norwegian shelf grows in a uniform way (Figure 3) and the iceberg scour patterns are closely aligned to several paleo-shelves. This suggests that there may have been a topographic control on current flow. This is similar to the present-day Nordic Seas where current patterns are cyclonic and flows are often topographically controlled (Tegzes et al., 2017).

A recent seismic reflection study from the northern North Sea margin (Norwegian Channel area; Figure 1b) shows elongate lenses of contourites deposited during the Early Pleistocene on paleo-slopes, parallel to the respective paleo-shelf breaks, and at present-day depths of 1–1.4 km below sea level (Figure 1b; Batchelor et al., 2017). The contourites are intercalated with different glaciogenic debrite units deposited during maximum glacial conditions. Thus, the contourites are thought to have been deposited during intervening interglacials by a southwestward-flowing current in intermediate or deep water that exited the Norwegian Basin through the Faeroe-Shetland Channel (Batchelor et al., 2017; Figure 1b). In contrast to this depiction, we would argue that the contourite deposits might be better explained by a recirculating cyclonic water mass flowing northeastward along the northern North Sea Margin (i.e., topographically controlled circulation similar to the present). Whether this current then (partly) followed a similar cyclonic path to contemporary intermediate and deep circulation would have depended upon the relative depth of the current and its relationship to the coeval bathymetry of the mid-Norwegian margin. However, even if this current was active (though potentially weaker and shallower during parts of the glacial stages), taking into consideration the estimated iceberg keel depths (200–500 m), it is less likely that it exerted a major control on northeastward iceberg transport along the upper slope of the mid-Norwegian margin.

Other geological and numerical modeling work has shown that Atlantic Waters were likely transported northward in (near-)surface currents in the Norwegian Sea during the Pleistocene. The strength of this flow, similar to the amount of deepwater production in the Nordic Seas, likely varied through time (Henrich et al., 2002; Huber, Meggers, Baumann, & Henrich, 2000; Jansen et al., 2000; Newton et al., 2016; Raymo et al., 2004). The last glacial cycle is the best understood time period of oceanographic evolution in the Norwegian Sea, and modeling studies have shown that even under maximum glacial conditions, there were still northward-flowing currents in the region (Bigg et al., 2012; Levine & Bigg, 2008). If modeled oceanographic regimes for the Last Glacial Maximum have general relevance to other Pleistocene glacials, the findings of the above studies provide strong complementary evidence that iceberg-scouring patterns observed here (Figure 3) represent a northeastward-flowing (warm) proto-NwAC.

It is possible that northward-flowing currents were related to a proto-Norwegian Coastal Current (NCC). However, the present-day NCC is a westward-thinning wedge crossing the continental shelf that did not actually develop until ~8–7 ka (Bjørklund et al., 1985)—that is, ~4 kyr into the current interglacial. If, as described above, Last Glacial Maximum conditions have a general relevance to Early Pleistocene glacial conditions, it seems unlikely that a proto-NCC would have been active during glacial stages when large numbers of deep-draft icebergs were floating around and reworking parts of the outer shelf and paleo-slope. Thus, we conclude from the evidence presented above that the record of scouring can be best explained by northeastward-flowing paleo-currents along the mid-Norwegian margin that are of (northern) North Atlantic origin and were probably an ancestor of the contemporary NwAC (i.e., a proto-NwAC).

The cumulative rose chart and those for individual Naust Formation units (Figure 3) show a secondary northwest-southeast component. This component is essentially perpendicular to the primary southwest-northeast component that is interpreted to represent the (near-)surface geostrophic current across multiple Pleistocene glacial stages. The secondary component is probably related to tidal currents, and it is rarely captured in scours >6 km. Therefore, where scour vectors have a secondary component, the icebergs were likely grounded only for a short tidal cycle. If icebergs were grounded across several tidal cycles, the northwest-southeast tidal signal would likely be lost within the scour vector as it would be superimposed onto the geostrophic current as it maintains a consistent trajectory (e.g., Newton et al., 2016).

Although the orientation pattern for the Naust Formation S unit (400–200 ka) appears to be more dispersed than for the other units, the same southwest-northeast and northwest-southeast trends are still clearly apparent (Figure 3). The number of scours within this unit is considerably less than in other units, and this may partially account for the increased scatter. Additionally, most of the scours in this unit are on the paleo-slope, implying the availability of many deep-draft icebergs, potentially calved from the Norwegian Channel Ice Stream into the deep waters of the Møre Basin and flowing northeastward into the Norwegian Sea (as indicated by the dominant trajectory trend) before recirculating in the Nordic Seas (e.g., Levine & Bigg, 2008).

It has been previously suggested that large numbers of deep-draft iceberg scours, observed on paleo-slope surfaces on the mid-Norwegian margin, might be linked to possible episodes of ice-shelf collapse and an increased flux of freshwater (Newton et al., 2016). Under such a scenario, that is, a Heinrich event (Heinrich, 1988), North Atlantic circulation can be (partially) disrupted by an increase in freshwater input to deep-convection sites, which may slow or even shut down northward-flowing (warm) currents in the (near-)surface ocean. Under such circumstances, it would be expected that scour orientation would become either more random due to iceberg drift being less influenced by the geostrophic current, or they would display a clearer west-east pattern as tidal currents dominate iceberg drift. Although either (or both) the reduced sample size or a reduced geostrophic current might explain the increased scatter, an important point to note is that the same geostrophic and tidal current trends as in the case of the other units are still clearly observable. This suggests that even during Naust Formation S time, when the records presented here indicate a weaker geostrophic flow, the proto-NwAC was still strong enough to move icebergs in the Norwegian Sea northward along the margin. Thus, throughout the Pleistocene, it appears that across multiple scouring episodes the proto-NwAC was present in the Norwegian Sea and was advecting heat toward the Arctic.

4.3. Pleistocene Environments in the Norwegian Sea

If the ice sheet margin in the Early Pleistocene was restricted to the coastal region, as has been previously suggested (Hjelstuen et al., 1999; Jansen & Sjøholm, 1991; Mangerud et al., 1996), then it would not have been possible for sufficiently deep icebergs to have traversed a shelf environment that was shallower than the paleo-slope. This is important because the large number of iceberg scours observed on the outer shelf and paleo-slope suggests the availability of deep-draft icebergs in the Norwegian Sea. Regardless of uncertainties in the precise estimate of water depths, whether the icebergs were sourced from the mid-Norwegian margin or further south, the above implies that the ice sheet margin must have extended well beyond the coastline. This fits well with recent seismic reflection observations and core data, suggesting that ice sheets probably extended onto the shelf during many Early Pleistocene glacials (Montelli et al., 2017; Newton & Huuse, 2017; Ottesen et al., 2009; Rea et al., 2018).

Ice-rafted debris originating from Fennoscandia observed across the northern North Atlantic (Bailey et al., 2013; De Schepper et al., 2014) suggests marine-terminating ice over parts of NW Europe during the Early Pleistocene. The earliest evidence for iceberg scouring offshore NW Europe has been observed in the earliest Pleistocene (Dowdeswell & Ottesen, 2013; Kuhlmann & Wong, 2008; Newton & Huuse, 2017), and this date correlates well with spikes in IRD on the Vøring Plateau (Figure 2a; Henrich & Baumann, 1994; Krissek, 1989). This provides complementary evidence that ice sheet extents may have been larger in the Early Pleistocene of NW Europe than hitherto believed. Additionally, even if a local source of the icebergs is ruled out and the parent ice sheet resided over Greenland or North America, this would imply that northward-flowing currents advected icebergs, and presumably warmer waters, into the Norwegian Sea during glacials (Bigg et al., 2012; Levine & Bigg, 2008).

The northward-flowing current along the Norwegian margin (i.e., proto-NwAC) appears to have coexisted with several iceberg-calving episodes during Early Pleistocene glaciations. These results, when considered alongside complementary modeling studies discussed above, present the possibility that while the Atlantic Meridional Overturning Circulation may have been weaker, a stable northward-flowing current system (i.e., proto-NAC-NwAC system) existed throughout the Early Pleistocene glacials. The northward heat transport of a proto-NwAC would help keep the margin relatively ice-free (both sea ice and icebergs) and could even destabilize marine-terminating ice sheets or glaciers, thus triggering the calving events that were responsible for iceberg scouring on the paleo-slopes offshore mid-Norway.

During and after the MPT, paleo-temperatures inferred from *Neogloboquadrina pachyderma* suggest that there is an increase in the contrast of environmental conditions between glacial and interglacial stages (Huber, Meggers, Baumann, Raymo, et al., 2000), and this is also shown by a marked increase in IRD at Ocean Drilling Program Sites 642–644 (Figure 2a). Permanent or perennial sea ice conditions are thought to dominate during glacials (possibly even encasing a significant part of the North Atlantic down to the midlatitudes), and depending on the perennial extent of the sea ice cover, the iceberg scouring was likely occurring during the subsequent deglacial.

The record of iceberg scouring presented in this study revealed that, at least during certain phases of the Pleistocene glacials (likely during deglaciations or more moderate glaciations—i.e., when deep-draft icebergs may be available), a proto-NwAC transported (warm) Atlantic Waters to high northern latitudes. This advection of heat could have provided the precipitation for the initial seeding of the ice sheets and may have helped promote deglaciation later in the glacial cycle.

5. Conclusions

Understanding the Pleistocene history of the NwAC and its response to changes in ice sheet volume is important for putting recent observations into a longer-term perspective. This work has used an extensive database of 3-D seismic reflection data offshore mid-Norway to investigate the Pleistocene stratigraphy for geomorphological evidence of oceanographic history. Across 33 semicontinuous regional surfaces ~17,500 iceberg scours were identified throughout the Pleistocene succession. These scours display a dominant southwest-northeast trend that suggests that the surface paleo-currents in the Norwegian Sea were flowing northward to higher latitudes and were broadly similar across multiple Pleistocene glacial cycles.

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