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Sedimentary Environment and Glacial History of the Northwest Passage (Canadian Arctic Archipelago) Reconstructed from High-Resolution Acoustic Data

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This paper is dedicated to Sönke Neben, a friend and colleague, whose tragic death occurred on the day of our submission.

Abstract: A 2420 km long profile of high-resolution sub-bottom echosounder data (PARASOUND) is interpreted for facies distribution and stratigraphy across the Canadian Arctic Archipelago including the continental slopes from Baffin Bay to Beaufort Sea through M'Clure Strait. Five units are identified and interpreted as (i) bedrock (Devonian sedimentary rocks), unconformably overlain by (ii) subglacial till, overlain by (iii) proglacial diamicton deposited during deglaciation with (iv) Holocene muds on top. Subglacial tills have a basinward counterpart of numerous thick stacked debris-flow deposits found on the continental slopes of Baffin Bay and the Beaufort Sea interfingering with stratified deep-sea sediments at the continental rise (v). The debris flows are interpreted as mostly LGM in age and built up major glacial Trough Mouth Fans at both ends of Northwest Passage. They are indicative of oceanward export of glacial debris from fast flowing ice streams at the shelf edge derived from the Laurentide and Innuitian ice sheets. Diamicton deposited during deglaciation is widespread in the inner part of the Northwest Passage but relatively thin. Evidence of moraines as part of the deglaciation deposits points to a re-advance of grounding ice in places, which we interpret as possibly Younger Dryas and early Holocene in age. Postglacial Holocene sediments of significant thickness (>0.2 m) were only found in depressions of the Lancaster Sound and Barrow Strait.

Zusammenfassung: Entlang einer 2420 km langen Profillinie durch den Kanadisch-Arktischen Archipel mit den angrenzenden Kontinentalhängen von der Baffinbay durch die M'Clure-Straße bis zur Beaufortsee werden hoch auflösende Sedimentechographien (PARASOUND) in Bezug auf Stratigraphie und Faziesverteilung ausgewertet. Es liegen fünf Einheiten vor, die, von unten nach oben, als (i) Untergrund (Devonische Sedimentgesteine mit Erosionsdiskordanz zum Hangenden), (ii) subglaziale Geschiebe, (iii) proglaziale Diamikte (Abschmelzphase) und (iv) Holozäne Ablagerungen interpretiert werden. Die subglazialen Geschiebe gehen auf den Kontinentalhängen in mächtige Schlammstrom-Ablagerungen über, die sich am Kontinentalfuß der Baffinbay bzw. Beaufortsee mit geschichteten Tiefsee-Sedimenten verzahnen (v). Die Schlammströme werden größtenteils als Ablagerungen des letzten Glazialen Maximums interpretiert und bauen Mündungsfächer glazialer Tröge an beiden Enden der Northwest-Passage auf. Diese signalisieren einen beckenwärts gerichteten Export von glazialem Detritus an den Schelfkanten aus schnell fließenden Eisströmen der Laurentischen und Innuitischen Eisschilde. Die während der Abschmelzphase abgelagerten Diamikte verteilen sich in der inneren Northwest-Passage über eine große Fläche, sind aber von relativ geringer Mächtigkeit. Moränen kommen lokal als Teil der Abschmelz-Ablagerungen vor und signalisieren Vorstöße des Eises innerhalb des Kanadisch-Arktischen Archipels während der Jüngeren Dryas und dem frühen Holozän. Holozäne Sedimente mit signifikanter Mächtigkeit (>0.2 m) werden nur in Depressionen des Lancaster-Sunds und der Barrow-Straße gefunden.

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INTRODUCTION

In summer 2008, RV "Polarstern" sailed along the Northwest Passage (NW-Passage) as part of the ARK-XXIII/3 Arctic Ocean Expedition (Fig. 1). In middle of August of that year, the sea-ice conditions in the Canadian Arctic Archipelago (CAA) were favourable to sail the passage on a 2420 km east-to-west line from the Baffin Bay into the Arctic Ocean (JOKAT 2009). In the Viscount Melville Sound, the M'Clure Strait and on the continental slope of the Arctic Ocean, sea-ice coverage was extraordinarily low (0 to 50 %) during August 19 and 25, 2008 (Fig.1). This allowed recording of high-resolution acoustic sub-bottom profiles along the cruise track of very high quality, which forms the main database of this paper. As the western part of this passage normally remains ice covered even during summer times, these marine areas remained largely unexplored up to now. Nonetheless, in particular the transition from the CAA into the Arctic Ocean is a key area for understanding the glacial history of the Canadian Arctic, Beringia and the entire Arctic Ocean. Satellite imagery of surface structures on the islands in the CAA reveal evidence for numerous ice streams that were highly variable during the Last Glacial Maximum (LGM) and post LGM times (STOKES et al. 2005, DE ANGELIS & KLEMAN 2008, STOKES et al. 2009). Recently, it has been argued that during LGM times large ice streams were flowing along the Amundsen Gulf and Viscount Melville Sound/M'Clure Strait extending to the shelf edge and possibly even into the Arctic Ocean forming a thick ice shelf (STOKES et al. 2005, JAKOBSSON et al. 2005, ENGELS et al. 2008, ENGLAND et al. 2009). This debate, however, lacks direct evidence from marine sediments, which is presented in this paper.

During the LGM most parts of the CAA including shelf areas (Fig. 1b) were ice-covered by parts of the Laurentide Ice Sheet (DYKE 2004). The Laurentide Ice Sheet was linked to the Greenland Ice Sheet by the Innuitian Ice Sheet, which covered most of the Queen Elizabeth Islands (ENGLAND et al. 2006), whereas the central part of Baffin Bay remained ice-free (EHLERS & GIBBARD 2007). The northwestern boundary of the Laurentide Ice Sheet was close to the present McKenzie River (EHLERS & GIBBARD 2007), from where an area of reduced ice coverage extended over Brooks Range, eastern Siberia and the Laptev and Kara seas (SVENDSEN et al. 1999, BRIGHAM-GRETTE et al. 2003).

The exact boundary and, in particular, the thickness of the ice

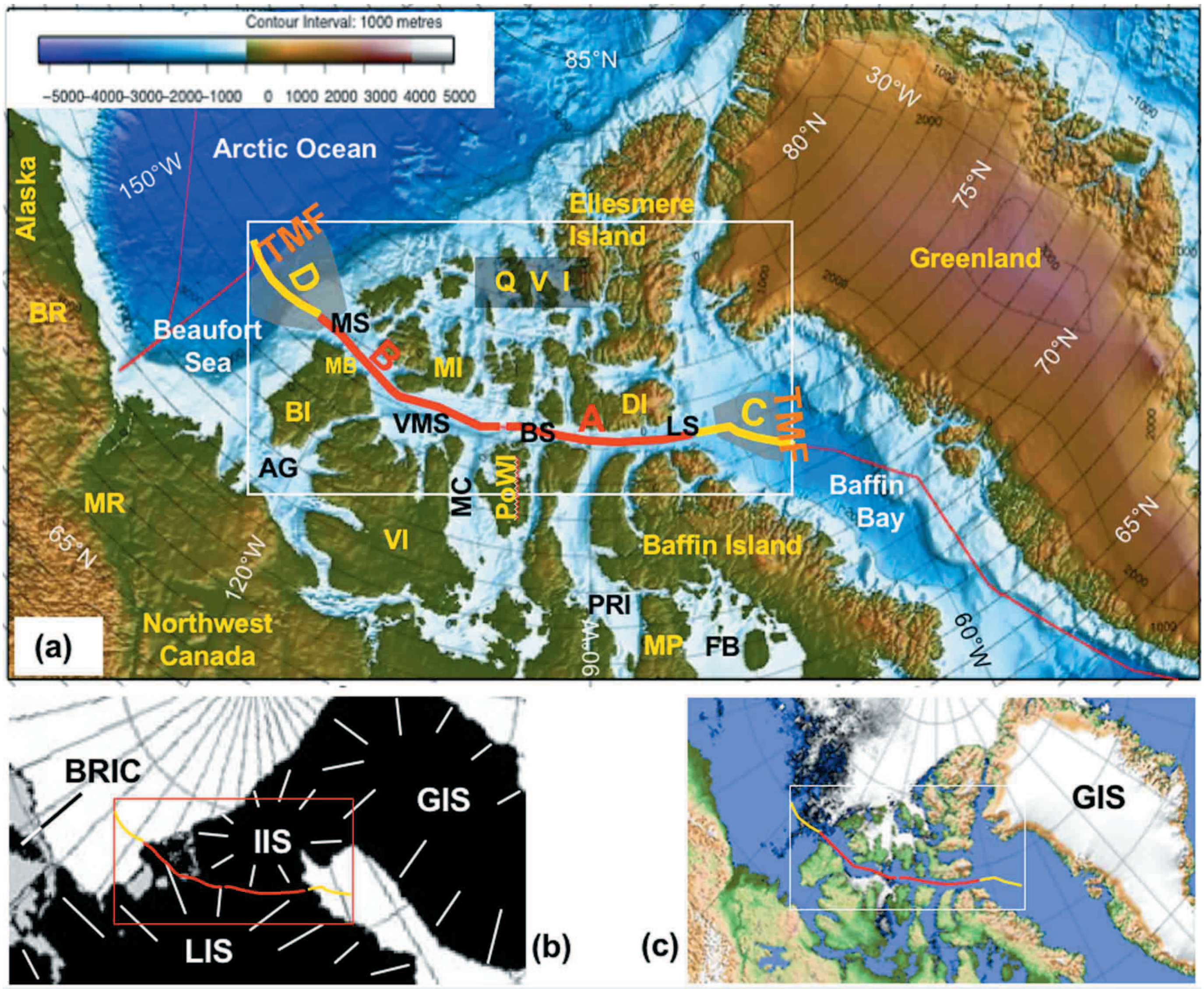

Fig. 1: The Canadian Arctic Archipelago (CAA), the area under investigation (inner rectangle) and the track line of RV "Polarstern" during cruise ARK-XXIII/3 along the NW-Passage in 2008 (sections A to D).
(a) Elevation, bathymetry and locations referred to in text: AG = Amundsen Gulf, BR = Brooks Range, BI = Banks Island, BS = Barrow Strait, FB = Foxe Bay, DI = Devon Island, LS = Lancaster Sound, MB = Mercy Bay, MC = M'Clintock Channel, MI = Melville Island, MP = Melville Peninsula, MR = McKenzie River, MS = M'Clure Strait, PoWI = Prince of Wales Island, PRI = Prince Regent Inlet, VI = Victoria Island, VMS = Viscount Melville Sound, QVI = Queen Victoria Islands. Map produced using GMT software (WESSEL & SMITH 1998).
(b) Same section as (a) with ice caps during the LGM: BRIC = Brooks Range Ice Cap, LIS = Laurentide Ice Sheet, IIS = Innuitian Ice Sheet, GIS = Greenland Ice Sheet (modified after EHLERS & GIBBARD 2007).
(c) Same section as (a) with ice cover on 23 August 2008. GIS = present day Greenland Ice Sheet and sea-ice coverage from blue (0 %) over dark grey (50 %) to white (100 %). Source: Archive of Polar View, University of Bremen (www.iup.uni-bremen.de:8084/amsr/amsre.html)

Abb. 1: Der Kanadische Arktische Archipel (CAA), das Untersuchungsgebiet (weiß umrandetes Rechteck) und die Kurslinie von FS „Polarstern" während der Expedition ARK-XXIII/3 auf der NW-Passage im Jahr 2008 (Abschnitte A bis D).
(a) Höhen, Bathymetrie und im Text erwähnte Lokationen: AG = Amundsen-Golf, BR = Brooks Range, BI = Banks-Insel, BS = Barrow-Straße, FB = Foxe-Bucht, DI = Devon-Insel, LS = Lancaster-Sund, MB = Mercy-Bucht, MC = M'Clintock-Kanal, MI = Melville-Insel, MP = Melville-Halbinsel, MR = McKenzie-Fluss, MS = M'Clure-Straße, PoWI = Prince of Wales-Insel, PRI = Prince Regent Inlet, VI =Victoria-Insel, VMS = Viscount Melville-Sund, QVI = Queen Victoria-Inseln. Erstellt mit Hilfe von GMT Software (WESSEL & SMITH 1998).
(b) Kartenausschnitt wie (a) mit den Eiskappen des letzten Glazialen Maximums (LGM): BRIC = Eiskappe des Brooks-Gebirges, GIS = Grönländisches Eisschild, IIS = Innuitisches Eisschild, LIS = Laurentisches Eisschild (modifiziert nach EHLERS & GIBBARD 2007)
(c) Kartenausschnitt wie (a) mit heutiger Eiskappe auf Grönland = GIS und Meereisbedeckung am 23. August 2008 von blau (0 %) über dunkel grau (50 %) bis weiß (100 %). Quelle: Archive of Polar View, Universität Bremen (www.iup.uni-bremen.de:8084/amsr/amsre.html)

sheet on the northwestern CAA came recently under debate. Reconstructions by DYKE & PREST (1987), DYKE et al. (2002), DYKE (2004) and HARINGTON (2005), leave parts of Melville and Banks islands ice free during the LGM, and suggest a floating ice shelf in the M'Clure Strait that never reached the shelf boundary of the Arctic Ocean. In contrast, according to reconstructions by ENGLAND et al. (2006, 2009), the Lancaster Sound and the M'Clure Strait formed the boundary zone between the Innuitian Ice Sheet and the Laurentide Ice Sheet (Fig. 1) suggesting major ice flows along these lines towards Baffin Bay and the Arctic Ocean. The M'Clure Trough Mouth Fan (TMF) has been interpreted from its morphology, together with petrographical evidence found in cores from the Arctic Ocean and Fram Strait, as a major pathway of glacial debris eroded in the Canadian Arctic and transported to the Arctic Ocean (STOKES et al. 2005, ENGLAND et al. 2009). In this paper we make a strong case for supporting this hypothesis by presenting evidence from acoustic facies that further characterize the M'Clure continental slope as typical glacial TMF similar to its eastern counterpart, the Lancaster Sound TMF on the slope of Baffin Bay (Fig.1).

Despite numerous reconstructions of the glacial history of the CAA based on terrestrial evidence (EHLERS & GIBBARD 2007 cum lit.), relatively little is published from marine environments. Submarine glacial flutings interpreted from acoustic evidence in the Viscount Melville Sound (MACLEAN et al. 1989) are used by ENGLAND et al. (2009) to strengthen the argument for a major ice flow at LGM times. Glacial flute marks and iceberg scours are also found in the straits and sounds further south in the CAA (MACLEAN et al. 2008). Two more recent Canadian ArticNet expeditions along the NW-Passage recorded 3.5 kHz sub-bottom profiles and obtained sediment cores (ROCHON et al. 2004, 2005). These data are being used to map seabed morphology, to interpret the regional geologic framework and to investigate the paleoceanographic history of the NW-Passage over the past 20,000 years. Some of the outcomes are published in conference volumes (e.g., BENNETT et al. 2006, SCHELL et al. 2006, BLASCO et al. 2008) and subsequent publications (SCHELL et al. 2008, LEDU et al. 2008, VARE et al. 2009). Marine sediments cored in the Lancaster Sound and Barrow Strait revealed basal calendar ages of 11.06 ka and 10 ka (LEDU et al. 2008, Vare et al. 2009), respectively, and are correlated with the results of this paper.

Both Canadian ArcticNet cruises went along the southern track of the NW-Passage, through the sounds and straits east of Prince of Wales Island and south of Victoria Island including the Amundsen Gulf (Fig. 1), and did not investigate the area between Viscount Melville Sound and the Arctic Ocean. Thus, there is some overlap between our findings and the ArcticNet cruise data resulting in similar evidence and conclusions on the glacial to postglacial situations in the Lancaster Sound and Barrow Strait area (BENNETT et al. 2006, LEDU et al. 2008, VARE et al. 2009). In the Burrow Strait based on the ArcticNet results, one sediment core was retrieved during ARK-XXIII/3 to extend the Holocene record further back in time and to calibrate the acoustic facies presented here. One major objective of the ArcticNet expeditions was the reconstruction of the sea-ice situation along the NW Passage during the Holocene (ROCHON et al. 2005, SCHELL et al. 2006, 2008, VARE et al. 2009). One major goal of the ARK -XXIII/3 expedition was the reconstruction of the glacial history of the Arctic Ocean including pathways of ice-rafted debris (STEIN et al. 2010 this vol.). Thus, the results of both the ArcticNet and ARK-XXIII/3 expeditions are mutually beneficial rather than competitive.

In this publication the inner part of the NW-Passage refers to the sounds and straits of the CAA between 75° – 76° N and 65°45' – 137° W (sections A and B in Fig. 1). The outer parts of the NW-Passage are the shelf to deep-sea transitions into Baffin Bay and the Arctic Ocean, respectively (sections C and D in Fig. 1).

METHODS AND MATERIALS

Sub-bottom acoustic profiling was carried out along the entire cruise track (Fig. 1) in 24h operation (NIESSEN & MATTHIESSEN 2009) using PARASOUND technique. The hull-mounted PARASOUND system DS III-P70 of RV "Polarstern" generates two primary frequencies of 18 and 22 kHz transmitting in a narrow beam of 4° at high power. As a result of the non-linear acoustic behavior of water, the so-called "Parametric Effect" (e.g. SPIESS 1992), two secondary harmonic frequencies are generated, of which the lower difference frequency (4 kHz) was used to obtain sub-bottom penetration of up to 50 m in the area under investigation. The primary advantage of parametric echosounders is based on the fact that the sediment-penetrating pulse is generated within the narrow beam of the primary frequencies (4°) thereby providing a very high lateral and vertical (0.2 m) resolution compared to conventional 4 kHz-systems (20 to 40° beam angle). The new PARASOUND DS III-P70 was installed on RV "Polarstern" in 2007. A more detailed system description is given by NIESSEN & MATTHIESSEN (2009) and NIESSEN et al. (2009a, 2009b).

Using software ATLAS HYDROMAP CONTROL the PARASOUND system was operated as "Single Beam Sub-bottom Profiler" in "Single Pulse" mode along the NW-Passage. Details on operation, sounding options and ranges used during ARK-XXIII/3 are published elsewhere (JOKAT 2009). Software ATLAS PARASTORE-3 was used for data storage in ASD (Atlas Sounding Data) and PS3 formats, on-line printing, replay and processing. Processing includes filtering (1-6 kHz), negative-flank suppression, sub-bottom TVG (time variable gain) and trace stacking (2 to 10 traces as simple stack) in order to improve the signal to noise ratio. For all profiles presented in this paper, locations and lateral scales are given in date and time (UTC). RV "Polarstern" positions can be extracted according to date and time (UTC) in one-minute intervals from the AWI database DSHIP (http://dship.awi.de/). Original PARASOUND data of the time window presented in Figures 2 and 3 can be extracted from the data base PANGAEA (www.pangaea.de).

The bathymetric survey was performed using ATLAS HYDROSWEEP DS2 (Atlas Hydrographic), a deep-sea multibeam echosounding system, which is hull-mounted. Data acquisition and processing is described in more detail in the cruise report (JURISCH et al. 2009). HYDROSWEEP was operated in the hard-beam mode with a resolution of 59 single depth points (preformed beams) per ping. Most of the time an opening angle of 90° was used, which results in a swath width of twice the water depth. In areas with water depths less than 350 m, the opening angle was switched automatically to 120°. In this mode a swath width of 3.4 times the water depth is recorded. The data presented here were recorded in medium-depth mode (~1000 - 120 m).

Core PS72/287-3 SL (74°15.95' N, 90°59.09' W; water depth 337 m) was recovered in Barrow Strait (C2, Fig. 2) using a gravity corer (STEIN et al. 2009). The location was selected according to PARASOUND based on previous information from the 2005 ArcticNet cruise (ROCHON et al. 2005). Prior to splitting and description the core was cut into 1-m-long sections and logged for physical properties using a Multi-Sensor-Core-Logger (www.geotek.co.uk). The details of the logging procedure and parameters are published in the cruise report (NIESSEN et al. 2009c). Ice-rafted debris (IRD) >2mm is counted in X-ray photographs of 1 cm thick sediment slabs subsampled from the working half of the core (STEIN et al. 2009). Core data can be extracted from the data library PANGAEA (www.pangaea.de).

All ages in this paper are presented in calibrated calendar years (ka BP 2000). Radiocarbon ages cited from the literature are converted to calendar years after REIMER et al. (2004).

ACOUSTIC STRATIGRAPHY AND FACIES

The distribution of different acoustic stratigraphies and facies is clearly related to water depth between the Western Baffin Bay (about 2400 m) across the NW-Passage (with depth as shallow as 150 m in the Barrow Strait) and to the continental rise of the Arctic Ocean at about 3500 m depth (Fig. 1). The stratigraphic pattern and facies as seen in PARASOUND online prints along the 2420 km long passage are summarized as simplified morphological/geological sketches (Figs. 2, 3).

In the entire area under investigation five main geoacoustic units can be distinguished, of which two have subunits with different facies:
Unit (1) acoustically transparent cover of up to 10 m in thickness;
Unit (2) well-stratified (2a) or massive sediments (2b);
Unit (3) chaotic glacial till (3a) or debris flow deposits (3b);
Unit (4) inclined stratified bedrock, and
Unit (5) well-stratified deep-sea sediments (Figs. 2, 3).
In areas shallower than 600 m to 800 m, between the M'Clure Strait and the Lancaster Sound, only units (1) to (4) are found. These units are similar to the units described in BENNETT et al. (2006), and they can be used to define a stratigraphy. On the continental slopes and off the continental rise only Unit (3) and Unit (5) are recorded, respectively. Unit (5) can only be interpreted in terms of facies as it forms the distal and undifferentiated counterpart of units (1) to (3).

Geoacoustic Unit (1)

This unit exhibits strong acoustic backscatter from the sediment surface (reflector R1) but is mostly massive to weakly stratified otherwise (Figs. 4, 5, 6). In places, a relatively weak reflector (R2) is visible near the base of unit (1) (e.g. Fig. 5). The unit is strongly variable in thickness (<1 m to about 10 m) and only present in restricted (patchy) areas of the passage (in sections A and D; Figs. 1, 2, 3). In the Lancaster Sound at about 550 m water depth, Unit (1) pinches out in westward direction (Fig. 2). It reappears in the Barrow Strait below 340 m water depth (Fig. 5a) and lenses out westward at 300 m water depth without any re-appearance to the end of the profile (Fig. 2).

Geoacoustic Unit (2)

This acoustic unit is characterized by higher amplitude reflections and appears as well-stratified (Unit (2a)) or massive and patchy in places (Unit (2b)) (Figs. 2, 3 and 4 to 8). The top of Unit (2) is characterized by a strong reflector (R3, Fig. 5). The lateral distribution of acoustic Unit (2) is more widespread than Unit (1) (Figs. 2, 3). Unit (2a) extends as drape into areas of shallower water, where the overlying Unit (1) pinches out over short lateral distances (e.g. in the Barrow Strait, Fig. 5a).

Towards the western end of the Lancaster Sound, well-stratified sediments of Unit (2a) are intercalated with the eastern end of a larger wedge-shaped feature, which is best described as the frontal slope of a moraine (Fig. 2, 4). The lower part of stratified Unit (2a) clearly continues horizontally under the tip of the feature. Its frontal slope rises the sea floor by 70 m over a distance of 7 km (Fig. 2). The feature is draped by the upper part of stratified sediment of Unit (2a) (Fig. 4) defining it as a Unit (2) deposit. Although the internal structure of the feature is not resolved, its stratigraphic position underlines a depositional origin presumably as till or diamicton (Unit (2b), Fig. 2). The morphology is interpreted to mark a major re-advance of grounding ice to a location, which is just north of the Prince Regent Inlet (Fig. 1). A similar situation can be described in the M'Clure Strait. A morphologic feature typical for a push moraine is oceanward intercalated with partly reworked and partly well stratified sediments of Unit (2a) (Fig. 2), and interpreted as diamicton or till. The morphology suggests that this deposit has also been formed by a re-advance of grounded ice into the M'Clure Strait (Fig. 2).

The lateral distributions of Units (2a) and (2b) are very different along sections A and B (Fig. 2). Well-stratified sediments of Unit (2a) are predominant in the Lancaster Sound and Barrow Strait, in particular in deeper water. Unit (2a) is absent in the Viscount Melville Sound, and is present in some areas of the M'Clure Strait and shelf, west of the moraine described above (e.g. Fig. 7). In areas up to 600 m of water depth, Unit (2) can appear to be reworked by ice gouging (Figs. 2, 3). In the Viscount Melville Sound Unit (2) appears as massive diamicton, forming elongated flutes roughly parallel to the shore lines (Fig. 8). The sediments are acoustically transparent and possibly consist largely of muds, which appear to be reworked and oriented into elongated flutes by a grounded ice stream. Diamicton and morphology are unaltered and uncovered and appear very "fresh" (Fig. 8). These features are similar to the flutings described by MACLEAN et al. (1989) and ENGLAND et al. (2009).

Massive sediments of Unit (2b) are also present west of the moraine in M'Clure Strait and on the adjacent shelf where they laterally interfinger with well-stratified sediments of Unit (2a) (Fig. 2). This observation convinced us to map both stratified (2a) and massive sediments (2b) as Unit (2).

Geoacoustic Unit (3)

Sediments of this unit are mostly acoustically transparent with some diffuse backscatter or exhibit irregular and discontinuous internal reflectors. Sediments can appear laterally over larger distances (Fig. 7) or patchy as isolated lenticular shaped features (Figs. 4, 5). The surface of Unit (3) can be hummocky in places, which is still visible at the sediment surface today (Figs. 6, 7), or smoothed by overlying sediments of Unit (2) and Unit (1) (Fig. 6a). These hummocks are irregular and no specific orientation is visible in the bathymetry (Figs. 6, 7).

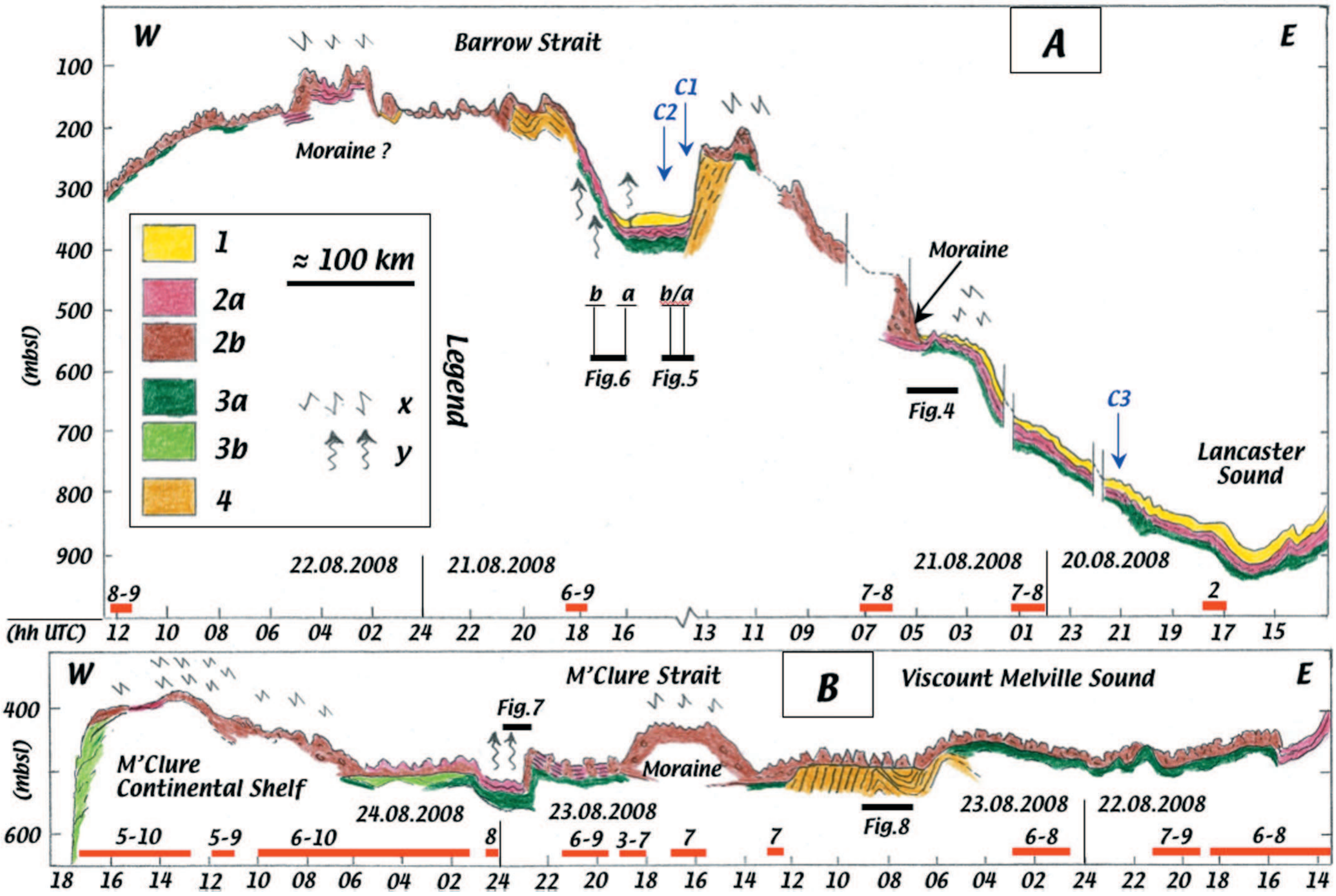

Fig. 2: Summary of units and facies as seen in PARASOUND sub-bottom profiles in the inner part of the NW-Passage redrawn and interpreted from hand sketches of the PARASOUND field book of ARK-XXIII/3 by first author. Note that only the bathymetry is true to scale (mbsl = meters below sea level) and based on PARASOUND sounding depths. Lateral distribution and sub-bottom extent of acoustic facies are strongly simplified. Sub-bottom structures are not true to scale and strongly height-exaggerated. The horizontal scale is time (in hours, hh UTC), separated according to date. RV "Polarstern" navigation data can be extracted by date and time from the AWI data base (http://dship.awi.de/).
Profiles A and B have total lengths of 842 km and 825 km, respectively. On average, ship speed was 11 kn and 10.25 kn on profile A and B, respectively, if not indicated differently above or below the red bars close to time scale. C1, C2 and C3 = locations of cores ARC-3, PS72/287-3 and 2004-804-009 discussed in text. Also marked are locations where profile sections are presented in figures 4 to 10.
Legend: 1 = Geoacoustic Unit (1) - massive to stratified marine sediments (Post Glacial). 2a = Facies of Geoacoustic Unit (2) - well-stratified diamicton, Late Glacial melt phase. 2b = Facies of Geoacoustic Unit (2) - patchy diamicton and moraines, Late Glacial melt phase. 3a = Facies of Geoacoustic Unit (3) – massive diamicton, Full Glacial/subglacial. 3b = Facies of Geoacoustic Unit (3) - debris-flow deposits, Full Glacial/pro and/or subglacial LGM. 4 = Geoacoustic Unit (4) - folded and faulted sedimentary bedrock (Devonian). x = area with surface sediments heavily ploughed by grounding ice. y = area with distinct morphological features, hummocks and pockmarks.

Abb. 2: Zusammenfassung von Einheiten und Fazies aus PARASOUND-Sedimentechographie-Profilen im inneren Teil der NW-Passage; gezeichnet und interpretiert nach Handzeichnungen aus dem PARASOUND-Expeditionsbuch ARK-XXIII/3 durch den Erstautor. Zur Beachtung: Nur die gezeigte Bathymetrie ist tiefentreu (m unter Meeresspiegel (mbsl) aus PARASOUND-Lotungen). Die laterale Verteilung und Tiefenerstreckung der Fazies wurde plakativ vereinfacht. Untergrundstrukturen sind nicht tiefentreu und stark überhöht dargestellt. Die horizontale Achse ist nach Stunden (hh UTC) skaliert und nach Datum unterschieden. Die zugehörigen Navigationsdaten der „Polarstern" können aus der Datenbank DSHIP des AWI, sortiert nach Datum/Uhrzeit, herunter geladen werden (http://dship.awi.de/).
Profile A und B haben Gesamtlängen von 842 km bzw. 825 km. Die durchschnittliche Schiffsgeschwindigkeit betrug 11 kn auf Profil A bzw. 10.25 kn auf Profil B wenn nicht an den horizontalen roten Balken über der Zeitskala in Knoten anders angegeben). C1, C2 und C3 markieren die Lokationen der Sedimentkerne ARC-3, PS72/287-3 and 2004-804-009, die im Text diskutiert werden. Außerdem sind die Abschnitte markiert, für die akustische Profil-Daten in den Figuren 4 bis 8 dargestellt sind.
Legende: 1 = Geoakustische Einheit (1) – ungeschichtete und geschichtete marine Ablagerungen, Postglazial. 2a = Fazies der Geoakustischen Einheit (2) – gut geschichtete Diamikte, Spätglazial/Abschmelzphase. 2b = Fazies der Geoakustischen Einheit (2) - lokal vorkommende Diamikte und Moränen, Spätglazial/Abschmelzphase. 3a = Fazies der Geoakustischen Einheit (3) - ungeschichtete Diamikte, Hochglazial/subglazial. 3b = Fazies der Geoakustische Einheit (3) - Schlammstrom-Ablagerungen, Hochglazial/pro- und/oder subglazial. 4 = Geoakustische Einheit (4) - gefaltete und tektonisch verworfene Sedimentgesteine des Untergrundes (Devon). x = Gebiete mit Oberflächensedimenten, die durch Grund berührendes Eis durchpflügt wurden. y = Gebiete mit punktuell auftretenden Oberflächenstrukturen, Buckel- und Trichter-Strukturen.

Unit (3) can be best characterized as subglacial to proglacial diamicton as in Unit (3a), which may be intercalated with acoustically transparent debris-flow deposits (3b) (e.g. Fig. 7). In terms of its facies, these sediments may be similar to the moraine feature described above. However, in case a complete stratigraphy is preserved (Figs. 4, 7), Unit (3) clearly underlies Unit (2) and thus appears to be older than the two moraines described within Unit (2). Where a complete stratigraphy is not exposed in PARASOUND profiles, the distinction between Unit (2) and Unit (3) diamicton may become difficult in places (e.g. Fig. 8).

On the continental slopes of the Lancaster Sound/Baffin Bay and M'Clure Strait/Beaufort Sea (deeper than 800 and 600 m), there is only one type of sediment found as deep as the PARASOUND penetration allows imagery. The facies can be characterized as numerous stacked debris-flow deposits and is mapped as Unit (3b). These deposits are of similar type on both slopes (off Lancaster Sound and M'Clure Strait, Fig. 3) forming typical subglacial to proglacial Trough Mouth Fans (TMF) (Figs. 1, 9, 10) in the senses of VORREN & LABERG (1997) or Ó COFAIGH et al. (2003, 2008).

Geoacoustic Unit (4)

This unit is only observed in the inner part of the NW-Passage (Fig. 2). The unit is stratified and often appears as slightly dipping or folded/faulted strata that is cut by a distinct and nearly horizontal unconformity on top (Figs. 2, 8), which forms a glacial surface of erosion. In places, Unit (4) is overlain by Units (3) or (2) (Fig. 2), but may also appear uncovered at the sea floor (Fig. 8). This unit is only visible in PARASOUND profiles if the sedimentary cover is very thin or absent. The acoustic character (penetration) and geometry (inclination, folds and faults) suggest that Unit (4) is bedrock consisting of relatively soft siltstones or mudstones. Devonian sedimentary rocks are widespread in the CAA and form the bedrock from the Lancaster Sound to the M'Clure Strait (WHEELERS et al. 1996).

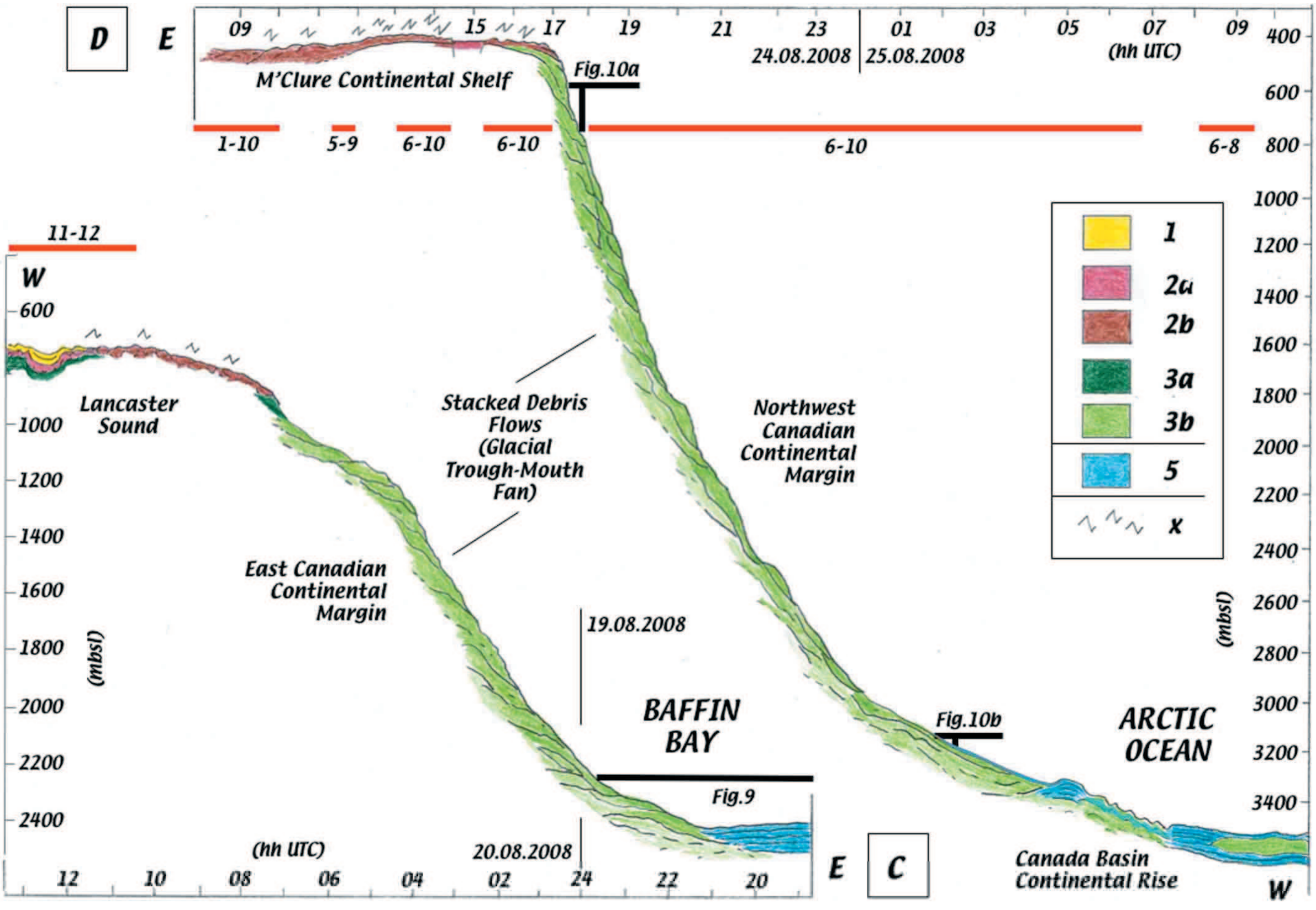

Fig. 3: Summary of units and structures as seen in PARASOUND sub-bottom profiles in the outer part of the NW-Passage. Profiles C and D have total lengths of 371 km and 382 km, respectively. On average, the ship speed was about 10.75 kn and 10 kn on profile D and C, respectively, if not indicated differently in kn above the red bars near the time scale. Locations are marked where profile sections are presented in figures 9 and 10.
Legend: 1 = Geoacoustic Unit (1) - massive to stratified marine sediments (Post Glacial). 2a: Facies of Geoacoustic Unit (2) - well-stratified diamicton, Late Glacial melt phase. 2b = Facies of Geoacoustic Unit (2) - patchy diamicton and moraines, Late Glacial melt phase. 3a = Facies of Geoacoustic Unit (3) – massive diamicton, Full Glacial/subglacial. 3b = Facies of Geoacoustic Unit (3) - debris-flow deposits, Full Glacial/pro and/or subglacial LGM. 4 = Geoacoustic Unit (4) - folded and faulted sedimentary bedrock (Devonian). 5 = Geoacoustic Unit (5) - facies of not differentiated well-stratified deep-sea sediments. x = area with surface sediments heavily ploughed by grounding ice.

Abb. 3: Zusammenfassung von Einheiten und Fazies aus PARASOUND-Profilen im äußeren Teil der NW-Passage. Die Distanzen betragen 371 km für Profil C bzw. 382 km für Profil D. Die durchschnittliche Schiffsgeschwindigkeit betrug 10.75 kn auf Profil D bzw. 10 kn auf Profil C, wenn nicht an den horizontalen roten Balken unter der Zeitskala in Knoten anders angegeben. Es sind Abschnitte markiert, für die akustische Profil-Daten in den Figuren 9 und 10 dargestellt sind. Legende und Einzelheiten wie zu Figur 2 (oben) und:
Legende: 1 = Geoakustische Einheit (1) – ungeschichtete und geschichtete marine Ablagerungen, Postglazial. 2a = Fazies der Geoakustischen Einheit (2) – gut geschichtete Diamikte, Spätglazial/Abschmelzphase. 2b = Fazies der Geoakustischen Einheit (2) - lokal vorkommende Diamikte und Moränen, Spätglazial /Abschmelzphase. 3a = Fazies der Geoakustischen Einheit (3) - ungeschichtete Diamikte, Hochglazial/subglazial. 3b = Fazies der Geoakustische Einheit (3) - Schlammstrom-Ablagerungen, Hochglazial/pro- und/oder subglazial. 4 = Geoakustische Einheit (4) - gefaltete und tektonisch verworfene Sedimentgesteine des Untergrundes (Devon). 5: Geoakustische Einheit (5) – Fazies der nicht differenzierten, gut geschichteten Tiefsee-Ablagerungen. x = Gebiete mit Oberflächensedimenten, die durch Grund berührendes Eis durchpflügt wurden.

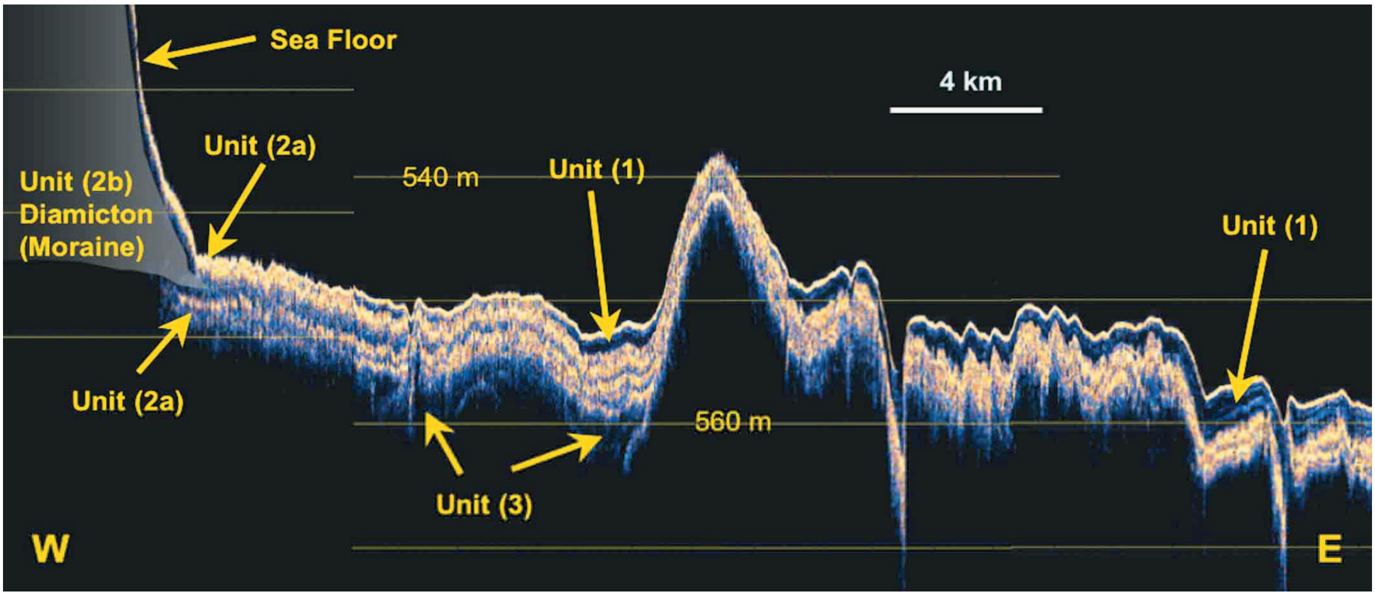

Fig. 4: Example of PARASOUND sub-bottom record from western Lancaster Sound including stratigraphic (= Geoacoustic) Units (1) to (3). Note the moraine feature intercalated with stratified Unit (2a) diamicton. Recorded between UTC 03:05 (E) and 05:30 (W) on 21.08.2008.

Abb. 4: Beispiel eines PARASOUND-Sedimentechographie-Profils aus dem westlichen Lancaster-Sund mit den stratigraphischen (Geoakustischen) Einheiten (1) bis (3). Zur Beachtung: Die gekennzeichnete Moräne verzahnt sich stratigraphisch mit den geschichteten Diamikten der Einheit (2a). Aufgezeichnet zwischen UTC 03:05 Uhr (E) und 05:30 Uhr (W) am 21.08.2008.

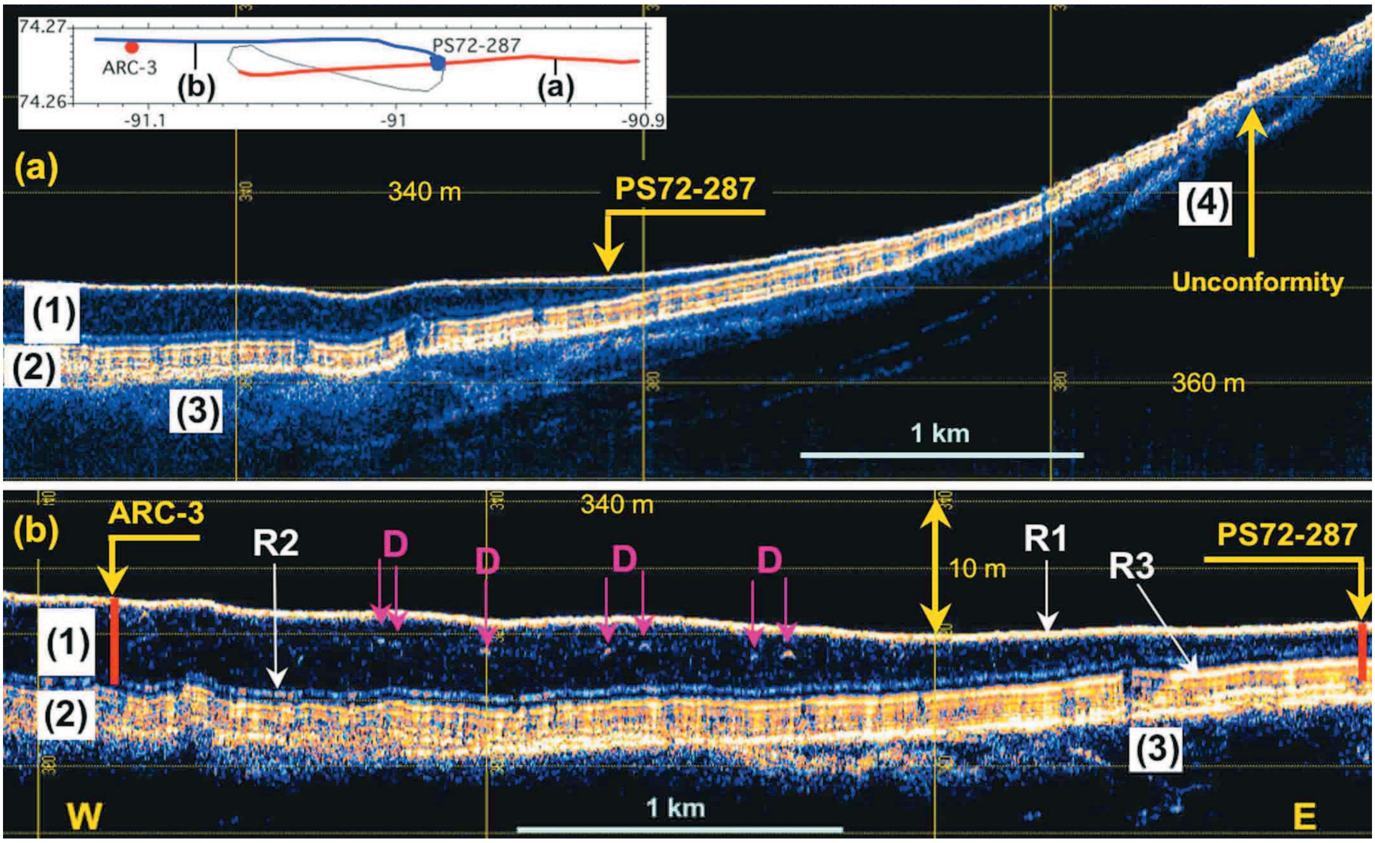

Fig. 5: Examples of PARASOUND sub-bottom records from Barrow Strait including stratigraphic (= Geoacoustic) Units (1) to (3). Key reflectors are marked R1 to R3. Arrows indicate increased diffraction "D". Coring locations PS72-287 and ARC-3 are marked in inset map (a), and profiles (a) and (b). Profile (a) was recorded during site survey for coring station PS72-287. Profile (b) was recorded leaving the station, while crossing over the position of station ARC-3 (see inset map in (a) with cruise track, latitude and longitude in decimal degrees). (a) = Recorded between UTC 12:16 (E) and 12:30 (W) on 21.08.2008. (b) = Recorded between UTC 15:35 (E) and 15:48 (W) on 21.08.2008.

Abb. 5: Beispiele von PARASOUND-Sedimentechographie-Profilen aus der Barrow-Straße mit den stratigraphischen (= Geoakustischen) Einheiten (1) bis (3). Schlüsselreflektoren sind mit R1 bis R3 gekennzeichnet. Die Pfeile zeigen einen Horizont mit verstärkten Diffraktionen. Die Kernlokationen PS72-287 und ARC-3 sind im Kartenausschnitt (a) und in den Profilen (a) und (b) gekennzeichnet. Das Profil (a) wurde während der Stationssuche (PS72-287) aufgezeichnet, das Profil (b) nach Beendigung der Station beim Überqueren der Station ARC-3 (siehe Inset-Karte in (a) mit Schiffskurs sowie Längen- und Breitengraden in Dezimalgrad). (a) = Aufgezeichnet zwischen UTC 12:16 (E) und 12:30 (W) am 21.08.2008. (b) = Aufgezeichnet zwischen UTC 15:35 (E) and 15:48 (W) on 21.08.2008.

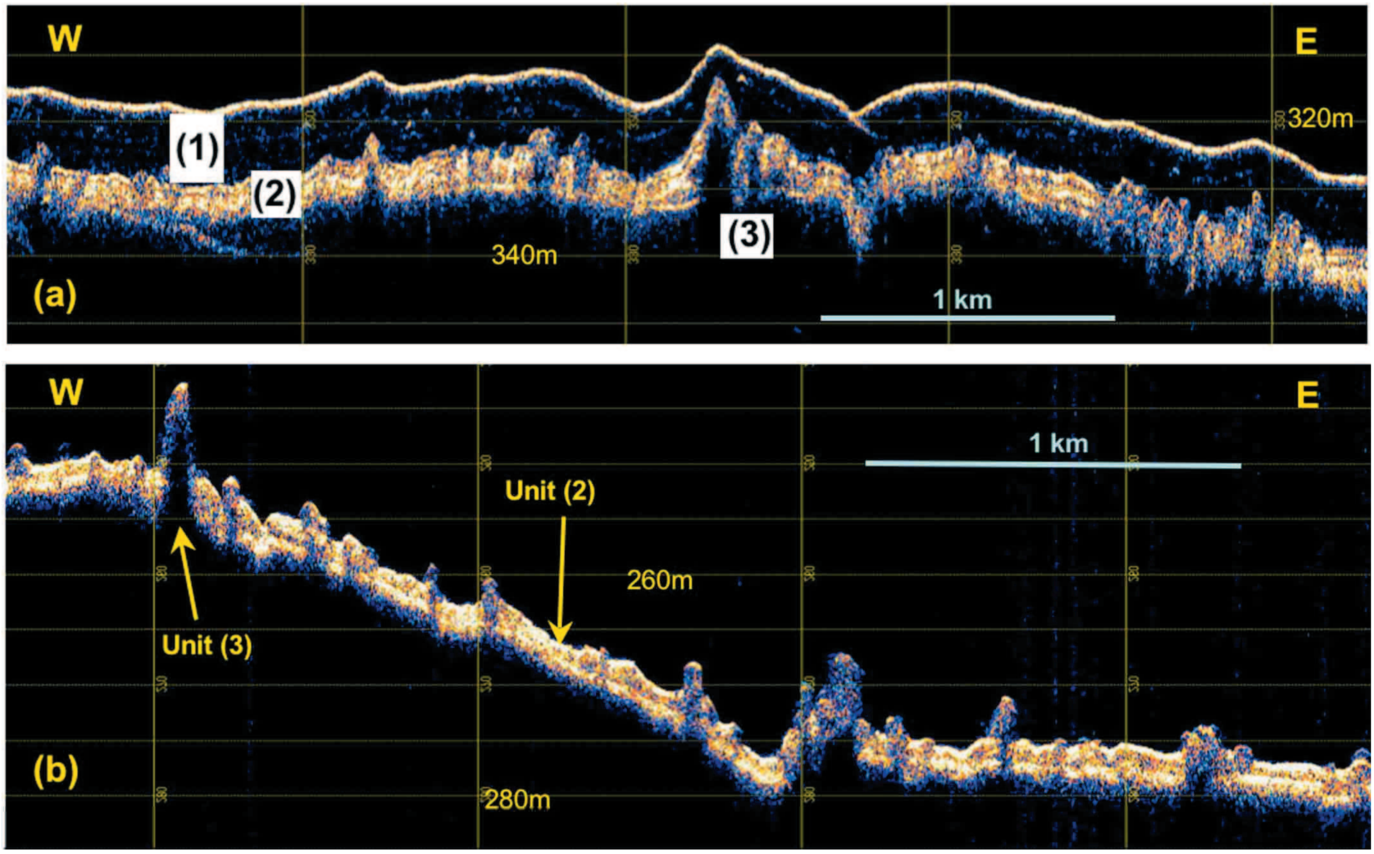

Fig. 6: Examples of PARASOUND sub-bottom records (a), (b) and Hydrosweep swath sonar records (c) from Barrow Strait including stratigraphic (= Geoacoustic) Units (1) to (3). Hummocks are visible at top of Unit (3), which are not, or not fully draped by Units (1) and (2). Note that no Unit (1) is identified in profile (b). (a) = Recorded between UTC 16:40 (E) and 17:03 (W) on 21.08.2008. (b) = Recorded between UTC 17:28 (E) and 17:40 (W) on 21.08.2008. (c) = Bathymetry of profile section (b) exhibit hummocky relief with no distinct lineation.

Fig. 6: Beispiele von PARASOUND-Sedimentechographie-Profilen (a), (b) und Hydrosweep-Fächersonar-Profil (c) aus der Barrow-Straße mit den stratigraphischen (= Geoakustischen) Einheiten (1) bis (3). Buckelstrukturen sind an der Oberfläche der Einheit (3) sichtbar, die nicht, oder nicht vollständig von den Einheiten (1) und (2) überdeckt werden. Zur Beachtung: Die Einheit (1) kommt im Profil (b) nicht vor. (a) = Aufgenommen zwischen UTC 16:40 Uhr (E) und 17:03 Uhr (W) am 21.08.2008. (b) = Aufgenommen zwischen UTC 17:28 Uhr (E) und 17:40 Uhr (W) am 21.08.2008. (c) = Die Bathymetrie von Profilausschnitt (b) zeigt das buckelige Relief ohne deutliche Lineation.

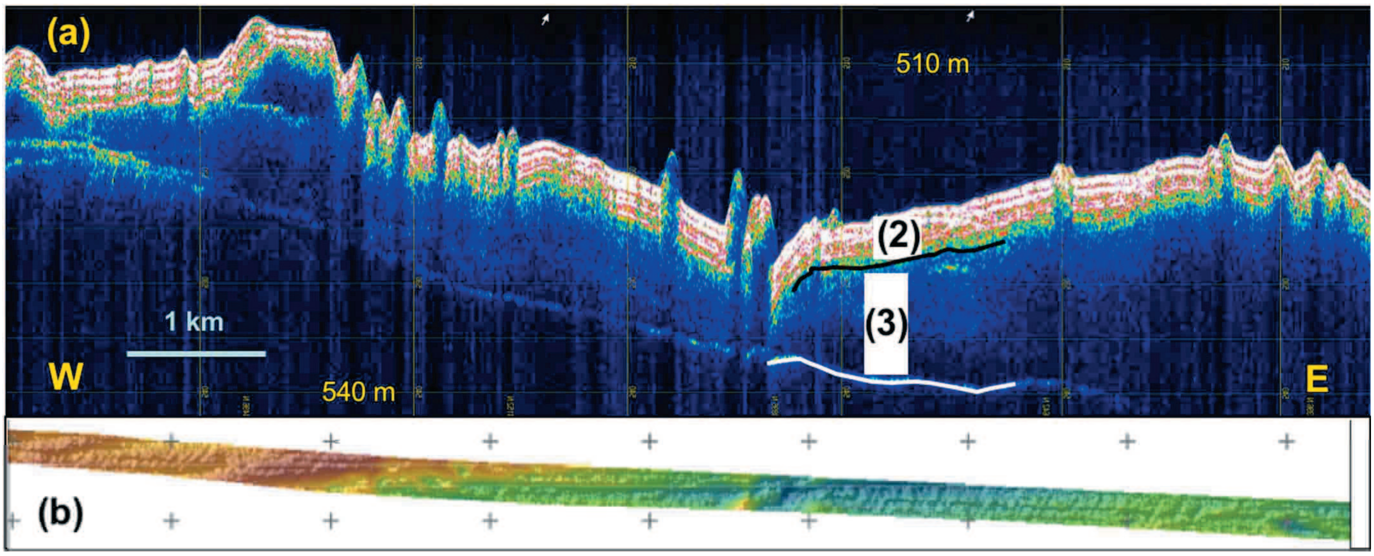

Fig. 7: Examples of PARASOUND sub-bottom records (a) and Hydrosweep swath sonar records (b) from M'Clure Strait including stratigraphic (= Geoacoustic) Units (2) and (3). Unit (2a) drapes Unit (3) except for places with distinct hummocks visible at the top of Unit (3). The Bathymetry (b) cannot resolve the distinct relief visible in the PARASOUND profile section (a) and does not exhibit major lineations. Recorded between UTC 22:39 (E) and 23:05 (W) on 23.08.2008.

Abb. 7: Beispiel eines PARASOUND-Sedimentechographie-Profils aus der M'Clure-Straße mit den stratigraphischen (= Geoakustischen) Einheiten (1) bis (3). Einheit (2a) überdeckt Einheit (3) mit Ausnahme von bestimmten Buckeln an der Oberfläche von Einheit (3). Bathymetrie (b) löst das im PARASOUND-Profilausschnitt (a) sichtbare Relief nicht deutlich genug auf und zeigt keine bevorzugten Lineationen. Aufgezeichnet zwischen UTC 22:39 Uhr (E) und 23:05 Uhr (W) am 23.08.2008.

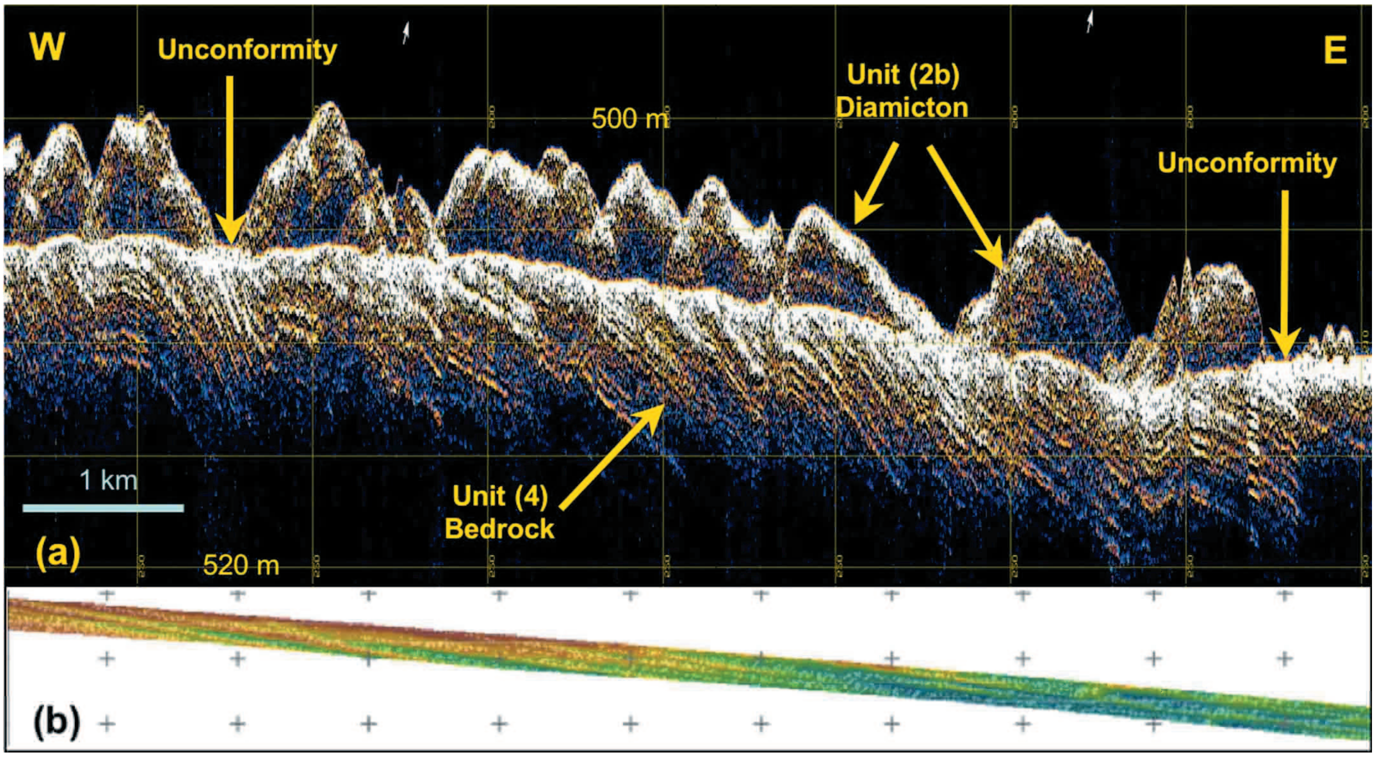

Fig. 8: Examples of PARASOUND sub-bottom records (a) and Hydrosweep swath sonar records (b) from Viscount Melville Sound exhibiting massive diamicton of geoacoustic Unit (2b) unconformably overlying bedrock, Unit (4). The bathymetry (b) exhibit that sediments are oriented forming distinct large-scale lineations (glacial flutings) in SEE-NEE direction parallel to the basin axis (Fig. 1). Recorded between UTC 07:40 (E) and 08:16 (W) on 23.08.2008.

Abb. 8: Beispiele eines PARASOUND-Sedimentechographie-Profils (a) und Hydrosweep-Fächersonar-Aufzeichnungen (b) aus dem Viscount Melville-Sund, die ungeschichtete Diamikte der geoakustischen Einheit (2b) diskordant auf Gesteinen des Untergrundes, Einheit, (4) zeigen. Die Bathymetrie (b) zeigt, dass die Sedimente orientiert sind und große Oberflächen-Lineamente in SOO-NWW-Richtung und parallel zur Beckenachse erzeugen (glaziale Furchen). Aufgezeichnet zwischen UTC 07:40 Uhr (E) and 08:16 Uhr (W) am 23.08.2008.

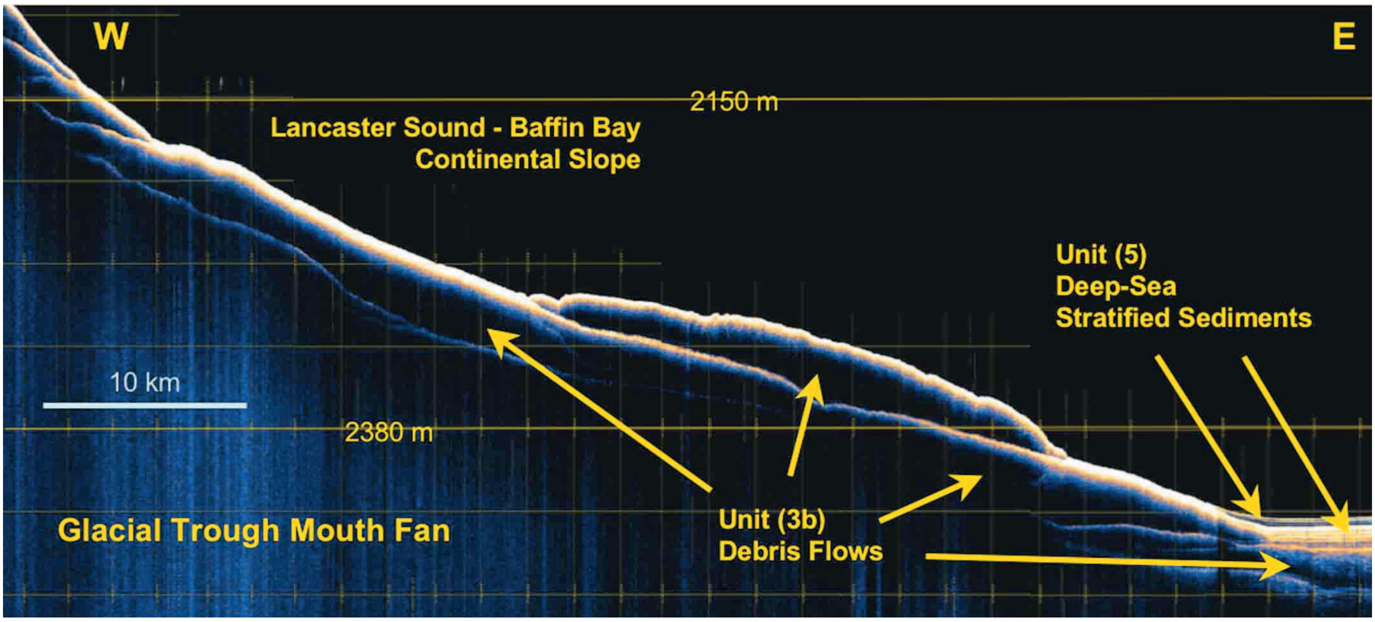

Fig. 9: Example of PARASOUND sub-bottom record from the eastern end of the NW-Passage exhibiting stacked debris-flow deposits of Unit (3b) forming foresets on a glacial Trough Mouth Fan interfingering eastward with undifferentiated well-stratified sediments of Unit (5). Recorded between UTC 21:00 (E) and 23:55 (W) on 19.08.2008.

Abb. 9: Beispiel eines PARASOUND-Sedimentechographie-Profils vom östlichen Ende der NW-Passage, das eine Akkumulation von Schlammstrom-Ablagerungen (Einheit (3b) zeigt. Diese bilden Vorschüttungen auf einem Mündungsfächer eines glazialen Troges und verzahnen sich gegen Osten mit undifferenzierten, gut geschichteten Ablagerungen der Einheit (5). Aufgezeichnet zwischen UTC 21:00 Uhr (E) and 23:55 Uhr (W) am 19.08.2008.

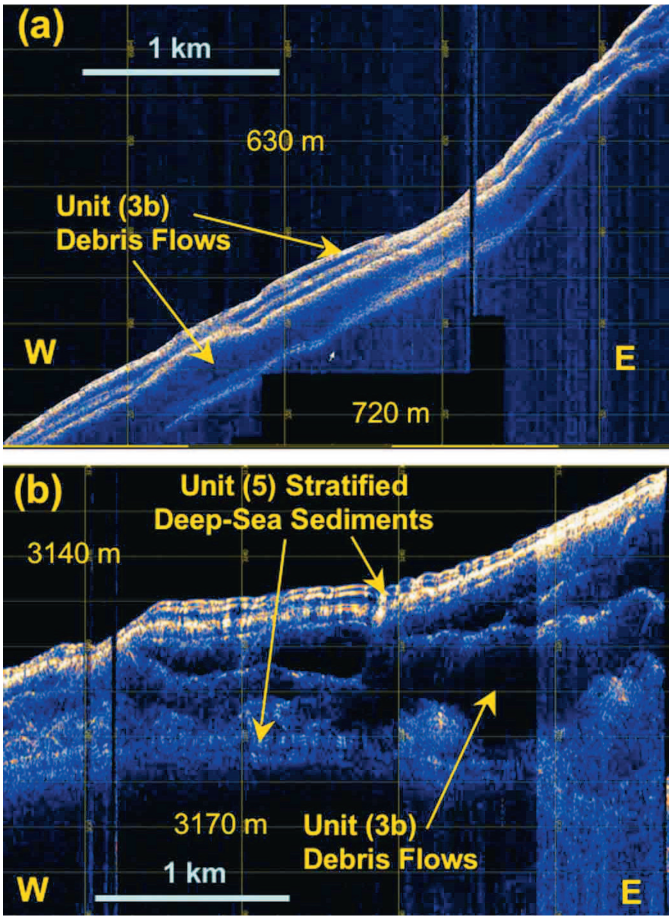

Fig. 10: Examples of PARASOUND sub-bottom records from the western end of the NW-Passage in the Arctic Ocean exhibiting stacked debris-flow deposits of Unit (3b) forming foresets on the M'Clure glacial Trough Mouth Fan (a) interfingering with undifferentiated well-stratified sediments of Unit (5) to the northwest (b).
(a) = Recorded between UTC 17:35 (E) and 17:50 (W) on 24.08.2008. (b) = Recorded between UTC 02:50 (E) and 03:10 (W) on 25.08.2008.

Abb. 10: Beispiele von PARASOUND-Sedimentechographie-Profilen vom westlichen Ende der NW-Passage im Arktischen Ozean, die eine Akkumulation von Schlammstrom-Ablagerungen der Einheit (3b) zeigen (a). Diese bilden Vorschüttungen auf einem Mündungsfächer des glazialen M'Clure-Troges und verzahnen sich gegen Nordwesten mit undifferenzierten, gut geschichteten Ablagerungen der Einheit (5), (b).
(a) = Aufgezeichnet zwischen UTC 17:35 Uhr (E) and 17:50 Uhr (W) am 24.08.2008. (b) = Aufgezeichnet zwischen UTC 02:50 Uhr (E) and 03:10 Uhr (W) am 25.08.2008.

Geoaccoustic Unit (5)

At both distal ends of lines C and D (Figs. 1, 3), in the continental rise to basin transitions (2400 m and 3500 m water depth, respectively), stacked debris flows of Unit (3b) disintegrate into isolated debris flows (Fig. 9, 10b). The latter are overlain by, or interfinger with, well-stratified deep-sea sediments which are classified as Unit (5). Because there are no distinct geometric differences in Unit (5), it is difficult to link deep-sea sediments to the Units (1) to (3) described above although they form their distal equivalents (Figs. 3, 9, 10).

SEDIMENT CORES AND CHRONOLOGY

From the area under investigation there are three sediment cores available to correlate lithology and chronology with the PARASOUND data. One 6 m long core (2004-804-009) is from the Lancaster Sound (ArcticNet, Rochon et al. 2004). Two sediment cores were retrieved in the Barrow Strait (ARC-3 and PS72/287-3). ARC-3 is a 6.41 m long core from the 2005 ArcticNet cruise (Rochon et al. 2005), and PS72/287-3 is a 4.63 m long core from the ARK-XXIII/3 cruise (this study and Stein et al. 2009). The locations of the cores are marked in the profiles (Fig. 2) and core lengths are drawn into a PARASOUND plot linking the two coring locations in the Barrow Strait (Fig. 5b).

Core PS72/287-3 recovered a more condensed section of geoacoustic Unit (1) and the top 1.5 m of Unit (2) including reflectors R2 and R3 (Fig. 5b). Lithology, stratigraphy and physical properties of PS72/287-3 are described in more detail by STEIN et al. (2009) and are summarized in Figure 11. Core PS72/287-3 is divided into two lithological units:

Lithological Unit I (0-3.12 m) is mainly composed of olive brown (upper 0.33 m) and olive gray to (dark) grayish brown, partly bioturbated silty clay to sandy silty clay. Ice-rafted debris (IRD) only occurs in minor amounts, with minimum values (almost absent) between about 1 and 2.5 m and increasing number in the uppermost 0.7 m (Fig. 11). Larger dropstones are very rare in Unit I.

Lithological Unit II (3.12-4.63 m) predominantly consists of grayish brown, light grayish brown, and light-gray to gray sandy silty clay and silty clay with common occurrence of large dropstones (IRD), ranging in size from 50-70 mm in diameter. The occurrence of these large dropstones is the main difference to Unit I. They are especially enriched between 3.78 and 3.99 m, between 4.12 and 4.28 m, and in the lowermost part of the core. In the intervals with highest amounts of large dropstones also maximum numbers of IRD grains >2 mm (to 10 mm) determined in the X-ray photographs, were found. These unsorted sediments characterized by a wide grain-size range from pebble-sized to clay-sized material, are classified as diamicton (Fig. 11). Furthermore, maxima in IRD coincide with maxima in wet bulk density and, although not always, in magnetic susceptibility (Fig. 11).

The boundary between lithological Unit I and Unit II (3.12 m) correlates with reflector R3, which forms the boundary between the geoacoustic units (1) and (2) (Fig. 5b). The correlation of the core PS72/287-3 with the PARASOUND profile (Figs. 5b, 11) suggests that reflectors R2 and R3 are caused by gradients towards higher sediment densities at 2.5 m and 3.12 m, respectively. Apparently, the density peak at about 1.1 m is not pronounced enough for creating a continuous reflector within PARASOUND Unit (1) (Fig. 5b, 11). However, in the Barrow Strait between 1 m and 1.5 m below sea floor, there is an increased number of diffractions visible within Unit (1) (Fig. 5b), which correlates with the density peak "D" and increased content of IRD in the core PS72/287-3 (Fig. 11).

Core ARC-3 recovered sediments from the geoacoustic Unit (1) with higher resolution and just penetrated into reflector R2 (Fig. 5b). The latter correlates well with a gradient of higher dry bulk density below 6 m sediment depth (VARE et al. 2009). The well constrained chronology of core ARC-3 is based on eleven ^{14}C AMS dates (mostly bivalves) ranging from 0.4 ka to 9.68 ka between 0.56 m and 6.4 m core depth, respectively (VARE et al. 2009).

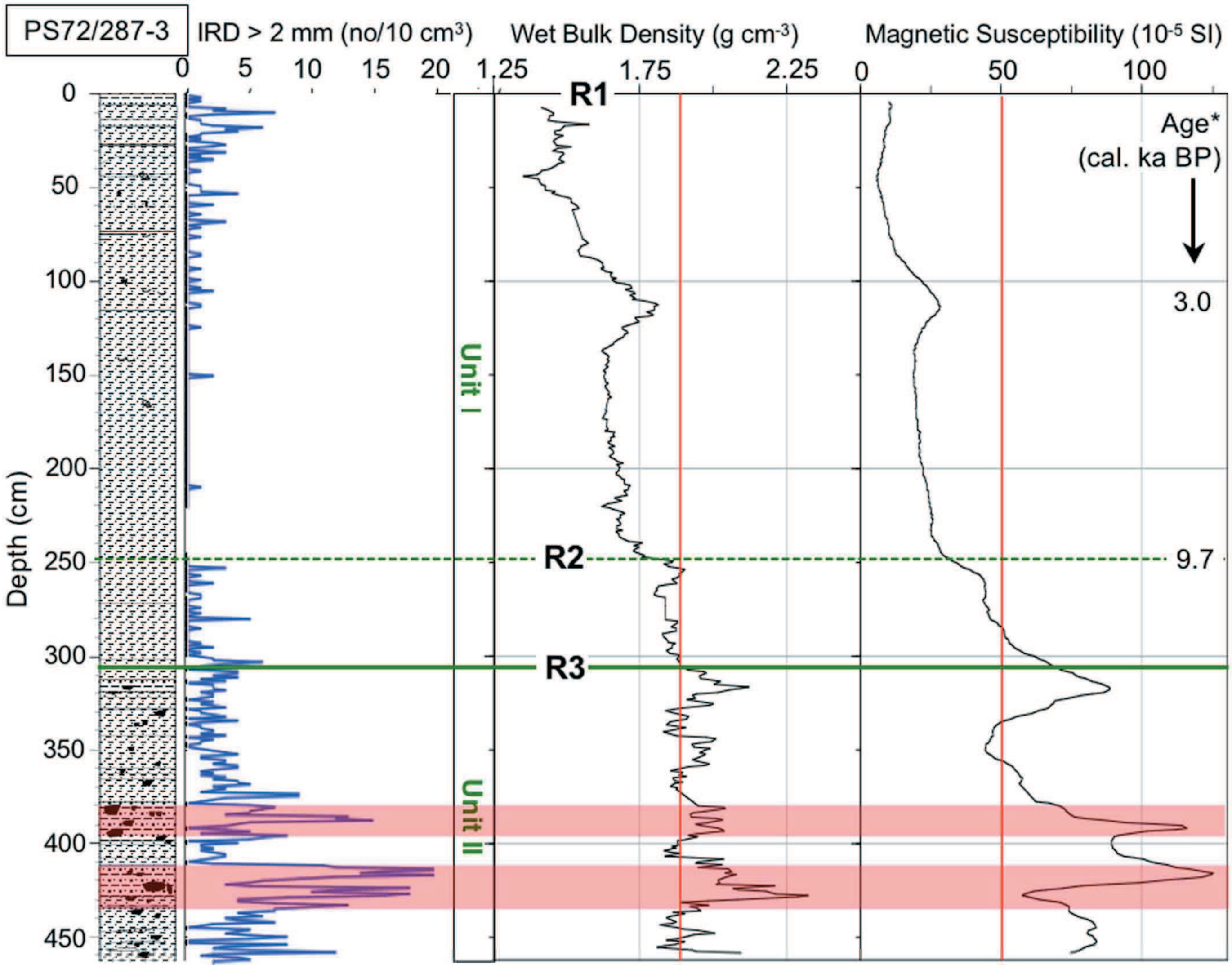

Fig. 11: Lithology, content of ice rafted debris (IRD) and physical properties of gravity core PS72/287-3 including interpretation of seismic reflectors R1, R2 and R3 (based on correlation with PARASOUND sub-bottom records, Fig. 5b) and chronology (based on correlation with dated core ARC-3, Vare et al. 2009). The two most prominent diamicton layers are highlighted as red bars.

Abb. 11: Lithologie, Anzahl vom Eis transportierter Klasten und physikalische Parameter des Schwerelotkerns PS72/287-3 zusammen mit der Interpretation seismischer Reflektoren R1, R2 und R3 basierend auf der Korrelation mit PARASOUND-Sedimentechographie-Daten (Fig. 5b) und Chronologie (basierend auf Korrelation mit dem datierten Kern ARC-3, Vare et al. (2009)). Die beiden markantesten IRD-Lagen sind mit roten Balken unterlegt.

There are two marker horizons in core ARC-3, which can be correlated with core PS72/287-3 in order to transfer parts of the age model. One is the PARASOUND-supported correlation of the down-core increase in dry bulk density (dated as 9.7 ka in ARC-3, VARE et al. 2009) with the wet bulk density gradient at reflector R2 (Fig. 11). The other is the correlation of a sharp upward increase of IP_{25} flux, a biomarker proxy of sea-ice coverage, at 3 ka in core ARC-3 (VARE et al. 2009) with the upward increase in IRD at about 1.1 m in core PS72/287-3 (Fig. 11).

Core 2004-804-009 from the Lancaster Sound has been taken at 74°11.2' N, 81°11.7' W in a water depth of 781 m (LEDU et al. 2008), which is 8.35 km north of the PARASOUND profile A (Fig. 2). With a water depth of 778 m at its nearest position to the core, geoacoustic Unit (1) is 5.5 m thick and exhibits relatively little lateral variation in thickness over a distance of 10 km (Fig. 2). Reflector R3 clearly marks the boundary to Unit (2) ranging from 5.5 m to 6.6 m sediment depth in the area. Core 2004-804-009 has been dated with four ^{14}C AMS samples (LEDU et al. 2008). Depth in core and calibrated calendar ages range from 2.17 m to 5.72 m and 6.38 ka to 11.06 ka, respectively. The core consists predominantly of silty clay with a strong downward increase in sand content to about 50 % at 5.6 m sediment depth, which is marked by a strong double peak in magnetic susceptibility (>2000 compared to otherwise <1000 instrumental units SI) (LEDU et al. 2008). As this transition will form a strong reflector in sub-bottom profiles, we suggest a link to reflector R3 in the PARASOUND profile of the Lancaster Sound. This gives the Unit (1)/Unit (2) boundary a calendar age between 10.2 and 11.06 ka, which is consistent with the chronology from the Barrow Strait (Fig. 11). Thus, all sediment ages from cores of the Lancaster Sound and Barrow Strait postdate the Pleistocene/Holocene boundary (11.59 ka, FRIEDRICH et al. 2004), which dates the stratified diamicton in the upper part of geoacoustic Unit (2) as early Holocene.

DISCUSSION

With only a few cores available, the chronology of the strata presented in the paper is not well constrained. Although the facies of geoacoustic Unit (3) suggests glacial/subglacial conditions in the entire area of investigation, its age remains speculative. Lithology and facies of Unit (2) suggest deposition during deglaciation, which lasted until the Early Holocene. However, the timing of its onset remains undetermined, because the base of Unit (2) is not cored. For this reason, the discussion is grouped into three periods without using chronostratigraphic names: a period of *Full Glacial* conditions followed by *Late Glacial* (deglaciation) and *Post Glacial* conditions.

Full Glacial

The predominance of subglacial and proglacial deposits of similar facies found at both ends of the NW-Passage is clear evidence that the area was covered by a thick ice sheet at times of maximum ice extent. In particular, the stacked debris-flows observed at both the Lancaster Sound/Baffin Bay and the M'Clure continental slopes are interpreted as major glacial Trough Mouth Fans (TMF) indicative of glaciated continental margins including ice flows (Ó Cofaigh et al. 2003, see also summary in Stein 2008). Stokes et al. (2005) have already interpreted the "duck-foot" feature seen in bathymetric maps at the mouth of the M'Clure Strait (Fig. 1) as a large TMF. The Parasound profiles demonstrate that the entire morphology of the M'Clure TMF is the result of accumulation of debris-flows forming stacked deposits close to the grounding line. The observed acoustic facies in Parasound profiles is similar to that of the Bear Island debris-flow fan described as a type location for a LGM glacial TMF (e.g. Vorren et al. 1989, Vogt et al. 1993). TMFs are widely regarded as compelling evidence for the existence of ice streams grounded at the shelf edge. In such an environment rapid ice velocities advect large volumes of sediments from the trough floor, which are discharged as debris flows at the shelf break to raise progradational foresets on the TMF (Vorren & Laberg 1997, Ó'Cofaigh et al. 2003, Stokes et al. 2005). Thus, our data (Figs. 3, 9, 10) suggest that high accumulation rates prevailed on both the M'Clure and Lancaster TMFs as long as the grounding lines of the ice streams were located at the shelf-slope boundary.

Dyke (2008) describes the existence of an ice stream in the Prince Regent Inlet and Lancaster Sound at LGM and Late Pleistocene times including the Younger Dryas (YD, about 12.5 to 11.6 ka, North Greenland Ice Core Project members (2004)). This ice stream flanked the Foxe Ice Dome located over Foxe Basin (Dyke 2008, Fig. 1) and the Innuitian Ice Sheet and extended as ice flow into parts of Baffin Bay (England et al. 2006, Ehlers & Gibbard 2007). Knudsen et al. (2008) described a sediment core from Northern Baffin Bay, of which the base is a subglacial till deposited prior to 12.5 ka. This core is retrieved from a water depth of 823 m. This is just above the depth of the downward onset of debris flow deposits mapped on the Lancaster Sound TMF as presented here (Fig. 3). We assume the TMF was active during the last LGM until about 12.5 ka or even until the end of the YD.

On the other side of the NW-Passage, Stokes et al. (2005) describe morphological evidence for the existence of several LGM ice streams over the northwestern CAA. Those in the M'Clure Strait and the Amundsen Gulf formed major ice streams, which extended into the Arctic Ocean. Several authors (Darby et al. 2002, Stokes et al. 2005, Darby & Zimmerman 2008) construct scenarios where events of IRD point to sources from Paleozoic rocks within the CAA. From cores in the Fram Strait and other locations within the Arctic Ocean, these IRD samples are enriched in carbonate and Fe-oxide (Darby et al. 2002) and thus indicative of being derived from the Laurentide and Innuitian ice sheets (Darby & Zimmerman 2008). This requires bedrock erosion in and major ice export from the CAA into the Arctic Ocean. Erosion of Paleozoic rocks is clearly evident in our data as bedrock is exposed in the Barrow Strait and Viscount Melville Sound forming a major glacial surface of erosion (Figs. 2, 3, 8). Six to seven of these well-dated IRD events occurred in the period from about 36.1 until 10.5 ka (Darby & Zimmerman 2008). Episodic ice flows from the CAA into the Arctic Ocean are suggested to be associated with periods of collapses of the Laurentide and Innuitian ice sheets in order to explain the events.

This is consistent with a recent revision of the NW Laurentide Ice Sheet towards generally larger ice masses and more northerly extent based on new terrestrial geological evidence and chronology from the M'Clure Strait area (England et al. 2009). In that study, LGM ice thickness of at least 635 m is proposed for the M'Clure Strait compared to less than 120 m reconstructed by Dyke et al. (2002).

On the M'Clure TMF, our findings of typical glacial debris-flow facies support the hypothesis of large export rates of debris from the CAA area into the Arctic Ocean. The acoustic penetration and resolution in our data set from the M'Clure TMF does not allow the interpretation of distinct episodes of debris-flow activity between 10.5 and 36.1 ka as suggested by Darby & Zimmerman (2008). It seems to be likely, however, that most of the deposition on the M'Clure TMF occurred during LGM times and may date as far back as >40 ka (Stokes et al. 2005). With a position of the grounding line possibly near the shelf edge, grounded ice persisted in the M'Clure Strait until at least 16.2 ka (Stokes et al. 2009). At the distal end of both the M'Clure and Lancaster TMF, the disintegration of debris flow deposits into well-stratified deep-sea sediments would allow a better chronology of the TMF activity, if these records were cored (e.g. Winkelmann et al. 2006).

In addition, we cannot conclude from our data, whether or not the ice flows continued to some distance into Baffin Bay and /or Beaufort Sea forming larger ice shelves during times of major glaciations in the past. Jakobsson et al. (2008) have proposed that, based on the size of the associated TMFs, M'Clure Strait and Amundsen Gulf ice streams probably delivered most of the ice to ice shelves in the western Arctic. This hypothesis was used to explain large-scale features indicative of erosion from grounded ice in elevated areas of the Arctic Ocean floor (e.g. Polyak et al. 2007).

Late Glacial

According to DYKE et al. (2002) significant deglaciation of the Laurentide Ice Sheet did not occur much before 16 ka. From relative ages of ice stream pattern in the western area of the CAA, STOKES et al. (2005, 2009) reconstructed that the M'Clure ice stream operated a number of times prior to major deglaciation and has terminated significantly earlier (at about 14.4 ka) than the ice stream in Amundsen Gulf, which became deglaciated by 11 ka. From radiocarbon dated shells in raised marine deposits found along the M'Clure Strait and other evidence, ENGLAND et al. (2009) suggest an ice retreat from the northwestern area of the CAA, commencing west of Mercy Bay (Banks Island/M'Clure Strait, Fig. 1) prior to 13.8 ka. The radiocarbon dates from the M'Clure Strait coastline indicative of marine limit predominantly fall between 12.9 and 13.4 ka suggesting a relatively rapid deglaciation (ENGLAND et al. 2009) of the M'Clure Strait at that time. This is consistent with the reconstruction of the M'Clure ice stream retreat into the M'Clintock Channel by STOKES et al. (2009) based on mapping of ice-flow sets on the adjacent islands. We assume that the well-stratified sediments of Unit (2a) found between the M'Clure Strait and the shelf edge (Figs. 2, 7) are relicts of proglacial sedimentation, which took place during this deglaciation.

Some flow sets indicate a re-advance into the Viscount Melville Sound and were previously dated as 12.8 to 11.5 ka (HODGSON 1994, STOKES et al. 2005). This suggests a re-advance of the M'Clure ice stream shortly after 13 ka, which correlates with the onset of the YD (STOKES et al. 2009). According to HODGSON (1994) and CLARK & STOKES (2001) the re-advance led to the formation of an ice shelf in the Viscount Melville Sound.

In the Viscount Melville Sound, diamicton of our Unit (2) is entirely massive and oriented as glacial flutes (Figs. 2, 8). We assume that muddy proglacial diamicton (possibly deposited as Unit (2a) during the previous deglaciation) was reworked into flutes by the late glacial re-advance of the M'Clure ice stream. This suggests the ice was grounded rather than forming an ice shelf. STOKES et al. (2005) interpreted the same flutings (MACLEAN et al. 1989) as relicts of earlier ice-stream operation including the LGM, which cannot be ruled out completely. However, in the M'Clure Strait (Fig. 2), a moraine-like feature is interpreted by us as additional evidence of a major re-advance of grounded ice in late glacial times as part of Unit (2). It has its most westerly tip at about 120° W just north of Mercy Bay/Banks Island and extends eastward to about 116° W (Figs. 1, 2), where STOKES et al. (2009) suggest the maximum extent of the YD ice stream re-advance. More data from cores are needed to constrain whether the moraine is of YD age, which would indicate an ice re-advance in the M'Clure Strait further to the west, or, whether it predates the YD, in which case it would mark an earlier re-advance during late glacial times.

The final deglaciation of the Viscount Melville Sound began after 12.05 ka with a complete withdrawal from Victoria Island by 9.5 ka (STOKES et al. 2009). West of the moraine, we assume that icebergs from this re-advance or final collapse of the M'Clure ice stream reworked most of the formerly stratified sediments of Unit (2a) into massive Unit (2b) diamicton. In the Viscount Melville Sound and probably further west to the Arctic Ocean, subglacial deposits are only covered by a very thin veneer of late and post-glacial sediments (MACLEAN et al. 1989). Thus, the final phase of ice retreat and the post-glacial time are not documented in our data, because the veneer is not resolved as sedimentary drape in the acoustic data presented here.

In the eastern realm of the inner NW-Passage, deglaciation occurred significantly later than in the west. The earliest evidence for deglaciation in the CAA comes from ^{14}C dates of moraines and lake sediments, which indicate the eastern foreland of Baffin Island becoming ice free by about 14 ka (BRINER et al. 2009). However, according to research on the Queen Victoria Islands (Fig. 1), the absence of deglacial landforms prior to 11 ka suggests that much of the retreat of the Innuitian Ice Sheet postdates the YD (HODGSON 1981, 1992, ATKINSON 2003). BRINER et al. (2009) review the key patterns and chronology of the retreat of the Laurentian Ice Sheet in the eastern Canadian Arctic. They note that many of the large and deep sounds and fjords rimming Baffin Island rapidly deglaciated between 12 and 10 ka. This includes the ice stream in Lancaster Sound and Prince Regent Inlet, which retreated over 1000 km in about 500 years after 10.8 ka (BRINER et al. 2009, DYKE et al. 2002), the sea reaching Melville Peninsula (Fig. 1) by 10.2 ka (DYKE 2008).

Our correlation of dated cores with late glacial deposits of Unit (2) suggests the deglaciation of Lancaster Sound was under way prior to 11.08 ka. LEDU et al. (2008) interpreted coarse-grained sediments at the base of core 2004-804-009 as indication of glacial instability (deglaciation) in the Lancaster Sound at 12.18 ka. However, the data base is not robust enough to determine the onset of this deglaciation. None the less, between Lancaster Sound and Barrow Strait it seems reasonable to assume that deglaciation is associated with the end of the YD (11.59 ka, FRIEDRICH et al. 2004) rather than predates the YD as reconstructed from the westernmost area of the NW-Passage. A significant earlier deglaciation in the northwestern CAA compared to the eastern Canadian Arctic was also noted by ENGLAND et al. (2006) and STOKES et al. (2009).

This is consistent with the interpretation of lithological Unit II in the sediment core from Borrow Strait, which probably represents the final stage of the last glaciation and/or the deglacial period. An extended ice sheet and its subsequent decay resulted in the formation of diamicton and large input of IRD into Lancaster Sound and Barrow Strait. As the end of deglaciation is dated to 9.7 ka (Fig. 11), the entire Unit (2) in Lancaster Sound and Borrow Strait was probably deposited in less than 2000 years in Early Holocene times, which is significant younger than suggested for the late glacial Unit (2) in the western realm. This also implies that the other significant moraine (part of Unit (2), Figs. 2, 4), found at the western end of the Lancaster Sound, marks an early Holocene re-advance possibly from the Prince Regent Inlet ice stream in the south (Fig. 1). Several early Holocene re-advances of ice were also found on southern Victoria Island and dated 11.05 to 10.2 ka (STOKES et al. 2009).

If the interpretation above is correct, full glacial and late glacial conditions persisted simultaneously until YD times in the Burrow Strait/Lancaster Sound and the Viscount Melville Sound/M'Clure Strait, respectively. In other words, late glacial Unit (2) was deposited at different times in the different areas. In the west, Unit (2) was mainly deposited prior to the YD and sedimentation starved during final retreat. In contrast, in the east, Unit (2) has accumulated after the YD until the early Holocene. This also explains why the sediments of Unit (2) are more stratified in the east. Re-advances of ice streams were relatively minor in early Holocene times and iceberg plough marks are restricted to shallower water. However, better chronologies of marine sediments are needed to test this hypothesis especially from the western realm of the CAA.

Postglacial

Significant postglacial sediments are only present in the Barrow Strait and Lancaster Sound (Unit (1), Fig. 2) and postdate 9.7 ka (Fig. 11). In the western part of the CAA, marine sedimentation starved after the area became deglaciated. The situation is somewhat different in the eastern part of CAA including the eastern Queen Victoria Islands and Baffin Island, where contemporary ice caps persisted until today (ENGLAND et al. 2006, BRINER et al. 2009). Possibly, the glaciated islands provided some fine-grained debris from glacial erosion distributed in the eastern basins (Fig. 2) for mud accumulation during the Holocene.

In the Barrow Strait, the elevated IRD values in the uppermost part of the Holocene record (Unit I, Fig. 5) suggest increased IRD input due to a re-advance of glaciers on the Queen Victoria Islands and Baffin Island as result of late Holocene neo-glaciation. At about 3 ka, re-advances of glaciers were recorded on Baffin Island (BRINER et al. 2009) and in many other glaciated regions including western Norway and the European Alps (NESJE et al. 2001, LEEMANN & NIESSEN 1994). This is consistent with the increase of sea-ice coverage in Barrow Strait since 3 ka, which is reconstructed from the biomarker record of core ARC-3 (VARE et al. 2009) indicative of climate cooling in the CAA after 3 ka.

It is obvious that Unit (1) sediments lens out over relatively short lateral distance and are restricted to deeper water, whereas Unit (2) sediments continue as stratified drape into shallower water (Fig. 5a). We suggest that Unit (1) is affected by both, stronger currents and water level changes. At LGM times, the areas of Lancaster Sound/Barrow Strait and Viscount Melville Sound/M'Clure Strait were covered with more than 500 m thick grounded ice (DYKE et al 2002, ENGLAND et al. 2009). Marine deposits marking raised shorelines from times of deglaciation are indicative of glacio-isostatic rebound (ENGLAND et al. 2009) and thus provide a measure of paleobathymetry in the straits and sounds. In the M'Clure Strait and Viscount Melville Sound, water depths were 40 m to about 100 m deeper than present, respectively, from 11.5 ka to 11 ka (ENGLAND et al. 2009). In the Barrow Strait and Lancaster Sound, the paleobathymetry during times of deglaciation is not known. However, the basins must have been significantly deeper during times when Unit (2) was accumulated. With subsequent glacioisostatic rebound and onset of Unit (1) sedimentation water depth became shallower despite eustatic sea level rise. In addition, in the Barrow Strait, relatively strong currents of up to 150 m s^{-1} were registered by moorings since the year 1998 (PRINSENBERG & PETTIPAS 2008), which may prevent sedimentation in shallower water. The currents are indicative of an eastward directed flow of water from the Arctic Ocean into Baffin Bay. We suggest that opening the deglaciated NW-Passage for currents combined with lowering water level at early Holocene times have caused the different geometries of Unit (2) and Unit (1).

CONCLUSIONS

• We present the first sedimentary evidence to further characterize the M'Clure continental margin as important glacial Trough Mouth Fan (TMF). Thus, an earlier hypothesis is supported suggesting the M'Clure Strait ice stream formed a major ice stream of the Laurentide Ice Sheet, which extended at least to the shelf edge of the Arctic Ocean.
• The chronology of the TMF deposits remains tentative because ages from sediment cores are not yet available. However, from the stratigraphic position and based on the discussion above we interpret the debris-flow deposits (Unit 3b) as largely LGM in age, which can also include deposits of pre-LGM and post-LGM age.
• Deglaciation of the M'Clure Strait/Shelf probably occurred prior to the YD whereas it postdates the YD in the Lancaster Sound and Barrow Strait. Thus, sediments of Unit (2), here described and interpreted as *Late Glacial,* are probably of late Pleistocene age in the M'Clure Strait/Shelf and Viscount Melville Sound, and are dated as early Holocene in the Barrow Strait.
• In the Viscount Melville Sound/M'Clure Strait, subglacial flutings and diamicton, together with the deposition of a submarine moraine, are taken as evidence for a major re-advance of a grounded M'Clure ice stream possibly associated with the YD. An early Holocene re-advance into the eastern Lancaster Sound is documented by a submarine moraine near the Prince Regent Inlet.
• Post-glacial sediments of significant thickness (>0.2-10 m) only occur in the inner part of the NW-Passage, in particular in deeper depressions of the Lancaster Sound and the Burrow Strait. Their onset indicates that the deglaciation terminated at 9.7 ka followed by a neoglaciation after 3 ka.
• The chronology of this study is not well constrained. Most of the PARASOUND profiles presented in the paper can be used as key locations for future sediment coring to test our interpretation.

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