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Large subglacial meltwater features in the central Barents Sea

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ABSTRACT

During the last glacial period large parts of the Arctic, including the Barents Sea, north of Norway and Russia, were covered by ice sheets. Despite several studies indicating that melting occurred beneath much of the Barents Sea ice sheet, very few meltwater-related landforms have been identified. We document ~200 seafloor valleys in the central Barents Sea and interpret them to be tunnel valleys formed by meltwater erosion beneath an ice sheet. This is the first account of widespread networks of tunnel valleys in the Barents Sea, and confirms previous predictions that large parts of the ice sheet were warm based. The tunnel valleys are interpreted to be formed through a combination of steady-state drainage and outburst floods close to the ice margin, as a result of increased melting within a period of rapid climate warming during late deglaciation. This is the first study documenting widespread tunnel valley formation at the northern reaches of a Northern Hemisphere paleo–ice sheet, during advanced deglaciation and beneath a much reduced ice sheet. This indicates that suitable conditions for tunnel valley formation may have occurred more widely than previously reported, and emphasizes the need to properly incorporate hydrological processes in current efforts to model ice sheet response to climate warming. This study provides valuable empirical data, to which modeling results can be compared.

INTRODUCTION

Over the past 2.6 m.y., the Barents Sea has undergone repeated shelf-wide glaciations, most recently during the late Weichselian, ca. 20 ka, during which the central part of the Barents Sea ice sheet remained marine based (grounded below sea level) (Svendsen et al., 2004a). Deglaciation from the Last Glacial Maximum (LGM) in the southwestern Barents Sea was well underway by ca. 17 ka (Rüther et al., 2011); the central Barents Sea was deglaciated between 16 and 14 ka (Fig. 1; Gataullin et al., 2001; Svendsen et al., 2004a, 2004b; Winsborrow et al., 2010; Andreassen et al., 2014; Bjarnadóttir et al., 2014; Hughes et al., 2016). Reconstructions of the late Weichselian Barents Sea ice sheet include a number of fast-flowing ice streams, indicating that lubricating meltwater was generated across large parts of the ice sheet base (e.g., Andreassen et al., 2008; Winsborrow et al., 2010; Bjarnadóttir et al., 2014). However, there have been few observations of subglacial meltwater features expected to form under such conditions. This study documents ~200 hitherto unknown meltwater features (tunnel valleys and eskers) in the central Barents Sea (Fig. 1), confirming, for the first time, that there was widespread channelized meltwater drainage beneath the Barents Sea ice sheet.

This is also the first account of widespread tunnel valleys (TVs) from the northern reaches of a Northern Hemisphere paleo–ice sheet. Previous studies have reported a general tendency for TVs to form in relation to large ice lobes and/or at ice sheet confluence zones along the southern margins of the Eurasian and Laurentide paleo–ice sheets during the LGM or early deglaciation (e.g., Huuse and Lykke-Andersen, 2000; Livingstone and Clark, 2016). Conversely, the results of this study indicate that suitable conditions for TV formation are not limited to such settings and can occur more widely, such as beneath the margins of much reduced ice sheets and during more advanced deglaciation.

DATA SETS AND METHODS

The spatial distribution of seafloor valleys and associated ridges (Fig. 1) was mapped based on bathymetric data from the echo-soundings database Olex (www.olex.no). The resolution of the Olex data (vertical ~0.1–1 m, horizontal ~5–50 m) (Items DR1 and DR2 in the GSA Data Repository[1]) allows for mapping of large geomorphic seafloor features (>100 m wide and >10 m deep). This mapping was verified and complemented with available multibeam swath bathymetry data (Items DR1 and DR2). The locations and main attributes of all seafloor valleys were mapped (Item DR3). Where data coverage was limited, valleys were mapped as undefined valley segments (Fig. 1). Available subbottom data (Items DR1 and DR2) were used to explore the degree of sediment infill of mapped seafloor valleys and acoustic properties of other related landforms such as eskers and moraines.

SEAFLOOR VALLEYS

Seafloor valleys were mapped extensively across the central Barents Sea (Fig. 1). Two types of valleys are identified: single straight valleys (Figs. 2A and 2B) and valley networks (Figs. 3 and 4). In plan form, the valleys are elongate and straight or slightly sinuous. The single straight valleys begin and or terminate abruptly (Figs. 2A and 2B) and occur in isolation or as clusters, interspersed between large areas with no valleys (Fig. 1). Valley networks are more varied, consisting of valleys with both abrupt and more gradual ends (Figs. 3 and 4); some are interconnected by large basins with gentle, yet adverse slopes (Fig. 3). All mapped valleys have undulating longitudinal profiles with several basins and steps along their thalwegs (Figs. 2A, 2B, 3, and 4C), while their cross-profiles (Figs. 2–4) vary from symmetric to asymmetric. Occasionally larger valleys have a narrower section incised into their base (Fig. 3, profile d), or broad, shallow valley shoulders sit atop narrow deep valleys. Valleys are typically 1–4 km wide (varying along the length), 1–17 km long, and 20–40 m deep (Item DR3). Olex data provide no subsurface information, so valley depths are minimum estimates. Subbottom data indicate that seafloor valleys may contain up to 50 m of sediments (Fig. 3, profile a; Fig. 2B, profile c), that their mapped extent based on Olex data is real (Fig. 3, profile a), and that they are eroded into sediments and in some cases into sedimentary bedrock (Fig. 3, profile a; Fig. 2B, profile c). Sediment thickness maps indicate that the valleys occur in Quaternary sediments up to 100 m (Vorren et al., 1992), and available geological maps show that the valleys incised into bedrock are mainly eroded into soft sedimentary bedrock, predominantly of Cretaceous age (Sigmond, 2002).

Several ridges are observed, superimposed on the mapped valleys (Fig. 1). These include sinuous ridges (<8 m high and <20 m wide) located within and oriented approximately parallel to the valleys (Fig. 4B, profiles a and b).

[1]GSA Data Repository item 2017040, Item DR1 (Figures DR1-A and DR1-B), Item DR2 (table), and Item DR3 (GIS shapefile) is available online at http://www.geosociety.org/pubs/ft2017.htm or on request from editing@geosociety.org.

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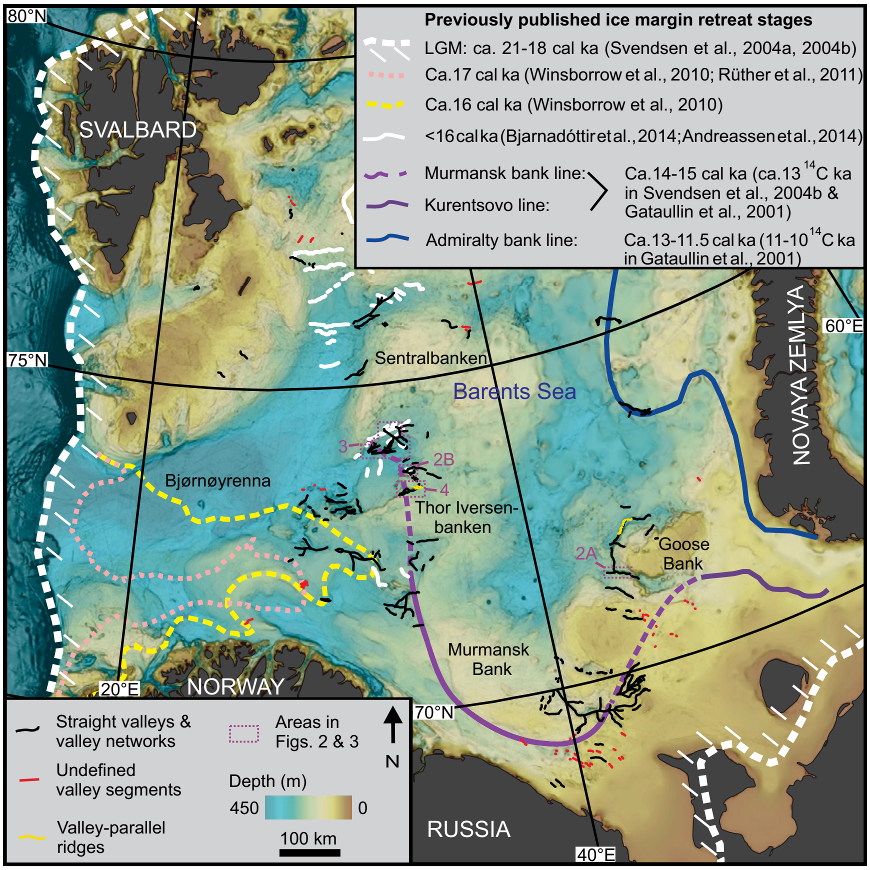

Figure 1. Overview map of the Barents Sea. The locations of straight valleys and valley networks are shown, along with undefined valley segments and valley-parallel ridges. A selection of previously published ice margin retreat stages and suggested ages is shown. In this paper all ages from the Barents Sea are given as rounded-off values of calibrated radiocarbon ages, based on the dates and age estimates reported in the original papers (i.e., cal ka, calibrated ^{14}C ages/1 k.y.). Violet boxes show the locations of areas shown in Figures 2–4. Bathymetry is from *International bathymetric chart of the Arctic Ocean* version 3.0 data set (Jakobsson et al., 2012). LGM—Last Glacial Maximum.

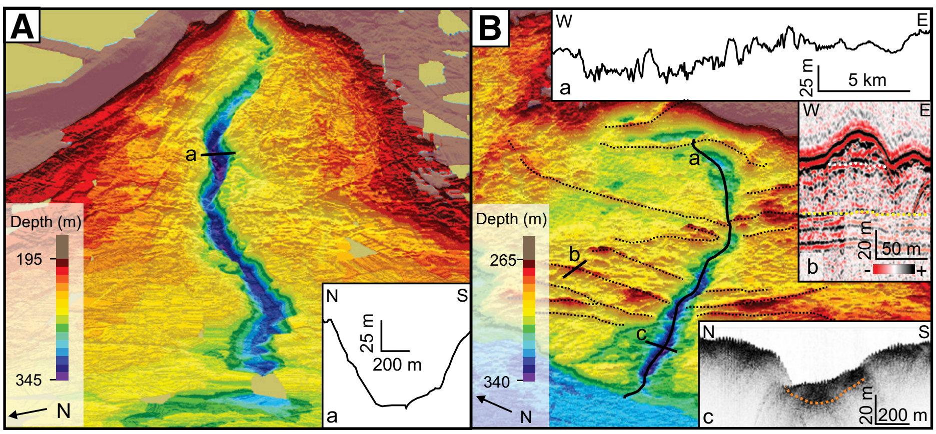

Figure 2. Seafloor valleys and moraines. A: Olex image (three-dimensional view [3-D], vertical exaggeration [v.ex.] 32) of a seafloor valley southwest of Goose bank, Barents Sea. Black line shows location of valley cross-profile a. B: Olex image (3-D view, v.ex. 32) of seafloor channel on Thor Iversenbanken. Recessional moraines (from Bjarnadóttir et al., 2014) are indicated by black dotted lines. Note that the westernmost moraines are breached, while the easternmost are not. Black lines show location of profiles a–c: a—longitudinal profile with overdeepening; b—single-channel seismic profile across a recessional moraine (white dotted line is basal reflector of a recessional moraine, yellow dotted line is boundary between sediments and bedrock); c—Chirp (compressed high-intensity radar pulse) profile across a seafloor valley (orange dotted line is base of valley sediment infill).

Where available, subbottom data show that the ridges are sedimentary features that are superimposed on the valleys (Fig. 4B, profile a). The ridges also include straight or semiarcuate ridges oriented transverse to the valleys (profiles a and b in Fig. 2B, and profiles a, b, and c in Fig. 3), previously interpreted as recessional moraines (Bjarnadóttir et al., 2014). Several of the recessional moraines continue undisturbed across valleys, while others have gaps at the point of intersection with the valleys (Figs. 2B and 3).

INTERPRETATION AND DISCUSSION

Interpretation of Seafloor Valleys and Ridges

The adverse slopes in the long profiles of the valleys, particularly near their downstream ends (Figs. 2A and 2B), imply that erosion by water driven by subglacial hydraulic potential gradients occurred; this and their sizes, geometries, and distributions support an interpretation of the valleys as TVs (e.g., O'Cofaigh, 1996; Kehew et al., 2012). The dimensions and geometries of the sinuous ridges observed on some of the valley floors (Fig. 4B, profiles a and b) fit the geomorphic criteria of eskers (Embleton and King, 1975), supporting the notion of meltwater flow in subglacial conduits through the valleys.

Formation of Observed TVs

The data set presented here sheds light on processes of TV formation, in particular whether they are formed by steady-state drainage and/or catastrophic meltwater floods. The relationship between the TVs and the recessional moraines provides some clues. Several moraines have gaps at the point of intersection with TVs (Figs. 2B and 3). Gaps in moraines indicate that meltwater was being evacuated steadily through the TVs as the ice margin retreated. Alternatively, the moraines may have been breached by either steady-state drainage or outburst floods through the TVs after moraine formation. Conversely, unbreached recessional moraines (Figs. 2B and 3) imply that meltwater flow through the TVs had ceased during or after moraine deposition. Recessional moraines both with and without gaps occur within a single TV network (Figs. 2B and 3), and a single recessional moraine may have a gap at the intersection with one TV within the same network and not another (TV1 and TV2 in Fig. 3). This indicates that parts of the network were active over prolonged periods during ice retreat, ruling out synchronous formation of the entire network by an outburst megaflood (cf. Brennand and Shaw, 1994). We suggest that different parts of the network developed gradually upglacier from the ice margin, through steady-state drainage, and were gradually abandoned as the ice retreated. It remains uncertain whether other TVs were generated by episodic outburst floods or steady-state drainage. Narrower, deeper channels and eskers within

TVs (such as observed in this study) have been attributed to fluctuating water levels, consistent with both steady-state flow and episodic outburst floods (e.g., Jørgensen and Sandersen, 2006), although esker building likely requires more time than during a brief outburst flood (Hooke, 2005). Eskers may not have formed at the same time as the TVs they reside in, and so may not represent conditions during TV genesis (Hooke and Jennings, 2006); however, they imply that meltwater was routed through the TVs during the last deglaciation. TVs may have been widened further by ice erosion after formation (Ehlers and Linke, 1989; Huuse and Lykke-Andersen, 2000), as supported by the occurrence of shallow wide shoulders within TVs.

Implications for Glacial History and Age of TVs

The large number and wide distribution of meltwater features demonstrate for the first time that the subglacial drainage of the central Barents Sea ice sheet was organized into networks of TVs that locally connected basins. A large number of the TVs presented here (Fig. 1) are oriented parallel to paleo–ice flow direction and terminate at documented paleo–ice marginal positions from the later stages of the last deglaciation, when the ice sheet had retreated toward the interior bank areas of the central Barents Sea and catchment sizes were greatly reduced (Gataullin et al., 2001; Svendsen et al., 2004b; Winsborrow et al., 2010; Bjarnadóttir et al., 2014). We suggest that these TVs were active, and likely formed close to ice margins during the last deglaciation of the Barents Sea. The occurrence of eskers further supports such an interpretation.

Published dates from the central Barents Sea are few and far apart geographically (Hughes et al., 2016), making it difficult to constrain the exact timing of deglaciation within this area. However, deglaciation of parts of the central Barents Sea occurred shortly after 16 ka (Polyak et al., 1995; Hughes et al., 2016), and ice retreated to the onshore areas of Norway, Russia, and Svalbard by 14 ka (Hughes et al., 2016). We believe it likely that the extreme and rapid warming at the onset of the Bølling-Allerød interstadial, ca. 14.7 ka (Rasmussen et al., 2006), led to greatly increased meltwater production, producing volumes likely to exceed the drainage capacity of the substrate and triggering TV formation close to ice margins. This hypothesis fits well with the mapped TV distribution in relation to paleo–ice margin positions.

TVs that do not terminate at paleo–ice margin positions may have been active during earlier stages of, or throughout, the glaciation. Similarly, where TVs are eroded into bedrock, it cannot be concluded whether they formed during the last glaciation or are inherited features that have been reused through several glaciations. Reoccupation of TVs through multiple

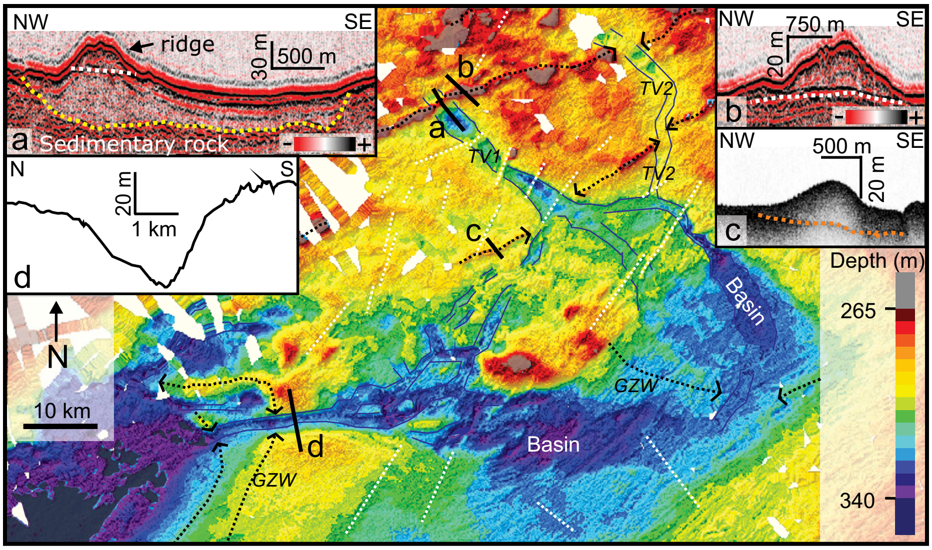

Figure 3. Olex (www.olex.no) bathymetry image of a channel system south of Sentralbanken. Recessional moraines and grounding zone wedges (GZW; from Bjarnadóttir et al., 2014) are indicated by black dotted lines; > and < symbols mark gaps in the moraines. Blue lines outline seafloor valleys (tunnel valleys, TVs). Basins connecting TVs are labeled. White dotted lines indicate vessel track artifacts. Black lines indicate locations of profiles a–d: a—single-channel seismic profile across a recessional moraine and the uppermost basin of a seafloor valley (yellow dotted line is valley base, white dotted line is base of moraine); b—single-channel seismic profile across a recessional moraine (white dotted line is base of moraine); c—Chirp (compressed high-intensity radar pulse) profile across a recessional moraine (orange dotted line is base of moraine); d—valley cross-profile.

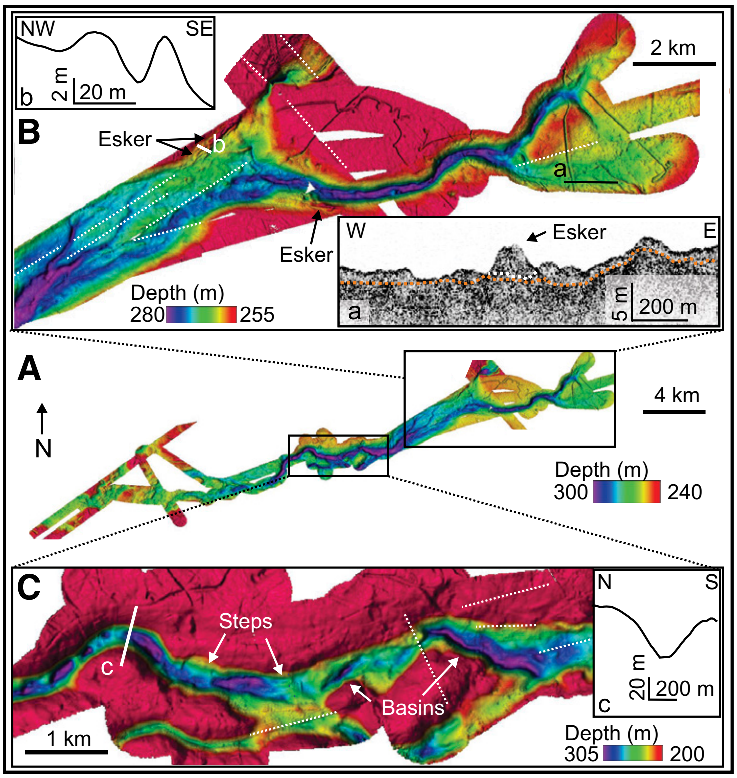

Figure 4. A: Multibeam swath bathymetry image of a valley system on Thor Iversen-banken. Rectangles mark locations of B and C (white dotted lines indicate artifacts in B and C). B: Easternmost part of channel system. Black line is location of Chirp (compressed high-intensity radar pulse) profile a, across a valley-parallel ridge. Profile a: Orange dotted line is internal reflector, white dotted line is base of valley-parallel ridge; white line is location of profile b. Profile b: Cross-profile of a valley-parallel ridge. C: Straight deep part of the network, highlighting the undulating thalwegs of the valleys. White line shows location of profile c. Profile c: Cross-profile of tunnel valley.

glaciations is known to occur (e.g., Piotrowski, 1994; Stewart et al., 2013), and although TV size may seem to indicate long-term erosion, we note that the bedrock in the Barents Sea is soft and easily erodible.

The dimensions and geometry of the TVs presented here are similar to descriptions from other regions (e.g., Kehew et al., 2102; Stewart et al., 2013; Livingstone and Clark, 2016); however, they also differ in several ways. For example, the TVs described herein formed beneath a marine-based ice sheet, in the northern sector of the Eurasian ice sheet and during advanced deglaciation in interior ice sheet sectors. Conversely, previous Northern Hemisphere accounts have largely been of terrestrial or shallow marine-based ice sheets, close to maximum ice positions in the southern sectors of the Eurasian and Laurentide ice sheets (Huuse and Lykke-Andersen, 2000; Livingstone and Clark, 2016).

CONCLUSIONS

This paper documents, for the first time, the occurrence of widespread networks of TVs formed beneath the marine-based Barents Sea ice sheet during the last glaciation. TVs form by subglacial meltwater erosion and indicate abundant channelized subglacial meltwater. The Barents Sea TVs are interpreted to be polygenetic features, formed through a combination of steady-state drainage, outburst floods, and ice erosion. The association of many of the TVs with known deglaciation retreat stages indicates that they formed close to the ice margin. We suggest that their formation was a result of a large increase in meltwater production in response to warming climate during the onset of the Bølling-Allerød interstadial. This is important because studies from the great Northern Hemisphere paleo–ice sheets have hitherto indicated that TVs preferentially form in their southern sectors, at maximum or early deglaciation positions in the outer ice sheet zones at the confluences of large ice lobes or ice sheets (e.g., Livingstone and Clark, 2016). The results of this study provide the first evidence that conditions suitable for widespread TV formation also occurred at the northern reaches of an Arctic paleo–ice sheet, during late deglaciation, at the margins of a much reduced ice sheet in the central part of the Barents Sea.

Modern ice sheets are currently undergoing the effects of warming climate; greatly increased surface melting is taking place in many glaciated regions. This resembles the conditions proposed for the Barents Sea ice sheet at the time of TV formation, further implying that TVs may currently be forming at modern marine-based ice margins undergoing intensive melting. In order to successfully model the response of modern or paleo–ice sheets to climate warming, it is essential to adequately incorporate hydrological processes such as TV formation. Empirical data, such as those presented here, are inherently valuable for evaluating the modeling results.

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