The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0

[1]Martin Jakobsson, [2]Larry Mayer, [3]Bernard Coakley, [4]Julian A. Dowdeswell, [5]Steve Forbes, [6]Boris Fridman, [7]Hanne Hodnesdal, [8]Riko Noormets, [9]Richard Pedersen,[10]Michele Rebesco [11]Hans-Werner Schenke, [12]Yulia Zarayskaya, [10]Daniela Accettella, [2]Andrew Armstrong, [13]Robert M. Anderson, [14]Paul Bienhoff, [15]Angelo Camerlenghi, [16]Ian Church, [17]Margo Edwards, [2]James V. Gardner; [18]John K. Hall, [1]Benjamin Hell, [19]Ole Hestvik, [20]Yngve Kristoffersen, [21]Christian Marcussen, [1]Rezwan Mohammad, [22]David Mosher, [23]Son V. Nghiem, [5]Paola G. Travaglini, [24]Pauline Weatherall

[1]Dept. of Geological Sciences, Stockholm University, Sweden; [2]Center for Coastal and Ocean Mapping/Joint Hydrographic Center, University of New Hampshire, USA; [3]Dept. of Geology and Geophysics, University of Alaska Fairbanks, USA; [4]Scott Polar Research Institute, University of Cambridge, UK; [5]Canadian Hydrographic Service, Canada; [6]Moscow Aerogeodetic Company, Russian Federation; [7]Norwegian Mapping Authority, Hydrographic Service, Norway; [8]The University Centre in Svalbard, Longyearbyen, Norway; [9]National Survey and Cadastre, Denmark; [10]Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Italy; [11]Alfred Wegener Institute for Polar and Marine Research (AWI), Germany; [12] Laboratory of Ocean Floor Geomorphology and Tectonics, Geological Institute RAS, Russian Federation; [13]Science Applications International Corporation, USA; [14] Johns Hopkins University Applied Physics Laboratory, USA;[15]ICREA and University of Barcelona, Spain; [16]Dept. Geodesy and Geomatics Engineering, University of New Brunswick, Canada;[17]University of Hawaii at Manoa, USA;[18]Geological Survey of Israel, Israel;[19]OLEX, Norway;[20]Dept of Earth Science, University of Bergen, Norway;[21]Geological Survey of Denmark and Greenland,

Denmark;[22]Geological Survey of Canada, Canada[23]Jet Propulsion Laboratory, California Institute of Technology, USA; [24]British Oceanographic Data Centre (BODC), UK.

Abstract

The International Bathymetric Chart of the Arctic Ocean (IBCAO) released its first gridded bathymetric compilation in 1999. The IBCAO bathymetric portrayals has since supported a wide range of Arctic science activities, for example, by providing constraint for ocean circulation models and the means to define and formulate hypotheses about the geologic origin of the Arctic Ocean undersea features. IBCAO Version 3.0 comprises the largest improvement since 1999 taking advantage of new data sets collected by the circum-Arctic nations, opportunistic data collected from fishing vessels, data acquired from US Navy submarines and from research ships of various nations. Built using an improved gridding algorithm, this new grid is on a 500 meter spacing, revealing much greater details of the Arctic seafloor than IBCAO 1.0 (2.5 km) and 2.0 (2.0 km). The area covered by multibeam surveys has increased from ~6 % in Version 2.0 to ~11% in Version 3.0.

1. Introduction

For generations there was only speculation as to what lay beneath the frozen sea ice of the high Arctic. Even towards the end of the 19th century, maps of the region depicted large continental land-masses beneath the ice. Then, from a handful of lead line soundings acquired during the *Fram Expedition* 1893-1896, Fridtjof Nansen compiled a bathymetric map that portrayed the central Arctic Ocean as a single deep featureless basin [*Nansen*, 1907]. While Nansen's map still represents the single largest step forward in Arctic Ocean bathymetric mapping, subsequent maps successively revealed a much more complex bathymetric landscape formed from the tectonic evolution of the Arctic Basin, ocean currents and glacial history [e.g. *Atlasov et al.*, 1964; *Johnson et al.*, 1979; *Perry et al.*, 1986]. In 1997, one century after the *Fram Expedition*, the International Bathymetric Chart of the Arctic Ocean (IBCAO) project was initiated in St Petersburg, Russia. The project had a single major objective: to collect all available bathymetry data for the compilation of the most up-to-date bathymetric portrayal of the Arctic Ocean seafloor. An Editorial Board was established consisting of representatives from the circum-Arctic Ocean nations plus Germany and Sweden. Three years later, the first bathymetric compilation from IBCAO was released to the public after an introduction at the AGU Fall Meeting in 1999 [*Jakobsson et al.*, 2000]. This first compilation consisted of a Digital Bathymetric Model (DBM) with grid cell spacing of 2.5 x 2.5 km on a polar stereographic projection. In 2008, Version 2.0 of the IBCAO DBM was completed at a finer grid spacing of 2 x 2 km [*Jakobsson et al.*, 2008]. This version was compiled from an expanded bathymetric database. In addition to the soundings acquired from submarines, icebreakers and from the pack ice, and depth contours digitized from published maps that were used in Version 1, Version 2.0 also included some multibeam sonar datasets. However, in IBCAO Version 2.0, only about 6 % of the area was compiled using multibeam data. During the *First Arctic-Antarctic Seafloor Mapping Meeting* held at Stockholm University in May 2011, it became obvious that a wealth of new bathymetric data had become available since the 2008 compilation of IBCAO 2.0 (Figure 1). Numerous bathymetric mapping campaigns in the Arctic Ocean have recently been carried out for scientific purposes and as a result of Arctic coastal states' interests in establishing extended continental margins under the United Nations Convention on the Law of the Sea

(UNCLOS) Article 76 [*Marcussen and Macnab*, 2011; *Mayer et al.*, 2010]. Vast amounts of single beam data have also been collected in the Arctic region using the *Olex* seabed mapping system (www.olex.no). Furthermore, since the release of IBCAO Version 2.0, single beam echo soundings from US nuclear submarine cruises between 1993-2005 have been declassified and the Geological Survey of Denmark and Greenland has released soundings from industry seismic surveys around Greenland for IBCAO use (Figure 1). Given the availability of these new data sources, a new IBCAO Editorial Board has been established for the purpose of compiling IBCAO Version 3.0. Here we describe the compilation of IBCAO 3.0, the new bathymetric data, and the major improvements that have implications for geological, geophysical and oceanographic analyses as well as for numerical modeling applications. IBCAO 3.0 will be the new standard bathymetric data set for the Arctic Ocean. Applying an enhanced gridding algorithm, the IBCAO 3.0 DBM is gridded from a substantially enlarged source database. While the base grid is still compiled at a resolution of 2 x 2 km grid cells on a polar stereographic projection, the higher resolution source data (primarily multibeam and Olex) are merged on to the base grid at a resolution of 500 x 500 m in a final step using the remove-restore method [e.g. *Hell and Jakobsson*, 2011; *Smith and Sandwell*, 1997]. This approach develops a final 500 x 500 m cell size grid which much better preserves the details where source data is dense than previous versions of IBCAO. On a broader scale, IBCAO 3.0 provides substantially improved insight into the geological processes responsible for the formation of the Arctic Ocean basin. The higher resolution data resolve canyons along the continental slopes as well as some of the more prominent glacial features that were not visible in previously released versions. While the area covered by multibeam surveys has increased from ~6 % in Version 2.0 to ~11% in Version 3.0, there are still are huge areas of the Arctic Ocean remaining to be mapped before we reach the same level of topographic characterization as that of the Moon or Mars [*Mazarico et al.*, 2011].

2. Methods

2.1. Bathymetric source data

The bathymetric data new to IBCAO 3.0 are shown in Figure 1 and references to each of the multibeam surveys, or group of surveys, are found in the Auxiliary Material. There are only a handful of research icebreakers with multibeam systems capable of operating within the heavy pack-ice covered central Arctic Ocean. Along the edges of the pack ice, however, several multibeam surveys by ice strengthened research vessels have made substantial contributions [e.g. *Dowdeswell et al.*, 2010; *Hogan et al.*, 2010; *Pedrosa et al.*, 2011; *Rebesco et al.*, 2011; *Westbrook et al.*, 2009; *Zayonchek et al.*, 2010]. In addition to all previously declassified bathymetric soundings acquired by U.S. Navy submarines, there is now an additional set released from cruises between 1993-2005 (Figure 1). These soundings provide depth information in several sparsely mapped areas but are only partly used in the Canada Basin. The reason for this is that U.S. and Canadian surveys conducted with the icebreakers *USCGC Healy* and *CCGS Louis St-Laurent*, carried out to establish the limits of the extended continentals shelf, are dense enough to constrain the flat abyssal plain of the Canada Basin. The seafloor mapping, navigation, and fishery system *Olex* (http://www.olex.no) is manufactured to interface with both single and multibeam echo sounders. Depths are collected by the system and merged into a locally stored depth database. Many *Olex* users share their data through *Olex* which hosts a continuously growing depth database. Because the majority of *Olex* users are fishermen there is a strong bias in the database coverage towards good fishing areas on the continental shelves (Figure 1). For

IBCAO 3.0, a snapshot of the *Olex* database was captured in October 2011. Depths were retrieved as median values on a 0.12 x 0.12 arc minute grid. Fishermen rarely calibrate their echo sounders (by measuring speed of sound in the water column). Instead, a nominal sound speed based on experience is commonly applied in the conversion between the echo travel-time to depth. This implies that there is an uncertainty in the *Olex* depth database regarding the applied sound speeds, though typically the sound speed used is between 1460 and 1480 m/s (pers. Comm. Ole B. Hestvik, *Olex*). To investigate travel time to depth issues, we compared depth values from the *Olex* sounding database in the area off the Storfjorden Trough, south of Spitsbergen, where the Italian *RV OGS-Explora* and Spanish *BIO Hespérides* carried out collaborative multibeam surveys [*Pedrosa et al.*, 2011] (Figure 2). This area was chosen for the comparison because the multibeam surveys are of high quality and carried out with regular sound speed control [*Pedrosa et al.*, 2011]. Individual depths from the *Olex* database were paired with depths from the provided 200 x 200 m multibeam grid for comparison. The criteria used to form a pair of depth values was that the two must be located closer than 50 m from each other. The map in Figure 2 shows the *Olex* depths paired with multibeam depths; 1999 depth values were selected for comparison. The mean difference ($\frac{1}{n}\sum_{i=1}^{n}(D_{Olex} - D_{multibeam})$; *depths are negative numbers*) is -4.9 m, suggesting a slight bias towards deeper *Olex* depths. However, considering that the mean depth of the compared values is 640 m, the mean difference is less than 1% of the water depth, which is better than the accuracy expected from a standard non-survey type single beam echo sounder. The distribution of depth differences does not show a clear bias above what can be considered outside of the accuracy of standard single beam echo sounders (Figure 2). Therefore, we left the *Olex* depth database as originally extracted. Numerous seismic reflection profiles have been collected by industry along Greenland's eastern and western continental margins for oil and gas exploration. Through the Geological Survey of Denmark and Greenland (GEUS), single beam soundings acquired along with the seismic reflection profiles have been released to be used in IBCAO 3.0 (Figure 1). For all surveys the metadata describes whether the echo sounding depths are in corrected meters, i.e. depths derived using a measured sound velocity profile of the water column, or referred to a nominal sound speed. In the latter case, 1500 m/s was used as a standard. Of the 43 surveys used, 18 contained uncorrected depths that were recalculated to refer to a harmonic mean sound velocity of 1463 m/s; a velocity that adjusted the depth values to fit well with sound speed corrected surveys as determined from track line cross-overs. MAREANO is a Norwegian program aimed at mapping the coastal and offshore regions of Norway (http://www.mareano.no). Bathymetry is one of the parameters included in the MAREANO seafloor characterization program. The high quality MAREANO multibeam compilation, to-date covering the area between about 67° and 72°N, has been provided to IBCAO at a uniform resolution of 25 x 25 m on a Universal Transverse Mercator (UTM) projection. As will be shown in the result section, these data make a huge improvement in the depiction of the Norwegian shelf as compared to the previously released IBCAO 2.0.

Depths extracted from Electronic Navigational Charts (ENCs) have been provided by several countries' hydrographic offices to the International Hydrographic Organization (IHO) for use in regional mapping projects affiliated with the General Bathymetric Chart of the Oceans (GEBCO). Because IBCAO is one of GEBCO's affiliated regional mapping projects all the ENC extracted depths within the compilation area have been used in Version 3.0.

2.2. Land topography

Narrow fjords, bays, or islands that only are slightly wider than the final IBCAO DBM resolution, in our case 500 m, are often difficult to preserve. This may, to some extent, be helped by including land topography in the full gridding process as it guides the gridded surface. The recently released Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010) [*Danielson and Gesch*, 2011] has been used in IBCAO 3.0, replacing the GTOPO30 [*U.S. Geological Survey*, 1997] used in IBCAO 2.0. Over Greenland the approximately 2000 x 2000 m resolution Digital Elevation Model (DEM) published by *Ekholm* [1996] is still used.

2.3. Gridding algorithm and source identification

The applied gridding algorithm is a further improvement of that developed to compile IBCAO 2.0 [see *Jakobsson et al.*, 2008]. The main improvement consists of adding the source data with a spatial horizontal resolution approximately equal to, or better than, 500 m in a final step using the remove-restore method [e.g. *Hell and Jakobsson*, 2011; *Smith and Sandwell*, 1997]. Further details about the gridding algorithm are described in the Auxiliary material. Along with the IBCAO Version 3.0 DBM, a source identification grid (SID) has been compiled (Auxiliary material). At a resolution of 2000 x 2000 m, this SID allows the user to identify the grid cells that are constrained by source data and not interpolated. The SID contains six codes distinguishing between data sources categorized as land, multibeam, single beam, Olex, contours from digitized maps, and other gridded bathymetric compilations (Auxiliary material).

3. Results and Discussion

3.1. General comparison between IBCAO versions 3.0 and 2.0

The IBCAO 3.0 DBM is, from several perspectives, best described by comparison to the preceding Version 2.0. One general, but striking, difference with 3.0 is the higher resolution of 500 x 500 m in all areas where the source data density permits compilation at this scale. This is the case in the shelf regions around the North Atlantic where *Olex*, MAREANO, and the released single beam soundings from industry seismic add substantially to the bathymetric source database (Figure 1). For example, it is possible in Version 3.0 to distinguish seafloor imprints from the paleo-ice streams draining the Scandinavian Ice Sheet during past glacial periods (Figure 3). Glacigenic features now visible that were barely seen in 2.0 include mega-scale glacial lineations (Figure 3), lateral and terminal moraines, and large iceberg plow marks. The full resolution MAREANO multibeam grid with 25 x 25 m cells provides an additional level of detail and can be requested directly from the MAREANO project (http://www.mareano.no).

Denmark, the U.S., and Canada all agreed to contribute with their Arctic Ocean UNCLOS Article 76 bathymetric surveys to IBCAO 3.0. For this reason, there is an improved representation of the Arctic Ocean continental shelf slopes of these countries, because the foot of the slope is a critical parameter in Article 76 [*United Nations*, 1999]. The continental slope along southern Greenland, the Barrow Margin and the perimeter of the Chukchi Cap is, for this reason, also better mapped in Version 3.0 (Figure 1). In Version 2.0, depths of the deeper parts of Canada Basin were corrected after it was found that several of the declassified single beam datasets from nuclear submarines had not been treated properly due lack of metadata information regarding applied sound speeds [*Jakobsson et al.*, 2008]. Yet another change, albeit smaller than the previous correction, is imposed in Version 3.0 owing to the UNCLOS surveys by icebreakers

USCGC Healy and *CCGS Louis St-Laurent*. These provide better positioned and sound speed-controlled soundings than the nuclear submarines are capable of using their inertial navigation system. The submarine soundings were thus removed from the gridding procedure in the deep Canada Basin, but only after being investigated for previously unmapped shoals. As a result of this update, the flat Canada Basin seafloor deeper than 3500 m is, on average, approximately 64 m deeper in Version 3.0 than in 2.0 (Auxiliary material). However, the average depth adjustment due to the new data in the region deeper than 3500 m is less than 2 %, estimated along a bathymetric profile across the entire basin (Auxiliary material). Canyons formed in the slopes offshore of the Arctic continental shelves are usually not precisely captured in DBMs gridded from randomly oriented sparse single beam tracklines and/or digitized bathymetric contours. This became evident along the continental slope of northern Alaska when IBCAO 1.0 was updated by incorporation of multibeam surveys from this area [*Jakobsson et al.*, 2008]. Cartographers who specialized on compiling bathymetric maps commonly interpret slope-canyon systems from sparse depth soundings using their geological knowledge and conceptually draw depth contours in order to illustrate the canyons' anticipated morphology. IBCAO 3.0 is still gridded from digitized depth contours where no other data are available. One should keep in mind that, in these regions, the precise locations of portrayed bathymetric features, such as canyons, may deviate from reality. Contours are used from six published maps [*Cherkis et al.*, 1991; *Intergovernmental Oceanographic Commission et al.*, 2003; *Matishov et al.*, 1995; *Naryshkin*, 1999; 2001; *Perry et al.*, 1986], although, large areas relying on contours in Version 2.0 can now be gridded directly from single or multibeam data (see SID in Auxiliary material). The overall IBCAO goal is to minimize the use of digitized bathymetric contours in the gridding process.

3.2. Improved coastline constraint

The approach of first gridding all the data with a constraint on the output values to not exceed 0.1 m depth, and subsequently adding the topography in a separate step, in combination with the higher resolution GMTED2010, improved the coastline constraint dramatically in Version 3.0 compared to 2.0 (Figure 3). This makes IBCAO much more useful for nearshore applications ranging from simple map making to regional ocean circulation modeling [e.g. *Lu et al.*, 2010]

4.0. Conclusions and outlook

Mapping of the world oceans' seafloor has resulted in some of the major breakthroughs in our understanding of earth system processes. The mapping of oceanic rift zones by Heezen [1960] led Hess [1962] directly to the formulation of the concept now known as seafloor spreading. Similarly, it was after submarine ridges and basins appeared on Arctic Ocean maps towards the end of the 1950s that geological provinces could be defined, allowing evaluation of hypotheses concerning the opening of the Arctic Basin [*Dietz and Shumway*, 1961; *B.C. Heezen and Ewing*, 1961].

Nuclear submarines have collected echo sounding data ever since they began to explore the Arctic Ocean for strategic purposes during the Cold War. In 1993 the U.S. Navy delighted the scientific community by committing to a trial cruise for what would become the Science Ice Exercise Program (SCICEX) [*Edwards and Coakley*, 2003; *Newton*, 2000]. Bathymetric mapping by nuclear submarines and our most powerful icebreakers have been instrumental in producing our current view of the perennially sea ice covered central Arctic Ocean seafloor. In addition, new innovative methods to map in severe pack ice are beginning to emerge, such as echo sounding from hoover crafts and the deployment of autonomous drifting echo sounding buoys [*Hall and Kristoffersen*, 2009]. We will work to continue on updating the view of the Arctic Ocean seafloor through IBCAO; however, the pace at which its central part is currently mapped is much too slow for the scientific community's need for a better bathymetric portrayal so critical for oceanographic, geological, geophysical and biological research and applications. The seafloor has a profound influence on numerous processes not obvious at a first glance. Its role in sea ice formation and evolution, which recently has been shown using IBCAO 2.0, may serve as one such example [*Nghiem et al.*, 2012 (in press)]. Even considering a scenario where sea ice continues its declining trend that may eventually lead to sea-ice free summers [*Wang and Overland*, 2009], the short Arctic summer period (and possibility of some ice hazard) will severely limit the pace of Arctic mapping. Large coordinated efforts as well as new innovative mapping methods adapted to the harsh Arctic Ocean environment are therefore needed. The IHO contribution with depths extracted from ENCs serve as one good example of such coordinated effort. The "crowd source" data from *Olex* have shown that a collective is capable of producing results far beyond what could be imagined by the mapping community!

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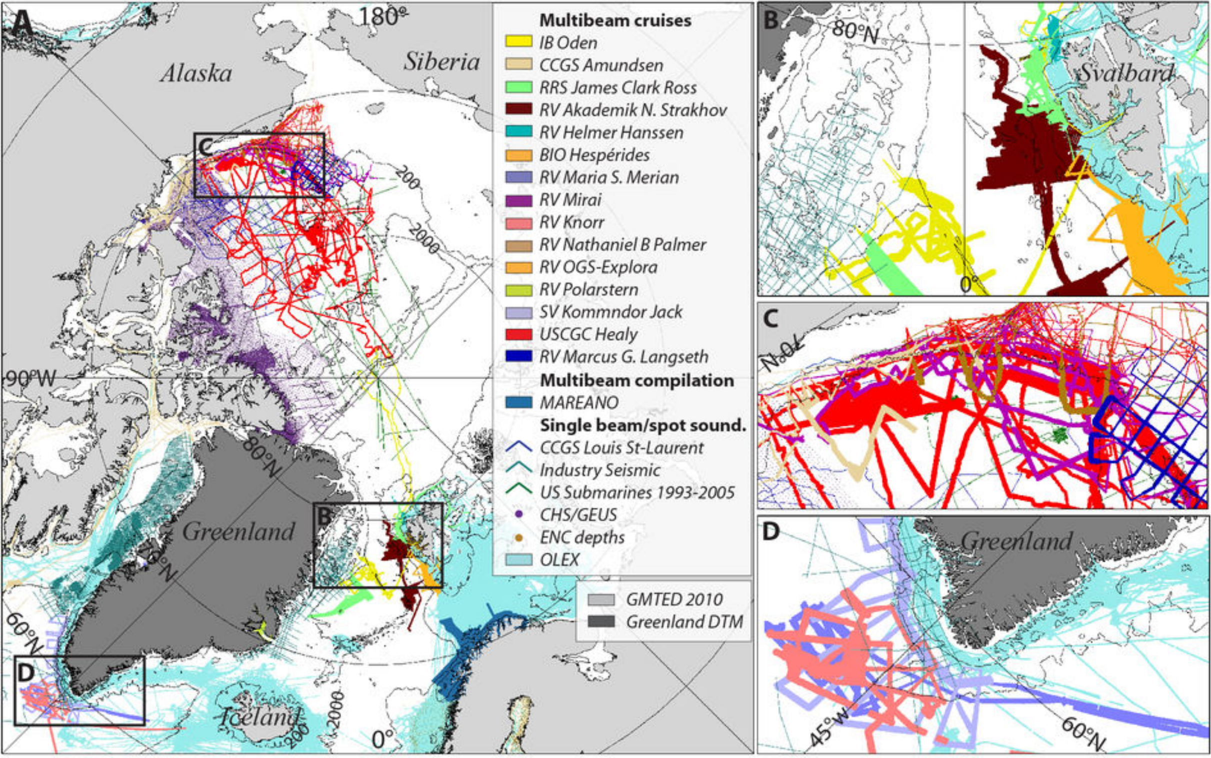
Figure Captions

Figure 1: A) Bathymetric data new to the IBCAO 3.0 compilation. A complete list with references to each multibeam survey or set of surveys is found in Auxiliary Material. **B-D)** Close-up maps of the areas where the newly included multibeam surveys are most concentrated.

Figure 2: A) Map showing the area south of Spitsbergen where depths from the multibeam survey of Italian *RV OGS-Explora* and Spanish *BIO Hespérides* are compared with depths from the *Olex* sounding database. The black dots are the soundings from *Olex* selected for comparison as they are located closer than 50 m from nodes of the 200 x 200 m resolution multibeam grid. **B)** Histogram showing the calculated depth differences.

Figure 3: Comparison between IBCAO 3.0 (A) and 2.0 (B) in the area of northwestern Norwegian continental margin where the MAREANO multibeam data makes a significant difference. Note the difference in portrayal of canyons along the slope; even the large Andøya Canyon (AC) and Malangen Canyon (MC) are barely visible in IBCAO 2.0 (D) compared to in IBCAO 3.0 (C). MSGL=Mega Scale Glacial Lineations.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RRS James Clark Ross
RV Akademik N. Strakhov
RV Helmer Hanssen
BIO Hespérides
RV Maria S. Merian
RV Mirai
RV Knorr
RV Nathaniel B Palmer
RV OGS-Explora
RV Polarstern
SV Kommndor Jack
USCGC Healy
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Multibeam compilation
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Single beam/spot sound.
CCGS Louis St-Laurent
Industry Seismic
US Submarines 1993-2005
CHS/GEUS
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Greenland DTM
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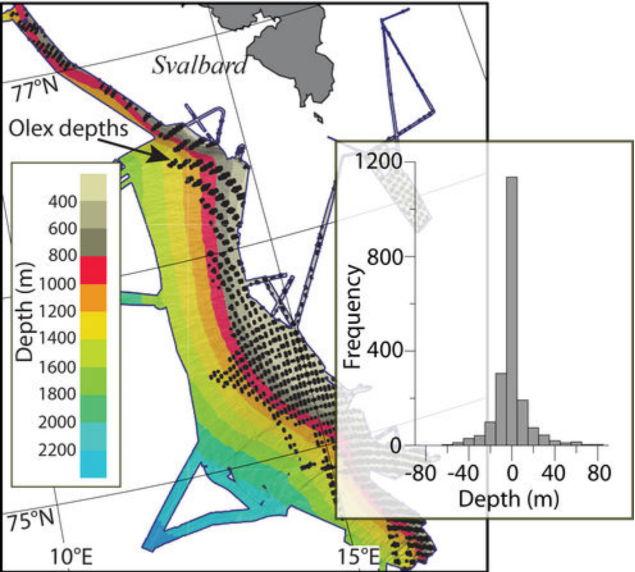
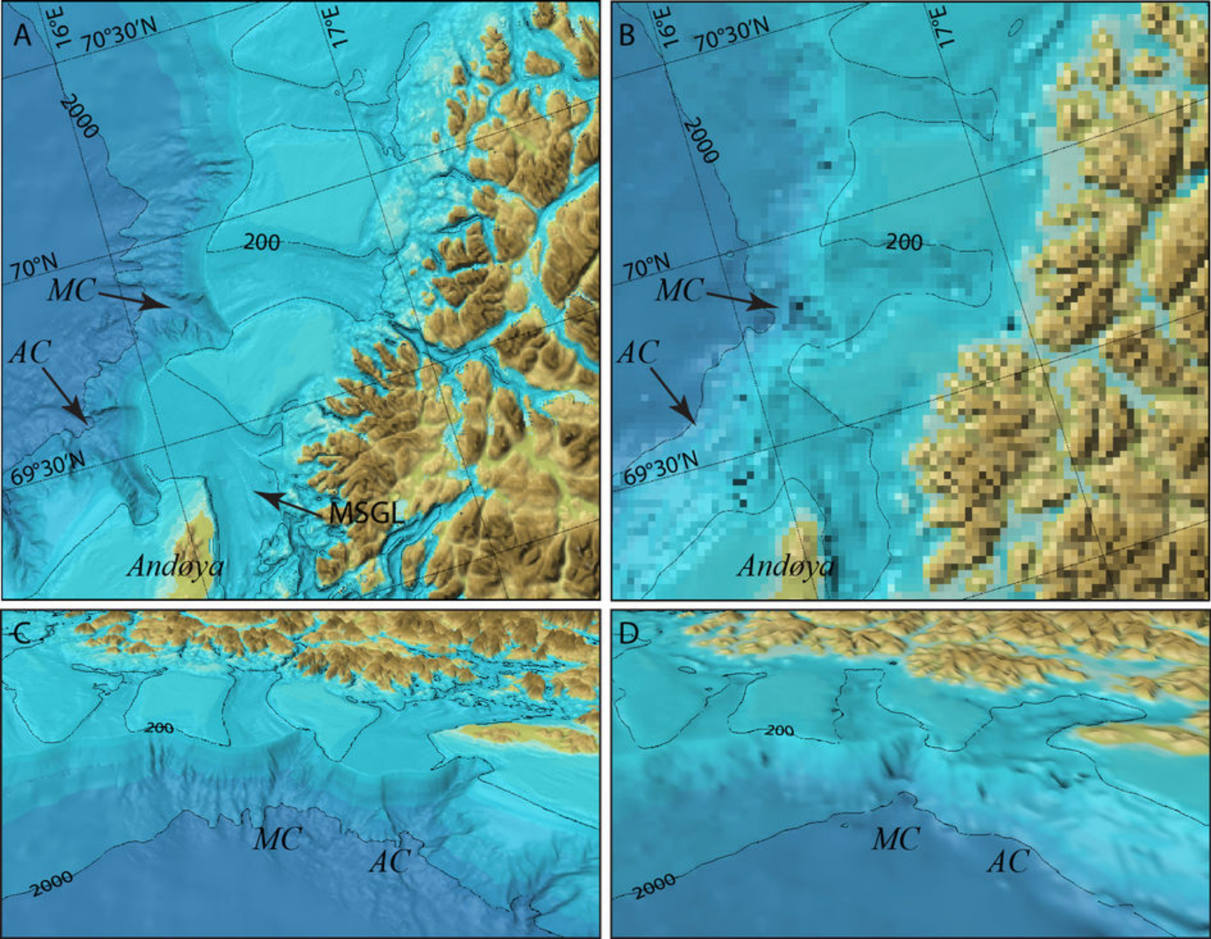
45°W
60°N


Svalbard
77°N
Olex depths
Depth (m)
400
600
800
1000
1200
1400
1600
1800
2000
2200
75°N
10°E
15°E
Frequency
1200
800
400
0
-80
-40
0
40
80
Depth (m)


A
16°E
70°30′N
17°E
2000
200
70°N
MC
AC
69°30′N
MSGL
Andøya
B
16°E
70°30′N
17°E
2000
200
70°N
MC
AC
69°30′N
Andøya
C
200
MC
AC
2000
D
200
MC
AC
2000