

The Nippon Foundation – GEBCO – Seabed 2030 Roadmap for Future Ocean Floor Mapping



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Panel 3 | New Tools and techniques in ocean mapping
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The Nippon Foundation – GEBCO – Seabed 2030

Roadmap for Future Ocean Floor Mapping



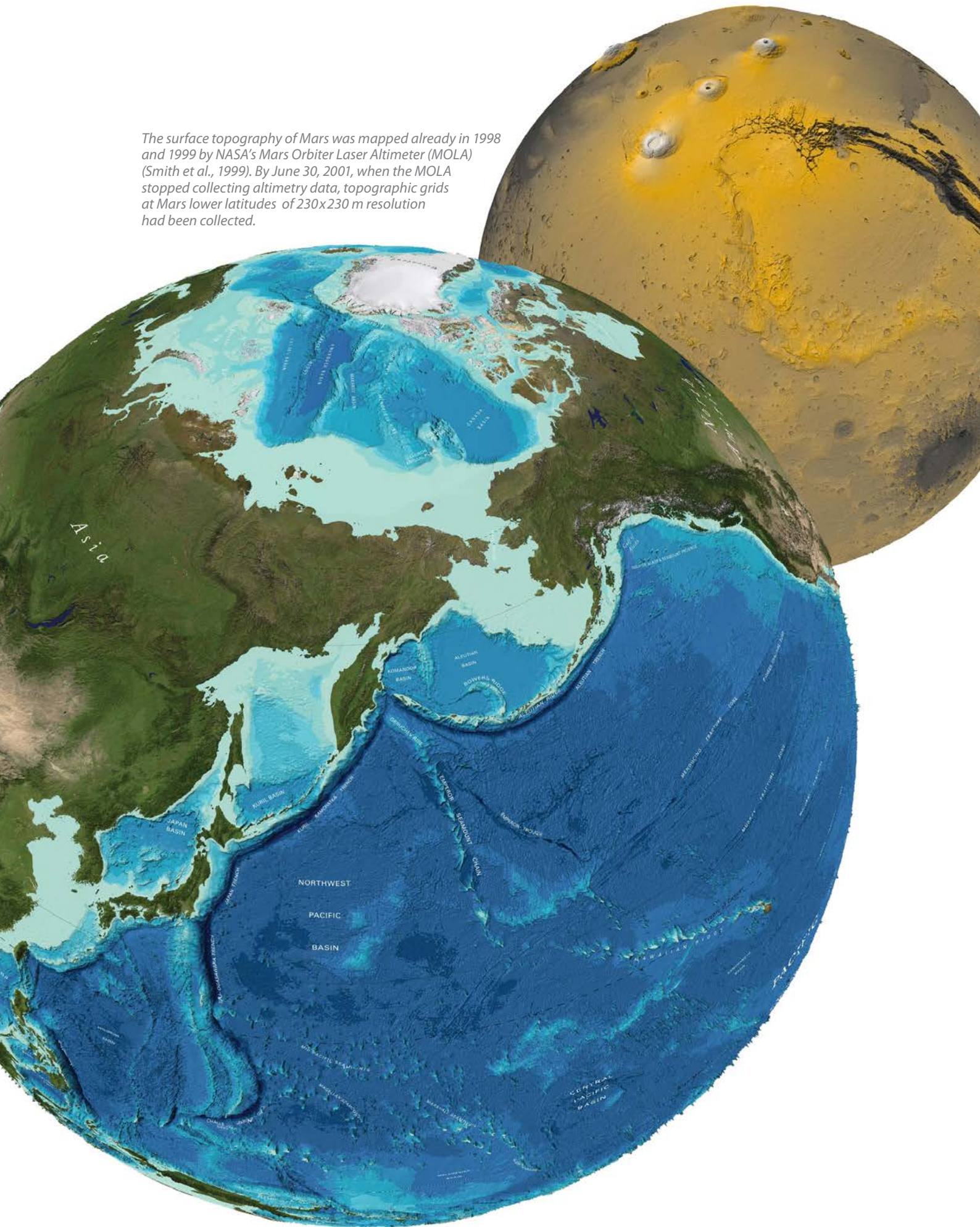


Depth sounding using lead line. Photo source: C&GS Season's Report Karo 1936-88. Provided from NOAA's Historic Coast & Geodetic Survey (C&GS) Collection. Photo taken 1936, southeast Alaska.

Table of Contents

Executive Summary	7
Extended Abstract	9
1.0. Introduction and goals	13
2.0. The role of The Nippon Foundation – GEBCO – Seabed 2030: Inspiring and coordinating the global effort to map the ocean floor	15
3.0. Perspectives on ocean mapping from the Forum for Future Ocean Floor Mapping, Monaco June 15–17, 2016	17
3.1. Use of bathymetry: The deep ocean perspective	17
3.2. Use of bathymetry: The coastal perspective	18
3.3. New Tools and techniques in ocean mapping	20
3.4. Mapping the world ocean floor	24
4.0. Status: How much of the World Ocean is mapped?	27
5.0. Seabed 2030: The road towards mapping the World Ocean floor	33
5.1. Background: The concept of Regional Mapping Projects and SCRUM	33
5.1.1. The concept of GEBCO_HiRes	34
5.2. Seabed 2030 structure	34
5.2.1. Regional Data Assembly and Coordination Centre (RDACC) and Global Data Assembly and Coordination Centre (GDACC)	34
5.2.2. Seabed 2030 within the GEBCO framework	36
5.2.3. Strategic Advisory Group and Review Panel	38
5.3. Seabed 2030 Milestones	38
6.0. Identified Challenges	41
6.1. Mapping the gaps	41
6.2. Bathymetry from sensitive areas	42
6.3. Keeping up with technology	42
7.0. References	42
8.0. Addendum 2020 Seabed 2030 mapping target resolutions	44

The surface topography of Mars was mapped already in 1998 and 1999 by NASA's Mars Orbiter Laser Altimeter (MOLA) (Smith et al., 1999). By June 30, 2001, when the MOLA stopped collecting altimetry data, topographic grids at Mars lower latitudes of 230x230 m resolution had been collected.





The Nippon Foundation – GEBCO – Seabed 2030

Roadmap for Future Ocean Floor Mapping

Executive Summary

About 71% of the Earth is covered by the World Ocean for which the bottom topography (bathymetry) is far less known than the surfaces of Mercury, Venus, Mars, and several planets' moons, including our own. Mapping through ocean water deeper than a few meters excludes the efficient use of electromagnetic waves such as radar and light, which forms the basis for methods used during terrestrial and extra-terrestrial mapping missions. While ocean surface height measured by satellites can be used to derive a coarse view of the ocean floor, it does not have sufficient resolution or accuracy for most marine or maritime activities, be it scientific research, navigation, exploration, shipping, resource extraction, fisheries or tourism. Traditional bathymetric mapping techniques rely on acoustic mapping technologies deployed from surface or submerged vessels and require broad international coordination and collaboration towards data assimilation and synthesis.

In the opening address of the Forum for Future of Ocean Floor Mapping (FFOFM) in Monaco in June 2016, Mr. Yohei Sasakawa, Chairman of The Nippon Foundation, set forth the initiative to partner with GEBCO to cooperatively work towards seeing 100% of the World Ocean mapped by 2030. This initiative led to the formulation of The Nippon Foundation – GEBCO – Seabed 2030, a global project within the framework of the General Bathymetric Chart of the Oceans (GEBCO) with the focused goal of producing the definitive, high resolution bathymetric map of the entire World Ocean by the year 2030. GEBCO, with its two parent organizations the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of United Nations Educational, Scientific and Cultural Organization (UNESCO), has partnered with The Nippon Foundation to launch Seabed 2030, jointly driven by the strong motivation to empower the world to make policy decisions, use the ocean sustainably and undertake scientific research informed by a detailed understanding of the World Ocean floor.

Based on GEBCO's successful experiences of working with Regional Mapping Projects, the structure of Seabed 2030 rests on the establishment of teams of experts at Regional Data Assembly and Coordination Centres (RDACCs) and a Global Data Assembly and Coordination Centre (GDACC). The regional teams will be responsible for championing regional mapping activities as well as assembling and compiling bathymetric information within their prescribed region. The global team will be responsible for producing centralized GEBCO products and centralized data management for non-regionally sourced data. In ocean regions where strong mapping initiatives are already operational, Seabed 2030 will strive to avoid duplication and instead work towards fostering a close collaboration for the most efficient use of global resources. This Road Map expands on the underlying motivation for undertaking the Seabed 2030 project, presents the perspective on ocean mapping from the forum held in Monaco 2016, provides an update on how much of the World Ocean is currently mapped, further outlines the Seabed 2030 project structure and plan, and identifies challenges and milestones ahead.



Mapping the entire World Ocean floor is an ambitious effort, specifically considering that 50% is deeper than 3200 m and large parts at high latitudes are permanently covered by sea ice. Swedish icebreaker *Oden* mapping in the central Arctic Ocean. Photo: Martin Jakobsson

Extended Abstract

Mission

Earth's land masses cover 29% of its surface and widely available maps of this surface show features down to a size of 30m or less. This stands in stark contrast to the ocean floor which covers the remaining 71% of Earth's surface, yet because the depths between the ocean surface and the seabed (bathymetry; derived from the Greek words for “deep” and “measure”) have not been accurately measured.

Systematic acquisition of deep ocean (>200m) bathymetric data began in earnest with the British Challenger expedition (1872–1876), generating 492 deep-sea soundings using a line to which a weight was attached. Deep-sea line soundings continued for the following 50 years, until echo-sounding technology became efficient. Nearly a century later, however, more than 80% of the World Ocean floor is still not mapped even at a resolution of 1 km using the echo sounding method. Oddly, we know the surface topography of, for example, Mars and our moon, at a far greater detail than we know the surface of our own planet beneath its oceans. During the Forum for Future Ocean Floor Mapping organized by GEBCO and the Nippon Foundation in 2016, the project Seabed 2030 was initiated, with the clearly set long-term aspirational goal of seeing 100% of the World Ocean floor topography mapped by 2030 so that:

No features of the accessible parts of the World Ocean floor larger than 100m remains to be portrayed.

This is a tremendously ambitious effort that, with current technology, will require nearly 1000 ship years (e.g., 1000 years for a single ship, ten years for 100 ships, etc.) and perhaps a bit too optimistic with 12 years at hand, specifically considering that 50% of the World Ocean is deeper than 3200m and parts are permanently ice covered. The complete mapping is our ultimate goal, however at a series of targets resolutions to be defined as a function of water depth. Seabed 2030 thus provides a Road Map, or guidelines and instructions, for future ocean floor mapping that builds on the century-long GEBCO legacy and the human capacity built by the GEBCO–Nippon Foundation training program over the past decade. The mission of Seabed 2030 is:

To empower the world to make policy decisions, use the ocean sustainability and undertake scientific research based on detailed bathymetric information of the Earth's seabed.

Organization

The General Bathymetric Chart of the Oceans (GEBCO) operates under the auspices of the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO), and aims to provide the most authoritative, publicly-available bathymetry data sets for the world's oceans. The Nippon Foundation's mission focuses on social innovation, in which “The future of our ocean” is one of seven key fields of activity.

Through the Seabed 2030 program, GEBCO and the Nippon Foundation have committed to build the necessary technical, scientific and management framework to compile all available bathymetric information into a seamless digital bathymetric map portraying of the World Ocean by the year 2030.

Why

Bathymetric data from the deep ocean (>200m) is critical for a wide variety of scientific applications, including marine geology and geophysics. A prime example is the few single beam echo sounding profiles across the Atlantic Ocean that enabled Bruce Heezen and Marie Tharp to portray the seabed during the late 1950's through 1960's. These bathymetric data played an important part in the formulation of one of the most prominent paradigm shifts in geosciences – the seafloor spreading and the plate tectonic revolution.

The shape of the seabed is also a crucial parameter for understanding ocean circulation patterns that relate to regional and global ocean-atmosphere processes that distribute heat between the tropics and poles, thereby preventing

a runaway thermal imbalance between these regions as well as the key parameter in numerical modelling for forecasting of tsunami wave propagation. In addition, ocean bathymetry is important for the study of tides, wave action, sediment transport, underwater geo-hazards, cable routing, fisheries management, resource exploration and exploitation, the extension of continental shelf (UN Law of the Sea treaty issues), military and defence applications, and represents a fundamental data set for confronting the growing challenges associated with climate change.

Bathymetry in the coastal perspective underpins marine and maritime spatial planning and decision-making, safety of navigation, and provides a scientific basis for models of tsunami inundation and storm surges, regional assessments of future sea-level rise, understanding marine ecosystems and habitat, and much more.

The more data we acquire about the details of seabed shape, the more we recognize that the ocean and its floor are more dynamic than we ever thought. Detailed knowledge about bathymetry and seabed shape are fundamental prerequisites for attaining an improved understanding of many of these subsea dynamic processes.

How

Modern bathymetric mapping relies on acoustic technologies deployed from surface or submerged vessels. Seabed 2030 will compile all available and newly collected bathymetric data into a high-quality, high-resolution digital model of the World Ocean floor. Given the vast expanses of the oceans, this can only be achieved through international coordination and collaboration with respect to data acquisition, assimilation and compilation.

Regional Mapping Projects will be established focused on gathering all bathymetric data from a specific region into a digital database that will enable experts to produce the best possible gridded bathymetric model, a digital 3D representation of the seafloor topography. The first Regional Mapping Project working along these lines was the International Bathymetric Chart of the Arctic Ocean (IBCAO), initially released in 2000 and later included in the GEBCO World Ocean bathymetric grid to represent the Arctic Ocean. Following the concept of IBCAO was the International Bathymetric Chart of the Southern Ocean (IBCSO).

Building on GEBCO's successful experience of working with Regional Mapping Projects, the Seabed 2030 project will establish four Regional Data Assembly and Coordination Centres (RDACCs), each having a defined ocean region of responsibility. An Editorial Board will be established for each region consisting of local experts and representatives of mapping activities. The Editorial Board will have two main tasks: (1) identify existing bathymetric data and (2), help coordinate new bathymetric surveys.

The IBCAO region will be increased to encompass the northern Pacific Ocean and the area of IBCSO will extend its northern boundary to 50°S forming two of the RDACCs (Arctic Ocean + northern North Pacific, and Southern Ocean). The remaining part of the World Ocean will be divided into a South and West Pacific Ocean RDACC and an Atlantic-Indian Ocean RDACC. Each RDACC, via its Editorial Board, will be responsible for coordinating mapping activities within their prescribed oceanic region as well as for bathymetric data assembly, integration and synthesis. The output of each RDACC will be submitted to the Global Data Assembly and Coordination Centre (GDACC), responsible for producing centralized GEBCO/Seabed 2030 products and ensuring the distribution of the final bathymetric products to the end users. Seabed 2030 will strive to avoid duplicating ongoing mapping efforts and work with, for example, the EMODnet and the Galway Statement implementation initiatives.

Challenges

Seabed 2030 recognizes that over 80% of the World Ocean remains unmapped with modern high-resolution mapping technology. It follows that the overall goal of leaving no features of the World Ocean floor larger than 100m unmapped by year 2030 involves substantial challenges. This goal can only be accomplished if new field mapping projects are initiated by many parties using many vessels.

Crowd sourcing (e.g., collecting bathymetric data from fishing vessels, recreational small boats, etc.) represents one approach for gathering bathymetric data in shallower water regions, but is less efficient in deeper waters due to depth limitations of standard echo sounders. Mapping of the deeper parts is at present by and large left to dedicated expeditions. This represents a major challenge due to the cost involved and the limited number of available research vessels that are equipped with modern deep-water multibeam sonars. To meet this challenge, Seabed 2030

will create a series of programmatic guidelines to be submitted to national and international funding agencies, with the goal to promote funding opportunities that will support and share the Seabed 2030 vision.

Bathymetric data from sensitive areas (territorial water, offshore industry competition/client confidentiality, military strategy) pose challenges in terms of access to bathymetric data. It is anticipated that as more data are contributed to Seabed 2030, and its products are broadly distributed and recognized, there will be an increased willingness of new groups to contribute data.

Keeping up with technology represents another challenge. The strategy of Seabed 2030 will evolve over time and a most critical step for this project is to make sure that processes, products and services are forward-looking and that efforts will be well-positioned to make use of new technologies as they become available.



The work by Bruce Heezen and Marie Tharp to portray the seabed during the late 1950's through 1960's played an important part in the formulation of one of the most prominent paradigm shifts in geosciences – the seafloor spreading and the plate tectonic revolution. Photo credit: Lamont-Doherty Earth Observatory



Photo: Zainulanuar Ghazali, CEO of Marine Science Technology (MAST) Sdn Bhd Malaysia. Host of the 2nd Indian Ocean Bathymetric Chart (IOBC) workshop.

1.0. Introduction and goals

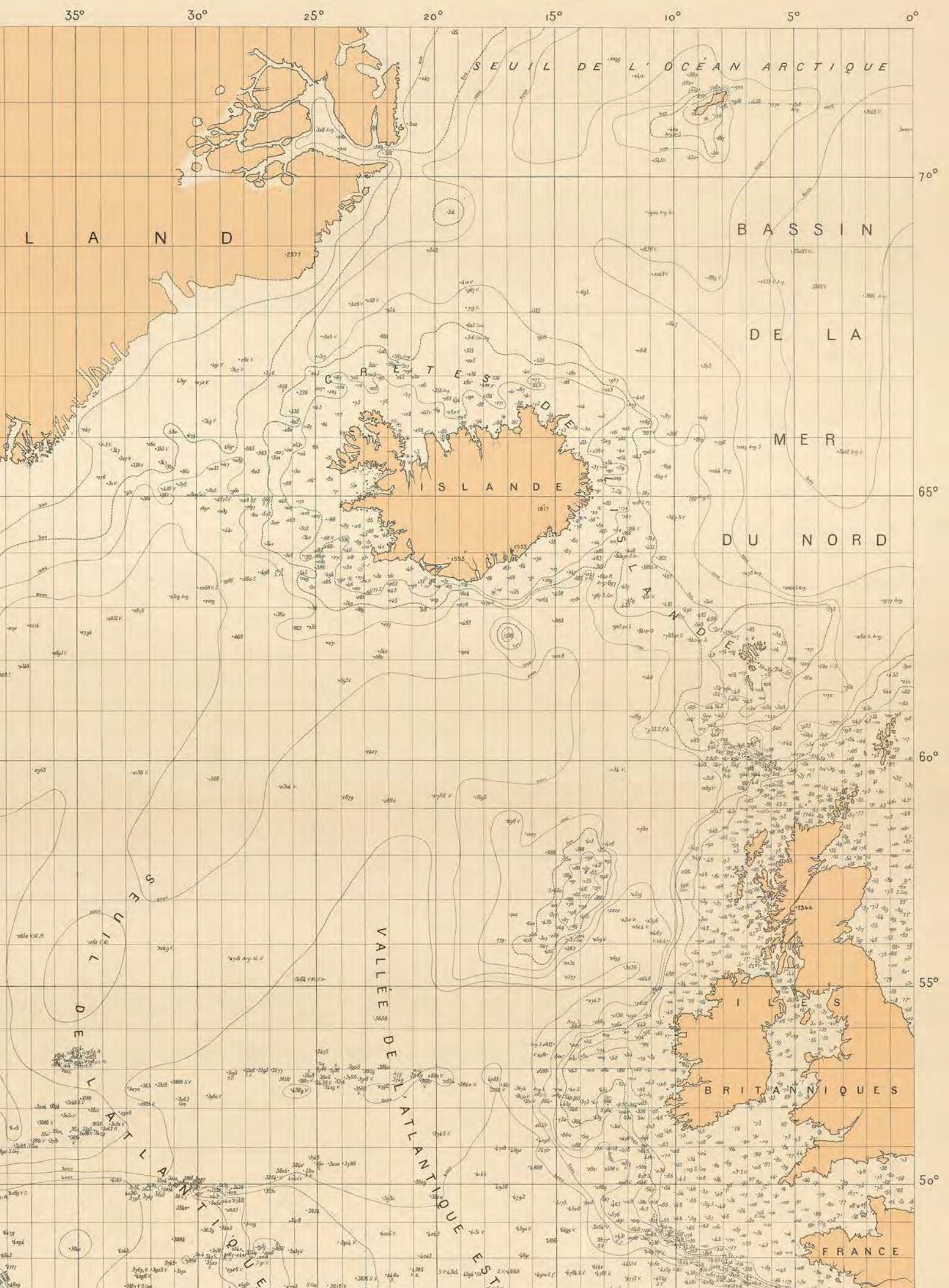
The oceans, covering 71% of the Earth's surface, are fundamental to sustaining life, controlling climate, facilitating commerce and a vast source of resources and economic wealth – yet our understanding of ocean and seafloor processes is quite limited due to the difficulties in operating in this environment. Foremost amongst the challenges of understanding the oceans and the seafloor is the fact that electromagnetic waves (e.g., light and radar) are highly attenuated in ocean water and thus the suite of optical and electromagnetic sensors that we have developed to map, observe, and better understand the land topography cannot penetrate more than a few meters in typical ocean waters. This has left seventy percent of our planet virtually unmapped, unobserved, and unexplored. Satellite measurements of the ocean surface height can provide a general view of the shape of deep ocean floor, but this general view does not provide the detail or accuracy required to understand critical ocean processes and to manage our ocean resources. Knowing the depth of the seabed, i.e. bathymetry, is of vital importance not only for navigation and coastal management, but also for a growing variety of inter-related uses. Mapping the depths of the oceans yield the shape of the seabed that is a fundamental parameter for understanding ocean circulation, tides, tsunami forecasting, fishing resources, wave action, sediment transport, environmental change, underwater geo-hazards, cable and pipeline routing, mineral extraction, oil and gas exploration and development, infrastructure construction and maintenance and much more. Given the limitations of electromagnetic sensing in the ocean, bathymetric details over the majority of the world's oceans must be obtained using modern acoustic mapping technologies deployed from surface or submerged vessels. The vast expanses of the oceans implies that broad coverage can only be achieved through international coordination. The General Bathymetric Chart of the Oceans (GEBCO) is a project with two parent organizations: the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of United Nations Educational, Scientific and Cultural Organization (UNESCO). GEBCO was initiated more than 100 years ago with the vision of portraying the World Ocean floor. This vision followed from societal needs and scientific curiosity.

During the Forum for Future Ocean Floor Mapping organized by GEBCO and The Nippon Foundation in Monaco 15–17 June, 2016, a new project “Seabed 2030” was initiated. This followed from an invitation by Mr. Yohei Sasakawa, Chairman of The Nippon Foundation, to partner with GEBCO with the goal of seeing 100% of the World Ocean floor topography mapped. The ambitious goal of The Nippon Foundation – GEBCO – Seabed 2030 was thus set to:

Leave no features of the accessible parts of the World Ocean floor larger than 100m unmapped by the year 2030.

This goal may be over-ambitious considering that that 50% of the World Ocean is deeper than 3200m and that there are considerable parts ice covered. However, we will hold that as our ultimate goal but we will define a series of targets with different resolutions according to water depth. The basic structure and initial implementation strategy of Seabed 2030 is introduced in this road map for future ocean floor mapping as it will constitute the centrepiece of GEBCO's activities for more than a decade ahead. It builds on 100 years of GEBCO's legacy and established regional connections in all corners of the World Ocean as well as the platform of human capacity built for over ten years through the GEBCO – Nippon Foundation training programme. The mission of Seabed 2030 is:

To empower the world to make policy decisions, use the ocean sustainably and undertake scientific research based on detailed bathymetric information of the entirety of the Earth's seabed.



Part of GEBCO Sheet B1, from the 1st Edition published 1903. Source: International Hydrographic Organization archive

2.0. The role of The Nippon Foundation – GEBCO – Seabed 2030: Inspiring and coordinating the global effort to map the ocean floor

The vision of portraying the World Ocean floor on a series of maps inspired the initiation of GEBCO in 1903 through the efforts of Prince Albert I of Monaco and Professor Julien Thoulet, University of Nancy, both of whom shared a strong passion for the ocean. This vision of portraying the depth and shape of the World Ocean floor remains at the heart of GEBCO and its community, though now with modern and emerging mapping and visualization technology the vision can become a reality.

As a project of both the IHO and IOC of UNESCO, the GEBCO community is in an excellent position to undertake a global coordinated effort to compile bathymetric information from all over the world, identify the areas of greatest need so that compilation efforts can be prioritized, increase the recognition of the importance of bathymetry at intergovernmental and public fora, and lead global efforts for coordinating the prioritization of mapping programmes.

GEBCO recognizes that vast areas of the World Ocean floor, especially those at great distances from coasts, are far from adequately mapped. Mapping from the coast to the deepest trenches involves reaching the remote regions, far from any national jurisdiction, and beneath the virtually unknown realms of Polar ice shelves and pack ice-covered oceans. These environments are as poorly known today as all of the deep ocean was for Prince Albert I and Professor Julien Thoulet more than 100 years ago.

As Seabed 2030 evolves we envision that:

- Seabed 2030 is recognized as THE authoritative international initiative for synthesis of a World Ocean portrayal of the seabed from the coasts to the deepest trenches.
- Seabed 2030 collaborates with academia, research organizations, government, and industry to develop leading edge technology and provide practical at-sea surveying experience, data processing expertise, database managers, software developers, geologists, geophysicists and other relevant ocean scientists.
- Seabed 2030 is universally recognized and respected as an international initiative, free of political bias or constraints and thus capable of gathering bathymetric data and resources from research labs, industry or academia of any nation. In return, Seabed 2030 will make data freely available to all.

The GEBCO community as a whole promotes the sharing of ocean mapping knowledge and expertise through active engagement and capacity building efforts engaging people who are leaders in all aspects of this field.

Through the Seabed 2030 programme, GEBCO and the Nippon Foundation have committed to build the necessary technical, scientific and management framework to synthesize all available bathymetric information into a seamless digital bathymetric model portraying the World Ocean by the year 2030. Seabed 2030 is launched as an operational Nippon Foundation-GEBCO programme, which will benefit from GEBCO's past and ongoing efforts of linking individuals, communities and organizations worldwide to enhance existing global networks to drive ocean mapping and provide a deeper understanding of the modern and past processes shaping the ocean floor.



Mapping using an Autonomous Underwater Vehicle (AUV) in Greenland waters. Photo: Martin Jakobsson

3.0. Perspectives on ocean mapping from the Forum for Future Ocean Floor Mapping, Monaco June 15–17, 2016

The Forum for Future Ocean Floor Mapping (FFOFM) brought together 200 individuals from 45 countries representing the “Blue Community”, from experts on ocean mapping to stakeholders and users of bathymetric information. The wide range of participants included those from academia, industry, governmental institutions and international and national organizations with interests in the ocean. The purpose of the FFOFM can be summarized under the following main points:

1. Raise awareness regarding the present state to which the World Ocean floor is mapped
2. Provide answers to a set of questions that may be generalized into the following:
 - Who are the users of bathymetry?
 - What is bathymetry needed for?
 - What bathymetric products do users want and what resolutions are required?
 - How can we map the gaps in bathymetric coverage?
3. Discuss the way forward towards mapping all the unmapped regions, which presently encompass more than 80% of the World Ocean area.

Following the first day of plenary presentations, the remaining two days of the FFOFM were organized into four panels for which the outcome is summarized below for each panel.

3.1. Use of bathymetry: The deep ocean perspective

The deep ocean, here defined as deeper than 200m, comprises the majority of our planet yet it remains largely unmapped and unexplored with modern mapping methods. Bathymetry from the deep ocean is critical for a wide

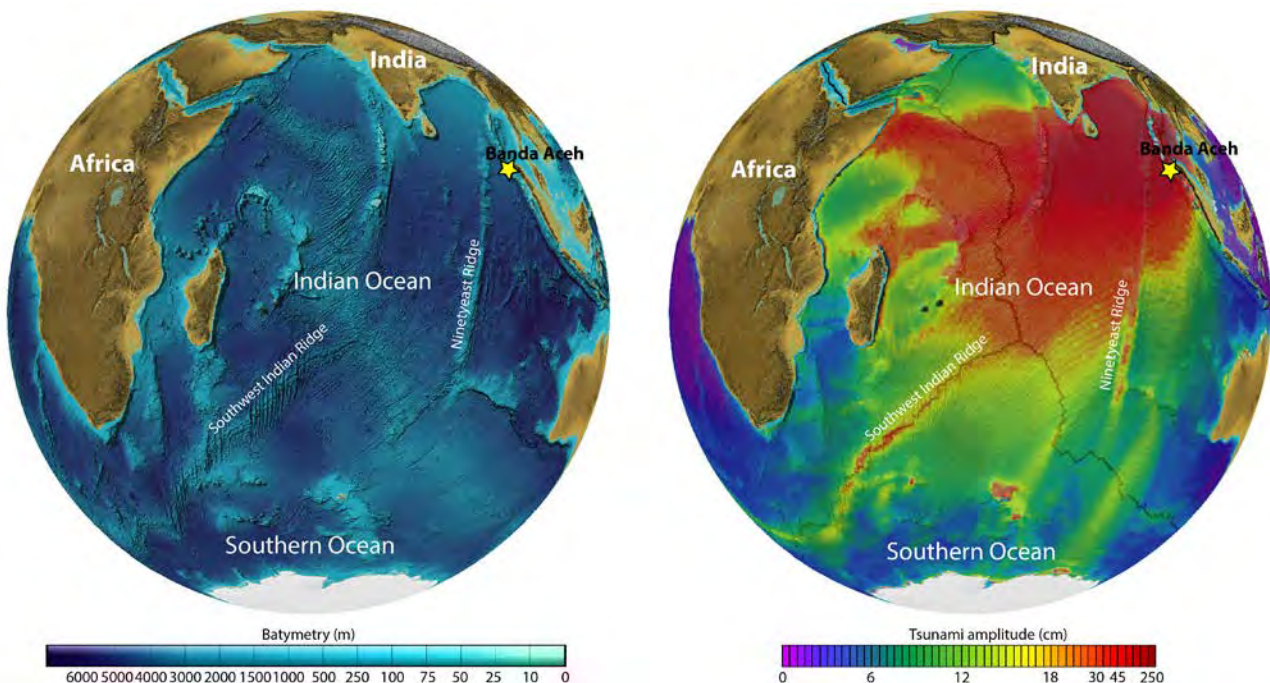


Figure 3.1: Illustration showing the bathymetry's role for the tsunami propagation following the earth quake 26 December 2004 outside of Sumatra. The left globe shows the seafloor bathymetry as portrayed by the GEBCO grid and the globe to the right has the tsunami amplitude overprinted (data from Titov et al. 2005). The seafloor ridges acted as efficient wave guides. The epicentre of the earth quake located approximately 260 km southwest of Banda Aceh, Sumatra, is marked with a yellow star. The illustration is modified from Jakobsson and Hell (2006).

variety of scientific applications including marine geology and geophysical studies of global tectonics and sediment transport, habitat, biodiversity and biogeography studies, understanding circulation patterns that relate to regional and global ocean-atmosphere (climate) processes, and numerical modelling for forecasting at different temporal and spatial scales including, for example, tsunami propagation. In addition, deep ocean bathymetry is important for resource exploration and exploitation, cable routes, fisheries management, the juridical extension of continental shelves, military and defence applications, and is a fundamental data set for confronting the growing challenges associated with climate change.

Until recently, measuring deep ocean bathymetry was almost exclusively carried out using deep-water hull-mounted sonar systems with the spatial resolution fundamentally limited by water depth. The spatial resolution of these deep ocean bathymetric data products is typically ~100–200m. At this resolution, the shape of the seafloor can be adequately measured to provide fundamental base-maps for detailed studies and to provide the quantitative information needed to understand the morpho-tectonic processes including the location and extent of mid-ocean ridge spreading centres and ridge segmentation, and the relationships between volcanism and tectonics on ridges and seamounts and faulting patterns at subduction zones. It also allows us to define at a scale appropriate for oceanographic and climate modelling, the flow paths of deep currents that distribute heat around the planet. With rapid advances in robotics and sonar technology over the last five to ten years, deep-diving submersibles including Autonomous Underwater Vehicles (AUVs) can now routinely be deployed in the deep ocean to acquire higher resolution sonar data by bringing sonar systems close to the seafloor. We are now able to bring the details of the seafloor shape into focus by mapping small portions of the deep ocean at meter to sub-meter resolution. This environment is truly at the frontier of earth science – the more data we acquire, the more we recognize that the deep ocean and its floor are more complex and dynamic than we ever thought. Such high resolution methods are not currently efficient or practical for large scale regional mapping, however.

The needs of the diverse community of stakeholders who use deep ocean bathymetry vary with respect to required resolution. Comprehensively mapping the deep ocean at ~100m horizontal grid resolution will provide fundamental baseline bathymetry that suits many needs, but higher-resolution data will still be necessary in many areas for many purposes. Comprehensive baseline bathymetry will help identify where higher-resolution data may still be required, however. In addition, re-surveying of the deep ocean will be necessary at different time scales due to the frequency and intensity of seafloor-changing earth processes in some regions. Since most of the deep-sea is beyond territorial waters, mapping efforts to date have been driven by the needs of scientific programmes or the specific needs of the commercial sector (e.g. oil and gas exploration and development and cable route surveys). Comprehensively mapping the deep ocean will require international coordination and cooperation to assemble opportunistically-acquired data and to conduct new campaign-style mapping efforts. The need for a bathymetric base map of the southeastern Indian Ocean became particularly evident in the search for the Malaysia Airlines flight MH370, which disappeared 8 March 2014 (Fig. 3.2). Efficient planning of the search missions with AUVs required bathymetric information with a resolution of about 100m.

Key considerations made at the FFOFM

- Deep ocean bathymetry has many important applications, and users have a variety of needs with respect to data resolution, frequency of re-survey, and data products.
- Mapping the deep ocean at a resolution of ~100m will provide a critical baseline of data and can be used to develop strategies for higher-resolution mapping and repeat mapping efforts.
- Mapping the deep ocean will require international coordination and cooperation.
- A critical first step in mapping the deep sea is to assemble a full inventory and display the spatial extent of existing data and gather important metadata that can be used to better understand the current status of existing data. Part of this involves identifying collaborations/incentives to gain public access to existing data that are not yet available.

3.2. Use of bathymetry: The coastal perspective

Seafloor mapping of coastal areas is key to all activities that impact the coastline or have a direct relationship with the coastline. Although scientists perceive the ocean floors as a continuum from the coastline down to the deepest abyssal plains, and the concept of marine spatial planning calls for continuous access to authoritative and accurate

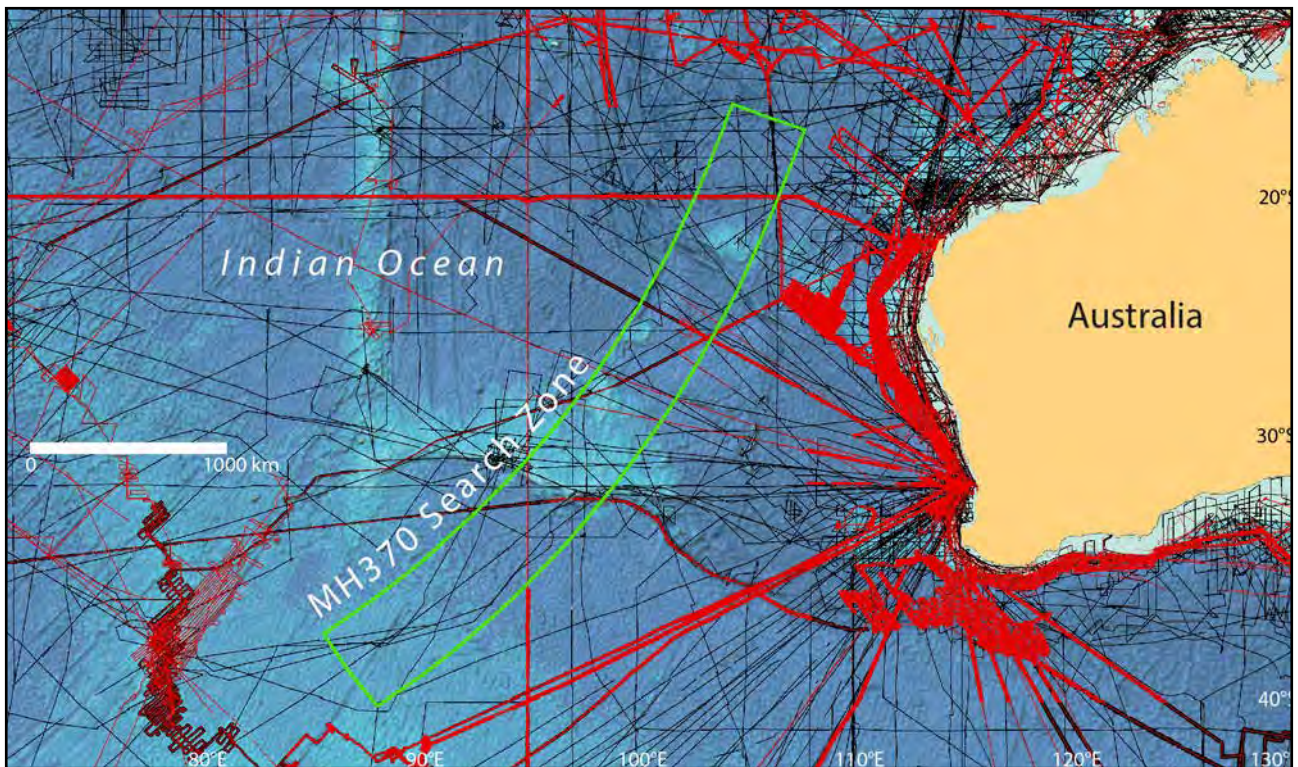


Figure 3.2: The need for high-resolution bathymetry in the deep ocean became strikingly evident outside of the scientific community following the disappearance 8 March 2014 of Malaysia Airlines flight MH370, on the route from Kuala Lumpur to Beijing. The seafloor in the projected search area (green box) was very poorly mapped at the time the search for parts of the fuselage could begin (Smith and Marks, 2014). Black lines are ship track lines along which single beam echo sounding data had been collected and red show multibeam bathymetry available at the time the search began. The bathymetric data coverage was far from sufficient to navigate underwater vehicles for close inspections of the seafloor. In essence, a search for a lost object the size of an aircraft would have a better start if it was lost on the planet Mars, which is substantially better mapped than the World Ocean.

data, there is a general requirement to make a distinction between “bathymetric mapping” (mapping of underwater depth of lake or ocean floors) vs. “hydrographic mapping” (mapping for safe navigation). While the former strives to accurately portray the shape of the seafloor, the latter is focused on charting bathymetric objects that constitute hazards to ship safety. We focus here on bathymetric mapping and the use of bathymetry beyond safe navigation – although data collected for one purpose can often be used for the other.

Bathymetry, especially in the coastal areas, underpins marine and maritime spatial planning and decision-making. The bathymetry of the coastal areas serves a wide community of stakeholders. It is also the area that is most vulnerable to the impacts of climate change and relative sea level rise. However, the lack of full public access to shallow water bathymetry implies that it is difficult to access the broad usage of it. This in turn implies that the value of having mapped the seabed and making the data available is generally underestimated for coastal regions. Furthermore, the dynamic nature of shallow water environments requires the consideration of temporal components (4D datasets) and repeated measurements for proper risk management and sustainable use of the seas. A major challenge is that mapping shallow waters with multibeam sonar is considerably more time consuming than mapping deep waters because the covered area (swath width) along a ship track is a function of water depth. Bathymetric data collected using other technologies than multibeam, such as LIDAR (Light Detection and Ranging) and satellite imagery, may prove particularly valuable for mapping shallow water as the technology evolves.

The scientific need for coastal bathymetry is well established – for example, for tsunami inundation models, erosion and accretion studies, regional assessments of future sea-level rise, geo-hazard prediction, studies of outlet glaciers’ sensitivity to inflow of warmer subsurface water in a warming ocean, and marine ecosystems’ dependency on the depth domain. The forms in which we make bathymetric data available may be critical as this links completely unexpected utilization, collaborations and outcomes.

Resolution is utterly important, but so are uncertainty and repeatability of the measurements. Depth accuracy of a few tens of centimetres and horizontal resolution of five to ten meters, globally, would be desirable, but given that most of our coastal waters are not even mapped to 100m resolution, it is probably only realistic to achieve global coverage at medium resolution in shallow water by 2030. Dynamic coastal areas mapped at highest resolution require continuous and repeated surveys, this will be the task of future generations. The data have to be collected with reference to a geodetic datum, ideally this reference should be to a known ellipsoid permitting easy conversion to any desirable vertical datum. While we offer broad guidelines in terms of defining achievable resolution levels, we must be flexible as technology, products, and requirements are ever-changing.

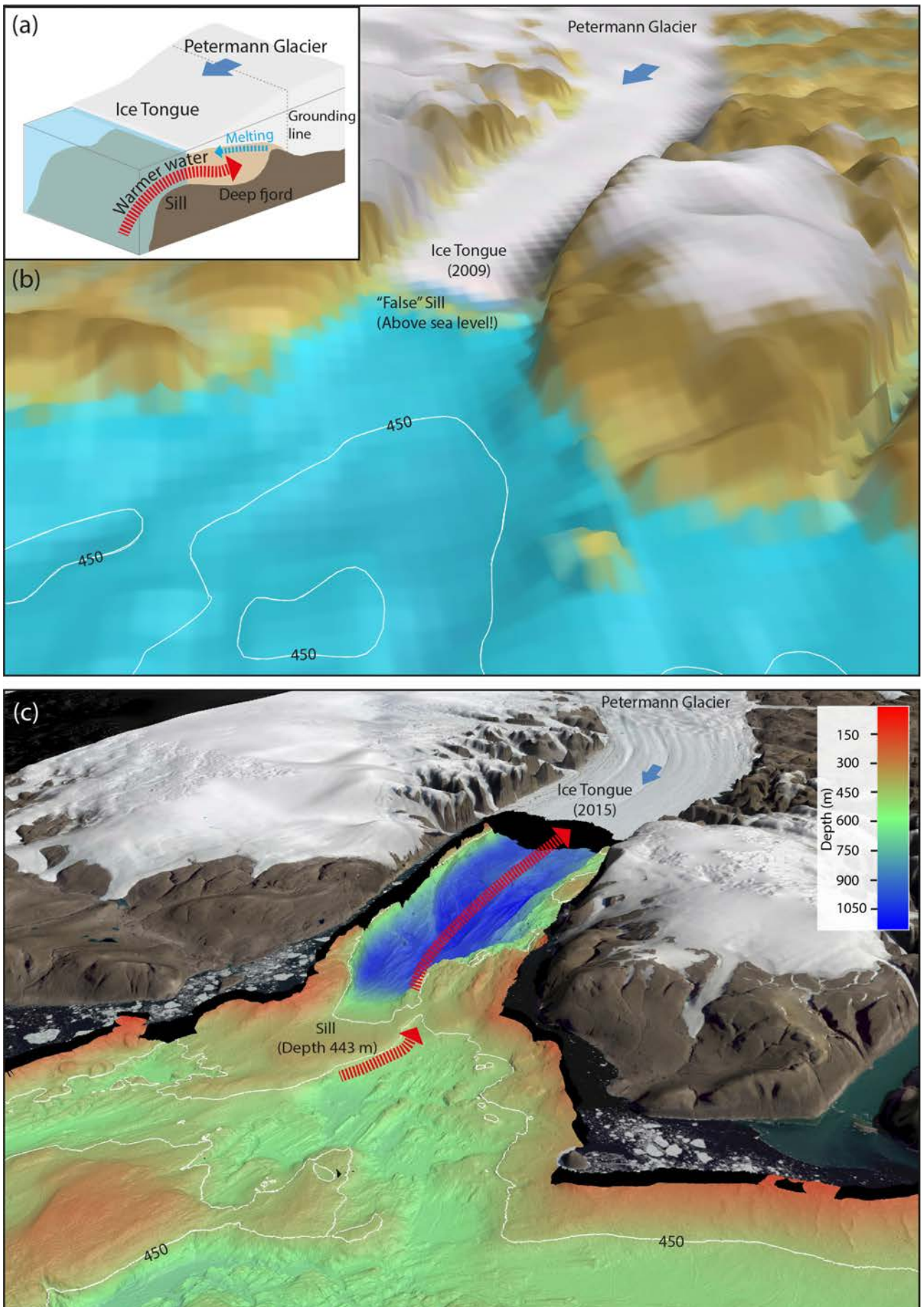
Key considerations made at the FFOFM

- Shallow water bathymetry underpins marine and maritime spatial planning and decision-making by governments.
- The bathymetry in coastal areas forms a critical spatial framework required to answer a broad range of scientific questions, including, for example, the local impact of tsunami inundation and storm surges, erosion and accretion, marine glaciers' sensitivity to influx of warm subsurface water and marine ecosystems' dependency on the depth domain and thereby sensitivity to future sea-level rise.
- An integrated technology approach is favoured in the coastal areas. LIDAR and satellite imagery will provide potential sources all to be considered as valuable bathymetric data contributors in addition to conventional multibeam and single beam echo sounders.
- More data will have to be contributed by the Hydrographic sector, following the handful of Hydrographic Offices that have permitted the use of shallow water bathymetry from ENCs (Electronic Navigational Charts).
- A critical first step in mapping shallow coastal waters is to assemble a full catalogue and display the spatial extent of existing data and gather important metadata that can be used to better understand the current status of existing data. Part of this involves identifying collaborations/incentives to gain public access to existing data that are not yet available. The survey industry can play a role here in helping to convince their customers to release their proprietary data and potentially manage the decimation (where necessary) and delivery of these data to GEBCO.

3.3. New Tools and techniques in ocean mapping

Do we have the tools and techniques to map the World Ocean floor? The past few decades have seen consistent improvements in the accuracy, resolution, and seafloor coverage offered by echo-sounding and LIDAR methods. The most widely used acoustic mapping technology is based on the multibeam echo sounder with the capability of mapping a wide swath underneath the vessel. The width of a mapped swath of the seafloor by multibeam sonars is approximately five times the water depth and often more. Interferometric sonars exist and are being developed with wider swath widths, and specifically suited for shallow water mapping or installation in AUVs due to their smaller size. However, the quality of depth measurements of interferometric sonars is not yet at the level of conventional multibeam echo sounders. The evolution of technology may see sonars based on a mix between the interferomet-

Figure 3.3: The importance of knowing the shape and depth of the seafloor can be shown with many specific examples. One such example is the influence of a fjord's bathymetry on outlet glaciers' sensitivity to inflow of warmer sub-surface ocean water (Holland et al., 2008). The dynamic behaviour of glaciers suddenly subjected to warmer ocean water may change and lead to rapid mass loss of ice, in turn causing sea-level rise that impacts living conditions far beyond the Polar Regions. a) Conceptual illustration of glaciers draining large ice sheets, such as the Greenland or Antarctic ice sheets, into the ocean. These glaciers commonly have a large floating parts referred to as ice shelves or ice tongues, when constrained in a fjord. Shallow bathymetric sills at the fjord entrance will help making the ice tongue and feeding glacier less sensitive to ocean warming and changes in ocean current regimes, which has been observed in several Polar areas and attributed as an effect of a warmer climate (Jacobs et al., 2011; Mougnot et al., 2015; Rignot et al., 2013). The illustration in a is for example representative for the Petermann Glacier, located on northwestern Greenland and draining about 6% of the entire Greenland Ice Sheet. The Petermann ice tongue appeared stable and located near the fjord's sill until 2010 and 2012, when Manhattan-sized pieces broke off and reduced the ice tongue by about 30–40% (Münchow et al., 2014). b) The Petermann Fjord as portrayed in IBCAO Version 3.0. The grid model had only a few single echo sounding measurements in the fjord area resulting in crude bathymetry and a false bathymetric sill appearing in the gridded model due to extremely sparse data. This sill even appeared to have sections above sea level. Such shallow sill would make the Petermann Glacier less sensitive to influx of warmer water. c) Complete multibeam mapping of the Petermann Fjord was carried out with Swedish icebreaker Oden in 2015 (Mix et al., 2015). The seafloor portrayal is in c is based on a 15x15 m multibeam grid. The true nature of the bathymetric sill was revealed. The sill is generally deeper than 350m, with a deepest passage of 453 m. This implies that the Petermann Glacier is much more sensitive to warmer subsurface water than IBCAO Ver. 3.0 suggests, which may explain the recent retreat history with massive calving events in 2010 and 2012. The multibeam bathymetry also revealed the past extension and behaviour of Petermann Glacier from a complex seafloor morphology consisting of glacial landforms.



ric and more conventional multibeam technology. If the size and power requirements of a sonar with multibeam capacity could be considerably reduced, gliders may be used for bathymetric mapping. This would extend the mapping range compared to what is achieved with the currently available AUVs.

While the echo sounding technique is constantly being improved, both with respect to performance and availability, mapping of the World Ocean floor is still a slow process. This is particularly true for the sea-ice covered and iceberg infested portions of the oceans and the most remote areas with sparse ship traffic such as the south Pacific and south Indian oceans. The development of unmanned vehicles of various sorts is likely an important element of any plan to fully map the World Ocean floor. In the more populated regions of the World crowd-sourced bathymetry offer a huge potential. Using crowd-sourced bathymetry is not new to GEBCO. Bathymetry provided by the Norwegian company Olex comprised a significant source for the compilation of the International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0 grid released 2012, as well as in the latest *GEBCO_2014* grid. The Olex depth measurements originate from their automatic charting system installed primarily on fishing vessels. Other companies using a crowd source approach philosophy have now also entered the market. Small and easy to install NMEA-loggers storing depths from any ship echo sounder already exist and are being further developed. Such methods could be used on a global scale, through adoption by shipping companies, cruise ship companies, and survey companies for example. IHO has a crowd-source working group with substantial GEBCO engagement. This working group is tasked to draft recommendations for the minimum metadata to be provided along with depth measurements, and discuss available technologies, post-processing, as well as online upload technologies and storage.

The gap between the coastline and where depth measurements exist on the continental shelf is large in several vast remote areas on Earth. Surveying of these areas using conventional methods from ships, and even with AUVs, may be enormously challenging and expensive. LIDAR is highly effective and relatively inexpensive for large scale re-

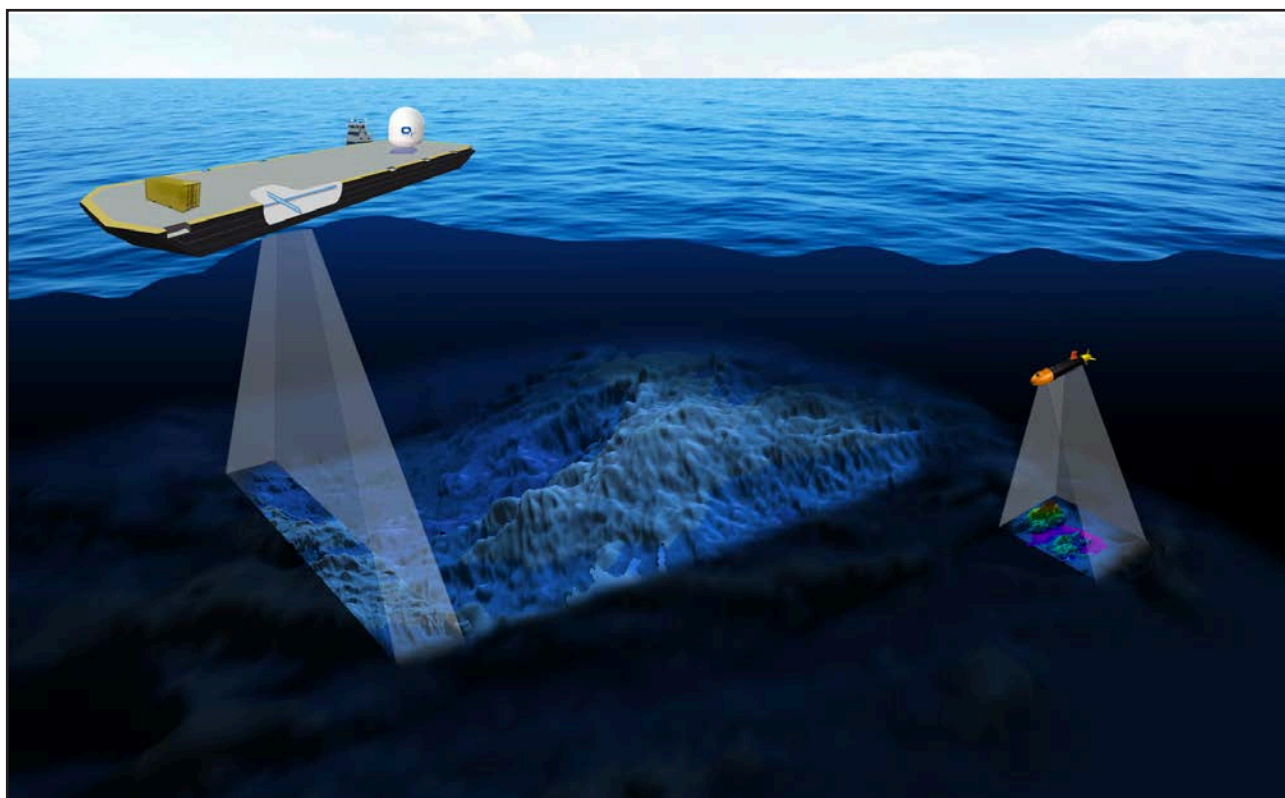


Figure 3.4: The concept of an unmanned mapping barge, monitored by satellite communication and equipped with an ultra-narrow beam deep-water multibeam (left). Such a barge would be able to systematically map the deepest sections of the open ocean from the surface at even higher resolution than 100x100 m. The sub-meter level of detail sometimes needed to investigate small scale processes at the seabed is today only possible to achieve in the deep ocean using AUVs equipped with high-resolution high frequency multibeam systems. These AUVs would serve as excellent complements to the mapping barge, but their present endurance, cost, and swath coverage does not make them the tool for mapping the entire World Ocean floor.

gional mapping, but is limited to areas of relatively clear water. In such remote areas, where other means of seafloor mapping is not easily feasible, bathymetry derived from satellite imagery is very promising. Freely available imagery, such as Landsat 8, as well as commercial higher-resolution satellite images, comprise vast sources of data with global coverage. Conventional “water penetrating” satellite derived bathymetry also requires relatively clear water, but the development of satellite-derived bathymetry methods that are not solely based on the optical spectrum may overcome turbid water issues, though their accuracy and resolution are considerably lower and the method will still be depth limited.

While new mapping efforts will undoubtedly be required, the Seabed 2030 project will also have to bring all available depth measurements together into a database for the compilation of a coherent bathymetric portrayal of the world ocean floor. Therefore, bathymetric post-processing and analyses software, database technology, computing infrastructure, and gridding techniques must be brought into the discussion with respect to available tools and techniques in ocean mapping as well as the latest developments in seafloor mapping technologies. The present GEBCO central bathymetric database as well as databases of Regional Mapping Projects under GEBCO reside on servers at their respective host organizations. Moving towards establishing more Regional Projects at host organizations around the world implies that there may be potential benefits from establishing shared cloud-based infrastructure for data storage as well as for gridding and processing routines (Virtual Research Environments and Infrastructures) that also can become part of new e-learning processes.

The *GEBCO_2014* grid, as well as the grids produced by linked Regional Mapping Projects, are based on vastly heterogeneous source data both in quality and spatial coverage with some areas well mapped while others are poorly mapped. In some areas of the world ocean, much higher resolution final grids would be possible to produce than the *GEBCO_2014* (0.5x0.5 arc min), IBCAO (500x500m), and IBCSO (500x500m) grid. GEBCO’s focus historically has been to produce the best uniform resolution grid of the global ocean. One approach to handle heterogeneous spatial coverage and provide high resolution where it exists is the hierarchy of tiled grids of different resolutions such as employed for the Global Multi-Resolution Topography (GMRT) synthesis (Ryan et al., 2009). Variable resolution grids are another approach but there are no widely-accepted grid formats for variable-resolution grids with resolution steered by the density of the source data. The BAG (Bathymetric Attributed Grid; Calder et al., 2005) is, however, an open grid format and API that Esri, Caris, QPS, and several other software vendors have been implementing for some time, that may be suitable for storing variable-resolution grids. Esri and NOAA NCEI have begun serving BAGs in the cloud as image services along with depth values usually relative to the Mean Lower Low Water (MLLW) datum (NOAA, 2017).

Key considerations made at the FFOFM

- Available commercial and custom-developed AUVs are optimal for high-resolution mapping of smaller areas, but limited with respect to duration, preventing longer (weeks) missions.
- Gliders equipped with multibeam sonars would substantially extend range compared to traditional AUVs, but available multibeam sonars are not yet small enough, and are currently too power-hungry to be installed on gliders.
- Fleets of low maintenance autonomous surface or underwater vehicles may provide a solution to the mapping of remote areas.
- An unmanned mapping barge, monitored by satellite communication and equipped with an ultra-narrow beam deep-water multibeam, would permit systematic high-resolution mapping of the deep world ocean. This is one idea raised to reach the goal of mapping the entire world ocean floor at a minimum resolution of 100x100m.
- Crowd sourcing is a powerful concept in ocean mapping that has a huge potential to substantially boost the targeted mapping, specifically in shallow water, but also in deeper water through adoption by shipping companies, cruise ship companies and survey companies.
- LIDAR bathymetry provides a highly effective and relatively inexpensive approach for large scale regional shallow-water mapping, but is limited to areas of relatively clear water.
- Shallow water bathymetry derived from satellite imagery constitutes a promising technique that may be particularly useful in remote areas where other available mapping methods not are feasible. Derived depths from satellite imagery are not as high quality and accurate as from other conventional mapping methods, but it is certainly better than nothing and has huge spatial coverage.

- A cloud-based infrastructure for the Regional Mapping Projects under GEBCO, and for the central repository as well as for gridding and processing routines, could prove to be beneficial and should be explored.
- Variable resolution grids will be more in demand as the end-user community begins to realize that this approach provides an option to get bathymetric overviews of large areas and details of smaller areas in one convenient database.
- GEBCO could drive the community of software vendors toward a solution, especially as software vendors increasingly see the wisdom of adopting and promoting open standards (e.g., those of the Open Geospatial Consortium or OGC).

3.4. Mapping the world ocean floor

Accessing all existing bathymetric data will go a long way towards filling the gaps in our world ocean coverage. At the moment, however, the mechanisms in place to identify or access these bathymetric datasets are not capable of identifying or gathering all existing bathymetric data. Current barriers (real or perceived) to sharing these data include concerns about national security, sovereignty, liability, loss of profit potential, comprise of strategic or competitive advantage, technical challenges, lack of coordination, desire for anonymity, commercial/legal contract restrictions, and a lack of understanding of the overall benefit to the well-being of our planet and the people on it.

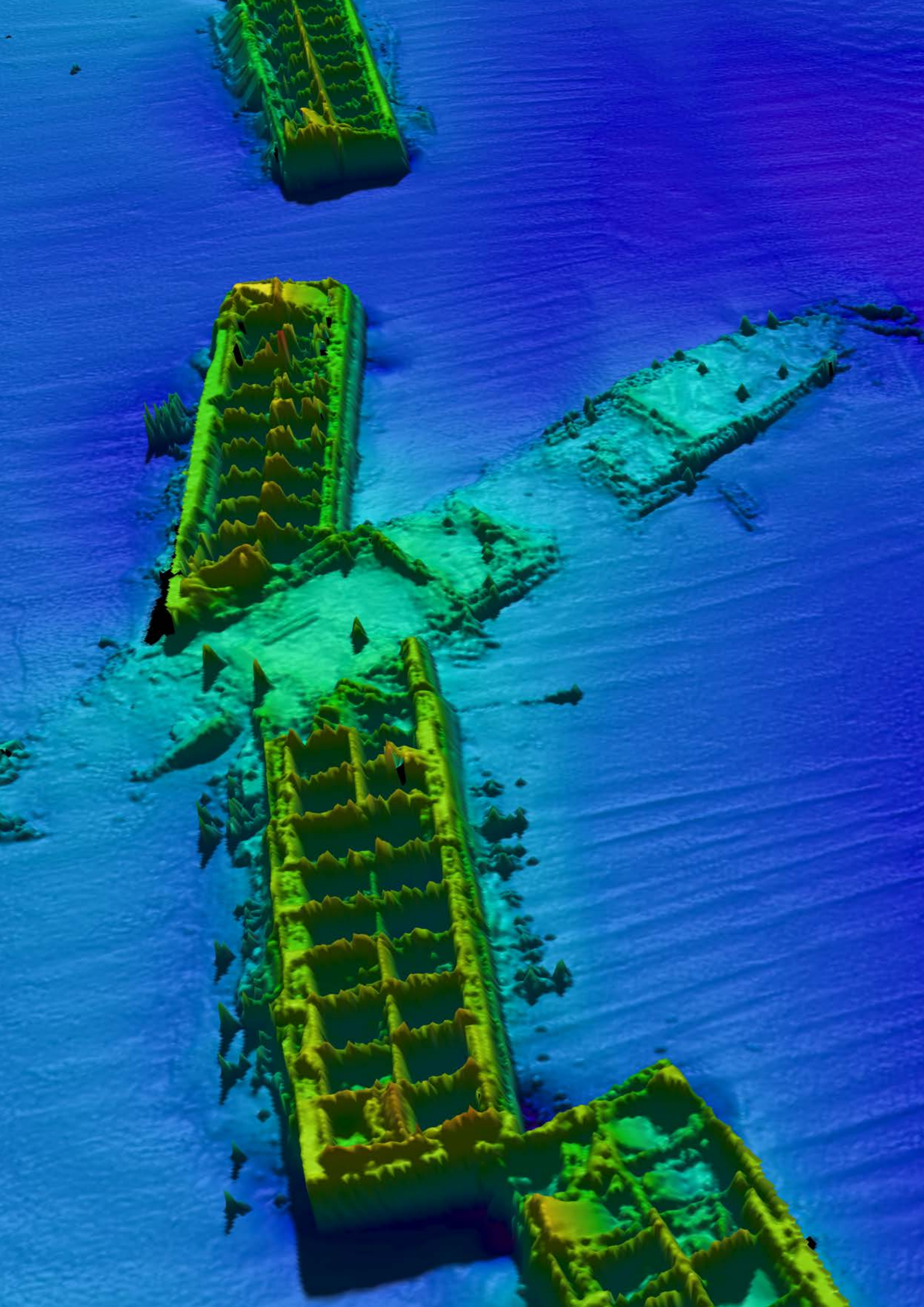
Currently there are probably dozens, if not hundreds of individual databases of bathymetric data in existence. These are largely held by national governments, national oil companies, international oil companies and survey companies, but also include submarine cable companies, deep sea mining companies, research organizations, and individual mariners. In many cases, these data are treated as proprietary and not shared or even known. As a result, to identify and access existing bathymetric data holdings, it is critical that those who hold the data are convinced to share it, even if at a decimated level. The survey industry can play a role here in helping to convince their customers to release their proprietary data and potentially manage the decimation (where necessary) and delivery of these data to the Seabed 2030 project. The IHO Digital Data Center for Digital Bathymetry (DCDB) was established in 1988 and has since the beginning of the 1990s functioned as the principle repository for bathymetric data contributed to the GEBCO project. The IHO DCDB is hosted by NOAA. On behalf of the IHO Member States, the centre archives and shares freely all bathymetric data provided with no restriction by the mapping community. The IHO DCDB is a fundamental resource for the Seabed 2030 project.

Another source of existing data could also be crowd sourced bathymetry. Crowd source efforts to date have largely been regional and focused on the fishing communities, but with the IHO's developing crowd sourced bathymetry initiative and portal, there is a mechanism to expand this concept to a much broader community. After accessing the existing data and identifying the remaining gaps in coverage, we need to fill in the gaps by crowd sourcing, conducting coordinated basin scale mapping campaigns and regional compilations, using satellite derived bathymetry, and fostering innovation of technologies for remotely controlled data collection.

Key considerations made at the FFOFM

- A programme aimed towards the complete mapping of the World Ocean floor must initially identify and access existing bathymetric data from hydrographic offices, industry, research organizations, and individual mariners. The benefits of sharing data must be emphasized.
- Bathymetric gaps can be filled using crowd sourcing, coordinated basin scale campaigns, satellite derived bathymetry, LIDAR bathymetry, regional compilations, and innovations in remotely controlled collection technology.
- Strong partnerships for collecting, sharing, and compiling data are an essential part of a global mapping effort.

High-resolution multibeam sonar image of remains of "Mulberry Harbors" and "blockships" of Omaha Beach in Normandy. The Mulberry Harbors were large (~80 m long) concrete caissons sunk off the beaches of Normandy to provide an artificial harbor during the WWII D-Day invasions. The blockships were old vessels sunk to also provide added protection for the artificial harbor. Two weeks after the invasion a Force 7/8 storm destroyed many of the caissons and blockships off Omaha Beach. Survey conducted by the Center for Coastal and Ocean Mapping, University of New Hampshire and the U.S. Naval Historical Center.





Multibeam control station on Icebreaker *Oden*. Photo: Björn Eriksson

4.0. Status: How much of the World Ocean floor is mapped?

We are used to seeing 3D-models of global terrain in software, on maps, and serving as a base for a multitude of portrayals of our planet. One such example is Google Earth, where the World Ocean floor appears completely mapped to the untrained eye. However, since Google uses some bathymetric products from the GEBCO community, we are more than aware that this is not the case. By zooming into any region of the World Ocean, the patchwork between areas mapped using the modern multibeam techniques, and areas where the bathymetry is just supported by sparse single beam tracklines or low resolution bathymetry derived from satellite altimetry, are readily seen. Furthermore, maps showing the global coverage of ship tracks along which bathymetry data that has been collected are often shown at a scale making it appear like there is a dense network, or even near complete coverage of ship tracks while in reality this is far from the case.

GEBCO's latest product is the *GEBCO_2014* grid (Weatherall et al., 2015). This is a global terrain model gridded at a regular interval of 30 arc-seconds (Figure 4.1). The Arctic Ocean in *GEBCO_2014* is comprised of a separate grid provided by the International Bathymetric Chart of the Arctic Ocean (IBCAO) and the Southern Ocean consists of a similar grid created by the International Bathymetric Chart of the Southern Ocean (IBCSO), two Regional Mapping Projects working within GEBCO. *GEBCO_2014* also includes the GMRT compilation of multibeam bathymetry from research expeditions throughout the global oceans (<http://www.marine-geo.org>), which is the largest source of multi-beam derived soundings contributing to the *GEBCO_2014*. In addition, some regions

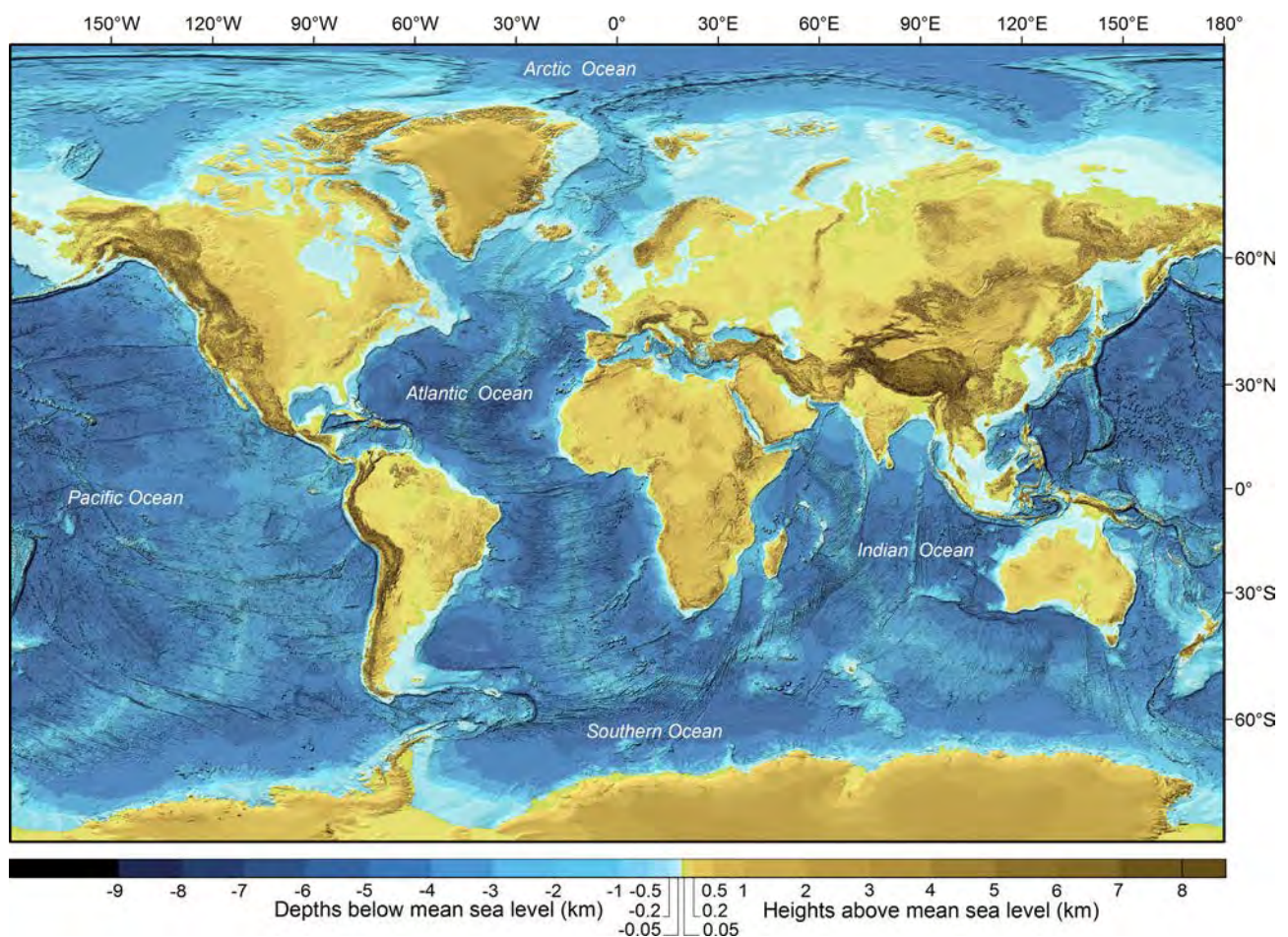


Figure 4.1: A shaded relief of the *GEBCO_2014* grid. Figure is from Weatherall et al. (2015).

are covered by external projects with similar setup as IBCAO and IBCSO. These include EMODnet covering European waters (www.emodnet-bathymetry.eu), and the Baltic Sea Bathymetry Database (<http://data.bshc.pro>) (Hell and Öiås, 2014). The *GEBCO_2014* grid was based on all publically available bathymetric data at the time of compilation (Figure 4.2). However, the available bathymetric data provided depth control points to only 18% of all the 30 arc-second (926m at the equator) grid cells in the *GEBCO_2014* product (Weatherall et al., 2015). In other words, the vast majority of the World Ocean is not even mapped at a resolution of about 1 km using the echo sounding method.

Between tracklines, large areas of the *GEBCO_2014* grid are based on interpolation guided by satellite-derived gravity data, except in most of the two Polar Regions where sea ice precluded the use of this method. *GEBCO_2014* started with the base grid from the previous *GEBCO_08* version, which included the altimetric-derived bathymetry model *SRTM30_PLUS* (Becker et al., 2009). The altimetry method has been crucial for seafloor mapping of the

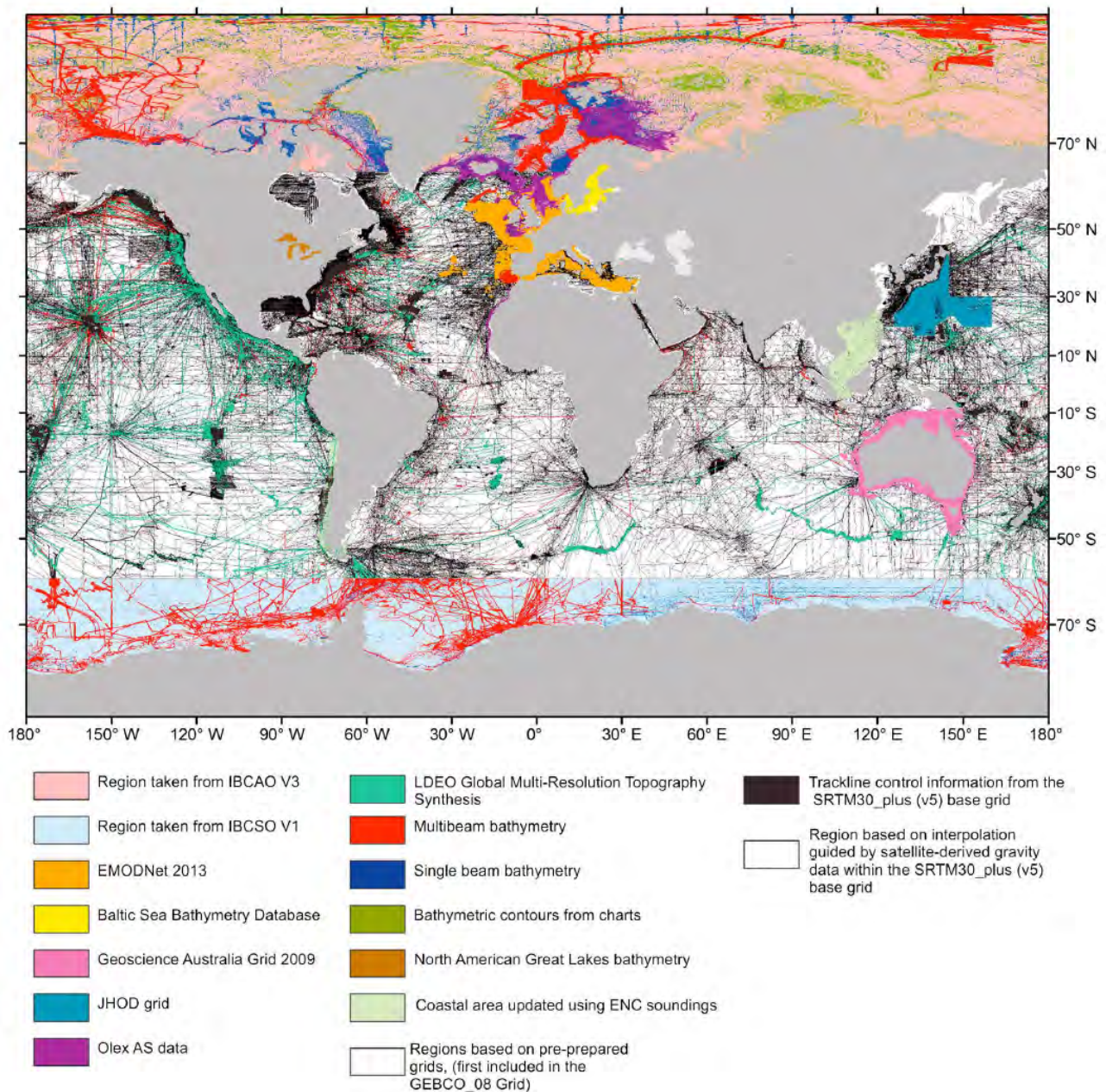


Figure 4.2: *GEBCO 2014* bathymetric data coverage. At this scale the World Ocean appears much better covered with ship soundings than it is. The fact is that the available bathymetric data used to compile *GEBCO_2014* provided depth control points to only 18% of all the 30 arc-second (926 m at the equator) grid cells. Figure is from Weatherall et al. (2015).

remote and deep parts of the world ocean because it is capable of generating general estimations of depths from the satellite-derived gravity field allowing the filling of gaps between sparse ship soundings (Smith and Sandwell, 1997). Satellite altimetric-derived bathymetry is far less precise and reliable than echo sounder-derived data, but the method is objective and superior in most non sea-ice covered areas to interpolation between sparse ship tracks by mathematical algorithms and hand-contouring. Altimetry-derived data are particularly good for mapping tectonic-scale features such as so-called “first-order” spreading ridge segments and the fracture zones that offset them, but much finer-scale features and accurate depths are often difficult to derive.

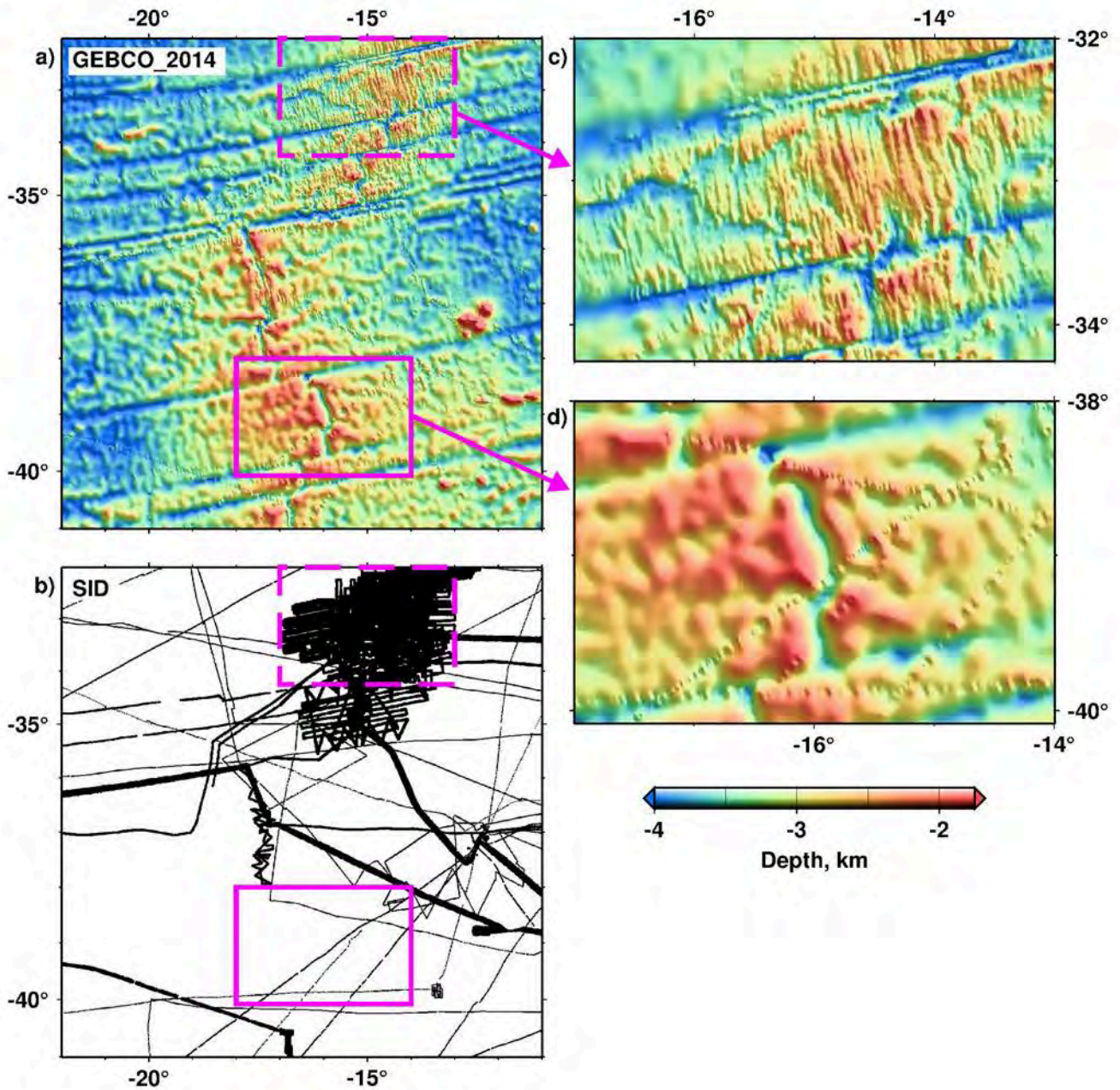


Figure 4.3: The GEBCO_2014 grid model over a portion of the southern Mid-Atlantic ridge where multibeam bathymetry is blended with a coarser grid based on interpolation using sparse single beam echo soundings guided by satellite altimetry. a) Overview of the Mid-Atlantic ridge section. b) The ship track lines along where bathymetric soundings were gathered and used in the model. c) An area that has been surveyed using multibeam. Details in the ridge morphology are readily evident in the incorporated multibeam survey. d) A segment of the spreading ridge where the depths estimated primarily from satellite altimetry. Only a hint of the ridge morphology is seen. The reason for the lack of detail in d is that the satellite altimetry cannot resolve small features due to the altimeter track spacing, and a physical limitation of the gravity method known as downward continuation. Figures from Weatherall et al. (2015).

The resolution of a bathymetric model is a function of the underlying data density, i.e. the coverage of satellite tracks for depth estimates and ship soundings. Multibeam surveys collect depth measurements at very high density and may be designed with overlapping swaths to provide full map coverage. When multibeam data are incorporated into a bathymetry model, their high data density improves the resolution of seafloor details (Figure 4.3). If we only display the multibeam bathymetry data included in the *GEBCO_2014* grid, the view is substantially less impressive than when all bathymetric data are shown compiled together (Figure 4.2. versus 4.4). The above highlights the need for increased bathymetric mapping programmes, specifically including the acquisition of high resolution multibeam.

Through analyses of the present GEBCO bathymetric database, we are able to make a first-hand approximation of the mapping effort needed if we want to obtain a continuous grid of bathymetric information at the resolution and

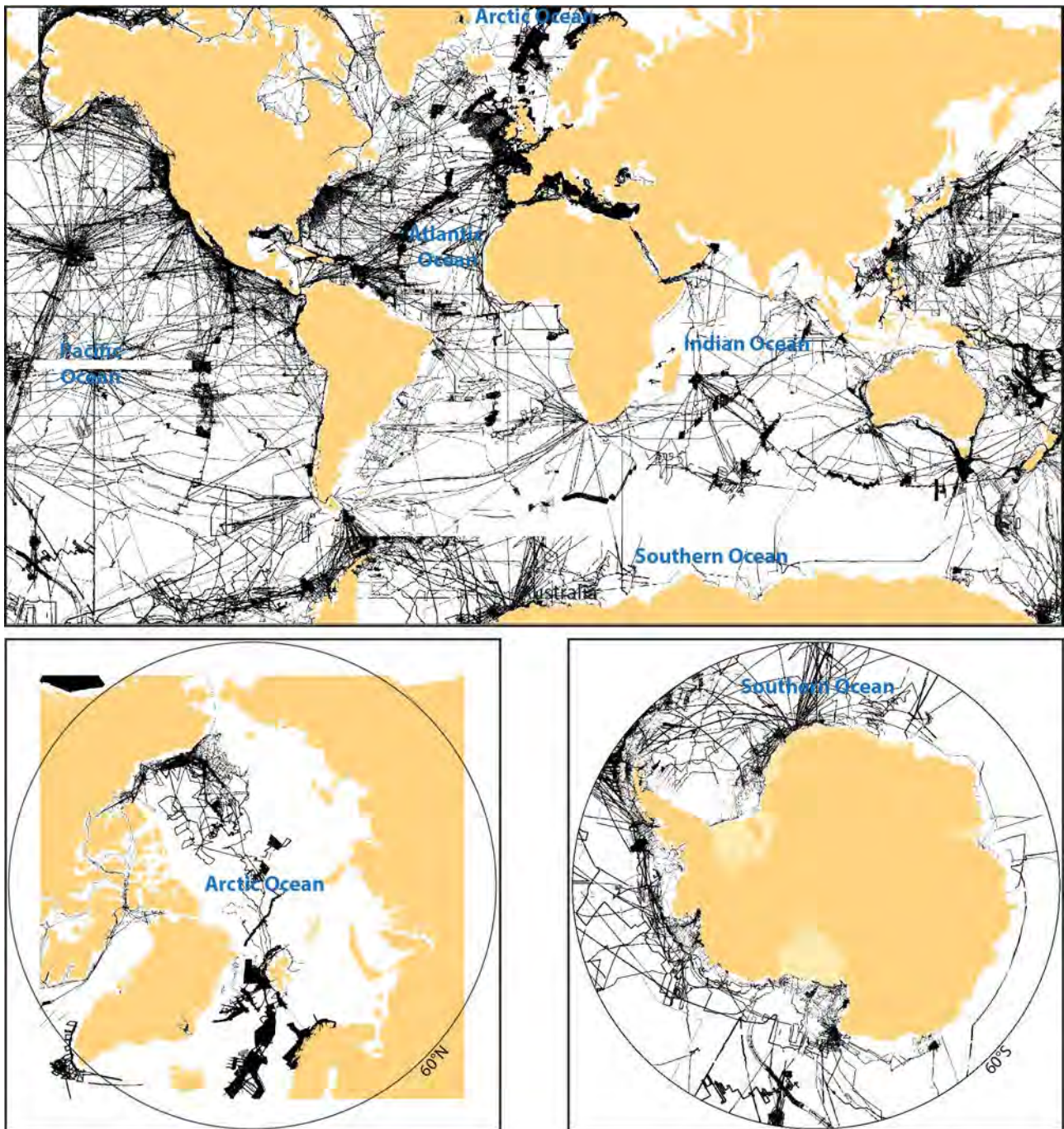


Figure 4.4. Multibeam bathymetry included in the *GEBCO_2014* grid.

precision that modern multibeam sounders offer (Weatherall et al., 2015). In order to assess this, *GEBCO_2014* grid nodes originating from altimetry have been selected using the Source Identification (SID) grid produced during the compilation of *GEBCO_2014*. These are converted to surfaces, and then classified in water depth intervals on the basis that these classes represent broad geomorphological features (continental shelf, continental slope and deep sea area) and that modern multibeam techniques and coverage are highly dependent on the water depth.

In order to compute an estimate of surveying effort given in Table 4.1, the following assumptions were made: 1) for each water depth interval, the average represents the distribution, 2) this average water depth is multiplied by a factor representing the projection of the swath width of a multibeam system on the seafloor- a conservative approach is to estimate that modern multibeam echo sounders survey 3.5 times the water depth, and 3) the speed of the survey boat is considered to be 7.5 knots (~10km/h). However, while 7.5 knots is conservative, it is purposely so as it does not take into account manoeuvring, meteorological and oceanic adverse conditions or deployment of auxiliary sensors (tide gauge principally in shallow waters, sound velocity profiling). Furthermore, the analyses have been carried out using the *GEBCO_2014* grid with a resolution of 30 arc seconds as a base and the grid cells with depth values from single beam echo soundings have been considered mapped. For this reason, the result is underestimating survey time rather than overestimating it.

Table 4.1. Survey efforts needed to map the world's ocean floor.

Water depth interval (modal water depth)	Average water depth (km)	Proportion of water depth (%)	Proportion of uncharted surface – this interval	Proportion of uncharted surface (overall ocean)	Cumulated surface of the GEBCO 2014 grid nodes originating from interpolated driven by altimetry (km ²)	Remaining effort (years) (for one survey boat)
>3000	4	75.3	85	69	230,910,385	188
3000–1000	1.5	13.0	72	15	34,143,193	74
1000–200	0.4	4.4	66	7	10,654,693	86
0–200	0.1	7.3	71	9	18,995,603	619

The results show that ~970 years would be required to survey the area of the *GEBCO_2014* grid today unconstrained by any sounding, and of these, ~620 years consist of the shallow areas between 0–200m water depths. In order to bring this value in perspective, we can consider that there are currently more than 700 multibeam systems on survey boats from national hydrographic offices, research institutions or private entities in the world (as estimated in 2003 by the IHO). Understanding that this approximation is based on idealistic assumptions, the order of magnitude for the remaining surveying effort appears to be a reachable goal. Moreover, our estimation is based on GEBCO's bathymetric database at the time of the compilation of the *GEBCO_2014* grid. While we believe that this is the most complete bathymetric database available, we are fully aware of that it is far from including all bathymetric data that has been collected. This highlights the need for increased national and international collaboration and coordination between bathymetric mapping initiatives to jointly map the World Ocean, the goal of Seabed 2030.



Launch of survey boat *RV Skidbladner* to multibeam map shallow near shore areas in Petermann Fjord, Northern Greenland. Photo: Björn Eriksson

5.0. Seabed 2030: The road towards mapping the World Ocean floor

The goal of the Seabed 2030 project is, by 2030, to provide the world with a high-resolution map of the World's Ocean floor, with no feature larger than 100m left unmapped. To achieve this, Seabed 2030 will compile all available bathymetric data into a high-quality, high-resolution digital model of the World Ocean floor. Bathymetric data and survey activities are dispersed across many countries and organizations, including governmental agencies, industry, academia and research organizations. Seabed 2030 will act as a coordinating body for aggregating existing data and prioritizing survey operations through the development of tools and products that highlight gaps in data coverage. Inspiring new mapping expeditions, targeting specifically unmapped areas will constitute one of the primary objectives of Seabed 2030.

The Seabed 2030 project design is based on GEBCO's experiences from successfully working with Regional Mapping Projects that contributed substantially to GEBCO by delivering regional bathymetric gridded compilations as well as the recent GEBCO_HiRes initiative. Within Seabed 2030, the entire World Ocean is divided into regions, for which data assembly, processing, and compilation fall under the responsibility of a dedicated team of experts based at home institutions. For each region, an Editorial Board will be established consisting of local experts and representatives of mapping activities. The Editorial Board has two main tasks: facilitate assembly of existing bathymetric data and helping to coordinate new surveys. It is through these Editorial Boards that new mapping campaigns and expeditions targeting unmapped regions may be initiated through a bottom-up approach. The background and rationale behind the Seabed 2030 project design is described in this section along with how the project is integrated into the GEBCO structure.

5.1. Background: The concept of Regional Mapping Projects and the Sub-Committee on Regional Undersea Mapping (SCRUM)

A Regional Mapping Project is a focused effort aiming to gather all bathymetric data into a digital database from a specific ocean region to produce the best possible gridded bathymetric model. The first Regional Mapping Project working along these lines was the International Bathymetric Chart of the Arctic Ocean (IBCAO), which was initiated as an IBC (International Bathymetric Chart) under IOC in St Petersburg, Russia, 1997 (Macnab and Grikurov, 1997). Previous IBCs worked along traditional approaches involving production of classical bathymetric contour maps. An Editorial Board was formed for IBCAO in St Petersburg consisting of key persons from nations with specific interest in the Arctic Ocean. The working "home" of IBCAO became Stockholm University, Sweden, where one person was fully committed to work on assembling all bathymetric data provided by the involved nations through the IBCAO Editorial Board, led by a Chairman. In addition, technical support staff available at the university as well as students assisted the work, which consisted of organizing the data into a database as well as merging and cleaning the data.

The first bathymetric grid produced by the IBCAO project was released in 2000 (Jakobsson et al., 2000). The most recent version 3.0 released 2012 (Jakobsson et al., 2012) is included in the *GEBCO_2014* grid to represent the Arctic Ocean (Weatherall et al., 2015). The gridding concept applied by IBCAO, from bathymetric data preparation, to gridding and quality control, is shown in Figure 5.1.

At a GEBCO Guiding Committee (GGC) in Silver Spring, Maryland, USA in May 2009, it was decided that a new Sub-Committee was required to coordinate, encourage, and provide an interface with the various regional mapping efforts being conducted by IOC, IHO and others. The sub-committee was proposed and later adopted under the name of SCRUM (Sub-Committee on Regional Undersea Mapping). During GEBCO's annual meetings, SCRUM has served as a forum where coordination and exchange of experiences has taken place between active Regional Mapping Projects. The International Bathymetric Chart of the Southern Ocean (IBCSO) gained momentum through discussions and exchange of experiences taking place within SCRUM. As a result of support from the

Nippon Foundation, and with a project home hosted by Alfred Wegener Institute, IBCSO released Version 1.0 of a gridded bathymetric compilation at 500x500m in 2013 (Arndt et al., 2013).

The concept of Regional Mapping Projects has proven successful. With respect to their operation and success, from experiences shared within SCRUM, we conclude the following:

1. An Editorial Board consisting of members with interest in a specific ocean region should be established and form the broad base for the bathymetric data gathering, assembly, integration and synthesis. The Editorial Board should be led by a Chairman.
2. A committed “home” institute should be established for a mapping project focusing on assembling bathymetric data from a specific region. The selected home should have a strong capacity within the field of ocean mapping and be internationally recognized in that capacity.
3. There must be human resources assigned to work on the bathymetric data gathering, assembly, integration and synthesis at the home institute/centre. This includes leadership, networking with data providers, database administration, bathymetric cleaning, merging and compilation as well as product evaluation.

5.1.1. The concept of GEBCO_HiRes

The concept of producing a higher resolution GEBCO bathymetry product has been discussed within the GEBCO community for several years, with the concept of “GEBCO_HiRes” first introduced in 2011 and a working group under SCRUM formulated at the annual GEBCO meeting in Venice in 2013. This concept presented a solution to the technical challenges of the sparse data coverage by leveraging the infrastructure of the Global Multi-Resolution Synthesis (GMRT, Ryan et al., 2009) to present multi-resolution data seamlessly integrated into a tiled set of gridded values. The proposed strategy for “GEBCO_HiRes” leveraged this technical infrastructure to assemble data of variable resolution into a new high-resolution GEBCO product. The source data for this product would include the primary content processed and curated for the GMRT which is derived from raw swath sonar data archived with the World Data Center at NCEI, as well as gridded data sets from the international community.

The experience of these prior syntheses efforts aimed to preserve the full native resolution of multibeam bathymetric data indicated clearly that significant human resources are needed. Work related to transformation of data from raw proprietary acquisition formats to the desired high-quality gridded data products is usually underestimated. In addition, navigation cleaning, sound velocity adjustments, and extensive sonar ping editing are commonly required and are manpower intensive. For example, a rough estimate of the person time for data processing represented by the swath sonar compilation of the GMRT is 20 person years (close to 1000 cruises processed at roughly one week/cruise conservative estimate). This content provides an important foundational dataset to leverage for the mapping goals of Seabed 2030.

From the concept of the GEBCO_HiRes, and the example of the GMRT synthesis we conclude the following:

1. Human resources needed for data cleaning and editing increase greatly as the desired data resolution increases and much greater manpower will be required to support the Seabed 2030 project than has been available for the existing GEBCO compilations.
2. Existing cleaned and processed swath sonar data compilations are of high value and can be leveraged to advance the mapping goals of Seabed 2030.

5.2. Seabed 2030 structure

5.2.1. Regional Data Assembly and Coordination Centre (RDACC) and Global Data Assembly and Coordination Centre (GDACC)

Building on GEBCO’s successful experience of working with Regional Mapping Projects, the Seabed 2030 project is based on the establishment of four Regional Data Assembly and Coordination Centres (RDACCs), each having a defined ocean region of responsibility (Figure 5.2). The division into four regions is based on ongoing regional mapping activities and collaborative networks between institutions within GEBCO. The area of the IBCAO has been increased to encompass the northern Pacific Ocean and the area of the IBCSO has an extended northern boundary from 60°S to 50°S. From this follows two RDACCs, one for the North Pacific-Arctic Ocean region and the other for the Southern Ocean. The remaining part of the World Ocean is divided into a South and West Pacific

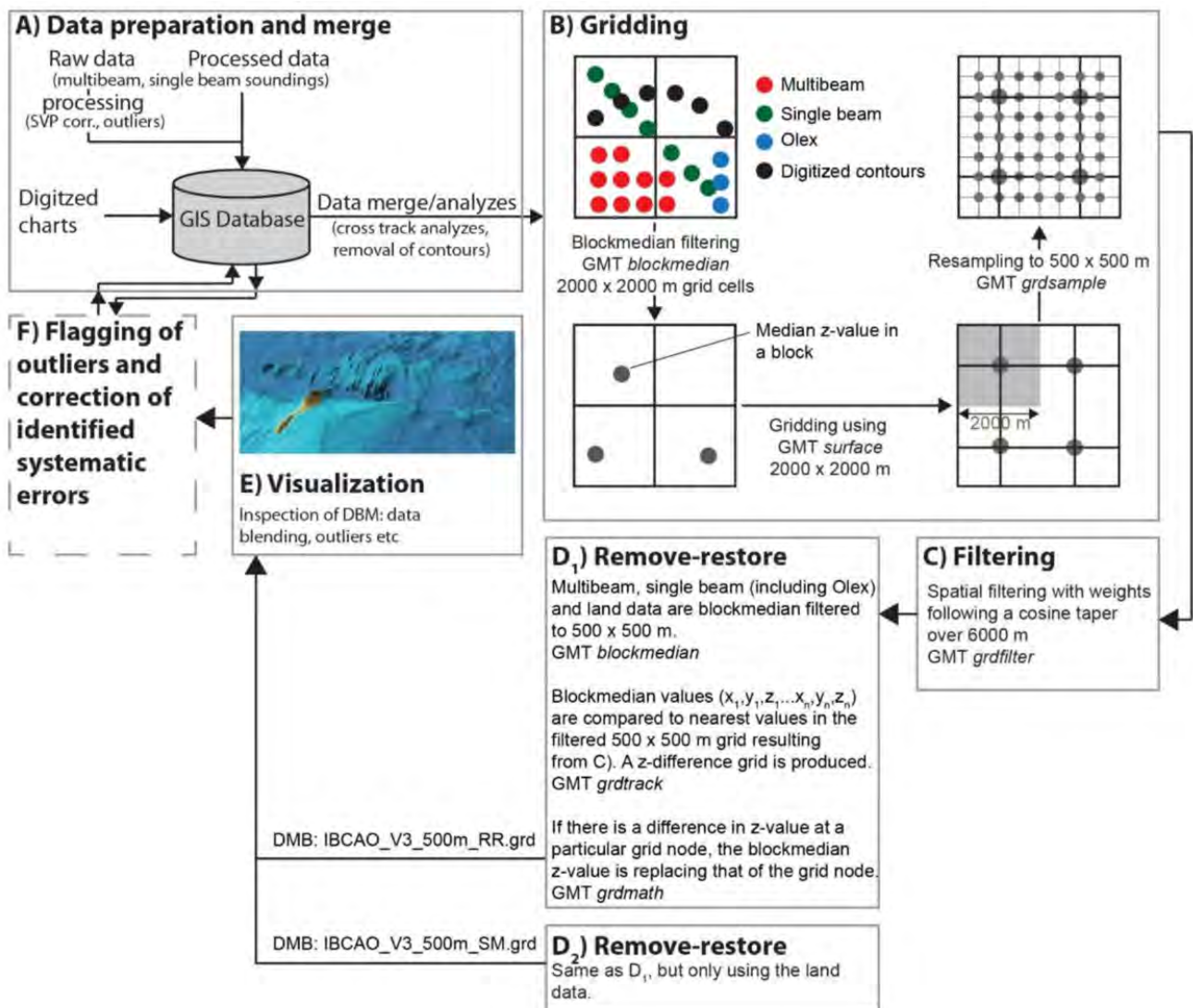


Figure 5.1. The technical procedure applied in the IBCAO project, from when data have been contributed by the involved parties through their Editorial Board representatives to the final production of gridded digital bathymetric model (here referred to as a DBM) representing the seafloor. The figure is from Jakobsson et al. 2012.

Ocean region and an Atlantic-Indian Ocean region (Figure 5.2.). Each RDACC is comprised of committed Seabed 2030 personnel who are responsible for championing and coordinating mapping activities within their prescribed oceanic region as well as for bathymetric data assembly, integration and synthesis.

An Editorial Board will be established along with each RDACC, which should consist of key representatives for the mapping activities within the ocean region of responsibility. Since the RDACCs responsibility will encompass huge areas of the World Ocean it is, however, not feasible that each country bordering the oceanic region is represented by an Editorial Board member. The two RDACCs for the North Pacific-Arctic Ocean and the Southern Ocean will be formed from IBCAO and IBCSO respectively and benefit from the existing established Editorial Boards, which have to be expanded to include members representing the larger oceanic areas of responsibility. It should be emphasized the RDACCs must strive to avoid duplication of other ongoing mapping activities, such as, for example, EMODnet, and work towards fostering a close collaboration for the most efficient use of global resources.

The output from the RDACCs will be provided to a Global Data Assembly and Coordination Centre (GDACC), which will be established to be responsible for producing centralized GEBCO/Seabed 2030 products and centralized data management for non-regionally sourced data that could, for example, be bathymetric data provided by industry working on global scales. Distribution of the final bathymetric products to end users will fall under the

GDACC’s responsibility. Furthermore, it is envisioned that the GDACC will administer seed project resources that will accelerate and facilitate the Seabed 2030 activities.

5.2.2. Seabed 2030 within the GEBCO framework

The Seabed 2030 project is designed to sit within the existing and well-functioning IHO-IOC GEBCO framework making full use of existing bodies such as SCRUM, the Technical Sub-Committee on Ocean Mapping (TSCOM) and also the Sub-Committee for Regional Undersea Feature Names (SCUFN) (Figure 5.3). This structure will ensure a solid governance of the Seabed 2030 project and benefit from the large networks provided by the IHO and IOC. This is particularly important since all hydrographic offices of IHO’s member states, having the mandate to map within their countries’ territories, constitute critical partners. Without the collaboration of the world’s hydrographic offices, there is little chance of reaching the goal of portraying the World Ocean bathymetry from the coast to the deepest trench. IOC is a functional self-standing body within UNESCO with a mandate to organize marine science within the UN system. This provides the Seabed 2030 project with a strong global network within the marine scientific community, including both bathymetric data users and potential providers.

SCRUM will provide the forum where the Editorial Boards of the ocean regions falling under the responsibility of the four RDACCs can meet yearly and exchange ideas as well as improve coordination on a global scale. TSCOM will continue to serve as forum for technical expertise, which will feed into the Seabed 2030 project. SCUFN’s work in naming newly-discovered seafloor features is important as it helps to highlight new bathymetric data from previously poorly mapped regions of the World Ocean. The preambles from the Terms of Reference and Rules of Procedure of TSCOM, SCRUM and SCUFN are included below in order to provide the history and information about these GEBCO Sub Committees that will support the Seabed 2030 project.

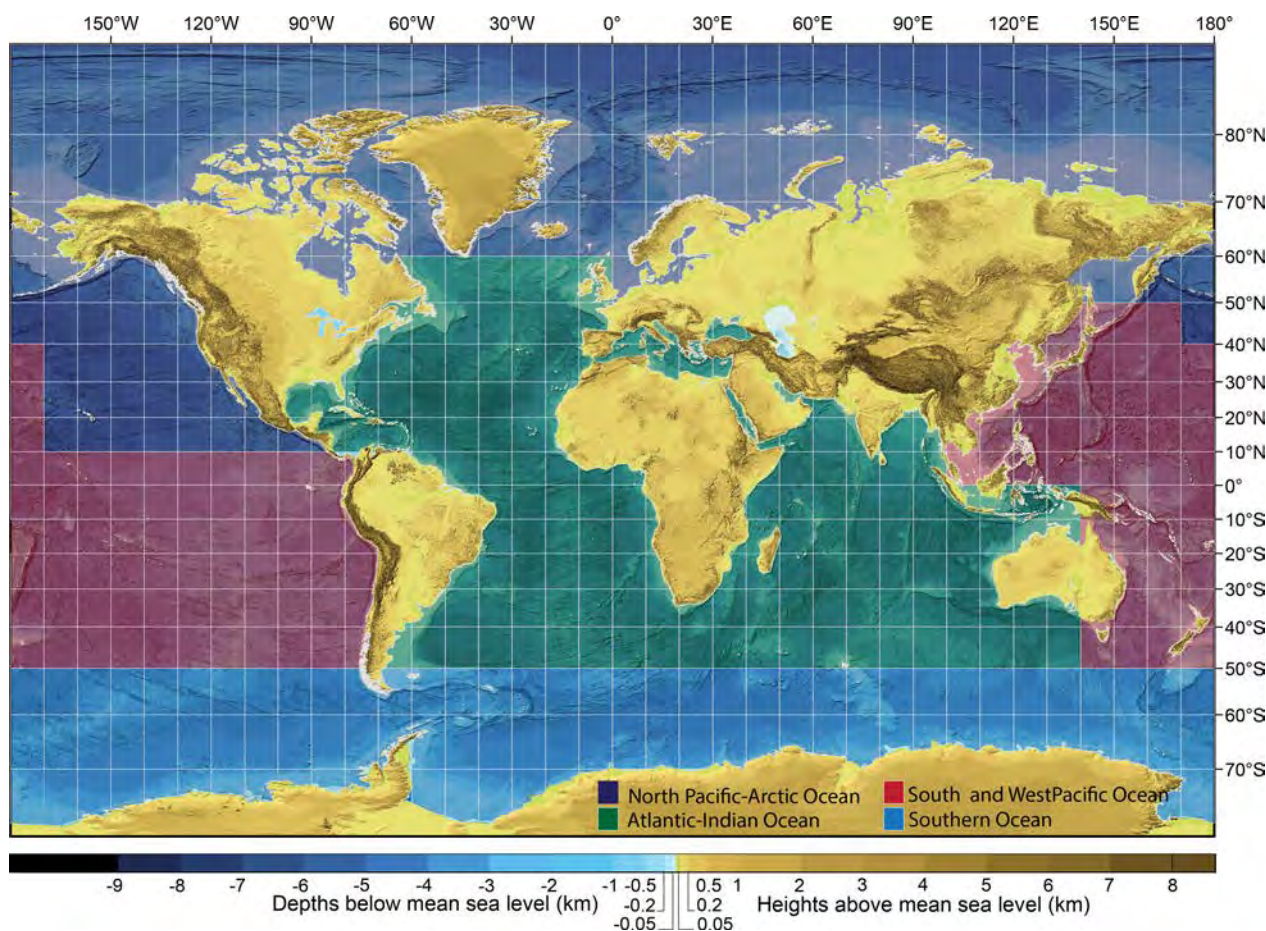


Figure 5.2. The World Ocean divided into four regions, each falling under the responsibility of a RDACC. This division is based on ongoing activities within GEBCO and to keep the number of RDACCs on a fundable level.

TSCOM: Preamble from Terms of Reference and Rules of Procedure

In May 1977, at the GEBCO Guiding Committee (GGC) IV, the Guiding Committee decided to form a small Sub Committee on Digital Bathymetry (SCDB) to “investigate... the question: Is there an advantage [in] having digital bathymetric data?” This led to a very positive report being submitted to the Guiding Committee in May 1983, the formation of a larger and more representative Sub Committee, with revised Terms of Reference, and a recommendation leading to the establishment of the IHO Data Centre for Digital Bathymetry. Over the years the annual meetings of this Sub Committee have gained increasing recognition as being of growing importance to the scientific community. From a meeting of five experts in 1984, the group had grown to thirty-six experts from twenty-five groups in thirteen countries by June 1999. By 2006 it was recognized that all GEBCO products and nearly all cartographic activities are “digital”, and after the SCDB XXII meeting in Bremerhaven, Germany it is proposed that, as part of the revision of the GEBCO structure, the sub-committee be renamed the “Technical Sub-Committee on Ocean Mapping” (TSCOM).

SCRUM: Preamble from Terms of Reference and Rules of Procedure

At a meeting of the GEBCO Guiding Committee (GGC) (and one IHB representative) in Silver Spring, Maryland, USA on 18–29 May 2009, it was decided that a new Sub-Committee was required to coordinate, encourage, and provide an interface with the various regional mapping efforts being conducted by IOC, IHO and others. In addition, such a Sub-Committee on Regional Undersea Mapping (SCRUM) could function as an Editorial Board endorsing regional products to be included in GEBCO. These Terms of Reference and Rules of Procedure were presented to the full GGC at the annual meeting on 1–2 October 2009 in Brest, France, and the creation of the Sub Committee was approved on an interim basis. At the following GGC meeting in Lima, Peru, on 18 September 2010, the Committee approved the formation of SCRUM on a permanent basis subject to the approval of IOC and IHO. Authority for the creation of this Sub Committee is included in the GGC Terms of Reference, § 8, which states that “The GEBCO Guiding Committee shall direct and monitor the work of the GEBCO Sub Committees and Working Groups; propose to IHO and IOC the creation or termination of Sub Committees, and create, maintain and terminate Working Groups as deemed necessary.”

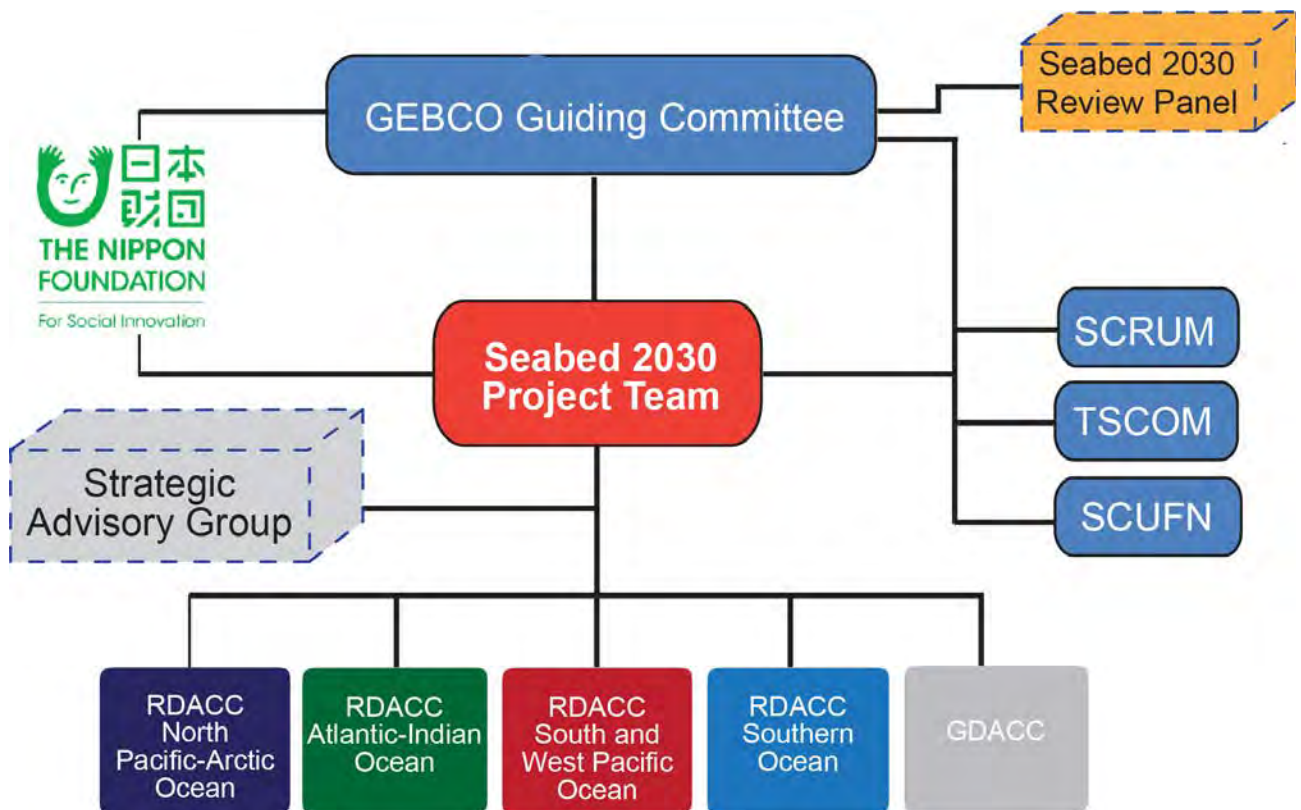


Figure 5.3. Structure of Seabed 2030.

SCUFN

SCUFN lacks a preamble in the Terms of Reference and Rules of Procedure. However, the main tasks of SCUFN may be summarized as maintaining and making available a digital gazetteer of the World Ocean undersea feature names, generic feature type and geographic position of features on the seafloor. Each undersea feature name proposal must be based on bathymetry that clearly portrays the feature. Today this usually means high-resolution multi-beam bathymetry. This implies that SCUFN gathers data primarily from poorly mapped areas of the World Ocean.

5.2.3. Strategic Advisory Group and Review Panel

A Strategic Advisory Group will be established to ensure that the Seabed 2030 leadership has access to required external expertise in making decisions, planning and implementing the work plans (5.3). This group is responsible for providing independent strategic and technical advice from the wider mapping community outside of GEBCO, implying that it must include members from industry, academia, and government. In addition, a Review Panel is proposed to form a part of the Seabed 2030 governance structure to provide the GEBCO Guiding Committee with independent input and review of the progress and deliverables from the Seabed 2030 project. The same applies to the Review Panel as for the Strategic Advisory Group in that it must include members from the key sectors of society with an interest in ocean mapping. Terms of references for the Strategic Advisory Group and the Review Panel will further outline the roles of these two bodies.

5.3. Seabed 2030 Milestones

A set of major initial Seabed 2030 milestones are listed in this *Road Map for Future Ocean Floor Mapping*.

1. Establish the Seabed 2030 project structure including the Strategic Advisory Group and Review Panel.
2. Establish the four RDACCs and the GDACC.
3. Develop a clear set of deliverables/standards for the initial teams at the RDACCs with respect to interoperable formats, technology/services, and products. This should include products and services that highlight data coverage and data gaps for each region, and can/should precede full data assembly/integration to inform ongoing mapping efforts to ensure that we map the gaps.
4. Develop outreach materials tailored to different target groups focused on soliciting data contributions, broadening awareness of Seabed 2030, and capacity building.
5. Establish Editorial Boards for each region and begin assembling data and products.
6. Display data coverage/gaps through web services in a map interface on the Seabed 2030 site to help with outreach for additional data contributions.
7. Establish the format for Seabed 2030 technical project meetings to review accomplishments and revise technical strategy/tools as necessary. Refine overall technical strategy as necessary.
8. Develop strategies and mechanisms to link the Seabed 2030 project with ongoing regional mapping activities such as for example the EMODnet, GMRT, Esri Ocean Basemap/Living Atlas, and Galway Statement implementation initiatives.

Photo-mosaic of hydrothermal vents from Lau Back-arc Basin, southwest Pacific Ocean, acquired during the R/V Falkor expedition FK160407 in 2016. The photos were taken at >2100 m water depth using a Canon EOS Rebel T5i Digital Camera mounted on the ROV ROPOS. The mosaic was retrieved from the Marine Geoscience Data System archive: <http://www.marine-geo.org>. Investigator: Charles Fisher, Penn State University.





Footage from Timor Sea – <https://schmidtocean.org/cruise/timor-sea-reef-connections>. Photo: SOI/AIMS/Andrew Hayward

6.0. Identified Challenges

6.1. Mapping the gaps

There is no doubt that the mapping goal of Seabed 2030 presents a significant challenge considering that our analysis in section 4 shows that ~970 years would be required to survey the completely unmapped part of the World Ocean using one modern multibeam vessel. The estimated 970 years does not even account for the fact that the quality of the bathymetric data varies substantially and that significant portions of the ocean floor must be remapped to meet modern standards. Even if more bathymetric data exist than used in our analyses, the Seabed 2030 mapping goal can only be achieved if new field mapping projects are initiated by many parties using many vessels.

Crowd sourcing has proved to be a very powerful way to continuously add to the mapped portion of the World Ocean. Olex™ and TeamSurv™ are two examples of companies that have shown how fishing vessels and small pleasure boats equipped with echo sounders are extraordinary resources able to constantly “map”. The key to get all to contribute and share their data has been that something must be offered in return for doing so. The return from Olex™ and TeamSurv™ has been in the form of providing the contributors with better maps that, for example, help fishermen improve their fishing, divers find better dive sites and recreational boaters avoid running aground. However, crowd sourced bathymetry is today only effective for mapping the shallow continental shelf waters where most of the fishing and leisure boats sail with sonars that are able to collect bathymetric data. There are also data quality issues with crowd sourced bathymetry, but the huge number of contributed soundings have, to some extent, helped to filter out the noise. The largest industry fishing vessels may have low frequency echo sounders that perhaps reach about 3000 m water depth, but practically no non-survey or research vessels have a full ocean depth echo sounders installed. Considering that 50% of the World Ocean is deeper than 3200 m (Figure 6.1), more than half is excluded from the current “crowd.” But this would change if more vessels are equipped with deep water echo sounders. Crowd source bathymetry is a phenomenal resource that has huge potential.

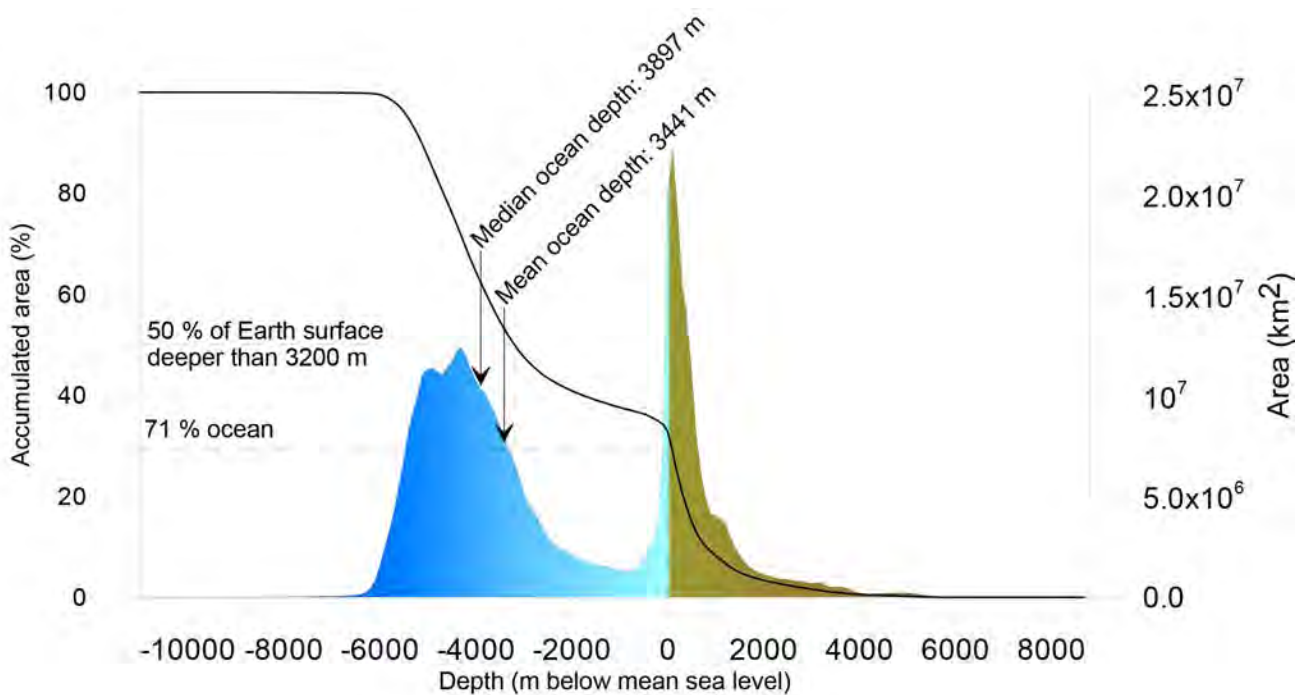


Figure 6.1. World Ocean hypsometry (area distribution versus depth and height) based on the GEBCO_2014 gridded bathymetric model. Modified from Weatherall et al. (2015).

To meet this challenge, Seabed 2030 will create a working group with the aim of drafting a series of programmatic guidelines, included in a white paper, to be submitted to national and international funding agencies. The goal is to promote the opening of funding opportunities and programmes for mapping expeditions and new crowd source initiatives that support the complete seafloor mapping by 2030.

6.2. Bathymetry from sensitive areas

There are several regions of the World Ocean where bathymetric information may not be easy to get for reasons that may be considered political, for example areas where disputes over countries' territorial waters or exclusive economic zone (EEZ) exist. In other international regions of the ocean, the offshore oil and gas industry may not be willing to share bathymetric data collected for exploration purposes due to competitive reasons and/or client confidentiality. Furthermore, the depth and shape of the ocean floor are considered information of military strategic importance in some countries, and high-resolution bathymetry data are therefore classified and access is restricted by national laws. All this presents a major challenge for Seabed 2030, and capacity building will be critical for addressing it. The international network of scholars from the Nippon Foundation-GEBCO postgraduate programme on ocean bathymetry hosted by the University of New Hampshire, USA, will continue to become an important resource in addressing this challenge. This programme, which began in 2004, has developed a network of more than 78 students from all over the world who will be important advocates for Seabed 2030, particularly as they move into senior positions within their national and academic organizations. Providing outreach materials and clear messaging will be important to facilitate their efforts. We anticipate that as more data are contributed to Seabed 2030, and its products are broadly distributed and recognized, there will be an increased willingness of new groups to contribute data. A critical aspect of the strategy is to establish early adopters, who will help create systems, processes, messaging and peer pressure that will help and encourage others to eventually follow.

6.3. Keeping up with technology

Ensuring that our strategy evolves to make use of new computing technologies, e.g. web services, cloud storage and computing, is a challenge that all long-term project face. This will be addressed through ongoing complementary efforts of Seabed 2030 team members as well as through dialog and partnership with industry. The most critical step we can take is to make sure that our processes, products and services are forward-looking and that our efforts will be well-positioned to make use of new technologies as they become available.

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8.0. Addendum 2020

Seabed 2030 Mapping Target Resolutions

The goal of seeing 100% of the World Ocean mapped by year 2030 must be accompanied by a specification of the required level of detail as this will vastly impact the effort. While satellite derived bathymetry is capable of mapping undersea features that are on the order of several kilometres or more in spatial extent (Becker et al., 2009), Seabed 2030 recognized that a broad range of applications require bathymetric gridded compilations that resolve smaller features on the order of tens of meters in scale. However, to make the already ambitious Seabed 2030 goal of having the entire World Ocean mapped by 2030 achievable, a specified mapping target resolution must be based on the existing global mapping capacity. This implies that the mapping primarily will be based on the existing multibeam echo sounding technology and the use of surface vessels. With these base parameters in mind, we defined mapping target resolution as a function of water depth (Mayer et al., 2018) (Table 8.1). These target resolutions are defined as grid-cell sizes because the end products of Seabed 2030 are three, gridded bathymetric compilations: the General Bathymetric Chart of the Ocean (GEBCO) global grid, the International Bathymetric Chart of the Arctic Ocean (IBCAO) regional grid on a north polar projection and the International Bathymetric Chart of the Southern Ocean (IBCSO) regional grid on a south polar projection.

Table 8.1. Defined target resolutions of the Seabed 2030 project. The % of the World Ocean is based on GEBCO_2014 grid.

Depth Range	Grid-Cell Size	% of World Ocean
0–1500 m	100×100 m	13.7
1500–3000 m	200×200 m	11
3000–5750 m	400×400 m	72.6
5750–11,000 m	800×800 m	2.7

The logic behind defined target resolutions

The most common deep-water multibeam system installed on vessels today have a beam width configuration of $2^\circ \times 2^\circ$. The foot print on the seafloor of a sonar beam at nadir (directly under the vessel) can be roughly estimated by

$$D_f = 2H \times \tan\left(\frac{\alpha}{2}\right) \quad (\text{Eq. 1})$$

where (D_f) is the foot print diameter of the nadir beam, (H) is the water depth underneath the transducer and (α) is the opening angle of the multibeam system, i.e. the beam width (Fig. 8.1). The foot print will expand away from the nadir beam with the cosine of the angle away from nadir. To be conservative, we chose to use the beam pointed 60° from nadir as a reasonable indication of the general spatial resolution of a multibeam system. This implies that D_f in Equation 1 has to be divided by $\cos(60^\circ)$ to compensate for the expanded foot print 60° away from nadir, as illustrated in Figure 8.1. Since $\cos(60^\circ)$ equals 0.5, the foot print is doubled. Table 8.2 shows calculated foot prints for specified water depths for a $2^\circ \times 2^\circ$ system. This table formed the basis for a grouping of depth ranges, which each received a target resolution.

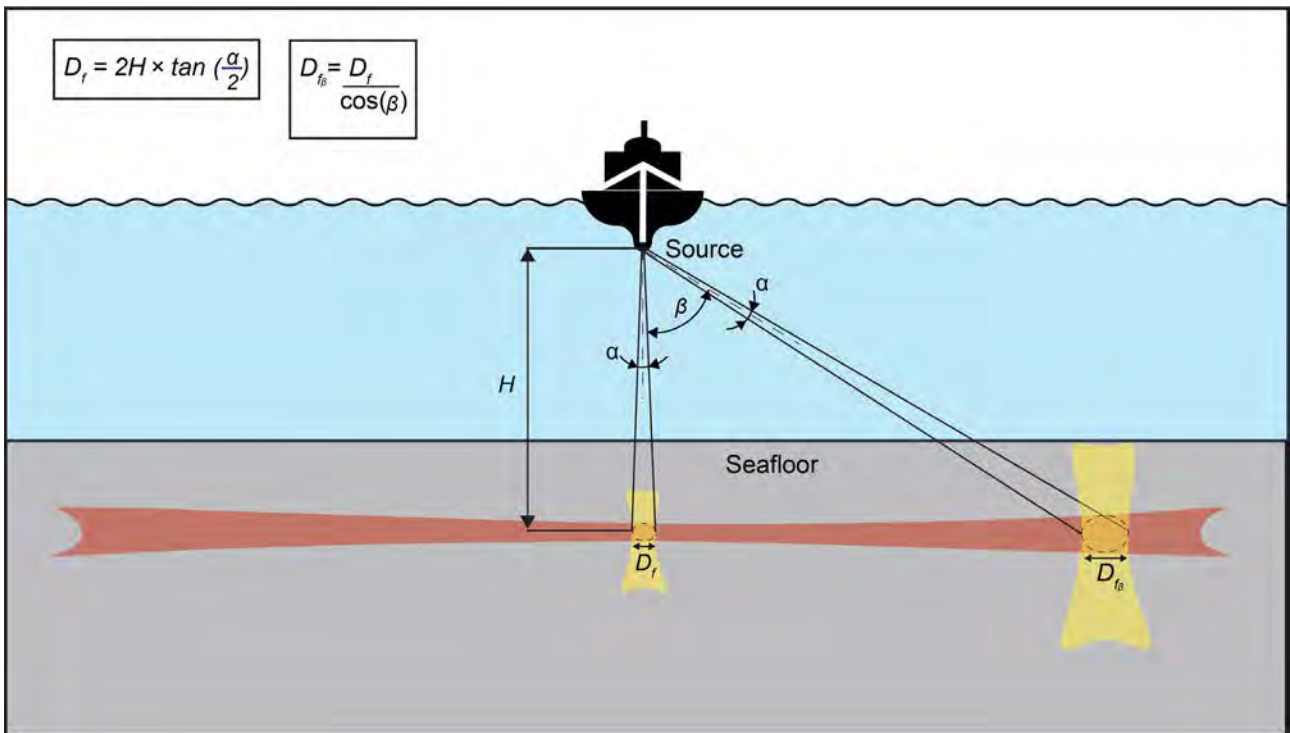


Figure 8.1. Calculated foot prints of a typical deep-water multibeam system, with a transmit and receive array producing $2^\circ \times 2^\circ$ opening angles of the beams, for specified water depths. The calculated foot prints are rounded to integers.

Table 8.2. Calculated foot prints of a typical deep-water multibeam system, with a transmit and receive array producing $2^\circ \times 2^\circ$ opening angles of the beams, for specified water depths. The calculated foot prints are rounded to integers.

Depth	$2^\circ \times 2^\circ$	$2^\circ \times 2^\circ$ 60° of nadir
0	0	
500	17	35
1000	35	70
2000	70	140
3000	105	209
4000	140	279
5000	175	349
6000	209	419
7000	244	489
8000	279	559
9000	314	628
10000	349	698
11000	384	768

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