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IMPROVED GLOBAL BATHYMETRY
Final Report of SCOR Working Group 107

UNESCO 2001

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IMPROVED GLOBAL BATHYMETRY
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SCOR Working Group 107

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Meetings

1. Southampton Oceanography Centre, Southampton, UK, 11-13 November 1996
2. Johns Hopkins University, Baltimore, USA, October 27-28, 1997

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Acknowledgements

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1. ABSTRACT

Accurate and detailed knowledge of global bathymetry is a prerequisite for progress in the scientific understanding of the different components of the earth's global systems, and for intelligent management of global resources. Data on the shape of the sea bed are necessary to select sites for communications cables and fisheries, to make inferences about the energy and mineral resource potential of ocean floor structures, to guide computer simulations of the behaviour of the oceans and of climate, and to forecast tsunamis. Improved knowledge of the shape of the seabed is one of the factors required for success of the planetary scale global observing systems (GOOS, the Global Ocean Observing System, and GCOS, the Global Climate Observing System) whose operations will help a larger human population to manage sustainably on an increasingly crowded Earth.

SCOR Working Group 107 on Improved Global Bathymetry was charged with: (i) establishing the scientific needs for improved knowledge of ocean depths (i.e., what scientific problems need what measurements?); (ii) specifying the accuracy and resolution requirements needed in different geographical and research areas (e.g. identifying limitations and gaps to be filled); (iii) recommending actions and priorities (such as what parts of the oceans should be tackled first).

The group identified a range of topics for which improvements in bathymetry were considered important, and quantified the scientific requirements in terms of horizontal and vertical resolution for a number of them. In the open ocean seawards of the continental shelf and slope there is a progressive increase in the requirement for horizontal (H) and vertical (V) resolutions from 5-10 km (H) and 10-50 m (V) over the open ocean, to 1-5 km (H) and 20 m (V) over open ocean sills, to 250 m (H) and 10 m (V) for abyssal hills, and finally to 100 m (H) and a few metres (V) in rift valleys. On the continental slope there is a requirement for 1 km (H), decreasing to 500 m (H) over canyons and ridges. On the continental shelf this increases further to 100-500 m (H) in water deeper than 10 m, to 50 m (H) in water less than 2.5 m deep.

The group identified 6 priority actions for the near future, and made 34 recommendations as to how those priorities could be met and other issues addressed. Several recommendations relate to changes that are required in the policies of national funding agencies so as to facilitate the acquisition of bathymetric data. Bearing in mind the constraints on funding, the working group decided that gathering additional data by ships equipped with swath bathymetry and side-scan sonar systems, though crucially important especially in data gaps, would not be the first priority. Much can be done already by working more effectively and efficiently with what has already been collected, so the initial focus should be on getting more data into the system.

We recommend that SCOR arrange the appropriate follow-up action to stimulate implementation. This might require the formation of an appropriate advisory panel, perhaps including some members of SCOR WG 107 for the sake of continuity.

Priority 1: **Turn equipment on to generate more data (all too often expensive echo-sounding equipment is not turned on, thus wasting the potential to acquire the data – a penny wise/pound foolish approach to scientific management).**

Priority 2: **Digitize the data that are presently available, and send new data automatically and in digital form to data centres.**

Priority 3: **Begin serious investment in data rescue (data archaeology).**

Priority 4: **Encourage cruises to fill the substantial gaps that exist especially in the South Pacific, South Atlantic, Indian, Southern and Arctic Oceans, in the Arabian Sea, in the back-arc basins between China and Kamchatka, and in places in the North Atlantic and the North Pacific (e.g. between Hawaii and North America).**

Priority 5: **Use new technology (e.g. drifting floats and autonomous marine vehicles) to gather new data from large data gaps.**

Priority 6: **Investigate the possibility of acquiring data from commercial ships by voluntary means.**

2. INTRODUCTION *(by C.P. Summerhayes[1] and W.H.F. Smith[2])*

The Earth works as an integrated system of interacting bio-geo-physico-chemical processes, all of which are influenced by land topography and ocean bathymetry. On land, tectonics, erosion, and sedimentation shape the land surface, and weather and climate are controlled by topography on scales ranging from large continental landmasses to small mountain valleys. In the oceans, currents and tides are controlled by the overall shapes of the ocean basins and also by the ridges, mountains and rough places on the sea bed, which steer the flow of water carrying heat, salt, nutrients, and pollutants, and which create sites where energy is put to work mixing these components of sea water. Sea life is abundant where seafloor topography causes nutrient-rich waters to "up well" from depth toward the surface. Erosion and sedimentation rates are much lower in the ocean than on land, and so detailed ocean floor topography reveals the pattern and geological history of mantle convection, tectonic plate boundaries, the cooling and subsidence of the ocean lithosphere, the distribution of ridges, plateaux and volcanoes that shape the ocean floor, and the sites which might hold energy, biological and mineral resources.

Accurate and detailed knowledge of global bathymetry is a prerequisite for progress in the scientific understanding of these global systems, and intelligent policies for management of global resources. Data on the shape of the sea bed are necessary in a great variety of applications: they are used to select sites for communications cables and fisheries, to make inferences about the geologic history and energy and mineral resource potential of ocean floor structures, and to guide computer simulations of the behaviour of the oceans. These simulations are important in predictions of the hazards faced by coastal communities if tsunamis should approach them, and in predictions of the future patterns of climate change on time scales of months to decades. Improved knowledge of the shape of the seabed is one of the factors required for success of the planetary scale global observing systems (GOOS, the Global Ocean Observing System, and GCOS, the Global Climate Observing System) whose operations will help a larger human population to manage sustainably on an increasingly crowded Earth.

SCOR Working Group 107 on Improved Global Bathymetry was charged with: (i) establishing the scientific needs for improved knowledge of ocean depths (i.e., what scientific problems need what measurements?); (ii) specifying the accuracy and resolution requirements needed in different geographical and research areas (e.g. identifying limitations and gaps to be filled); (iii) recommending actions and priorities (such as what parts of the oceans should be tackled first).

Two meetings were held, one in Southampton Oceanography Centre, Southampton, UK, 11-13 November 1996, and one at Johns Hopkins University, Baltimore, USA, October 27-28, 1997. At each meeting the Working Group reviewed progress against the terms of reference and against key questions, including: what is the state of the art of ocean bathymetry? which regions are in need of further study? at what spatial and vertical resolution? what targets can be identified from model runs? what should the priorities be? who are the potential users? what more (if anything) is required.

For each meeting background papers were requested from the members of the Working Group. These papers are reproduced here for information and to provide substance to the discussion, conclusions and recommendations. We are most grateful to all those who took the time to prepare background material and to attend the meetings to give us their views.

Inevitably in a project of this kind, of limited duration, we have not been able to cover everything. For instance we have not reviewed the problems of marine geomorphology, and topics like the homogeneity of the mid-ocean ridge. However, in the two meetings of the Working Group, and in the accompanying background papers, we believe we have amassed the evidence for a strong and compelling case in favour of improving the global bathymetric database.

Readers are asked to bear in mind that most of the documents presented here were prepared originally in 1996 and 1997, and that they therefore tend to reflect the position at that time. However, most authors were subsequently able to provide updates reflecting recent developments that took place during

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the gestation of this report. In addition, the international bathymetry community has not stood still while we put this report together, and so some of the recommendations made here are already being or have been attended to. Nevertheless, much still remains to be done and the overall priorities and the bulk of the recommendations remained valid at the time of finalisation of the report (autumn 2001).

A. SUBMITTED PAPERS

3. THE GENERAL BATHYMETRIC PERSPECTIVE

3.1 **THE GENERAL BATHYMETRIC CHART OF THE OCEANS (GEBCO)** (*by P. M. Hunter*)*

3.1.1 Preamble

The General Bathymetric Chart of the Oceans (GEBCO) has been in existence as an idea since 1899 and as a series of published maps since 1903. At present, it functions under the auspices of the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC). The GEBCO community involves people who work in hydrographic offices, scientific establishments and other agencies located around the world. They co-operate to provide the definitive global bathymetry by collecting depth data, compiling bathymetric contour maps and providing advice and expertise. Much of its work is guided and carried out through annual meetings of its various committees and sub-committees.

3.1.2 The GEBCO 5th Edition

The GEBCO that most people are familiar with are probably the printed maps of the 5th edition. These were published by the Canadian Hydrographic Service between 1975 and 1982, apart from a major revision of sheet 5.12 covering the South Atlantic Ocean that was published in 1994. It comprises sixteen sheets at a scale of 1:10,000,000 at the Equator on the Mercator projection and two polar sheets at a scale of 1:10,000,000 on the stereographic projection, the contours are shown in corrected metres.

The GEBCO 5th edition was based on the following sources:

(i) analogue data plotted onto the 1:1 Million scale series of Collected Soundings Sheets, maintained for GEBCO mapping purposes by volunteering Hydrographic Offices. Compiled over a period of thirty to forty years, this was a major source.
(ii) digital data archived in the National Geophysical Data Centre's (NGDC) Geophysical Data System (GEODAS).
(iii) soundings data which were never entered into either of the two earlier datasets.
(iv) bathymetric contours from special surveys and published maps.

These data varied considerably in accuracy, both in depth and position, depending on the sounding apparatus fitted in, and the navigational methods employed by, the numerous ships that made the measurements. During the compilations of the earlier editions of the GEBCO, it was possible for a depth based on an early model of echo-sounder, positioned by a star observation to have as much influence on the contouring process as one measured by modern means.

Added to these data was the invaluable wealth of experience of some twenty-five scientific co-ordinators who were responsible for compiling the bathymetric contours. Coming from both hydrographic and scientific backgrounds, they contributed expert understanding of the data that went a long way towards eliminating many of the errors inherent in the earlier editions.

3.1.3 The GEBCO Digital Atlas (GDA)

The latest bathymetric product, known as the GEBCO Digital Atlas, was first published in 1994. It is based on contours derived from scanned images of the 1:10,000,000 scale sheets of the GEBCO 5th Edition which were then vectorised. Published on CD-ROM as digital vector contour strings, in conjunction with the source track lines and survey boxes, the World Vector Shoreline (WVS) and the IHO *Gazetteer of Names of Undersea Features* and display software, it was intended as a viewable map and a source for bathymetry to be downloaded for use in other applications. Its first edition contains replacement bathymetry for the Mediterranean Sea (1:1,000,000) and the South Atlantic Ocean (1:6,000,000). (The numbers shown inside the brackets indicate the scale at which the map was digitized).

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The second edition, GDA97, contains updates for the Indian Ocean south of 31° South (1:2,000,000), the Weddell Sea (1:1,000,000) and the Northeast Atlantic Ocean between 47° and 64° North (1:1,000,000).

Future editions will have new contours for the Indian, Arctic, Southern and Northeast Atlantic Oceans. A gridded version will be published in conjunction with the contours.

Some areas of the world, such as the South-east Pacific Ocean, have very little data. There, some of the lines of echo-soundings are separated by more than 500 kilometres; it is to the credit of the sheet co-ordinators of the GEBCO maps for this region that such good bathymetric maps exist.

3.1.4 Updating the GEBCO Digital Atlas

The present policy is to update the contours of the GDA with the best possible available bathymetry. The problem with this policy is that invariably bathymetry is compiled with a purpose other than GEBCO in mind. GEBCO is evolving a set of flexible rules to be applied before it includes any new bathymetry into the GDA. A glance at the following list of recent maps offered as being suitable for updating the GDA reveals a variety of contour specifications.

Bathymetry of the Norwegian, Kara and Barents Seas. Contoured in uncorrected metres at a contour interval of 200 metres. The contours are in digital form.

Bathymetry of the Indian Ocean. Contoured in corrected metres at a contour interval of 500 metres. The contours are in analogue form.

Bathymetry of the Bay of Biscay. Contoured in corrected metres at a contour interval of 200 metres. The contours are in analogue form.

Bathymetry of the Weddell Sea. Contoured in corrected metres at a contour interval of 100 metres. The contours are in digital form. Contours are shown at 50-metre intervals for depths shallower than 700 metres.

Bathymetry of the Canary and Madeira Abyssal Plains. Contoured in corrected metres at a contour interval of 100 metres. The contours are in digital form. Contours are shown at the 10-metre intervals on the abyssal plain.

After its own internal reviewing procedures to check that the bathymetry is suitable, GEBCO is prepared to digitize analogue contours and in some cases to add intermediate contours that are missing but which are desirable in the GDA. Unfortunately, this immediately slows the updating process, as resources to carry out these tasks are limited. Thus no matter how many new maps are identified, unless they are in digital form they cannot be quickly assimilated into the GDA. Even digitized maps can be rejected on the grounds of sub-standard digitizing, making it necessary for GEBCO to either redo the work or to hope that the originators will. The problem of how to handle a map created in uncorrected metres is a little harder to deal with. In some areas the depth correction may be negligible, so that at the small scales at which GEBCO usually works the contours would not need repositioning. But often this is not the case; some maps may need redrawing in corrected metres, a time consuming job. It may be that gridding and re-contouring from the resultant grid may provide the solution. Unfortunately, this may lead to a loss of some of the fine detail such as deep-sea channels.

At present GEBCO requires contours at intervals of 500 metres. Although this was not laid down in its original specifications in 1975, contours at these intervals are shown on the Fifth edition and thus are included in the GDA. In particular, the 2500-metre contour is an important base line to the UNCLOS as one of the methods for defining a country's EEZ.

The digital GDA has the ability to represent every contour that is digitized and saved in it, as it does not have the aesthetic presentation restrictions of the printed map. But it is unfortunately derived from maps specified by other organizations. The lack of intermediate contours in the areas where gradients are small make the production of other products such as grids difficult. A policy to include additional contours on published maps to represent these flatter areas would be a benefit.

3.1.5 IOC Regional Bathymetric Mapping

Although not part of the GEBCO project, the IOC's Regional Bathymetric Mapping projects are of major importance to it and it takes a great interest in their progress.

The IOC, with the aid of the IHO, sponsors six International Bathymetric Chart series. They are located in the Mediterranean Sea (IBCM), the Caribbean Sea and Gulf of Mexico (IBCCA), the Central Eastern Atlantic Ocean (IBCEA), the Western Indian Ocean (IBCWIO), the West Pacific Ocean (IBCWP), and the Arctic Ocean (IBCAO). Each series contains a number of 1:1,000,000 scale maps on the Mercator projection. The largest (IBCWP) comprises 110 map sheets, stretching from New Zealand to the Russian coast. Two chart series have been completed, the IBCM as printed maps and digitized contours, and the IBCAO as a gridded dataset. Many of the other chart series have published maps. A seventh chart series for the South-east Pacific Ocean is currently under consideration.

The projects include digitizing of the contours, and, in the case of the IBCAO, production of a gridded dataset; the digital files will in turn be used in future updates of the GDA. The IBCM is already working towards its second edition.

The compilation process involves the countries of the region. This involvement often unearths and enables many new datasets to be used for bathymetric contours and in many cases introduces the techniques of bathymetric mapping to the countries. New data are passed to the recently formed IHO Data Centre for Digital Bathymetry (DCDB), located at the National Geophysical Data Centre in Boulder, USA. The DCDB works with the co-operation of the IHO's and has effectively replaced the old GEBCO Collected Soundings sheets.

3.1.6 A gridded GEBCO

A gridded version of the GEBCO is under construction and will be published with the next edition of the GDA. A working group has been discussing gridding methods and the problems that working from a dataset such as the GDA contours, poses. The area chosen as a prototype was the recently updated South Atlantic Ocean that exhibits a range of relief types, such as abyssal plains, mid-ocean ridges and continental margins. It should be noted that it is virtually impossible to exactly reproduce the GDA contours from the grid.

The grid seeks to provide a suitable replacement for the 5-minute by 5-minute DBDB-5 grid, created by the US Navy during the early 1980s and used as the marine component for the ETOPO-5 product, with a 1.0-minute by 1.0-minute grid. The GEBCO grid also contains topographic information derived from the GLOBE dataset.

3.1.7 Problems that affect GEBCO's ability to provide “the definitive global bathymetry”

If GEBCO is to continue to provide the definitive global bathymetry a number of problems need to be addressed.

First, new contour compilations must be carried out that GEBCO can obtain permission to use. After a published bathymetric map has accomplished its purpose it could be released to GEBCO. If the map is still a profitable seller it is unlikely that incorporating it in the GEBCO would harm its sales, as all GEBCO needs are the bathymetric contours. The map itself would remain a viable product.

Second, there are not many people interested in contouring large areas of the seafloor. Twenty years ago, at the start of the 5th edition, there were a number of people with the expertise, necessary support and will to compile and contour new bathymetric maps - particularly at regional scales. Now these bathymetrists are few and far between and support for their activities is dwindling.

It is not enough to assume that to produce a bathymetric map all one needs to do is to collect all the soundings together and contour them in a 'join the dots' fashion. That would be fine if all data were perfectly positioned, measured and recorded without errors, but unfortunately that is not the case. The process is more involved. In many cases other data must be referred to such as, echo-sounder profiles, multibeam contours, sonar images or existing maps, in order to locate the main physiographic features before any contour lines can be drawn. In the early stages of bathymetric mapping, shape has a more important function than exact depth. Some features such as canyons and channels have more or less inviolate properties like rivers on land, so depth contours must be drawn to show these. It is this sort of knowledge that inexperienced cartographers or a computer are unable to call on.

Third, the scales of bathymetric maps have changed over the years. Once maps were compiled for whole oceans, now the interest is in looking at very large-scale features. Often the surveys are carried out by multibeam echo-sounder systems resulting in maps at scales greater than 1:50,000 with contours at intervals of ten or twenty metres. The overall effect is of a number of 'postage stamps' scattered across the oceans. It is fortunate for GEBCO that work is carried out such as the Bathymetry of the Bay of Biscay that combines some these 'postage stamps' into a regional synthesis.

Fourth, new contours need source data, mainly individual depth soundings or multi-beam contours. Not all data are available to bathymetrists for a variety of reasons. The principal collectors of data are the military, hydrographic offices, academic and other government institutions and commercial firms. The military data are often classified and very seldom are released for external bathymetric mapping. Hydrographic data, particularly in depths greater than 200 metres generally are made available routinely. Academic data are often unavailable because a scientist regards them as his own property or even, in some cases, they are lost because they were not archived properly at an early stage. Proprietary data, such as those collected by an oil company are sensitive because they would divulge to their competitors that there was an interest in the area. Data are often perceived as having intrinsic value, thus many are now unwilling to “give them away”.

To counteract the last problem in the academic sphere, the United Kingdom's Natural Environment Research Council (NERC) has instigated a policy for archiving single-beam bathymetric data collected during its research cruise operations. After each cruise, the data are edited and submitted to National Geophysical Data Centre (NGDC) in Boulder, USA. This process occurs automatically without the intervention of the principal scientist. Since 1992 the total number of bathymetric surveys provided by the United Kingdom for inclusion on the GEODAS/TRKDAS CD-ROM has risen from 41 to nearly 300. The author estimates that there are still more than 200 digital surveys originating from the UK academic research community to add to that total and a similar number of analogue ones too.

Fifth, the general public's perception of the quality of available bathymetry is that perfect bathymetric maps exist, on a global basis, at resolutions to be found in shallow water areas. They assume that this sort of detail is readily available to them to support their scientific projects. Funding agencies of marine science topics should be encouraged to ask that any proposals for scientific experiments should include provisions for site surveys and bathymetric maps and that the bathymetry should be made available to GEBCO and the data sent to the NGDC.

Sixth, even when new data becomes available they do not always make a big difference to the bathymetry. Close inspection of recent data coverage by NGDC's GEODAS reveals that many new surveys cover “old ground”. In some cases this is because a more sophisticated surveying system has been used. For instance the use of multi-beam surveys on the mid-ocean ridges are evident in the later compilations. But in other cases, such as in the case of the tracks to and from a study area, data collection is repeated in the same places and the gaps remain. A policy to review the locations of existing data, and to plan new surveys and passage tracks to and from survey areas to occupy unsurveyed seafloor, should be encouraged. Use of the Internet to publish existing data coverage, at sites such as NGDC, could facilitate this.

References

For further information about GEBCO please refer to the following publication:

IOC, IHO, and BODC, 1994, *“Supporting Volume to the GEBCO Digital Atlas”*, published on behalf of the Intergovernmental Oceanographic Commission (of UNESCO) and the International Hydrographic Organization as part of the General Bathymetric Chart of the Oceans (GEBCO); British Oceanographic Data Centre, Birkenhead. This volume accompanies a CD-ROM. 78 pages and 4 Annexes.

3.2 INTERNATIONAL HYDROGRAPHIC ORGANIZATION (IHO) ACTIVITIES RELATED TO BATHYMETRY (*by C. Andreasen**)

3.2.1 Introduction

The International Hydrographic Organization is an intergovernmental organization presently consisting of 62 Member Governments (11 additional nations are pending membership). These Member States are normally represented within IHO by their national Hydrographic Offices, about 2/3 of which are naval organizations, i.e., Navy or Coast Guard. The main purposes of IHO are to co-ordinate the activities of the Hydrographic Offices; seek uniformity in nautical charts and documents; enhance technology transfer and technical co-operation/assistance; and foster the development of hydrography, descriptive oceanography and the exchange of hydrographic information in support of maritime safety and protection of the environment. The resulting data and products are also supportive of marine science and industry.

The IHO has major requirements for hydrographic/bathymetric data to support the provision of nautical charting products, and the IHO Member States operate over 300 ships for hydrographic surveying and oceanography and produce over 26,000 maps and charts. In coastal areas a few Member States are now conducting airborne laser bathymetry and multi-beam systems are in common use. With regard to the scientific requirements for bathymetry, the IHO has strong interest in knowing the scientific requirements for bathymetric data so the national Hydrographic Offices of IHO Member States may respond to scientific needs to the degree possible when surveys are conducted and also to include the scientific requirements as an element of the overall budgetary justifications for survey operations. Because IHO's role generally is to respond to hydrographic and bathymetric requirements rather than providing a basis for such requirements we have not wanted to be included in the core Working Group and this submission is to inform the Working Group of the IHO's overall activities.

3.2.2 Background

International co-operation in the field of hydrography and the formation of the IHO began with a series of conferences beginning just before the turn of the century and continuing until just after World War I with the then International Hydrographic Bureau (IHB) being formed in 1921. H.S.H. Prince Albert I of Monaco, who was a physical oceanographer of note, was involved in these meetings and offered to host the Bureau in Monaco. The General Bathymetric Chart of the Ocean (GEBCO) had been compiled at the Oceanographic Musée in Monaco prior to the formation of the IHB and, with its formation, this activity was transferred to the IHB. The task of compiling the bathymetry into the GEBCO series eventually became too great for the small staff of the Bureau and, in 1962, the Member States agreed to a system of Volunteering Hydrographic Offices which would collect the track-line information and compile these data on a series of plotting sheets (1:1 million scale for compilation at 1:10 million) providing coverage for the entire world. With the establishment of this system, the IHO/IHB was designated by ICSU as the World Data Centre for Bathymetry.

Because global bathymetric data are sparse in many areas, it was found necessary for compilers to have a knowledge of marine geophysics to properly guide the bathymetric contouring and provide a quality product. As only a few of the Hydrographic Offices had such a capability, the Intergovernmental Oceanographic Commission (IOC) and IHO developed a joint programme to support GEBCO. It was through this effort that the 5th Edition of GEBCO was completed, which has since been digitized and is available on CD-ROM as the GEBCO Digital Atlas (GDA). The development of the GDA now makes it possible for easier updating and a second edition of the GDA on CD-ROM was issued in late 1996.

Annually, the IHO issues IHO Publication B-4, "*Information Concerning Recent Bathymetric Data*" which is an annual listing to report the existence of newly available bathymetry, analogue or digital, intended to foster exchange of bathymetric information between nations. In 1990, the IHO Member States agreed to the establishment of an IHO Data Centre for Digital Bathymetry (IHO DCDB) to be co-located with the World Data Centre A for Marine Geology and Geophysics at the National Oceanic and Atmospheric Administration's National Geophysical Data Centre in Boulder, Colorado and to encourage digital data to be

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submitted to the IHO DCDB. Since the establishment of the IHO DCDB, IHO Publication B-4 has been modified to include the usual sections on analogue and digital data plus a third section to indicate the coverage of data in the IHO DCDB, with an indication of data added during the past year, for each of the GEBCO sheet areas. In 1992, at its I.H. Conference of IHO Member States, it was agreed to abandon the concept of maintaining plotting sheets by 1996. To ensure that the data on plotting sheets are not lost, the IHO has polled its Member States to determine the status of the sheets and their intentions for maintaining the data. In general, Member States are digitizing these data.

The IHO DCDB has been growing in size. In 1996, the GEODAS CD-ROM issued from NOAA's National Geophysical Data Centre included over 13 million nautical miles of bathymetry from nearly 4,000 cruises with 31 million records. The GEODAS database has been divided into two distinct applications, GEODAS/TRKDAS for marine geophysical track-line data and GEODAS/HYDAS for hydrographic (bathymetric) survey data. As the IHO DCDB has not been in existence for very long, there is much yet to be done with regard to getting data from Member States into the database.

3.2.3 Current IHO Activities Related To Bathymetry

A number of the basic technical documents of the IHO are under revision at the present time. The work of revision is co-ordinated through the IHB in Monaco, but the actual technical work results from more than 40 Working Groups, Committees and Commissions for which the Member States provide representatives.

IHO periodically assesses the status of worldwide hydrography, which is published in IHO Publications S-55 (all areas except Antarctica) and S-59 (Antarctica). Efforts are in progress for updating S-55 at the present time and a new version is planned for early 1997 The publication is used to illustrate deficiencies throughout the world, help in the justifications for assignment of hydrographic resources and to guide technical assistance efforts.

The IHO is in the process of revising IHO Publication S-44 "*Standards for Hydrographic Surveys*" which govern the standards of depth measurement worldwide. Changes include incorporation of multi-beam and laser hydrographic methods. Depth accuracy will now be at 95% rms and include tides rather than 90% rms without the inclusion of tides. Inclusion of geostatistical software for use in creating a bathymetric model has been considered but Member States feel the development of this software (Hydrostat written by the Canadian Hydrographic Service) is not yet developed well enough for inclusion as a required part of the standard. The software will probably be included for developmental purposes under the intent of application at some future date. The S-44 Standard is a minimum standard to be met in conducting hydrographic surveys and must be able to stand up in court since Hydrographic Offices are held liable for their products.

IHO adopted the WGS-84 datum for horizontal positioning many years ago and Hydrographic Offices are transitioning their chart products to this datum, but IHO also is considering the adoption of the WGS-84 (G730) ellipsoid as a global vertical reference surface. This would provide a common link between the many vertical datums in use. For hydrographic surveys it would be used in conjunction with 3D GPS and can eliminate problems with the meteorological effect on tides and the settlement and squat effect on the hydrographic vessel. GPS measurements will have to be obtained for all tidal benchmarks and it may be necessary for VLBI, precise gravity, etc. to be incorporated into the system. IHO is also considering a common worldwide tidal datum for charts, currently Member States have expressed favour for Lowest Astronomic Tide.

IHO in co-operation with IOC is in the process of developing a Part 4 for its GEBCO Guidelines, which will outline the recommended data to be recorded when operating multi-beam systems and the number of significant figures to be recorded. This is not a standard format for the recording of multi-beam data, which is currently system dependent and controversial amongst users, particularly scientists who want to do special processing of data.

Electronic Chart Display and Information Systems (ECDIS), wherein electronic navigational charts from Hydrographic Offices would be used in lieu of paper charts is causing Hydrographic Offices to digitize their existing paper charts. About a decade ago, IHO began an international effort to develop an international exchange standard such that digital data could readily be transferred from one Hydrographic Office to another. This led to the development of a standard for ECDIS such that the basic data used in electronic chart systems throughout the world would be in a standard format. This standard has now been agreed within the International Maritime Organization as a change to SOLAS (Convention on Safety of Life at Sea), and it is now possible for an ECDIS to be used in place of a paper chart for navigation. (Several steps must yet be accomplished with regard to data collection, development of standards for hardware and updating before this becomes reality). Some Hydrographic Offices are issuing raster chart products, which normally is a preliminary step in the production of ECDIS vector chart data, i.e., chart separates are raster scanned adjusted for datum corrections and then vectorized, which can be partially done by automatic means. While raster data sets are useful for background purposes and comparisons, the vector data sets being created will have the added utility of allowing one to select features, e.g., bathymetric contours or shoreline. Over the next decade, it can be expected that global coverage of raster and vector charts will become available.

IHO issues a publication S-60 "*User's Handbook on Datum Transformations involving WGS-84*" which provides conversion information relating to the worldwide horizontal datums used in nautical charting.

IHO publishes a Hydrographic Dictionary and the standards for chart symbology both for paper charts and ECDIS.

IHO in co-operation with IAG (International Association of Geodesy) produces publication S-51 "*Manual on Technical Aspects of the United Nations Convention on Law of the Sea*" and a Geodetic Commentary to it. IHO in co-operation with IOC is also in the process of writing a book on what must be done to delimit a nation's claims under Article 76.

In addition to the IHO DCBD referred to above the IHO also maintains an international database of tidal constituents, which is available for use by scientists but has a rather lengthy application procedure due to concerns for controlling the tidal information made available for navigation.

The IHO is also to revise its publication S-23 "*Limits of Oceans and Seas*" but has not done so in recent years due to workload, political complications and the difficulty of gaining agreement of the Member States.

Finally, in co-operation with IOC, IHO maintains the GEBCO series of bathymetric charts and an international gazetteer of geographical names of undersea features, which is not addressed here in that others associated with the project are participating in the meeting.

3.2.4 Future Considerations

Scientists will have requirements for bathymetric data and information at larger scales and higher resolution, and it will be essential that these data be in digital form and as freely available as possible. While the advancement of technology, in providing more accurate bathymetric data of higher and higher resolution, will make better science possible and will no doubt promote increasing scientific requirements for bathymetry, not all the issues that will impact a scientist's access to improved bathymetry are technical. As scientific demands for larger scale information evolve, there will be questions related to copyright; whether the databases should be centralized or distributed; and political issues concerning data in areas of national sovereignty. How to foster better access to data, classified and non-classified; how to ensure data quality or at least identify the quality of available data, etc. also needs to be addressed.

Nautical charts are copyrighted products and Hydrographic Offices are held liable for their marine safety related products. The IHO is currently in the process of evolving from a long history of allowing any Hydrographic Office to copy the nautical information products of another Hydrographic Office and is in the process of working toward a system of bi-lateral agreements with reimbursement in cash or in kind.

Also, the advent of digital cartographic methods has led to commercial firms copying Hydrographic Office products, sometimes without the payment of royalties. In other cases, the emphasis on privatization is causing Hydrographic Offices to develop private sector partnerships. At the present time there are lawsuits between the H.O.'s and private firms, which make access to the data used in chart compilation a somewhat sensitive issue. The legal position that a "fact" can be copied without infringement of copyright can be problematical for scientific access to bathymetry in coastal areas because H.O.'s will be reluctant to release original survey data that could injure their position in court.

IHO has developed a model agreement for use between Hydrographic Offices and commercial firms, which is under review by the Member States at the present time and will be considered for adoption at the next International Hydrographic Conference of Member States in April 1997. Hopefully, the future will bring accommodation between the Hydrographic Offices worldwide and commercial firms involved in the manufacture of electronic charts and access to original data may become less sensitive.

As we in Government and academia invest substantial amounts of money in the collection of bathymetric data, I would suggest that consideration should be given to our getting better organized and consider the possibility of developing a more formal relationship between Hydrographic Offices and academic institutions that collect bathymetry throughout the world. Scientific institutions often have needed to restrict access to data for a time period when research conclusions are developed and results are published. After this has been done the bathymetric data may become available to Hydrographic Offices but I suspect that sometimes it does not. Perhaps a short formal agreement should be developed between academic institutions and their national Hydrographic Offices wherein, when bathymetry is to be acquired, notice is given to the Hydrographic Office and some level of meta data are exchanged. National Hydrographic Offices might well be interested in a better system of access to bathymetric information and may be willing to act as a regional depository or centralized index for bathymetric data. Agreements could specify the terms for release of data. In return, the agreement could specify use of Hydrographic Office data for scientific purposes and restrict use for commercial purposes such that institutions might have better access to Hydrographic Office data.

Hydrographic Offices currently depend on ship commands to report information about bathymetric hazards encountered, but it may be that the detailed bathymetry collected by scientists would reveal additional hazards information that could be important. If data sets were submitted to Hydrographic Offices, they could assess them for hazards and divulge only the hazard information while holding the basic data until it is cleared for unrestricted use. With the advent of modern communications and file transfer, it should be possible to enhance co-operation with minimum effort and expense.

Finally, one of the focuses of the IHO's technical assistance efforts is in the South China Sea. We contracted a study of shipping traffic patterns in the area and have been assessing the status of hydrographic surveying in the region. As a part of this effort, the U.K. Hydrographic Office agreed to fund an effort to approach commercial acquirers of geophysical data, including bathymetric data, related to oil and gas exploration and development. As one might expect, this is a difficult task due to the security imposed over the commercial nature of such data. However, in this age of digital data it is easier to separate the basic bathymetric data from other data of more importance from a commercial aspect and we are hopeful that access to such bathymetric data, at least for the future may improve.

In developing the scientific requirements for bathymetry it will be necessary to address the needs for original survey data and various types of gridded bathymetry. What are the needs for nested grids, are grids required in the deep waters to define features that normally would only be charted at small scales, should the bathymetry be integrated to ECDIS for use with the ship's primary navigation system in offshore areas where navigation safety is not an issue, and should there be a standard method for computation of the bathymetric grid?

IHO looks forward to being apprised of the conclusions of the Working Group on this important task. It is important that we work co-operatively to build a quality bathymetric database to meet our respective needs.

3.3 SCIENTIFIC NEEDS AND SPECIFICATIONS FOR BATHYMETRY (*by J.K. Hall[*]*)

What are the scientific needs?

In the near future we should have a relatively clear idea of what the bathymetry and topography of the Earth is, on a grid of 100 m or so. Plans for a Shuttle Radar Topography Mapper (SRTM) mission are being prepared to try to generate a land Digital Elevation Model (DEM) for 890% of the Earth at 30 m resolution (Interagency Ad Hoc Working Group on SAR, 1996). This booklet lays out most of the reasons that land DEM data is needed, many of which are similar to those for bathymetry. One scientific need for improved bathymetry that is often overlooked is the fact that often the regional scientific nuggets that we dig out through drilling, bottom-sampling experiments like coring, dredging and heat flow, or *in situ* seismic measurements, we are ultimately able to predict from detailed topography.

What are the specifications for accuracy and resolution?

The specifications for accuracy and resolution of a global bathymetric data set should be as high as possible. Unlike the land case, a global bathymetric DEM will be based upon the following:

a) all the inshore hydrography, obtained by finally digitizing all the existing hydrographic fair-sheets. All inshore data must be shifted to the WGS-84 datum of GPS;
b) all the offshore track-line bathymetry, spot soundings, and swath compilations, with datum shifts to WGS-84 wherever possible;

c) pseudo-bathymetry from satellite altimetry for all the vast deep-water areas. The transfer function for correcting the depth of the dense basement to the sediment-water interface will have to be based upon modelling of the sedimentation on the mid-ocean ridges, equatorial sedimentation in the past, and all the ground-truth from single beam tracks.

Naturally, the accuracy of these data should be as good as possible. Where dense GPS data are available, then earlier datasets can be ignored. However, the ocean is so vast and our yearly output is so small, that virtually all historical data must be considered.

For the gridded DEM, the ultimate goal should be to about 0.05’ or about 100 m. This is apparently what the classified datasets are attempting to attain. However, under the assumption that historical data will finally be digitized and not lost, it would be possible to initially work at 0.1’ or 180 m.

The mistake we have repeatedly made in the past is to set our grid according to what the data density can support. Hence, while the 5’ ETOPO-5 was a tremendous leap forward, it does not show the island of Bermuda, which probably has upwards of 100,000 hydrographical soundings around it. We should aim for the densest grid possible, commensurate with our past, present, and anticipated future inshore hydrography and swath mapping capabilities.

We should not try to use computational schemes that allow us to jump from one density to another. Use of such schemes just guarantees that only a small percentage of the potential users or suppliers will be able to use them. This was justifiable once when data storage was prohibitively expensive, but today this is no longer the case. Hall (1993) showed that worldwide elevation data can be kept as two-byte integers. Under the proposed packing scheme resolution is 0.1m from +2,500 to –2,000 m, and one metre thereafter to the top of Everest or the bottom of the Mariana’s Trench. This certainly satisfies the anticipated needs, while guaranteeing that DEMs of 0.1’ resolution for one square degree take up about 705kByte of storage without compression. For the 64,800 one degree squares worldwide, this amounts to less than 46 Gigabytes. With compression (to 20%) this comes out to about one new high-density CD or 8 new Jaz optical cartridges. Expansion to 0.05’ merely multiplies these figures by four.

The gridding scheme used in for the 2nd edition of the International Bathymetric Chart of the Mediterranean (IBCM) is the multi-quadratic surface method of Hardy (1971), in which a surface is fitted to

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all the data points. For *n* data points this involves the solution of *n* equations in *n* unknowns, and then evaluation of each data point by calculating the distance to all the surrounding data points that were used. Because of its tremendous computational demands, such a method is anathema to those who would like to compute a DEM for an ocean basin in a few minutes or hours using GMT. However for gridding it is acknowledged to give the best representation of all the data. And for the method used for the IBCM, which involves carefully and interactively looking at all the data, it cannot be beat. In addition it gives the opportunity to calculate a one-byte overlay to the DEM, giving for each element of the DEM the distance (in grid nodes) to the nearest depth sounding. It is this overlay that will indicate where new data are required, and where satellite altimetry is useful.

What actions and priorities are needed?

In deciding on actions and priorities we have to accept certain facts of life in this undertaking, which are:

- the world ocean is huge;
- generally very little money has been available for civilian projects;
- the military is wary of civilian efforts at high resolution bathymetry;
- ships are expensive and not efficient at gathering bathymetry on a global scale;
- bathymetry is not sexy, except swath mapping over sexy features;
- the number of bathymagicians worldwide capable of making area compilations is probably far less than 100, excluding the classified military workers.

The project must be done on a number of fronts, which would make it different from GEBCO and the various regional mapping projects of the IOC Consultative Group on Ocean Mapping (CGOM). The following points come to mind:

(i) There must be a resounding scientific voice behind the need for such a project. This voice can be a handle for other peripheral groups to get funding to support these activities, and to make a diversion of manpower into data acquisition, archiving, digitization and analysis a legitimate activity. This scientific voice can also show that bathymetry can be sexy. For a time in the 1960s and 1970s Bruce Heezen and Marie Tharp showed that it was, as did Walter Smith and Dave Sandwell in the early 1990s. Higher resolution data, with appropriate hypsometric colouring and shading, can prove that bathymetry, together with land data, can really be attractive. But it must come with a scientific seal of approval, otherwise those who dabble in it will have to continue doing so at academic risk and with near-zero support.

(ii) There must be real money available for compilational efforts, for work at sea, and for more detailed satellite altimetry as well as satellite bathymetry in shallow clear waters. The IOC-UNESCO-IHO IBCM group was the first regional mapping project, and is to date the most successful. And yet for most of nearly two decades of work the annual budget has been about $5,000, to cover bathymetry, gravity, magnetic, seismicity, recent sediments, and Plio-Quaternary sedimentation.

(iii) The project must be a true symbiosis of the traditional proponents of such work: academia, governmental hydrographers, industry, NGOs, plus the military. However, because of the quantum increase in resolution, this must be expanded to include inshore and littoral environmental and fishing groups, telephone cable companies, shipping companies, etc. Experience with IBCM suggests that the best way to carry out the project is to accelerate the creation of regional mapping groups like those of the IOC CGOM until the entire world is covered. There should be an International Bathymetric Chart of the Arctic, the Red Sea, the Antarctic, etc. SCOR Working Group 107 should not try to replace those groups, but could prepare the way for their creation and for channelling their bathymetric results into a worldwide compilation. This would not be a clone of GEBCO, which is tied to the idea of producing a new edition every decade or so. At its present scale and format (500 m contours), GEBCO exists as something that might be replaced by products of the regional groups. Alternatively, GEBCO could become the umbrella organization for putting out the digital products produced by the regional groups. Until GEBCO goes to a digital output format (shaded relief with hypsometric colouring and CD) it will sit in a backwater.

(iv) Somehow the input of the military must be increased. In the past few years there has been a return to the cold war mentality on the part of the US Navy, which led to the demise of a US-Russian effort to completely map the Arctic Ocean with a Seabeam-equipped Russian nuclear submarine, and reclassification of the 0.5' bathymetric DEM that was to have been released with the 0.5' Globe DEM from the Defence Mapping Agency (which itself has recently been reclassified). Liberalization can be accomplished through political pressure, public pressure (the reason SOSUS arrays are now being used for whale research), scientific pressure (on our associates who make these databases and want their work acknowledged), and marketplace pressure (IBCM) intends to produce a product that is mostly superior to what the US Navy has).

(v) What will be the format of the Improved Global Bathymetry? As indicated above, the format should be a dense DEM on a grid of 100-200 m, carrying resolution to a metre or less. The accuracy in many (most) cases will be less, but at least the foundations will be laid for data that will slowly be acquired at higher standards. This dataset can then be used digitally at all scales, and can be output in analogue fashion at scales from 50,000 to 100 million. Analogue output as shaded hypsometrically coloured posters will go a long way to bringing the work to the attention of the public, and to making the data immediately understandable.

(vi) Mechanically, how should the project go forward? Assuming that no budget yet exists, a number of infrastructural steps must be taken:

(a) digitization of the near-shore hydrography. Scientists and hydrographers tend to scoff at the last 200 years of inshore hydrographic work done by Britain, the USA, Russia, France, Italy, Germany, Holland, Greece, Turkey, Spain, Japan, China, and other (colonial) maritime nations. However, in many cases this is the only data that exists, and only a small percentage of it would up on the sailing charts. This data should be scanned onto computers, digitized, and harmonized to metric units and the WGS-84 datum. Several countries have already done this, and others are working on it. This data will be the basis for all inshore mapping.

(b) digitization of all deep-sea soundings from the various series of Million scale and Quarter-Million Scale Ocean Sounding Sheets, from sounding track holdings of NGDC, the volunteering IHOs, marine institutions, and all other holders of data. There is a huge amount of data that has never got to NGDC. Much of this data is already digital (western military), or is analogue and requires digitizing (Russia).

(c) archiving swath surveys where the DEM essentially exists at the appropriate standard. Earlier work is likely to be available only in analogue form as contour maps in uncorrected units. These areas will have to be converted to DEMs through digitization of the contours and then corrected. The general rule must be that new swath surveys should be submitted as soon as possible in the chosen grid and format, before the data becomes a fatherless jumble of files.

(d) during and after these steps the gridding should be going on by means of simple PCs. This can be accomplished by defining a DEM file (from 1 square degree to many square degrees), and then working graphically across this file, taking in a quarter million pixels at a time, and seeing what data exists where. The surface is then calculated by roping off up to 300 data points at a time and calculating a surface. The DEM for a smaller internal area can then be generated, plotting out the interpolated pixels with ten repeating spectral colours for 1, 10, 20, or 50 m intervals. This allows enough data overlap so the surface is without discontinuities caused by interpolation. For areas with very little data the interpolation is smooth and effortless.

(e) as initial gridding is completed, the one-byte overlay giving data density can serve to identify where additional coverage should be sought, or obtained by going to sea. The overlay is amenable to sue on board ship, to allow slight course alterations to close up holes. The initial gridding files, on CD, could also be used as a medium of exchange to get additional contributions.

(f) for a detailed 100 or 200 m DEM, a better World Vector Shoreline (WVS) from the Defence Mapping Agency is needed. Comparisons of the WVS-2 with shorelines in the Mediterranean and Red Seas have shown the details to be sadly wanting. With the proper detail, harmonization of the hydrographic surveys to the WGS-84 datum becomes a simple process.

(g) this DEM should include land topography. For the 2nd edition of the IBCM it is planned to use the 0.5' Globe dataset re-interpolated smoothly to 0.1'. Where better datasets exist they can be seamlessly dropped in. These efforts must be integrated with the efforts of the land topography community.

(h) every effort should be made to demonstrate to those who go to sea that oceanic bathymetry is not well known, and that it is their responsibility to assist in its collection. Experience shows that the Lamont-Doherty philosophy that everything should be operating while a ship is at sea is truly a minority opinion. Many vessels with ocean-going echo-sounders travel untold kilometres with the sounders not in operation. Once this was understandable because of the paucity and poor quality of the navigation, but it is criminal now that GPS is everywhere. When questioned about this, people usually say that the bottom topography is already well known by someone, or that if data is needed they can return. Perhaps one solution is to pay for data ($100 per 1000 nautical miles), or, in the long run, to develop a very simple sing-around system that could be piggy-backed on slow boats and output the results together with the navigation on a small PC.

(vii) Assuming that meaningful budgets appear sometime after this project gets off the ground, what then?

(a) digitization on a large scale requires money. While the NOAA-NGDC effort resulted in soundings at a rate of many pennies per sounding, the methods developed in Israel produce 250-600 soundings per hour of heads-up digitizing of scanned records on a simple PC with data checking by surface fitting. A relatively small budget could accomplish the final digitization of much of the world's analogue data. Russian holdings could be obtained by providing computer systems, scientific pressure, and wages.

(b) acquisition of future data by paying for it ($100 per 1,000 nm) could possibly achieve good results, or by paying one day's cruise time ($10-20,000) provided that the ship transited holes in the coverage. This method should not interfere much with the shipboard routine during transits. often by taking 1-10 nm off the direct route, a 2D picture can become 3D.

(c) bigger budgets plus a good scientific voice might get additional phases of measurement from existing satellite platforms like TOPEX, GEOSAT, ERS1/2 etc. Often, after the primary investigations are over, it is possible to enter a maintenance phase where much additional data is taken at a very minimal cost. The altimetry from ERS-1 and 2, or their newer follow-on should be useable for increasing the density of coverage of the 3-4 km diamonds of the GEOSAT mission.

(d) for the Arctic, a new non-governmental approach to Dr. Yuri Kislev of SEVMORGEO in St. Petersburg could possible result in another 15,000 soundings for the deep Arctic from Soviet Arctic ice stations. However, an appreciable amount of funding would probably be required ($50,000 or more).

(e) SCOR money or scientific leverage could result in improving the WVS2 World Vector Shoreline. If ships were to routinely measure the dock locations at all ports of call, then the local maps could be immediately harmonized and used to correct the local hydrography and to produce coastlines good to 1:15,000 scale.

(f) after the initial gridding, big budgets and scientific leverage might get TOBI and modified GLORIA data from areas that are crucial but neglected.

(g) in parallel the Working Group might think of preparing a bibliographic GIS with article references and map/chart availability on a worldwide basis.

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3.4 THE ROLE OF SATELLITE ALTIMETRY IN GLOBAL BATHYMETRY (*by W.H.F. Smith*[*])

A variety of radar and laser devices designed to measure various aspects of the elevations of Earth's surface features (sea surface, ice, land and vegetation canopy topography) have been placed in orbit around the Earth, or are planned for future missions. Each of these may properly be called a satellite altimeter. In the global bathymetry context, the important satellite altimeter missions are those which have a radar altimeter designed to measure the topography of the ocean surface while averaging out the effects of surface waves, and also to operate in "geodetic" (as opposed to "exact repeat") orbits, which furnish a (nearly) global network of data profiles along closely spaced survey tracks (typically 5 km apart or so). Two such missions have flown, the U.S. Navy's GEOSAT (GEOdetic SATellite) "Geodetic Mission" and the European Space Agency's ERS-1 (European Remote Sensing satellite 1) "Geodetic Phase". No such missions are currently operating or planned for the future.

The ocean surface topography approximates the shape of an equipotent of the Earth's gravity field (a "level" surface, the "mean sea level") and so one may use these altimeter data to estimate the locations and magnitudes of anomalies in the marine gravity field over ice-free areas of the oceans (Sandwell and Smith, 1997). In areas covered by permanent sea ice it is also possible to estimate gravity anomalies, albeit with less precision and resolution, if one assumes that the sea ice is uniform in thickness and freely floating on the ocean surface (Laxon & McAdoo, 1994; McAdoo & Laxon, 1997).

Gravity anomalies arise from lateral variations in the density structure of Earth's constituent materials. The density contrast between seawater and sediments or rock is many times greater than the density variations among rock and sediment types, and so the variations in sea floor topography are potentially the largest source of marine gravity anomalies, larger than those which arise from sub-seafloor geologic structures. However, sea surface gravity anomalies are not perfectly correlated with sea floor topography. Topographic variations over horizontal distances longer than a few hundred kilometres (a few times the typical thickness of the oceanic lithosphere) generally are isostatically compensated, and hence do not produce gravity variations. Topographic variations over horizontal distances shorter than 10 km or so (a few times the typical sea floor depth in a region) produce gravity anomalies too weak to be resolved by sea surface altimetry. Furthermore, the correlation between sea surface gravity and sea floor topography should be somewhat non-linear, with the severity of the non-linearity increasing with the ruggedness of the bottom topography. These limitations preclude the use of satellite altimetry as a direct measurement of absolute ocean depth; rather, altimetry may be used for reconnaissance of seafloor topography in the "tectonic fabric" range of horizontal spatial scales (10 to a few hundred km) (Smith, 1998).

The direct measurement of depth is done by ships carrying various acoustical devices. These have different characteristics of accuracy, precision, and resolution, and have been and are deployed with varying density and navigational quality throughout the ocean basins, so that the state of the global bathymetric database is quite heterogeneous (Smith, 1993). Furthermore, as these data have been synthesized into hand-drawn contour charts (e.g. GEBCO), charts which were later digitized and interpolated to produce gridded representations such as ETOPO-5, the scientific prejudices and artistic styles of the individuals who drew the charts have influenced the portrayal of bathymetry. In contrast, satellite altimeter data are of uniform quality, free of any prior prejudice or hypotheses, and uniformly distributed over the entire global ocean (with the exception of the Arctic Ocean north of 82 degrees latitude). Therefore satellite altimetry data are of great value in the reconnaissance of the global abundance and distribution patterns of tectonic features, and in the selection of sites for further study by ships.

The quality of gravity anomalies estimated from altimeter data is conventionally assessed by comparison of their values with values measured by ships equipped with gravimeters. This assessment furnishes the state of the art of altimeter gravity for the foreseeable future, as no further "geodetic" altimeter missions are proposed. The resolution of the data is described in terms of the shortest wavelength that is coherent in a spectral coherency analysis (a measure of the correlation between altimeter-derived anomalies and ship-measured anomalies as a function of spatial wavelength); this is typically 20-30 km, indicating that features as small as 10-15 km can be resolved. The precision of the data is characterized by the root-mean-square (rms) difference between the altimeter and ship data, after adjustment for an overall mean difference; typical values are 3-7 mGal (milli-Gal; 1 mGal = 10^{-5} m/s^2). (For comparison, the global

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rms average amplitude of gravity anomalies is around 35 mGal, and large seamounts and trenches have anomalies on the order of 300 mGal.) The absolute accuracy of altimeter-derived gravity anomalies is tied to the gravity field models used in satellite orbit calculations, and cannot be assessed by comparison with shipboard measurements, as ship gravimeters are relative instruments and require calibration of their absolute level; these calibrations are usually in error by 10 mGal or more (Wessel and Watts, 1988). Assessments of altimeter-derived gravity anomaly estimates may be found in Neumann et al., 1993; Marks, 1996; and Sandwell and Smith, 1997.

A reliable reconnaissance estimate of sea floor topography from altimeter-derived gravity is difficult to obtain because the sea-surface gravity anomalies are imperfectly and non-linearly correlated with sea floor topography, and the correlation depends on both the average depth in a region and the density of seafloor materials in the region. Errors in the estimates are expected to be largest where one or more of the following conditions hold: (1) the regional seafloor depth is a large fraction of the horizontal dimensions of the topographic features of interest; (2) the local relief is nearly as large as the regional seafloor depth (e.g. seamounts rise from great depth to near the surface); (3) thick sediment or prominent sub-seafloor crustal structures contribute significantly to the gravity field. Errors in gravity are amplified during topography estimation by an amount that grows exponentially with the ratio of regional depth to width of the topographic structure; hence condition 1. The non-linearity in the gravity-topography correlation increases as the ratio of local relief amplitude to regional depth increases, hence condition 2. When condition 3 holds the gravity field can no longer be attributed to sea floor topography, preventing topographic estimation. If none of these conditions is severe, then the situation is suitable for the use of altimetry to estimate local depth variations, and the errors in depth can be expected to scale with the errors in gravity by about 13 metres per milliGal. For a gravity rms error of 5 mGal the rms depth error would be 65 m. If the seafloor topography is sinusoidal then the amplitude error might be about 1.4 times the rms error, and the error in the estimated peak-to-trough relief of a ridge and trough structure would be about 2.8 times the rms error, or about 180 m.

Optimal resolution of seafloor topography by altimetry depends critically on the design of error-suppressing filters used in the data processing scheme; the design of such filters is detailed in Smith and Sandwell (1994). Smith and Sandwell (1994) also describe a scheme whereby "ground truth" measurements of actual depth from shipboard echo-sounding data are used to calibrate and control the altimeter estimation process. The 1997 solution by Smith and Sandwell (1997) probably represents the state of the art in this technique. An example of this estimate is shown in Figure 3.4.1 in what is probably a worst-case situation, as both conditions 1 and 2 above hold, and the estimate was made in an area of very sparse "ground truth" control data. Shown is a profile in an area west of the East Pacific Rise near a linear seamount chain which was discovered only by altimetry and which has been called the Foundation Seamounts. (Further details of their discovery are noted in Smith and Sandwell, 1997). The profile portrays depth on the vertical axis versus the distance travelled by the R/V *l'Atalante* along the horizontal axis (survey obtained in 1997; Marcia Maia, Chief Scientist). Profile B shows the actual soundings obtained from the centre beam of a Simrad 12-D multi-beam acoustic swath survey system on board *l'Atalante*. Profile A shows the bathymetry along this line as represented in ETOPO-5, and Profile C shows the estimate made by Smith and Sandwell (1997) before the *l'Atalante* data were obtained (that is, with no "ground truth" available in this area). Numbers associated with profile B give the average depth along the profile (3656 m), and the rms variation about the average depth (791 m). Numbers associated with profile A [and in square brackets with profile C] are the average difference between the depth according to this representation and the ground truth depth (165 m; [respectively, 23 m]) and the rms of these differences (580 m; [respectively, 250 m]). Taking the rms amplitude of profile B (791 m) as the typical magnitude of the actual topographic variation (the "signal"), and the rms differences on A and C as the typical magnitude of the error in these representations of bathymetry, one may say that the error in A, ETOPO-5, is about 73% of the signal, while the error in C, the altimeter-derived estimate, is only about 32% of the signal. Profile B includes all topographic variations reported by the Simrad multi-beam system. If the profile were smoothed to include only wavelengths long enough to be resolvable by altimetry, then the statistical agreement between B and C would improve. Qualitatively, one may say that several seamounts and a ridge-and-trough structure appear in both B and C, which do not appear in A. Thus, even in this worst-case situation, the value of altimetry for qualitative or semi-quantitative reconnaissance of bathymetry is demonstrated. However, it is also clear that altimetry cannot assign an absolutely accurate and precise value at a point. This implies that machine-drawn contours of altimeter-estimated bathymetry may not look as aesthetically pleasing as hand-drawn contour charts.

The altimeter-derived bathymetry estimate can be compared with the ETOPO-5 representation. "ETOPO-5" (Earth TOPOgraphy on a 5 arc-minute grid) is a patchwork quilt of data stitched together from different sources and distributed by NGDC since 1988. The marine component in depths below 200 m is "DBDB-5" (Digital Bathymetric Database at 5 arc-minute grid), produced in 1978 by Navoceano, the US

Naval Oceanographic Office. DBDB-5 was gridded from digitized contours taken from hand-drawn contour charts. Contour values on some of these charts represent depths corrected for the variation of sound velocity (“Mathews correction” or “Carter correction”) while others were uncorrected (“nominal depths”). No attempt to harmonize these various data was attempted.

The Committee for the General Bathymetric Chart of the Oceans (GEBCO) is currently in the process of producing a grid from digitized contours of the 5th edition of GEBCO and more recent contours. These also are hand-drawn, a mixture of corrected and uncorrected values, and also date to the 1970s in many areas of the oceans.

In contrast to the ETOPO-5 and the GEBCO gridded product, the Smith and Sandwell altimeter-based map includes an extensive compilation of more recent data from sources such as Lamont-Doherty Earth Observatory (LDEO), Scripps Institution of Oceanography (SIO), Woods Hole Oceanographic Institutions (WHOI) and French sources, and ignores those NGDC data which could not be quality-controlled. Smith and Sandwell applied the Carter correction for sound velocity to all soundings, and data were directly ingested into the algorithm described in Smith and Sandwell’s 1994 and 1997 papers, without the intermediate step of hand-drawn contours.

Comparisons between the altimeter-based values and ETOPO-5-based values can be made in the form of estimates of mean depth, mean slope, and rms residual variation about the mean planar trend, all three quantities estimated in 1/4 degree squares. The mean depths appear to show broad regional areas where the difference in mean depth exceeds 100 m, an amount which appears to be too large to be due to systematic errors in altimetry, sound velocity correction, or regional geology. It is possible that a lack of control on the 1970s contour charts due to a sparsity of data could explain the discrepancy. For instance in some areas (e.g. the South Pacific) the mid-ocean ridge axis was located on the basis of earthquake epicentres, and then the contours portraying the depth on ridge flanks were drawn at a fixed distance from the epicentres, because there was little or no ground truth available. In addition, the altimetry finds more seamounts than are shown on bathymetric charts, which might also explain some of the differences.

Maps of the slope of the plane of the seabed, and of the rms residual variation about this plane, also show clear differences between the ETOPO-5 and altimetry-based representations of bathymetry. The slopes and roughnesses indicated by the altimetry appear to have a global distribution pattern in accord with what one would expect from the plate tectonic theory. In contrast, the distribution of slopes and roughnesses indicated in ETOPO-5 appears to reflect the density of available data and the individual interpretations and contouring styles of the mappers who drew the various charts. A particularly conspicuous example of this is at the 60 degrees south parallel in the South Pacific, where the contours to the north were drawn by J. Mammerickx at the Scripps Institution of Oceanography, and the contours to the south were drawn by a group in New Zealand. Seafloor complexity appears to increase abruptly to the south of this parallel in ETOPO-5, whereas the altimetry shows no such change (Figure 3.4.2)

In summary both the roughness and slope shown by ETOPO-5 tend to be underestimates because of the density of the data and the way in which they were processed. The altimetry may have some advantage in that it yields a globally uniform and unbiased estimate of the tectonic fabric of the ocean basins.

Recognizing that ETOPO-5 is based on old data and that a great deal of high quality data has been collected since then, it is worth noting that there is a great deal of unused data available for bathymetric compilations (some of which has been used for the Smith and Sandwell maps). What is needed is the bathymetric equivalent of IODE's GODAR (Global Ocean Data Archaeology) project (which is largely for physical oceanographic data) to dig out unused (and often undigitized) bathymetric data and get them into the system. Data rescue may cost money, but little compared with the cost of new collection.

Roughness gives a feel for where tidal energy may dissipate. The more detailed the topography, the more accurate the calculations of tidal dissipation are likely to be. While 50% of tidal energy is dissipated in shallow seas, much of the rest is dissipated near seamounts in the open ocean, where there is enhanced mixing by internal waves caused by tides (three times as much as away from seamounts). The number of seamounts shown on the altimetric map is twice that shown on ETOPO-5, suggesting that there is much more dissipation of tidal energy in the open ocean than had formerly been supposed.

Comparing the altimetric and ETOPO-5 bathymetries at 3,500 m (in the Atlantic) shows that the former displays many narrow deep connections between basins, while the latter shows fewer but larger connections. However, this level of detail is apparent at the 2-minute scale, and may be lost at the 1/4 degree scale currently used in computer simulations of the global ocean circulation.

This observation raises the question of whether or not it is necessary to survey the newly found sills, for example to confirm that they are real. One problem concerns cost. Physical oceanographers rarely use echo-sounders during their cruises. Because it costs a lot to take an echo-sounding technician along to run the appropriate instrument during a cruise, they would rather do without (which may be false economy). Lists of sills for which verification is needed could be made widely available, with the encouragement that research vessels should survey them when possible.

Before carrying out an expensive survey it would be instructive to do some theoretical tests, for instance (i) to see what effect the two topographies (fine scale sills versus coarse scale sills) would have on inter-basinal exchange, and (ii) to see what happens in models with and without newly identified sills in the topography. This could be done by comparing new and old model output. Such a test was made by Harley Hurlbert, who showed sills were important, as confirmed by Tokmakian (4.4, below).

At the 1st meeting of the SCOR 107 working group there was a question about the possibility of running a test of circulation through the Romanche Fracture Zone to find out what aspect of the topography provides the critical control on the pattern of turbulence (e.g. depth, width, and/or roughness). According to Killworth (personal communication), Ferron's (1998) simulations of flow through the Romanche Fracture Zone (which is essentially non-rotating because so close to the equator) found that the orientation of the channel made little difference, but changes to its depth had strong effects if these were near the controlling sills. Width changes were less important. Topographic roughness is essentially untested, since his and other models do not carry roughness as a parameter.

The horizontal resolution needed in bathymetry by ocean modellers seems to be a grid size of about 2 to 5 minutes (around 4-10 km), but variable - i.e. higher on the shelf and in the upper 1 km of the water column, and lower in deeper water, where 5 minutes (around 10 km) is usually adequate. Some ocean modellers would like to have a horizontal resolution of 1 km and a vertical resolution of 50 m. Other users may have different requirements. For example, higher resolution is needed for hazard assessment of tides and tsunamis in shallow water; tsunami modelling requires better than a 500m grid with 2-5 m depth resolution, which is like the EuroGOOS user requirement of 500 m horizontal and 2 m vertical resolution. For some shelf users, even finer scale resolution may be required (e.g. down to 1/10 of a degree or about 180 m horizontally). In many instances data at this resolution are available in hydrographic archives, from early admiralty surveys; they lack the benefit of GPS control on position, but are a lot better than nothing.

Altimeter-derived maps should be used not as bathymetric maps, but as guides to bathymetry, because the altimetric technique cannot resolve fine-scale variability and will never be fully representative of topography. In the absence of controlling bathymetric data, 25 km is the wavelength below which resolution deteriorates on the altimetric map. Even so, smaller features can be seen, e.g. down to 10km, even when bathymetric data is not available. When bathymetric data are available to calibrate the altimetric data, resolution improves to 1-3 km (the size of the grid boxes used to compile the altimetric data). Despite these caveats, Peter Hunter (personal communication) has reported that comparisons of bathymetry and altimetry off W. Africa at appropriate scales showed very few problems (in fact, the altimetry showed up errors in the bathymetric data!).

In terms of obtaining other data to help identify geological features so that the altimetric maps could be adjusted for geological influence, it is noted that the new GRACE (gravity) satellite mission will not solve the problem, because it will fly at an altitude of 400 km, so will not resolve wavelengths less than that.

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Figures

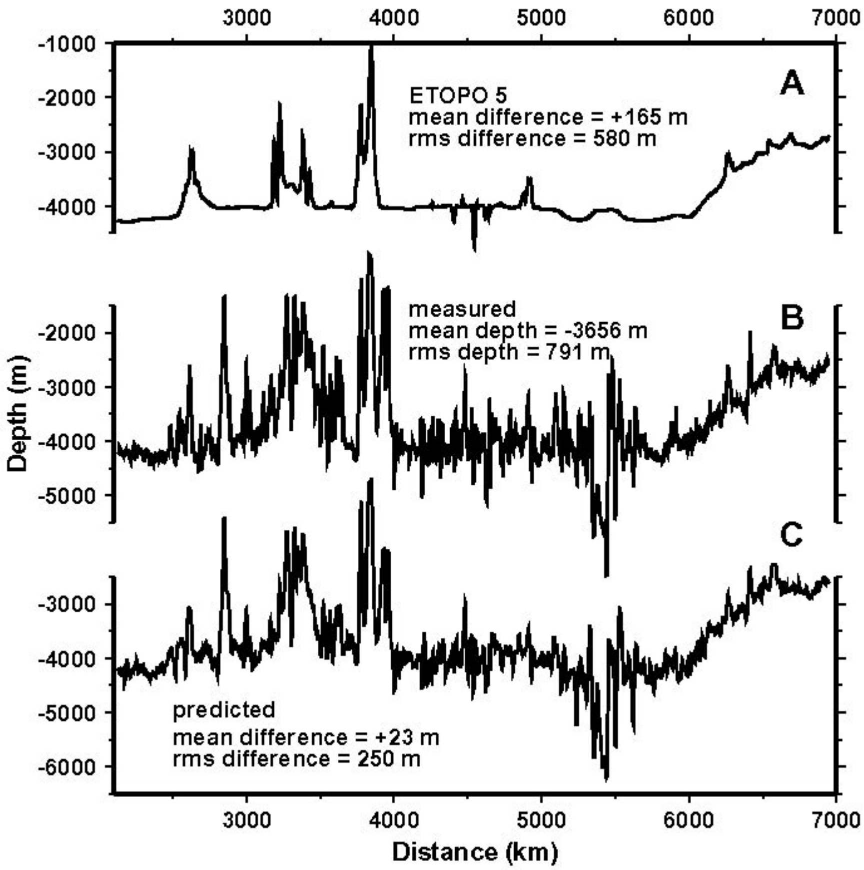
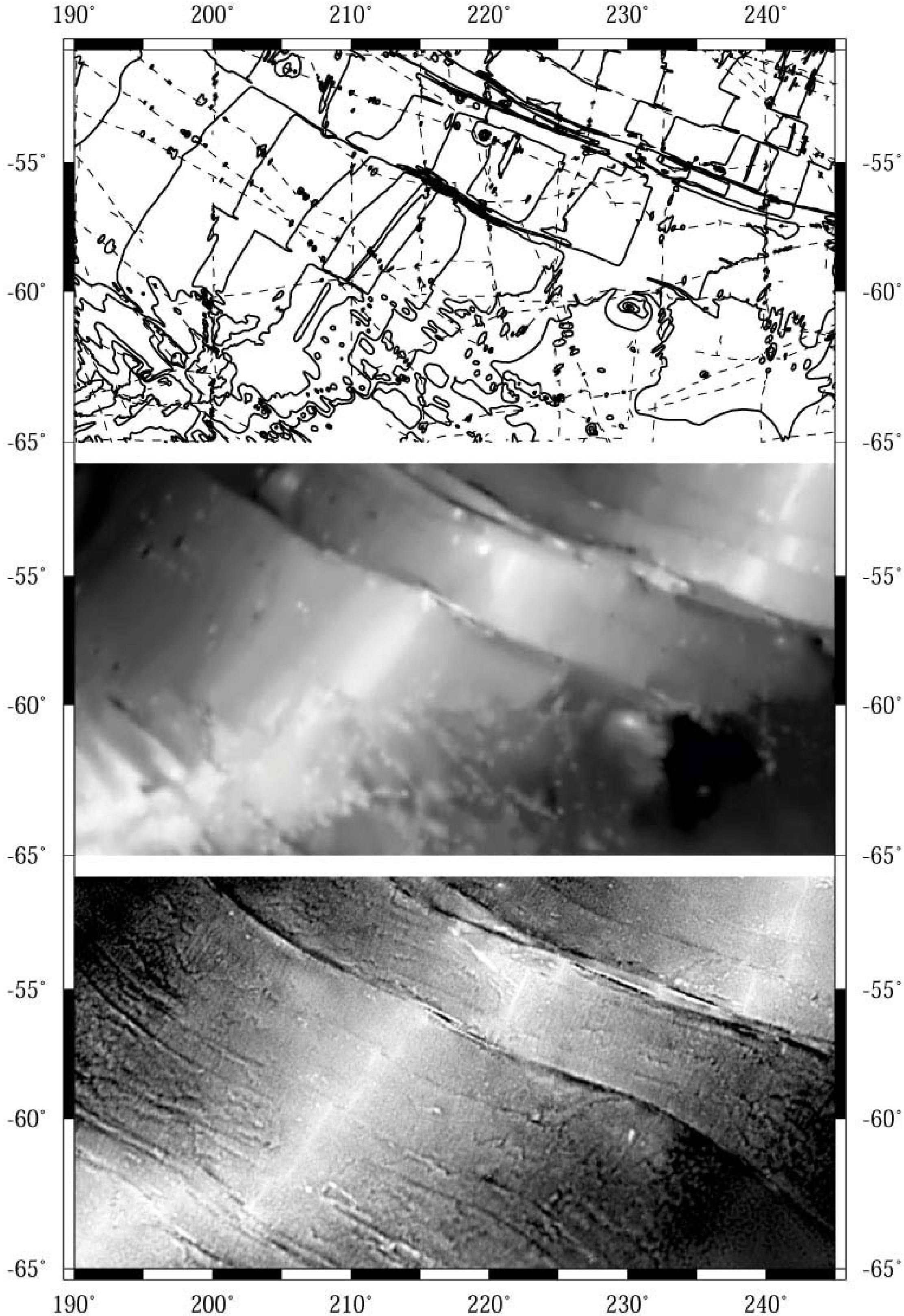


Figure 3.4.1 Bathymetric profile from R/V *L'Atalante* (1997) west of the East Pacific Rise:
A: from ETOPO-5 database;
B: from center-beam of swath bathymetry echo-sounder;
C: estimate from Smith and Sandwell (1997) before ground truth data were available from *L'Atalant*e.
Numbers represent measured mean depth and root mean square (RMS) amplitude of the depth signal, in B, and the differences from those figures, in A and C.

Figure 3.4.2 (following page) Bathymetry of the Pacific-Antarctic Ridge in the South Pacific.
Top: 500 m contours (solid lines) and track control (dashed lines) from the GEBCO 5th edition charts. Note lack of control for fracture zones, and change of texture at 60°S;
Middle: depth image from ETOPO-5. Note how texture corresponds to GEBCO contours;

Bottom: depth image from satellite altimetry.



4. THE MARINE PHYSICS PERSPECTIVE

4.1 INACCURACIES IN OUR KNOWLEDGE OF THE OCEAN BATHYMETRY: A LIMITING FACTOR FOR OCEAN TIDE MODELLING (*by C. Le Provost**)

4.1.1 Introduction

Bottom topography is a major controlling parameter on ocean dynamics. It is extremely important that correct bathymetry can be introduced in ocean circulation models. Ocean tide modelling is typically a domain where numerical simulations have reached a stage where the inaccuracies in the available bathymetric databases represent a clear limiting factor for new progress. The aim of this note is to present the state of the art in this area of ocean tide modelling, to show some sensitivity studies related to bathymetry inaccuracies, and to illustrate on examples the major role of bathymetry in controlling the physics of the response of the ocean, at the local or global scale.

4.1.2 State Of The Art In Global Ocean Tide Numerical Modelling

<u>4.1.2.1 Level of accuracy of the more recent solutions produced in the mid-nineties</u>

Global Ocean tide numerical modelling started thirty years ago with the pioneering works of Tiron et al (1967), Bogdanof and Magarik (1969) and Pekeris and Accad (1969).

Numerical models are based on the Laplace Tidal Equations, completed by dissipation (bottom friction is the major contributor to the tidal energy dissipation over the continental shelves and shallow water seas where tidal currents are amplified). A strong improvement in numerical tidal models resulted in the seventies from the introduction in the equations of the effects of earth tides, ocean tide loading, and self-attraction: see Zahel (1977), Accad and Pekeris (1978), Estes (1980), Gotlib and Kagan (1981). However these solutions only qualitatively agreed with *in situ* observations: their accuracy was not at the level required for new geophysical applications. Hence the need to compensate for the deficiencies of these unconstrained models by additionally forcing the solutions to fit observed data. This was the way Parke and Hendershott (1980) and Schwiderski (1980, 1983) got their solutions. Indeed, Schwiderski's solutions have been considered as the best available through the last decade. With a resolution of 1º x 1º, they cover the world ocean, except for some semi-enclosed basins like the Mediterranean Sea. They include 11 co-tidal maps: four semi-diurnal (M, S, N, K) 2, four diurnal (K, O, P, Q)1, and three long periods (Ssa, Mm, Mf). But the accuracy of these solutions was dependent on the quality of the observations used, and they suffered from the same weakness as the purely hydrodynamic models over the areas where data were not available.

In order to improve the purely hydrodynamical models it was necessary to reproduce details of the tidal motions over the shelf areas and the marginal seas, by reducing the resolution down to a few tens of kilometres. Models have been developed with grids of variable size: 4º over the deep ocean, 1º over some continental shelves, and 0.5º in particular shallow seas (Krohn, 1984). Another approach uses the finite element (FE) method which allows one to improve the modelling of rapid changes in ocean depth, the refinement of the grid in shallow waters, and the description of the irregularities of the coastlines (Kuo, 1991; Le Provost and Vincent, 1991). A global FE tidal model has been implemented recently over the world ocean with a mesh size of the order of 200 km over the deep oceans, reducing to 10 km near the coasts (Le Provost et al., 1994). Pelagic and island data are used to calibrate this model, but the final runs are done without forcing the solutions to fit to the data, as Schwiderski did.

Systematic differences from the Schwiderski solutions are noticeable: for the main tidal component M2, they are of the order of 10 to 20 cm, even more in particular areas. Compared to the available observed data, the FE solutions are in many places closer to reality than the Schwiderski's ones: they offer an improved set of hydrodynamic solutions. However, discrepancies remain, partly because of uncertainties in the bathymetry.

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A way to compensate the weaknesses of the numerical models is to make a compromise satisfying the assumed dynamic equations and all the available data of good quality, treated as an inverse problem. This approach is usually known as 'data assimilation'. Several tentative solutions with data assimilation have been reported over the last five years. A global tidal inverse at 1° resolution using the dynamic equations plus data from 55 gauge stations and 15 loading gravity stations has been produced (Zahel, 1991): the inversions do lead to much better agreement with data. And more recently satellite data assimilation has allowed us to reach a level of accuracy never obtained before: Egbert et al. (1994), Kantha et al. (1995), Le Provost et al. (1996).

Table 4.1.2.1 illustrates the level of accuracy reached by the more recent tidal solutions. It contains the root mean square difference of some solutions compared to a set of sea truth data sets issued from 103 tide gauge stations uniformly distributed over the word (Le Provost, 1994). These solutions are issued from Schwiderski's model, Cartwright and Ray (1991) first solutions issued from Geosat altimetry, Le Provost et al (1994) FES94.1 purely hydrodynamic solutions, CSR3.0 (Eanes and Bettadpur, 1996) solutions issued from 2 years of analysis of TOPEX/Poseidon (T/P) data, and FES95.2 (Le Provost et al., 1996) solutions issued from the assimilation of T/P derived data sets into the above introduced FE model. What must be noted in Table 4.1.2.1 is the very significant improvement observed since the 1980s, both for the more recent FES94.1 hydrodynamic model (with a gain of 1 cm on the global root sum square estimate of tide predictions over the 102 stations used for comparison), and for the highest quality solutions obtained either directly from the analysis of the available altimeter data (CSR3.0), or indirectly through data assimilation (FES95.2) with a gain of the order of 2 cm.

Table 4.1.2.1: Tidal RMS comparisons to 103 Tide Gauge Stations (cm)

Model	Q1	O1	P1	K1	N2	M2	S2	K2	RSS
Range				12		59	38	22	
Schwiderski	0.35	1.22	0.61	1.43	1.22	3.86	1.66	0.59	4.84
Cartwright and Ray	0.46	1.23	0.63	1.89	0.98	3.20	2.21	0.67	4.59
FES94.1	0.28	1.05	0.45	1.16	0.91	2.85	1.59	0.50	3.80
FES95.2	0.28	1.05	0.39	1.17	0.90	1.72	1.13	0.50	2.83
CSR3.0	0.30	1.00	0.41	1.18	0.82	1.64	1.10	0.55	2.74

4.1.3 Some sensitivity studies of ocean tide simulations to bathymetry

As noticed above, the inaccuracies observed even in the more highly performing hydrodynamic models are partly due to uncertainties in the bathymetry. The physics of ocean tide gravity waves is indeed dependant upon the depth through several processes: the celerity of these waves is directly related to the square root of the depth, velocity fields and dissipation are partly controlled by the local water depths (Figure 4.1.1).

It is possible to find in the literature sensitivity studies giving some insights into the order of magnitude of the changes in tidal solutions induced by changes in the bathymetry. Some examples follow.

Lyard and Genco (1994) addressed this problem within their investigations on how to approximate bottom topography in the finite element ocean tide model developed by Le Provost and Vincent (1991). Their tests were carried on the North Atlantic. And they compared solutions computed with the same model and the same conditions (forcing, open boundary conditions, parametrisation of dissipation) except for the description of bathymetry over each triangle of the discretized domain: either a linear interpolation computed from the ocean depth issued from ETOPO-5 data bank, or a more sophisticated interpolation which they called 'optimal'. It is not useful within this note to describe what is behind this 'optimal' interpolation. What is our concern here is to notice the statistical differences between the two tested bathymetries:

(i) the global mean depth integrated over the domain was the same for the two cases;
(ii) the extreme differences were –275 m and +300 m, and the RMS difference was 33 m, with typical wavelength of these differences of the order of the size of the triangulation of the domain, i.e. 800 km (It would be interesting to know is such values are representative of what must be the

uncertainty on the real bathymetry in ETOPO-5). The tests were done on the simulation of the major tidal component: M2.

Solutions for this wave in the North Atlantic typically look like an amphidromy, with a nodal point in the centre of the basin and amplitudes increasing up to 1 to 2 m over the different continental margins around. Lyard and Genco observed that the differences between their two simulations with different bathymetries were coherently distributed over the basin, ranging from a few centimetres in the deep ocean to a mean range of 4 to 7 cm over significant areas: the entrance of the English Channel, the Labrador Sea, the east coast of Florida, and increasing up to ten centimetres (or even more) in specific places: the Amazon plateau, the entrance of the Hudson Bay. These differences are important, if we consider the level of accuracy of the global ocean tide solutions now available.

Another instructive example is the one reported by Le Provost (1993) showing how changes in ocean depths can influence computed tides over large distances. This sensitivity exercise was also carried with the finite element model developed by the Grenoble Ocean Modelling Group. When investigating tides over the South Atlantic Ocean, it appears the dissipative processes taking place in the Weddell Sea under the permanent Ice Shelf were important for the global quality of the simulated solutions over this sub-basin.

However, it appeared that finding a good bathymetry and correct permanent ice shelf thickness was not easy. This resulted in the realization of two experiments: one with an incorrect guessed difference between the bottom of the Weddell Sea and the base of the ice shelf (of 100 m), and the other with the correct value (varying around 300 m). Considerable changes were observed over the Weddell Sea between the two responses. But more spectacular was a change of more than 10 cm in the Gulf of Guinea, about 8,000 km away from the area where bathymetry was modified. By the way, the M2 tidal solution was improved when using the 'correct' bathymetry.

These two examples are related to global ocean tide modelling, with uncertainties on the bathymetry of the order of a hundred metres. Numerous examples are available in the literature of sensitivity tests for regional coastal models with changes in the bathymetry of only a few to ten metres for water depths of the order of a hundred metres: here also solutions can be very sensitive to such changes. Davies and Aldridge (1993), for example, found that a modification of the order of 8% in the depth of their 3-D model of the Irish Sea was necessary to fit their simulations to observed data (sea surface elevations and currents).

4.1.4 Bathymetry And Topographically Trapped Tidal Waves

Diurnal tidal waves are particularly sensible to bottom topography. The existence of topographically trapped tidal waves has been analytically demonstrated by several authors in the sixties: Mysak (1967), Buchwald and Adams (1968), Saint Guily (1968), Longuet-Higgins (1968), Rhines (1969). Since then, these waves have been observed over shelves and at the shelf break in many places in the world ocean. Their characteristics are dependant upon the slope of the shelves along which they are trapped and propagate. Such features appear as local structures of rather short wavelengths, of the order of some hundred of kilometres. As they are quasi non-divergent, their presence is mainly observable through the local intensification of the currents that they induce.

The area of the Yermak Plateau, north of Iceland, is a typical area where intense diurnal oscillations have been observed, and several modelling studies have allowed explanation of the main processes taking place there (Kovalik and Proshutinsky, 1993; Le Provost and Genco, 1994). The Fram Strait, between Greenland and Iceland, is a key area for the world ocean circulation, because it is the place where sea ice for the Arctic Ocean enters the Atlantic Ocean. When observing this ice drift by following the position of ARGOS beacons released on the ice pack, Gascard et al. (1991) noted a trapping of their 'floats' which were turning around with a period of one day over the edge of the Yermak Plateau. The CEFMO model has been applied to the simulation of the diurnal tides over this area (Le Provost and Genco, 1994). A regional model extending from 75ºN to 85ºN, and from 40ºE to 32ºW allowed refinement of the computational mesh down to 4 km resolution over the Yermak Plateau. Open boundary conditions were supplied by the global solution produced by Le Provost et al. (1994). Bottom topography was deduced from a local bathymetry supplied by Gascard et al. (1991). Solutions were computed for two diurnal tidal components: K1, of period 23.93 h, and O1, of period 25.82 h. These solutions confirmed the existence of topographically trapped quasi non-divergent waves, but revealed also the extreme sensitivity of the ocean response to frequency, i.e. to the shape of the bottom slopes, if we refer to their frequency wave number dependency on bathymetry and its slopes.

The K1 wave is amplified under a typical double Kelvin wave propagating along the whole western edge of the Yermak Plateau. The sea surface oscillation is only weakly intensified, rising up to 10-15 cm along the shelf break. But the main signature is on the velocity field which is dominated along the western side of the Yermak Plateau by a system of cyclonic and anti-cyclonic eddies propagating northward, i.e. having the top of the plateau to their right, with velocities locally reaching up to 30 cm/s. The energy fluxes associated with this local system clearly show that the trapped energy propagates anti-cyclonically southward along the tip and northward along the foot of the shelf edge. The characteristics of these features in term of phase speed and wavelength fit relatively well with the theory of shelf waves, for which the shape of the shelf break is a key parameter.

By contrast, the O1 response looks locally very different. The numerical simulation reveals a localized area of intense trapping, at the northern end of the Plateau. The sea surface elevation is there also amplified up to 12-14 cm although the O1 astronomical forcing is weaker than for K1. But it is in the velocity fields and energy fluxes that the local resonance clearly appears, showing that the eddy structure already observed in the K1 solution here reduces to a couple of cyclonic-anti-cyclonic eddy systems reaching their maximum of intensity when sitting on top of the steepest part of the shelf break. The ocean response to the diurnal tidal forcing appears thus over this area critically dependent on the shape of the bathymetry. This has been why modellers need to get the more accurate bathymetry especially when addressing the simulation of such specific features.

4.1.5 Conclusions

Bathymetry plays an important role in the physics of ocean tides, both for the controlling their propagation and their possible resonance within each ocean basin, and as an important parameter in their damping through bottom friction in coastal areas. Ocean tide modelling has made important progress over the last few years, especially in connection with the huge set of information coming from satellite altimetry. Models are now at the stage where uncertainties in bathymetry appear as a clear limiting factor for new progress and understanding of the physics, at global scale but also for regional processes, as shown above for topographically trapped waves. From the sensitivity studies here reported, it appears that specifications for accuracy and resolution could be as follows: over the deep ocean, 10 m accuracy with 5 km resolution, with an improved resolution down to one km over the continental slopes, and a few metre accuracy on the continental shelf with a hundred metres resolution in coastal areas. This is needed over the word ocean, because of the global dependency of the accuracy of the tidal solutions to bathymetry. However, some priorities could be put over the continental shelves where tidal dissipation is known to take place (Figure 4.1.1).

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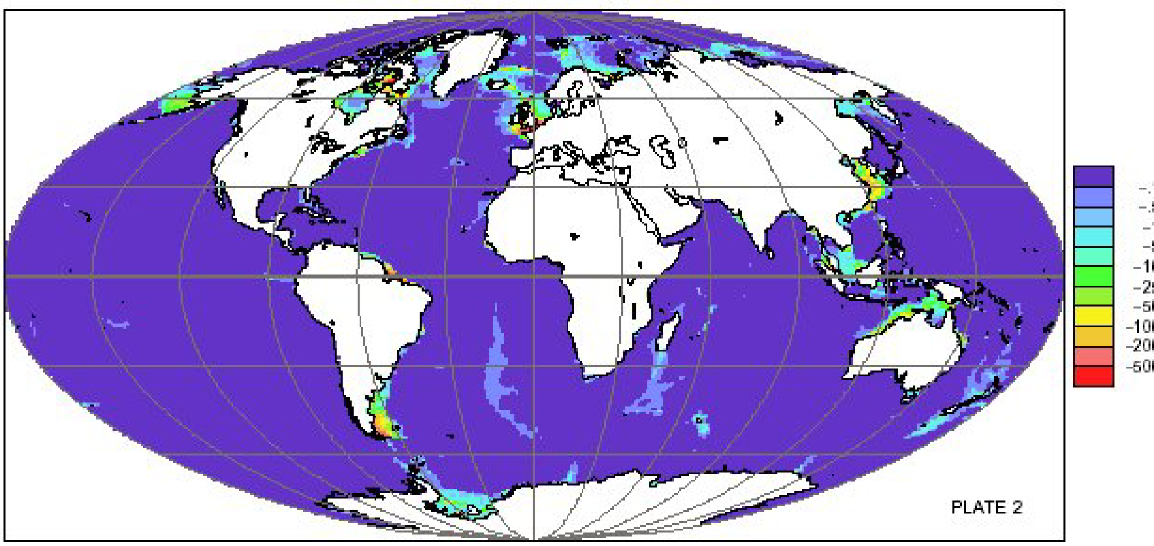
Figures



4.1.1 Map of main areas of M2 tidal dissipation by bottom friction (from LeProvost and Lyard, 1997). The quality of tidal solutions for regional and local tidal modelling applications depends on the accuracy of the bathymetry in these areas. Units in KWatt/km² represent the rate of dissipation per unit of area of the tidal bottom friction.

4.2. NOTE ON A PRIORITISED LIST OF AREAS WHERE IMPROVEMENTS ARE REQUIRED FOR TIDAL CALCULATION *(by C. Le Provost*)*

Tidal energy is dissipated through bottom friction and internal tide breaking. These mechanisms are linked to bathymetry: bottom dissipation is related to the intensity of the flows, hence to the depth of the water column, and generation of internal tidal waves are due to the interaction of the barotropic tides with bottom hills, middle ridges and continental shelf edges. It is then important to improve our knowledge of bottom topography over these areas of dissipation and internal wave generation.

The new developments in ocean tide numerical modelling, combined with assimilation of altimeter data issued from TOPEX/POSEIDON, have led recently to revise estimates of global tidal energy budgets (Egbert, 1997, Le Provost and Lyard, 1997, Lyard and Le Provost, 1997). Global and regional budgets have been established, telling on one side where the energy input by astronomical forcing (2.45 TW) takes place, and on the other side how and where this energy is dissipated.

One major feature emerging from these studies is that a quarter of this energy input takes place over the South Atlantic Ocean. Also, it appears that ocean tides work against astronomical forcing over three main areas: Eastern Indian Ocean, South West of the South American Continent, and around New Zealand.

This energy is mainly dissipated by bottom friction over the main continental shelves; however it seems that about 10% of it must be dissipated by through internal waves (Munk, 1997). One outstanding conclusion of these revised estimates is that 40% of the tidal energy is dissipated over the North Atlantic Ocean, pointing towards the importance of this basin in term of control of the ocean response to the tidal astronomical forcing. Energy is redistributed from the areas of energy input to feed the areas of dissipation: the Pacific Ocean, the Indian Ocean and the South Atlantic Ocean receive more energy in total than they dissipate, in contrast with the Atlantic Ocean and the Arctic Ocean, where a large deficit must be compensated by a net influx of energy from the other basins. One third of the total M2 energy input by astronomical forcing over the world ocean flows northwards through the Equatorial Atlantic.

Concerning bottom friction, detailed energy dissipation estimates have thus been computed over the different areas of energy dissipation, telling where the major areas of dissipation are. One set of such numbers for the major M2 tide is given on the following table 4.2.1 and figure 4.2.1 issued from Le Provost and Lyard, 1997. These results clearly indicate where better bathymetry can help to improve the computation of tidal energy dissipation and then tidal modelling and prediction. These areas are, by decreasing order of importance, given the energy dissipated there and their surface coverage: the Hudson Bay, the Yellow Sea, the Amazon shelf, the European shelf and the Patagonian shelf.

Our knowledge of internal tide energy distribution is not enough advanced to allow similar identification of areas where better bathymetry could help for a better understanding of the physical mechanisms leading to internal tidal wave generation and dissipation.

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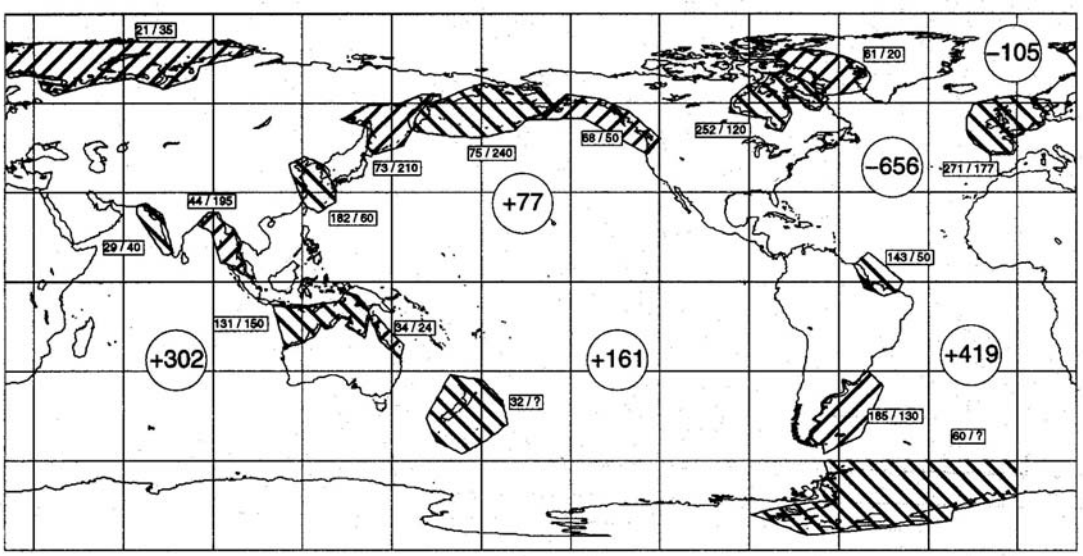
Table 4.2.1: Regional distribution of tidal energy dissipation by bottom friction *(from Le Provost and Lyard, 1997*). Units are Giga Watts. S is the area of integration, in 106 km^2.

The area identification code is the following: 1: Barents Sea and Kara Sea; 2: European Continental Shelf; 3: Hudson Bay; 4: Baffin Bay; 5: Amazon shelf; 6: Patagonian shelf; 7: Weddell Sea; 8: Ross Sea; 9: Mozambique Channel; 10: West India coast; 11: Gulf of Bengal and Andaman Sea; 12: Timor Sea; 13: Arafura Sea; 14: Yellow Sea; 15: Okhotsk Sea; 16: Bering Sea; 17: Gulf of Alaska; 18: East Australian Coral Reef; 19: New Zealand Plateau.

Area	1	2	3	4	5	6	7	8	9
S	2.3	2.2	1.2	0.8	1.1	2.8	4.9	5.7	1.1
D	**-21**	**-271**	**-252**	**-61**	**-143**	**-185**	**-60**	**0**	**0**
Miller	-35	-177	-120	-20	-50	-130			
Cartwright. et al		-360+/- 40				-245+/- 25			

Area	10	11	12	13	14	15	16	17	18	19
S	0.8	1.4	1.85	0.9	1.3	1.7	3.2	1.5	0.5	4.0
D	**-29**	**-44**	**-101**	**-30**	**-182**	**-73**	**-75**	**-68**	**-34**	**32**
Miller	-40	-195		-150		-60	-210	-240	-50	-24

Figure 4.2.1 *(from Le Provost and Lyard, 1997).* Total M2 energy dissipated by bottom friction over the major areas of tidal dissipation, in units of GW. The left numbers in each rectangle correspond to values computed from the FES94.1, and the right numbers are Miller's estimates, over the nearest hatched zones. The numbers within the ellipses distributed over the different basins (Arctic Ocean, North and South Atlantic Oceans, Indian Ocean, North and South Pacific Oceans) correspond to the excess (sign +) or deficit (sign -) of tidal energy computed from the balance between the energy received from astronomical forcing and the energy dissipated over each basin. The units are also in GW.



4.3 TOPOGRAPHY AND GLOBAL OCEAN MODELS (*by R. Tokmakian* and A.J. Semtner**)

4.3.1 Introduction

Global ocean models have now become very realistic (Semtner, 1995). Various modelling efforts using different formulations at increasingly higher resolutions are helping to expand our knowledge of the circulation of the global oceans. The different modelling efforts can be categorized by the equations used to define the flow (primitive equation, quasi-geostrophic, or hydrodynamic) and by how they define their vertical and horizontal structure (z-level, layer, or isopycnal models). All the models require that the topography of the ocean be known to some extent to produce realistic flows. This paper describes some of these models and how topography determines the flow and other physical aspects of the ocean. In addition, thoughts are provided as to where increasing our knowledge of the bathymetry may lead to improvements in the simulations of the global oceans. Because of the authors' familiarity with the primitive equation, z-level model known as Semtner/Chervin (or Parallel Ocean Climate) model, most of the examples will be from this model, but with a few examples from other models.

Modellers have long incorporated some sort of topography into their models. Initially, because of the model formulations and limitations in computer speeds, the topography was required to have simplified coastlines and very smooth topography. With increasing resolution and more accurate numerical formulations, models can now include more complicated geometries. In the early 1990s, the Semtner/Chervin model (Semtner and Chervin, 1992) was formulated at a resolution of one-half degree and with a smooth topography created from the ETOPO-5 bathymetric data set. Incorporating a direct computation (or prognostic) of the surface height field rather than indirectly using the density field to compute the surface pressure field and increasing the resolution to 1/4 of a degree on average (Stammer, et al. 1996), a more detailed topography is now included in the Semtner/Chervin model. This model formulation allows islands and steep bathymetric features to be resolved. Other methods may allow topography to be refined further, such as using a variable bottom coordinate system or the use of hybrid coordinates; that is, combining the use of z-levels in the model's top layers and sigma (density following) layers in the bottom regions of the model. Currently the Semtner/Chervin model's bottom layer is 400 metres thick, with the mid-point at 5.

4.3.2 Influence Of Topography

The topography of a model influences the flow in several ways. It can affect the mean of the flow, the variability, or the thermohaline (or flow due to density) flow. In addition, topography may enhance vertical mixing and the correct coastline definition influences the variability near the coasts. Examples of each of these are given in turn.

<u>4.3.2.1 Mean Abyssal flow</u>

Increasing the resolution of the grid from one-half degree to a resolution of an average one-quarter degree with a free surface, allowed the model topography of the Semtner/Chervin model to include many islands and small resolution features. An example of the change in the flow can be seen in Figure 4.3.1a and b, showing the mean of the abyssal flow between 3 and 5 km for the 1/2 degree and 1/4 degree models, respectively. The topography of the 1/4 degree model (Figure 4.3.1b) now includes many more topographic features. A close look at the flow east of New Zealand near 35°S, 170°W shows that the mean flow has been altered, affecting the amount of water that is transported northwards around the Louisville Ridge structures.

In an effort to improve the circulation in particular areas of their 6 layer hydrodynamic model, a team at the Naval Research Lab (NRL) modified the bathymetry in various regional areas starting with the ETOPO-5 database and extending it with the use of Defense Mapping Agency (DMA) data, the London Times Atlas and personal contacts. The report of their work, McManus, Townsend, and Metzger, 1995, gives the specific locations where specific modifications were made. Figure 4.3.2 (taken from Figure 3 of the McManus et al. report) shows the differences in transport in the Intra-Americas Seas. It is believed that the changes allow the model to simulate the complicated flow in the region more accurately.

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4.3.2.2 Variability

Variability of the ocean's circulation can also be affected by the shape of the topography. In Gille's Ph.D. thesis (Gille, 1995), a comparison of the 1/4 degree Semtner/Chervin model eddy kinetic energy field with Geosat altimetric data (Figure 4.3.3, Gille's figure 4.20) shows the difference in the model EKE values versus that of Geosat. Gille states "unlike the model results which suggest that only three topographic features are important in the momentum balance, the altimeter data show a broader energy peak at Drake Passage (60°W), and increased energy near the Crozet Plateau (40°E) and at the Eltanin and Udintsev Fracture Zones in the central Pacific (140°W)", suggesting that these additional ridge structures are also sources of increased eddy kinetic energy.

Wilkin and Morrow (1994) examined the 1/2 degree Semtner/Chervin Model looking at the flow over the Macquarie Ridge. The model's topography is too broad and has almost no variability in the flow, while Geosat shows somewhat increased eddy kinetic energy (EKE) in this region. The conclusion is that the very steep bathymetry of the Macquarie Ridge is contributing to the EKE seen in the data (but not in the 1/2 degree model) by causing instabilities in the flow as it crosses the ridge. The model results in this region are somewhat improved in the 1/4 degree resolution version.

4.3.2.3 Thermohaline flow

In the deep water, flow occurs due to changes in density rather than being forced at the surface by wind. Speer, Mercier, Messias, and Memery, 1994 and Mercier and Bryden, 1994, show how topography influences the deep flow. The Romanche Fracture Zone in the mid-Atlantic constricts the flow of Antarctic Bottom Water flowing northward, causing it to pile up behind a deep sill. The flow then cascades over the sill into the eastern Atlantic. The model without the resolution in the topography, does not simulate this process correctly, although recent examination of the deep flow shows some flow north-eastward in the general area. Additionally, various sills and trenches in the Arctic ocean influence the bottom flows and need to be defined precisely.

Another region which depends heavily on having correct topography is Indonesia. The flow in and around these islands is the major pathway for Pacific Ocean water to flow into the Indian Ocean as part of the so-called "ocean conveyor belt". The Semtner/Chervin models allow for too much flow through some pathways and not enough through others. Part of the problem is that the model resolution is not fine enough. But also, the ETOPO-5 topography in this region is thought not to be accurate.

4.3.2.4 Enhanced mixing

Mixing of water vertically has also been seen to be affected by the topography. In the region of the Arctic Ocean, a high resolution primitive equation model (one-sixth of a degree on average) shows that with tidal forcing, vertical mixing is enhanced over extreme topographic features (Parsons, pers. comm.).

4.3.2.5 Coastline Definition

The definition of coastlines will also contribute to the accuracy of the temporal variability that a model simulates occurring at the coast. Figure 4.3.4 shows a comparison between the 1/4 degree Semtner/Chervin sea level heights and the sea level as measured by a set of tide gauges along the western coast of America. The model simulates these features, including the 1992 El Niño signal well at the first 3 stations between 9°N and 6°S. The high resolution model topography allowed for in the 1/4 degree model over the 1/2 degree Semtner/Chervin model, partly is responsible for the reproduction of the ocean flow in this region.

4.3.3 Summary

As has been briefly described, modelling of the global ocean depends on an accurate bathymetry to correctly simulate the mean and variable ocean circulation patterns. Specifically, in regions that include many small scale features such as in Indonesia or the Caribbean, an accurate topography should improve the circulation. Second, sills and trenches in areas where deep flow occurs between one basin or another should be carefully handled. And third, the producers of bathymetric data sets should strive to produce sets which are accurate to the grid resolution which modellers are working towards, namely 1/12 of a degree or greater.

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Figures

Figure 4.3.1 (upper) Velocity averages between 3 km and 5 km depth, from Semtner/Chervin models comparing a 0.5 degree model (upper panel) with a 0.25 degree model (lower panel). The 0.25 degree model includes many islands and small resolution topographic features. The white areas represent shallow water, with the topographic bulge at 43°S and 180°-190°E representing the New Zealand Plateau. Here mean flow has been altered, affecting the amount of water transported north over the Louisville Ridge.

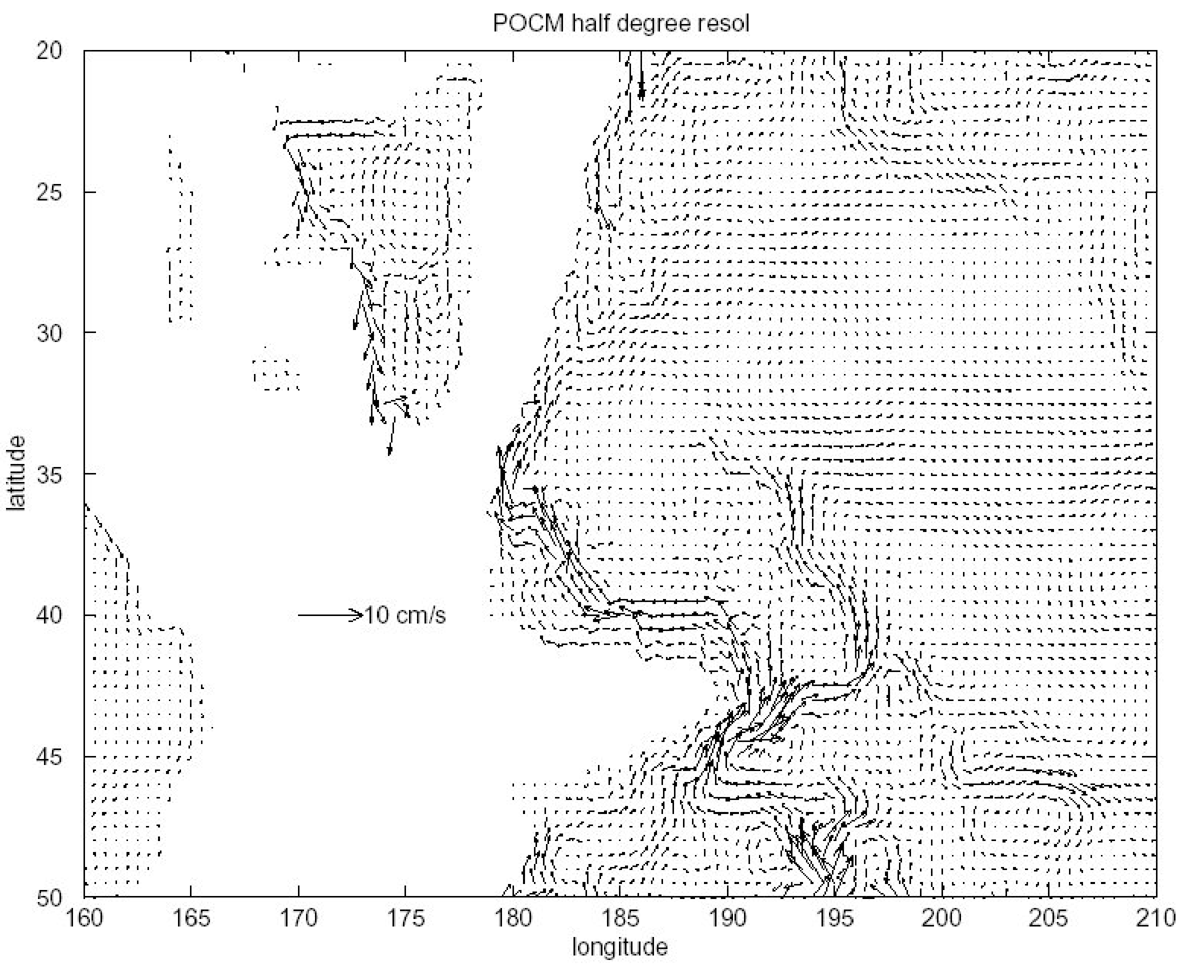
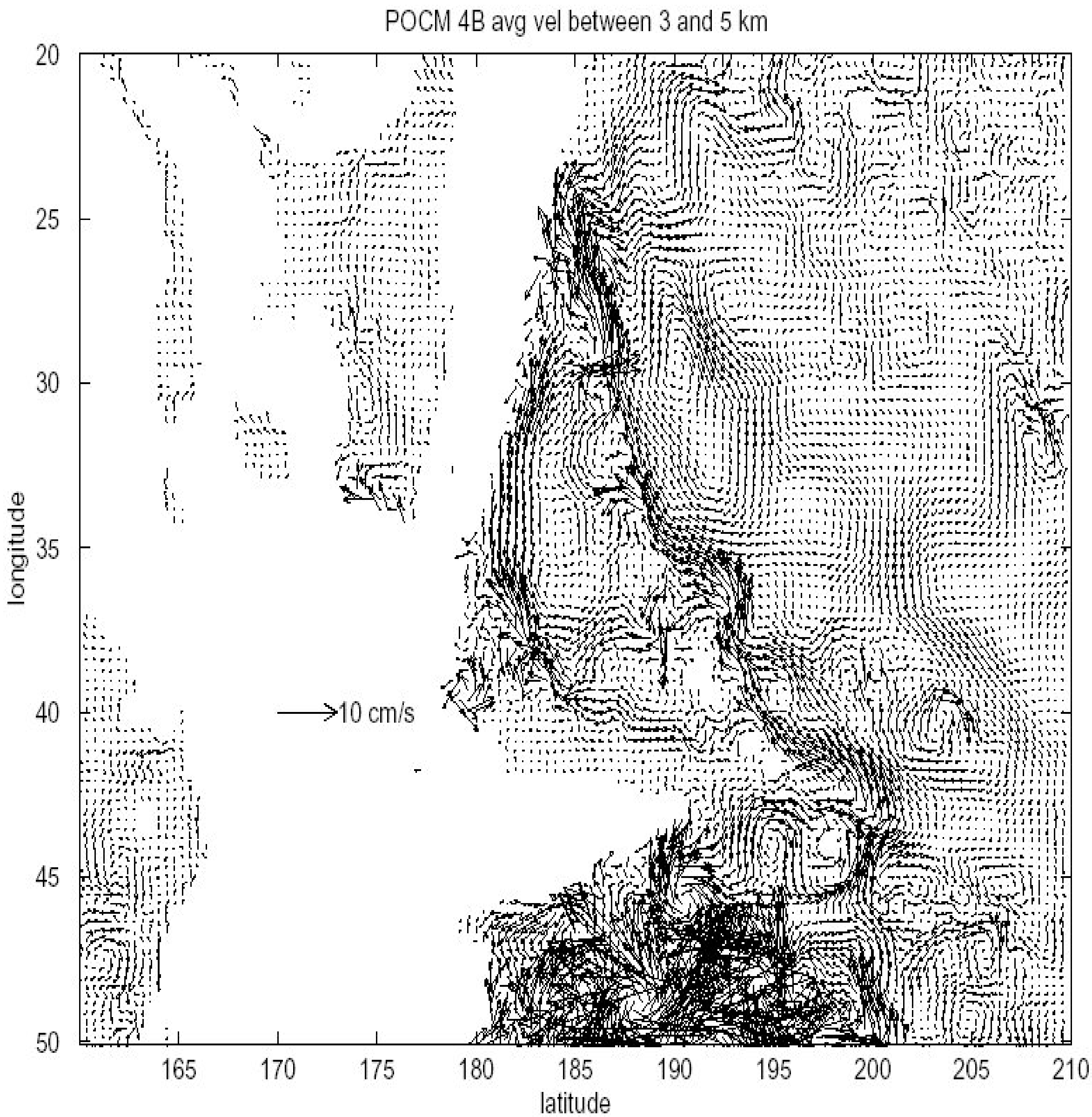


Figure 4.3.1 (lower) Velocity averages between 3 km and 5 km depth, from Semtner/Chervin models comparing a 0.5 degree model (upper panel) with a 0.25 degree model (lower panel). The 0.25 degree model includes many islands and small resolution topographic features. The white areas represent shallow water, with the topographic bulge at 43°S and 180°-190°E representing the New Zealand Plateau. Here mean flow has been altered, affecting the amount of water transported north over the Louisville Ridge.



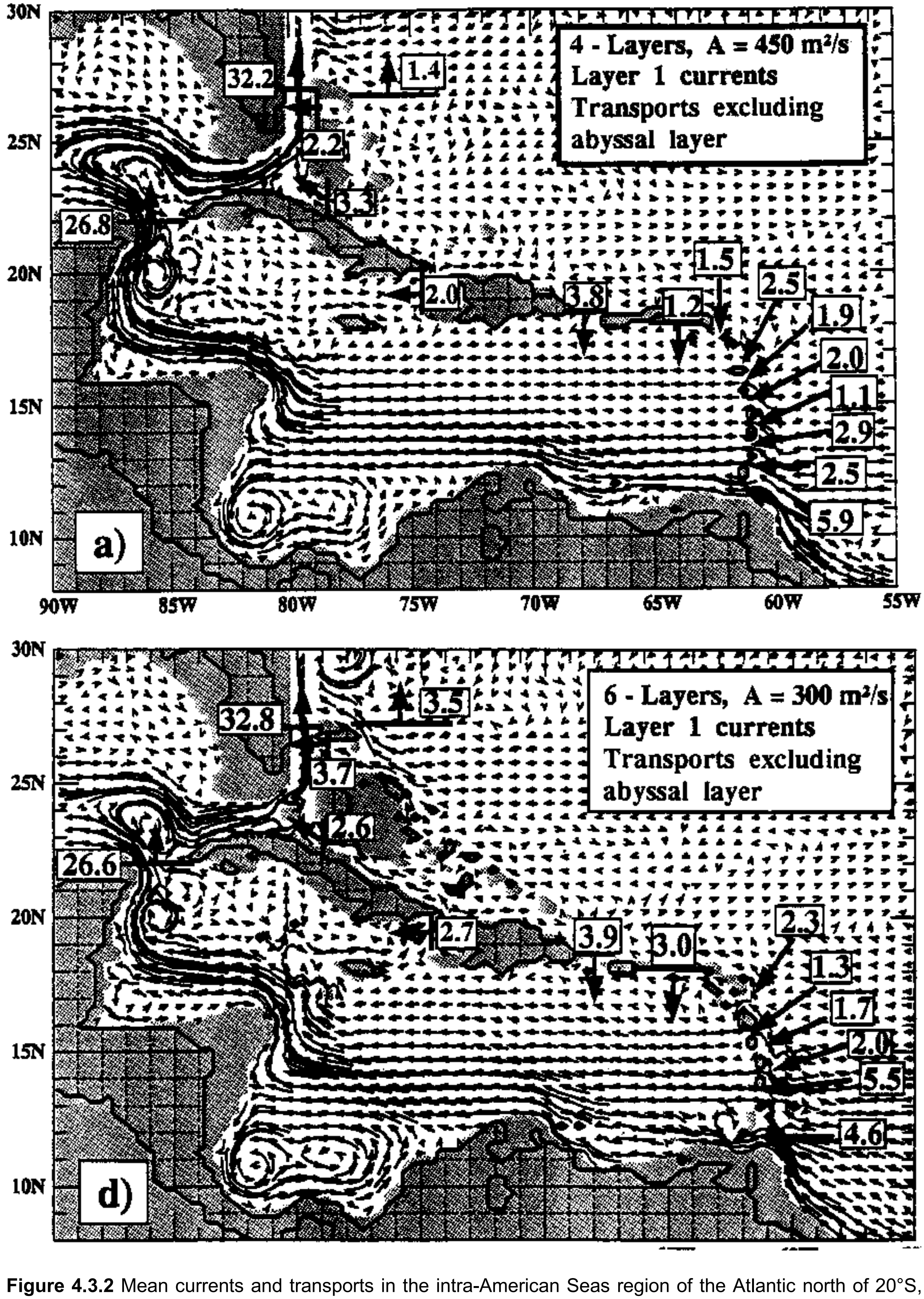


Figure 4.3.2 Mean currents and transports in the intra-American Seas region of the Atlantic north of 20°S, from the 0.25 Naval Research Laboratory Ocean Model (NLOM), with a model boundary based just on ETOPO-5 data (upper panel) and with improved bathymetry (lower panel).

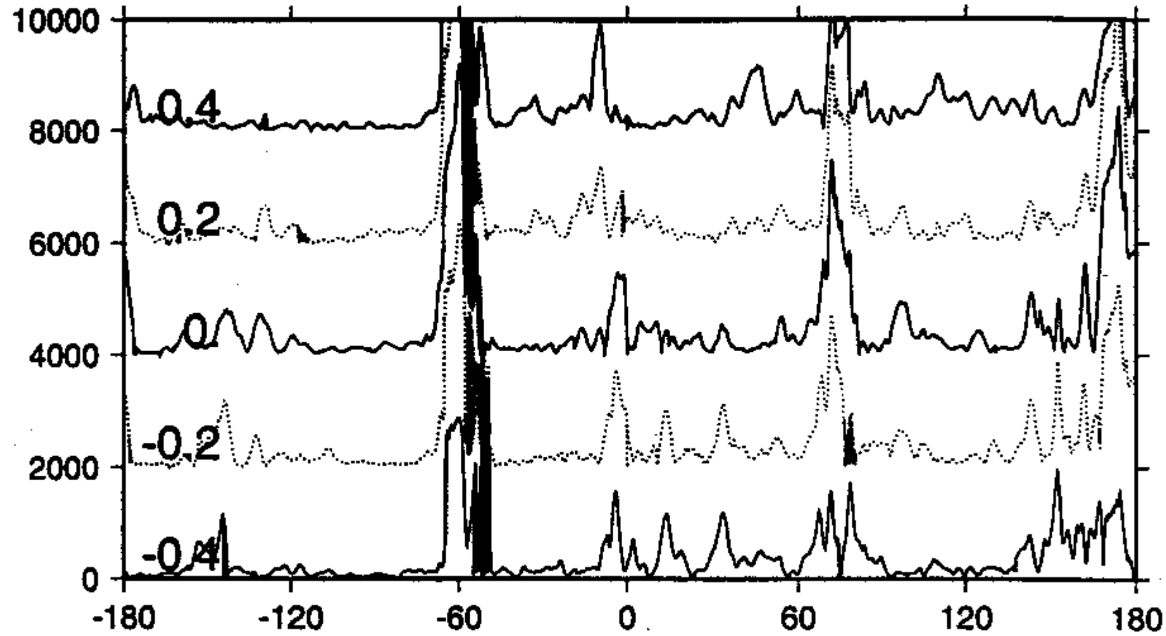
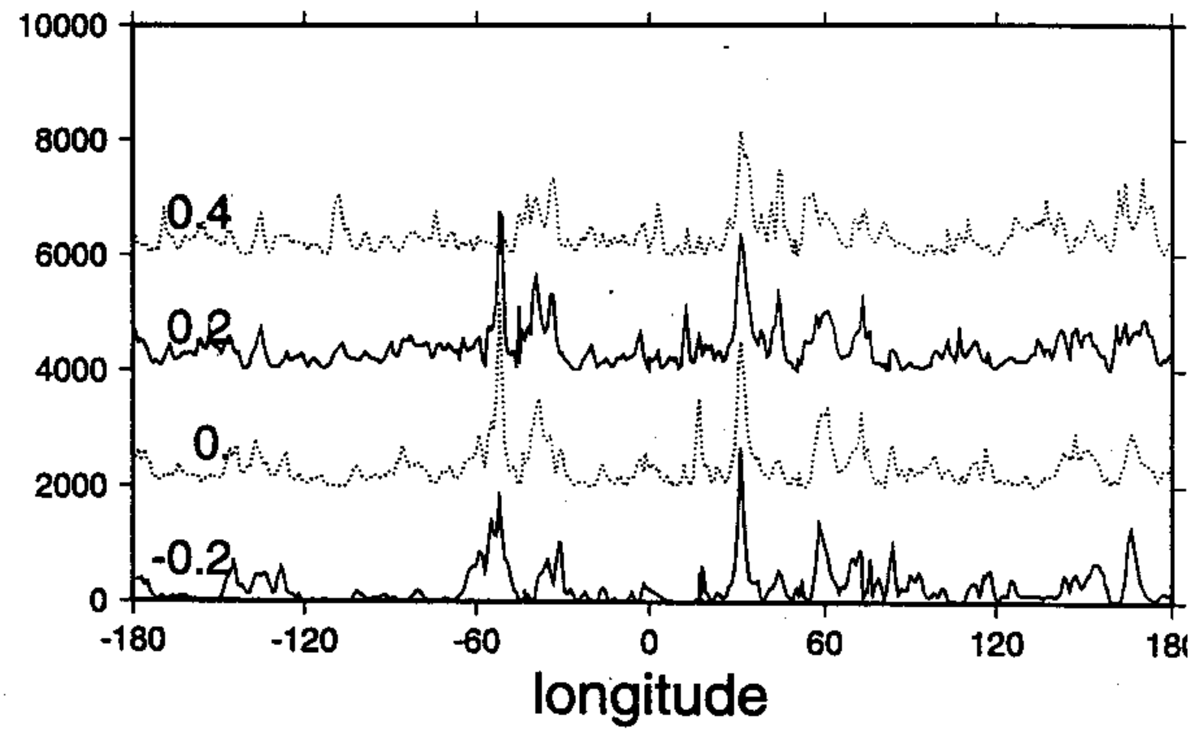


Figure 4.3.3 Mean kinetic energy along surface height contours.
Upper panel = energy for 0.25 degree Semtner/Chervin model output in cm^2sec^{-2}, along height contours corresponding to -0.4, -0.2, 0.0, +0.2, +0.4 metres;



Lower panel = mean energy along height contours in Geosat altimeter data, for contours -0.2, 0.0, +0.2 and +0.4 metres. Average error is 160 cm^2sec^{-2}.

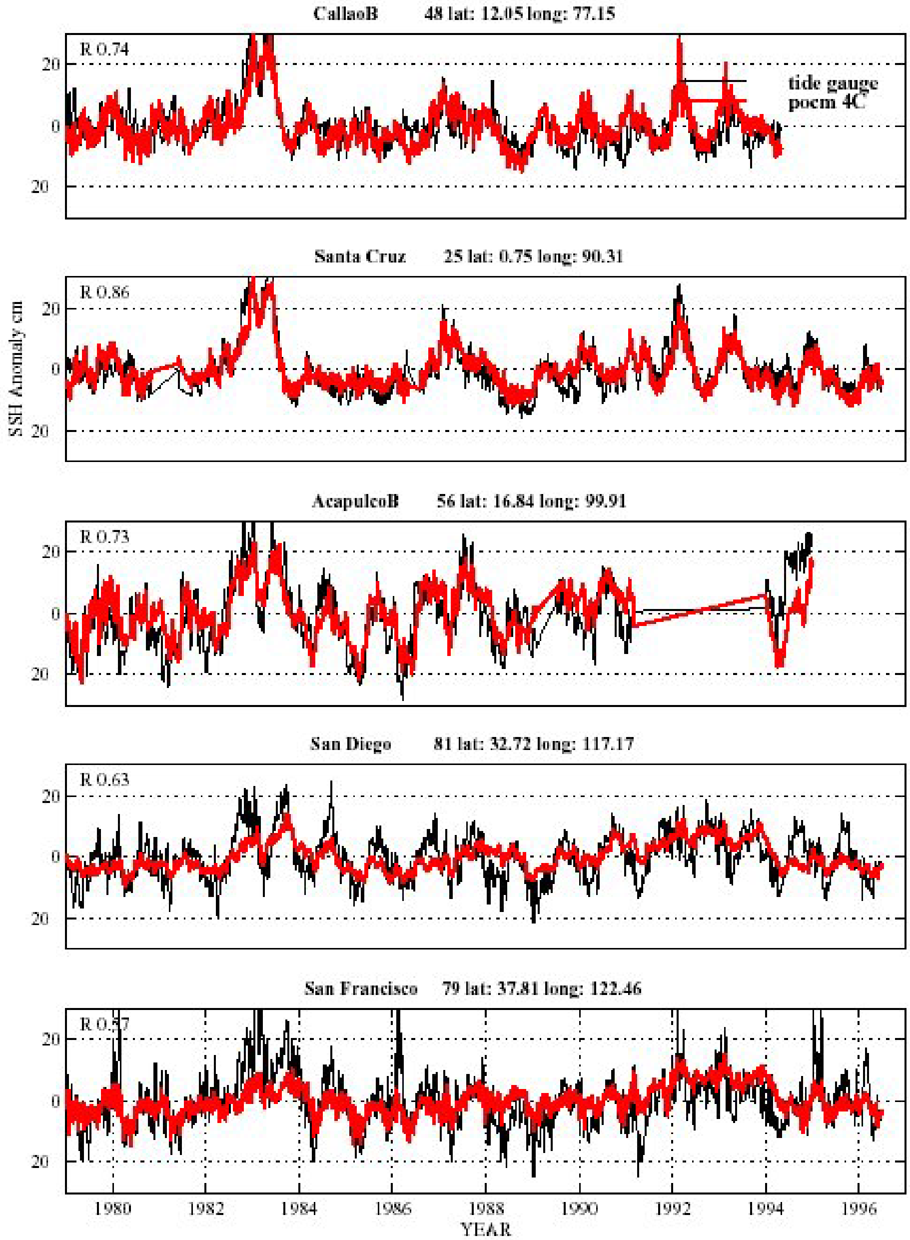


Figure 4.3.4 Comparison of tide gauge sea-level data (thin line) with model sea surface height (heavy line).

4.4 SENSITIVITY OF OCEAN MODELS TO DIFFERENT BATHYMETRIES (*by R.Tokmakian*)[*]

4.4.1 Introduction

As a part of the SCOR WG 107 on Improved Global Bathymetry, two ocean model simulations were compared in light of their bathymetry, which was constructed from two different data sets. Although the two simulations are not directly comparable, their formulations are related and can provide an indication of the difference in circulation patterns that would result using one bathymetric data set or the other.

First, a brief description of the models. At an average resolution of 1/4 degree (Mercator grid) the Parallel Ocean Climate Model (POCM) (Stammer, et al., 1996) has 20 levels in the vertical. The model is closed off at 65°N and does not include the Arctic. The second model is the fully global Parallel Ocean Programme (POP) (McClean, et al., 1998) model at an average resolution of 1/3 degree. The grid is rotated in the northern hemisphere to avoid singularities at the pole. The POP model has 32 levels in the vertical. Both models are primitive equation models with a free surface formulation, which allows for topography as rough as the grid scale to be incorporated. In other words, no smoothing is applied to the topography other than that required to fit the spatial and vertical grids. A long-term mean from each of the runs is used for the comparison, 9 years for the POCM and 15 years for the POP model. Both model runs are forced with similar wind stresses derived from ECMWF 10-metre winds.

The bathymetry for the POCM has been derived from the ETOPO-5 data set, while that for the POP model is derived from the relatively new Smith and Sandwell (1997) data set. This second data set was created by combining satellite altimetry measurements of gravity with available depth soundings. The two data sets are related in that some of the depth soundings are also used in the ETOPO-5 bathymetry.

Several regions are examined to determine the influence of the topography on the circulation patterns. Regions with relatively shallow and deep topographic features are examined. The shallow regions are the flow through Indonesia and the Florida Straits. Deep flow is examined in the area of the Romanche Trench (approximately at the equator along the mid Atlantic Ridge) and the Crozet Plateau area in the Southwest Indian Ocean.

4.4.2 Shallow Regions

In the Indonesian seas, Figure 4.4.1, the left plot shows the surface circulation from the POCM model, and the right is that of the POP model. *In situ* measurements show that the flow into the Indonesian seas is mostly through the Makassar Strait, 3.5°S, 115°E (Gordon, et al. 1998), while a small amount of flow passes through to the east *via* the Eastern Channel (3.5°S, 120°E). The POCM model and a similar model at 1/6 degree have a much reduced inflow through the Makassar Strait, the POCM model transport through the strait being approximately 2 Sv. With the new bathymetry, the POP model simulation produces a flow through the Makassar Strait much higher and more realistic at 8.52 Sv (McClean, pers. comm.).

In the Florida Straits, Figure 4.4.2, the two simulations show somewhat different flows, which are both different from what is observed. Schmitz and Richardson (1991) give a transport of 28.8 Sv for the flow into the Caribbean Sea through 4 passages (Granada, St. Vincent, St. Lucia, and Dominica) in the Lesser Antilles plus southward flow through the Windward Passage (between Haiti and Cuba). The POCM simulation's bathymetry does not include the Lesser Antilles, but the total flow between Puerto Rico and South America is 19.34 Sv westward, comparable to the total of 18.9 Sv westward, calculated from the *in situ* measurements. The POP model at 1/3 degree, which includes these islands, shows a total transport of 13.6 Sv westward, with the discrepancy due to the small transport through the Granada passage (4.6 Sv vs. 1.4 Sv). It can be seen in Figure 4.4.2b, that the island of St. Vincent is too large, and with its reduction the transport would most likely increase. In another simulation of the Atlantic at 1/10 degree using the POP model (Smith, et al., 1998), the transport through the Florida Straits is much better, approximately 18Sv, approaching the 28.8Sv seen in observations. Both the 1/3 degree POP model and the POCM show a transport through the Florida Straits on the order of 8Sv. North of 24 degrees, the Florida Current transport is about right, because the northward flow to the east of the Bahamas has joined the flow coming through the Straits. Thus, both the topography and the resolution affect the strength of the flow into and out of the Caribbean and through the Florida Straits.

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4.4.3 Deep Flows

Two areas have been chosen to look at the deep flows. The first is an examination of the flow in the Romanche Trench area (Figure 4.4.3). Speer and Mercier (1994) and Mercier and Bryden (1994) calculate a transport of Antarctic Bottom Water (ABW) of 2.4Sv over the sill in the Romanche Fracture Zone (0.5°N, 15°W) between 3,000 and 4,000 metres. This flows from the Brazil Basin on the west into the eastern basin. The fracture zone is completely missing from the topography of POCM, but it is in the bathymetry of the POP simulation. However, neither simulation produces the flow as seen in observations, that of ABW flowing into the eastern basin (Figure 4.4.3). The reasons for the inaccurate simulation are many. Neither model shows true ABW at this latitude, and the model may need more accurate physics for flow over sills. Figure 4.4.3 does show very different flow to the right of the Mid-Atlantic Ridge, with the POCM having much stronger flow than in the POP simulation.

The other area of deep flow which was examined was that around the Crozet Plateau in the Southwest Indian Ocean (Figure 4.4.4). To the north of Crozet, the deep flow in the region of the Subtropical Front (43°S, 42°E) at a depth of 1980 metres is about 1.22 Sv in POCM, while POP shows a similar flow of 1.38 Sv. Through a trough in the Plateau (46°N 50°E), the Polar Front flows north with a transport of 1.65 Sv in POCM and a more constricted flow of 0.39 Sv in the POP simulation.

4.4.4 Summary

Two ocean simulations have been compared in four areas with respect to their bathymetry. Improvement in the circulation can be related to the incorporation of the new topography in the POP run in the area of Indonesia and the Florida Straits. Other areas, such as the Romanche Trench, have a more accurate bathymetry, but the flow is still not correct due to other inaccuracies in the model. The new topography of Smith and Sandwell (1997) when combined with a higher resolution model such as at 1/10 degree should produce an even more realistic flow.

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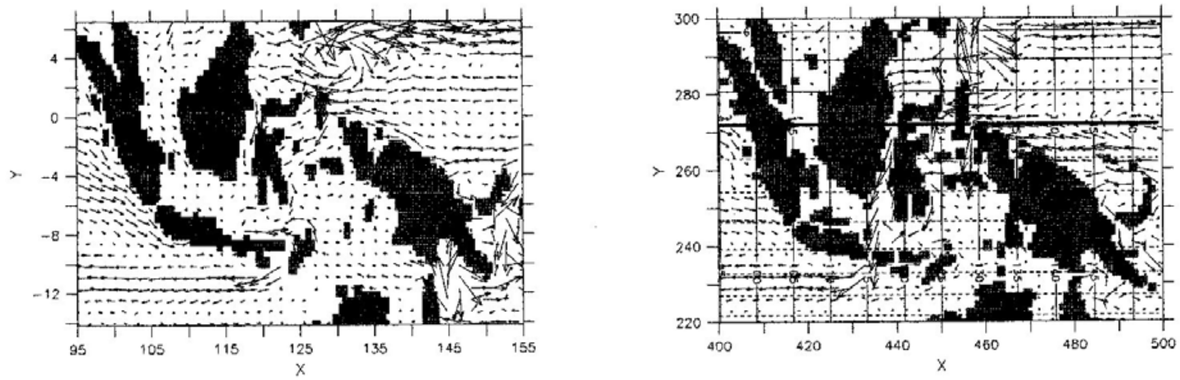
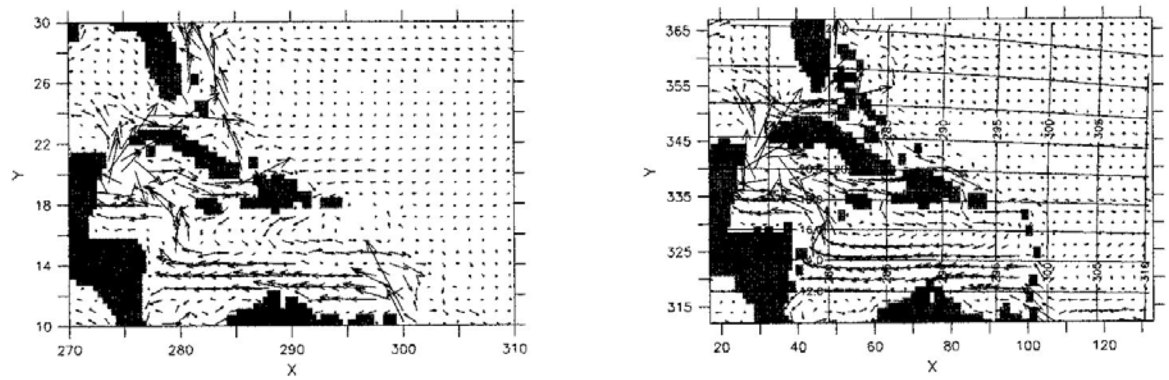
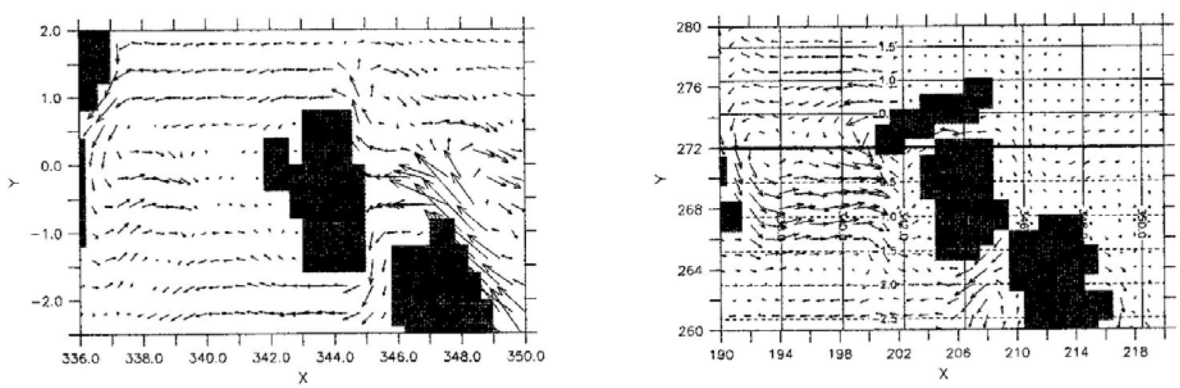
Figures



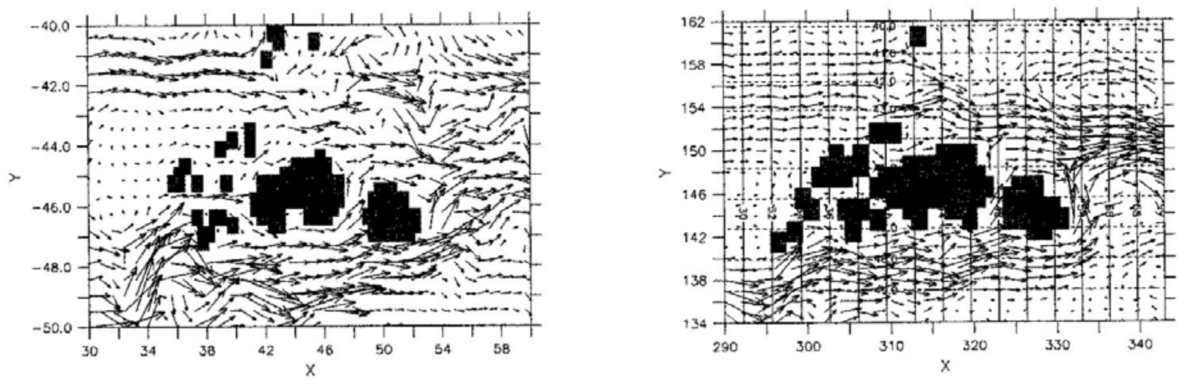
4.4.1. a) Surface flow (37.5 m) of POCM in the region of Indonesia; vector is in cm, axes are latitude and longitude.
b) Similar region for POP simulation; axes are X, Y grid points (due to rotated grid), overlaid with latitude/longitude lines; vectors are in cm.



4.4.2. a) Surface flow (37.5 m) of POCM in the region of Florida Straits; vector units are in cm. Axes are latitude/longitude.
b) Similar region for POP simulation (1988 m); axes are X, Y grid points (due to rotated grid), overlaid with latitude/longitude lines; vectors are in cm.



4.4.3. a) POCM deep flow (1975 m) in region of Romanche Trench; vector units are in cm. Axes are latitude/longitude.
b) Similar region for POP simulation (1988 m); axes are X, Y grid points (due to rotated grid), overlaid with latitude/longitude lines; vectors are in cm.



4.4.4. a) POCM deep flow (1975 m) in region of Crozet Plateau, Southwest Indian Ocean; vector units are in cm; axes are latitude/longitude.
b) Similar region for POP simulation (1988 m); axes are X, Y grid points (due to rotated grid), overlaid with latitude/longitude lines; vectors are in cm.

4.5 TOPOGRAPHIC REQUIREMENTS NEAR SILLS FOR OCEAN MODELS (*by P.D. Killworth**)

4.5.1 Theory of flows through sills

The flow of the ocean is intrinsically tied to the shape of the topography over which it moves. These effects vary from gradual steering by slowly varying topography to outright blocking effects by abrupt topography and coastlines. In between these extremes, and ubiquitously, are the narrow straits and sills that form the connections between deep ocean basins (Thompson's 1995 survey lists over 100 sills and straits; Saunders' 1998 shorter listing is enclosed as Table 4.5.1, below). A deep water mass is forced to pass through these constrictions if it is to leave one basin and enter another. In some cases this is accompanied by less dense water flowing in the opposite direction (the Gibraltar Strait is a good example, with light Atlantic water entering the Mediterranean while denser Mediterranean water leaves westwards for the Atlantic).

The dynamics of these straits control the amount of water passing through them. The transport through a strait, in turn, directly determines the water mass structure in both basins. This is because the transport gives a time scale for the basin to empty, which in combination with source terms for the basin water masses, implies particular temperature and salinity characteristics. Thus the structure and transformation of large scale water masses in the ocean owe much to control at sills; and, by extension, so does the manner in which ocean climate changes (cf. Bacon, 1998). If ocean general circulation models are to correctly simulate climate change it is essential that they accurately represent sill and strait flows.

The problem of hydraulic control has, of course, been studied for over a century. Despite this, understanding of the problem in an oceanic context, where stratification and rotation may both be important, is lacking. Stratified flows have almost exclusively been treated in a layered context, examples being Armi and Farmer (1986) and, more recently, Odulo et al. (1997). Continuous stratification has been treated mainly as a similarity problem, including Wood's classic (1968) paper, and more recently Williams and Armi (1991). Killworth (1992) is one of the few studies of the behaviour of a fully stratified fluid, although multiple layer approaches can yield similar answers (Engqvist, 1996).

These papers all related to non-rotating fluids. The problem becomes considerably more difficult when rotation is added, since cross-sill variability appears. Pratt and Lundberg (1991) give a review, and Whitehead (1995) gives a partial review of more recent work. Almost all work in situations other than single layer channel flow has needed gross simplifications, the most popular being a restriction of the potential vorticity to a uniform value, either zero or some arbitrary constant. Neither of these choices are physically realistic, since they necessarily imply changes in along-sill velocity across the sill whose values are much higher than observed. Killworth and McDonald (1993), Killworth (1994, 1995) address maximum principles in a single rotating layer with arbitrary potential vorticity distribution, and show that the Whitehead et al. (1974) laboratory results form an achievable upper bound to the sill through-flow for such configurations. Almost no work addresses the effects of friction, with Johnson and Ohlsen (1994) being an important exception. Effects familiar from non-rotating studies such as shock fronts, etc., remain far from understood (Nof, 1986; Pratt, 1987). Exclusively, no attempt has been made to include the barotropic flow component, which will react with the topography and stratification on length scales which differ from either those of the topography itself or the internal deformation radii; Wadley and Bigg (1996) show how difficult it is to create a meaningful numerical problem in this vein.

Another fundamental difference between rotating and non-rotating flows is the manner in which the upstream (and downstream) flow approaches the sill. In non-rotating fluids this occurs as a wide slowly varying, usually sub-critical, flow. In a rotating fluid, for most extant solutions, the upstream flow is confined to a boundary layer, so that upstream flow, and geometry, details are not only important, but can dominate the solution.

A major omission in theories is that of time dependence, despite early work by Wang (1987, 1989). Flows through sills are unsteady for two reasons: first, they are naturally unsteady because of internal dynamics such as instabilities; and second, they are unsteady because of externally varying forcing such as tides, seasonal variability, etc. In natural situations in which rotation plays only a minor role (such as the

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Gibraltar through-flow) tides often induce major variability (Bryden et al., 1994). In particular, the interface between in- and outflow rises and falls at the sill during the tidal cycle. Helfrich (1995) showed that the effects of such forcing were important in a two-layer non-rotating model when particle excursion or signal propagation during a period of the forcing was of the order of the along-sill length scale, and unimportant either in the limit of little or very large excursion. In other words, rapidly varying forcing 'averaged out', while slowly varying forcing had a response that resembled the local steady state at that part of the cycle. Helfrich also found that, unlike most theories of hydraulic control, geometric details of the entire sill area affected the through-flow.

Adding rotation to unsteady flows introduces a new time scale, the rotation period, and so may change the parameter regime for which rapid oscillations can be averaged out. For example, tidal forcing occurs at periods close to the inertial period and so may be able to initiate Kelvin or topographic waves at the sill.

This brief summary of theoretical work on sills has glossed over some fundamental limitations that the theories possess:

- the sills are assumed to be 'slowly varying' along the sill, in the sense that across-sill variations are much more rapid than along-sill;
- flows are assumed laminar, despite observations of baroclinic and barotropic instability in sills;
- the dynamics are largely assumed to be those of a perfect fluid, with little extant work on effects of mixing of water masses and of momentum, despite clear observations that mixing is important in most sills.

To date, we have a variety of formulae representing flow over sills:

- Non-rotating, one-layer, reduced gravity flow of fluid whose surface upstream is a height h above the height of the 'col' of the sill has a hydraulically controlled flux of $(g'(2h/3)^3)^{1/2}$, where g' is a reduced gravity for the layer
- Non-rotating two-layer exchange flow (e.g. Gibraltar in- and out-flow) has a maximum controlled flux of $0.25WH(g'H)^{1/2}$ where W and H are the width and depth of the sill, assumed rectangular
- Rotating, one-layer, reduced gravity flow in the same configuration has a maximum controlled flux of $g'h^2/2f$, where f is the Coriolis parameter
- There are no extant formulae for rotating, stratified fluid flow at sills.

The first two of these formulae assume simple geometries and so can be viewed, in some indeterminate sense, as bounds on the through-flow. The last of these is explicitly an upper bound, and Killworth (1994) shows ways to compute the reduction factor for other given, but still simple, geometries. In general for any of these formulae, the 'real' through-flow would be given by some fudge factor multiplying one of these formulae, the value of which would be determined numerically in some manner we do not yet understand how to achieve.

4.5.2 Needs of numerical models

4.5.2.1 Coarse resolution models

Coarse resolution models, such as those used for climate studies, are the most sensitive to details near sills. Roberts and Wood (1997) give an enlightening example (Fig. 4.5.1). It shows the topography of the Greenland-Iceland-Scotland ridge in the Met. Office coarse resolution z-coordinate model climate model. The top diagram shows the original topography used. This resulted in no net flow across the ridge. Changes in topography by as little as one grid box, indicated in the lower three diagrams, resulted in gross changes not only to cross-ridge flux (12 Sv being achieved in the bottom diagram) but also to the location of this flux, and to the composition of the water mass actually crossing the sill. Put another way, a 50% change in heat flux at the GIS ridge latitude can be achieved by the addition or subtraction of a single grid box. It is unclear whether the most realistic results are given by excavating to the deepest, widest, or deepest and widest, points. Certainly current practice of taking median or (worse) mean depth over the grid point using a source of fine resolution depth data is flawed if used in coarse models.

4.5.2.2 Medium-resolution models (eddy-permitting)

To date, even the finest resolution global models cannot resolve the sill flows adequately; for example, the DYNAMO inter-comparison of three eddy-permitting N. Atlantic models (Willebrand et al., 2001) showed large differences between the three model responses in the Denmark Strait, despite – formally, at least – the models possessing the same forcing and topography. For the foreseeable future, even eddy-permitting models, to function adequately, will need parametrisations of some kind to represent sill flow correctly; the problem is far more urgent for the ocean component of coarse resolution climate models, which usually have to undertake major excisions of ocean floor even to possess a sill between basins at all.

4.5.2.3 Fine-resolution models (eddy-resolving)

Recently, two truly fine-resolution, local, studies have been performed, simulating the Vema Channel and Romanche Fracture Zones. In both cases, it was possible to obtain an accurate simulation with sufficient resolution. In the Vema Channel simulation by Jungclaus and Vanicek (1998), the float behaviour observed by Hogg was reproduced, with the flow switching sides within the channel (as predicted in theory by Straub 1998). Again, there was strong mixing and re-circulation present. Ferron's Romanche Fracture Zone used high vertical resolution (and free slip on the vertical walls to lessen frictional retardation) and a realistic mixing scheme (Mellor-Yamada). The fit with data is shown in Fig. 4.5.2. High vertical mixing rates (0.1 m^2 s^{-1}) are found downstream of the sills. It was important that local depth and constriction widths were included accurately (as well as boundary conditions, no-slip being vital). Resolutions of 5 or 10 km along-channel, and 2.5 or 5 km across-channel, and 20 m vertically, were required for this simulation. Orientation of the channel (including straightening!) made little impact.

Thus there are examples when numerical modelling with 'adequate' resolution has been capable of reproducing reality. However, (a) this resolution is far beyond the ability of any climate model in the foreseeable future, and (b) without either data or large resources, it remains impossible to determine what constitutes 'adequate' resolution.

4.5.2.4 Other approaches

In all cases, the conditions on either side of the sill in numerical models change with every time step, so that a parametrisation of the sill through-flows in each layer (or level) must be one that reacts to external change. In a simple one-layer reduced gravity model, unpublished attempts to include Killworth's (1994) maximal flow results as a parametrisation result in growing two-grid-point numerical noise; a similar finding occurs if, for example, a unit Froude number is simply imposed in a one-dimensional channel model at a point of maximum topographic height. Unpublished work by Pratt and Chechelnitsky (1997) begins to suggest an approach based on wave propagation both in the basin and near the sill, but connecting both sides of the sill, and accounting for potential hydraulic shocks, is still a major problem. The approach has not been tested in numerical models to our knowledge.

How much information, then, would an eddy-permitting numerical model need to function 'correctly'? (Quote marks are used since we do not really know how we would measure or define the word at present.)

Numerical modellers have two possible approaches. One is to use some method, e.g. nested grids, to have truly fine resolution in the vicinity of each sill, thus actually solving the equations of motion properly. Given the large number of sills in Thompson's list, this is probably impractical, but we pursue the problem anyway for completeness. The only clue as to resolution required is that the grid spacing to yield quantitatively correct answers is a small fraction of a 'deformation radius', the natural length scale for ocean dynamics. This scale increases with stratification and decreases with f, thus being largest near the equator (high stratification, low f) and smallest near the poles (low stratification, high f). Thus if such a scale is to be well resolved, grid spacings must be small compared with the smallest deformation radius relevant, which is of the order of 5 km in the Arctic. This argument would imply a spacing of around 1 km for topography information in such areas. In addition, non-ideal dynamics would require extra information such as roughness lengths, etc.

Gerdes and Beckmann (unpublished) have extended Fox and Maskell's (1996) work to see if nesting can be used as a general method to improve the representation of passage through-flows. Two-way nesting experiments were performed with a 1° geopotential co-ordinate model of the Northern North Atlantic, between 50°N to 75°N. A nest was placed in the Denmark Strait and around Iceland, twenty by ten degrees wide. The resolution inside the nest was increased by a factor of 3, both horizontally and vertically. As a reference, experiments without the nest and with increased resolution throughout the domain were conducted. The focus of this study was on the effects of the nest on the coarse grid solution. The expected effects of the nesting approach were twofold: (a) a less diffusive (more advectively dominated) solution, with less wide/thick currents; (b) widening of passages.

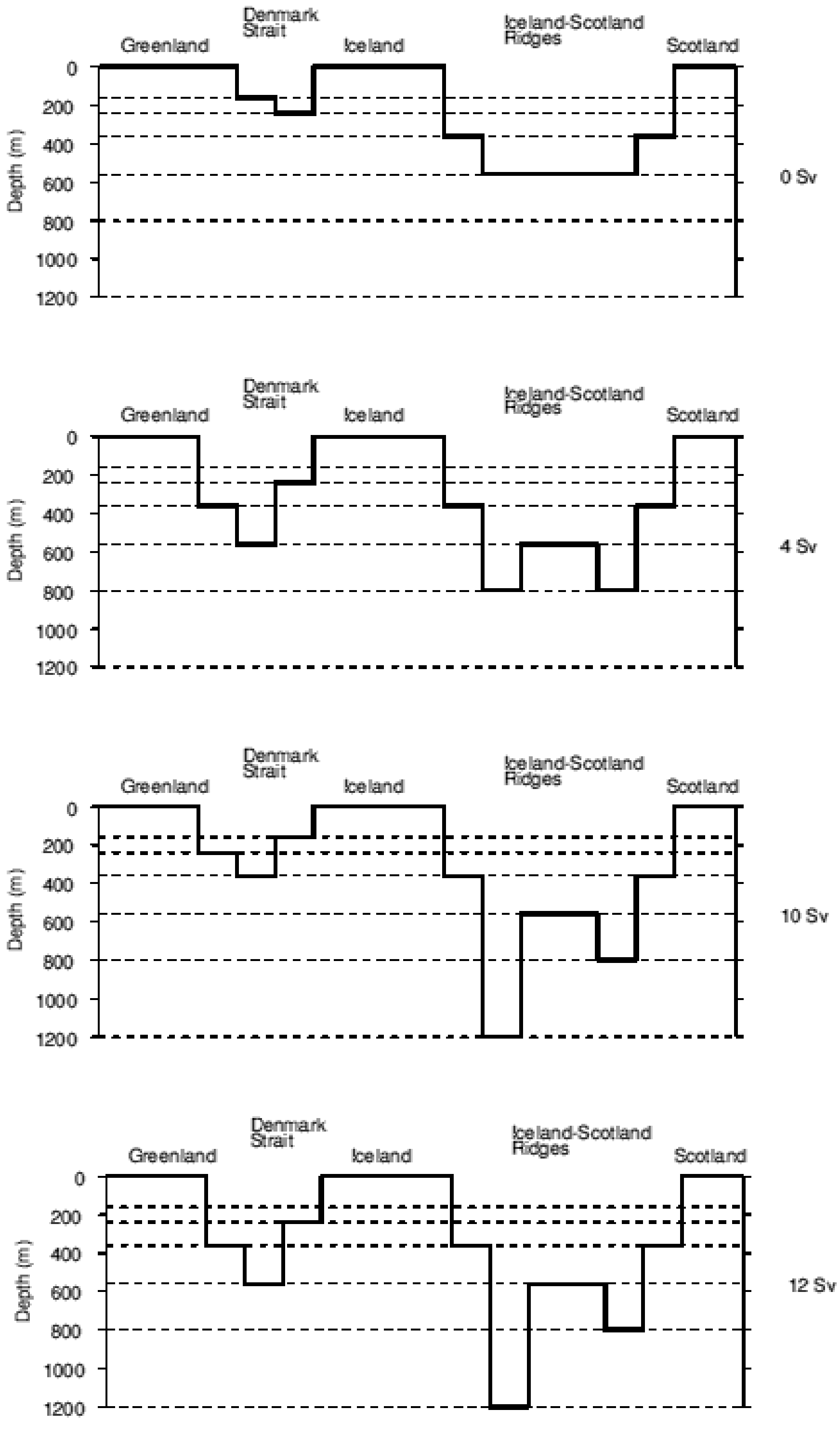

Figure 4.5.1 adapted from Roberts and Wood (1997). The variation in net throughflow (in Sverdrups, equal to 1 million $m^3\ s^{-1}$) at the GIS ridge as the topography is varied in a coarse resolution model. Grid point depths are shown by dashed lines, and grid point widths are as indicated.

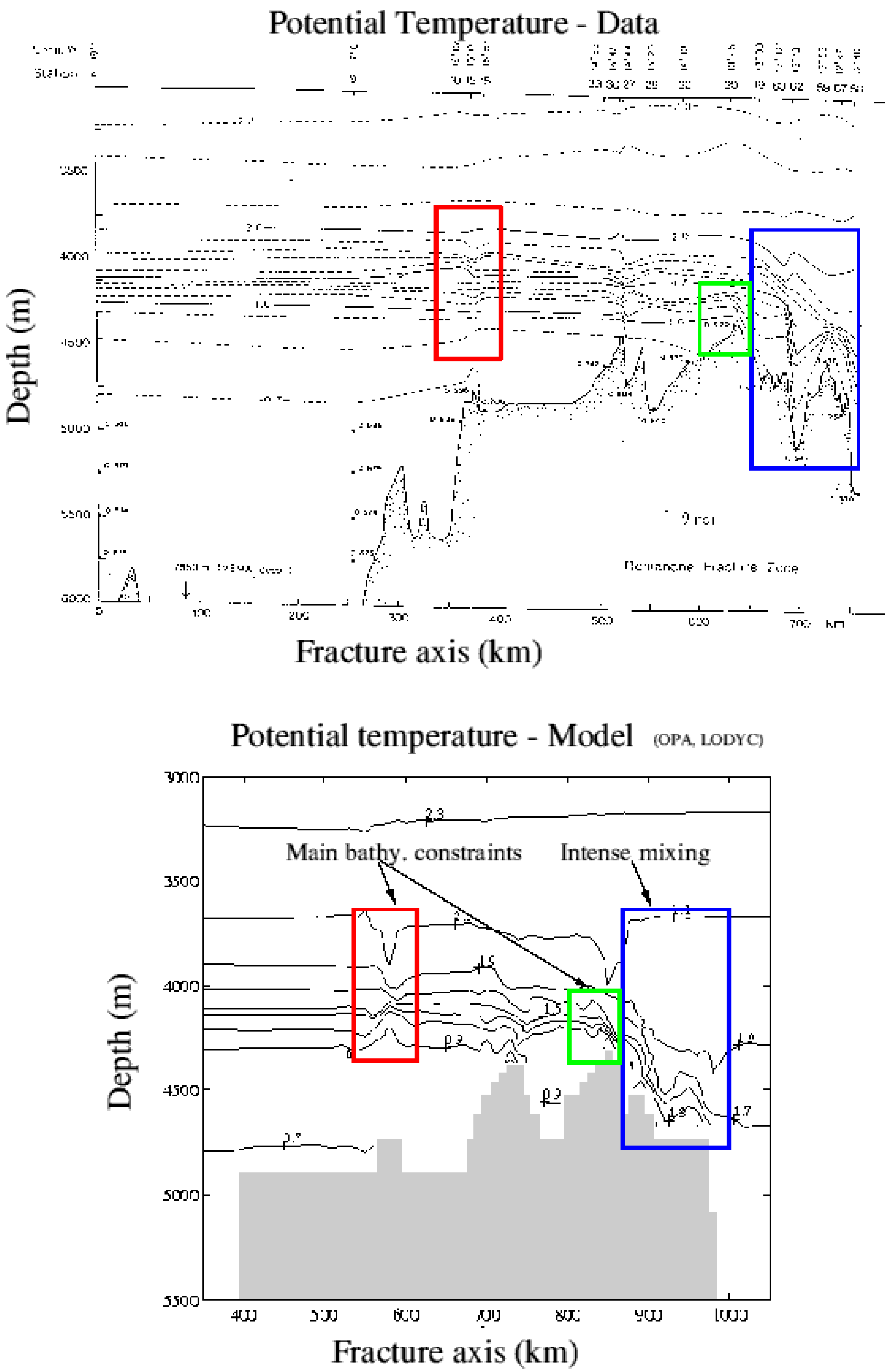

Figure 4.5.2 (from Ferron, 1998) Simulation and data from the Romanche Fracture Zone, using a very fine resolution model.

The results can be summarized as follows:

1. Technical aspects: some restrictions to topography in the nest need to be considered: volume conservation; isobaths should intersect the nest boundaries at right angle. There is a rather strong sensitivity of the results on the placement of the nest boundaries.
2. While one way nesting works fine and in the expected way (i.e., the solution inside the nest looks much better), two-way nesting failed to improve the solution outside the nest significantly: apparently, the necessary averaging at the nest boundaries reduces the impact of the nest too much.
3. Even a moderate nesting factor (3 in this case) can cause partial reflection at the nest boundaries, both inside and outside the nest. This can be reduced by additional smoothing, averaging in time, or restoring zones at the nest boundaries; however, these measures further reduce the net effects of the higher resolution in the nest on the outside domain.
4. Nesting is expensive; for a nest area of, say, 2% of the horizontal domain at a three-fold increase in resolution leads to an additional CPU requirement of 2% × 3^4 = 162% of the original model, even without the coupling overhead.
5. With respect to the opening of passages, the overall impression was that (without a bottom boundary layer – BBL – model) the improvement was small.

It was felt that stronger nesting ratios would prove even more problematic with respect to partial refection of waves, and increase costs dramatically; nesting in sigma or isopycnic models might perform better, because the topography is assumed to vary smoothly between grid points; and a combination of nesting and a BBL sub-model may improve matters (this is untested).

In conclusion, nesting alone does not solve the problem of through-flows in coarse resolution z-co-ordinate models. However, despite these difficulties, it is clear that nesting remains an approach which must be further investigated, as it is a natural approach at least for sills which are generally accepted to be important to climate.

The second approach is to use a parametrisation such as those above (though, as noted, these do not work in time-varying situations). For wide sills that are well resolved, like the Bering Strait in the OCCAM model, simple frictional parametrisations can be used successfully (though their physical applicability is not guaranteed). It is likely that the parametrisations will be specifications of time derivatives of flows and tracers at some key point near the sill, which will connect with a similar key point beyond the sill in the other ocean basin. To get these parametrisations will involve both theory (of the kind discussed above) plus high resolution model runs for the specific sill to obtain the fudge factors to add to the parametrisations. Thus again, high topographic resolution will be needed.

A third approach – to deduce the fudge factors by monitoring the flow through a sill, together with upstream, downstream, and meteorological data, is beyond international observing abilities at this time.

4.5.3 Conclusion

For numerical general circulation models to function correctly and represent water masses and through-flows adequately, resolution of topographic sills on the scale of about 1 km will be needed, no matter which approach is used to handle the problem of the sills.

<u>Table 4.5.1</u>: Sills and Straits *(Prepared by Peter Saunders, Southampton Oceanography Centre)*

Simon Thompson wrote a manuscript entitled “Sills of the Global Ocean: a compilation”. This was published in Ocean Modelling issue 109, Oct. 1995, but the material is also on the Web at the OCCAM site: www.soc.soton.ac.uk/JRD/OCCAM/sills/furthersills.html. Thompson describes the location, sill depth and width of 100 sills.

Below I list sills and straits for which transport estimates have been made, in all cases employing moored current metre arrays. Many of these measurements were not made in the WOCE period. Transport determinations have been made at other locations using hydrography alone. I know of no way of estimating the reliability of theses latter estimates and so have not included them.

<u>Atlantic Ocean</u>

FRAM STRAIT: S.Jonsson and A.Foldvik 1992; ICES Hydrog. Comm. CM 1992/c:10, 10 pp.
DENMARK STRAIT: Ross, 1984 supported by more extensive measurements by R.R. Dickson and J. Brown 1994; JGR 99, C6, 12319-12341.
FAEROE BANK CHANNEL: P.M. Saunders 1990; JPO 20, 29-43.
CHARLIE GIBBS FRACTURE ZONE: P.M. Saunders 1994; JGR 99, C6, 12343-12355.
STRAIT OF GIBRALTAR: H.L. Bryden, J. Candela and T.H. Kinder 1994; Prog. Oceanog. 33, 201-248.
FLORIDA STRAIT: K.D. Leaman, R.L. Molinari and P.S. Vertes 1987; JPO 17, 565-583 and for a long time series J.C. Larsen 1992; Phil. Trans. R. Soc. Lond. A 338, 169-236.
DISCOVERY GAP: P.M. Saunders 1987; JPO 17, 631-643.
CEARA RISE: M.M. Hall, M. McCartney and J.A. Whitehead 1997; JPO 27,(9),1903-1926.
ROMANCHE FRACTURE ZONE: H. Mercier and K.G. Speer 1998; JPO 28(5), 779-790.
VEMA CHANNEL: N. Hogg, P. Biscaye, W. Gardner and W.J. Schmitz 1982; J.Mar.Res. Supplement V40, 231-263 and N. Hogg et al. 1998; in preparation.
HUNTER CHANNEL: W. Zenk et al. 1998; in preparation.
DRAKE PASSAGE: T. Whitworth III and R.G. Peterson 1985; JPO 15, 810-816.

<u>Indian Ocean</u>

STRAIT OF BAB EL MANDAB: S.P. Murray and W. Johns 1997; Geophys. Res. Let. 24, (21), 2557-2560.
CROZET KERGUELEN GAP: R.R. Dickson et al. 1996; EOS Trans. AGU, 77(46) Supplement p. 406 and R.R. Dickson et al. 1998; in preparation.

<u>Pacific Ocean</u>

BERING STRAIT: L.K. Coachman and K. Aagaard 1988; JGR 93(C12), 15535-15539.
TIMOR PASSAGE: R. Molcard, M. Fieux and A.G. Ilahude 1996; JGR 101(C5), 12411-12420.
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VITIAZ STRAIT: S. Murray, E. Lindstrom, J. Kindle and E. Weeks 1995; US WOCE Notes 7(1), 21-23.
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4.6 OCEAN TOPOGRAPHY FOR OCEAN MODELLING *(by D.J. Webb[1])*

The following key points formed the core of a presentation to the Working Group by David Webb at the meeting in Southampton.

(i) The ocean modelling community needs bathymetric data on a regular grid. DBDB-5/ETOP05 uses a 5-minute grid. Presumably it is accurate in well-surveyed regions and is less accurate in remote areas of the ocean. Any new data set should us a 5-minute grid or better.

(ii) Over most of the ocean an accuracy of 50m is required. Where there is a question of the representativeness of the measurement, it should be the best estimate of the average depth of the surrounding grid cell. The depth should be in metres, with no additional correction for sound speed.

(iii) Priority should be given to providing better measurements of bathymetry in the sill regions between the major ocean basins. (A preliminary list of such sills is given, on the www, in http://www.soc.soton.ac.uk/JRD/OCCAM/sills.html).

(iv) Where the sill region is to narrow to be resolved well in the main dataset, additional information is needed on the depth of the sill, it's width and any other information on factors which might affect the flow past the sill. The latter may include information on nearly choke points, a vertical cross section of the main channel at the sill, the length of the main channel and information on nearby secondary channels.

(v) At a lower level of priority are surveys of regions that steer the major currents. For example, for the ACC such regions include, Drake Passage, the northern and north-eastern flanks of the Kerguelan Plateau, and the south-eastern flank of the Campbell Plateau off New Zealand.

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4.7 THE TSUNAMI PERSPECTIVE (*by H.Yeh*[1])

A tsunami is a gravity water wave that is generated by dislocation of the ocean bottom, for example, due to seismic faulting, volcanic eruption, or submarine landslide. A typical wavelength of a fault-generated tsunami in deep water is in the order of several tens to hundreds of kilometres. Hence even over a 4000-m deep abyssal plain, its propagation and evolution are strongly affected by the bottom bathymetry. Even tsunamis generated by volcanic eruption and submarine landslides have much longer wavelengths than storm-generated waves. Once a tsunami approaches a shore, the shoaling of the seabed causes the wavelength to decrease and the amplitude to increase. Hence, unlike other ocean-related topics, tsunami analyses require integrated bathymetric data for entire ocean basins plus dry coastal topographic information on the valleys that tsunamis may run up once they have crossed the shoreline. Furthermore, detailed information for temporal and spatial variations of bathymetry at tsunami source is critical to determine the generation mechanism of tsunamis, although it is extremely difficult to monitor such ocean-floor variations and is even impractical at the present time.

Accurate and high-resolution bathymetric data are required for numerical simulations of tsunami generation, propagation, and run-up on coastal areas. In addition, bathymetric data are needed for placement of tsunami instruments, development of tsunami inundation mapping, assessment for submarine landslides, and hind-casting earthquake source mechanisms by solving the inverse problem. No matter how sophisticated the prediction models are, unless the data on bathymetry and coastal topography are sufficient, predictions from the models are unreliable and might yield misleading information.

In the tsunami research community, the importance of bathymetric and coastal topographic data have been emphasized and discussed recently at several workshops. The following report is based on the last of a series of the workshops, which was held in Seattle in 1998 (the International Workshop on Bathymetry and Coastal-Topography Data Management) and funded by the NSF (USA) and the ESTO (Japan) (Yeh, 1998).

For tsunami computations, resolution finer than, say, 1-minute (around 2 km) may not be necessary in deep-water bathymetry (deeper than 2,000 m, approximately). Nevertheless, if there is a narrow canyon or ridge say 2km wide in water say 1000m deep, then a 500m grid would be needed for accurate modelling. Deep-water bathymetric data have improved considerably with the advent of satellite altimeter data (Smith & Sandwell, 1994). Deep-water bathymetric data are likely to be improved significantly in the next few years, through cooperative international efforts.

A problem remains in shallow-water bathymetric data (from continental slopes and shelves), where much finer resolution is critically required for proper tsunami computations. Our estimate (Yeh, 1998) shows that a grid size smaller than 500 m is needed for the continental shelf less than 250 m deep; indeed, perhaps a 100 m grid size is desirable. A 100 m grid is needed where the depths are less than 10 m, and a 50 m grid where depths are less than 2.5 m. The available data are often not collected with such fine resolution. Furthermore, since shallow-water bathymetric data are usually collected and managed by regional organizations for regional interests, bathymetric data sets are often not as coordinated internationally and not as standardized as deep-water data. In most countries hydrographical charts are copyright and cannot be digitized without the approval of the national Hydrographic Office. Despite these difficulties there have been considerable recent advancements and improvements in the application of the multi-narrow-beam echo-sounder systems, which can provide high-resolution bathymetric maps of shelf areas. There is an urgent need for shallow-water bathymetric data to be pooled, standardized, and managed by some appropriate international organization(s).

The vertical datum for shallow-water bathymetry is a serious concern, because a small difference in a datum creates large (relative) errors in bathymetry. Since tsunami computation requires the integrated data of deep-water and shallow-water bathymetry, and coastal topography, a non-unified datum for the various data causes troublesome inconsistencies and makes conversions difficult. In general, topography data are often measured from MHHW (mean high high water) level and bathymetry data are customarily measured

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from MLLW (mean low low water) level. Note that there are at least 66 different datums all around the world, e.g. Tokyo pale, Osaka pale, MLLW, MLW, MSL, MHW, MHHW, Highest Astronomical tidal level, Lowest Astronomical tidal level, etc.

During the Seattle workshop, participants attempted to establish a standardized datum to make the conversion of digital data to other datums convenient. A common datum for both bathymetry and topography is needed bearing in mind the need for an efficient procedure for integrating bathymetric data with coastal topography data. Participants reached a consensus that the most appropriate common datum for both bathymetry and topography data is the WGS84 system of a mean-Earth ellipsoid. A minor problem with this choice is that the actual sea surface may deviate up to 30 m above or below the ellipsoid surface. Hence such data without conversion are inappropriate for a specific use: e.g. navigation, construction, and tsunami computations. However, this datum is time-invariant and is directly related to the present measurement practice with the global positioning system (GPS). Once we set this common datum and manage the data in the format of latitude, longitude, depth or elevation based on this datum, the data can be readily converted to other datums and vice versa. The conversion algorithm to other datums from the ellipsoid surface should be provided, as well as the local tide information. Once all the data are converted to the format (latitude, longitude, depth or elevation from the ellipsoid surface), the local depth of interest at any time can be computed by the conversion algorithm and tide information.

Even though the emphasis of the Seattle meeting was on digitized gridded and/or contour data sets, the raw data information must be retrievable so that data accuracy and precision can be estimated. Even if the original raw data cannot be open to the public, information about, for example, the measurement densities, should be given so that the accuracy and precision of the processed data can be estimated. One example is the JBIRD data set developed by JODC. Within a given mesh (approximately 1 km by 1 km), the following information is given in the coding: 1) mesh code (indicating the mesh location), 2) average depth value, 3) the minimum depth, 4) the maximum depth, 5) the number of raw data points, and 6) the standard deviation. Such data coding provides sufficient information about the raw data without presenting the raw data themselves. It is desirable that such coding for unavailable raw data should be standardized internationally. When the data are updated, it should be based on the original raw data to avoid, where possible, processing (modifying) the previously processed (modified) data.

The Seattle meeting attempted to identify areas where data were especially deficient. Shallow-water bathymetric data and topographic data are commonly unavailable from remote areas.

In summary, for tsunami research it is essential to acquire accurate and integrated data from the entire ocean basin including coastal topography up to 30 m above sea-level or up to 5 km inland from the shore-line. Shallow-water bathymetric data and coastal topographic data with a common datum are the topmost priorities.

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5. THE MARINE GEOLOGICAL PERSPECTIVE

5.1 THE NEEDS OF MARINE GEOLOGY AND BATHYMETRIC CAPABILITY (*by A.S. Laughton[*]*)

5.1.1 Deep sea sounding capability

Until the advent of echo sounding in the 1920s all data on oceanic depths were obtained by the means of a weighted line and "feeling" the bottom. The first attempt to contour the world's oceans was made in 1903 when cartographers, financed by Prince Albert I of Monaco, interpreted the collection of 18,000 line soundings and published the first edition of the General Bathymetric Chart of the Oceans (GEBCO).

Since then technology has enabled a rapidly increasing number of soundings in the oceans to be acquired. The early echo sounders, indeed up until the 1950s, used a rather inaccurate timing system based on a governor-controlled motor. The watch-keeper was required to time 32 revolutions of the rotating stylus with a stopwatch and apply corrections to the recorded depth. Because of the limited arc of recording of the sounder and because of errors and uncertainties of phase, many of the soundings submitted to the database were inaccurate and sometimes considerably in error.

The demands of marine geologists in the mid 1950s for accurate depth measurements produced the Precision Echo Sounder (Luskin et al. 1954), in which the timing was crystal based and the recording technology based of the linear sweep of the facsimile machine, developed for the transmission of meteorological maps. These echo sounders were still using the relatively wide beam transducers resulting in the bias of soundings to off-track shoaled areas and the confusion of multiple hyperbolae. Narrow beam echo sounders gave refined delineation of the profile under the ship but gave no information about depth off-track, so that parallel survey tracks had to be extremely close and well navigated to give saturation surveys.

The impetus to overcome this problem came in the late 1960s and early 1970s from the US Navy because of the increasing importance of submarine warfare and anti-submarine activities. Transducers that wrapped around the hull of the ship gave a fan of narrow beams in the transverse direction that could be processed, by the computer techniques that were becoming available, to give a wide swath of discrete soundings. Combined with the forward motion, contour charts could be continually generated during survey and saturation surveys were carried out.

The Harris Array system, as the multi-beam echo sounder was called, was classified until details were published by Glenn in the International Hydrographic Review (Glenn, 1970). The US Navy used the system extensively for defence purposes but regrettably for science the data was classified and unavailable. Once released, the multi-beam swath bathymetry techniques were taken up by industry and a number of commercial systems are now installed and widely used on survey and research ships all over the world. A review in April 1996 for the GEBCO Guiding Committee by Norman Cherkis of the NRL showed 183 ships worldwide are equipped with seafloor swath mapping systems.

At the same time marine geologists required more detail of the shape of the sea floor and had to develop their own techniques. Submarine sonar was developed into geological side-scan sonar for oblique insonification of the continental shelf and gave sonographs that were equivalent to sub aerial views of land topography in a setting sun. The system was translated in the late 1960s and 1970s into a long range deep ocean side-scan sonar (GLORIA) which has been extensively used in conjunction with swath bathymetry to survey more than 5% of the ocean floor (Laughton, 1981).

Whilst GLORIA has been able to give rapid surveys of large areas and delineate the major geological features, the demands of marine geologists were for ever greater detail. Near bottom side-scan sonars such as Deep Tow and it's various successors have filled this need albeit limited to slow speeds and small areas.

There is now a substantial armoury of swath echo-sounding and side-scan sonar systems that can address virtually all of the needs of the marine geologist, the surveyor, the defence community or the sea floor engineer.

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5.1.2 Navigation

Measurement of depth is not meaningful unless the position of the measurement is known. Until the advent of radio aids, navigation away from the coast depended on celestial observations, which in cloudy conditions were frequently unavailable. Decca, Consul and Loran radio aids were introduced in the post war years but were of limited coverage. Global coverage was not available until Transit satellites were in operation in the 1960s, but even these were infrequent (one to two hours between satellite fixes) and were subject to various errors.

It was not until the advent of GPS in recent years that position fixing in the open ocean ceased to be a problem and instant and continuous fixes were routinely available.

Until Transit and GPS, detailed surveys of morphological features required radar navigation relative to anchored buoys. Ranges were limited to some 20 miles depending on the radar and on whether radar transponders were used, and there were constant problems of buoy movement due to the scope of the mooring and to dragging anchors in areas of high current or bad weather. It is surprising, in the face of these difficulties, that sensible surveys were in fact made.

The consequences of these navigational difficulties is that many of the soundings taken before the present decade or two suffer from uncertainties in position that may amount to several miles. Combining data from different cruises and different eras requires judgement and frequently correction in depth and position.

5.1.3 Bathymetric Data-bases

On a regional basis and for the purposes of navigation, the collection and banking of survey data in the coastal and continental shelf regions was, and is, the responsibility of national Hydrographic Offices, who use the data to prepare navigational charts.

Apart from the navy requirement for deep ocean bathymetry for military purposes, resulting in classification, the acquisition of deep-sea soundings was limited to survey ships on passage and to research vessels. These were, on the whole, randomly distributed over the oceans, and little coordinated effort has been made to obtain a uniform coverage.

Following the International Geophysical Year in 1957-58, international databases were set up for a wide range of geophysical data. WDC A and WDC B were set up in the USA and in the USSR respectively. The role of data centre for oceanic soundings was delegated by WDC A to the International Hydrographic Office in Monaco, who set up a network of national Hydrographic Offices to create and maintain plotting sheets collecting all oceanic soundings at a scale of 1: 1,000,000 in designated areas. These manually generated (but latterly computer printed) plotting sheets have recently been phased out following the recognition that all sounding data is now acquired and submitted in digital form.

The IHO was unable to handle the massively growing digital database of soundings, many of which were going straight to the National Geophysical Data Centre of NOAA in Boulder, Colorado. The USA offered to become the international data centre for digital soundings under the auspices of the IHO. This now operates under the name of the "IHO Data Centre for Digital Bathymetry" (DCDB).

Strict conditions are laid down by the IHO for the incorporation of data into the IHO DCDB and these have been developed by IHO in conjunction with NGDC and with GEBCO. These are published by the IHO in BP-0007 " GEBCO - Guidelines for the General Bathymetric Chart of the Oceans" (IHO, 1991) which includes chapters on the GEBCO Organizational Framework, Bathymetric Data Management (both analogue and digital data), Single Beam Echo-sounder Data, Multi-beam Echo-sounder Data and Underway Geophysics.

All new sounding data should now be submitted via national hydrographic or other offices to the DCDB, which maintains a global marine geophysical database called GEODAS which is accessible both as a CD-ROM and through the Internet.

5.1.4 Global coverage of sounding data

In 1995 GEODAS received over 1.5 million soundings increasing the total holdings to some 30 million soundings. Compare this to the 18,000 soundings that were the basis for the first GEBCO charts of 1903! The base holds 13 million miles of track on which soundings were taken giving a global average of 8 nautical mile track spacing. But this is very misleading since the vast majority of tracks are in the intensely surveyed coastal regions.

By 1958, one of the most densely sounded sheets of the GEBCO 4th edition, sheet AI in the central North Atlantic, was based on 370,000 soundings whereas in the South Pacific, sheet B'II published in 1955, was based on only 9,000 soundings. Today this contrast still exists. In the Southern Oceans there are regions several hundred miles wide in which no soundings have ever been recorded. Even in the North Atlantic there are regions fifty miles wide without sounding data.

This contrast in sounding density is not unexpected on account of the inaccessibility of the Southern Oceans, but is of concern to those who study global aspects of geology. Compare this to the topographic database that is available to land geologists.

But numbers alone can be deceptive. This database includes data that have been collected over many decades with different instruments, different depth accuracy and different quality of navigation and includes some gross errors in depth and position. Many tracks are along almost identical routes from port to port or radiate from islands. They have a highest concentration where research or survey has been done for reasons unrelated to the morphology and along port-to-port passages.

The sounding database is extremely anisotropic. Along track the spacing of plotted soundings is about 1 nautical mile, limited by the scale of the plotting sheet, although the original data would allow depth soundings every few seconds. In contrast across the track, the spacing may be tens or even hundreds of miles. This anisotropy poses severe problems for the generation of contours, both manually and by computer.

For many years the scientific community was aware of the existence of huge areas of detailed survey that had been carried out for defence purposes but was classified and hence unavailable to science. Fortunately some of this has now been declassified but without indication of it's origins and hence it's reliability. The first declassified swath soundings were those made available as contoured "P- charts" for the mid-ocean ridge study, Project FAMOUS, in 1973 (Phillips and Fleming, 1978) and contributed significantly to the subsequent submersible and geophysical studies. However there are still significant areas of what one assumes are high quality surveys that are still classified and one can only guess at where these might be.

5.1.5 Needs of the marine geologist

The problems of the geology of the ocean floor range from the understanding of the global processes that generate the large-scale features down to the detailed mechanisms generating micro-topography. Luckily, compared with the parameters needed by physical oceanographers, the morphology does not change significantly, with a few exceptions, over the lifetime of the geologists and definitive mapping can be done once and for all.

Naturally the geologist will ask for the highest resolution and the most complete bathymetric coverage that is available to provide the basis for his interpretation, and in addition side scan sonar data that can give the backscattering characteristics and a continuity of image that is not available from swath sounding. In the study of small features, such as vents, seamounts, channels, faults and fracture zones, this does not present a problem. But with ocean scale or global features the lack of coverage severely limits the interpretation, particularly of the remoter areas of the Pacific and southern oceans. It is up to the current generation of marine earth scientists to identify where the greatest limitations at present are. It is interesting to note that the morphological details of the surface of Venus, surveyed by the SAR system on the Magellan satellite at an expense of some $1 billion, are better known than those at the bottom of our oceans and have enabled geologists and geophysicists to speculate on processes which are seen there and which may operate in the earth.

The need for better bathymetry arises not only from the academics but also from those who seek mineral resources from the oceans, and those who wish to establish claims and subsequently to exploit their economic zones under the UN Law of the Sea Convention.

5.1.6 The current role of GEBCO

The role of GEBCO has always been to interpret the collected soundings on a global basis in the form of contour charts. It has never been proactive in initiating or carrying out surveys but has processed data collected by others. The 1st Edition of 1903 was based on relatively little data. The 5th Edition, which was prepared by marine scientists working closely with the hydrographers, took ten years to compile and was completed in 1984 (GEBCO, 1984). It comprises 16 Mercator sheets and 2 polar sheets. The interpolations that were essential to fill gaps in the data were made in the light of the most up to date knowledge of submarine geological processes.

In the last decade, technology has advanced to enable the 5th Edition of GEBCO to be made available as the GEBCO Digital Atlas (GDA) on a CD-ROM (GEBCO 1994, 1997). This has enabled the contours to be computer manipulated to aid the user. About 1000 GDAs have already been distributed worldwide.

However GEBCO is only too well aware that the contours used are derived from data that is now getting very old and do not reflect the advances of the last two decades. The advantage of a computer database of contours is that it can be readily updated, and the third major revision to the GDA is nearly complete.

Modellers want to have gridded databases, which can match the gridded nature of the modelling technique. DMA have already published such a gridded database as ETOPO 5, the marine portion of which is DBDB 5 based on contours held by the US Navy. The grid size is 5 minutes. The problem with this is that the source and track positions are not revealed and so there is no way of assessing its reliability in any area.

New insights into the topography of the ocean floor have come from the measurements of sea level gravity by radar altimetry from satellites, as already described by Walter Smith. This data set has the huge advantage of a more or less uniform global coverage with relatively close spaced "tracks", from which a gridded database can be generated and manipulated. However it is a gravity field and not bathymetry and the conversion to bathymetry cannot be uniquely done. Smith and Sandwell have made efforts to combine gravity and the limited bathymetric data to give "predicted" bathymetry (Smith and Sandwell, 1994).

GEBCO is currently tackling the non-trivial problem of how to produce a gridded database from the contours of the GDA, which have themselves been generated with considerable interpolation and interpretation by geoscientists. These problems arise from the extremely inadequate coverage of basic sounding data and how to interpolate between widely spaced tracks but at the same time taking advantage of the high sounding density along track. It is planned to include a gridded database at a one minute grid interval in the third issue of the GDA.

5.1.7 Conclusions

The present data set globally is a mish-mash of random tracks of soundings of irregular and uncertain accuracy both in depth and in position with very large gaps. Marine scientists and cartographers have struggled to interpret these into meaningful contour charts. Apart from surveys undertaken for defence purposes and some scientific surveys of limited area, there are no extensive surveys of the deep ocean.

The time is now appropriate to consider a systematic survey of deep ocean bathymetry.
The technology now exists to make saturation surveys.
There are nearly 200 ships equipped with suitable swath sounders and side-scan sonars.
Navigation is no longer a problem.
The morphology is nearly independent of time on the scale of millennia.

What are needed now are:
(i) a co-ordinated plan with identification of priority areas;
(ii) an international commitment;
(iii) resources.

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5.2 **GLOBAL RIDGE BATHYMETRY** (*by Ph. Blondel[*]*)

5.2.1 Introduction

Knowledge of the Earth and its environment are proving increasingly crucial, and not only for scientific reasons. Specifically, information about the Earth's topography is of interest not only to geoscientists, but also to physical oceanographers (to constrain ocean circulation models), marine chemists (to assess the distribution of chemical products, harmful or not, in the deep ocean), governments (extensions of the Exclusive Economic Zones), and industries (e.g. cable or pipe-line companies). Unfortunately, two thirds of the planet is covered by oceans, which prevent direct access to its topography. It has become a cliché to say that more is known about planets at the other end of the Solar System than about the Earth. It is nonetheless true, and for example the whole of Venus has been mapped with a ground resolution of 100 metres or less. The Earth has the same size, but the best bathymetric compilations exhibit resolutions of 5 minutes of a degree, or slightly less (equivalent to 5 nautical miles or 9.4 kilometres). The establishing of a Global Ridge Bathymetry Database is therefore of prime importance, and the present article aims at showing the efforts of the international programmeme Inter-Ridge and of different national programmemes. Although it greatly benefited from the input of many scientists worldwide, this article does not aim to be a consensus of all voices inside the international ridge community. Instead, it shows the problems to address, the achievements from the national programmemes that make up Inter-Ridge, and the possible way forward.

5.2.2 Inter-Ridge and National Initiatives

Inter-Ridge is an initiative for international co-operation in mid-ocean ridges studies. It groups 6 Principal Members (France, Germany, Japan, Spain, UK, USA), 5 Associate Members (Canada, Italy, Norway, Portugal, Spain), and 11 Corresponding Members (Australia, Denmark, Iceland, India, Korea, Mexico, New Zealand, Russia, South Africa, Sweden, Switzerland). To further the existing links with SCOR, Inter-Ridge recently applied for a formal SCOR Affiliation (Sloan, 1996). Inter-Ridge is designed to encourage scientific and logistical co-ordination, with particular focus on problems that cannot be addressed as efficiently by nations acting alone or in limited partnerships. Its activities range from dissemination of information on existing, single institution experiments to initiation of fully multi-national projects (more information is available on the Inter-Ridge server: http://www.intridge.org).

A particular domain of interest is the acquisition of a balanced set of global-scale data on the entire mid-ocean ridge system. More than 50,000 km of ridges girdle the Earth where lithospheric plates move apart and new crust is formed (Fig 5.2.1). They are the most dynamically active places on the Earth's surface, and concentrate most of the world's volcanic activity and a large part of the seismicity in zones only a few kilometres wide. Scientific surveys have been conducted by all member countries of Inter-Ridge, in collaboration or in the framework of their national programmemes (such as Bridge for the UK, De-Ridge for Germany or Dorsales for France). They have produced huge amounts of bathymetric data (several Terabytes). Each country, or, more appropriately, each institution has different ways of handling and distributing the resulting datasets. It was felt that now was the time to synthesize these processes and regroup bathymetry data into one single dataset available to the whole scientific community.

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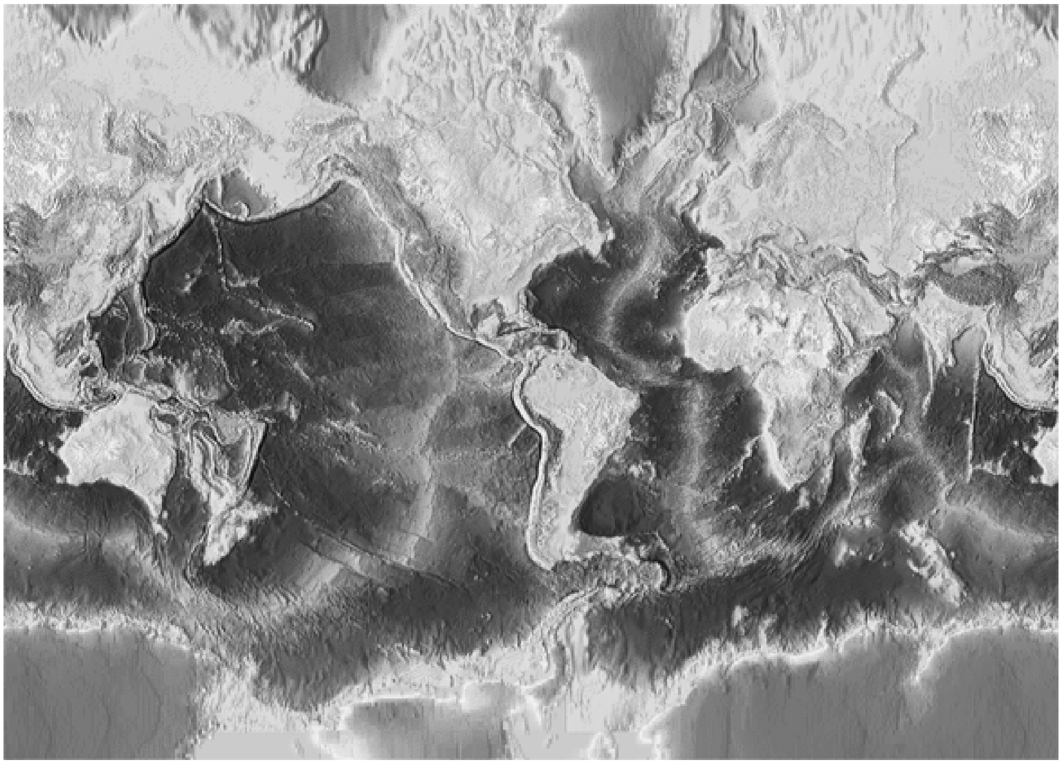

Fig 5.2.1 Low-resolution global topography (ETOPO-5 database, 5' resolution); mid-ocean ridges stand out

5.2.3 Bathymetry Data Processing

Sonar systems providing bathymetry can be roughly divided into echo-sounders (one single beam oriented vertically), multi-beam (several beams on each side of the ship) and side-scan sonars (one beam on each side) (e.g. de Moustier, 1988; Kleinrock, 1992; Somers, 1993; Blondel and Murton, 1997). These systems can be hull-mounted, shallow-towed, or deep-towed. Bathymetry data is supplemented by navigation and attitude information. Navigation contains the ship's position, along with its heading, speed and acceleration. Attitude data generally contains roll, pitch and yaw (and, in case of deep-tow systems, tow-altitude, platform heading, and reference net position). Navigation indicates where the sonar is, and attitude indicates where the sonar looks. Both are important, and in this article, the reference to bathymetry implicitly includes navigation and attitude as well.

Depending on the origin of the bathymetry (point values for echo-sounders, or series of individual measurements for multi-beam and side-scan sonars), different operations will need to be performed. Pre-processing consists in the preparation of the data for processing. This includes cleaning the navigation and attitude files, and, if necessary, changing headers and formats. Processing *per se* is the transformation of raw bathymetry into usable images, or grids, that are topographically and geometrically correct representations of the seafloor. This usually consists in the detection and filtering of spurious values, and the gridding, interpolation and contouring of individual (x; y; z) values. Post-processing includes grid interpolations, mosaicing, cosmetic operations (e.g. contrast enhancement, shading), statistics, and detailed image analyses (feature extraction, etc.).

All these steps need to be documented as precisely as possible. This allows the accuracy of the data to be checked, and, if new algorithms are available, improvement of the transformation to bathymetry. The decision on the ground resolution of the final dataset rests on the final objectives. Geophysical surveys tend to stay as close as possible to the maximum resolution (generally 100 metres). Other surveys may be more interested in large-scale mapping, or only in the dangers to surface navigation. Quality assessment standards have been set by well-known institutions, such as IHO (International Hydrographic Office) or GEBCO (GEneral Bathymetric Charts of the Oceans). Although not formally set as standards, stricter rules for checking the accuracy of bathymetric measurements have also been introduced by individual scientists within the Inter-Ridge community.

5.2.4 Archiving and Distribution of Bathymetry Products

Archiving of Bathymetry Data

Archiving of processed data is an important problem. It is often very difficult for an interested scientist to access the bathymetry needed for a particular project, or at least to know where it is and how to get it. For example, bathymetry has been collected in the northern portions of the Mid-Atlantic Ridge by several institutions, and for some portions the resulting datasets are stored in half a dozen institutions scattered among 4 countries. The project initiated by Inter-Ridge of a "Global Ridge Bathymetry Database" presents the obvious advantage of regrouping the bathymetry available on mid-ocean ridges and back-arc areas into one single dataset, simplifying access to it, and thus saving time and energy.

Another important problem is the format of the bathymetry data. Following recent meetings (e.g. Stewart, 1990; Blondel and Parson, 1994; 1995), and the growing concern of end-users, some de facto standards have been seen to emerge and be gradually accepted. Text dissemination is more and more achieved through Word-RTF and Text formats. Graphics files are easily exchanged with PostScript and a set of specific raster file formats (e.g. JPEG, GIF, TIFF). Many easily accessible types of software from the public domain exist for translation between these formats. The choice of a common format for acoustic data is much more difficult to attain, as often it is specifically adapted to the sonar system in use, and to the processing computer. New formats, called HDF (Hierarchical Data Format) and NetCDF (an offspring of HDF), are architecture-independent and data-independent. They have been used in several successful kinds of bathymetry processing software such as M-B (e.g. Caress et al., 1996) and GMT (Wessel and Smith, 1991). Consultation of sonar users showed that the main desire was for the archived data format to be self-describing (Blondel and Parson, 1995). This does not preclude the use of the NetCDF data format, but its use is neither necessary nor sufficient for the data to be self-describing.

Copyrights/Licences

Once an archiving methodology has been defined, the dissemination of the data needs to be considered. Who can provide data to the central archive? How should the data be distributed? And, concomitantly, to whom? Proprietary rights have always been considered important by scientists. The "gentlemen's agreement" system, through which use of acoustic data is freely granted as long as the proper references and acknowledgements are made, has prevailed for a long time. But the origins and extent of funding for bathymetric surveys have dramatically changed in recent years. In particular, joint ventures with private companies or associations between several countries (e.g. through the European Community) have become quite common. Different funding bodies have different copyright rules, allowing different access at different costs. Furthermore, no one person or laboratory can be pinpointed as owner of the data, and new rules have to be established. The same questions arise with licensing. What are the limits under which the data can be used, reproduced, printed, re-distributed, etc.? Is the simple reference to the origin of the map sufficient, or should specific distribution fees be established? Following common business practices, it would be worth introducing formal agreements, somewhat like software agreements, binding the two parties.

Physical/Electronic Distribution

The traditional way of distributing bathymetry data was by the large-scale production of maps, which were physically sent by mail to the end-users. Because of the high amount of data involved, and to better match the customers' requirements, leading institutions now provide bathymetric data on tapes (e.g. United States Geological Survey), on CD-ROMs (e.g. GEBCO), or print tailor-made maps in small quantities (e.g. Geological Survey of Canada). Electronic distribution has accelerated the process, by allowing on-line access to maps or portions of maps through the Internet (ftp or World-Wide Web).

A successful way of blending these different approaches has been demonstrated by a pilot study, the US RIDGE Multi-beam Synthesis. Bathymetric data acquired at mid-ocean ridges with funding from the US National Science Foundation is grouped at the host site (Lamont-Doherty Earth Observatory). Its accuracy is checked, and in some cases the data is reprocessed. The raw and processed data are accessible on-line via the World-Wide Web (http://imager.ldeo.columbia.edu/) and on a series of CD-ROMs. Services for map generation and map printing are also offered on a cost-reimbursable fee structure. The current database groups cruises in the Mid-Atlantic, Pacific and Antarctic regions.

A similar approach has been chosen when implementing the BRIDGE Data Stewardship programmeme (Harrison and Blondel, 1997; Harrison et al., 1997). All data acquired in the course of the British Mid-Ocean Ridge Programmeme from the Natural Environment Research Council are collected at the

Southampton Oceanography Centre. Bathymetric data (mainly multi-beam), and all datasets ranging from multi-channel seismic to water column measurements, are archived in a self-describing format and rigorously quality-controlled before distribution. The production and release of the final BRIDGE dataset, marking the end of the programmeme, is scheduled for the year 2000 (see http://earth.leeds.ac.uk/~bridge for details).

5.2.5 Toward a Global Ridge Bathymetry Database

Inter-Ridge has taken the formal decision to compile the bathymetric datasets of mid-ocean ridges (and possibly back-arc areas) produced within current national initiatives (such as RIDGE or BRIDGE) into one single database (Fig.5.2.2). The aim is to make high-resolution bathymetry more accessible to the world's scientific community and maximize the scientific return, by sharing the burden of distribution and archiving within one single facility. Another expected return of this project will be the dissemination of bathymetric products to other groups than the mid-ocean ridge community (e.g. physical oceanography, satellite altimetry).

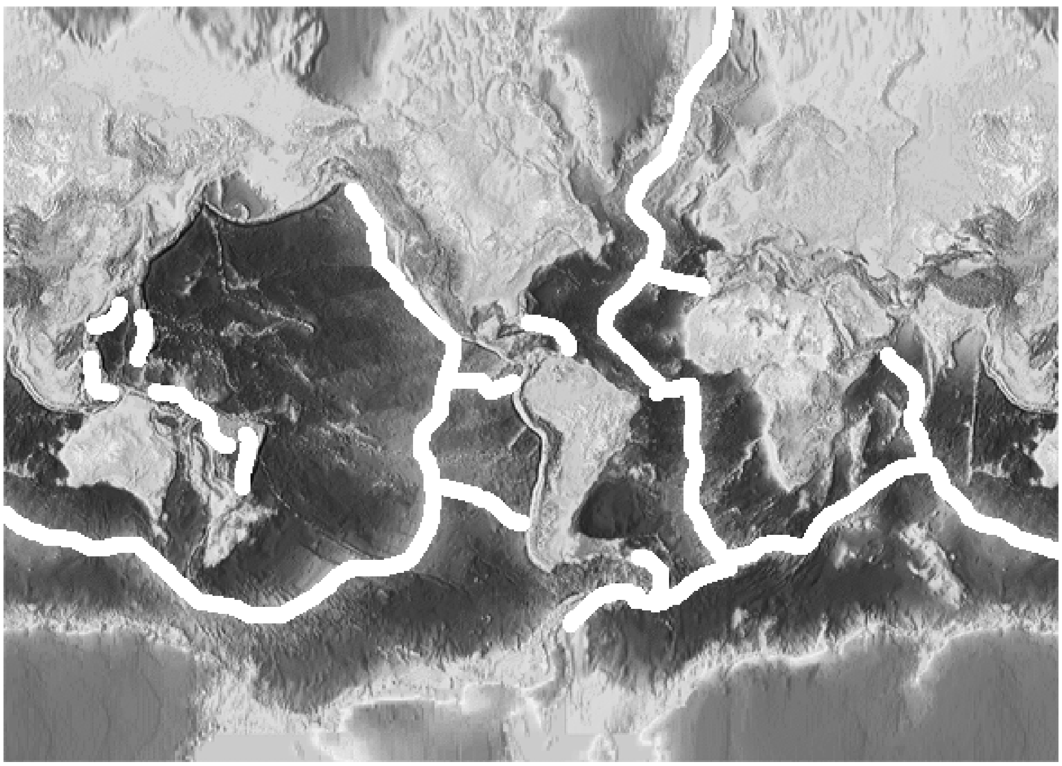

Figure 5.2.2 Possible extent of the Inter-Ridge "Global Ridge Bathymetry Database", superposed in white over ETOPO-5 topography.

The problems to address are numerous. First, a global inventory of all bathymetric data acquired so far in the whole world needs to be made. Second, consultation of data providers and data users should clear the uncertainties related to copyright and licensing by establishing unambiguous "rules of the road". The actual compilation of the global database is the most difficult part. Where will it be hosted? Could different sites be responsible for different parts of the project? If the choice of one single site proves to be unwieldy, it would be possible to have one major site acting as front-end and customer-interface for distributed sites each responsible for a different region. How would the quality control be performed? Data dissemination could easily model the RIDGE Multi-beam Synthesis, with on-line access via Internet, and physical distribution via CD-ROMs and tailor-made maps. One large question is how this work would be funded: national agencies or international cooperation?

Consultations between members of the international ridge community have taken place since the inception of this Inter-Ridge project in December 1996. The worldwide inventory of ridge bathymetry is under way, country-by-country. Some programmemes (e.g. in France, Italy, Spain, the US, or the UK) have or are starting inventories at the national scale. These initiatives are at varying stages of advancement, and in some places the data is only archived but not released yet (and the format not decided). This means that a single, central facility is not feasible. A distributed approach has been selected instead. Most data will be compiled and made accessible through linked national www sites. Some data will also be compiled at the Southampton Oceanography Centre, and presented on a www site different from the BRIDGE server. Data dissemination (when feasible) still proves to be a difficult area. Some countries provide distribution at cost and on an ad hoc basis (e.g. in the US); others are still waiting for decisions from their funding bodies (e.g. in the UK). Finally, the absence of a central facility precludes the physical distribution via CD-ROMs (for the moment).

The final establishment of a "Global Ridge Bathymetry Database" is still a distant goal. But it is not that far off. Important groundwork has been made by several national programmemes, such as RIDGE or BRIDGE. This project also benefits from the experience accumulated by other international programmemes, such as SCOR, GEBCO or IHO. Bringing together the strength and motivation of scientists everywhere, Inter-Ridge is ideally placed for this task. Scheduled for the beginning of the new millennium, the "Global Ridge Bathymetry Database" will be a perfect summary of the advances in the knowledge of our planet which started only a quarter of a century ago.

Acknowledgments

The support of the SCOR WG 107 Organizing Committee in scheduling this presentation is gratefully acknowledged. I would also like to thank the members of the Inter-Ridge Working Group on "Global Ridge Bathymetry" for their scientific input. Some of the ideas expressed in this article were brought forward, discussed and refined during a BRIDGE Workshop about "Sonar Processing in the UK" held at the Institute of Oceanographic Sciences (UK) in June 1994. They were updated through discussions with various colleagues from the Southampton Oceanography Centre.

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6. THE REGIONAL PERSPECTIVE

6.1 AN IMPROVED PORTRAYAL OF OCEANIC BATHYMETRY IN THE ARCTIC, BASED ON A GRID DERIVED FROM GEBCO BATHYMETRIC CONTOURS (*by R. Macnab[1], G. Oakey[1] and D. Vardy[2]*)

6.1.1 Introduction

The portrayal of shaded relief is a useful technique for visualizing and interpreting bathymetry, topography, and other continuous surfaces (such as gravity and magnetic fields) that are most often defined as Z values at the X and Y mesh points of regular grids. In general, a shaded relief image displays significantly more information about surface texture than does a standard contour map, regardless of the interval between isolines. This has obvious benefits not only when analysing and correlating the surface characteristics of one or more parameters, but also when searching for errors or flaws in the database which manifest themselves as breaks or discontinuities in the surface.

For cartographers and geoscientists alike, the availability of public domain data sets in computer readable form has led to substantial progress in the visualization and analysis of surface relief in both continental and oceanic areas. In particular, two data sets hold significant potential for portraying such information in regional settings: the ETOPO-5 description of global land and seafloor relief in grid form (National Oceanographic and Atmospheric Agency, 1988), and a set of contour lines for the world ocean, digitized from the General Bathymetric Chart of the Oceans (GEBCO; Jones et al. 1994).

For certain applications, e.g. the regional portrayal of shaded relief in the Arctic, the usefulness of either of these two data sets is limited by one or more shortcomings: the construction of the ETOPO-5 grid gives rise to unrealistic and unattractive portrayals of the floor of the Arctic Ocean, whereas the GEBCO contours come in a form that is not directly amenable to the production of shaded relief plots, nor do they contain relief information on land. However if the ETOPO-5 and GEBCO data sets are combined with due regard for their inherent limitations, their best features can be retained to produce an acceptable description of the land and sea area in the Arctic.

6.1.2 The ETOPO-5 grid of global surface relief

ETOPO-5 defines elevations and depths at 5-minute intervals of latitude and longitude. Details of its construction and of its constituent data sets have not been publicly documented, however, due to its ready availability, this data set has found widespread favour with investigators and mapmakers who need to express, to model, or to visualize generalized relief at global or regional scales.

In its regularly distributed form, ETOPO-5 is afflicted with severe spatial inhomogeneities in the polar regions: the north-south intervals between grid points remain constant, but the east-west intervals diminish ultimately to zero on account of meridional convergence towards the North and South Poles (Figure 6.1.1). These inhomogeneities can lead to noticeable artifacts in the visualization of ETOPO-5, particularly in shaded relief representations; this is well demonstrated by the radial striations emanating from the Pole in Figure 6.1.2, which portrays ETOPO-5 in the Arctic Ocean with simulated illumination from the upper left hand corner of the illustration.

6.1.3 A new grid configuration

To circumvent the visualization problem described above, we decided to develop a gridded data set that was more amenable to the presentation and processing of bathymetry in the Arctic Ocean. After some investigation, we devised a master grid configuration that consisted of a square-celled Cartesian grid with its origin at the North Pole, and its major axis oriented along the Greenwich Meridian (Figure 6.1.3 portrays the general distribution of grid points within the Arctic Ocean, while Figure 6.1.4 illustrates the total extent of the master grid). A constant interval of 5 km in the X and Y directions was selected in order to achieve a grid of

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manageable proportions, but which retained a uniform resolving power over the map area that compared very favourably with the ETOPO-5 grid.

The primary focus of the project was to develop a better representation of the bathymetry in the central Arctic Ocean, but for the sake of consistency between the Arctic Ocean and adjacent waterways, the master grid was made large enough to encompass all oceanic areas north of 64°N. The square configuration meant that the master grid was oversized (see Figure 6.1.4); however a sizeable number of grid points remained empty on account of their locations over dry land, so the inclusion of extraneous bathymetric values located south of 64°N was not considered problematic.

6.1.4 The GEBCO map series

In the Fifth and current Edition, the General Bathymetric Chart of the Oceans (GEBCO; International Hydrographic Organization, 1997) consists of 18 separate map sheets. Maps for the Arctic and Antarctic regions are constructed in a polar stereographic projection at a scale of 1:6 million; the remaining 16 maps are constructed in a Mercator projection at a scale of 1:10 million. For depths that exceed 100 m, contours are portrayed at intervals of 100 m or multiples thereof. On any given map sheet, the magnitude of these intervals is selected on an area-by-area basis to suit local densities of sounding observations or the slope of the sea floor.

We chose to base the contents of the new Arctic bathymetric grid on the information shown in GEBCO Sheet 5.17 (Canadian Hydrographic Service, 1979), which portrays depths north of 64°N. We picked Sheet 5.17 because: (a) it is widely circulated and it is the closest thing we have to a standard chart of the region; (b) the principles and techniques of its construction are well documented (IHO/IOC/CHS, 1984); and (c) sounding control is illustrated by means of overprinted ship's tracks that indicate the locations of bathymetric profiles that were used to develop the contour lines.

6.1.5 Gridding the GEBCO contours

On the original GEBCO maps, depth contours were drawn manually, however they have since been converted to digital form for distribution in the GEBCO Digital Atlas (GDA; Jones et al. 1994). In the GDA, contour line segments are defined and stored as variable-length strings of points whose locations are defined by geographic (latitude and longitude) coordinates; each segment is headed by a record that defines among other things the depth of that particular string, as well as the number of points in the string. The spacing between points varies.

Contour lines inside the master grid area were extracted from the GDA; those for the Arctic Ocean proper are shown in Figure 6.1.5. Prior to gridding, the line segments were subjected to four preparatory procedures: (1) they were re-formatted by extracting depth values from each string header and appending them to every pair of geographic coordinates within that string; (2) geographic coordinates were converted to their X and Y equivalents (in km) within the master grid; (3) wherever the distance between converted points exceeded 5 km, linear interpolation was used to insert regularly-spaced intermediate points along the contour lines at a maximum interval of 5 km; and (4) depth values corresponding to the contour points were binned in 5-km square cells over the entire grid area. Binning consisted of averaging the X, Y, and Z coordinates of all points in each bin, and of assigning the averaged Z value to the position defined by the averaged X and Y values.

Gridding was performed with programme *surface*, which is distributed as part of the public domain GMT data visualization package (Wessel and Smith, 1991). *surface* approximates the shape of a thin elastic membrane which is under tension and which is constrained to pass through all data points (Smith and Wessel, 1990). The operator designates the tension of the membrane by entering a number ranging from 0.0 (no tension) to 1.0 (high tension); for this application, a factor of .99 was specified to apply a high tension to the membrane, thereby minimizing the curvature of its surface between the contour lines.

To check how well the outcome of the gridding procedure reproduced the original input data, synthetic contours were extracted from the new grid, plotted, and then overlaid directly onto GEBCO Sheet 5.17 for a visual comparison. In all instances, the synthetic contours matched the published contours exactly, confirming that the new grid was an accurate replication of the bathymetric information portrayed on the original map.

Figure 6.1.6 was prepared with the new grid to illustrate the floor of the Arctic Ocean in shaded relief. A comparison with Figure 2, which was prepared with the regular ETOPO-5 grid, indicates a substantial improvement in the quality of visualization: featuring a higher level of detail in the deep ocean basin, this image is also completely free of the radial striations that were produced by meridional convergence in the vicinity of the North Pole.

6.1.6 An application of the new bathymetric grid

One of the first applications of the new grid was to produce a digital replica of GEBCO Sheet 5.17 that portrayed not only the depth and shaded relief of the sea floor, but also the elevation and shaded relief of all adjacent landmasses north of 64°N. This was achieved by constructing a composite grid that merged the new GEBCO oceanic grid with the landward component of ETOPO-5; prior to merging, the latter was re-sampled at regular 5 km intervals using the same grid configuration as for bathymetry. In principle, the zero contour level (ZCL) in ETOPO-5 is a rendition of the shoreline; to retain this particular contour level in the composite grid, the two constituent grids were actually merged at the 50 m isobath, i.e. the ETOPO-5 grid was used to define not only elevations on land, but also near-shore bathymetry to a depth of 50 m.

The resulting composite grid was processed with a suite of in-house display software to create a plot that portrayed depth and shaded relief. This plot was overlain with the World Vector Shoreline (WVS). Intuitively, the WVS should have been a reasonably close match to the ZCL in ETOPO-5, however discrepancies of 25 km or more appeared in many locations; in our experience, this is not an unusual occurrence when these two data sets are combined in this fashion. In this instance, we resorted to manual editing of selected ETOPO-5 components in order to eliminate some of the more glaring discrepancies between coastlines, but made no further effort to improve the match. This apparent lack of agreement between two important public-domain data sets clearly needs to be addressed in a more rigorous fashion.

The new map was produced in a two-tone colour scheme (blue and buff below and above sea level, respectively). Contour lines were not overprinted, however the intervals between colour gradations closely match the contour intervals of Sheet 5.17. Hence depth and elevation ranges are easily read directly from the map, while variable shading conveys a realistic representation of the slope and roughness of the seabed and the surrounding landmass. A black and white version of the map is shown in Figure 6.1.7.

In hardcopy form, this map is available in two scales: 1 to 6 Million, which is the scale of GEBCO Sheet 5.17, and approximately 1 to 23 Million (Geological Survey of Canada, 1994). In computer-readable form, the map is available as a PostScript plot file for direct output to a colour plotter at any user-defined scale.

Acknowledgements

We acknowledge the communal perspective of Walter Smith and Paul Wessel, developers of the public-domain GMT software package, particularly the *surface* programme that was applied to such good effect in this study. Karl Usow under the direction of Jacob Verhoef developed other routines that were used at various stages to manipulate and display the data sets described in this report.

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Figures

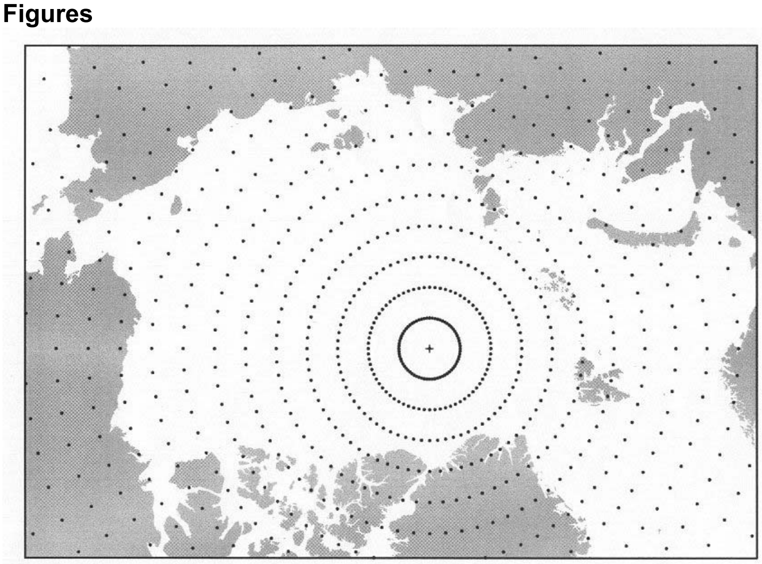

Figure 6.1.1 General configuration of the ETOPO-5 grid in the Arctic. The standard ETOPO-5 grid defines topography and bathymetry at intervals of 12 points per degree of latitude and longitude. For clarity, this figure only illustrates every 24th point in the north-south direction, and every 60th point in the east-west direction. Inhomogeneities in the spacing of grid points are obvious throughout the map area, due to the pronounced east-west convergence of grid points with decreasing distance to the North Pole.

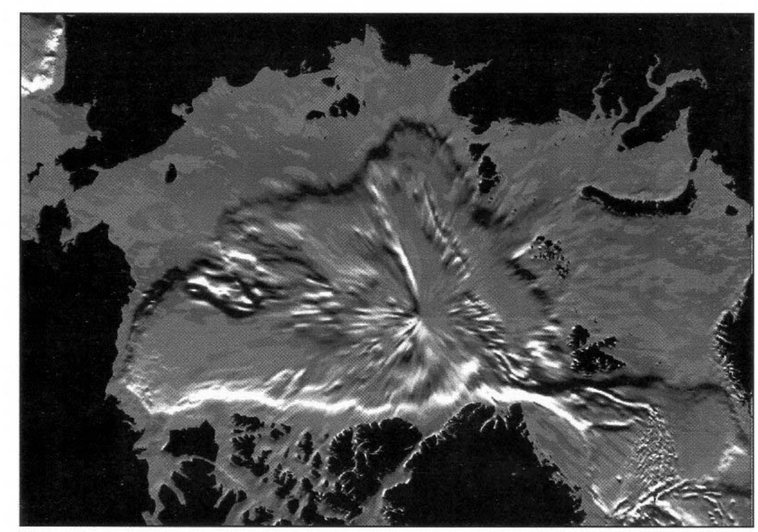

Figure 6.1.2 Shaded relief portrayal of the floor of the Arctic Ocean created from the ETOPO-5 global relief grid, which defines topography and bathymetry at intervals of 5 minutes of latitude by 5 minutes of longitude (Figure 6.1.1 illustrates the layout of the grid configuration). Simulated illumination is from the upper left hand corner of the image. Striations emanating radially from the North Pole are artifacts caused by the pronounced east-west convergence of data points in the vicinity of the Pole.

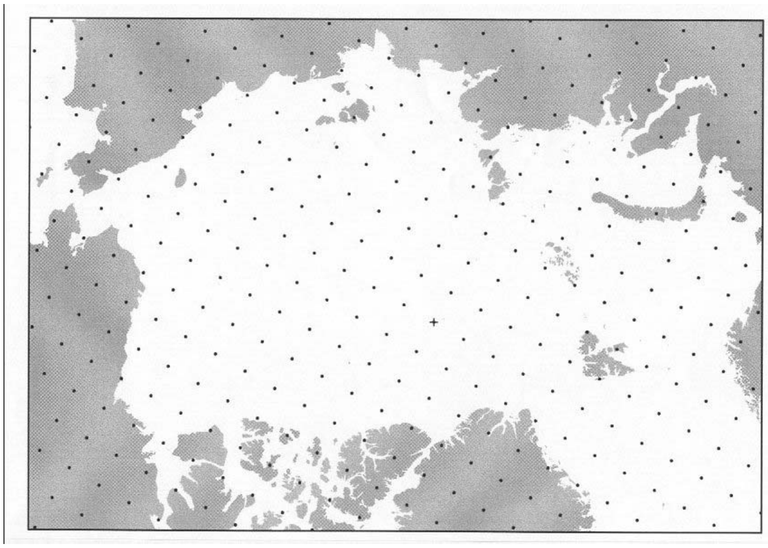

Figure 6.1.3 General configuration of a rectangular grid, which was designed expressly to facilitate the visualization and processing of Arctic bathymetric data. The origin of the grid is at the North Pole (location indicated with a cross), and its major axis coincides with the Greenwich Meridian (see also Figure 4). Grid points are uniformly spaced at intervals of 5 km in the X and Y directions throughout the map area. For clarity, this figure only illustrates every 50th point in either direction.

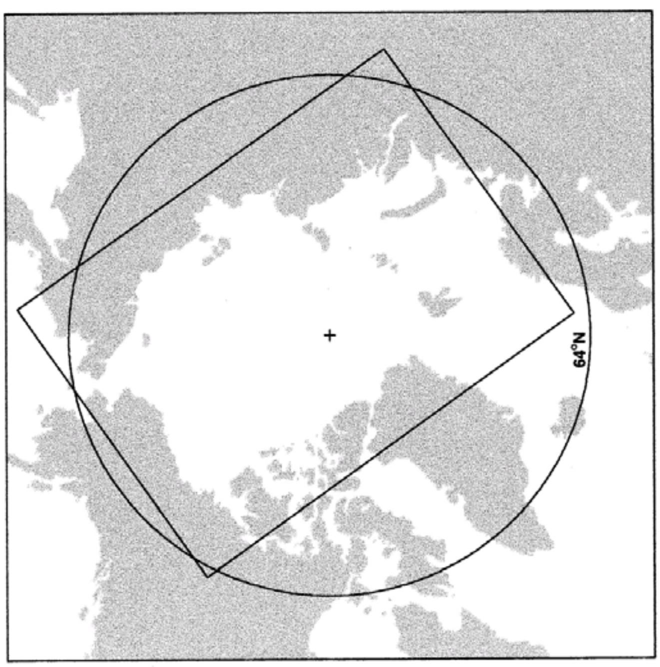

Figure 6.1.4 In order to portray bathymetry as far south as 64°N, depth values defined by GEBCO contours were computed at intervals of 5 km over a master grid centred at the North Pole and covering the area outlined by the large square in this figure. The major axis of the master grid coincides with the Greenwich Meridian. The oblique rectangle in the middle of the image outlines the area portrayed in Figures 6.1.1-3 and 6.1.5-6.

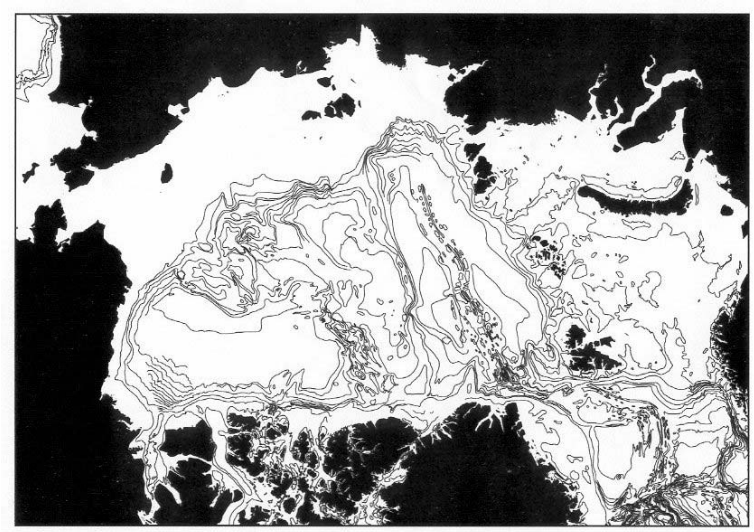

Figure 6.1.5 Arctic bathymetric contours extracted from the GEBCO Digital Atlas (GDA). Drawn originally by hand for the Fifth Edition of the General Bathymetric Chart of the Oceans, these contours were digitized recently and placed into public circulation in a computer-readable form. For clarity, this figure does not illustrate all the information north of 64°N that was extracted from the GDA for the purposes of this study; contours are shown at 200-metre intervals only, while areas such as Baffin Bay, the Canadian Arctic Archipelago, and the Norwegian-Greenland Sea, are only partially or not shown.

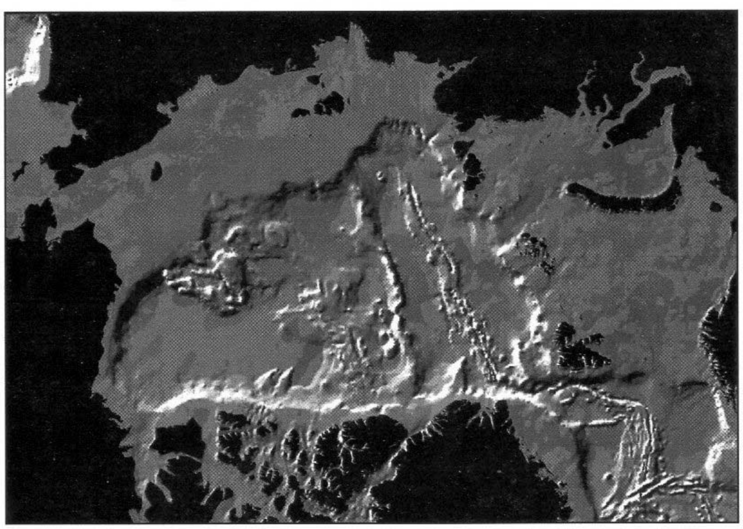

Figure 6.1.6 Shaded relief portrayal of the floor of the Arctic Ocean created from a Cartesian grid of depth values derived at 5 km intervals from bathymetric contours that have been extracted from the GEBCO Digital Atlas. Simulated illumination is from the upper left hand corner of the image. The grid was created by means of a minimum curvature technique with variable tension; it contains more detail than a comparable plot of ETOPO-5 information, and is free of the radial artifacts that are caused by meridional convergence (see Figure 6.1.2).

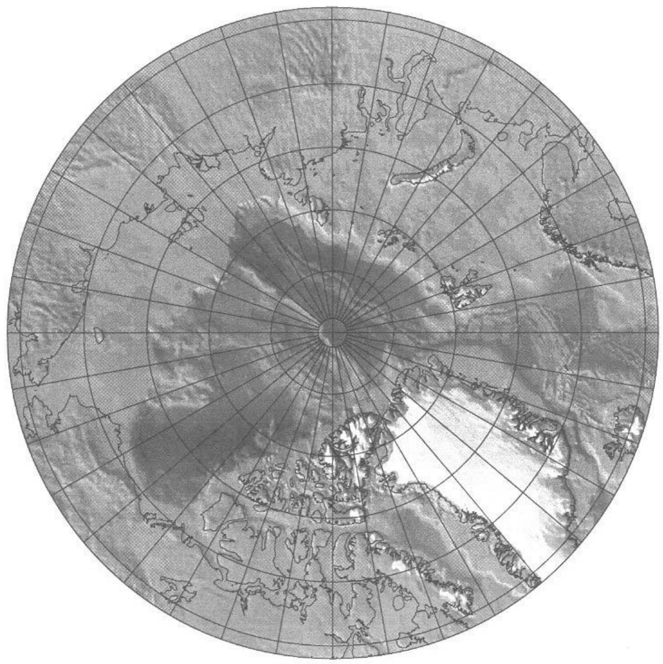

Figure 6.1.7 Black and white rendition of the new Arctic map, portraying the contents of a composite 5-km grid which combines bathymetric information from the GEBCO Digital Atlas and topographic information from the ETOPO-5 global relief data set.

6.2 REGIONAL COMPILATIONS: A LOW-COST APPROACH FOR IMPROVING BATHYMETRIC MAPS IN SELECTED AREAS (*by R. Macnab[*]*)

6.2.1 Why compile bathymetry?

Regional descriptions of oceanic depths are obtainable from charts such as the General Bathymetric Chart of the Oceans (GEBCO; International Hydrographic Organization, 1997) and from public-domain data sets such as ETOPO-5 (National Oceanographic and Atmospheric Administration, 1988). These portray the sea floor in a generalized fashion over large areas, but their limited resolutions tend to exclude finer morphological detail. In recent years, numerous surveys have mapped various-sized portions of the world ocean in greater detail; these data sets have improved significantly our knowledge of bathymetry within limited areas, but not all have been integrated with a view to producing coherent and detailed descriptions of the sea floor over large oceanic regions.

Properly planned and executed, bathymetric compilations offer opportunities to recycle and to rationalize disparate sets of observations in regions where there is enough data to yield superior descriptions of the seafloor. Although labour-intensive, the 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.

6.2.2 Two fundamental considerations

Success in many if not most compilation projects will hinge not only on the quality and quantity of the data sets that are being assembled, but also on the level of human resources that can be devoted to the project.

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 according to the quality of its information content. These talents and inclinations are often found in research laboratories, as opposed to data centres; while the latter provide excellent service as repositories of observations, their compilation activities tend to be limited because their mandates and resources don't permit them to engage extensively in the assessment, manipulation, and interpretation of data.

In constructing the database, original observations should be used wherever feasible. As much as possible, these should represent the condition of the data at the time of collection; using original observations will minimize 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.

6.2.3 Classes of data

A coherent database can be developed from four general classes of data:

- profile (single-beam) soundings
- point soundings
- swath (multi-beam or interferometric) soundings
- contour maps

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 digitized from original analogue records.

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Contour maps may be hand-drawn 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 digitized; 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.

6.2.4 The construction and manipulation of bathymetric grids

Ultimately, observations in the compilation database will be homogenized into a single grid of depth values for ease of handling and visualization. Usually, this final grid is composited from a series of intermediate sub-grids that correspond to various amalgamations of the constituent data sets, and which cover different parts of the study area. These sub-grids are constructed at different processing stages. For instance, sets of profile and point sounding observations often feature some overlap, and it is usually more effective to defer creation of the intermediate sub-grids until the data sets have 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; often they are converted to sub-grids at an early stage in the proceedings, and then are subjected to block adjustments such as re-levelling or tilting.

When all constituent data sets have been adjusted, their sub-grids are merged to create the final grid. To facilitate this process, all sub-grids must of course refer to the same origin, and use a common grid spacing.

6.2.5 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. *Public domain data* is circulated for general use, with no restrictions on its further distribution. The remaining data sets are not in the public domain, and some negotiation is often needed to obtain access to them. *Proprietary data* is collected to meet the specific aims of an organization, 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 organization 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 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).

6.2.6 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 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 insonified 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 seawater 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.

6.2.7 Typical 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 the judicious 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 usually to eliminate all data sets that supersede the introduction of modern positioning systems.

Digitizing 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 localized peaks or hollows in the sea floor. Fortunately, procedures exist to automate this procedure; for instance, a fourth-order difference technique that was originally developed for processing magnetic data (Verhoef et al. 1996) 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 6.2.1).

Data attributes need to be homogenized to ensure meaningful inter-comparisons between sets of observations. For example, all soundings should be reduced to a common velocity of sound to minimize apparent discrepancies that 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 database typically contains a large number of profile soundings, making it impractical to scan and inter-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 a quality assessment 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.

In practice, the statistical analysis of crossover errors is performed after every application of corrections and/or deletions to one or more sets of profile soundings; an overall decrease in the statistical error suggests that the correction/deletion is successful, while no change, or an overall increase, indicates that it is not.

6.2.8 Topography on surrounding land

Increasingly, geoscientists are concerned with past or present processes that affect the sea floor near the coast; in some cases, these extend from or onto adjacent land areas, and their effects may be readily discerned by observing the topographic characteristics of terrain above sea level. In certain applications, new insights on such processes can be achieved by overlaying remote sensing information such as satellite or SAR (Synthetic Aperture Radar) 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 the ‘standard’ public-domain coastlines (e.g. WDB-II, WVS) and the zero levels in custom or public-domain grid sets of onshore-offshore surface relief.

6.2.9 Display techniques: contour lines vs colour shaded relief

In general, a plot of colour-shaded relief will portray significantly more textural information than 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 database, thereby providing a powerful diagnostic tool in the evaluation and adjustment of observations.

6.2.10 Final compilation products

To maximize its value to the end user, a comprehensive compilation should lead to the creation and circulation of several end products. As a 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.

6.2.11 Work in progress: a compilation of bathymetric data from the NW Atlantic Ocean

As part of the preparations for a Canadian claim to jurisdiction over seabed resources beyond 200 nautical miles (according to the provisions of Article 76 of the Law of the Sea), the Geological Survey of Canada and the Canadian Hydrographic Service have been engaged in a compilation of all available bathymetric data in waters adjacent to the Atlantic coast of Canada (Macnab et al. 1996). The opportunity has been seized to provide not only an up-to-date portrayal of the sea floor in deep water where Article 76 applies, but also in the shallower waters of the continental shelf and near-shore regions.

As shown in Figure 6.2.2, the compilation has so far assembled substantial quantities of soundings that were collected in the NW Atlantic by Canadian and non-Canadian agencies, and which are available in digital form. At present, most of the accumulated data sets have been incorporated into a comprehensive data- base. Some errors remain to be corrected, and coverage in the central Atlantic is incomplete; however, even in its current preliminary form, the data-base has lent itself to the production of a grid that contains significantly more detail and resolution than the public-domain DBDB-5 grid of global bathymetric values (DBDB-5 is the oceanic component of ETOPO-5).

Already this preliminary grid has attracted the enthusiastic attention of in-house investigators who recognize features that have escaped notice on previously available maps. It has also drawn attention to those areas where additional measurements will be needed to complete a regional portrayal of the sea floor. On completion of the project, the final grid will be placed in the public domain. Informal discussions are under way with European colleagues on the feasibility of extending the compilation to the NE Atlantic and up into the Norwegian-Greenland Sea.

6.2.12 A proposed compilation of bathymetric data from the Arctic region

Ample anecdotal evidence exists concerning the inadequacy of published charts of the Arctic Ocean, particularly in the deep waters of the central basins. Numerous field investigators operating from ice camps or from icebreakers have reported significant differences between observed and charted depths, leading to planning and operational difficulties in activities where reliable depths need to be known in advance. Laboratory investigators are no less disadvantaged, as reasonably detailed bathymetry is a prerequisite to understanding the tectonic development and framework of any oceanic region; a partial consequence is that the opening history of the Arctic Ocean, which is key to the plate tectonics of the Northern Hemisphere, remains poorly known.

The reasons for this state of affairs are manifold, e.g. the permanent ice cover of the central Arctic Ocean has made it difficult and costly to collect soundings; climate and distance to operating bases on land have posed formidable logistical problems; and perhaps most significantly, the region has until recently served as a theatre for superpower politics. However, improved technology coupled with significant political developments are changing this picture, raising the possibility of long-awaited improvements to the description of the Arctic sea floor.

Unlike the NW Atlantic, public-domain bathymetry of the Arctic region is very sparse. One chart that is widely referred to for a portrayal of the sea floor north of 64°N is GEBCO Sheet 5.17 (Canadian Hydrographic Service, 1979). This was developed in 1979 from the very limited data set shown in Figure 6.2.3, which illustrates sounding track-lines extracted from the GEBCO Digital Atlas (Jones et al. 1994) that were used to prepare the manually-drawn contour maps of the GEBCO Fifth Edition. Relative to Sheet 5.17, it should be noted that this plot is somewhat misleading: not all track-lines between 64°N and 72°N in the Norwegian-Greenland and Barents Seas were used in the construction of this particular sheet. Given the mapmaking techniques that were in use at the time, some or many of the soundings along these tracks may exist only in analogue form; in any event, they represent data sets that were collected with the aid of an older generation of navigation aids, and so their accuracy must be considered suspect.

Figure 6.2.4 illustrates public-domain bathymetry that is available in digital form from data centres in Canada and the USA. The density of these data sets is decidedly inhomogeneous, and is totally inadequate for constructing a detailed map of the sea floor throughout the main part of the Arctic Ocean. It is not unreasonable to assume that other data sets exist: clearly this issue will require some investigation, followed by negotiations for the release of new or un-circulated information that will help paint a more accurate picture. The Russian Navy, for instance, is known to have accumulated numerous soundings throughout the region, which are currently being used to develop a 1:10 million hand-drawn contour map; there are indications that these soundings may also be converted eventually to grid form.

Perhaps the most promising development in Arctic bathymetry is the US Navy's SCICEX programme, which dedicates specific submarine missions to unclassified mapping and research beneath the permanent polar pack. The general policy is to release data into the public domain no later than two years after the cruise completion date. So far, cruises in 1993, 1995, and 1996 have collected single-beam soundings in key areas selected on the basis of scientific priorities (Figure 6.2.5); in 1998, the programme is expected to include a swath mapping capability. The SCICEX programme represents a significant advance in Arctic bathymetry supported by relatively modern positioning systems; every effort will be made to incorporate this new information into the proposed database, as it will no doubt play an important role in the consolidation and levelling of other observations.

Acknowledgements

In many ways, this report is a distillation of the knowledge, experience, and contributions of colleagues in several organizations. Allen Stark of Terra Firma Consultants undertook the compilation of bathymetric data from the Northwest Atlantic, and was approaching the end of this project when tragically he perished in a diving accident. David Monahan and Keith White of the Canadian Hydrographic Service were instrumental in securing quantities of high-quality survey information for inclusion in the compilation database. Gordon Oakey and Walter Roest of the Geological Survey of Canada have been tireless providers of advice and expertise in the handling and visualization of surface relief information. Bernard Coakley of Lamont-Doherty Earth Observatory provided the SCICEX track information. David Vardy of Blue Vajra Computing produced the figures, created in part with geographical display software that was developed by Karl Usow of Blue Vajra Computing under the direction of Jacob Verhoef of the Geological Survey of Canada. Walter Roest and David Monahan reviewed the manuscript and made valuable suggestions for improvement.

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Figures

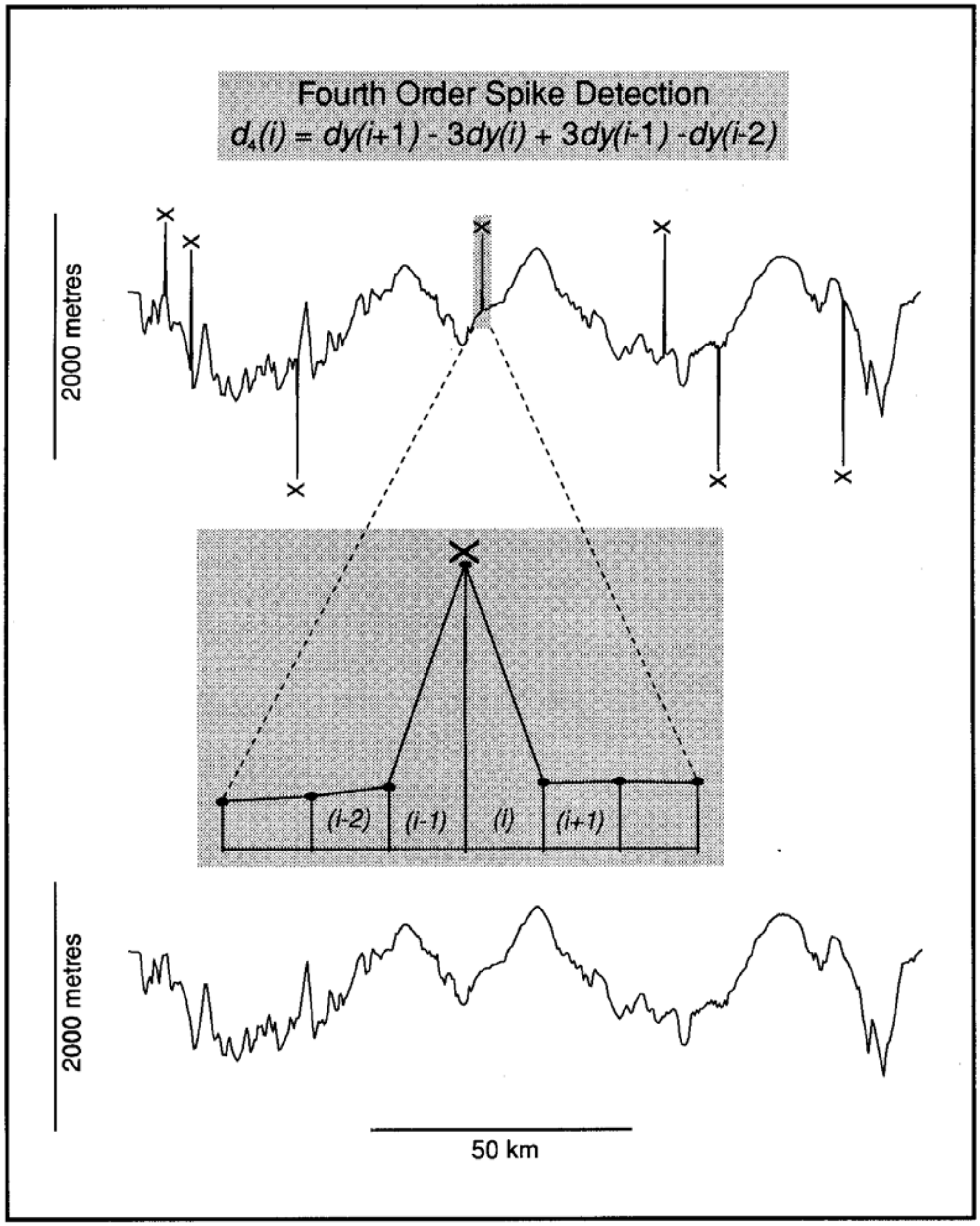

Figure 6.2.1 Simple spikes in a bathymetric profile can be detected and eliminated by an automatic fourth-order difference procedure.

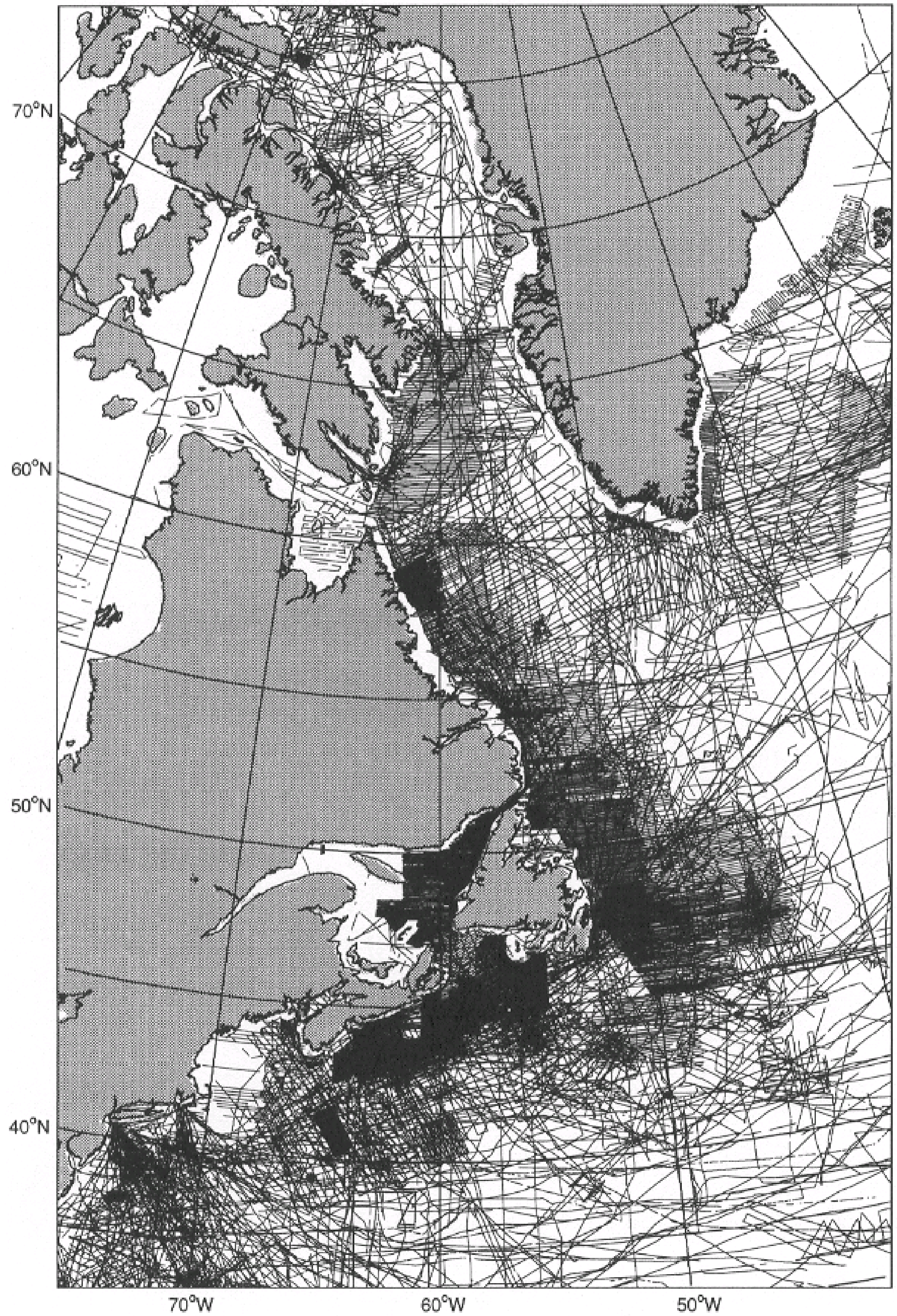

Figure 6.2.2 For over thirty years, Canadian and other agencies have collected bathymetry in the Northwest Atlantic. These observations provide the foundation for a significantly improved portrayal of the sea floor in this region. The track-lines shown here were extracted for the most part from the digital archives of the Geological Survey of Canada, with supplementary information from US and Russian sources.

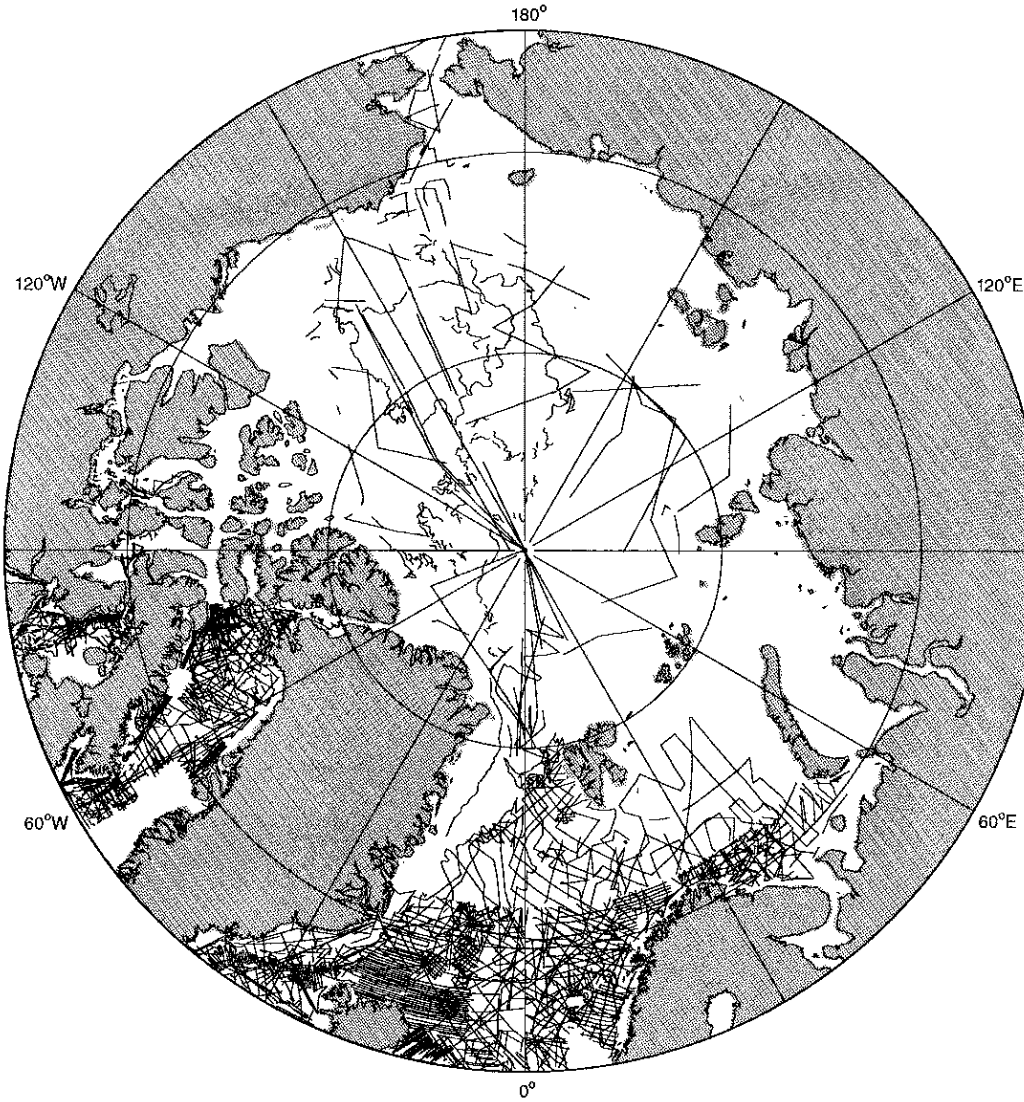

Figure 6.2.3 Since its publication in 1979, GEBCO Sheet 5.17 has provided a standard for Arctic bathymetry. The track-lines in this figure indicate the distribution of the mostly analogue soundings that were used to produce Sheet 5.17 (not all track-lines between 64°N and 72°N were used). The track-lines shown here were extracted from the GEBCO Digital Atlas.

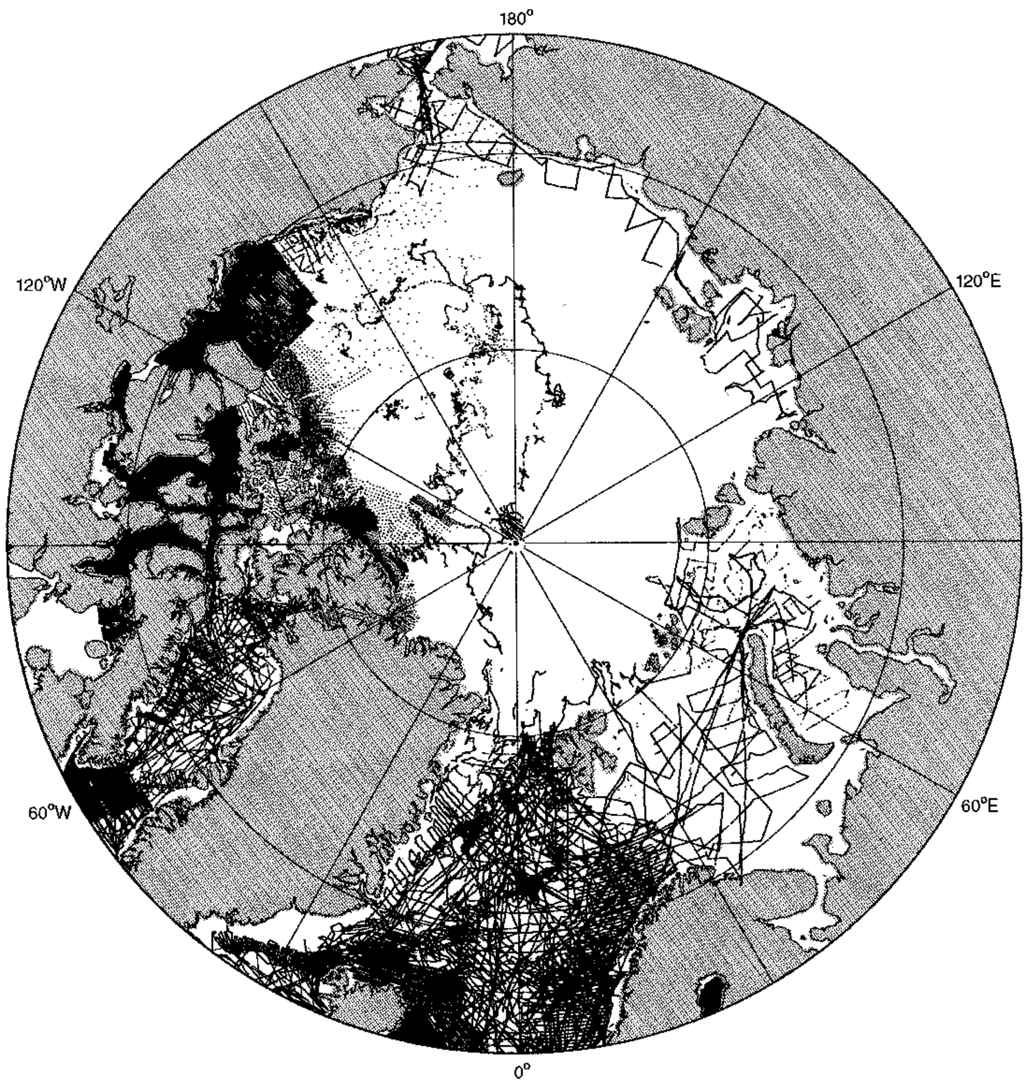

Figure 6.2.4 North of 64° N, numerous sets of bathymetric observations are now available in digital form for potential use in developing an improved Arctic map. The track-lines shown here were extracted from the digital archives of the Geological Survey of Canada and from sources in the US and Russia.

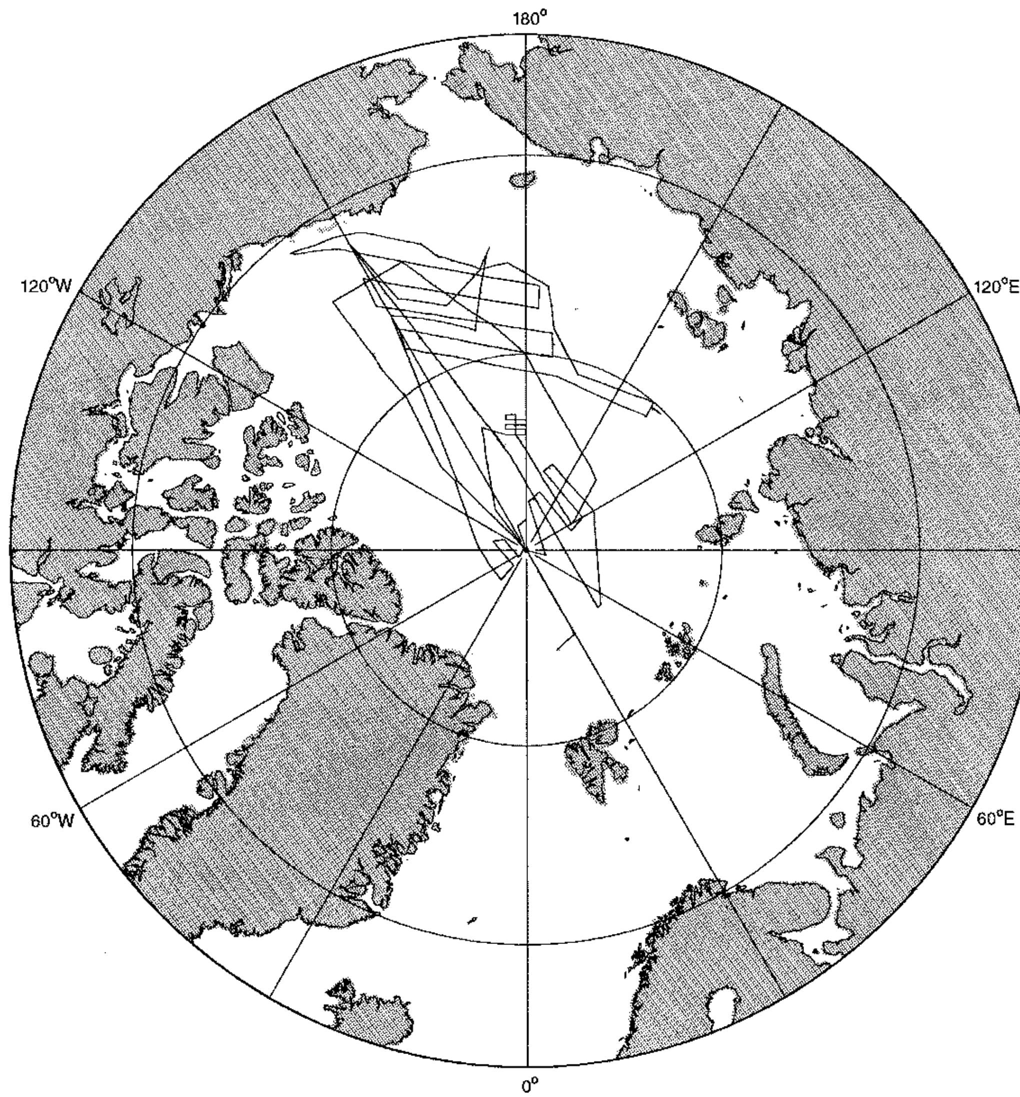

Figure 6.2.5 Under the auspices of the SCICEX programme, the US Navy in 1993 and 1995 deployed nuclear submarines on unclassified mapping and research missions beneath the Arctic pack. On those missions, bathymetric observations were collected along the tracks shown here; they are destined for the public domain, as are similar observations that were collected in 1996. The track-lines shown here were provided courtesy of Bernard Coakley of the Lamont-Doherty Earth Observatory.

6.3 SOUTHERN OCEAN BATHYMETRY: THE NEW BATHYMETRIC CHART OF THE WEDDELL SEA, ANTARCTICA (*by H.W. Schenke**)

6.3.1 Summary

The hydrography of the Southern Ocean plays a key role in the modelling of ocean processes and for investigations of climate change problems. In particular, ocean areas off the huge ice-shelves, like the Ross Sea and the Weddell Sea, which are nearly the whole year covered with sea-ice, are of special interest. Transport mechanisms of the Antarctic bottom water and circulation processes are controlled to a certain extent by the seafloor topography. The bathymetry of the Atlantic sector of Antarctica was fairly unknown until 1983, when the Alfred Wegener Institute for Polar and Marine Research (AWI) started its scientific activities by sending its ice-breaking research vessel *Polarstern* into the extremely hostile Weddell Sea region. Since then, more than 40 expeditions have taken place in this region. Multi-beam and single beam data were collected on random tracks, and a few systematic surveys were carried out in selected areas. Based on the data collected by R/V *Polarstern*, and on additional echo sounding data supplied by several national Hydrographic Offices, research institutions and the IHO Digital Bathymetric Data Centre (DCDB), a new Bathymetric Chart of the Weddell Sea (AWI BCWS) was developed in the scale 1:1 Million. Six sheets of the southern Weddell Sea were completed recently covering the area between 66° to 78° southern latitude and 0° to 68° western longitude. The heterogeneous type of bathymetric data and the lack of data in ice-covered areas required the incorporation of supplementary geophysical and geographical information. A new semi-automatic approach was developed for the terrain modelling and for contouring. In coastal regions sub-glacial information was included in order to model the bathymetry in the transition zones. The bathymetry of the southern Weddell Sea will be presented and discussed with regard to its scientific importance and benefit for other disciplines.

6.3.2 Introduction

The ocean floor is the habitat for floral and faunal species, its topography has a major impact on the circulation of water masses, and its morphological features contain information about the Earth's geological history.

The rapid development of multi-beam sonar techniques for surveying the topography of the sea bottom, in particular the use of hydro-acoustic signals (side-scan sonar and backscatter) for geomarine studies, has led to growing scientific interest in the field of bathymetry.

The AWI has been involved in bathymetric surveying and mapping since 1983, when the research icebreaker R/V *Polarstern* was put into operation. The ship was equipped with the multi-beam system Seabeam in order to perform effective bathymetric surveying in the last completely unknown regions of the Arctic and Antarctic Oceans (Schenke, 1987). In 1989, Seabeam was replaced by the newly developed multi-beam system Hydrosweep DS, which is characterized by reinforced transducers (for operation in ice-covered areas), a larger swath width and the cross-fan calibration technique (Schenke and Schreiber, 1989). Because of its technical and scientific design as a multidisciplinary research platform, *Polarstern* cannot solely be used as a bathymetric survey ship. Only in areas of special geoscientific investigations, are multi-beam surveys carried out with complete area coverage. These were effected during more than 20 expeditions to the South Atlantic and the Weddell Sea. Usually, multi-beam data are continuously recorded by the operator also during transits. During all other expeditions just single beam sonar data were recorded. Today the multi-beam data are corrected and post-processed during the expedition in order to minimize the workload afterwards. Survey data from previous cruises with less precise positioning were processed and corrected in a time-consuming process after the expedition.

6.3.3 Bathymetric surveying with R/V *Polarstern* in the South Atlantic

Since 1983 more than 40 expeditions into Antarctic waters were carried out: during 21 cruises multi-beam sonar data were obtained and on the remaining cruises only single beam sonar data were collected.

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The operation area of *Polarstern* is mainly concentrated between South Africa or South America and the Neumayer Station in Antarctica (72°S, 8°W), the ice-shelf edge of the Ronne-Filchner-Ice-Shelf and the Antarctic Peninsula (Fig. 6.3.1). Only a small number of box-surveys was performed by *Polarstern* in Antarctica: Off Kapp Norvegia (a pre-site survey for the Ocean Drilling Programme) and in the northern part of the Filchner Trough for special sedimentological studies (Hagen et al. 1994). Multi-beam data were also recorded during geophysical surveys and transects along the coast. In order to improve the bathymetric data coverage, the transit profiles between South America or South Africa and Antarctica were placed parallel to existing lines, and in the ice-covered waters of Antarctica all new tracks were placed in areas of sparse data.

6.3.3.1 Quality control of bathymetric data

To ensure a good quality of the measurements, multi-beam surveys are only carried out by trained operators. For navigation and positioning, an integrated navigation system, based on the NNSS Transit Doppler Satellites and standard dead-reckoning systems, was used until 1992. Today, this system is replaced by the Global Positioning System (GPS) operating in real-time differential mode (RT-D-GPS), which supplies an accuracy of better than ±10m, even in Antarctica (Schenke, 1990b). Ship's attitude control is performed by a GPS-based system with three antennas, which measures in real-time heading, roll and pitch (Schenke and Wübbena, 1992). The control of heading is especially important during operations in high latitudes, where mechanical gyro systems are generally deviated by transient errors, especially during ice-breaking. Navigation data as well as the multi-beam measurements are carefully checked by the operators during the cruise.

In areas of box surveys, sound velocity profiles are measured by a CTD and compared to the automatically determined mean sound velocity value, derived from the Hydrosweep cross-fan calibration process. Up to 20 sound velocity values can be used for the automatic slant range correction, the absolute depths are determined by applying the best mean sound velocity value.

During the first checks on board, outliers in the navigation and multi-beam data are discovered with an automatic programmeme followed by a preview plot, which helps to browse through the data in order to detect further erroneous measurements. The final cleaning is done by a half automatic procedure, which allows visualisation of data from the entire survey area. Final random and systematic errors can be recognised by checking the surroundings of doubtful measurements. Bad data, outliers or other wrong measurements are labelled.

Single beam sonar data, which are usually recorded during cruises without multi-beam operations, are checked by comparing the recorded digital depths against the analogue recordings in a semi-automated process. The ship‘s positions are evaluated and corrected, if necessary. However, due to a severe lack of personnel, this work cannot be done continuously, and therefore a tremendous amount of data is not checked until today.

6.3.3.2 Data archiving

Cleaned and corrected data are stored in sequential files at the institute as well as on Polarstern. The availability of all existing data on *Polarstern* enables scientists to perform ideal cruise planning, and a post-processing of complete bathymetric data sets including multi-beam and single beam data can already be done during the cruise.

After the final correction, the data are transferred to the German bathymetric data centre, which is located in Rostock as a subsidiary department of the Federal Agency for Navigation and Hydrography (BSH). After the release by the originator the data is sent to the IHO Digital Bathymetric Data Centre (DCDB) in Boulder, Colorado, USA.

6.3.3.3 Scientific use of bathymetric products

None of the three ocean going German research vessels *Sonne, Meteor* and *Polarstern* are purely used for systematic bathymetric surveying. All three ships have multidisciplinary tasks, and are used during each cruise by many different groups. Systematic surveys with the multi-beam system are only performed if the geomarine programme requires a high-resolution bathymetric chart (i.e. ODP pre-site survey, sediment studies, local surveys for moorings, studies of small features on the ocean floor, etc.). In general, bathymetry is considered as a by-product during cruises and extra ship's time is often not available for comprehensive surveys. To achieve a better multi-beam and single beam data coverage from cruises in one region, the working strategy at the AWI is to collect systematically data in the operation area of *Polarstern* over a long time period. In addition, bathymetric data from other national and international institutions are included.

6.3.4 Charting the bathymetry of the Weddell Sea, Antarctica

6.3.4.1 Scientific objectives

The Southern Ocean between the south-east Pacific, the Indian Ocean and the South Atlantic is, with respect to its morphological structures and the environmental conditions, one of the most hostile regions on Earth.

The bathymetric regimes include abyssal plains, ocean ridges, glacially formed continental shelves and deep sea trenches. During the last decades only very few expeditions have penetrated the Weddell Sea because of its year-round sea ice coverage. Only ice-breaking research vessels like *Polarstern* have performed bathymetric surveys (Schenke, 1993).

The earlier compilation of the GEBCO Sheets 5.16 and 5.18 suffered much from the small amount of measurements and from the unknown quality of older data. However, the GEBCO-Sheet 5.16, re-compiled by John La Brecque, Philip D. Rabinowitz and Carl Brenner from Lamont-Doherty Earth Observatory (LDEO), N.Y., USA, in 1981, was for the first scientific cruises of *Polarstern* an important basis and a substantial contribution to geomarine research in this region. The poor data quality and sparse distribution of bathymetric measurements is clearly visible in the overlapping area of Sheets 5.16 and 5.18. Since nearly the same data sources were used for the compilation of the bathymetry, particularly in the area of the continental shelf, many differences in the contour lines are noticeable.

Since the Weddell Sea and the southern Atlantic is the main operation area of *Polarstern*, a large amount of bathymetric data was collected over the past years. Therefore the GEBCO Sheet 5.16 was chosen as a case study for a new compilation technique to update GEBCO with respect to its sixth edition. In the framework of a research and development programme at the AWI, all available bathymetric data in this region were quality-checked and compiled. For this purpose AWI has developed and used new techniques. After more than three years, a completely revised new bathymetric chart of the southern part of the Weddell Sea is available (Hinze, 1994).

6.3.4.2 Collection of bathymetric data

The compilation of a high resolution bathymetric chart does not only demand depth measurements to the seafloor. Especially in Antarctica, additional information about the coastline and coastal features, and for the geomorphological interpolation of the near-shore regions the bedrock topography underneath the ice-shelves and ice sheets, must be known.

The collected data originate from many different sources, from land and marine expeditions and from hydrographic surveys during the last 40 years

Due to the rapid technical development in sonar techniques and in navigation systems, the received external data are of different accuracy and reliability. Within the last decade, few areas of the Weddell Sea were surveyed systematically. The general situation of hydrographic surveys in Antarctic waters is still very far from being satisfactory and the existing marine cartographic products and nautical charts are not at all uniform. In most areas of the Weddell Sea the distribution of track-lines is irregular, soundings are available along the tracks as single beam or multi-beam data. In some regions, mainly the operation area of Polarstern, the density is more satisfactory. In the regions of the continental shelf systematic multi-beam surveys were performed. In some other regions like the central Weddell Sea even single soundings are spaced more than 100 km apart from each other. In order to develop an optimal bathymetric chart, all available depth measurements were included in the mapping process. As it is not feasible to discard older data of less accuracy, it is necessary to combine them with the more recent, taking into account the accuracy of the position and the depth measurements.

All assembled measurements and the data digitized by AWI were transformed into a standard input format for the DTM programme and validated by special semi-automatic procedures. Later, for the final validation and interpolation, additional geological and geophysical information sources, as from satellite altimetry, were used.

6.3.4.3 Data analysis and cleaning

The utilized bathymetric data for the AWI BCWS originate from many different sources:

- scientific institutions;
- hydrographic offices;
- IHO Data Centre for Digital Bathymetry;
- existing charts, including track and source control;
- expedition reports and publications;
- private communication.

The quality and accuracy of this heterogeneous type of data had to be carefully checked and analysed in order to avoid the creation of any artefacts and of non-existing sub-marine features. As a first step, the data was checked in an automatic process by comparing single measurement to a digital terrain model (DTM), which was determined on the basis of all existing data using a relatively large grid size of several kilometres. Measurements which show large differences compared to precise data, were removed. A final cleaning was carried out during the seafloor modelling process by comparing raw data to the primary DTM. Reviewed and validated measurements were included in the fundamental bathymetric database.

6.3.4.4 Development of a Digital Terrain Model

The verified and collected bathymetric data were used for the calculation of the DTM. The model was determined in an iterative process taking into account the different data quality and accuracy. For final verification and scientific validation the depth values were cross checked with any other available information of the seafloor, e.g. predicted bathymetry, currents, gravity anomalies, morphology. The digitisation of the contour lines was done with the help of the Computer Aided Resource Information System (CARIS), which is a Geographic Information System widely used for the generation of Nautical Chart and other scientific applications.

Several different programmes for the DTM calculation are available at AWI, each with its own advantages and disadvantages (Schenke, 1990a). The determination of a DTM from complex bathymetric data is crucial, especially if the data are of different quality. The accuracy of the bathymetric measurements in the Weddell Sea varies extensively and the data distribution is extremely patchy and inconsistent.

A more robust procedure was developed in order to reduce the effect of the above-mentioned data problems. The programme GIRA used for this work, is designed to read and process bathymetric data from ship tracks, single points, multi-beam data or partially gridded data in order to determine a new regional grid by the method of Swain. The regional grid is merged with the actual data points by using bi-cubic spline interpolation based upon the Briggs and Swain method. GIRA is an advanced modification of a FORTRAN programme supplied by the LDEO in 1984. Special routines were included to account for the different data quality and spacing. Furthermore the programme was modified for a meaningful use in high latitudes. Uniform grid distances in latitude and longitude are required to satisfy the modelling of a regular grid.

The DTM depths were computed from appropriately weighted input measurements separately for each sub-sheet. The chart scheme of the AWI BCWS is sub-divided into sheets which are related to the GEBCO Ocean Plotting Sheet (OPS) index (Fig. 6.3.2), into sub-sheets of 2° Lat. x 5° Long. For each sub-sheet individual model parameters for DTM calculation were chosen in order to account for the special conditions within this area, e.g. data density and roughness of topography. Some of the model parameters were:

- individual grid distances for each sub-sheet;
- individual weighting for each input data set.

The DTM processing was done on VAX/VMS work-stations. The interpolation of the contour lines was performed with a separate programme. The interpolated sections of the contour lines with the grid form a polygon. In order to determine a smooth contour line, a 5-degree polynomial fit was applied. In areas of sparse data, the derived contour lines are validated with all available scientific information like the gravity field, satellite imagery or magnetic lineaments and, if necessary, interactively modified with a graphic editor.

6.3.4.5 Cartographic layout

The publishing of the AWI BCWS in the form of a printed map and in digital contour lines demands a suitable and conform editing of the chart content, as there are contour lines, coastlines, surface structures, and the legend. At the AWI, the programme CARIS is generally utilized to create and manipulate the chart content. The whole bathymetric chart and the inset maps were prepared by using CARIS. The geo-referenced work was carried out with CARIS, and for the cartographic layout and for the preparation of the print files, the Macintosh programmeme FREEHAND was used.

The printed AWI BCWS sheets include seafloor topography, data sources, data distribution, and depth accuracy. The distribution of all measurements that were used for the DTM modelling, is represented by marked grid cells. All populated DTM elements are printed on the backside of the sheet and supply track control and spatial distribution of measurements. The inset maps provide overviews on the spatial representation of source data and accuracy within the chart. An example is given with the OPS 567 (Fig. 6.3.3).

The seafloor topography is shown using blue contour lines. On the 1: 1 Million charts contour lines are solid for the 100 m intervals and in areas of boxed swath surveys and in shallow waters the intermediate 50 m contours are shown in dashed lines.

The coastlines, ice front, and grounding lines of the ice-shelves are included in the map in order to attain a complete impression about the different boundary conditions for the sea. Additionally, glaciological information concerning the position of crevasses and ice inlets and the extension of ice rises, ice islands, glaciers, and ice tongues is mapped.

6.3.5 Future work

The bathymetry of the southern Weddell Sea is published as a printed map in the scale of 1:3 Million in the AGU Antarctic Research Series (ARS), in 1998 (Schenke et al., 1998). Furthermore, the contours are included in the latest edition of the GEBCO Digital Atlas (GDA) published in 1997 (IOC, IHO and BODC, 1997). Finally the six sheets of AWI BCWS (Fig. 6.3.2) at the scale of 1:1 Million. will be published as a printed paper chart by AWI. The sheet 567 and 568 were printed in 1998.

The AWI programme of charting the Weddell Sea will be continued by extending the work to the northern part of GEBCO 5.16, covering the OPS 509-512 and 533-536. Because of the difficult morphology of the Scotia Sea and the Scotia Arc this work may last again several years. Many expeditions have led into this region, however, a good coverage of data is not yet realized. The compilation of this part of GEBCO 5.16 will be done in the frame of a joint international project by the British Antarctic Survey, the Vernadsky Institute, Moscow, and the AWI.

6.3.6 Summary

Bathymetric work has mainly been focused on the compilation and processing of survey data in the regions where the *Polarstern* has carried out her expeditions. The results are presented in the form of a DTM of the sea floor, and are subsequently used for drawing charts and for detailed geomarine studies. Based on these contour lines, a new DTM was recently determined with a grid of 2.5’ x 2.5’.

Polarstern has been conducting bathymetric studies of the southern and eastern Weddell Sea since 1983. The unique data gathered in this region of the Southern Ocean has been systematically processed, archived and utilized for the production of the new ”AWI Bathymetric Charts of the Weddell Sea” (AWI BCWS), at a scale of 1:1.000.000. The bathymetric modelling and research analyses of the charts are based on multi-beam sonar and echo sounder measurements taken during *Polarstern* cruises. The AWI BCWS is the first large-scale bathymetric chart in this region of Antarctica. The chart No. 567 of the Filchner Trough (Fig. 6.3.3) was printed in 1998, followed by the 1:3 million chart, which was published by Schenke, et al. in 1998. The main area covered by the sheet 567 is the continental shelf north of the Filchner-Ronne-Ice-Shelf, and shows the topography from the shelf edge to the abyssal plain of the Weddell Sea. This bathymetric chart with isolines at 50 m and 100 m intervals (broken and continuous lines, respectively), supplies much more detailed information than existing charts, thus generating new information about the ocean floor in this region.

The clearly defined current structures on the continental slope north of the Filchner Trough are of particular interest. Surveys of these areas with the Parasound sediment profiler confirm these morphologic structures, which are also seen on existing sediment echo type maps. The three extended ridges north of the Filchner Trough are interpreted as large levees deposited by bottom current flows down the continental shelf. The continental shelf to the east of the Filchner Trough, off Coats Land displays previously unknown channels and trenches, orthogonally arranged to the Antarctic coastline.

The AWI BCWS is the basis for further systematic research in the Weddell Sea. Research on sedimentation in current controlled areas will be intensified in the future using integrated bathymetric and hydro-acoustic methods in combination with oceanographic and sediment physical data.

The 1:1 Mio sheets 551 (Larsen Basin), 552 (Antarctic Canyon), 553 (Explorer Escarpment), 566 (Ronne Trough), 568 (Lyddan) will be printed by AWI in 1999.

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Figures

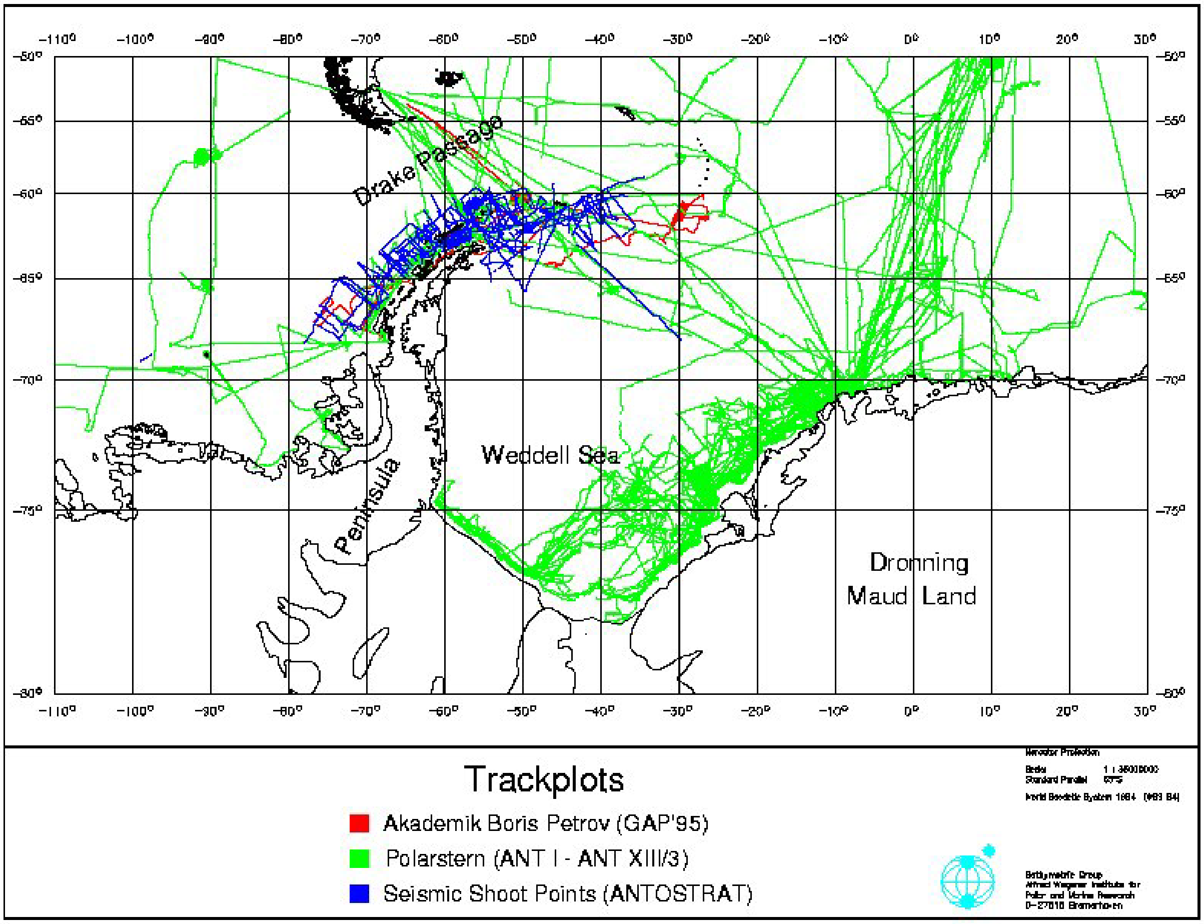
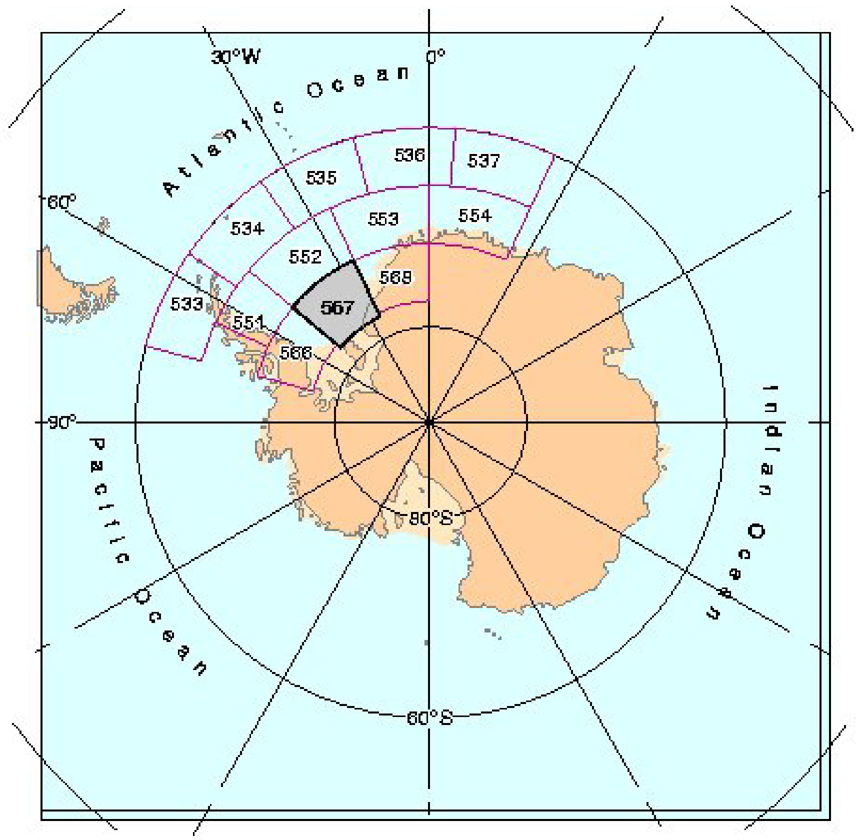


Figure 6.3.1 Track chart of data used as basis for improving regional bathymetry

Fig. 2:

Sheet Index of the AWI BCWS



Scale 1 : 80000000

Figure 6.3.2 Index of AWI bathymetric sheets

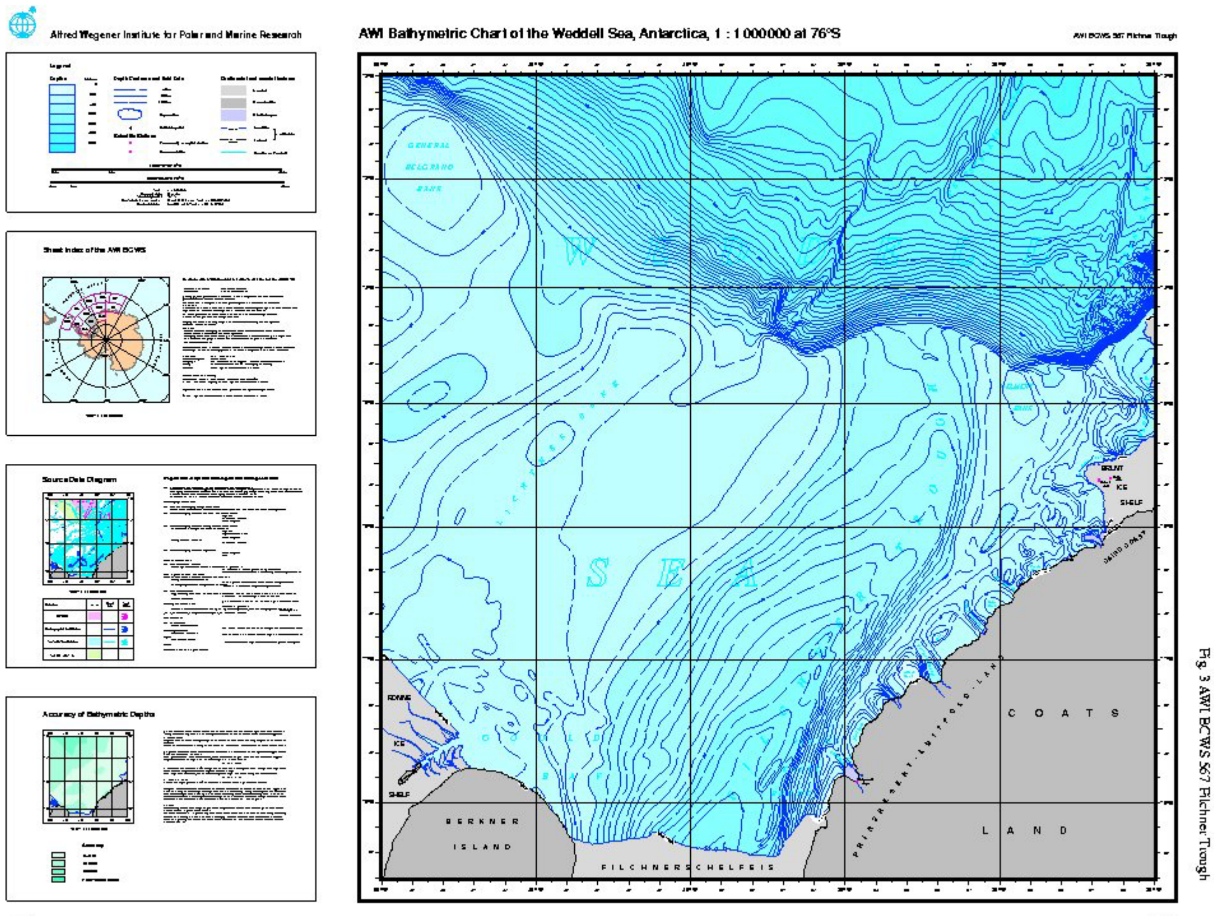


Figure 6.3.3 AWI bathymetric chart 567 of the Weddell Sea

6.4 THE JAPANESE PERSPECTIVE: NEW ASPECTS OF IMPROVED GLOBAL BATHYMETRY

(by K. Kobayashi)*

6.4.1 Introduction

In practice, there are three main categories of bathymetric survey: (1) general global mapping, (2) swath bathymetry from sea surface with nearly 100 % coverage, (3) extremely accurate mapping by near-bottom survey. First, thanks to recent progress in accurate positioning of ships by the Global Positioning System (GPS), and precise swath mapping of topography using multi-beam echo-sounders, we can now survey the deep-sea topography systematically to an accuracy of few metres in water depths and a few tens of metres in position, providing the potential for very detailed surveying.

Although this kind of systematic survey capability is now widely available, it has not been much used for EEZs, where the accuracy of bathymetric charts is generally on the low side (to several tens of metres in water depths and a few hundred metres in position) Accuracy tends to deteriorate further away from the EEZs towards the open sea. Bathymetric maps with depth contours of about 250 m are available over almost all of the world's oceans in the ETOPO-5 database. Free air gravity anomaly maps simulating bathymetry can be obtained from satellites altimetry data, although their bathymetric details need verification and analysis. Nevertheless, both kinds of maps are quite useful in providing a general overview of topography and in stimulating conceptual ideas about tectonic setting. More detailed data are being gathered in selected regions using modern technology for particular missions in pure and applied sciences as well as to meet social needs such as hazard prevention, environmental assessment and proper use of natural resources.

These three categories of survey methods should be distinguished for the purposes and objectives of each individual survey, but not as ranks or values of the work. In this report a few examples of these concepts of investigation will be described with special reference to mapping off Japan, although the situation is the same in the other countries and areas over the world.

6.4.2 General bathymetric mapping of the northwestern Pacific Ocean by Japanese vessels

In Japan several survey or research vessels are equipped with multi-beam echo-sounders: the Survey Vessels *Takuyo, Shoyo, Meiyo, Kaiyo* and *Tenyo* of the Hydrographic Department of the Maritime Safety Agency of Japan; the Research Vessel *Hakuho-maru* of the Ocean Research Institute of the University of Tokyo; the Research Vessels *Yokosuka, Kaiyo, Kairei* and *Mirai* of JAMSTEC; and the Survey Vessel *Hakurei-maru-II* of the Metal Mining Agency.

The Hydrographic Department is publishing bathymetric charts of the oceans in the north-western Pacific with a scale of 1:500,000 and a contour interval of 100 m. A set of charts of bathymetry, magnetic total force anomalies and free air gravity anomalies with a scale of 1:3,000,000 is also published for the seas around Japan. Figure 6.4.1 illustrates the bathymetric and tectonic features of the north-western Pacific Ocean where most of the Japanese efforts are focussed. It is used as a base map for the Ocean Drilling Programme Legs 125 and 126 (Fryer et al., 1990).

6.4.3 Precise Survey Of Selected Regions

Regions in and close to the Japanese EEZ have been investigated bathymetrically in more detail. A set of four bathymetric charts of 1/100,000 scale was compiled by the Hydrographic Department for particularly important regions, such as the seas off Tokai (Enshu-nada), where a large earthquake is forecast to occur in the near future. A bathymetric chart of 1:2,500,000 was published in 1991 for a region of 36°N-24°N and 122°30'E-145°E, mostly based upon new data, with swath coverage of 50% in most target regions except for areas with very complicated topography. A series of charts of 1,000,000 are being published for most of the surveyed regions (for example, for an area east of Nansei-syoto (Ryukyu Islands) covering 30°N-

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24°N, 130°E-140°E). Charts of gravity and geomagnetic anomalies are published for the same areas, since the ships measure these values along the same tracks. A survey has been completed for the north-eastern Japan Sea (in which a destructive earthquake occurred in 1994). Bay and shelf regions were surveyed by S/V *Tenyo*.

The seas surrounding the Japanese islands are characterised by the prevalence of subduction of the ocean floor. R/V *Hakuho-Maru* of the Ocean Research Institute, University of Tokyo, has measured swath bathymetry of selected regions with 100 % coverage. The bathymetric data already published include the westernmost Kuril Trench to central Japan Trench, the Ayu Trough region southeast off Philippines and seas surrounding the ridge triple junction in the Indian Ocean.

The Japan Trench east of NE Honshu (Sanriku) coast is formed by subduction of the 128 to 138 Ma old seabed of the NW Pacific basin. There the magnetic lineations of the subducting crust are nearly perpendicular to the trench axis, although the trench axis is convex towards the Pacific. Swath bathymetric mapping by R/V *Hakuho-maru*, and by the French vessel *Jean Charcot*, has shown that the ocean-ward slope of the Japan Trench is dissected by a great number of normal faults, most of which trend parallel to the axis, whereas some faults run oblique to the axis. In contrast, the outer slope of the western Kuril trench, trending in a direction close to the magnetic lineaments, has faulted scarps exactly parallel to it and oblique to the trench axis by about 10 degrees (Fig. 6.4.2, Kobayashi, 1991).

All of the faulted scarps on the ocean-ward slope of the trench are most probably formed by extensional forces acting on the surface of the oceanic crust when it is bent downward at the trench wall. There exist two types of the axial-parallel faults, those with scarps facing the island (i.e. the trench axis) and those facing the ocean, forming horst-and-graben morphology. The total number and relative heights of each type of faults are nearly the same. Both the tops of the horsts and bottoms of the grabens are inclined toward the trench axis. This means that down-going motion along the trench slope is caused by the dipping angle of the slope and not by the faulting. Gigantic underwater earthquakes repeatedly occurred on this ocean-ward slope in 869, 1611, 1677, 1896 and 1933, each causing large tsunamis that heavily damaged the Sanriku coast.

The landward slope of the Japan Trench appears to be affected by the fault patterns typical of the subducting ocean crust. The toe of the slope is faulted down parallel to the subducted ocean crust. The base of the landward wedge is being tectonically eroded by the subducting crust. Several large slumps caused by slope failure are recognized in the topography of the landward slope.

The stress regime in the landward crust is compressional, with a principal axis parallel to the direction of relative convergence of two plates along the Japan and Kuril Trenches. At present NE Honshu is under compression as a whole. An incipient subduction zone, oriented west to east, lies along the eastern margin of the Japan Sea. It caused the 12 July 1993 earthquake southwest of Hokkaido, and a large tsunami that destroyed a town in the Island of Okushiri. Nevertheless, tectonic erosion prevails under the landward prism of the Japan Trench.

In contrast to the predominance of tectonic erosion in the Japan Trench, accretion of sediment prevails on the landward wedge of the Nankai Trough, where the 15 to 30 Ma old Shikoku Basin floor is being subducted beneath SW Japan. The eastern part of the Nankai Trough has been extensively surveyed under the auspices of French-Japanese co-operative projects: KAIKO-I, II, KAIKO-Nankai and KAIKO-Tokai. Detailed bathymetric maps have been completed from work by the *Jean Charcot* (1984), and the *Takuyo*, *Hakuho-maru* and *L'Atalante* (1996). Repeated ridge-and-trough morphology trending nearly parallel to the Nankai Trough axis (roughly perpendicular to the magnetic fabrics of the subducting Shikoku Basin) is clearly identified in the bathymetric charts.

The Nankai Trough axis is covered by thick deposits of turbidites transported along the axis from rivers situated in the northeast. These sediments are gradually accreted to the landward wedge from its base. A dynamic boundary between the subducted slab and the upper wedge, the so-called decollement, was identified by seismic reflection profiling and confirmed by drilling (c.f., ODP hole 808 of Leg 131; Taira, Hill, Firth, et al., 1991). A similar structure of sedimentary accretion characterises the Barbados region in the western Atlantic.

Notable at the eastern end of the Nankai Trough is the Zenisu Ridge, which lies southeast of the Nankai Trough. The Zenisu Ridge is one of a suite of en echelon ridges associated with the western portion of the Izu-Bonin arc. An embryonic subduction zone is suspected on the southern flank of the Zenisu Ridge including an emerged rocky reef called Zenisu originally by Japanese fishermen. In an attempt to monitor the subduction process, the precise position of Zenisu is being measured by repeated use of GPS. If new subduction has already begun south of the Zenisu Ridge, then the rate of movement of Zenisu relative to Honshu must be smaller than the expected rate of convergence between the Shikoku Basin plate and Honshu. Given the accuracy of GPS we should be able to measure the convergence in a decade or less.

Bathymetry by JAMSTEC has been focused on site-survey for submersible dives, where several precise charts were completed. Swath bathymetric maps of 100 % coverage have been already published for the MARK (Mid-Atlantic Ridge-Kane Fracture Zone) and the TAG (Transatlantic Geotraverse) hydrothermal mound areas, the North Fiji Basin (by the French-Japanese STARMER Project), the Lau Basin-Havre Trough Boundary (New STARMER and Inter-Ridge programmemes), and the Palau and Yap Trenches in the western Pacific. An unreported deepest spot was discovered in the Yap Trench at 19°29.957'N, 138° 40.987'E, by a swath bathymetric survey by the Yokosuka, and found to be as deep as 8,946 m, compared to the previous deepest site of 8,650 m at 8°25'N, 137°56'E.

Two newly launched ships, *Kairei* and *Mirai*, will work with swath bathymetry in global aspects. A precise spot measurement of water depth was reported for the world's deepest site in the Mariana Trench (Challenger Deep). JAMSTEC's unmanned submersible confirmed it to be situated at 11°22.59'N, 142° 25.85'E. The maximum depth was determined by a pressure gauge on the vehicle and calibrated with CTD values during the dive. The depth is 10,911+10 m, which is close to the value defined by swath bathymetry by the *Takuyo* (10,924 m). Avoidance of redundancy (overlapped effort in the same spots) will be an important task in future.

6.4.4 Extremely Accurate Mapping Of Focused Sites

Near-bottom measurement by advanced tools has recently revealed micro-topography such as hydrothermal chimneys, mud/serpentine diapers, fissures and cracks with dimensions as small as a few centimetres across. The features of hydrothermal venting areas have been particularly well investigated, but the detail of trench slopes has been extensively clarified as well.

Many such bottom observations have been made by manned submersibles, which are capable of continuously mapping the bottom by visual observation with the aid of their altimeters. Features of hydrothermal mounds have been precisely drawn by this means at the TAG (Trans-Atlantic Geotraverse) hydrothermal mound, at some zones on the East Pacific Rise crest, and on the Juan de Fuca Ridge in the north-eastern Pacific. These sites, as well as cracks in trenches, have been revisited repeatedly so that their secular changes over several years could be revealed.

In the northwestern Pacific region, hydrothermal chimneys in the Okinawa Trough (west of the Ryukyu islands) and in the Izu-bonin rift zone west of the Izu-Shichito Ridge as well as in the Mariana Trough have been extensively investigated. Both the US research submersible Alvin and the Japanese Shinkai 6500 worked on the Mariana vents, while the Japanese Shinkai 2000 was used for the Okinawa and Izu hydrothermal studies. For these highly detailed topographic studies, swath mapping provides just the raw base-maps; submersible observations by either manned or unmanned vehicles, including the deep-towed TAMU2, provided the fine detail and defined the positions and shapes of active vents.

Mega-plumes ejected from black smoker vents are identified by deep-towed instruments such as tow-yow (a name of a nephelometre with CTD operated up and down in a similar manner to a toy yo-yo). The mass flux through these hydrothermal vents to the deep-ocean has recently been recognized as playing an essential role in the interaction of the earth's deep interior with surface environments. It has been postulated that a large hydrothermal event might even affect the onset of an El Niño event; this idea needs to be examined by direct monitoring of the hydrothermal vents on the deep-ocean floor.

A number of small isolated diapers have been discovered on the lower slopes of the ocean trenches near Japan. On the lower parts of the extensional Mariana and Izu-Bonin Trenches, small conical mounds composed of serpentinite diapers have been found and investigated in detail by submersibles and drilling. Similar serpentinite diapers have also been found in the rift valleys and transform faults in the mid-Atlantic Ridge (e.g. MARK site). Deep-towed side-scan sonar instruments such as TOBI played an important role in defining the shape and existence of these diapers.

In contrast to serpentinite, mud diapers are distributed in the accretionary wedges of the compressional boundaries. In the landward toe of the Nankai Trough a line of mud diapirs was defined by the side-scan sonar IZANAGI. Such diapered injection of probably methane-rich fluid indicates locally high pore pressure related to the disintegration of methane hydrate. Similar mud diapers are identified on the crest of the ocean-ward slope of the Japan Trench, where the sedimentary surface is under extension.

Zones of seepage of cold water transported from deeper sedimentary layers through shallow detachment faults or thrusts have been recognized on the landward wedge in the Nankai Trough at depths of 3,800 to 1,800 m, in the Japan Trench (at 6,350 to 5,500 m), and in Sagami Bay (at 1,800 m), as well as elsewhere (e.g. Oregon margin, Florida escarpment, Barbados). Communities of benthic animals including Calyptogena (clams with bivalves) have been discovered around these seeps. They are fed with methane-rich water that reduces sulfate in seawater to hydrogen sulphide. The clams are aligned along the seabed expressions of faults that can be recognized only by submersible observation. At the Sagami Bay site off Hatsushima Island the seepage is being continuously monitored by TV cameras and geophysical instruments connected to a land station by cable.

Detailed sedimentary structures as well as the micro-topography of the eastern Nankai Trough wedge were investigated by use of French deep-towed PASISAR in March-April 1996, enabling identification of the configurations of shallow detachment faults and the BSR (bottom simulating reflector), and correlation of sub-bottom structure with slope failure (mass wasting on steep slopes). Similar slumping on the landward slope has been found in other regions including the Japan Trench (see Fig. 6.4.2) and the MARK zone in the mid-Atlantic Ridge.

Landslides are usually generated by seismic shocks when the angle of slope is critical due to rapid uplift. Sub-bottom failure is often caused under the influence of fluids, sometimes related to high methane concentration. Methane hydrate is solid under high hydrostatic pressures at temperatures close to the sea bottom (-3ºC), whereas it is decomposed to form a layer of fluids (BSR: bottom simulating reflector) at a certain depth in sediment where the geothermal gradient exceeds the critical temperature of hydrate stability. Even if the magnitude of an earthquake is moderate, the slump it gives rise to may cause a large tsunami, hence the need to assess possible slope failure near inhabited coasts, as one means of improving the detection of possible future hazards. Precise swath bathymetry is the first step in this exercise, and detailed observations of bottom features together with detailed surveys of sub-bottom structures are necessary to accomplish the task.

Materials displaced by slumps in the forms of debris flows and landslides accumulate on trench slopes as talus deposits. The shape and nature of these deposits should be examined by direct observation and sampling rather than bathymetry alone, to refine the model of slumping for any given area. Mapping the detailed topography of deep-sea channels can also be useful. For a variety of reasons, among them the influence of topography, deep-sea channels usually meander. In areas of tectonic activity, the history of meandering may reveal the tectonic history of vertical motions in that region. Studying channels may also prove useful in determining pollution pathways. Newly dissected narrow channels and gullies on the bottom may indicate the routes and velocities of recent bottom currents. It has recently been found by submersible observation that garbage including vinyl sheets and metal cans can be transported by such bottom currents to settle in flatter areas, usually on the flank of scarps.

6.4.5 Need for Precise Bathymetry Data to Meet Social Requirements

One of urgent needs of improved bathymetry is to contribute to improving programmemes of prevention of disasters from tsunamis. There are two different ways of correlating bathymetry to tsunamis. One is to map potential landslides, since submarine landslides may cause tsunamis. On the landward walls of trenches a number of locations have very steep slopes exceeding slope failure angles. They may collapse when an earthquake shock or deep-sea turbidity current triggers slumping. Several slopes with horseshoe shaped topography are identified on the landward walls of trenches with thick sediment cover, such as the Japan Trench and Nankai Trough. The horseshoe shapes represent landslip scars that are presumed to have caused tsunamis of appreciable size but without associated detectable earthquakes. If this supposition is true, careful examination of slope topography in association with physical properties of sediment with high pore water pressure is needed to forecast possible occurrence of landslides on the trench walls and associated tsunamis.

The second way in which bathymetry is correlated to tsunamis is through reinforcement of tsunami-wave amplitude by particular bottom topography. If the seabed over which a tsunamis passes shallows and narrows markedly toward the coast, the resulting tsunami will be greatly amplified following the law of tsunami wave velocities. Detailed bathymetric data are necessary for the numerical simulation of tsunami amplitudes everywhere along a tsunami-prone coast.

6.4.6 Japan Oceanographic Data Centre (JODC)

Bathymetric data are managed in Japan by the Japan Oceanographic Data Centre (JODC). It holds files of data in digital form: e.g., ETOPO-5 (depth data over the world expressed by 5' mesh). It also stores data from several international projects such as TOPEX/POSEIDON (NASA CNES satellite altimetry), and from joint French-Japanese work (KAIKO).

Bathymetric data for areas surrounding Japan is being digitized from available charts by the Hydrographic Department and the MIRC (Marine Information Research Centre) of the Japan Hydrographic Association. The plan of mesh size for digitising data is:

2' for the whole northwestern Pacific;
1' for near-water and
500 m mesh for coastal zones and bay areas;
This work is schedule for completion in 1999.

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Figures

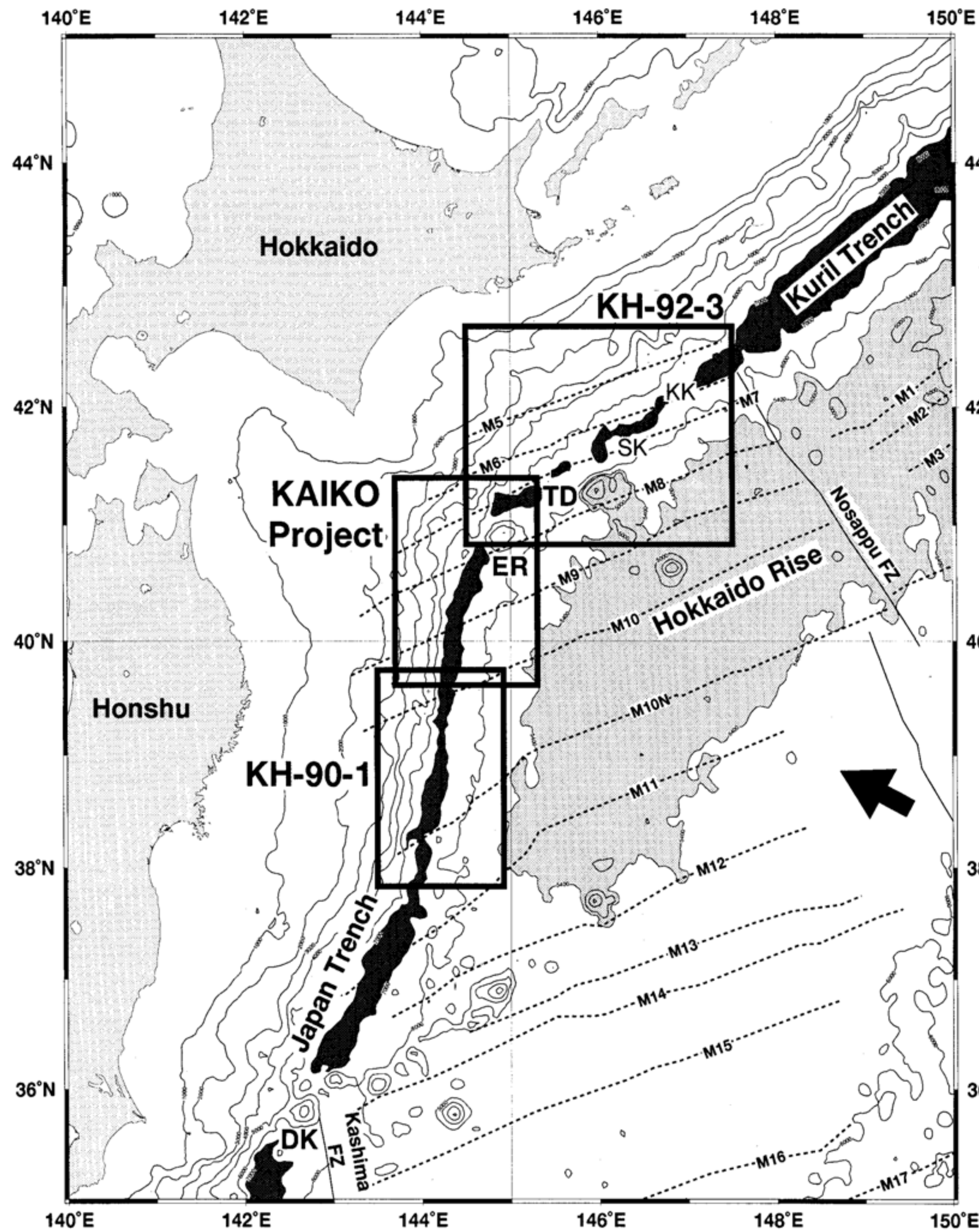

Figure 6.4.1 Bathymetric and tectonic features of the northwestern Pacific Ocean, showing the Japan Trench and its relation to regional magnetic anomalies (M) and Fracture Zones (FZ) (from Kobayashi et al., 1998); note that Figure 6.4.2 represents detail from the box labelled KH-90-1. Depths greater that 7,000m (trench axis) are darkly shaded; the outer swell (Hokkaido Rise) above 5,400m is lightly shaded. Arrow denotes direction of plate convergence.

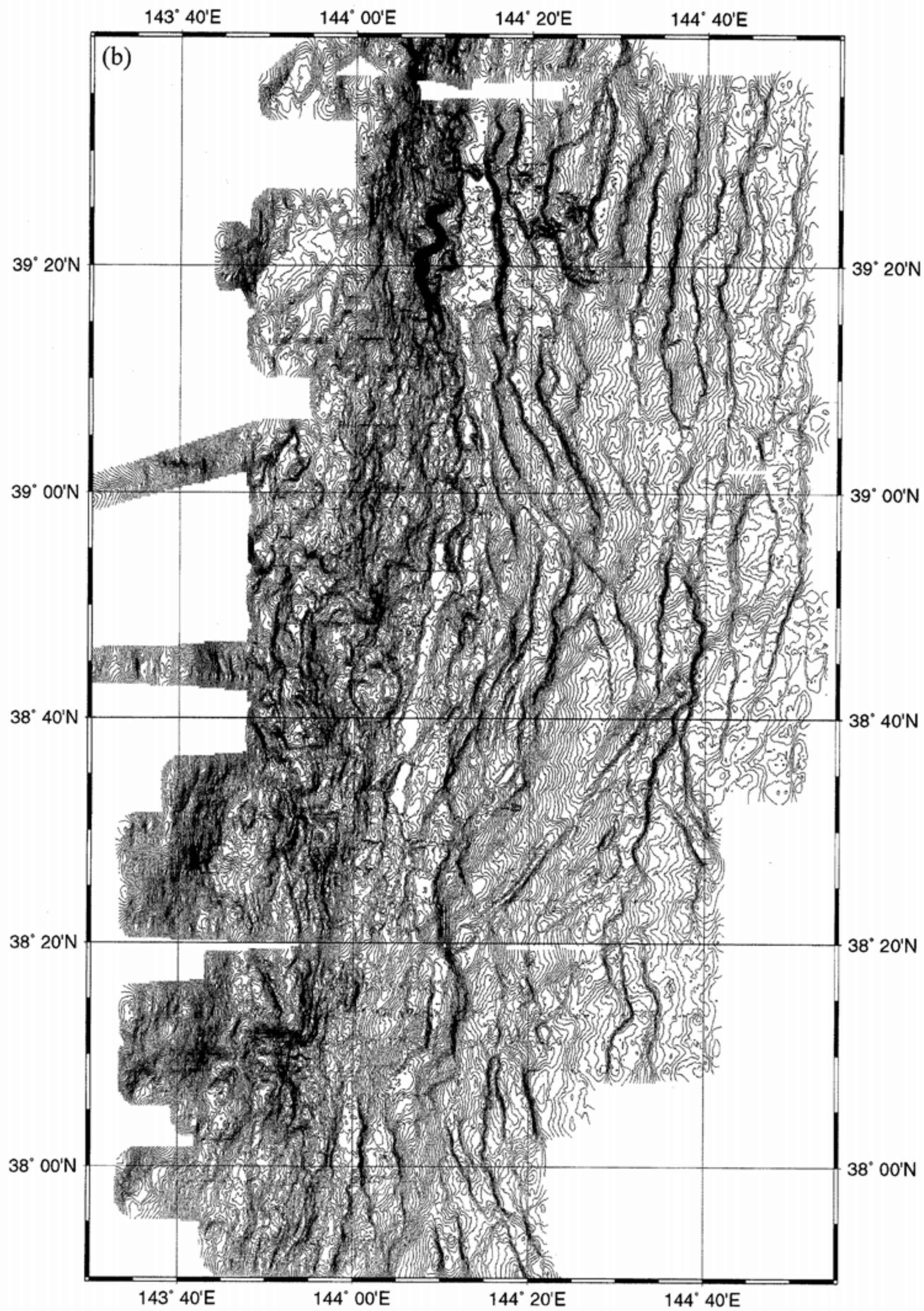

Figure 6.4.2 Swath bathymetric map of the northern Japan Trench (Kobayashi et al, 1998); for location see Figure 6.4.1.

6.5 RUSSIAN INITIATIVES FOR IMPROVED OCEAN BATHYMETRY: A BRIEF REVIEW

by (G. Udintsev[*])

The present growing interest in ocean bathymetry shows the increased understanding of the role of the topography of floor of the seas and oceans both in processes of movement of water masses, near bottom sea currents and tidal currents, and in recognizing the location of potential mineral reserves and living resources.

Historical interest in bathymetry in Russia does not date back very far, and serious efforts at compiling bathymetric maps of the oceans were made only in the middle of the nineteenth century. It was then that the first Russian bathymetric map of the World Oceans appeared, compiled by M. A. Rykachev (1882) and maps of the topography of the floor of the seas surrounding Russia, compiled by K. S. Staritsky (1898).

The history of international efforts to make bathymetry the basis for oceanographic and especially marine geological-geophysical studies began with the 7th International Geographical Congress (1899), which brought together oceanographers from a number of countries, including Russian oceanographers, and resulted in the creation of project of compilation - GEBCO. The first edition of GEBCO appeared in 1903, and this map in the middle of the passing century went through two continually updated editions in 1912 and 1932. The positions of the isobath were defined, moreover, by the method of linear interpolation, which is traditional for hydrographers. However even then attempts were being made to divert from this method in favour of a method based on notions of the origin of forms of underwater topography, for example, on Fritjof Nansen's map of the topography of the floor of Arctic seas (1905), and later on the Veatch and Smith map of the eastern continental margin of North America (1939).

In the middle of the twentieth century knowledge of the topography of the ocean floor and the structure of the floor of seas and oceans expanded substantially, and the former methods for compiling bathymetric maps were no longer satisfactory to nearly all groups of scholars and oceanographers, first and foremost among them the geologists and geophysicists. After the years of World War II, to a great extent thanks to the broad use of self-recording echo-sounders, all marine geologists came to the conclusion that there was a need in constructing the isobaths to renounce the use of the method of linear interpolation, and make the basis of the definition of their contours concepts regarding the structure and origin of forms of the topography of the ocean floor, and regarding its structure. In accordance with these concepts the compilers of bathymetric maps renounced the formal contouring of areas of equal depths, and attempted to show characteristic forms of the topography of the floor and correspondingly to contour them with isobaths. This took place simultaneously among many groups of marine geologists, and among such geologists in Russia, who compiled using such geomorphological method a series of bathymetric maps for Far East Seas, for Pacific, Indian, Atlantic Oceans and for Arctic Seas, so it was natural that there was a nearly instantaneous agreement of the compilers of bathymetric maps of various countries in their criticism of the 4th edition of GEBCO, which began in 1964, compiled using the old method of linear interpolation of depths, and in the acknowledgement of the need for bathymetry compilation to be guided by methods of geomorphology. As is known, the 4th edition was suspended, and it was decided to unite the efforts of hydrographers with the experience and knowledge of marine geomorphologists and geologists. In 1966 this was at the basis of the beginning of the creation of the 5th edition of GEBCO, which was concluded in 1984.

In the 1960s and 1970s the development of the study of the submarine topography of the ocean floor was enormously helped by the broad use of detailed (regional) studies, the appearance of the methods of satellite navigation, side- scanning sonars and multi-beam echo-sounders, and the application together with studies of the topography of the ocean floor of a wide range of geophysical methods. All of this still further impacted on the attempt to reflect in the drawing of the isobaths the nature of the topography of the ocean floor and of its structure. However, detailed complex geological-geophysical studies of the ocean floor were limited to sections covering small areas, between which the drawing of the isobaths was defined to a significant extent by the intuition of the compiler and by his knowledge of the types of topography of the ocean floor and its origin.

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A new and revolutionary step in marine geology and in compiling bathymetric maps was the use of the results of satellite altimetry. The work of Walter Smith and David Sandwell marks an extremely important step forward the improvement of bathymetric maps. If there are grounds for speaking of possible inaccuracies in the definition of the depths in the method of these authors and even in some, very rare cases, of the appearance on these maps of certain artificial forms of the topography, the significance of maps with predicted bathymetry is simultaneously and absolutely unequivocally great for defining the general contours of the topography, the extent and outlines of forms of the topography of the ocean floor, which up until then were defined by geomorphologists or theoretically, or through extrapolation from sections of the floor which had been studied in detail. We received in the maps of the above-mentioned authors at last the long awaited real geomorphological basis for more accurate bathymetry.

Based on this, we see prospects for improving bathymetric maps both in the development of detailed (regional) surveying in the most complicated regions which are key for an understanding of the structure of the ocean floor, and maps for understanding the ways of near bottom transportation of water masses and in the use of maps with predicted bathymetry, based on the data of satellite altimetry, as a geomorphological base for a correct lineation of isobaths, based on geomorphological interpolation of the measured data between the sections of the areas of detailed survey, between profiles of continuous sounding or between scattered point depths data.

The efforts of Russian marine geomorphologists, working on the improvement of bathymetric maps, were focused during the past year on four regions of the ocean. These are:

(i) The North Atlantic and Arctic Seas (The P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences, M. V. Rudenko, Murmansk Marine Biological Institute of the Russian Academy of Sciences, G. G. Matishov, Acoustical Institute of the Russian Academy of Sciences, A. V. Iljin),

(ii) Equatorial Atlantic (Vernadsky Institute of Geochemistry, G. B. Udintsev, A. B. Kniazev, Geological Institute of the Russian Academy of Sciences, G.V. Agapova, N.N. Turko),

(iii) North-West Pacific (Pacific Oceanological Institute, Far East Centre of the Russian Academy of Sciences, A.S. Svaritchevsky), and

(iv) Western Antarctic (Vernadsky Institute of Geochemistry of the Russian Academy of Sciences, G.B. Udintsev, A.B. Knjazev, A.V. Koltsova).

Each group has a rather large archive of the measured depths, maps of the areas of detailed surveys (regions) and general bathymetric maps of the areas of their interests.

The general direction of work is taking place in stages such as:

(i) Collection and archiving of data, both digitized and in the form of analogue records and plotting sheets, obtained from various oceanographic institutes and from Russian Hydrographic Survey (GUNIO).

(ii) Digitizing of analogue depths records and data of plotting sheets.

(iii) Compilation of a digital model of the topography of the ocean floor on the basis of a digitized archive of data and data of GEODAS.

(iv) Computer construction of a graphic database in the form of marks of depths on plotting sheets on a scale of 1:1 million or 1: 2 million.

(v) Construction of a graphic representation of the digital model of the topography of the ocean floor, combined with the database, breakdown of the imaging by related plotting sheets.

(vi) Editing of a graphic representation of the digital model of the topography of the ocean floor in accordance with the model of the predicted topography (predicted bathymetry) based on the data from satellite altimetry with simultaneous clarification of contours of the isobaths of the digital model of the topography, based on measurements of the depths and on clarification of the depths in predicted bathymetry.

In work on the region of the Western Antarctic we carried out initial stages of the indicated order of operations for 20 plotting sheets of a scale of 1:2 million and continue this with further intent to carry out editing of bathymetry, based on the depth measurements, using for corrections of contours of topography the maps of predicted bathymetry based on data of satellite altimetry.

Work is being conducted in approximately the same manner for other regions of the ocean indicated above, but was going more slowly due to delays in obtaining the basic copies of predicted bathymetry and software necessary for such operations. Now there is good co-operation between all groups, and Russian investigators have been supplied with the necessary maps, obtained from Walter Smith and David Sandwell, with the necessary software, which should lead to continued progress.

6.6 THE INDIAN OCEAN PERSPECTIVE (*by A. Gouveia*[1])

At the second meeting of the Working Group, Dr. Gouveia reported that in India only one person was working on global modelling, using a 1-degree by 1/3 degree approach. Modelling was also taking place in the Arabian Sea and Bay of Bengal, using 5-minute grids. In these areas there was no significant problem with ETOPO-5 as the database. In coastal regions resolutions of 500 m to 1 km were required.

Dr Gouveia noted that ETOPO-5 does not represent accurately the bathymetry of the shelf edge. Instead it shows a shelf edge bulge as an artefact of the interpolation algorithm [DBDB-5 was a deep water system starting at 200 m; the interpolation algorithm pushed the slope up way over the real shelf edge to create a shelf edge bulge.]

India is collecting swath bathymetric data. Outside the EEZ these data are being sent to the World Data Centre, for instance from the Carlsberg Ridge and the central Indian Ocean. It is possible that during the colonial era the shelf was surveyed in detail by the British Admiralty and that the soundings are available in archives.

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7. THE COMMERCIAL PERSPECTIVE

7.1 COMMERCIAL DRIVERS FOR IMPROVED WORLDWIDE BATHYMETRY (*by H.W. Young*[1])

7.1.1 Introduction

For commerce in general the main driver for global bathymetry is not the bathymetric data itself, but the better ocean modelling and the improved weather forecasting that will result. For maritime commercial interests improved tidal prediction is also an additional significant driver. However maritime industries as a whole are too diffuse to be approached directly for support, advice or contributions: they will just use the results of research for their own needs. They see no commercial profit in investing in this research themselves.

The great majority of marine industry is interested in accurate bathymetry on the continental shelf in depths down to 300 metres. It has been assumed in this paper that global bathymetry will do little to satisfy this need, and that conventional surveys will continue to be required for such purposes. The main benefit of global bathymetry is seen to be the completeness of the coverage and the new data it provides in the deep ocean and on the slopes.

Those maritime industries involved in the deep ocean and the slopes have a greater interest in global bathymetric data. They are few, but include significant players such as the oil and gas industry, the fishing industry, and the communications industry for submarine cables. Less important, but with future development potential are waste disposal, and extraction of minerals from the deep, with occasional deep salvage work as opportunities permit. Serving these end users are the survey and geophysical companies for gathering data, whose activities impinge most closely on SCOR WG 107 work. The main business of these companies, however, is on the continental shelf, where 98% of survey work is carried out.

This paper will therefore consider the end-user commercial companies with interests in the deep ocean. It will not discuss the continental shelf nor the contribution of government agencies to these tasks.

7.1.2 End-Users Operating Off The Continental Shelf

a) The Oil and Gas Industry:
This is by far the largest end-user industry worldwide. Its main interest is on the continental shelf, where tidal and weather prediction are important, and where bathymetry is obtained from comparatively local surveys. However the relationship between gravimetric and bathymetric data is important, and as exploration extends further over the edge of the shelf, all types of deep-water information become of increasing interest. The exploitation of this interest is discussed below.

Surveying for the industry is carried out by survey companies for bathymetry and by geophysical companies for seismic exploration, which also involves a knowledge of local bathymetry. About 26% of the survey industry, (worth about US$200 million annually), and virtually all the geophysical industry (with a marine component worth about US$600 million annually) work for the oil and gas end-user. The oil and gas companies carry out no surveying for themselves.

b) The Fishing Industry:
The majority of commercial fishing is on the continental shelf, but migratory fish such as Tuna are caught in the upper levels of the deep ocean, and the industry needs better ocean modelling to identify uprising nutrients to predict fish stock variations and movements generally. This work, however, is mainly carried out by government fishery research laboratories, which also carry out specialized fish stock assessment surveys. Discovery of hitherto unknown shallow waters can lead to development of new fishing grounds, but the potential is small in the context of the industry as a whole.

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c) The Communications Industry:
In spite of satellite contributions to communications, fibre-optic cables are an important element of the industry. There are about 250 significant submarine cables in existence with a total length exceeding 400,000 km. The choice of route depends on the level of cable armour and need for burial as well as the shortest distance and the need to avoid obstacles. Thus the communications industry requires detailed route surveys for cable laying, and more general bathymetry for initial route planning. The surveys are carried out mainly by survey companies, and are estimated to be worth about US$24 million per year, though this fluctuates. Improved ocean modelling is also of interest.

The high cost and international aspects of most projects results in cable systems being owned by consortia of companies (for example one trans-Atlantic cable involves 31 organizations). This makes it difficult for an approach to be made to the industry as a whole for support for global bathymetry.

d) Waste Disposal:
Waste disposal is becoming an increasingly serious problem as pollution controls and shortage of sites on land force up the cost of conventional disposal methods. If suitable methods can have devised to protect the environment, disposal in the deep ocean could become increasingly attractive economically. Global bathymetry with systematic coverage of abyssal plains and improved ocean modelling would be a necessary precondition.

e) Mineral Extraction:
The current industry is based on sand and aggregate extraction from the continental shelf. Future development of deep recovery of nodules depends on the cost relative to extraction from on-shore, and also on certain strategic considerations for countries without such resources. The technologies for deep recovery are being developed, but so far commercial extraction has not started to any great extent. Global bathymetry might be useful in determining potential sites in the rather distant future, when the deep ocean industry may be significant as resources ashore deplete.

f) Wet Salvage:
Wet salvage is the recovery of cargo and information from ships or aircraft that have sunk, as opposed to dry salvage, which aims to prevent the ship sinking. Wet Salvage from the deep ocean is a rare and expensive business, and though global bathymetry would be helpful, it is scarcely a significant economic force.

7.1.2.1 Summary of End Users

The most important end users are the oil and gas industry and the communications industry. The communications industry is difficult to approach for SCOR WG 107 work, but the oil and gas industry has a more coherent organization and clearer needs which are discussed below. The majority of the commercial community will take the results of research that depends on global bathymetry, rather than invest in research directly.

7.1.3 The Bathymetric/Gravimetric Link For The Oil Industry

The potential for oil and gas sector interest in global bathymetry has been discussed with representatives of the British Geological Survey (BGS) and De Montfort University (Leicester).

Ocean heights, determined from satellite altimetry, can be transformed to reveal the earth's gravity field. Both are determined by a combination of bathymetry and the density of the rocks beneath the sea-bed. The oil and gas industry has so far been particularly interested in what satellite altimetry can reveal about the thickness and density of sub sea rocks, because this indicates the presence of sedimentary basins, which may be suitable sites for detailed exploration, and also more general information about large scale geological structures. However, there is ambiguity between anomalies due to bathymetry and those due to density variations, so the industry has a natural interest in determining ways to separate these out. There is a further potential, but more general, interest in the outcome of ocean current modelling, as these affect the feasibility of drilling for and extracting oil and gas in deep water.

Smith and Sandwell (1994) examined the possibility of improving bathymetry models by a method based on downward continuation of gravity/geoid's anomalies onto a long wavelength representation of the sea bed topography. Those authors have since applied the method to produce an improved map of the ocean floor covering southern latitudes. The availability of computer codes (such as that developed by BGS) to calculate the effects of both density and topography variations rapidly in 3 dimensions permits this method to be taken further forward. In principle, geological, geophysical, and oceanographic constraints could be built into a global 3-D model that would simultaneously account for both bathymetry and variations in crustal density. Lee et al. of BGS, in a paper presented at the annual meeting of the European Association of Geophysicists and Engineers) and Arabelos (of the University of Thessaloniki, in a paper published via the Internet) have independently shown that this is practical.

It is believed that a programmeme of work along these lines would be of sufficient appeal to the oil industry to attract sponsorship and financial support (partially or wholly). It would also provide access to relevant control data from seismic surveys held by the oil companies. "Joint Industry Groups", such as the Western Frontiers Association, convened by BGS to support environmental investigations in the NE Atlantic, would form an appropriate means through which to approach the industry. An appropriate next step might be the organization of an international scientific discussion meeting at which both industry and academic representation would present their interests and capabilities, with a view to forming a working plan and identifying a potential group of sponsors.

7.1.3.1 Summary of Oil industry Interest

The oil and gas industry, has a specific need not so much for the bathymetry as for the associated sub sea rock data which is also embedded in the satellite altimetry. A possible approach for their support would be to propose a programmeme of work to resolve the bathymetric/sub sea rock ambiguity, so that the industry needs were satisfied by the latter while SCOR WG 107 obtained the benefits of more accurate bathymetry from the satellite data. Such a plan would also release relevant data held by the oil companies.

Attempts to implement such a plan by getting more work done by BGS have failed due to lack of funding, and attempts to get more general funding from the oil industry have failed because the status of global bathymetry at present is not sufficiently firm or clear. Investment is unlikely to be made unless a formal project is in place. Should such a situation develop Hugh Young & Associates would be able to liaise with BGS and oil industry contacts to try and set up an international scientific discussion meeting, including academic representation from SCOR WG 107, and to see if industry sponsorship and funding could be made available for such a programmeme.

7.1.4 Survey Industry Technical Developments

Whatever combination of methods are finally recommended for improving global bathymetry, acoustic depth measurement from a floating platform is likely to be required at some stage. The survey industry is concerned to reduce the costs of such platforms, as ship time forms the most expensive component of their task. Autonomous air-breathing semi-submersibles are being considered for this purpose, lying half way between ships and drifter buoys in capability and cost. These developments are in the early stages at present but could significantly reduce the cost of obtaining direct acoustic measurement of bathymetry in the next decade.

7.1.5 Conclusions and Recommendation

In general the commercial interest in global bathymetry is diffuse, and involves taking the results of research and applying them to commercial problems, rather than investment in obtaining the bathymetric data.

An exception is the oil and gas industry, which has a specific need not so much for the bathymetry as for the associated sub sea rock data which is also embedded in the satellite altimetry results. If a formal global bathymetry project were to be established, oil industry investment might be forthcoming.

The survey industry is interested in developing technologies which reduce the expenditure on ship time, such as autonomous semi-submersibles, and these could significantly reduce the cost of obtaining direct acoustic measurement of data for global bathymetry.

It is recommended that a formal project for global bathymetry be set up as soon as possible after the way ahead is clear in order to focus industrial interest. This is unlikely to be forthcoming until a clear methodology can be presented.

References

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B. CONCLUSIONS AND RECOMMENDATIONS

8. SCIENTIFIC REQUIREMENTS FOR IMPROVED GLOBAL BATHYMETRY

8.1 TOPICS WITH SCIENTIFIC NEEDS FOR IMPROVED BATHYMETRY

The working group identified the following topics for which there were scientific justifications for improvements in bathymetry. YES or NO indicate where the group considered that bathymetry is a key limiting factor in furthering our understanding of ocean processes or applications:

- **ocean models:** YES – especially for steering of currents by straits and deep topography, and for sills controlling exchange of deep water, but also for most of the ocean floor (where there are commonly discrepancies between altimetric estimates and ETOPO-5 bathymetry).

- **deep water circulation** (channels; mudwaves): YES - for controlling paths of bottom currents.

- **tides:** YES - need detailed shelf edge and shelf bathymetry, and bathymetry of seamounts/banks which dissipate tidal energy.

- **tsunami forecasting:** YES - requires detailed bathymetry of continental shelves in areas at risk, and knowledge of continental slopes in areas prone to slumping (trenches, volcanic slopes). YES - requires knowledge of deep ocean bathymetry, because the wavelengths of tsunamis are so long that they 'feel' the bottom over most of their route, and so can be influenced by deep ocean bathymetry.

- **upwelling and fishing resources**: YES - need detailed knowledge of bathymetry of seamounts/banks.
- **wave climate:** YES - detailed knowledge of coastal seas is needed for modelling storm surge accurately.

- **coastal sediment transport:** YES - near-shore.

- **continental shelf morphology:** YES – for geomorphological understanding (and tides and tsunamis).

- **environmental impact baselines** (e.g. pre-deposition of waste): YES.

- **plate motions:**
  - **tectonic fabric of ocean basins**:
    - (i) NO - for plate motions on the broad scale, except in places like the Arctic, where for instance the Lomonosov Ridge has changed position by 5 degrees from one map to another.
    - (ii) YES - for details of off-axis spreading history.
    - (iii) YES - for assessing back arc basin evolution.
  - **ridge dynamics** (axial valleys; fracture zones etc.): YES - Altimetry can suggest other places and processes on the mid ocean ridge that need to be looked at to test hypotheses based on work done in the research areas of the Inter-Ridge Project.
  - **structural trends** (for resource potential): YES - e.g. to measure plate buckling at trenches.
  - **age/depth relationships** (mantle dynamics): YES.

- **seafloor fabric**: YES - as detailed as possible for mapping and understanding evolution of abyssal hills.

- **continental margin sediment thickness** (oil and gas): YES - for accurate prediction of subsurface structure.

- **slope stability** (islands and continents): YES - slope gradient is a key factor.

- **paleoceanography**: YES - for channels on continental shelves.

- **industrial needs:**
  - **platform siting**: YES - on continental slopes and shelves.

- **pipeline siting**: YES - over entire length of pipeline.
- **cable siting**: YES - over entire length of cable route.
- **fisheries:** YES - to assess possible new fishing grounds
- **waste disposal:** YES - to characterize possible sites
- **mineral extraction:** YES - to characterize possible sites

- **social needs:**
  - **delimiting juridical continental shelf to define EEZs**: YES - States with wide continental margins have 10 years after the ratification of UNCLOS (Nov. 1994) to map their margins beyond 200 nautical miles, especially to determine the 2,500 m isobath to +/- 1%, or the foot of the slope or some significant natural prolongation.
  - **education** (visualisation; awareness): NO.

8.2 QUANTITATIVE SCIENTIFIC REQUIREMENTS

Certain scientific requirements can be quantified as follows:

<u>Ocean Models:</u>

Correct simulation of ocean circulation depends on an accurate bathymetry. The working group noted that high resolution bathymetry is commonly available for regional and coastal seas models. They also noted that high resolution bathymetry is probably not critical for climate models with resolutions of 1-2 degrees, where formation of deep water and its flow down slopes is a critical issue. In that case the topography is a smooth field, and the level of detail provided by the Smith and Sandwell map is probably not significant. Better parametrization of sub-grid scale processes is necessary, rather than a better topography

For the open ocean, Tokmakian and Semtner (4.3, above), and Webb (4.6, above) call for bathymetric data sets that are accurate to the grid resolution that modellers are working towards, namely 1/12 of a degree or finer (i.e. 5 nautical miles, or about 10km or less). Bathymetric resolution in the open ocean needs to be at a resolution higher than the Rossby radius, which is around 200 km near the equator, decreasing to around 30 km at mid-latitudes and to less than 10 km in polar regions. In the vertical an accuracy of +/-50 m is required; depths should be best estimates of the average depth of the surrounding grid cell, uncorrected for sound speed (Webb, 4.6, above).

As noted by Tokmakian and Semtner (4.3, above), there is a special need in global ocean models for accurate (and improved) bathymetry: (i) in regions with many small scale features, like Indonesia or the Caribbean, and (ii) where deep flow occurs through sills between one basin and another.

Following Webb (4.6, above), the working group calls for priority to be given to providing better measurements of bathymetry in the sills between the major ocean basins. Coarse resolution models are incredibly sensitive to even single grid point changes in topography. Killworth (see 4.5, above and personal communication) calls for resolution of topographic sills on the scale of about 1 km to represent through-flows adequately. He notes that near the equator (where rotation is unimportant) 20 m vertical resolution and 5 km horizontal resolution may be adequate (Ferron, 1998), while at high latitudes, 1 km horizontal resolution and about 20 m vertical resolution my be acceptable.

Killworth notes that numerical and analytical modelling of flow through sills remains difficult, with even eddy-permitting models differing strongly in both water mass properties and flow rates across well-resolved sills. Only in very highly resolved cases (dedicated process studies using state of the art numerical models in confined regions) have modellers been able to reproduce observations adequately. Parametrizations of sill flow remain elementary, and nesting of fine resolution models within coarser models, to represent sill flow, presents as many problems as it cures.

Where sills are too narrow to be resolved well bathymetrically, modellers need information on the depth of the sill, its width and any other information on factors which might affect the flow, such as information on choke points, vertical cross sections, the length of the main channel and information on nearby secondary channels (Webb, 4.6, above).

Comparing the outputs of ocean models made at 1/3 degree resolution and using either ETOPO-5 topography or Walter Smith's map, Tokmakian (4.4, above) shows a significant improvement using the latter, because it shows many more paths across the mid-ocean ridge than are shown in Thomson's list (based on ETOPO-5 bathymetry). Sills are only used in the model where they are visible in one of the 300 m thick depth slices used in the model. To be picked to be included in the model a sill has to be 2 grid points wide so as to get flow. Where necessary, the bathymetry used in the model can be modified to show a given sill. Tokmakian (4.4, above) has demonstrated that the incorporation of improved bathymetry from altimetric data especially in regions of sills does improve the representation of the circulation.

As a second priority, Webb (4.6, above) calls for surveys of regions that steer the major currents. In the case of the Antarctic Circum-Polar Current, these would include, for example, Drake Passage, the northern and north-eastern flanks of the Kerguelan Plateau, and the south-eastern flank of the Campbell Plateau off New Zealand.

The Working Group recommends:

(i) research on sill flow, using high resolution modelling, nesting, and parametrization, with the aim of finding an approach that can be successfully applied in climate and other models.

(ii) research on the sensitivity of numerically modelled sill flow to model resolution and topographic details, resolution and orientation.

<u>Tsunami modelling:</u>

As pointed out by Yeh (4.7, above, and 1998) fine resolution is critically required for proper tsunami computations. On continental slopes and shelves a grid size smaller than 500 m is needed for the depths less than 250 m deep; indeed, perhaps a 100 m grid size may be preferable. A 100 m grid is needed where the depths are less than 10 m, and a 50 m grid where depths are less than 2.5 m. A 500 m grid would also be needed for accurate modelling for narrow canyons or ridges say 2 km wide in water say 1,000 m deep. Resolution finer than, say, 1-minute (around 2 km) may not be necessary in deep-water bathymetry (deeper than 2,000 m, approximately).

A common datum for both bathymetry and topography is needed bearing in mind the need for an efficient procedure for integrating bathymetric data with coastal topography data. The most appropriate common datum for both bathymetry and topography data is the WGS84 system of a mean-Earth ellipsoid.

The amplitude of tsunamis is greatly reinforced where the seabed over which they pass shallows and narrows markedly toward the coast, so to improve tsunamis models there is a need to make shallow-water bathymetric data available.

As earthquakes may generate major submarine slumps, the displacement of which may cause tsunamis, there is a need to use swath bathymetry to produce accurate bathymetric maps as the basis for mapping real and potential landslides to help assess the risk of slope failure near inhabited coasts. Such studies need to be combined with analyses of slope stability (Kobayashi, section 6.4).

<u>Tides</u> (continental margins) :

The accuracy of the computation of tidal energy dissipation and then tidal modelling and prediction depend on the bathymetry. Le Provost (4.1, above), noted from sensitivity studies that specifications for accuracy and resolution could be as follows: over the deep ocean, 10 m accuracy with 5 km resolution, with an improved resolution down to 1 km over the continental slopes, and a few metres accuracy on the continental shelf with 100 metres horizontal resolution in coastal areas. The highest priority is to improve bathymetry over the continental shelves where tidal dissipation is known to take place. In 4.2 (above) C. Le Provost provided a list of areas where improvements are needed for tidal calculation; they include, in decreasing order of importance, Hudsons Bay, the Yellow Sea, the Amazon shelf, the European shelf and the Patagonian shelf.

<u>Tides and Upwelling (Seamounts):</u>

The influence of seamounts on tides is an active area of research, and consensus has not yet emerged. Internal ocean waves can propagate horizontally through regions where there is vertical stratification of density in the water column. These waves may be forced by tides, and if they impinge upon seamounts the tidal energy may be dissipated as it is put to work mixing the water and reducing its stratification. A few seamounts have been equipped with moored, water column instruments, and these studies have shown that, in the vicinity of seamount flanks below the seamount summits, vertical mixing is increased by a few orders of magnitude over background levels far from seamounts.

One theory for the interaction of internal waves with the sea bottom suggests that mixing should be strongly enhanced in areas where the sea floor topography has a slope that is near a "critical slope". The critical slope is a function of the horizontal propagation velocity of the wave (such as may be characterized by the frequency of a tidal constituent relative to the Coriolis frequency), and the vertical buoyancy stratification of the seawater (as characterized by the Brunt-Vaisala frequency). The traditional assumption has been that only those seamounts that rise to near the surface, and thus have steep slopes in the pycnocline, will be significant sites of dissipation and mixing. However, if the theory is correct, then gentler slopes in deep water might also be significant, as the critical slope is less where the stratification is less. For a semi-diurnal tide in moderate latitudes the typical value for a critical slope in a typical pycnocline is around 30 degrees, a figure that is seen in multi-beam bathymetric surveys of the near-summit flanks of large seamounts. For the same tide in deep water the critical value might be 3 degrees, although it is difficult to say, because it is difficult to obtain accurate values of the Brunt Vaisala frequency in deep water. In the traditional view, seamounts are not a significant source of tidal dissipation, and a significant fraction of the observed tidal energy loss cannot be explained. Since satellite altimetry has shown that seamounts, and rough ocean floor, are more abundant than had been previously recognized, we may anticipate that the question of tidal mixing and dissipation will become increasingly studied. If accurate estimates of seafloor slope become critical, then altimeter data alone will be insufficient to study this problem, and acoustic measurements will be required. What these requirements will be cannot be guessed now, as the relevant physics of the fine-scale structure of the ocean water column has not yet been articulated.

The Group recommends that efforts be made to check the hypothesis suggested by altimetric data that seamounts cause much more dissipation of tidal energy in the open ocean than had formerly been supposed.

Mid-Ocean Ridges:

Bathymetric information is needed to better document and map both large-scale segmentation (extending the bathymetry to uncharted areas) and small-scale segmentation (using 100 m ground resolution or better). The time history of segmentation can be addressed through off-axis studies (up to a few hundred kilometres on each side of the ridges; see seabed texture, below).

Repeated surveys with high vertical resolution systems (metric) can be used for the study of current processes of important scientific and/or human interest, like the volcanic building noticed during a repeat survey of the Juan de Fuca Ridge, and the development of landslides on some axial valley walls.

Seabed Texture:

Seabed texture covers a range of horizontal and vertical scales, from the grains of sand and mud which form the bottom to the volcanic seamounts and limestone caps which may be 100 km horizontally and 4 km tall. Textures at the finest scales are important in characterizing the transmission and reflection of acoustic energy at various frequencies, and in assessing the velocity of currents over the sea-bed and the ability of the sea bed to hold submarine cables, anchors, and drilling platforms. At the largest scales, seamounts are important clues to the geological history of the ocean basins, and may be important sites of fish habitat and the mixing and dissipation of tidal energy (above). The seabed texture at intermediate scales (horizontal scales of a few hundred metres to a few tens of kilometres and vertical scales from a few metres to a few hundred metres, i.e. those scales which extend from near the resolution limit of altimetry down to the resolution of multi-beam acoustic swath-mapping systems) appears to be generated by transient, episodic, or unstable processes of faulting and magmatism associated with the seafloor spreading process.

One bathymetric manifestation of these processes, abyssal hills, has been studied for some time using acoustic swath bathymetry. However, the ubiquitous ness of these features was not realized until the upper end of this scale of texture had been globally revealed by satellite altimetry. It is likely that a lack of understanding of the seafloor spreading process, as much as a lack of detailed bathymetry, is a limitation on progress in this area. While it is likely that additional bathymetric data will be required to advance our understanding of these phenomena, it is also likely that satellite altimetry may be used for reconnaissance, to select sites for promising further study, and that conventional funding mechanisms will eventually approve the collection of such data.

According to John Goff (personal communication), adequate characterization of abyssal hill fabric requires a minimum horizontal resolution of around 0.25 km, and minimum vertical resolution of about 10 m, both easily accessible with usual multi-beam instruments. A lot of progress has been made toward identifying the controlling factors on the formation of abyssal hill fabric - particularly spreading rate, axial morphology, crustal thickness, and proximity to segment boundaries. Refinement and better quantification of these relationships is certainly possible, and will undoubtedly be accomplished as more and more near-axis flank multi-beam surveys are performed. This should not require significant extra effort. The big gap in data is areas well away from mid ocean ridge axes. There are numerous important scientific issues to be addressed off-axis, in particular questions regarding the history of ridge development and understanding the transition between axial high and axial valley morphology. Abyssal hills are perhaps our most sensitive indicator of past changes in ridge morphology. The problem here is that the areas required to address these issues can be vast, and beyond reasonable capabilities of multi-beam surveys. Sparse single beam surveys can be of marginal help, but context is very important for decoding abyssal hill fabric, especially segment boundary geometry, and that can only be addressed with fairly complete surveys. Satellite gravity data may be of some assistance if a relationship between gravity fabric and abyssal hill fabric can be established (limited though it may be). Whether or not this can be done is an open question, but based on anecdotal observations of correlations between changes in gravity and abyssal hill fabric it appears possible. Hence gravity may be used to supplement well-placed, off-axis, multi-beam surveys to address ridge development history.

Continental shelf and slope morphology:

John Goff (personal communication) pointed out that there is a glaring lack in shallow water swath-bathymetry mapping capability available to the academic community. This is a serious handicap in studies of continental shelf morphology, fabric and geomorphology, as well as for tidal and tsunami modelling. **The Working Group recommends increased collection of swath bathymetric data from continental shelves.** Such a development may come about in one way from the equipping of hydrographic ships with swath systems, in which case the data should be made widely available to the scientific community. There is considerable industrial interest in improved bathymetry on the continental shelf and upper slope, especially in the oil and gas, communications and fisheries sectors.

Paleoceanography:

The working group noted that high-resolution bathymetry can be used to location of paleo-shorelines and channels on continental shelves, providing the potential for preparing paleo-geomorphic maps covering the coastal landmass and adjacent offshore area, on a 500 m grid spacing, to enable studies of changes associated with movements of in sea-level through time.

Continental margin sediment thickness:

Walter Smith pointed out to the group that altimetry can identify gravity anomalies with an accuracy of 3-7 mgal and a resolution of 20-25 km, depending on conditions (Smith and Sandwell, 1997). These anomalies may be caused partly by variations in seafloor depth, and partly by sub-seafloor structure (e.g. by variations in sediment thickness). This last property is of interest in assessing petroleum potential. If some bathymetric data are available to calibrate the correlation between seafloor depth variations and gravity anomalies, then correlation parameters may serve as a proxy for sediment thickness (Smith and Sandwell, 1994). If bathymetric data are "sufficient" to characterize the gravity effect of sea floor depth variations, then the sediment thickness needed to explain the non-seafloor component of the gravity model may be derived mathematically. In this case, "sufficient" means adequate to resolve anomalies to 20 km full wavelength at 1 mgal accuracy. This would require a bathymetric grid with a resolution of 5 km resolution horizontally and 10-25 m vertically. This is a minimum requirement, as the gravity effect of seafloor topography is much greater than the effect of sub-seafloor structures. Thus one needs to be able to estimate the gravity effect of the seafloor with high accuracy, so as to be able to estimate sediment thickness from the residual gravity to lesser accuracy.

Table 8.1: Summary Scientific Requirements

Topic	Area	Horizontal Resolution	Vertical Resolution
Ocean models	Open Ocean	10 km	50 m
	Sills	1-5 km	20 m
Tsunami models	Continental Shelf <2.5 m deep	50 m	
	Continental Shelf 2.5-10 m deep	100 m	
	Continental Shelf 10-250 m deep	100-500 m	
	Canyons and Ridges	500 m	
	Open Ocean	>2 km	
Tides	Open Ocean	5 km	10 m
	Continental Slope	1 km	
	Continental Shelf	100 m	Few m
Mid-Ocean Ridges	Rift Valleys	100 m	Few m
Deep Sea Floor Fabric	Abyssal Hills	250 m	10 m
Paleoceanography	Continental Shelf	500 m	
Subsurface Geology	Continental Margin	5 km	10-25 m

In summary, in the open ocean seawards of the continental shelf and slope we can see a progressive increase in the requirement for horizontal (H) and vertical (V) resolutions from 5-10 km (H) and 10-50 m (V) over the open ocean, to 1-5 km (H) and 20 m (V) over open ocean sills, to 250 m (H) and 10 m (V) for abyssal hills, and finally to 100 m (H) and a few metres (V) in rift valleys. On the continental slope we see a requirement for 1 km (H), decreasing to 500 m (H) over canyons and ridges. On the continental shelf we see a progressive increase in requirement from 100-500 m (H) in water deeper than 10 m, to 50 m (H) in water less than 2.5 m deep.

An ultimate long-term goal would be is a gridded global bathymetric Digital Elevation Model (DEM) with a horizontal resolution of 100-200 m and a vertical resolution of around 1 metre. There is good scientific justification for such a goal in the short term for the continental shelves and the median valleys of the mid-ocean rift system. Achieving such demanding goals requires the creation of a partnership between academia, governmental hydrographers, industry, NGOs, plus the military, probably initially with a regional focus to bring together groups with interests in common sea areas to create international bathymetric charts of those areas, with the compilations then being channelled into a global compilation. **The Group recommends that partnerships between academia, hydrographers, industry, NGOs, and navies be created to develop regional international bathymetric charts as the basis for creating a gridded global bathymetric Digital Elevation Model or appropriate resolution (which could vary depending on water depth).**

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9. KEY ISSUES AND ASSOCIATED RECOMMENDATIONS

9.1 DATA GAPS

Figure 9.1 shows the evolution of NGDC bathymetric data holdings from 1975, to 1985 and 1995. The comparison of track line density makes it plain that gaps are steadily being closed; nevertheless there are still substantial gaps especially in the South Pacific, South Atlantic, Indian, Southern and Arctic Oceans, and in the Arabian Sea. Data is also sparse in some back-arc basins, especially between China and Kamchatka. Even in the North Atlantic and the North Pacific, which are relatively thickly covered, there still are notable gaps in areas furthest from land (e.g. between Hawaii and North America).

On continental shelves the main areas where improved bathymetry is needed to improve tidal calculations are: Hudsons Bay, the Yellow Sea, the Amazon shelf, the European shelf and the Patagonian shelf.

For the Arctic, the working group noted that SCICEX, the US Navy's under-ice civil science activity, is collecting underway geophysical data from a submarine for use in the public domain; these data will include swath bathymetric data collected using SEAMARC-II. The operation is confined to those parts of the Arctic beyond the EEZs of other nations, so not everything will be covered.

Arctic specialists participating in recent Arctic Bathymetry Workshops (St. Petersburg, September, 1997; and Copenhagen, 1998) (see Macnab and Grikurov, 1997; and Macnab, 1998), identified several potential data sources and ascertained to what extent the data were releasable. The US Navy is planning to release (or has recently released) data from 21 recent under-ice cruises. Data is also available from drifting ice stations. Access is needed to the extensive holdings of Russian Navy data (see 9.4, below) to provide the most complete coverage possible, so as to develop a reliable high quality bathymetric map of the Arctic.

The cost of filling data gaps can be calculated as follows (from Walter Smith): take the average depth of the oceans (4.3 km); take the width of a typical swath-mapping system (two times the water depth); take the typical velocity at which these systems can survey without losing data on the edges of the swath (10 knots, or 5 m/s); this gives a rate of mapping of area of 154.8 km^2/hour. Now take the area of unmapped ocean (on the order of 60-70% of the area of the earth, or 300 - 360 million km^2), and you get 1.9 – 2.3 million hours, or 220-260 years of ship time. If you use a number larger than 4.3 km for the typical depth, you get a smaller number; using 5 km you get 73% of these values. 4.3 is taken from the hypsometry in the 1997 paper by Smith and Sandwell. At typical costs of US$15,000 per day of ship time for ships with these systems (that figure may be low; it may be closer to US$20,000) one estimates a cost of this mapping as US$1200 to 1400 million. This number may be more robust than the ship time calculation, which may depend on the swath system involved.

Costs will be variable depending on the platform used. A wide range of multi-beam echo-sounding systems exists for obtaining swath bathymetry; these include hull-mounted systems as well as towed systems, like the UK interferometric system GLORIA. Each system covers different areas at different rates, depending on its design. All can generate some form of side-scan sonar image in addition to bathymetry, but not all can provide high quality side-scan image processing and display.

Table 9.1: A comparison of surveying systems (based on hypothetical average water depth of 2,500 m), in December 1996.

System	Swath width (multiple of water depth)	Vertical resolution	Track spacing
swath ship A	X 7	20 m	17.5 km
swath ship B	X 4	20 m	10.0 km
swath ship C	X 3	20 m	7.5 km
swath ship D	X 2	20 m	5.0 km
GLORIA	X 9	20-50 m	24.0km

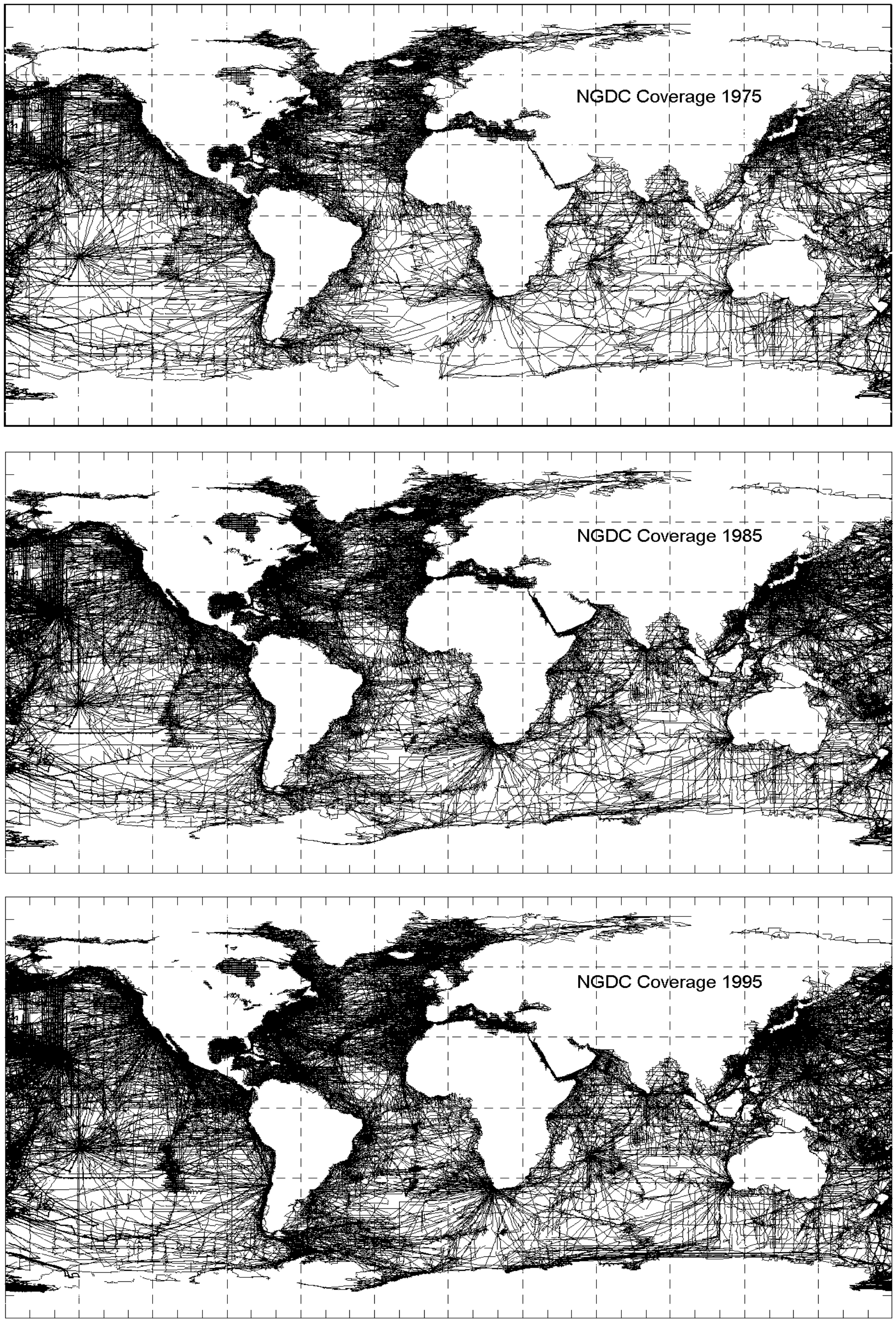

Figure 9.1.1 (provided by Peter Hunter) shows the evolution of NGDC bathymetric data holdings from 1975,to 1985 and 1995.

Operational costs using these systems for bathymetric surveying will vary depending on resolution required, vessel used, and post-cruise processing requirement. GLORIA resolution is usually near 50 m but can be improved by using it with a multi-beam system to calibrate the GLORIA data. Trade offs between resolution and speed of coverage will determine ultimate cost.

Resources of the order mentioned above are unlikely to be found, so while some new data will come from targeted seabed surveys, much new data from gaps have to be obtained by other means, e.g.:

(i) by encouraging science (and simultaneous bathymetric data collection) in data gaps (see below);
(ii) by encouraging commercial ships to take (and report) soundings en route;
(iii) by encouraging Hydrographic and research vessels to keep their sounders on at all times, especially in data gaps;
(iv) by developing new technology to do the job (e.g. sounders on floats or AUVs);
(v) by encouraging navies to collect unclassified bathymetric data under ice;
(vi) by satellite altimetry (in this report we ignore shallow water LIDAR from aircraft because it is essentially a coastal tool).

To encourage scientists to do their science in data gaps they need to be informed about the existence of the gaps, for example by publishing them in print and on the Web. Although it would be up to individual researchers to decide on the scientific questions that could be addressed in filling particular gaps, Working Group 107 provides some guidelines. For instance, altimetry can help to suggest what scientific questions need resolving in areas where the bathymetry is lacking (e.g. the discovery by altimetry of a new hot spot in the form of the Foundation Seamounts needs following up by field work on the ground). **The Group recommends that Peter Hunter's NGDC track charts be placed on the Internet so as to encourage people to fill data gaps.**

To encourage commercial ships' captains to collect data to fill gaps **the Group recommends attempts be made to get funds from agencies like the Defence Mapping Agency to fund echo-sounding on commercial transits.** If such a practice could be developed, and these ships took different routes each transit, some gaps would soon be filled. It may be worthwhile developing a "black box" approach - i.e. fully automating the system so that no manning is required, or making it simple - as in the approach used for XBT launching in the IOC's Ship of Opportunity (SOOP) programmeme, and for Meteorological observations in the WMO's Voluntary Observing Ship (VOS) programmeme. One problem may be the poor quality of transducer technology on commercial ships; however, single beam is better than no beam at all. **The Group recommends Antarctic tourist cruise ships be approached to provide data.**

It is common practice, especially on UK and US research ships and hydrographic vessels to turn their sounders off when not engaged in specific survey or science activities (e.g. on transit), thereby missing a golden opportunity to provide valuable new information in data gaps. [*Historical research by one of the committee members at one major marine institute showed that only 11% of all the cruises mounted by that institute during the past 35 years collected bathymetric observations that now reside in an accessible database system. This despite the fact that large areas of the seabed nearby remain unmapped*.] This scenario is probably not atypical. The reason given is usually one of cost (not being able to afford to pay a technician to do the work). But this ignores the tremendous waste of resource in having a multimillion-dollar vessel, and a costly echo-sounding system in the first place, then not using them to collect potentially valuable data for want of a few hundred dollars in technician time - it is false economy. This is more a problem with research vessels than for hydrographic ships, which are mostly deployed near-shore in relatively shallow water, nevertheless the principle is the same whatever the vessel. To deal with these matters, **the Group recommends that:**

- **funding agencies be asked to recognize the waste of resource involved, and to fund echo-sounding on transit on research vessels;**

- **funding agencies develop mechanisms for ensuring that data are digitized and sent with track data to NGDC; and**

- **at the very least hydrographic ships and research vessels should keep their centre beams on at all times (reducing the requirement for data processing), and especially during transit.**

Floats are in widespread use these days to acquire subsurface ocean data from around the world as part of programmemes like WOCE and CLIVAR. If these floats, many of which cross data gaps, could be equipped with a simple pinger they would provide an inexpensive means of acquiring data from these gaps at low cost by capitalizing on existing programmemes and technologies. Data are sent back to base periodically by ARGOS satellite. **The Group recommends that consideration be given to equipping floats (like Argo floats) with pingers to indicate water depth.**

Autonomous Underwater Vehicles (AUVs) are now being developed and may see widespread use in the not too distant future. Some (e.g. the Canadian DOLPHIN vehicle and the US ORCA) are equipped with multi-beam sounders. A new generation of air-breathing AUVs, using semi-submersible technology, are being developed, which will make this technology more widely available. AUV's like these or the NERC's AUTOSUB and others offer the potential for seabed surveys at costs much below those estimated for surface ships (above). **The Group recommends that consideration be given to making low cost bathymetric surveys using autonomous marine vehicle technology, which could be particularly effective under ice.**

The working group recognized that there is a requirement for States wishing to establish EEZs that they must map at least parts of their continental margins accurately (especially the outer limits). This activity will generate new bathymetric data. **The Group recommends that nations be encouraged to add bathymetric data from EEZ surveys to the international pool of data (via NGDC).**

Finally, as recommended by Ron Macnab (section 6.2), **the Group recommends that to ensure maximum benefit, the objectives of bathymetric compilations 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.**

9.2 DATA POLICY

The preceding discussion makes plain the need for expressions of data policies by funding agencies. In some cases those policies exist and what may be required are specific adaptations to them. Ideally (paraphrasing the UK NERC's data policy, 1996), such policies should recognize that data are a resource in their own right. Properly managed and used, they can potentially be used and re-used by future researchers. Environmental data are often irreplaceable; they are always unique. They can also be extremely expensive to collect. For these reasons great importance should be attached to ensuring that maximum benefits are derived from data once acquired.

These are laudable sentiments, and provide the *"raison d'être"* for bathymetric data rescue (see 9.3, below). However, the NERC policy, like others, lacks one essential feature in that it does not cover the failure to use the opportunity to use expensive equipment, once installed, to capture bathymetric data routinely. In part this is a direct result of the modern management approach of costing each operational activity separately. In that approach, as applied in the NERC, the funding of ship operations is seen as entirely separate from the funding of science, and collecting echo-soundings is seen as a science operation not a ship operation. But, because funding the routine collection of bathymetric data does not make for attractive proposals, scientists do not get funded to do the work either. As a result the funds to collect such data are never made available, to the detriment of efforts to build the global bathymetric database that is needed for a great deal of science. Bathymetric work is funded only when there is a direct need justified by a science proposal, not where there is an indirect need, as for global bathymetry in the support of international science that may be as yet unspecified.

Given that bathymetric mapping is the only direct means we have for mapping the hidden surface of our planet, 72% of which is covered by water, it is highly unsatisfactory that low cost opportunities to contribute to such mapping are being lost for the sake of relatively tiny amounts of money. The value of the loss to international science vastly outweighs the cost of collection. **The Group recommends that the issue of the substantial loss of internationally potentially valuable bathymetric data through a de facto policy of failure to collect them requires serious consideration by environmental science funding agencies, leading to corrective action in this matter.**

As recommended in paper 3.1 (Peter Hunter), to enable GEBCO to continue to provide the definitive global bathymetry **the Group recommends the following:**

- **release of published bathymetric maps to GEBCO for incorporation into current GEBCO maps;**

- **provision of funds by funding agencies for the employment of people with appropriate expertise to compile and contour new bathymetric maps - particularly at regional scales.**

- **that agencies funding marine science topics should require that any proposals for scientific experiments should include provisions for site surveys and bathymetric maps, and that the bathymetry should be made available to GEBCO and the data sent to the NGDC.**

- **that funding agencies develop policies to review the locations of existing data, and require principal investigators to plan new surveys and passage tracks to and from survey areas to occupy unsurveyed seafloor**

9.3 DIGITIZING DATA

Bearing in mind the need to move towards Digital Elevation Models of global bathymetry, considerable effort needs to go into digitizing what is already available, such as the 200 years-worth of near-shore hydrographic data, which should be converted to metric units and the WGS-84 datum to provide the basis for all inshore mapping, and the many widely scattered present holdings of deep-sea soundings. **The Group recommends digitizing all available data.**

9.4 GETTING DATA INTO DATA CENTRES

A key question is "How can we get data into the NGDC?" Centrally funded posts are required to process the data for submission to NGDC, since project scientists are usually reluctant to provide the manpower to do this work on science project funds. That is why in the UK very little data went into NGDC until Peter Hunter was funded centrally to do this as part of a UK contribution to GEBCO. Before his appointment data from 40 UK cruises had been entered into NGDC; following his appointment, data from 400 cruises were entered in 5 years. Thus to get more data out of projects and into NGDC for general use requires giving the task a higher profile, providing funds for it, and appointing someone to the job. This means in turn the requirement for a national policy, which in turn means making a good science case for funding the work. The SCOR Working Group 107 report is intended to provide the basis for people to use to develop a good science case for supporting funding for this activity. The ultimate *“raison d'être”* is providing data essential to support science. **The Group recommends that funding agencies support an appropriate number of centrally funded posts to ensure that the widest possible use is made of expensive-to-collect bathymetric data.**

9.5 ACCESSING ALREADY COLLECTED BUT ‘UNAVAILABLE’ DATA

Aside from considering how to add new data, we also need to rescue old unused and often undigitized bathymetric data from archives, using the approach developed in the IOC's Global Ocean Data Archaeology project (GODAR), which has rescued large amounts of physical oceanographic data, especially from Russian archives (e.g. see IOC, 1993 and 1994a and b). **The Group recommends that major research institutions and funding agencies take steps to identify material that has not yet been submitted to central archives (NGDC), and provide funds to enable these data to be rescued.** Such data rescue may cost money, but little compared with the cost of new collection.

Ron Macnab gave the working group an example of a data rescue project using magnetic data. The goal was to obtain the best possible magnetic data set to support construction of a magnetic map for the Arctic, to form the basis for improved geological interpretation of the origin of the Arctic Basin. This required:

(i) finding original proprietary data, grids and contour maps;
(ii) getting the owners to agree that the data would be released in final grid form;
(iii) publishing the data as grids, lines and maps in such a way that it was possible to tell what the source was without seeing the original data, only the gridded data and tracks.

To improve bathymetric maps of the Southern Ocean, **the Group recommends that Antarctic Treaty countries should be encouraged to release and exchange data.** Some countries, for example the UK, have expressed a willingness to release data on condition that others release their holdings.

Some gaps may be filled wholly or in part by extracting data from naval archives. For instance, in the USA the MEDEA Working Group (MEDEA is not an acronym) has a task force reviewing the worldwide bathymetric data holdings of the US Navy. The task force concluded it would be useful to release significant amounts of these data for civilian use. Data release is encouraged by the Potomac Declaration (ACOPS, 1998).

Many navies might consider requests to make more bathymetric data available. The US Navy data represent an investment of 100 ship years. Their release could enable completion of GEBCO's mapping of the northern hemisphere. However, even if the bathymetric data have no military significance, it still may not prove possible to have them declassified because navies are sensitive about other countries knowing where their ships were at any point in time.

The Group recommends that navies declassify and release bathymetric data to the scientific community, and that at the very least such data are released in gridded fashion within a 0.5-minute (900 m) grid. Further consideration needs to be given to identifying the need for the release of bathymetry at a particular scale. For instance it might be useful if depths could be made available in grid boxes of specified size and with defined levels of confidence. NAVOCEANO holds the key to most classified data, and could advise us on this vexed question. The group recognized that the US Navy has been downsizing, which means they have fewer people to assign to such a non-operational task, so the question of funding may arise.

It might be possible to use classified military bathymetric data to improve unclassified depth estimates, without revealing sensitive details of the location, density, accuracy or precision of navy surveys. In principle, the classified data could be used to calculate the "Nettleton slope" (explained below) at intervals sufficiently widely-spaced (e.g., 100 km) so that the slope values could be unclassified and released for use in altimetric depth estimations. The "Nettleton slope" is calculated by the "Inverse Nettleton procedure" as follows. The gravitational attraction of topography depends to first order on a constant that is proportional to the density contrast across the topographic interface (Bouguer, 1749). L. L. Nettleton (1939) suggested that the density of topography that yielded a best-fit topographic correction could be determined by trial and error in what would now be called a regression procedure. Smith and Sandwell (1994) describe an "inverse Nettleton procedure" in which the inverse of Bouguer's constant is determined by linear regression of (suitably filtered) altimeter-derived gravity anomalies against available ground-truth bathymetric soundings. This procedure yields one parameter used in the estimation of seafloor topographic variations from altimetry, namely the number of metres of depth variation per milliGal of gravity variation, which Smith and Sandwell called the "Nettleton slope".

We may also envisage a difficulty in that in many quarters (not least the navies), there is a perception that the bathymetry is all known - even though it clearly is not. People are used to seeing published bathymetric charts which look "complete", not realising how scant the database was that was used to compile them.

Russia also has a lot of analogue bathymetric data, and it would be ideal if a means could be found to assist them in digitizing these data to get them into the public domain, for example by scanning the data into a digital file. Some of this work has been done already, for example Kathy Crane apparently has been digitising Russian data from the Barents Sea, with NRL assistance (e.g. Crane, 1997). Although cost should not be a problem, the release of data may require a relaxation of national security requirements, and involve high-level diplomacy. **The Group recommends that money be found to facilitate the digitizing of Russian bathymetric data for wider release.**

Russia is in the process of digitizing bathymetric data, using lineations from the Smith map to guide the compilation of bathymetric maps, and using the resulting bathymetric map to correct the altimetry derived map. The recent focus has been on the Scotia Sea, the Bellingshausen Basin (with Germany) and several areas off Japan. This methodology provides an acceptable means of correcting for geologically induced changes in the altimetric data, e.g. at sharp geological boundaries, like trenches, where the algorithms for interpreting bathymetric data from altimetric data do not work well.

Aside from the question of the unavailability of military data to academic institutions, there is also the question of the unavailability of academic data to Hydrographic Offices, as addressed in section 3.2 (C. Andreasen). To deal with this matter **the Group recommends**:

- **the development of a more formal relationship between Hydrographic Offices and academic institutions that collect bathymetry throughout the world, so that notice is given to the Hydrographic Offices when bathymetry is to be acquired, some level of meta data are exchanged, and agreement is reached on when and under what conditions data will be made available;**

- **that academic institutions and Hydrographic Offices work together to address the needs for original survey data and various types of gridded bathymetry**;

- **that bathymetry be integrated to ECDIS for use with the ship's primary navigation system in offshore areas where navigation safety is not an issue.**

Finally, it is noted that many commercial companies hold bathymetric data (e.g. cable companies, and geophysical survey companies), which could be useful. Some such companies are prepared to release data if asked, but such companies may be reluctant to put their data into NGDC. **The Group recommends that geophysical survey companies be approached (perhaps through joint industry groups such as the Western Frontiers Association) to determine their willingness to release bathymetric data.**

To attract industry interest into collecting additional bathymetric data at sea **the Group recommends organising an international scientific discussion meeting at which both industry and academic representation would present their interests and capabilities, with a view to forming a working plan and identifying a potential group of sponsors.**

9.6 STANDARDS

For Hydrographic ships, IHO sets a standard of measurement of +/- 1% of depth at depth greater than 30 m (see S55 IHO State of Hydrography). There appear to be no comparable stated standards of measurement for bathymetric measurements made by research vessels. **The Group recommends that standards of measurement be set for bathymetric data collected by research vessels, and the application of a standard method for computation of bathymetric grids.**

Given the advent of GPS, a strong case can be made for shifting data (especially inshore) to the WGS-84 datum of GPS.

9.7 EDUCATION/AWARENESS

The working group recommends (i) that bathymetric maps should be made available as educational tools on the Web and through media such as CD-ROM, as GEBCO is now doing; and (ii) that articles be written in popular science magazines (*New Scientist, Scientific American*) drawing the importance of mapping the surface of our planet to the attention of the wider (voting) public.

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Smith, W.H.F., and Sandwell, D.T., 1994, cited above.

10. PRINCIPAL PRIORITIES

The initial focus should be on getting more data into the system, as represented by the 6 priorities, ranked below. In making this ranking we agree with A. Laughton (section 5.1, above) that the time is now appropriate to consider a systematic survey of deep ocean bathymetry, given that the technology now exists to make saturation surveys, that there are nearly 200 ships equipped with suitable swath sounders and side-scan sonar, and that navigation is no longer a problem.

Since the meetings of SCOR WG 107, a workshop was convened in June 2000 by the Naval research Laboratory in the USA to launch a "Global Ocean Mapping Project" (GoMAP) with the ambitious objective "to map/image all the world's oceans floors with at least 100% swath bathymetry and side scan sonar…". The project, as yet unfounded, was estimated to cost $500-$1000 million to fund some 300 deep water and 700 shallow water ship years (Vogt et al., 2000, EOS, 257-258; Vogt, 2000, EOS, 498).

Bearing in mind the constraints on funding, SCOR WG 107 decided that gathering additional data by ships equipped with swath bathymetry and side-scan sonar systems, though crucially important especially in data gaps, would not be the first priority. Much can be done already by working more effectively and efficiently with what has already been collected.

Priority 1: **Turn equipment on to generate more data (all too often expensive echo-sounding equipment is not turned on, thus wasting the potential to acquire the data – a penny wise/pound foolish approach to scientific management).**

Comments:
(i) Generic and fundamental; not focussed on a particular data gaps.
(ii) In some countries funds must be found for staff to do this.
(iii) Implicit in this is increased awareness, accompanied by changes in data policies.
(iv) Relatively low order of difficulty, depending on success in comments (ii) and (iii).
(v) Encourage the collection of data of the highest possible quality

Priority 2: **Digitize the data that are presently available, and send new data automatically and in digital form to data centres.**

Comments: as for Priority 1 (i) through (iv).

Priority 3: **Begin serious investment in data rescue (data archaeology).**

Comments:
(i) Generic, but unlikely to fill major gaps like the South Pacific.
(ii) Will require (low level) funding for digitizing data and for coordinators in data centres.
(iii) Requires declassification and release of data by navies.
(iv) Low order of difficulty (maybe high when dealing with navies).

Priority 4: **Encourage cruises to fill the substantial gaps that exist especially in the South Pacific, South Atlantic, Indian, Southern and Arctic Oceans, in the Arabian Sea, in the back-arc basins between China and Kamchatka, and in places in the North Atlantic and the North Pacific (e.g. between Hawaii and North America).**

Priority 5: **Use new technology (e.g. drifting floats and autonomous marine vehicles) to gather new data from large data gaps.**

Comments:
(i) Generic, with a payoff in large data gaps like the South Pacific where there are drifter programmemes.
(ii) Encourage use of AUVs as cheap survey tools (including under ice)
(iii) Champions needed to write appropriate proposals and carry out the development and testing.
(iv) Relatively low order of difficulty, depending on outcome of comment (iii) and availability of funds.

Priority 6: **Investigate the possibility of acquiring data from commercial ships by voluntary means.**

Comments:

(i) Generic, with a payoff along trade routes across data gaps like the South Pacific.
(ii) May require funding of echo-sounding equipment.
(iii) Will require training of personnel, as well as an interface with a responsible data centre, with funding implications.
(iv) Relatively high order of administrative difficulty (negotiations), and possibly technical too (depends on quality and ability of presently installed sounding systems), or financial (e.g. for installing new systems).

The working group recognized that what it wanted to see achieved could be ranked in several other ways, for instance, in terms of cost (which is in a way a measure of achievability), raising awareness is likely to be the cheapest option, closely followed by data rescue/archaeology (Priority 3), and then by turning on equipment (Priorities 1 and 2, above). Putting pingers on drifters may also prove to be cheap (Priority 4). Solutions involving ships (Priorities 4 and 6) and AUVs (Priority 5) are likely to be much more expensive.

In terms of geographic areas, data rescue is in hand for some geographic areas (like the Arctic, including Russian Arctic data). Undoubtedly this reflects the high priority already placed on the Arctic as one of the last great-unknown frontiers on the face of the planet. Other areas are less well served, although some progress is being made in the Antarctic.

In terms of science payoff, surveys that improve the input to ocean models could be seen as highest priority, because such models bear on our ability to understand and forecast climate change, which has profound human consequences. An example of the importance of this kind of study is that the sill at the mouth of the Persian Gulf is now known to be 120 m deep, not 80 m, changing the exchange parameters between the Gulf and the adjacent Arabian Sea. Improved bathymetry for tsunami modelling is likely to have the greatest short-term effect on human life, in tsunami-prone regions.

However, aside from these few examples it is NOT clear that it would repay effort to devise some elaborate prioritization scheme for the other topics listed in section 8.1 for example. For each of these topics, champions can be found to make the case for specific scientific studies in specific areas. We prefer to purse a policy that leads to the major data gaps being filled in.

Finally, we recommend that SCOR arrange the appropriate follow-up action to stimulate implementation in these priority areas, and to address the recommendations below in an effective manner. This might require the formation of an appropriate advisory panel, perhaps including some members of SCOR WG 107 for the sake of continuity.

ANNEX 1

LIST OF RECOMMENDATIONS

The working group recommends (in order of appearance in text):

1. **research on sill flow, using high resolution modelling, nesting, and parametrization, with the aim of finding an approach that can be successfully applied in climate and other models.**

2. **research on the sensitivity of numerically modelled sill flow to model resolution and topographic details, resolution and orientation.**

3. **that efforts be made to check the hypothesis suggested by altimetric data that seamounts cause much more dissipation of tidal energy in the open ocean than had formerly been supposed.**

4. **increased collection of swath bathymetric data from continental shelves.**

5. **that partnerships between academia, hydrographers, industry, NGOs, and navies be created to develop regional international bathymetric charts as the basis for creating a gridded global bathymetric Digital Elevation Model or appropriate resolution (which could vary depending on water depth).**

6. **that Peter Hunter's NGDC track charts be placed on the Internet so as to encourage people to fill data gaps.**

7. **attempts be made to get funds from agencies like the Defence Mapping Agency to fund echo-sounding on commercial transits.**

8. **Antarctic tourist cruise ships be approached to provide data.**

9. **funding agencies be asked to recognize the waste of resource involved, and to fund echo-sounding on transit on research vessels;**

10. **funding agencies develop mechanisms for ensuring that data are digitized and sent with track data to NGDC; and**

11. **at the very least hydrographic ships and research vessels should keep their centre beams on at all times (reducing the requirement for data processing), and especially during transit.**

12. **that consideration be given to equipping floats (like Argo floats) with pingers to indicate water depth.**

13. **that consideration be given to making low cost bathymetric surveys using autonomous marine vehicle technology, which could be particularly effective under ice.**

14. **that nations be encouraged to add bathymetric data from EEZ surveys to the international pool of data (via NGDC).**

15. **that to ensure maximum benefit, the objectives of bathymetric compilations 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.**

16. **that the issue of the substantial loss of internationally potentially valuable bathymetric data through a de facto policy of failure to collect them requires serious consideration by environmental science funding agencies, leading to corrective action in this matter.**

17. **release of published bathymetric maps to GEBCO for incorporation into current GEBCO maps;**

18. provision of funds by funding agencies for the employment of people with appropriate expertise to compile and contour new bathymetric maps - particularly at regional scales.

19. that agencies funding marine science topics should require that any proposals for scientific experiments should include provisions for site surveys and bathymetric maps, and that the bathymetry should be made available to GEBCO and the data sent to the NGDC.

20. that funding agencies develop policies to review the locations of existing data, and require principal investigators to plan new surveys and passage tracks to and from survey areas to occupy unsurveyed seafloor.

21. digitizing all available data.

22. that funding agencies support an appropriate number of centrally funded posts to ensure that the widest possible use is made of expensive-to-collect bathymetric data.

23. that major research institutions and funding agencies take steps to identify material that has not yet been submitted to central archives (NGDC), and provide funds to enable these data to be rescued.

24. that Antarctic Treaty countries should be encouraged to release and exchange data.

25. that navies declassify and release bathymetric data to the scientific community, and that at the very least such data are released in gridded fashion within a 0.5-minute (900 m) grid.

26. that money be found to facilitate the digitizing of Russian bathymetric data for wider release.

27. the development of a more formal relationship between Hydrographic Offices and academic institutions that collect bathymetry throughout the world, so that notice is given to the Hydrographic Offices when bathymetry is to be acquired, some level of meta data are exchanged, and agreement is reached on when and under what conditions data will be made available;

28. that academic institutions and Hydrographic Offices work together to address the needs for original survey data and various types of gridded bathymetry;

29. that bathymetry be integrated to ECDIS for use with the ship's primary navigation system in offshore areas where navigation safety is not an issue.

30. that geophysical survey companies be approached (perhaps through joint industry groups such as the Western Frontiers Association) to determine their willingness to release bathymetric data.

31. organizing an international scientific discussion meeting at which both industry and academic representation would present their interests and capabilities, with a view to forming a working plan and identifying a potential group of sponsors.

32. that standards of measurement be set for bathymetric data collected by research vessels, and the application of a standard method for computation of bathymetric grids.

33. that bathymetric maps should be made available as educational tools on the Web and through media such as CD-ROM, as GEBCO is now doing;

34. that articles be written in popular science magazines (*New Scientist, Scientific American*) drawing the importance of mapping the surface of our planet to the attention of the wider (voting) public.

ANNEX 2

LIST OF ACRONYMS

ACOPS	Advisory Committee on Protection of the Sea
BODC	British Oceanographic Data Centre
CARIS	Computer-Aided Resources information System
CGOM	IOC Consultative Group on Ocean Mapping
DCDB	IHO Data Centre for Digital Bathymetry
DEM	Digital Elevation Model
DTM	Digital Terrain Model
ECDIS	Electronic Chart Display and Information System
ERS-1	European Remote Sensing Satellite - 1
ETOPO-5	Earth Topography on a 5 arc-minute grid
GEBCO	General Bathymetric Chart of the Ocean
GEODAS	Geophysical Data System
GEOSAT	Geodetic Satellite (USA)
GIS	Geographical Information System
GOOS	Global Ocean Observing System
IAG	International Association of Geodesy
ICSU	International Council of Science
IHO	International Hydrographic Organization
NAVOCEANO	Naval Oceanographic Office (USA)
NERC	Natural Environment Research Council (UK)
NGDC	National Geophysical Data Centre (NOAA)
NOAA	National Oceanic and Atmospheric Administration (USA)
SOLAS	International Convention for the Safety of Life at Sea
VLBI	Very Long Baseline Interferometry
WVS	World Vector Shoreline