The central Arctic Ocean, including its surrounding seas, extends over an area of c. 9.5 × 10^6 km² of which c. 53% comprises shallow continental shelves (Jakobsson 2002) (Fig. 1a). The surface of this nearly land-locked polar ocean is at present dominated by a perennial sea-ice cover with a maximum extent every year in late February to March and a minimum in early to mid-September (Fig. 1a) (Serreze et al. 2007). Outlet glaciers producing icebergs that drift in the central Arctic Ocean exist on northern Greenland, Ellesmere Island and on islands in the Barents and Kara seas (Diemand 2001) (Fig. 1a). Ice shelves, although substantially smaller than those found in Antarctica, presently exist in some of Greenland’s fjords (Rignot & Kanagaratnam 2006), on Severnaya Zemlya (Williams & Dowdeswell 2001) and along the northern coast of Ellesmere Island (Jeffries 1992; Williams & Ferrigno 2012). Existing ice shelves around the Arctic Ocean are primarily formed through accretion of multiyear sea ice and gain their mass from snowfall and/or basal freezing.

The central Arctic Ocean has undergone substantial transformation with respect to physiography and ocean configuration during the major Quaternary glaciations. The c. 2550 m deep Fram Strait between Greenland and Svalbard (Fig. 1b) was the only remaining connection to the world ocean when sea level dropped by c. 120 m at the Last Glacial Maximum (LGM) (Lambeck et al. 2014) and ice sheets occupied the Barents and Kara seas (Svendsen et al. 2004). Cross-shelf troughs eroded in the seafloor terminate at the continental shelf edge bordering the deep central Arctic Ocean basin (Fig. 1a). These, and the streamlined glacial bedforms within them, indicate where large ice streams were active during full-glacial periods (Batchelor & Dowdeswell 2014). Deep-drafted icebergs calved from the ice streams and drifted in the central Arctic Ocean before exiting through Fram Strait. Dated iceploughmarks occur on bathymetric highs, extending into the central Arctic Ocean from the continental shelves, and on crests of ridges in the deep central basin (Jakobsson 1999; Polyak et al. 2001; Jakobsson et al. 2008; Dove et al. 2014). Furthermore, mapping of glacial landforms and sediment coring provide evidence for a c. 1 km thick ice shelf that may have covered the entire central Arctic Ocean during the peak of the Marine Isotope Stage 6 (MIS 6) glacial period c. 140 ka ago (Jakobsson et al. 2016). Large ice shelves may also have been present in the central Arctic Ocean during younger as well as older glaciations (Polyak et al. 2007; Jakobsson et al. 2014).

Here, the central Arctic Ocean glacial landform record that has emerged from geophysical mapping of High Arctic continental shelves and the ridges and plateaux of the central Arctic Ocean over the last two decades is set out. This record has permitted a re-examination of the hypothesis of an ice-sheet-fed floating ice-shelf system over the deep Arctic Ocean (Mercer 1970; Hughes et al. 1977).

**Arctic Ocean continental-shelf landforms**

**Cross-shelf troughs (CSTs) and trough-mouth fans (TMFs):**

The northermmost sectors of Barents, Kara, Beaufort and Lincoln seas and the Canadian Arctic Archipelago host bathymetrically well-defined cross-shelf troughs (CSTs) that terminate at the shelf break facing the deep central Arctic Ocean (Fig. 1a). Using the International Bathymetric Chart of the Arctic Ocean (IBCAO) digital bathymetric grid (v. 3.0; Jakobsson et al. 2012a), 20 CSTs with at least 150 m bathymetric expression were outlined and analysed by Batchelor & Dowdeswell (2014). They classified the troughs into three types using the characteristics of bathymetric profiles along the trough-axis and the presence or otherwise of a bathymetric bulge linked to glacial sediment deposition. Several of the identified CSTs can be traced back into one or more deep tributary fjords on adjacent landmasses such as Svalbard, Ellesmere Island and northern Greenland. The three largest CSTs, all extending more than 500 km in length, are the troughs of St Anna, M’Clure Strait and Amundsen Gulf (Batchelor & Dowdeswell 2014) (Fig. 1a, c, d). By contrast, the shallow and relatively flat continental shelves of the Laptev, East Siberian and Chukchi seas lack bathymetrically well-expressed CSTs (Fig. 1a).

Major sedimentary depocentres known as trough-mouth fans (TMFs) can be deﬁnitely mapped beyond the mouths of CSTs using high-resolution bathymetric mapping and seismic-reflection records (e.g. Vorren & Laberg 1997). These depocentres build up under full-glacial conditions when the ice streams occupying CSTs deliver large quantities of deformable subglacial sediment to the seafloor (e.g. Vorren & Laberg 1997; Dowdeswell & Siegert 1999). Several of the CSTs identified by Batchelor & Dowdeswell (2014) appear to have associated TMFs at their mouths (Fig. 1); however, only those located in the North American sector of the Arctic Ocean are described from seismic-reflection proﬁles. 2D seismic-reﬂection proﬁles of the 10 000 km² TMF associated with the large Amundsen Gulf Trough (Batchelor et al. 2014) (Fig. 1c) shows that the outer shelf is characterized by a prograding wedge of acoustically semi-transparent sediment up to 500 m thick containing eight sediment sequences relating to a series of past glacials. East of the Amundsen Trough is the huge M’Clure Strait Trough with a TMF estimated to be six times larger than that of Amundsen Gulf (Batchelor et al. 2014). To the west of Amundsen Gulf, however, the Mackenzie Trough appears to lack a well-developed TMF (Batchelor et al. 2014). By contrast, the mouth of Hinlopen Trough north of Svalbard provides an example of an area that is well mapped with modern multibeam technology (Batchelor et al. 2011; Hogan et al. 2013). The bathymetric data show that the Hinlopen Trough ends abruptly in the huge slide scar of Hinlopen Slide.

**Streamlined landforms and transverse ridges**

The seafloor of CSTs is often dominated by mega-scale glacial lineations (MSGLs) and closely related, but more subtle, streamlined linear to curvilinear glacial-sedimentary landforms (England et al. 2009; Hogan et al. 2010; Andreassen et al. 2014; Batchelor et al. 2014). Additional streamlined landforms, often with rock cores, are drumlins and crag-and-tails, for example those mapped in the Amundsen Gulf Trough (Batchelor et al. 2014; MacLean et al. 2015) and in some parts of Barents Sea CSTs (Ottesen et al. 2007; Hogan et al. 2010; Andreassen et al. 2014).

Large transverse-to-flow asymmetrical sedimentary wedges identified at the seafloor by subducted ridges, known as grounding-zone wedges (GZW)s, are mapped within several CSTs ending at the shelf break facing the deep Arctic Ocean. Examples include GZW(s) in three of the troughs located in the Beaufort Sea: Mackenzie, Amundsen Gulf and M’Clure Strait troughs (Batchelor et al. 2014; Batchelor & Dowdeswell 2015). GZW(s) also exist in most of the CSTs that have been mapped using multibeam methods on continental shelves of western Svalbard and the Barents Sea (e.g. Ottesen et al. 2007; Rebescos et al. 2011; Andreassen et al. 2014). Although a lack of high-resolution seafloor imagery may...
explain why GZWs have not been identified in CSTs of the Lincoln and Kara seas, some of the mapped High Arctic troughs do apparently lack such features. An example is the Kvitøya Trough, NE of Svalbard (Hogan et al. 2010). Finally, it should be noted that there is a general similarity in morphology and size between the Arctic Ocean and Antarctic GZWs mapped in CSTs (Jakobsson et al. 2012b; Batchelor & Dowdeswell 2015).

Relatively small ridges both along and transverse to CST long-axes, and hence ice-flow direction, are present in many of the mapped troughs as well as outside on the flatter continental shelf (e.g. Ottesen et al. 2007; Hogan et al. 2010; Andreassen et al. 2014; Batchelor et al. 2014). Notably, such morainic ridges also exist in the East Siberian and Chukchi seas on the continental slope in water depths even greater than 500 m, away from cross-shelf troughs and the shallow continental-shelf margin (Niessen et al. 2013; Dove et al. 2014; Jakobsson et al. 2016) (Fig. 2a).

Ice-keel ploughmarks

The vast continental shelves fringing the central Arctic Ocean are heavily scarred by iceberg ploughmarks as, for example, shown in extensive multibeam imagery of the shelf around Svalbard (Ottesen et al. 2007). Although there are regions where ploughmark patterns are influenced by prevailing directions of ocean currents, and hence iceberg drift, large areas of the continental shelf seafloor are dominated by apparently randomly orientated ploughmarks. However, the huge East Siberian Sea and inner Laptev Sea, and much of the Beaufort Sea, are very shallow with water depths often < 50 m. Deep-keeled icebergs calved from major ice streams and outlet glaciers into the Arctic Ocean cannot drift into these shallow waters. In addition, much of the area of these shallow shelves was emergent above sea level during past full-glacial periods. The many chaotic ploughmark patterns identified on these shallow...
shelves are produced by sea-ice pressure ridge keels; examples come from the Laptev and Beaufort seas at water depths ≥40 m (e.g. Héquette et al. 1995; Ananyev et al. 2016).

**Arctic Ocean ridge and plateau landforms**

Areas of the Arctic Ocean seafloor that are not traditionally included as parts of the continental shelves that fringe the deep-ocean basin include both structural ridges such as the Lomonosov Ridge and extensive plateaux that extend from the continental shelf into the central Arctic Ocean basin, such as the Chukchi Rise and Plateau, Morris Jesup Rise and Yermak Plateau (Fig. 1a). The submarine landforms of these areas are described here.

*Iceberg ploughmarks*

Iceberg ploughmarks were mapped by Vogt et al. (1994) in water depths of at least 850 m on the Yermak Plateau (Fig. 1a). These ploughmarks were the first glacier-related landforms discovered beyond the continental shelves in the deep (>500 m) central Arctic Ocean. Prior to this, iceberg ploughmarks had been reported by Hunkins et al. (1962) from the <300 m deep flat-topped crest of polar seas.

**Fig. 2.** Multibeam imagery of submarine glacial landforms from the central Arctic Ocean (located in Fig. 1a). (a) Recessional moraine ridges on the slope off Herald Canyon (*Oden*; modified from Jakobsson et al. 2016). (b) MSGL-like streamline landforms on Northwind Ridge (*Healy*). (c) Large iceberg ploughmarks on Morris Jesup Rise (*Oden*). (d) Two sets of MSGL-like landforms on Arlis Plateau (*Oden*; modified from Jakobsson et al. 2016). Multibeam acquisition system for USCGC *Healy* Seabeam 2140. Frequency 12 kHz. Grid-cell size 30 m. Multibeam acquisition system for IB *Oden* EM 122. Frequency 12 kHz. Grid-cell size 15 m.
Fig. 3. (a) Location map of Lomonosov Ridge (red box, map from IBCAO v. 3.0). (b) Chirp sonar profile showing stratigraphic unconformity on the Lomonosov Ridge caused by glacial erosion of the ridge crest (Jakobsson 1999). Chirp sonar acquisition system EdgeTech SC-512. Frequency 0.5–12 kHz (pulse 2–4 kHz, 100 ms long). (c) Multibeam bathymetry of Lomonosov Ridge showing MSGL-like features crossing it (modified from Jakobsson et al. 2016). Acquisition system EM 122. Frequency 12 kHz. Grid-cell size 15 m. (d) Bathymetric profile between y and y’ located in (c). VE × 29.
Fig. 4. Multibeam bathymetry from the southern Lomonosov Ridge crest off the Siberian continental margin. (a) Location map (red box, map from IBCAO v. 3.0). (b) Bathymetric profile between x and x’ shown in (d). VE × 23. (c) Multibeam image of the MSGL-like features. Multibeam acquisition system EM 122. Frequency 12 kHz. Grid-cell size 15 m. (d) Multibeam bathymetry of the Lomonosov Ridge crest showing MSGL-like features crossing the ridge (modified from Jakobsson et al. 2016).
the Chukchi Plateau (Fig. 1a). In the late 1990s, mapping of the Lomonosov Ridge between about 86 and 88 °N revealed a flat-topped ridge crest down to about 1000 m below modern sea level (Jakobsson 1999; Polyak et al. 2001) (Fig. 3a, b), thought to be eroded by the impact of keels from armadas of icebergs (Kristoffersen et al. 2004). However, early data from the Lomonosov Ridge consisted primarily of seismic-reflection and sub-bottom profiles, which precluded detailed morphological characterization (Fig. 3b). Comprehensive seafloor imagery of some of the eroded areas on the Lomonosov Ridge only became available in 2014 (SWERUS-C3 expedition described further below).

Multibeam images of Morris Jesup Rise, extending north from the northern continental shelf of Greenland (Fig. 1), have also revealed large iceberg ploughmarks down to a maximum water depth of 1045 m (Jakobsson et al. 2010; Jakobsson & O’Regan 2016). The two largest mapped ploughmarks cut across the rise; their impact with its western flank indicate drift from west to east along the northern continental shelf of Greenland toward Fram Strait (Fig. 2c). The larger of these two ploughmarks has a width of about 500 m and a relief of 10 m.

**Streamlined landforms and transverse ridges**

Multibeam bathymetry from the Northwind Ridge and Chukchi Plateau (Fig. 1a) shows that their shallow crests, at water depths of 900 m, are imprinted by linear to slightly curved parallel grooves and ridges closely resembling MSGLs (Polyak et al. 2001; Jakobsson et al. 2008; Dove et al. 2014) (Fig. 2b). The eastern, inner section of the Chukchi Plateau also shows three partly mapped larger (up to 15 km wide by 2.5 km long, with 40 m relief) streamlined landforms, possibly drumlins, which are parallel in orientation to the adjacent MSGL-like features (Dove et al. 2014). The largest MSGL-like features on the Northwind Ridge are between 200 and 1000 m wide and have relief approaching 40 m from the ridge top to groove bottom (Jakobsson et al. 2008).

MSGL-like features, similar in size and spatial extent to those mapped on the Northwind Ridge and Chukchi Plateau, also exist on the flat-topped crest of the Yermak Plateau (Dowdeswell et al. 2010; Jakobsson et al. 2010). These were first mapped by Vogt et al. (1994) using side-scan sonar. They trend from NNW to SSE, suggesting an ice-flow direction from the central Arctic Ocean towards Fram Strait.

Multibeam data collected during the SWERUS-C3 expedition (2014, IB Oden) show that streamlined landforms cross the

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**Fig. 5.** Ice-sheet reconstruction of LGM after the maximum version of Hughes et al. (1977), including a 1 km thick ice shelf in the Arctic Ocean.

**Fig. 6.** Schematic landform-assemblage model for the central Arctic Ocean shelf–slope–basin system.
Lomonosov Ridge crest at about 85° N, 153° E (Fig. 3a, c) (Jakobsson et al. 2016). This is one of the flat-topped areas previously assumed to be eroded by armadas of icebergs. The grooves and ridges are highly parallel, have relief of c. 10–15 m, and are generally between 200 and 500 m wide, although some are >500 m wide. (Fig. 3c, d). They occur to a maximum water depth of <1000 m. The form of the flanks of the flat-topped ridge crest suggests a stoss side on the Makarov Basin side (Fig. 3a), implying ice flow across the ridge towards the Amundsen Basin.

Multibeam bathymetry collected from the southern section of the Lomonosov Ridge off the Siberian continental shelf at about 81° N, 143° E (Fig. 4) (SWERUS-C3; Jakobsson et al. 2016) revealed two sets of streamlined landforms with slightly different orientations on the ridge crest. Their widths range over c. 400–800 m and their relief is c. 10–15 m (Fig. 4b, c). These features strongly resemble MSGLs. In this section of the Lomonosov Ridge crest, the MSGL-like features extend as deep as 1280 m. The grooves and ridges on the ridge crest at about 81° N, 143° E, are assumed to be eroded by armadas of icebergs. The grooves and ridges are 10–15 m wide, and some exceed 200 m wide. (Fig. 4b, c). These features strongly resemble MSGLs. In this section of the Lomonosov Ridge crest, the MSGL-like features extend as deep as 1280 m below present sea level on the Makarov Basin side, and reach c. 900 m on the Amundsen Basin side (Fig. 4d). Stoss and lee sides are more clearly developed here compared to the Lomonosov Ridge crest at about 85° N, 153° E. Inferred ice flow is diagonally across the ridge from the Makarov Basin side to the Amundsen Basin side.

The Arlis Plateau forms a <1000 m deep section of the Mendeleev Ridge at about 75° N, 180° E/W (Fig. 1a). Multibeam data show two sets of streamlined landforms on the plateau top (Niessen et al. 2013), one suggesting ice flow almost directly from the East Siberian Sea continental margin and the other indicating flow along the long-axis of the Mendeleev Ridge. Subsequent mapping (SWERUS-C3 expedition) showed the MSGL-like landforms to extend to a water depth of about 1200 m. These emanating from the East Siberian margin (white arrows in Fig. 2d) appear older as they are overprinted by the second set.

Morainic ridges, probably formed transverse to the direction of past ice-flow, occur along the margins of the Chukchi Plateau and southern Northwind Ridge (Dove et al. 2014). On the Lomonosov Ridge, the flattened ridge crest off the Siberian continental shelf contains small arcuate ridges with a relief of about 6 m (Fig. 4d). These ridges have their pointed edges facing southwards, towards the youngest ice-flow direction across the ridge. By contrast with CSTs on the continental shelves fringing the Arctic Ocean, GZWs are rarely identified on central Arctic Ocean bathymetric highs and ridges crests. However, on the flat crest of the southern Lomonosov Ridge at about 85° N, 153° E, there is a single faint sediment wedge with relief of about 15 m (Fig. 4d). There are GZW-like features mapped on the Northwind Ridge and Chukchi Plateau (Dove et al. 2014).

Discussion: an Arctic Ocean geomorphic system

Before submarine glacial landforms were mapped in the central Arctic Ocean, Mercer (1970) hypothesized the existence of a pan-Arctic ice shelf during at least one full-glacial period. By contrast, the unprotected ice shelves of the Arctic Ocean were interpreted by Hughes et al. (2016) to imply the former presence of a coherent 1 km thick ice-shelf extending over the entire central Arctic Ocean basin up to that first proposed by Mercer (1970) and later by Hughes et al. (1977). This newly proposed pan-Arctic ice shelf, based on submarine geomorphic evidence, was preceded by the suggestion of a smaller ice-shelf system confined to the Canadian Arctic Ocean based primarily on the discovery of MSGL-like features on the Northwind Ridge and Chukchi Plateau (Jakobsson et al. 2010) and along the Beaufort Sea continental margin (Engels et al. 2008). Prior to the collection of multibeam data from the Lomonosov Ridge crest, the first mapped evidence of ice grounding on the ridge crest was interpreted to signify a deep-keeled armada of drifting and grounding icebergs (Kristoffersen et al. 2004).

In summary, mapped landforms show traces of extensive inland ice-sheets, ice streams on the Arctic continental shelves and huge deep-drafting-associated ice shelves in the central Arctic Ocean during full-glacial conditions. This has led to the Arctic Ocean ice-shelf hypothesis formulated by Mercer (1970) being revisited (Jakobsson et al. 2016), based on detailed observational evidence of glacial landforms on the seafloor of the ridges, plateaux and shelves of the Arctic Ocean. Dating of sediment cores from these areas suggests that the most extensive ice-shelf system in the Arctic Ocean existed during MIS 6, about 140 ka ago. In addition, the existence of extensive ice-shelf systems from older glaciations (Polvak et al. 2007), or of younger, smaller ice-shelves of more limited thickness, cannot be excluded.

A full-glacial ice-sheet-fed ice shelf, at least 1000 m thick, covering the Arctic Ocean represents the greatest degree of ice cover in the Northern Hemisphere during the Quaternary Ice Age. Its reconstruction has only been possible due to the recent acquisition of swath-bathymetric evidence from the central Arctic Ocean and its surrounding high-latitude continental shelves, which is summarized in the schematic model in Figure 6. It is probably the fact that the Arctic Ocean is a deep-sea basin surrounded for the most part by landmasses that allowed a thick floating ice-shelf to develop during at least one full-glacial period. By contrast, the unprotected Southern Ocean margin of the Antarctic’s continental ice sheet implies consistently high rates of mass loss by iceberg production that restrict the sustained growth of large ice-shelves beyond protected embayments such as the Ross and Weddell seas.

References

LANDFORMS OF THE CENTRAL ARCTIC OCEAN


