Something Old, Something New

Compiling Historic and Contemporary Data to Construct Regional Bathymetric Maps, with the Arctic Ocean as a Case Study

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Regional maps that are accurate and up to date are not available for significant portions of the world ocean. Pending the advent of detailed survey operations, this situation could be partially mitigated in several areas, through judicious combinations of historical and modern data sets to yield adequate portrayals of the seafloor. This paper outlines some general principles relating to bathymetric compilations, and offers an example, by describing a recent project to construct a modern data base and map of the Arctic region.

Introduction - The Need to Blend Historic and Modern Data

Worldwide, the new generation of swath sounding systems is fuelling a veritable explosion of bathymetric data sets in specific target areas, whereas the quantity of observations being collected with conventional single-beam instruments remains relatively static due to their low rates of acquisition. In terms of accuracy and resolution, data sets collected with modern instruments are an indisputable improvement over those obtained with older equipment. However, the older data sets, collected during an era of wide-ranging, traditional survey missions, often feature a much broader geographical coverage. Representing the cumulative output of survey programmes that have been mounted over the past several decades, many of these older data sets are likely to remain in use for several decades more before they are supplanted by modern observations. Their anticipated longevity provides ample justification for adopting an organised approach to their management and utilisation.

Modern techniques for studying, managing, and exploiting the sea floor have spawned a growing demand for better representations of bathymetry, in both printed and digital form. In many instances, these representations can only be derived from a mix of modern and legacy data, which raises a host of problems in assembling, combining, and utilizing data sets that are not only fragmented and incompatible, but which exist in multiple formats and which feature a wide range of accuracies, resolutions, and geographic densities. However with proper planning and execution, bathymetric compilations offer opportunities to recycle and to rationalize disparate sets of observations in regions where there is enough data to improve existing descriptions of the seafloor. Although labour-intensive, this approach is far cheaper than mobilizing a new survey mission; in fact, by identifying the areas where expensive technical and human resources can be deployed to best effect, a good compilation will promote substantial economies in the planning and execution of subsequent survey operations.

Two Critical Factors in Mobilising a Compilation: Who and What

Ideally, a compilation process should be driven by one or more individuals who have a genuine scientific interest in the outcome, and who are competent to assess data sets according to the quality of their information content. These talents and inclinations exist in many research laboratories and data centres. While the latter provide excellent service as repositories of observations, their compilation activities tend to be limited because their mandates and resources do not permit them to engage extensively in the assessment, manipulation, and interpretation of data. On the other hand, staff in research laboratories are usually motivated to enhance, condition, and qualify their data sets before engaging in investigations; therefore when time and resources permit, compilations are often undertaken as preludes to research projects, with due care and attention being given to the structure and the contents of the relevant data bases.

In constructing the data base, original observations should be used wherever feasible. As much as possible, these should represent the condition of the data at the time of collection; the use of original observations will minimise contamination by incorrect or undocumented procedures that might have been applied to the data subsequent to its acquisition. In situations where original observations are not available, every effort should be made to obtain a record of the procedures that were applied, in case it should prove necessary to undo some of the earlier steps.

Classes of Data

A compilation data base can be developed from four general classes of information:
- Profile (single-beam) soundings
- Point soundings
- Swath (multibeam or interferometric) soundings
- Printed maps (displaying depth in contour or point form)

The procedures for handling these classes of data will vary. Currently, most bathymetry is recorded in digital form at the time of collection or shortly thereafter. Therefore modern profile, point, and swath soundings are likely to be available in computer-readable form, and will be immediately amenable to digital manipulation. Older data sets may first need to be digitised from original analogue records.

Contour maps may be hand- or machine-drawn, and their creation usually includes some level of processing or interpretation; more often than not, the construction of the contours is only partially documented, if at all. If hand-drawn, the contours will need to be digitised; if machine-drawn, they may already be available in digital form. As a general rule, it is advisable to check the veracity of the contours against profile or other soundings of known accuracy.

Maps that display point values often portray only subsets of the available data, selected according to certain criteria such as cartographic legibility and relevance to the safety of navigation. Usually it is a straightforward matter to capture the point values from a scanned image using an OCR (Optical Character Recognition) technique, or on a digitising table with manual entry on a keyboard if only a small number of points is involved.

Data Sources and Public Release

A candidate data set may belong to one of four categories, according to its origin and to constraints on its distribution. In general, the first category is freely available, whereas some negotiation is often needed to obtain access to the remainder.
- Public domain data is circulated for general use, with no restrictions on its further distribution

- Proprietary data is collected to meet the specific aims of an organisation, and is retained (usually) to preserve a competitive advantage
- Classified data is collected for military purposes, and its release is perceived as detrimental to national security
- Commercial data is acquired by or on behalf of an organisation that markets the data to clients who lack the resources or the expertise to collect their own data

To ensure maximum benefit, the objectives of the compilation should include the publication of maps and the production of a digital data set that can be placed in the public domain for free and unrestricted use by the general community. These objectives need to be well articulated to prospective data contributors. To avoid problems at later stages of the project, ownership of the constituent data sets should be clearly defined at the beginning, as should the conditions for their onward distribution once the compilation is completed. Therefore at the time the data sets are transferred to the compilation project, formal permission should also be obtained for their incorporation and release as an integral part of the final grid, and for their portrayal in the final map(s).

Data Errors and Problems

A number of errors, some more significant than others, can complicate the consolidation of data sets. Positioning errors will obviously have a substantial impact on the portrayal of the sea floor, especially in

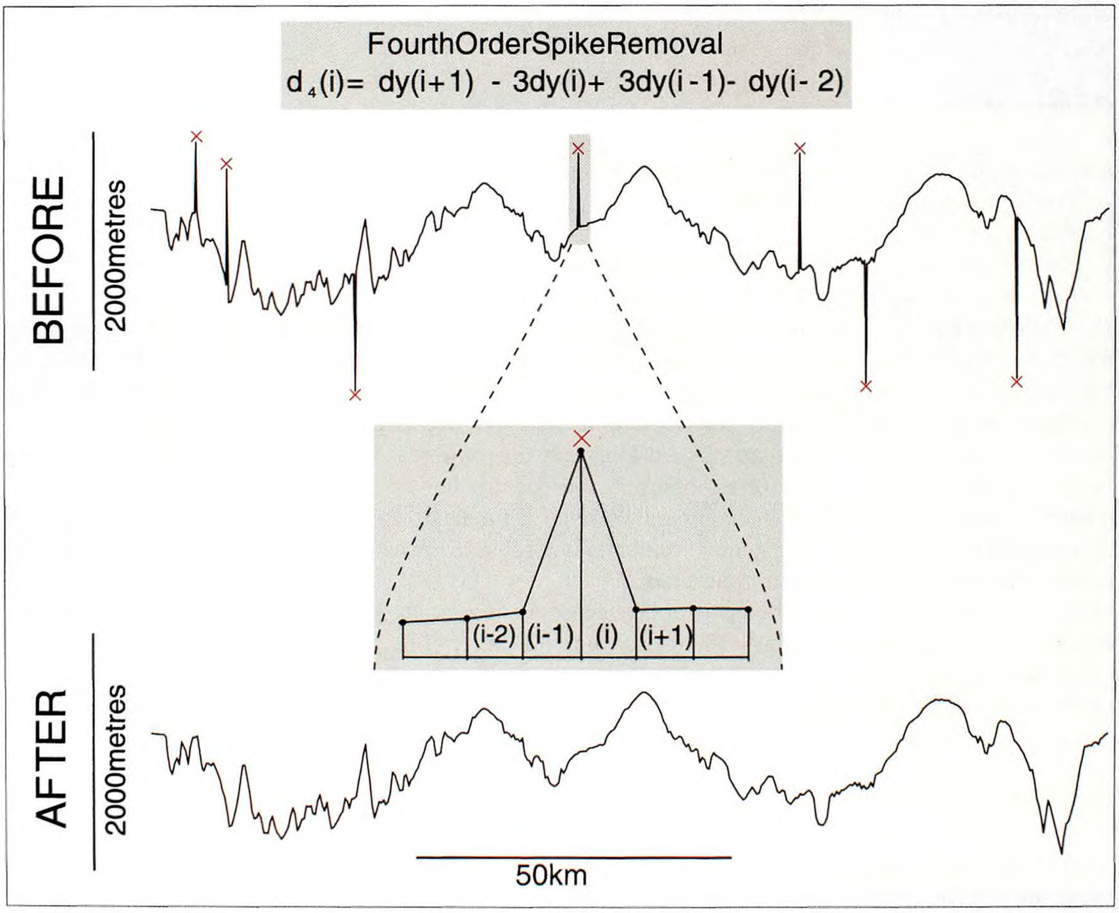
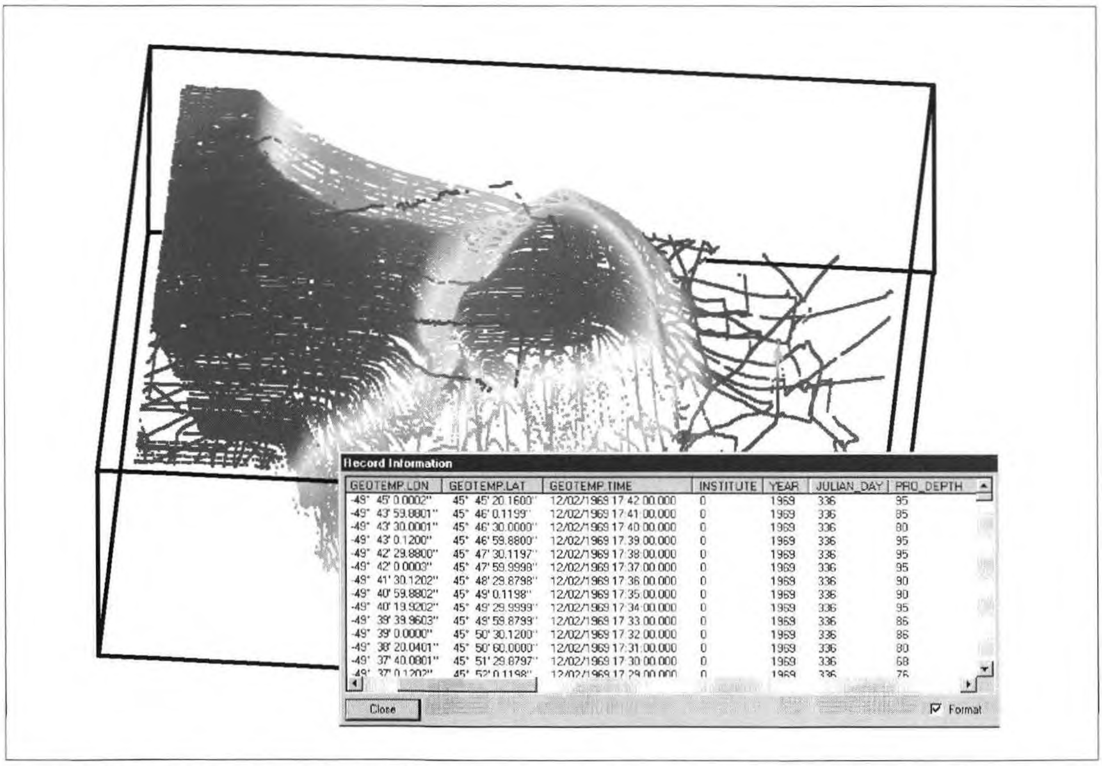


Figure 1: *Simple spikes in a bathymetric profile can be detected and eliminated by an automatic fourth-order difference procedure. (From Stark et al, 1997)*

older data sets. Echo sounders do not make direct measurements of depth: they measure the time it takes for a sound pulse to travel to the seabed and back, and this time is multiplied by an assumed velocity of sound in sea water to obtain a depth value; historically, not all sounders have used the same sound velocity, so two different systems operating at the same time in the same location could well yield two dissimilar depth values. Moreover, the returned signal represents something approaching the average depth of the ensonified portion of the seabed; by averaging over a broad area, a wide-beam sounder may fail to register features that a narrow-beam system would easily detect. Finally, the velocity of sound in sea water varies with time and location; different procedures have been devised to correct for these variations, but the results are not always compatible owing to inconsistencies in their design and application.

Typical Data Correction Procedures

Different classes of errors call for different correction procedures. As a general rule, older data sets are more prone to positioning errors on account of the limited capabilities of early navigation systems; these errors can sometimes be corrected through careful adjustment of sounding locations, however if more recent observations in a given region are plentiful, the simplest and most reliable procedure in this situation is often to eliminate all data sets that pre-date the introduction of modern positioning systems.
Digitising or other errors can introduce random spikes in some profile and grid data sets. These need to be identified and removed in order to eliminate artifacts that are manifested eventually as highly localised peaks or hollows in the sea floor. Fortunately, procedure exist to automate this procedure; for instance,



GEOTEMP.LON	GEOTEMP.LAT	GEOTEMP.TIME	INSTITUTE	YEAR	JULIAN_DAY	PRO_DEPTH
-49° 45' 0.0002"	45° 45' 20.1600"	12/02/1969 17:42:00.000	0	1969	336	95
-49° 43' 59.8801"	45° 46' 0.1199"	12/02/1969 17:41:00.000	0	1969	336	85
-49° 43' 30.0001"	45° 46' 30.0000"	12/02/1969 17:40:00.000	0	1969	336	80
-49° 43' 0.1200"	45° 46' 59.8800"	12/02/1969 17:39:00.000	0	1969	336	95
-49° 42' 29.8800"	45° 47' 30.1197"	12/02/1969 17:38:00.000	0	1969	336	95
-49° 42' 0.0003"	45° 47' 59.9998"	12/02/1969 17:37:00.000	0	1969	336	95
-49° 41' 30.1202"	45° 48' 29.8798"	12/02/1969 17:36:00.000	0	1969	336	90
-49° 40' 59.8802"	45° 49' 0.1198"	12/02/1969 17:35:00.000	0	1969	336	90
-49° 40' 19.9202"	45° 49' 29.9999"	12/02/1969 17:34:00.000	0	1969	336	95
-49° 39' 39.9603"	45° 49' 59.8799"	12/02/1969 17:33:00.000	0	1969	336	86
-49° 39' 0.0000"	45° 50' 30.1200"	12/02/1969 17:32:00.000	0	1969	336	86
-49° 38' 20.0401"	45° 50' 60.0000"	12/02/1969 17:31:00.000	0	1969	336	80
-49° 37' 40.0801"	45° 51' 29.8797"	12/02/1969 17:30:00.000	0	1969	336	68
-49° 37' 0.1202"	45° 52' 0.1198"	12/02/1969 17:29:00.000	0	1969	336	76

Figure 2: *Main image: an oblique view of the uncorrected data base over Flemish Cap and the Grand Banks of Newfoundland, portraying the distribution of ship tracks which are colour-coded according to observed values of depth at each point of observation. A few bad profiles stand prominently clear of the coherent data points in the background. Inset: a listing of the values and attributes of the bad profiles, following selection by the user. (From Harding et al, 1999)*

a fourth-order difference technique that was originally developed for processing magnetic data (Stark et al, 1997) has been modified to remove bathymetric readings that can be identified unequivocally as spikes, and to flag suspect data points whose elimination requires some human intervention (Figure 1).

Data attributes need to be homogenised to ensure meaningful comparisons between sets of observations. For example, all soundings should be reduced to a common velocity of sound to minimise apparent discrepancies which are in fact due to non-uniform calibration factors between different sounding systems. Similarly, for preliminary comparison and adjustment, soundings should be reduced to their uncorrected form wherever possible, to avoid seeming disagreements between those that have been corrected for the variation of sound velocity in the water column, and those that have not.

A compilation data base typically contains a large number of profile soundings, making it impractical to scan and compare data points individually for the purpose of assessing the success or failure of corrective procedures. Fortunately, the large population of profile soundings suggests a statistical approach to the analysis of discrepancies at track crossover points. A crossover point is a location where two independent measurements have been obtained on two separate profiles at different times, and where the expected discrepancy should be zero. More often than not however, discrepancies exist at crossover points, and a description of these errors, often as functions of location and time of measurement, provides a basis for assessing the quality of the data base. At various stages of the correction process, these discrepancies can also be used to indicate the effectiveness of specific corrections through a statistical quantification of the reduction that they induce in the entire set of combined errors.

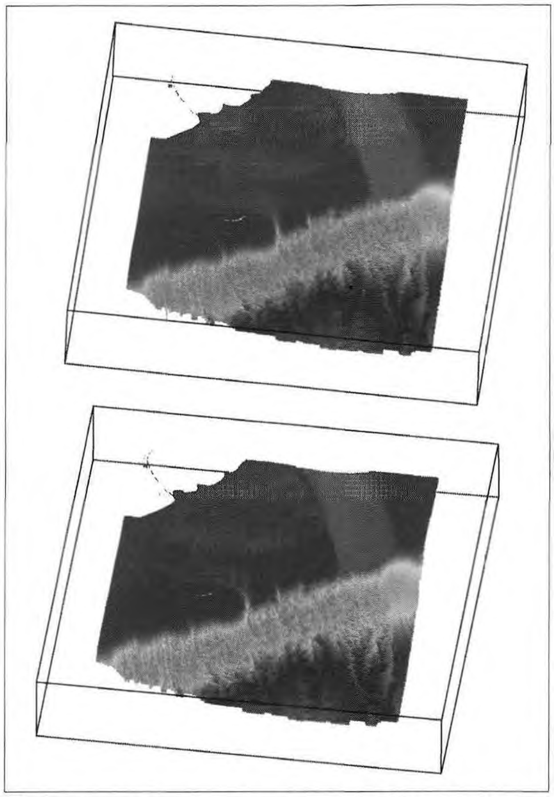


Figure 3: *Upper image: an oblique view of the sea floor, constructed from uncorrected data and showing a series of bad points across a channel on the continental shelf, as well as a single outlier on the continental rise. Lower image: the same data set after it has been subjected to an automated cleaning procedure, which assesses each observation point for its level of coherence with the surrounding points; bad points in the channel have been eliminated, as well as the outlier on the continental rise. (From Harding et al, 1999)*

A more recent approach provides a means for cleaning any kind of point data set, provided the information is stored in HH (Helical Hyperspatial) Code (Varma et al, 1990). HH Code is multidimensional and expresses dimensions in interleaved binary format to achieve high levels of data compaction, as well as extremely rapid indexing and retrieval. Large data sets formatted in HH Code are thereby amenable to complex operations that would be computationally prohibitive if conventional coding were used.

HH-encoded data can be cleaned manually or automatically (Harding et al, 1999). Figure 2 illustrates how erroneous data points can be visually identified, and then manually selected for adjustment or elimination. The automated approach, on the other hand, is based on an assessment of the statistical compatibility of each data point with its neighbours, the degree and radius of compatibility being selected by the operator. This process eliminates many of the tedious, time-consuming, and error-prone steps that are the norm when editing data that is coded conventionally.

Figure 3 illustrates the effectiveness of the automatic cleaning technique. The upper image, constructed from uncorrected data, shows a series of erroneous points crossing a broad channel on a continental shelf, along with a single outlier on the continental rise. The lower image shows the same data set after it has been subjected to the procedure; the erroneous crossing points have been eliminated, along with the outlier.

Topography on Surrounding Land

Increasingly, geoscientists are concerned with past or present processes that affect the sea floor at or near the coast; in some cases, these processes extend from or onto adjacent land areas, and their effects may be readily discerned by observing the topographic characteristics of terrain above sea level. This information is now available on a global basis, at a resolution that is adequate for regional portrayal of land elevations (US Geological Survey, 1997). For certain applications, new insights on past phenomena - e.g. changes in sea level, glaciation, drainage and erosion - can be achieved by overlaying remote sensing information such as satellite or SAR imagery onto the topography. In other applications, there may be good reason for delimiting precisely the separation between bathymetry and topography by overprinting the display with a coastline; special effort may be required in these situations to achieve a satisfactory co-registration between coastlines that are publicly available in vector form (e.g. World Data Base II, World Vector Shoreline) and the corresponding zero or sea levels in custom or public-domain grid sets of onshore-offshore surface relief.

The Construction and Manipulation of Bathymetric Grids

Ultimately and for ease of handling and visualisation, observations in the compilation data base will be homogenised into a single or master grid of depth values. Methods of doing this will vary according to the nature of the data sets that are being merged, to the processing facilities at hand, and to the preferences of the compiler. For instance, if the data base in a certain region consisted entirely of unrelated but overlapping track soundings and digitised contour lines, one approach could be to focus initially on the reduction of all point values to a coherent assemblage containing two types of sequences: (1) varying depth measurements along ship tracks, and (2) fixed values spaced appropriately along contour lines. Then this amalgam of track and contour values could be used to construct the master grid.
An alternative approach would be to composite the master grid from a series of intermediate sub-grids that corresponded to various combinations of the constituent data sets, and which covered different parts of the study area. These sub-grids would be constructed at different processing stages. For instance, sets of profile and point sounding observations often feature some overlap, and it would usually be more effective to defer creation of the intermediate sub-grids until the data sets had been individually adjusted to achieve the desired levels of agreement. On the other hand, swath soundings and contour maps tend to feature some degree of internal coherence; therefore they could be converted to sub-grids at an early stage in the proceedings, and then subjected to block adjustments such as re-levelling or tilting. In any event, once all constituent data sets had been adjusted, their sub-grids would be merged to create the master grid. To facilitate this process, all sub-grids would refer to the same origin, and would feature a common grid spacing and orientation.

Display Techniques: Contour Lines Versus Colour Shaded Relief

In general, a plot of colour shaded relief will portray significantly more information of a qualitative and textural nature than will a standard contour map, regardless of the magnitude of the intervals between colour changes and isobaths. This has obvious benefits when analysing the surface character of the seabed or of the topography above sea level; in some applications, the relief information can be superimposed on another parameter such as the gravity or magnetic field to illustrate correlations that would not otherwise be very obvious. The shaded relief technique also helps pinpoint errors and inconsistencies in the data base, thus providing a powerful diagnostic tool in the evaluation and adjustment of observations. Contour lines, while less informative from a morphological perspective, have the quantitative advantage of permitting a user to determine approximate depth at any given point through visual interpolation between the isobaths that are printed on the map. A practical solution that blends the strengths of the two display techniques is to overprint the shaded relief presentation with labelled contour lines.

Final Compilation Products

To maximise its value to the end user, a comprehensive compilation should include the creation and circulation of several end products. At minimum, these should include: a suitably-spaced grid of depth values in an easy-to-read digital form; appropriately-scaled maps that can be readily printed on demand; and comprehensive documentation that fully describes all the constituent data sets as well as the procedures that were employed in their treatment.

An Example and a Case Study: a Compilation of Bathymetric Data from the Arctic Ocean

In recent decades, it has been well recognised that published maps of the sea floor north of the Arctic Circle, particularly in the deep central basin of the Arctic Ocean, are not totally accurate, and that in certain areas, there are significant discrepancies between observed and charted depths. The principal cause of this situation has been the lack of sounding information needed to construct reliable and detailed charts: certain regions remain inadequately mapped on account of difficult operating conditions, or because critical data sets have not been made available for widespread public use.

Prospects for improving this state of affairs brightened considerably in the late 90s on account of three significant developments: (1) the US Navy's SCICEX program, which in 1993 began mobilising unclassified mapping and research missions aboard nuclear submarines operating beneath the polar pack (Delaca and Gossett, 1997); (2) the de-classification of historic data sets collected in the same region by US and British submarines between 1957 and 1982 (Showstack, 1997); and (3) access to significant information collected by the Russian Navy, and released in map and chart form (Head Department of Navigation and Oceanography et al, 1999). Whether modern or historic, these sources of information have offered the prospect of important new insights into the depth and morphology of the floor of the Arctic Ocean, and have made it possible for marine scientists and cartographers to contemplate the creation of a regional data base that could be applied, among other purposes, to the construction and publication of better maps.

The initiative to create a modern digital data base of Arctic depth observations had its genesis during an informal workshop held in 1996 at the Polar Marine Geosurvey Expedition in St. Petersburg-Lomonosov, Russia (Kazmin and Macnab, 1996). This encounter assembled technical specialists from the five coastal states that border the Arctic Ocean (Canada, Denmark, Norway, Russia, and the United States of America) to discuss scientific and technical issues relating to the preparation of continental shelf claims beyond 200 nautical miles, according to the bathymetric and geological criteria set forth in Article 76 of the Law of the Sea. (United Nations, 1997).

A significant outcome of these deliberations was the recognition that all five Arctic coastal states have valid grounds for developing continental shelf claims beyond their 200 nautical mile limits, and that the possibility exists of overlapping claims between neighbouring states. It was also recognised that neighbouring claims based upon incompatible data sets would only add to the levels of contention in situations where overlaps existed, and that many problems in this respect could be minimised if claims were based upon common data sets. Workshop attendees therefore recommended that coastal states around the Arctic Ocean consider joint action to develop integrated data bases for continental shelf delimitation by pooling their respective information data holdings.

In 1997, a second workshop was organised at the Institute for Geology and Mineral Resources of the Ocean (VNIIOkeangeologia) in St. Petersburg, Russia, with a view to initiating an international collaboration for the development of a modern data base of Arctic bathymetric measurements and for the construction of a new International Bathymetric Chart of the Arctic Ocean, known in abbreviated form as IBCAO (Macnab and Grikurov, 1997). As envisaged, the data base would incorporate in digital form all available bathymetric information north of 64N, for the benefit of mapmakers, researchers, and others requiring a detailed and accurate knowledge of the depth and shape of the Arctic seabed.

Participants at the 1997 Workshop described the contents and status of their Arctic bathymetry data sets, and agreed upon a broad plan for consolidating some or all of these data sets into a single, coherent data base. They also nominated a working group of national representatives who would assume responsibility for getting the work done. In addition to representatives of the five original coastal states, the group included representatives of Germany and Sweden, two countries with strong scientific interests in the Arctic. Within a few months, the group received the formal endorsement of the International Arctic Science Committee (IASC), the Intergovern-mental Oceanographic Commission (IOC), and the International Hydrographic Organisation (IHO), on the grounds that support from these organisations would lend weight and credibility to the project while raising its profile in the appropriate sectors of the international community. The group was also formally designated as the Editorial Board for the International Bathymetric Chart of the Arctic Ocean (EB-IBCAO), and at the same time it was expanded to include Iceland in recognition of that country's status as an Arctic coastal state.

Candidate Data Sets for the Arctic Compilation

One product of the 1997 workshop was an inventory of known data sets that could figure in the construction of the digital data base. In 1998, a third workshop was hosted by the Royal Danish Administration of Navigation and Hydrography in Copenhagen (Macnab and Nielsen, 1999), where this inventory was partitioned geographically to signify data availability within the Exclusive Economic Zones (EEZs) of the six coastal states and the three High Seas zones (Figure 4). It was recognised at the time that varying quantities of digital public domain data existed within all partitions, and that they were obtainable from data centres, or directly from originating institutions.

It was also recognised that proprietary data sets existed in several areas, however a consensus emerged that if these were to figure in the compilation, they would be used only in the EEZs of the owner states.

Proposed Outputs of the Arctic Compilation

An important objective of the project was to develop several kinds of products that would suit a range of user needs. Foremost among these were digital outputs that users could import directly into their own computers for analysis or further manipulation. Ideally, these would consist of: (1) an organised database of original soundings in the form of point, profile, and swath observations, cleared for release into the public domain; (2) a selection of isobaths that had been digitised from published maps and charts; and (3) derivatives such as contours, original and synthetic profiles, and bathymetric models expressed in grid form.

Other kinds of products would consist of conventional contour maps (e.g. a modern re-construction of GEBCO Sheet 5.17) and contemporary shaded relief portrayals. Documentation was also perceived as an all-important product, to provide users with complete information relating to all data sets used in the compilation, and descriptions of the procedures employed in their manipulation.

It was agreed that these products would be distributed in three forms: digital, electronic, and paper. Digital outputs would consist of CD-ROMs or suitable media containing: public domain data bases of original observations and digitised contours; derivative products (e.g. grids); plot files for selected map products; documentation (text and graphics); and possibly a selection of standard software tools to support basic operations such as data conversion, manipulation, and visualisation. Electronic outputs would replicate those available on CD-ROM or other media, but would be archived at one or more sites and accessible through the World Wide Web for selective downloading as required. Paper outputs would consist of maps printed in quantity or on demand, the latter with optional provision for user-specified parameters, e.g. area, scale, contour interval, colour, shading, etc.

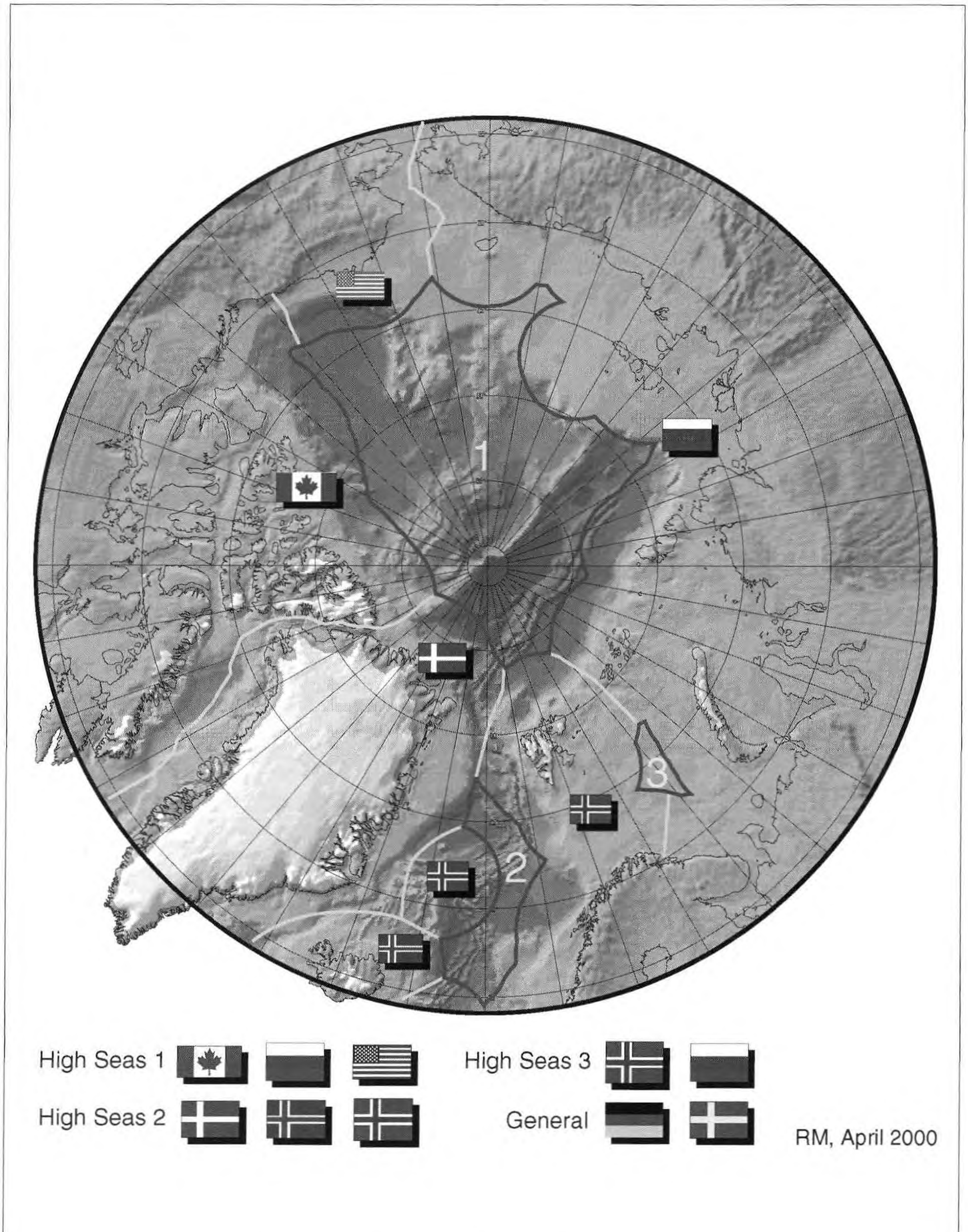


Figure 4: *Approximate limits of the Exclusive Economic Zones (EEZ's) of the Arctic coastal states, illustrating a proposed scheme for partitioning the compilation project. Bilateral limits are shown in green, High Seas limits in pink. Each coastal state assumed responsibility for managing the compilation of public-domain and proprietary bathymetry within its own EEZ. Contiguous states assumed a cooperative responsibility for compiling public-domain data in each of the three High Seas Zones*

Partitioning the Project Geographically

Taking into account data sensitivities, workloads, and resources, it was agreed that project tasks would be partitioned between the EEZs of the six coastal states and three High Seas zones (Figure 4). Institutional responsibilities for each of the six national EEZs were therefore allocated as follows:

- Canada	Geological Survey of Canada; Canadian Hydrographic Service
- Denmark	Royal Danish Administration of Navigation and Hydrography
- Iceland	Icelandic Hydrographic Service
- Norway	Norwegian Petroleum Directorate; Norwegian Hydrographic Service
- Russia	Head Department of Navigation and Oceanography; Research Institute for Geology and Mineral Resources of the World Ocean
- USA	Five Oceans Consulting; National Geophysical Data Center; Tulane University;

Joint responsibilities for the three High Seas zones were proposed on a national, rather than institutional basis:

- Arctic Ocean	Canada Russia USA
- Norwegian-Greenland Sea	Denmark Iceland Norway
- Barents Sea	Norway Russia

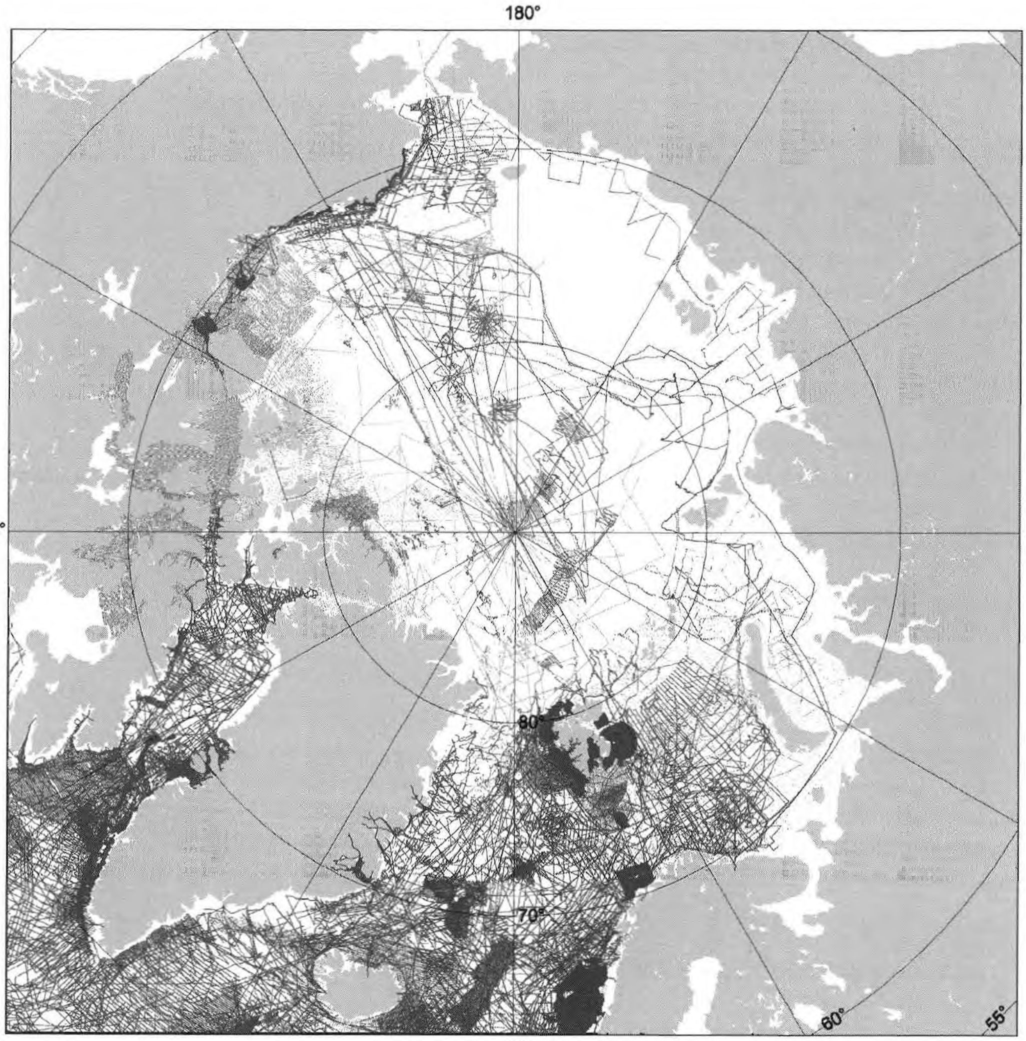
While this approach to partitioning gave prominence to coastal states, it was not exclusionary: the involvement of investigators from institutions in non-coastal states, e.g. Sweden, Germany, and other countries with Arctic interests, was encouraged and very welcome. Also, it was understood that active and constant interaction was essential among all partitions to harmonise operational procedures, to negotiate data exchanges, to discuss problems of mutual interest, to seek advice and consultation, and to maintain the compatibility of outputs.

Bathymetric and Topographic Data

Bathymetric data sets were assembled from a variety of sources, as illustrated in Figures 5 and 6. Modern digital information was obtained during recent icebreaker and submarine cruises. Older digital information consisted of recently-declassified soundings collected between 1957 and 1988 by submarines of the US and UK Navies, and of observations obtained from the public-domain archives of world and national data centres. Non-digital values were extracted from hydrographic charts and compilation maps published by the Russian Federation Navy, by the US Naval Research Laboratory, and by other agencies, portraying depth in the form of point soundings and hand-drawn contours (contour information was used only to supplement original bathymetric measurements). Land relief was derived largely from the USGS GTOPO30 topographic model (US Geological Survey, 1997), with the exception of Greenland where the topographic model developed by KMS, the Danish National Survey and Cadastre, was used (Ekholm, 1996). Coastline definition was provided by the World Vector Shoreline (WVS) in all areas except Greenland and northern Ellesmere Island, where an updated coastline was available from KMS (Ekholm, ibid).

Methods

All original soundings were corrected for sound velocity using Carter's Tables, or CTD profiles where available. Profile and point observations were adjusted where feasible, or flagged as unusable with a suite of



US and British Royal Navy nuclear submarine cruises (1958 - 1988).

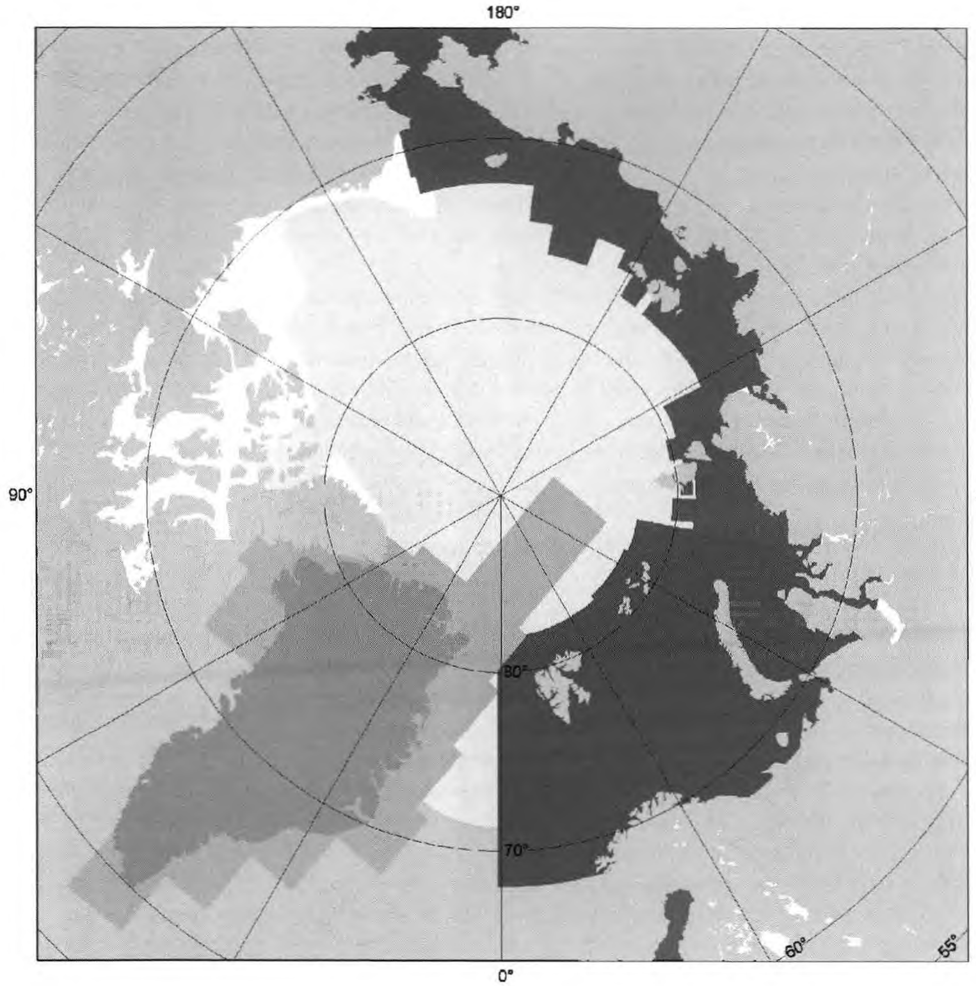
Soundings collected by nuclear submarines during the SCICEX program (1993-1999).

Soundings collected by surface vessels primarely obtained from four archives:

(1) the US National Geophysical Data Center (NGDC)
(2) the US Naval Research Laboratory (NRL)
(3) the Canadian Hydrographic Service (CHS)
(4) the Royal Danish Administration of Navigation and Hydrography (RDANH)

Recent acquisitions provided by agencies that mobilized missions aboard the Swedish icebreaker Oden (1991, 1996) and the German research vessel Polarstern (1990, 1994, 1995, 1997) are also marked in blue.

Figure 5: *Original bathymetric measurements in digital form, used to construct a beta grid for the International Bathymetric Chart of the Arctic Ocean (IBCAO). (From Jakobsson et al, 2000)*



Contours drawn during this present work in order to faciliate the computer gridding.

Charts published by the US Naval Research Laboratory (Perry et al., 1985; Cherkis et al., 1991; Matishov et al., 1995).

Navigational charts published by the Russian Federation's Head Department of Navigation and Oceanography (HDNO).

Contours retrieved from GEBCO Digital Atlas.

Greenland DTM developed by KMS, the Danish Cadaster and Mapping Agency (Ekholm, 1996).

Newly-published Russian map (Head Dep. of Navigation and Oceanography et al., 1999).

GTOPO30 topographic model (U.S. Geological Survey, 1997).

Bathymetry in the Gulf of Bothnia was derived from a digital grid compiled by Seifert and Kayser (1995).

Figure 6: *Coverage of navigational charts and compilation maps, from which point measurements and hand-drawn contours were extracted to supplement the original observations shown in Figure 5. (From Jakobsson et al, 2000)*

tools and statistical routines based upon the Helical-Hyperspatial (HH) scheme for data encoding (Varma et al., 1990). Subsequently, all data (isobaths, land and marine relief grids, point, profile and swath observations, and vector shorelines) were imported into Intergraph's MGE (Modular GIS Environment) with projection parameters set to polar stereographic on the WGS 1984 ellipsoid, true scale at 75N.
Observations along ship tracks were sub-sampled to maintain a minimum of 500-1000 m between every point in each track. Soundings were colour-coded according to depth to facilitate the rapid visual inspection of the statistical cleaning results. Outliers, cross-track errors, and the fit between isobaths and original observations data were checked during this process. Suspicious soundings were removed, and where contours showed major discrepancies with soundings, the contours were adjusted manually to fit the new bathymetric track line data.
The foregoing editing process was performed throughout the entire map area, developing an assemblage of coherent point vales that consisted of sequences of varying depths along ship tracks, and fixed depths along isobaths. Then this amalgam of track and isobath values was used to construct a grid with a cell size of 2.5 x 2.5 km, over a surface under tension and with continuous curvature. The grid, in turn, was used to construct a shaded relief representation of the seabed and adjacent land areas (Figure 7).
Detailed information that describes the map's constituent data sets, as well as the procedures that were employed in their handling and management, is contained in Jakobsson (2000).

Conclusions

Through the assembly and rationalisation of original depth observations complemented by information extracted from published maps, the IBCAO project has created a digital data base of Arctic bathymetry that surpasses all others in terms of coherence and completeness. Whether in map or grid form, the resulting description of the sea floor represents a substantial improvement over existing portrayals (Jakobsson and Macnab, 2000). In addition to supplying important corrections to older bathymetric models, the new products feature increased detail and resolution in both deep and shallow areas; consequently they serve as important new sources of information for interpreting complementary scientific data, and for planning future field operations.
Over and above its technical achievements, the IBCAO project demonstrated success in marshalling the skills and expertise of representatives from eleven research and survey organisations in eight countries, and in focussing the group's efforts on the attainment of its objectives in a timely and harmonious manner. In several ways, the project represents a workable paradigm that could benefit comparable map-making initiatives in other parts of the world ocean.
While the IBCAO project has reached the end of its initial implementation phase, it remains a work in progress: attention is being turned now to the formulation of a long-term strategy for maintaining the data base, and for producing updated versions of the grid and map as new information becomes available. An essential element of this strategy will be to identify an institutional base for the project, where it can benefit from stable organisational support, and from secure allocations of resources for ensuring that upgrades and maintenance are performed on a regular basis.

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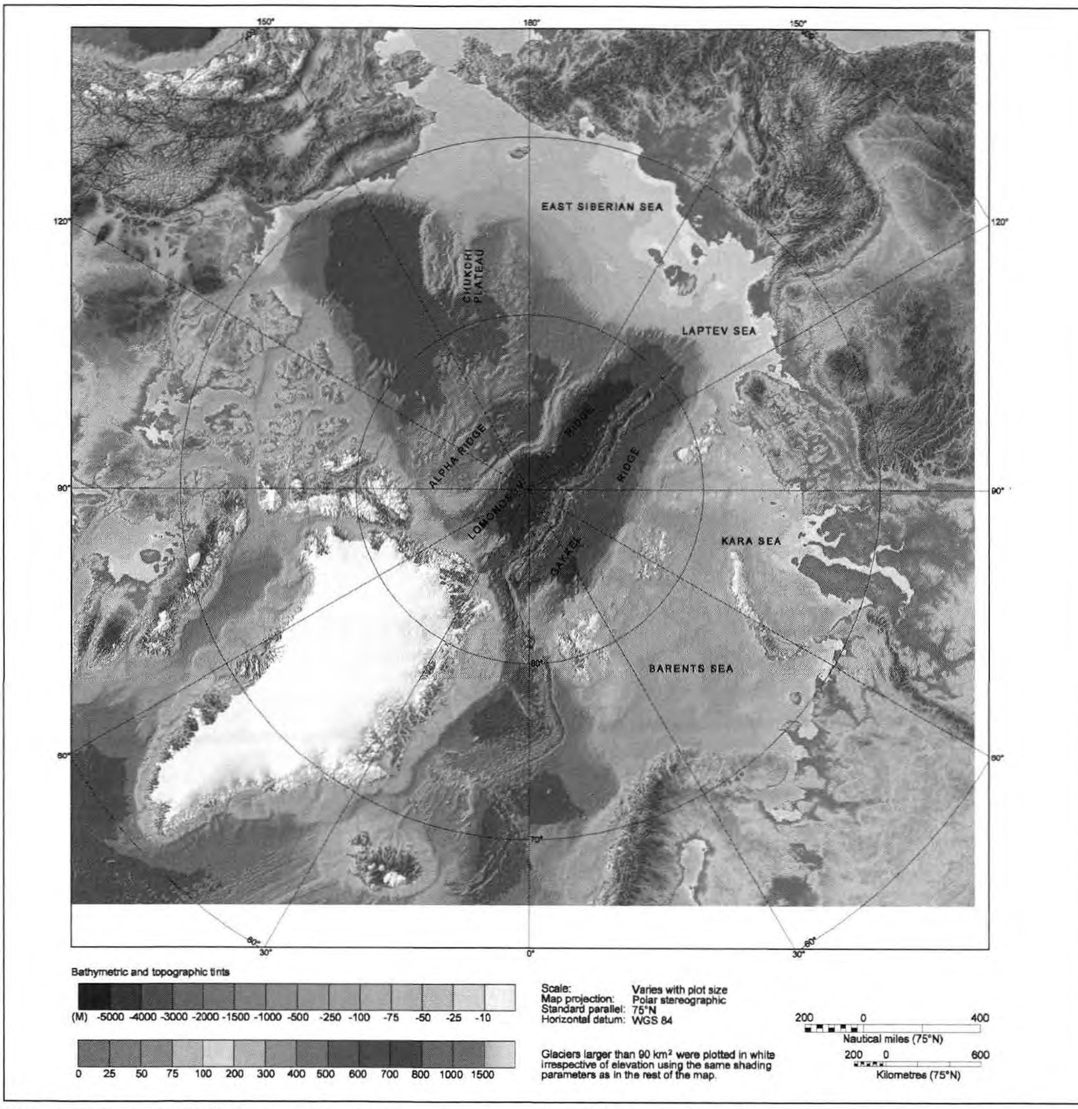

Figure 7: *A shaded relief map of the Arctic region, constructed from a uniform Cartesian grid centred upon the North Pole, with cell size 2.5 X 2.5 km. (From Jakobsson et al, 2000)*

Canada) played key roles in the preparation of grids and maps related to the International Bathymetric Chart of the Arctic Ocean. Many other colleagues and associates at the national and international levels contributed by providing information or by expressing opinions that helped clarify some of the more complex aspects of bathymetric compilations. These individuals are too numerous to enumerate here, and while their views are reflected throughout this dissertation, errors of interpretation are the authors' alone.

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