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SEA FLOOR MAPPING IN THE ARCTIC: SUPPORT FOR A POTENTIAL US EXTENDED CONTINENTAL SHELF

By Larry A. Mayer, A. Armstrong, B, Calder and J. Gardner (USA)



Abstract

For the United States, the greatest opportunity for an extended continental shelf under UNCLOS is in the ice-covered regions of the Arctic north of Alaska. Since 2003, CCOM/JHC has been using the icebreaker *Healy* equipped with a multibeam echosounder, chirp subbottom profiler, and dredges, to map and sample the region of Chukchi Borderland and Alpha-Mendelev Ridge complex. These data have led to the discovery of several new features, have radically changed our view of the bathymetry and geologic history of the area, and may have important ramifications for the determination of the limits of a U.S. extended continental shelf under Article 76.



Résumé

En ce qui concerne les Etats-Unis, la plus grande possibilité d'extension du plateau continental dans le cadre de la Convention des Nations Unies sur le droit de la mer réside dans les régions englacées de l'Arctique, au nord de l'Alaska. Depuis 2003, le CCOM/JHC a utilisé le brise-glace HEALY, équipé d'un sondeur multifaisceaux, d'un sondeur de sédiment chirp et de dragues, pour cartographier et échantillonner la région de l'ensemble « Chukchi Borderland » et de l'« Alpha-Mendelev Ridge ». Ces données ont conduit à la découverte de plusieurs nouveaux éléments, ont changé radicalement nos points de vue sur l'histoire de la bathymétrie et de la géologie dans la zone et peuvent avoir des ramifications importantes en ce qui concerne la détermination des limites du plateau continental étasunien étendu dans le cadre de l'Article 76.



Resumen

Para los Estados Unidos, la mayor oportunidad de extensión de la plataforma continental en el marco de la Convención de las Naciones Unidas sobre la Ley del Mar reside en las regiones cubiertas por el hielo del Artico, al Norte de Alaska. Desde el 2003, el CCOM/JHC ha estado utilizando el rompehielos *Healy*, equipado de un sondador acústico multihaz, un perfilador de sub-fondo por ondas moduladas en frecuencia, y de rastras, para cartografiar y muestrear la región del conjunto de «Chukchi Borderland» y de la «Alpha-Mendelev Ridge». Estos datos han llevado al descubrimiento de varias nuevas formas del relieve, han cambiado radicalmente nuestra visión de la historia de la batimetría y la geología en la zona, y pueden tener importantes ramificaciones para la determinación de los límites de la plataforma continental estadounidense ampliada en el marco del Artículo 76.

Article 76 of The United Nations Convention on the Law of the Sea (UNCLOS; U.N. 1997), stipulates that coastal states may, under certain circumstances, gain sovereign rights over the resources of the seafloor and subsurface of “...submerged extensions of their continental margin...” beyond the recognized 200 nautical mile (nmi) limit of their Exclusive Economic Zone (EEZ). The establishment of an extended continental shelf (ECS) under Article 76 involves the demonstration that the area of the ECS is a “natural prolongation” of a coastal state’s territorial landmass, and then uses a series of formulae and limit lines that are based on determination of the “foot of the slope,” (defined in Article 76 as “the maximum change in gradient at its base”), the underlying sediment thickness, and the locations of the 2500 m isobath and the 350 nmi line from the territorial sea base line to establish the limits of the ECS. Although the United States has not yet acceded to the UNCLOS, increasing recognition that implementation of Article 76 could confer sovereign rights over large and potentially resource-rich areas of the seabed beyond its current 200 nautical mile (nmi) limit has renewed interest in the potential for accession to the treaty and spurred U.S. efforts to map areas of potential extended continental shelf.

A detailed analysis of the relevance of current U.S. data holdings to a potential U.S. submission under Article 76 was conducted by Mayer et al., (2003). This analysis includes the identification of regions where the collection of new, modern multibeam bathymetry data would substantially improve the quality of a potential submission for an extended continental shelf under Article 76. These regions include the east coast of the U.S., areas in the Bering Sea, the Gulf of Mexico, the Chukchi Borderland region of the Arctic and potentially the Gulf of Alaska and areas around Hawaii and other Pacific islands (Guam, Johnston Atoll, etc.). Since the publication of this study, the Center for Coastal and Ocean Mapping/Joint Hydrographic Center at the University of New Hampshire has, through direction and funding from NOAA and the U.S. Extended Continental Shelf Task Force (a multi-agency task force chaired by the State Dept. and co-chaired by NOAA and the USGS), collected more than one million square kilometers of new, high-resolution multibeam sonar data in regions where the U.S. has the potential for an ECS; the most recent overview of these data was presented at the 2008 Canadian Hydrographic Conference (Gardner et al., 2008).

The greatest potential for an extended continental shelf beyond the current 200 nmi limit of the U.S. EEZ is found in the area of the Chukchi Borderland of the Arctic Ocean, a tightly clustered group of generally high-standing, N-S-trending bathymetric elevations that form a natural prolongation from the Chukchi Shelf north of Alaska. As noted in the Mayer et al., (2003)

study, this area is also an area where the existing database of bathymetric data was far too sparse to support a well-defended ECS submission. For these reasons, the Arctic has become the focus for the collection of new high-resolution multibeam sonar data since 2003. New multibeam data in the Arctic also significantly add to the scientific database needed to support the growing recognition of the critical role that the Arctic Ocean plays in the climatic and tectonic history of Earth (IPCC, 2007). New bathymetric and high-resolution subbottom profiler data (as well as associated CTD measurements) can also help define the nature of deep circulation in the Arctic Basin as well as the history and distribution of ice in the region, a key component in understanding the global climate system.

The Chukchi Borderland juts northward between eastern Siberia and western Alaska into the deep Amerasia Basin north of the Chukchi Sea (*Fig. 1*). The borderland occupies a rectangular area about 600 by 700 km, or some four percent of the Arctic Ocean. This area encompasses three, approximately north-south-trending segmented topographic highs: the Northwind Ridge, the Chukchi Cap and Rise, and the western plateaus which are located westward of an agreed maritime boundary line with Russia. The plateau-like crests of the Chukchi Borderland rise, in some cases, as much as 3,400 m above the adjacent basin and they are relatively shallow (depths between 246 and 1,000 m). The ridges have steep flanks, which in some places exhibit remarkable linearity over hundreds of kilometers, especially along the east side of the Northwind Ridge (*Fig.1*).

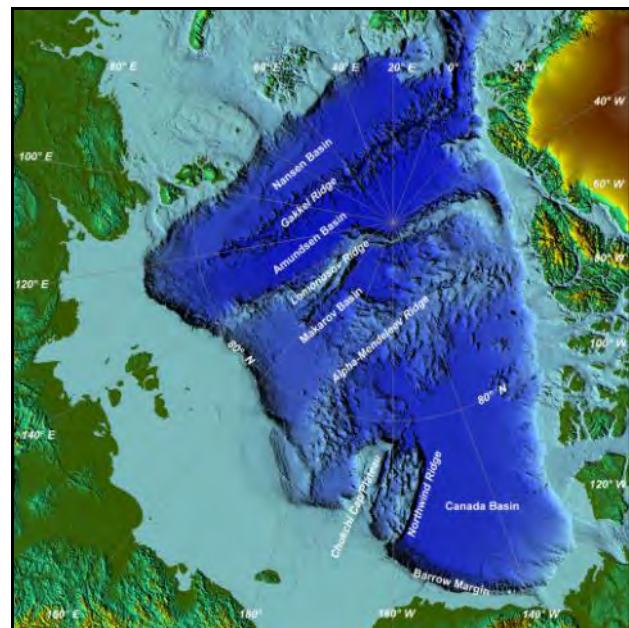


Fig. 1. Physiographic map of the Arctic Ocean (after Jakobsson et al., 2003,2008).

The University of New Hampshire's Center for Coastal and Ocean Mapping/Joint Hydrographic Center (CCOM-JHC) has conducted four cruises to the Chukchi region (2003, 2004, 2007 and 2008) to collect data in support of a potential submission for an extended continental shelf under UNCLOS Article 76. From a bathymetric perspective, the key targets for the establishment of an extended continental shelf for the U.S. in the Arctic are the determination of the location of the foot of the slope and the 2500 m isobath. All of the CCOM-JHC cruises were conducted aboard the U.S. Coast Guard Ice Breaker *Healy* (WAGB-20 -- *Fig. 2*) using a 12-kHz L-3 Communications Seabeam 2112 multibeam system as the primary bathymetric data source. Additionally, high-resolution sub-bottom profiles were collected using a Knudsen 320/BR chirp profiler; these profiles proved to be extremely useful for determining morphologic features critical to establishing an ECS. This report summarizes the accomplishments to date of the CCOM-JHC Arctic Ocean mapping.



Fig.2 The USCGC *Healy* entering the ice pack in Arctic Ocean ice. Photo by Steve Roberts NCAR/LDEO.

HEALY 2003:

The initial mission in 2003 was a 10 day, 3000 km long, exploratory cruise (September 1-11, 2003) to demonstrate the viability of using the multibeam echosounder to follow specific bathymetric targets (in particular the 2500 m isobath) in ice-covered waters (HLY-0302). The 2003 cruise left from Barrow Alaska and steamed to the US-Russian boundary line at 78° 30'N 168° 25'W and followed the 2500 m contour to 78° 35'N 159° 07'W (*Fig. 3*). Ice conditions ranged from 70 to 90% coverage of mostly first-year ice. The cruise collected ~3000 km of high-resolution multibeam echosounder data and made several significant discoveries including:

- substantially changed the position and complexity of the 2500-m isobaths;
- further evidence for pervasive ice and current erosion in deep water (flutes and scours) ;
- evidence for gas-related features (pock-marks), and ;
- a previously unmapped seamount that rises more than 3000 m above the surrounding seafloor.

This NE-SW trending seamount, some 18 km wide and 40 km long with a slightly concave and northward tilted crest, has been officially named Healy Seamount (*Fig. 3*).

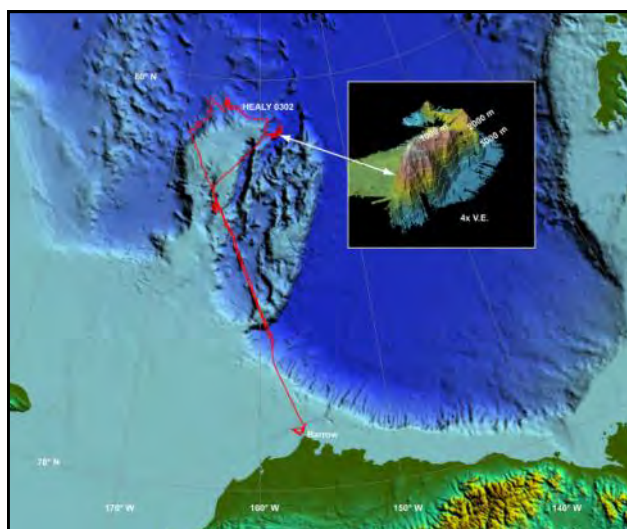


Fig.3 : Cruise track for HLY-0302 and 3-D image (vertical exaggeration 4x) of Healy Seamount, discovered on this cruise. Healy Seamount did not appear on any previous chart and rises more than 3000 m above the surrounding seafloor.

Most importantly, the 2003 cruise demonstrated that it was possible to collect useful multibeam echosounder data while operating in 90% ice cover and to follow critical bathymetric targets.

HEALY 2004:

The second cruise, originating in Nome, Alaska and returning to Barrow, Alaska, spent 20 days at sea from October 6 to October 26, 2004 (HLY-0405). This cruise covered approximately 6700 km and completed most of the mapping of the 2500-m isobath that was begun the previous year, as well as a detailed survey of the foot of the slope over a segment of the continental margin east of Barrow, AK (*Fig. 4*). The total area surveyed during HLY-0405 was approximately 20,000 km² (5830 nmi²). The *Healy* transited northward from Nome over the Northwind Ridge until it intersected the 2500 m isobath at approximately 77° 10'N, 154° W, the point where the 350 nmi cutoff limit from the coast of northern Alaska intersects the 2500 m isobath on the eastern flank of the Northwind Ridge.

Ice was first encountered at about 76°N, and by 77°N the ice was very heavy 90 to 100% with significant percentages of multi-year ice, many ridges and very few leads. Progress was slow and the *Healy* often had to back and ram. Nonetheless, the 2500 m isobath was mapped along the Northwind Ridge to approximately 78° 45'N. During this time, only ~185 km were covered in 4 days. Data were difficult to collect in these conditions and data quality suffered but the 2500 m isobath was still clearly defined. About 5000 km² (1458 nmi²) of seafloor was mapped during the transect to the north and back (Fig. 4).

At 78° 45'N, the *Healy* had great difficulty breaking through the multiyear ice ridges (one ridge took more than eight hours to break through) and the decision was made to move south to the relatively ice-free waters of the continental slope east of Barrow.

This area was chosen so that the foot of the slope could be defined in the central portion of the northern Alaskan margin. The foot of the slope can be used in this region as a starting point for determination of the “Gardiner Line” – one of the formula lines used for making an ECS submission under UNCLOS Article 76. Complete overlapping multibeam bathymetry was collected over a region of 15,435 km² (4500 nmi²), that ranges in water depth from about 650 m to 3900 m. This margin is dominated by a series of 400 to 600 m high ridges that extend to the NNW for more than 80 km from the upper slope. The ridges appear to be, at least in part, sedimentary in origin, possibly through an interaction of a strong geostrophic slope current and Mackenzie River sediment that has reached the slope (Fig. 4).

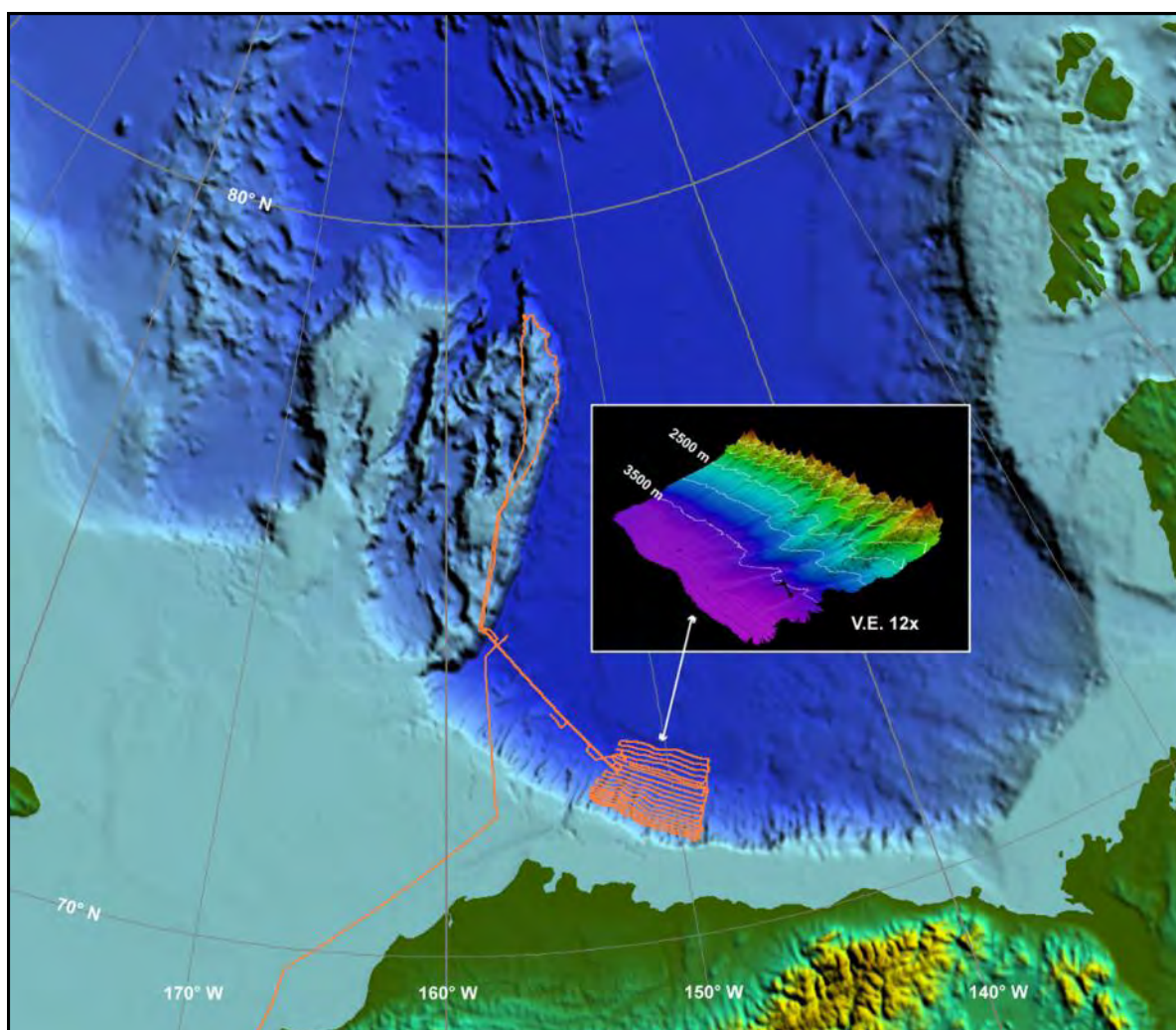


Fig. 4: Cruise track for HLY-0405 and 3-D image (vertical exaggeration 12x) of the full-coverage mapping of a 15,435 km² area of the Barrow Margin. This region was mapped when heavy ice prevented mapping at the top of Chukchi Cap.

HEALY 2007:

HLY-0703 was conducted from August 17 to September 15, 2007, with both embarkation and disembarkation from Barrow, Alaska. The cruise track covered approximately 10,000 km (5400 nm) in 30 days (*Fig. 5*). Using a nominal swath width of 7 km, the total area surveyed during HLY-0703 was approximately 70,000 km² (20,400 nmi²). The primary objectives of the cruise were:

- 1) to complete the mapping of the 2500 m isobath that began on HLY-0302 and HLY-0405;
- 2) to begin to define the foot of the slope around the northern and eastern margins of Chukchi Cap; and;
- 3) to further map an area of pockmarks originally discovered on HLY-0302. All objectives were achieved, far beyond expectations.

Ice was first encountered at approximately 76°N. Although the ice was pervasive, it was mostly large pieces of thick, multiyear ice broken up enough to allow relatively easy passage at 3-6 kts (though backing and ramming was occasionally required). Beginning at the U.S./Russian maritime boundary line, an exploratory, zig-zag pattern was run to better define the foot of the slope. No definitive foot of the slope was apparent until a long excursion to the north revealed a clear transition (both bathymetrically and on the high-resolution sub-bottom profiles) between the slope and flat-lying abyssal plain sediments at approximately 81° 15'N (*Fig. 5*). Several north-south transits found that this same slope/abyssal plain transition occurs on the northern end of the cap above 81°N. Several prominent topographic highs, one that shoaled above 2500 m, which may allow the re-definition of the 2500 m isobath, were also discovered and mapped.

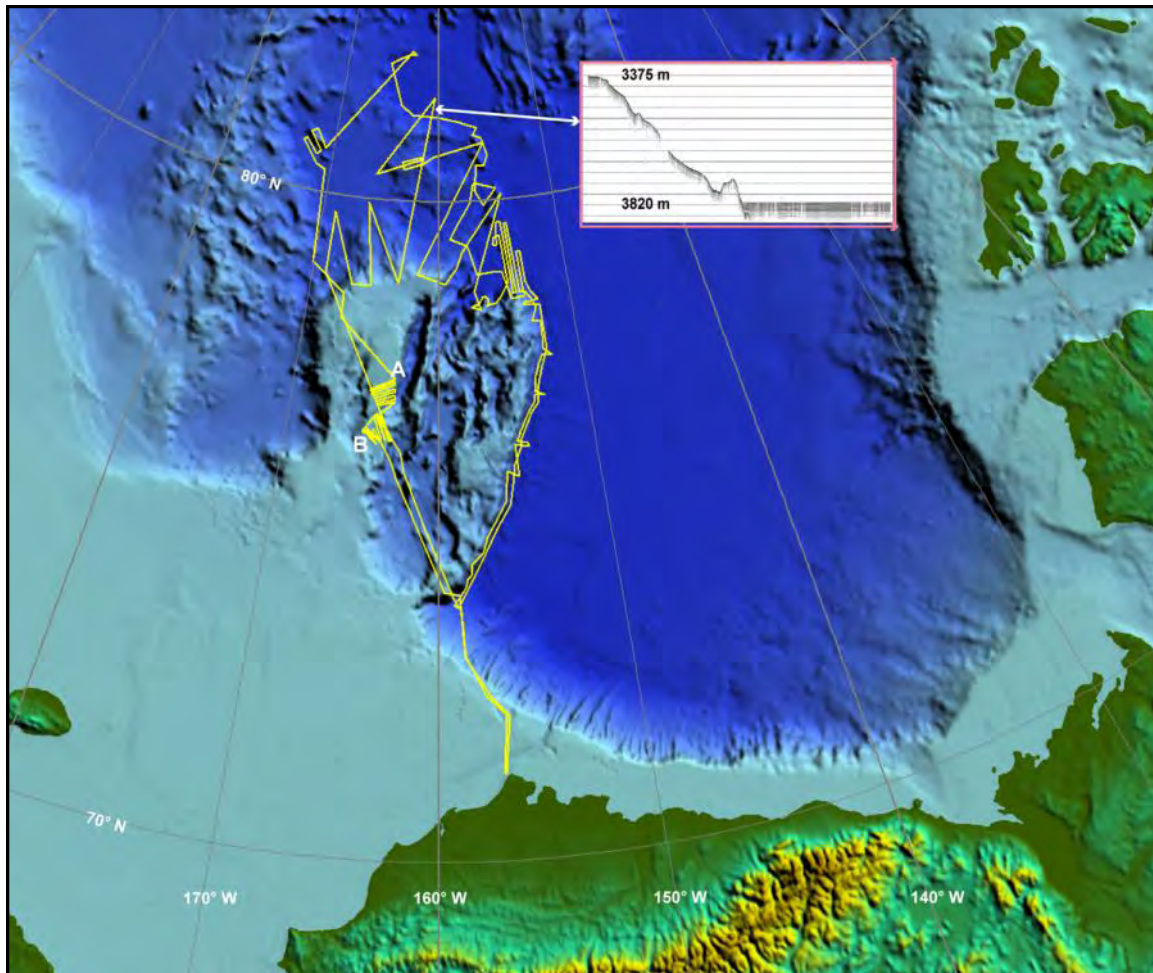
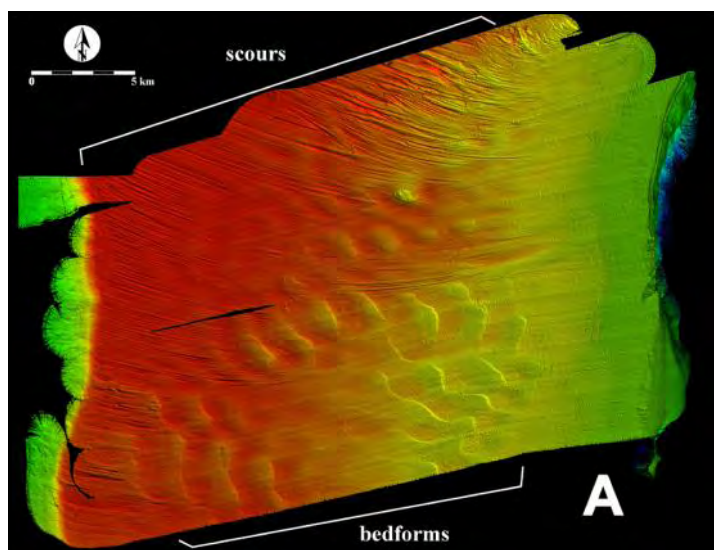
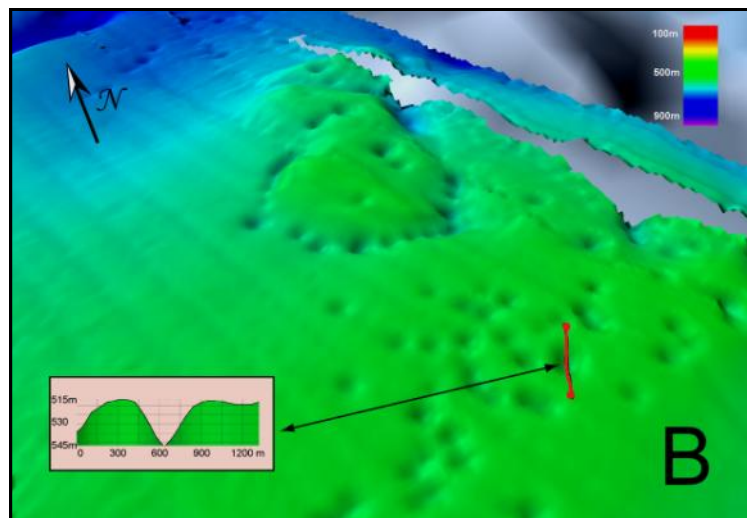


Fig. 5: Cruise track for HLY-0703 and a Knudsen chirp sonar profile showing the characteristic relationship found at the foot of the slope. Here flat-lying abyssal plain sediments abut directly against the high-standing margin. "A" and "B" refer to the groove field and pockmark field shown in Figures 6 and 7.

A well-developed foot of the slope was traced down and then back up the eastern side of Northwind Ridge, revealing a very sharp and clear slope/abyssal plain transition where the abyssal plain sediments consistently occur at a depth of approximately 3820 m. Following this transition to the north, allowed the clear definition of a continuous foot of the slope around the northern most extreme of Chukchi Cap to the northernmost point of the survey (82° 17'N); at this location, the slope/abyssal plain transition appears to continue to the north and east.

Several large and well-defined pockmarks (probably related to gas extrusion) were discovered during HLY-0302 in a shallow region of the Chukchi Cap at approximately 76° 30'N, 163° 50'W. The survey of this region was extended in 2007 to generate a better map of the distribution of these pockmarks. An approximately 40 km by 14 km area was mapped revealing numerous pockmarks of various sizes, but typically 300-400 m in diameter and 30 to 50 m deep (Fig. 5) [labeled B], 6).

Fig.6: Pockmarks found on HLY-0302 and 0703, including a near-circular ring of pockmarks. For location see –B” on Figure 5. Pockmarks are typically about 300 to 400 m in diameter and 30 to 50 m deep. These examples are found in approximately 500 m of water.



Simultaneous collection of subbottom profiles revealed an apparent relationship to subsurface faulting but the nature of this relationship will need further study. A remarkable group of 20 pockmarks were mapped that form a circular ring that is 4 km in diameter (Fig. 6).

Abutting the pockmark area is a series of closely spaced, NW-SE oriented, parallel grooves in water depths of 400 to 500 m. Given the parallel nature of these features, they appear to be related to ice-sheet flow rather than individual icebergs scours. Even more intriguingly, south of these grooves, as the water depths get slightly deeper, there is a series of large, dune-like features that appear erosional in origin in the high-resolution subbottom profiles (Fig. 7). We speculate that these may be related to flow under an ice-shelf that was not grounded but was near the seafloor.

Fig.7: Closely-spaced parallel grooves found on HLY-0703. For location see –A” on Figure 5. Grooves are typically 2 to 5 m deep and have a spacing of 150 to 200 m.

HEALY 2008:

The fourth bathymetric survey leg, HLY-0805, departed Barrow on 14 Sept. 2008 and steamed north to resume mapping of the region thought to represent the foot of the slope in the vicinity of 82° N, 162° W. Mapping continued east to follow the morphologic expression of the base of the slope until approximately 150° W where the character of the base of the slope changed and the mapping switched to a reconnaissance mode. This mode of survey continued until the easternmost extent of the survey was reached at approximately 139° W. At this point, several regions that were suspected to shoal above 2500 m were mapped. A total of 5767 km were surveyed (3114 nmi) on HLY-0805 covering an area of approximately 34,600 km² (assuming an average swath width of 6 km) (*Fig. 8*).

HEALY-0805 also dredged key areas on the Alpha-Mendelev Ridge complex and the Chukchi Cap-Northwind Ridge in order to better understand the geologic and tectonic history of this remote region. A total of seven dredges were taken, four on the southern portions of the Alpha-Mendelev Ridge complex, two on ridges north of the Chukchi Borderland and one in the northwestern Northwind Ridge area (*Fig 8*).

The first dredge site on the southern Alpha-Mendelev Ridge complex yielded samples from an outcrop of layered tuffaceous rock (hyaloclastite) that appears to represent a deposit of a shallow phreatomagmatic eruption (Mayer et al., 2008; Brumley et al., 2008).

The second dredge from the same vicinity contained over 90 kg of mud and ice rafted debris (IRD). The third dredge, from another feature on the southern Alpha-Mendelev Ridge Complex, also brought back only mud and IRD. The fourth dredge, from the same general vicinity as the third, was predominantly mud and IRD; however, the dredge haul also included iron concretions and manganese crusts along with one sample of a possible altered ash deposit. The fifth dredge, from the northern margin of the Chukchi Borderland, recovered more than 450 kg of mud with about 2.25 kg of IRD of various rock types. The sixth dredge from a very steep (~60°) slope on the northern Chukchi Borderland was mud free and contained more than 90 kg of basalts, some with fresh glassy rims and pillow-like structures that appear to have erupted within continental material (Andronikov et al., 2008). Finally, the seventh dredge from the western wall of Northwind Ridge had very little mud but more than 300 kg of rocks that probably represent both outcrop and angular talus from the foot of the steep slope from which it was dredged. Samples from this dredge contain a range of rock types including sedimentary (including sandstones and mudstones), metamorphic, and basaltic, all supporting the notion that Chukchi Cap is of continental origin. Further analyses of all of the dredge samples are currently underway.

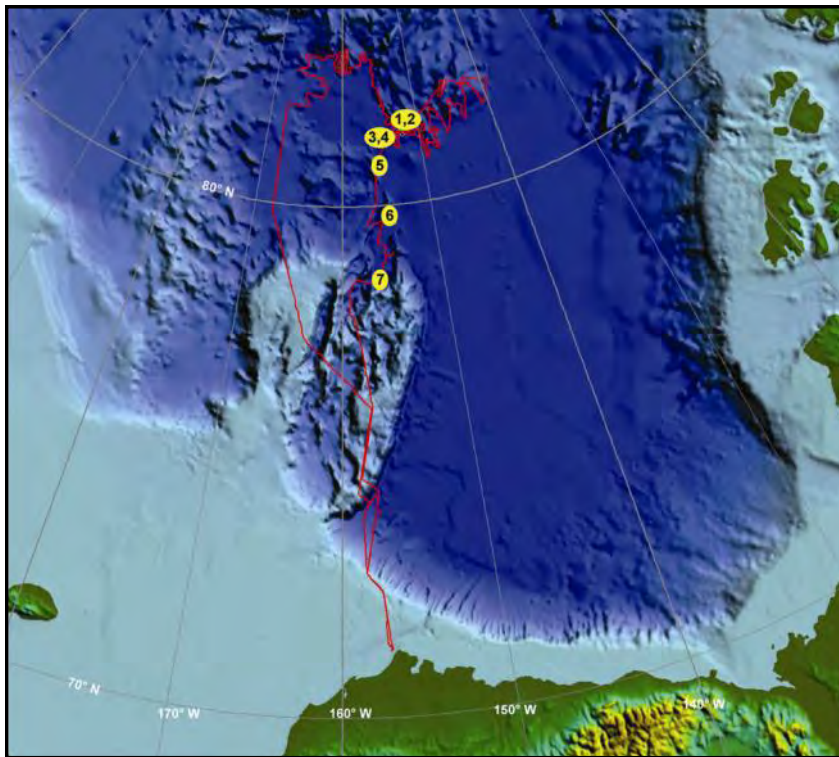


Fig. 8: . Cruise track for HLY-0805 showing location of dredge stations.

A second expedition took place in 2008 (HLY-0806) that was a collaborative effort between Canada and the U.S. During this two-ship effort, *Healy* broke ice ahead of the Canadian icebreaker *Louis S. St. Laurent* so that it could collect deep seismic-reflection profiler data (in order to measure sediment thickness) in the open water created by the *Healy*. A 2009 cruise to the Arctic is planned, again in company with the *Louis S. St. Laurent* and again with the primary purpose of collecting seismic data from the *Louis S. St. Laurent*. All bathymetric data collected during Law of the Sea cruises on the *Healy* and full cruise reports of each of the expeditions described here can be found at the CCOM/JHC

website: <http://www.ccom.unh.edu/law.of.the.sea.html/>.

CONCLUSIONS:

Four expeditions on the USCG Cutter *Healy* to the ice-covered regions of the Arctic have demonstrated that it is possible to use an icebreaker equipped with a modern multibeam sonar system to collect high-resolution bathymetric data and to trace bathymetric features even in 90 to 100% coverage of first year ice. In multi-year ice with few leads it was possible, but very difficult, to collect usable data and progress was very slow (averaging less than 1 knot). Since 2003, more than 150,000 km² of new multibeam sonar data have been collected in the region of the Chukchi Borderland and the Alpha-Mendelev ridge complex. The primary motivation for these surveys was to collect data in support of a possible U.S. submission for an extended continental shelf under Article 76 of the United Nations Convention on the Law of the Sea. The data collected thus far have dramatically changed our knowledge of the bathymetry of this region of the Arctic; numerous new features have been mapped including a newly named seamount (Healy Seamount) that stands more than 3000 m above the surrounding seafloor. The new data will have significant impact on a potential U.S. submission under Article 76 as they demonstrate that the “foot of the slope,” the key feature from which the limits of an extended continental shelf is determined, is much further seaward than previously recognized. Preliminary analyses of dredge samples taken on one of the *Healy* cruises in the regions of Chukchi Cap and the Alpha-Mendelev ridge complex also call into question previous notions of the geologic origins of these features and may also have implications for an Article 76 submission.

In addition to its value for Law of the Sea, the multi-beam sonar data and dredge samples collected during the *Healy* expeditions will have important implications on our overall understanding of Arctic geology and processes.

The bathymetry and rock samples collected are already becoming critical components of regional reconstructions of the tectonic and geologic history of the region (e.g. Brumley et al, 2008; Andronikov et al. 2008). Newly mapped fields of pockmarks are indicative of hydrocarbon potential and may host chemosynthetic communities and the discovery of a series of closely spaced, NW-SE oriented, parallel grooves in water depths of 400 to 500 m far out on the Chukchi Cap implies that there was a grounded ice-sheet more than 400 nmi from the nearest land. Understanding how an ice-sheet formed so far from land will require a rethinking of current ice models for the region.

All bathymetric data collected on U.S. ECS mapping cruises, including those in the Arctic are made available to the public soon after collection. The data as well as 3-D models can be found at <http://www.ccom.unh.edu/law.of.the.sea.html> or the National Geophysical Data Center. Future expeditions, planned for 2009 and beyond will likely add even more to our growing knowledge to this critically important, yet difficult to study, region.

ACKNOWLEDGEMENTS:

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Biographies of the Authors

Larry Mayer is a Professor and the Director of the Center for Coastal and Ocean Mapping at the University of New Hampshire. He graduated magna cum laude with an Honors degree in Geology from the University of Rhode Island in 1973 and received a Ph.D. from the Scripps Institution of Oceanography in Marine Geophysics in 1979. At Scripps he worked with the Marine Physical Laboratory's Deep-Tow Geophysical package, applying this sophisticated acoustic sensor to problems of deep-sea mapping and the history of climate. After being selected as an astronaut candidate finalist for NASA's first class of mission specialists, Larry went on to a Post-Doc at the School of Oceanography at the University of Rhode Island where he worked on the early development of the Chirp Sonar and problems of deep-sea sediment transport and paleoceanography. In 1982, he became an Assistant Professor in the Dept. of Oceanography at Dalhousie University and in 1991 moved to the University of New Brunswick to take up the NSERC Industrial Research Chair in Ocean Mapping.

In 2000 Larry became the founding director of the Center for Coastal and Ocean Mapping at the University of New Hampshire and the co-director of the NOAA/UNH Joint Hydrographic Center. He is currently co-chair of the NOAA's Ocean Exploration Advisory Working Group, a member of the National Science Foundation's Ocean Observatories Initiative Program Advisory Committee, and the State Dept's Extended Continental Shelf Task Force. Larry's present research deals with sonar imaging and remote characterization of the seafloor as well as advanced applications of 3-D visualization to ocean mapping problems and applications of mapping to Law of the Sea issues, particularly in the Arctic.

Captain Armstrong is the NOAA Co-Director of the Joint Hydrographic Center at the University of New Hampshire. Along with his UNH counterpart, he manages the research, mapping, and educational programs of the Center. He has been actively involved in the Joint Hydrographic Center UNCLOS efforts, including serving as Co-Chief Scientist on the Center's Arctic seafloor mapping cruises. He is past president of The Hydrographic Society of America and a member and past chair of the FIG/IHO/ICA International Advisory Board on Standards of Competence for Hydrographic Surveyors and Nautical Cartographers. Captain Armstrong has over 35 years of hydrographic experience with NOAA, including positions as Officer in Charge of hydrographic field parties, Commanding Officer of *NOAA Ship Whiting*, and Chief of NOAA's Hydrographic Surveys Division. He has a B.S. in geology from Tulane University and an M.S. in technical management from The Johns Hopkins University

Dr. Brian Calder is a Research Associate Professor at the Center for Coastal and Ocean Mapping & Joint Hydrographic Center at the University of New Hampshire. He graduated MEng and PhD in Electrical & Electronic Engineering from Heriot-Watt University in Edinburgh, Scotland in 1994 and 1997 respectively, but was subsequently seduced into sonar signal processing for reasons that are now obscure. His research interests have previously covered speech recognition, texture analysis, object detection in sidescan sonar, high-resolution sub-bottom profiling, simulation of forward-looking passive infrared images, acoustic modeling and pebble counting. Currently, they revolve around the application of statistical models to the problem of hydrographic data processing; ocean mapping, and associated technologies

James V. Gardner is a marine geologist and Research Professor at the University of New Hampshire's Center for Coastal and Ocean Mapping. His research is focused on deep-seafloor mapping with multibeam echosounders, marine geomorphology and deep-sea processes. He received a B.S. in geology from San Diego State University in 1967 and a Ph.D. in 1973 in marine geology from Columbia University-Lamont-Doherty Earth Observatory. Jim joined the U.S. Geological Survey's Pacific Marine Geology group in Menlo Park, CA at the where he worked for 30 years on a wide variety of seafloor mapping, marine sedimentological and paleoceanographic problems in the Bering Sea, North and South Pacific Ocean, north-east Atlantic Ocean, Gulf of Mexico, Caribbean and Mediterranean Seas, and the Coral Sea. Jim joined the University of New Hampshire in 2003 where he is in charge of the U.S. Law of the Sea bathymetry cruises as well as involved in research methods to extract meaningful geological information from multibeam acoustic backscatter through ground truth and advanced image analysis methods.
