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Aligned glaciotectonic rafts on the central Barents Sea seafloor revealing extensive glacitectonic erosion during the last deglaciation

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[1] Erosion rates on glaciated continental shelves are remarkably high, especially within ice stream troughs. Although glaciotectonic erosion may have considerably contributed to enhanced glacial erosion of these landscapes, entrainment mechanisms of glaciotectonically emplaced megablocks and rafts remain little understood. Here we report a northeast-southwest trending chain of over 1300 glacial rafts, observed on the seafloor in Bjørnøyrenna, a paleo-ice stream trough with particularly high erosion rates. The landform assemblage adjacent to the glacial rafts includes streamlined bedforms and crevasse-squeeze ridges and may represent a lateral shear zone where a paleo-ice stream met cold stagnant ice during the last deglaciation. Individual glacial rafts along the chain are up to 30 m high, tend to be elongated with lengths and widths on the order of tens of meters, and are oriented from northeast-southwest to north-south. The north-southern rearrangement of rafts may reflect a compressional strain regime along the ice stream margin. **Citation:** Rüther, D. C., K. Andreassen, and M. Spagnolo (2013), Aligned glaciotectonic rafts on the central Barents Sea seafloor revealing extensive glacitectonic erosion during the last deglaciation, *Geophys. Res. Lett.*, *40*, 6351–6355, doi:10.1002/2013GL058413.

1. Introduction

[2] Glaciers and ice sheets are important agents of denudation. In particular, high-latitude continental margins were to a large degree sculptured by Pleistocene glaciers, and their glacial landscape has been preserved relatively intact since deglaciation [e.g., *Vorren et al.*, 1998]. One of the continental margin areas that experienced the highest erosion rate during the Pleistocene is that of the south-western Barents shelf [*Laberg et al.*, 2012]. Here an average of 1000–1100 m of sedimentary rock have been removed from the glacial troughs, while the bank areas experienced 500–650 m of erosion [*Løseth et al.*, 1992; *Richardsen et al.*, 1993; *Laberg et al.*, 2012]. Bjørnøyrenna (Bear Island Trough), 850 km long and up to 180 km wide, is the most pronounced cross-shelf trough on the formerly glaciated Barents shelf (Figure 1a) and has repeatedly been occupied by ice streams during the Pleistocene [*Andreassen et al.*, 2004, 2007]. Indirect evidence that Bjørnøyrenna experienced an exceptional sediment discharge comes from the size of its trough mouth fan off the western Barents shelf margin (Figure 1a). With an area of 215,000 km^2 [*Vorren and Laberg*, 1997] and volume of 670,560 km^3 [*Vorren et al.*, 1991], the Bjørnøyrenna Trough Mouth Fan is the largest on the north-western European margin.

[3] Erosion under Bjørnøyrenna ice streams involved the Cenozoic to Mesozoic subcropping bedrock (Figure 1b). These sedimentary rocks have proved particularly susceptible to glacitectonic deformation, as documented by the repeated occurrence of glacitectonically emplaced megablocks (> 1 km^2) and rafts (< 1 km^2) within Pleistocene glacial sediments inferred by *Andreassen et al.* [2004, 2007] (located in Figure 1a). Direct evidence for the occurrence of a megablock comes from a borehole on the western Barents Sea margin, which has revealed the presence of a 15–25 m thick, heavily fractured, interval of mid-Cretaceous sedimentary rock embedded in Late Weichselian till [*Sættem*, 1994] (located in Figure 1a). Numerous blocks, interpreted as glacial rafts, have also been found within the eastern buried part of the large arcuate grounding zone system in outer Bjørnøyrenna (Figure 1a; dotted red line), a buried push moraine that was formed at the initiation of the last deglaciation, around 17 cal ka ago [*Rüther et al.*, 2011].

[4] In this paper we present the first account of an exceptionally large amount of aligned glacial rafts observed directly on the sea floor in northern Bjørnøyrenna. The main chain of glacial rafts presented here is 50 km long, with 1384 mapped rafts resulting in a total volume of 0.1 km^3.

2. Material and Methods

[5] Overview maps are based on version 3 of the International Bathymetric Chart of the Arctic Ocean (IBCAO) bathymetric data set [*Jakobsson et al.*, 2012]. The remaining data presented here were acquired during two consecutive scientific cruises with R/V *Helmer Hanssen* in 2011 and 2012. The swath bathymetric data (Figures 2a and 2c–2e) were collected with a hull-mounted Kongsberg Simrad EM300 multibeam echo sounder, processed in Neptune and gridded to 10 m in Interactive Visualization Systems (IVS) Fledermaus. The ArcGIS software was used as platform for geomorphological mapping and statistical morphometric analyses (Figure 2b). In particular, raft azimuth and length were derived as the azimuth and length of the longest line inscribed within each raft surface. Width was measured as the longest line perpendicular to the length line, while raft height was derived as the difference in elevation between the highest raft pixel and the lowest elevation recorded within 20 m of each raft. The single channel seismic line (Figure 2f) was acquired at a shot rate of 3 ms with a controlled bubble air gun (Mini GI). It was band-pass filtered and displayed in SeiSee.

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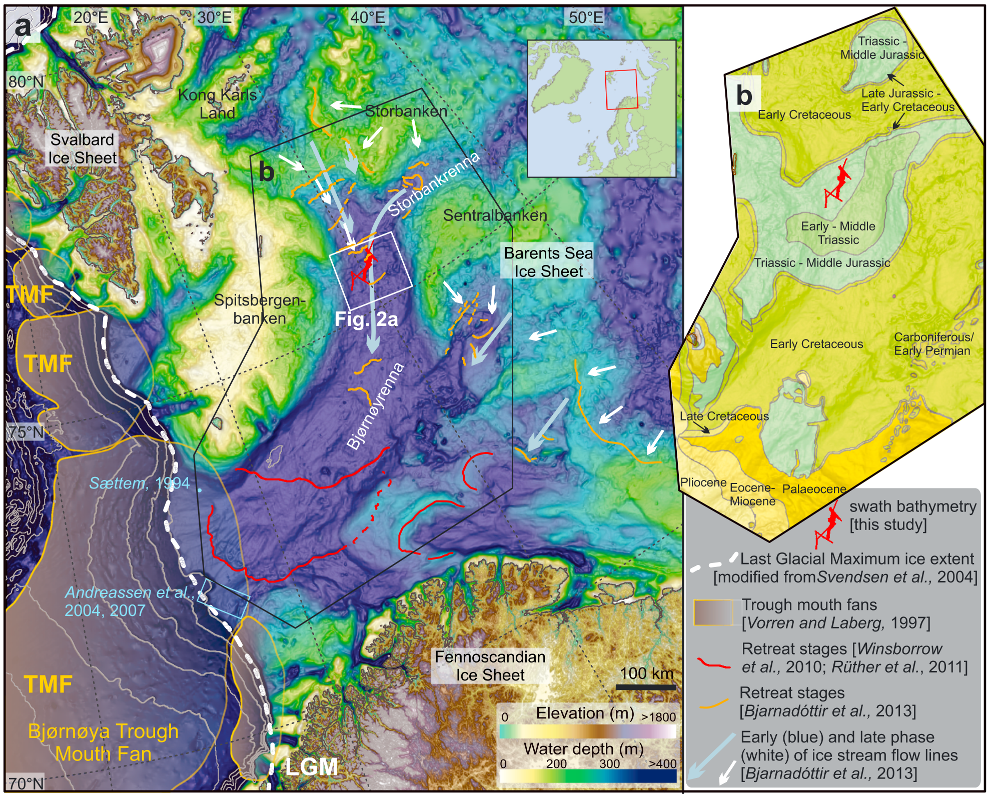

Figure 1. Location map for the studied area including (a) summary of the location of trough mouth fans and known retreat stages and (b) information on the subcropping bedrock [*Sigmond*, 1992].

3. Results and Interpretation

[6] The study area is dominated by four main morphological landforms: curvilinear furrows, longitudinal-to-flow ridges, small ridges, and mounds.

3.1. Curvilinear Furrows—Iceberg Ploughmarks

[7] Curvilinear furrows, 1–5 m deep and 10–500 m wide, occur in shallow terrains and trend predominantly north-south (Figure 2d). They are interpreted as iceberg ploughmarks and their relatively straight directions suggest that icebergs drifted fairly uniformly from an upstream paleo-ice front (Figure 1a).

3.2. Longitudinal Ridges—Streamlined Bedforms

[8] Longitudinal ridges between 100–200 m wide, 1–15 km long, and 2–4 m high (Figure 2e; black arrows) are located in the southern reaches of the acquired swath bathymetric data set. With elongation ratios from 1:10 to 1:75, and a consistently parallel arrangement along the northeast-southwest paleo-ice flow direction, these ridges have at least some of the typical characteristics of mega-scale glacial lineations [*Clark*, 1993]. However, they are all initiated by streamlined higher grounds at their upstream ends, in a configuration similar to crag-and-tail features [*Benn and Evans*, 2010]. Longitudinal ridges are therefore interpreted as streamlined bedforms possibly initiated by protruding bedrock acting as a crag.

3.3. Low-Relief Ridges—Crevasse-Squeeze Ridges

[9] Other ridges, less high (1–2 m) and considerably shorter (0.1–1 km) than those described above, are found in the area. Some of these low-relief ridges are found nearby or adjacent to the long streamlined bedforms but are oriented transverse to past ice flow and have a spacing of 400 m (south-eastern part of Figure 2c, including the bathymetric profile). Others are more widespread, especially around the main chain of mounds, and form incomplete rhombohedral patterns (Figure 2c, indicated with black circle). Both these sets of low-relief ridges are interpreted as crevasse-squeeze ridges [*Sharp*, 1985; *Ottesen and Dowdeswell*, 2006].

3.4. Mounds—Glacial Rafts

[10] Arguably, the most striking landform in the study area is a series of flat-topped mounds, which are partly aligned in chains (Figures 2a, 2b, and 2e). A total of 1384 mounds were identified and mapped from the swath bathymetry which fully covers one of these chains for roughly 50 km (Figure 2a). Overall, this chain of mounds trends NE to SW (230°), in a direction roughly parallel to that of the inferred paleo-ice stream flow. Single mounds' length varies between 30 and 2413 m (mean 228 m, standard deviation 233 m), while their width is between 25 and 1197 m (mean 121 m, standard deviation 111 m). They are between 1 and 30 m high (mean 7.2 m, standard deviation 4.8 m) and cover an area of between 500 and 1,282,000 m^2 (mean 30,692 m^2, standard deviation 78,528 m^2). The resulting cumulative volume for all the mapped mounds is 0.1 km^3. Three crosscutting bathymetry swaths suggest that similar chains may be located directly to the west of the continuously imaged chain of mounds, while farther west mounds are less pronounced, less elongated, and do not seem to form chains (Figure 2a).

[11] Mounds tend to be elongated and their preferred orientations vary across the study area and form spatial clusters (Figure 3a). The westernmost less elongated mounds are

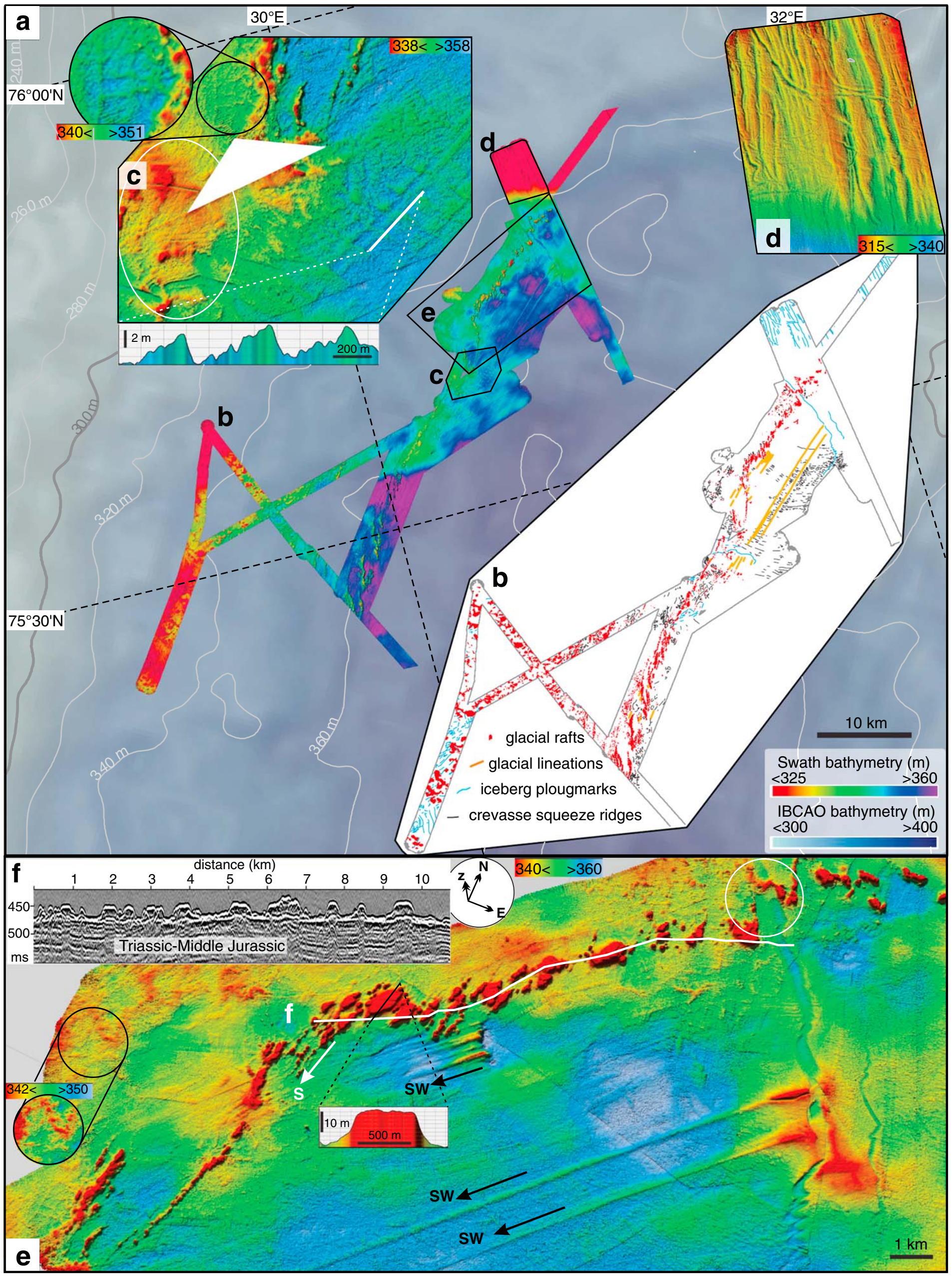

Figure 2. Overview over bathymetric data set and mapping together with selected details of the swath bathymetry data. (a) The swath bathymetric data set shown together with regional IBCAO data. (b) Summary of results of the geomorphological mapping presented in this study. (c) Rhombohedral and transverse crevasse-squeeze ridges and examples of ploughmarks eroding glacial rafts. (d) Subparallel iceberg ploughmarks. (e) Example of the spatial configuration of glacial rafts aligned in a chain together with well-developed streamlined bedforms in the south and an illustration of sea floor roughness in the west. (f) Seismic profile through several of the glacial rafts.

randomly oriented. Along the main chain, however, several segments can be identified which display a development from a majority of NE-SW (200-220°) toward single N-S trending mounds (170–190°; compare Figures 2e, 3a, and 3b). In some places mounds are found to be eroded by iceberg ploughmarks, suggesting that they consist of easily erodible material (indicated by white oval in Figure 2c and white circle in Figure 2e). Yet, corresponding ploughmarks are not as deep on the mounds as on adjacent sea floor or they may stop halfway into the mounds, revealing at least some resistance as possibly provided by stiff till or soft bedrock. Meanwhile, the seismic profile demonstrates that they are not bedrock outliers but have a clear base reflection (Figure 2f).

[12] At first sight, the mounds in the main chain (compare Figure 2e) might resemble an incomplete esker complex [*Warren and Ashley*, 1994] or a shear lateral moraine [*Stokes and Clark*, 2002]. However, both options are inconsistent with the morphology of the mounds, and in particular with the fact that they are flat topped, with surfaces up to 1,000,000 m^2, and almost vertical flanks (compare bathymetric profile in Figure 2e). Furthermore, the esker and lateral moraine options are hard to reconcile with the widespread occurrence of

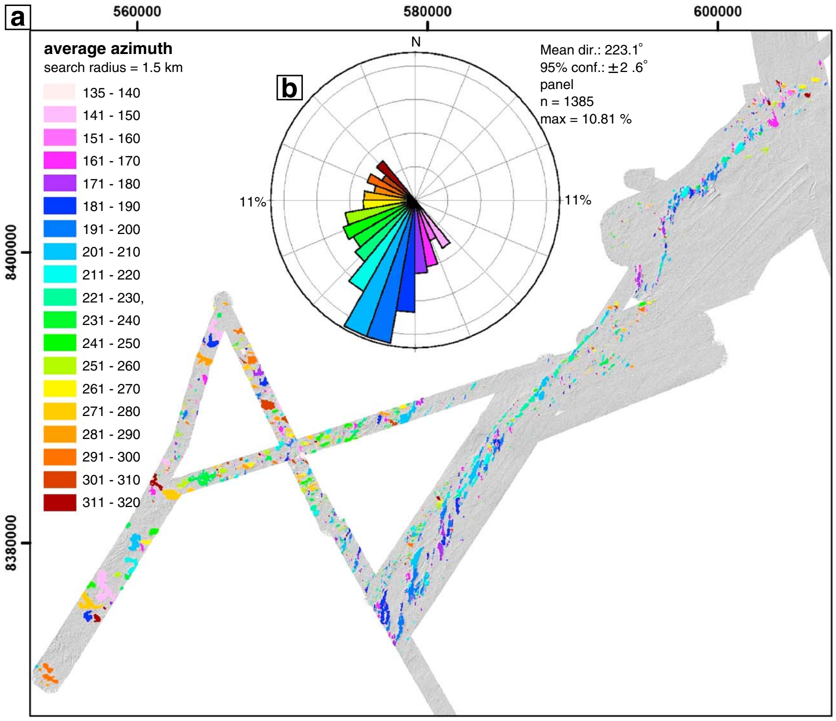

Figure 3. Results of the morphometric analyses of rafts illustrating the (a) spatial distribution of the average azimuth and the (b) relative abundances of measured azimuths.

broader mounds to the west of the chain and with the significant seafloor roughness (e.g., Figure 2e; highlighted black circle). Instead, the mounds are best explained as glacial rafts (sensu *Aber and Ber* [2007]), blocks of soft bedrock or partly lithified till entrained upstream under the Storbankrenna Ice Stream, transported and deposited further downstream (compare Figure 1a).

4. Implications and Discussion

[13] The occurrence of glacial rafts in association with delicate subglacial bedforms such as crag-and-tail features and crevasse-squeeze ridges suggests that rafts were released subglacially rather than at an ice margin. In the following, it is suggested that their arrangement and observed preferred orientations may reflect deposition in a marginal ice stream shear zone. This is supported by the occurrence of crevasse-squeeze ridges and their rhombohedral patterning. Physical concepts demonstrate that basal crevasses under glaciers that are grounded to their beds can only form under high tensile stresses combined with high basal water pressure equaling the ice overburden pressure [*van der Veen*, 1998]. In addition, for basal crevasses to be filled with underlying till, a sudden transition from fast ice flow into stagnation is required [*Sharp*, 1985]. Observed crevasse-squeeze ridges are therefore indicative of a rapid change in the stress regime from fast-flowing ice with high basal water pressures into stagnating ice under low basal water pressures, similar to that inferred from surge-type glaciers at the end of the active phase [cf. *Ottesen and Dowdeswell*, 2006]. Furthermore, their rhombohedral patterning around the main chain of rafts indicates fracturing of basal ice at different angles, a mechanism that requires concurrent extensional and compressional forces. The chain of glacial rafts has an overall NE-SW orientation, while individual rafts' main axes show preferred orientations on a continuum from NE-SW to N-S, likely reflecting rearrangement due to oblique shear occurring under compressional strain at the lateral ice stream margin. Further to the west, rafts show a much more random orientation, lack of elongation, and lack of alignment; this may suggest that these rafts were not influenced by compressional and extensional strain and were emplaced beyond the ice stream shear zone.

[14] Single terrestrial examples of flat-topped glacial rafts were published as early as the 1950s, and the common occurrence of megablocks and rafts throughout glaciated plains was recognized in the 1970s [*Aber and Ber*, 2007]. While terrestrial examples of single, flat-lying rafts are common, we only know of one case where several rafts are found aligned in a chain [*Ringberg et al*., 1984]. Chains of megablocks and rafts are often submerged in till as inferred from marine 3-D seismic data [*Andreassen et al*., 2004, 2007] and may, therefore, easily remain unnoticed in the absence of geophysical data. Discussions of entrainment and transport mechanisms have long been dominated by the idea that the substrate freezes to the underside of a cold-based ice [*Aber*, 1988; *Banham*, 1975]. However, there is increasing awareness that subglacial hydrology in general and hydrofracturing in particular may be closely linked to glaciotectonic activity and glacier dynamics [*Boulton and Caban*, 1995; *Rijsdijk et al*., 1999; *Kjær et al*., 2006]. Notably, the initial detachment of rafts may be explained by elevated pore-water pressures as evidenced by microtextures indicative of water escape occurring along décollement surfaces [*Phillips and Merritt*, 2008]. In Bjørnøyrenna, the transition from Early Cretaceous bedrock in Storbankrenna toward Triassic-Middle Jurassic strata is situated just upglacier from the described chain of rafts (Figure 1b). The transition from highly permeable Cretaceous bedrock substrate into less permeable till or Triassic-Middle Jurassic strata might have caused

elevated pore water pressures and led to failure along décollement surfaces in Cretaceous bedrock. The rafts would then have traveled for at least 30 km before being deposited in a chain along the ice stream shear margin.

[15] The timing of these events remains poorly constrained. However, the observed seafloor signature associated with the chain of rafts, characterized by streamlined bedforms and stagnation features, implies that the area was free from streaming, grounded ice shortly after the formation of the bedforms, thus allowing for their preservation. As suggested in a recent study by *Bjarnadóttir et al*. [2013], the Storbankrenna Ice Stream was active and fed into Bjørnøyrenna at an early phase of the last deglaciation (Figure 1a; light blue arrow), which started at 17 cal ka [*Rüther et al*., 2011]. Subsequently, ice flow patterns became more topographically controlled during the latest phase of last deglaciation and did no longer reach the study area (Figure 1a, white arrows and associated retreat stages) sometime before Kong Karls Land became ice free, at 11.2 cal ka [*Salvigsen*, 1981].

[16] In summary, this study provides the first account of a chain of glacial rafts observed directly on the seafloor corresponding to a cumulative raft volume of 0.1 km^3 mapped over an area of 522 km^2. Based on the observed landform assemblage and preferred orientation of rafts, we infer that their emplacement may have occurred along a lateral ice stream shear margin. It is likely that raft material was not only emplaced but also entrained and transported in a subglacial environment. Overall, circumstances and mechanisms of megablock and raft entrainment remain relatively poorly understood despite them exerting an important control on the extent of erosion on glaciated plains and shelves.

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