**GEBCO-Nippon Foundation**

# Seabed 2030

*The Roadmap for Future Ocean Floor Mapping*

## Executive Summary

## 1.0. Introduction and goals

The oceans, covering seventy percent of the Earth's surface, are fundamental to sustaining life, controlling climate 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 that 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 Earth 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 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. Underwater depths 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, and much more. Given the limitations of electromagnetic sensing in the ocean, bathymetric details must be quantified using modern acoustic mapping technologies deployed from surface or submerged vessels; given the vast expanses of the oceans, 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 UNESCO. GEBCO's vision of portraying the World Ocean floor follows from critical societal needs and scientific curiosity and builds on technological developments. In order to achieve this vision, a new program "Seabed 2030" is being developed by the GEBCO community:

***The GEBCO - Nippon Foundation - Seabed 2030, is a global program with the focused goal of compiling a high-resolution openly available Digital Bathymetric Model (DBM) portraying the World Ocean seabed at the highest resolution possible from the coast to the deepest trenches by the year 2030. This DBM should efficiently provide bathymetric information to end users and leave no features of the World Ocean floor smaller than 100 m unmapped by the completion of the program.***

Seabed 2030 builds on 100 years of GEBCO's legacy and established regional connections to all corners of the World Ocean as well as the platform of human capacity built for over 10 years through the GEBCO - Nippon Foundation training program. 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 Earth's seabed.***

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 centerpiece of GEBCO's activities for more than a decade ahead. Behind the Seabed 2030 program lays the wider perspectives of the "blue community" on ocean mapping and the need for bathymetric information captured during the Forum for Future Ocean Floor Mapping organized by GEBCO and Nippon Foundation in Monaco 15-17 June, 2016.

## 2.0. The role of GEBCO – Nippon Foundation – 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 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 the best position to undertake a global coordinated effort to synthesize bathymetric information from all over the world, identify the areas of greatest need so that synthesis efforts can be prioritized, increase the recognition of the importance of bathymetry at intergovernmental forums, and lead global efforts for coordinating the prioritization of mapping programs.

GEBCO recognizes that vast areas of the World Ocean floor, especially those at great distances from coastal and national areas of jurisdiction, are far from adequately mapped. Mapping from the coasts to the deepest trench involves reaching the high seas, 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 initiative for synthesis of a World Ocean portrayal of the seabed from the coast to the deepest trenches.*
- *Seabed 2030 makes use of experts from industry, academia and research organizations 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 program, 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. While Seabed 2030 is launched as an operational program, GEBCO will continue to link individuals and organizations worldwide and enhance existing global networks to drive ocean mapping and a deeper understanding of the modern and past processes shaping the ocean floor.

## 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 (F-FOFM)* brought together 200 individuals from 45 countries representing the "blue community," from experts on ocean mapping to stakeholders and users of bathymetric information. A 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 F-FOFM 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:
    a. Who are the users of bathymetry?
    b. What is bathymetry required for?
    c. What bathymetric products do users want and what resolutions are required?
    d. 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 F-FOFM were organized around 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 200 m, 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 variety of scientific applications including marine geology and geophysical studies, habitat, biodiversity and biogeography studies, understanding circulation patterns that relate to regional and global ocean-atmosphere (climate) processes, and numerical modeling 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 extension of continental shelves, military and defense applications, and is a fundamental data set for confronting the growing challenges associated with climate change.

***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 epicenter 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).*

***Figure 3.2:*** *The need for high-resolution bathymetry also in the deep ocean became strikingly evident also 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 extremely 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 where single beam echo sounding data have been collected and red show multibeam bathymetry available at the time the search began. The bathymetric data coverage was far from even sufficient to send down underwater vehicles for close inspections of the seafloor. In essence, a search for a lost object of the size of an aircraft would have a better start if it was lost on the planet Mars, which is substantially better mapped the World Ocean.*

Until recently, measuring deep ocean bathymetry was almost exclusively achieved using deep-water hull-mounted sonar systems with the spatial resolution of these data fundamentally limited by water depth. The spatial resolutions of the deep ocean bathymetric data products were seldom better than ~100-200 m. At this resolution, the shape of the seafloor can be adequately imaged 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 ridges and ridge segmentation, and the relationships between volcanism and tectonism on ridges and seamounts. It also allows us to define at a scale appropriate for oceanographic and climate modeling, the flow paths of deep currents that distribute heat around the planet. With rapid advances in robotics and sonar technology over the last 5-10 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 dynamic than we ever thought.

The needs of the diverse community of stakeholders who utilize deep ocean bathymetry vary with respect to required resolution. Comprehensively mapping the deep ocean at ~100 m horizontal grid resolution will provide fundamental baseline bathymetry that suits many needs, but higher-resolution data will still be necessary for some purposes. In addition, re-surveying of the deep ocean will be necessary at different time scales due in some regions due to the frequency and intensity of seafloor-changing earth processes. Since most of the deep-sea is beyond territorial waters, mapping efforts to date have been driven by the needs of scientific programs or the specific needs of the commercial sector (e.g. 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.

**Conclusions**

- Deep ocean bathymetry has many important applications, and users have a variety of needs with respect to resolution, frequency of re-survey, and data products.
- Mapping the deep ocean at 100 m resolution 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, cooperation, and would benefit from a campaign-style approach.
- A critical first step in mapping the deep sea is to fully 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 Data Infrastructure calls for continuous access to authoritative and accurate data, there is a general requirement to have 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’s safety. We focus here on bathymetric mapping and the use of bathymetry beyond safe navigation.

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. 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. The forms in which we make bathymetric data available may be critical as this links completely unexpected utilization, collaborations and outcomes.

The scientific need for coastal bathymetry is well established -- for example, for tsunami inundation models, regional assessments of future sea-level rise, studies of outlet glaciers’ sensitivity to inflow of warmer subsurface water in a warming ocean, and marine ecosystems’ dependency on the depth domain.

***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 behavior 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;*

*Mouginot 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 stabile and located near the fjord's sill until 2010 and 2012, when Manhattan-sized pieces broke off and reduced the ice tongue with 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 measurement 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 appeared even 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 15 x 15 m multibeam grid. The true nature of the bathymetric sill was releveled. The sill is generally deeper than 350 m, which 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 suggest, which may explain the recent retreat history with massive calving events 2010 and 2012. The multibeam bathymetry also reveal the past extension and behavior of Petermann Glacier from a complex seafloor morphology consisting of glacial landforms.*

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 5-10 m, globally, would be desirable. Given that most of our coastal waters are not even mapped to 100 m resolution, it is probably only realistic to achieve wider 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 referenced to geodetic datum, with tide corrections having lower priority, being important for the safety of navigation and inundation maps. However, it becomes clear that caution is needed in terms of defining figures of fixed resolution because technology, products, and requirements are ever-changing.

**Conclusions**

- 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 broad range of scientific questions, including, for example local impact of tsunami inundation and storm surges, marine glaciers' sensitive 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 favored in the coastal areas. LIDAR, satellite imageries, multibeam, single beam, open ROV data have all to be considered as valuable data contributions.
- A cultural change is required with respect to data sharing in the Hydrographic sector, for example, by following the handful of Hydrographic Offices that permitted the used shallow water bathymetry from ENCs (Electronic Nautical Charts).
- Coordination between ocean ship surveys are required for efficient use of the global mapping capacity.

## 3.3. New Tools and techniques in ocean mapping

Do we have the tools and techniques to map the world ocean? While new mapping efforts will undoubtedly be required, the Seabed 2030 project will also focus on bringing all available depth measurements together into a database for the compilation 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 past few years have seen consistent improvements in the accuracy, resolution, and seafloor coverage offered by echo-sounding 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 around five times the water depth and sometimes better. 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 current evolution of technology may see sonars based on a mix between the interferometric and more conventional multibeam technology.

***Figure 3.4:*** *The concept of an unmanned mapping barge, steered 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 100 x 100 m. The sub-meter level of detail sometimes needed to investigate small scale processes at the seabed is today possible to acquire in the deep ocean using AUVs (right) 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 cover does not make them the tool for mapping the entire World Ocean floor.*

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. The development of unmanned vehicles of various sorts is therefore key to fully map the World Ocean floor. In the more populated regions of the World crowd-sourced bathymetry hold 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 crowd source 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. 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, and 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 the areas using conventional methods from ships, and even with AUVs, may be enormously challenging and expensive. Furthermore, LIDAR is expensive and limited to 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 data sources with global coverage. The development of satellite-derived bathymetry methods that are not based on only the optical spectrum may overcome the non-clear water issue.

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 offers several potential benefits derived from shared cloud-based infrastructure for data storage as well as for gridding and processing routines.

The GEBCO 2014 grid, as well as the grids produced by linked Regional Mapping Projects, are based on vastly heterogeneous source data implying that some areas are well mapped while others are very poorly mapped. In some areas of the world ocean, much higher resolution final grids would be possible to produce than the GEBCO 2014 (0.5 x 0.5 min), IBCAO (500 x 500 m), and IBCSO (500 x 500 m) grid. But since there are no widely-spread grid formats for variable sized grids that common software can read, grids with a single set cell-size have been the focus of GEBCO, even if the gridding approaches lend themselves well to produce variable sized grids with resolution steered by the density of the source data. The BAG (Bathymetry Attributed Grid) is, however, a grid format that Esri, Caris, QPS, and several other software producers have begun to implement, which may be suitable to store variable sized grids.

**Conclusions**

- 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 small enough, and 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, steered 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 resolution substantially better than 100 x 100 m.
- Crowd sourcing is a powerful concept in ocean mapping that has a huge potential to substantially boost the targeted mapping, specifically in shallow 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 conventions mapping methods, but it is a source better than nothing with 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 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, but it must be kept in mind that software vendors often do not adopt open standards, the Open GIS Consortium (OGC) does, and then software vendors adopt/promote those.

### 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 mechanism in place to identify or access these bathymetric datasets is 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, 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 visible. 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.

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 recent 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 on technologies for remotely controlled data collection.

**Conclusions**

- A program 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.
- The bathymetric gaps must be filled using crowd sourcing, coordinated basin scale campaigns, satellite derived bathymetry, regional compilations, and innovations in remotely controlled collection technology.
- Strong partnerships for collecting, sharing, and compiling data are an essential global mapping effort.

# 4.0. Status: How much of the World Ocean 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 mapped areas using the modern multibeam techniques, and areas where the bathymetry is just supported by sparse single beam tracklines at best, are readily seen. Furthermore, maps showing the global coverage of ship tracks along which bathymetry data has been collected are often shown at a scale making it appear like there is a dense network, even near complete coverage, of ship tracks.

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. In addition, areas are covered by external projects with similar setup as IBCAO and IBCSO. These include EMODnet covering European waters, and the Baltic Sea Bathymetry Database (Hell and Öiås, 2014). The *GEBCO_2014* grid was based on all 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 (926 m 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.

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

***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).*

Between tracklines, large areas of the *GEBCO_2014* grid are based on interpolation guided by satellite-derived gravity data, except for in most of the two Polar Regions where sea ice precluded the use of this method. This is because *GEBCO_2014* started with the base grid form the previous *GEBCO_08* version, in turn including the altimetric bathymetry model *SRTM30_PLUS* (Becker et al., 2009). The altimetry method has been crucial for seafloor mapping of the remote and deep parts of the world ocean because it is capable of generating general estimation of depths from the satellite-derived gravity field, to fill gaps between sparse ship soundings (Smith and Sandwell, 1997). However, it does far from provide the precision and detection capabilities as reliable as echo sounders, but the method is objective and superior in most non sea-ice covered areas compared to interpolation between sparse ship tracks by mathematical algorithms and hand-contouring. Large features such as spreading ridge segments and fracture zones that offset them have been mapped by the altimetry method.

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 (Figure 4.2. versus 4.4). The above highlights the need for increased bathymetric mapping programs, specifically including the acquisition of high resolution multibeam.

***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. Figure us from Weatherall et al. (2015).*

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

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 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 geormorphological 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 (~10 km/h). However, this does not take into account maneuvering, meteorological and oceanic adverse conditions or deployment of auxiliary sensors (tide gauge principally in shallow waters, sound velocity profiling). Furthermore, the analyses has 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 | Remaining effort (years) (for one survey boat) |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | driven by altimetry (km$^2$) | |
| >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 yields 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 0-200 m water depth. In order to bring this value in perspective, we can consider that more than 700 multibeam systems are equipping surveying boats from national hydrographic offices, research institutes or private bodies in the world (as estimated in 2003 by the IHO). Withstanding that this approximation is based on idealistic assumptions, the order of magnitude for the remaining surveying effort appears to be considered as a reachable goal. Moreover, our estimation is based on GEBCO's bathymetric database at the time of the compilation of the GEBCO_2014 grid. Even if this most likely is the most complete bathymetric database, we are fully aware of that it far from include all available data of today. 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.

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

**Seabed 2030 will provide users with the definitive high-quality high-resolution bathymetric portrayal of the World Ocean from the coast to the deepest trench. Seabed2030 will make this World Ocean bathymetric compilation accessible and easy to use through a suite of useful tools and products.**

## 5.1. Background: The concept of Regional Mapping Projects

The structure of Seabed 2030 proposed here is based on GEBCO's experiences from successfully working with Regional Mapping Projects that contributed substantially to GEBCO by delivering regional bathymetric gridded compilations. A Regional Mapping Project is focused on gathering 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 choice of placing the project "home" at a university had some advantages:

1. The university environment is well suited to develop and test new techniques for handling and compiling bathymetric data since universities are by nature driven by research and innovation motivations.
2. Universities are generally viewed as having less ties to nations' political agendas than governmental agencies.
3. The university environment makes it possible to involve students in the work which builds the future capacity of ocean mapping.

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).

At a GEBCO Guiding Committee (GGC) in Silver Spring, Maryland, USA 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 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 forum where coordination and exchange of experiences have taken place between active Regional Mapping Projects. The International Bathymetric Chart of the Southern Ocean (IBCSO) gained momentum through discussions and change of experiences taking place within SCRUM. Following from support from Nippon Foundation and with a project home hosted by Alfred Wegener Institute, IBCSO released Version 1.0 of a gridded bathymetric compilation at 500 x 500 m in 2013 (Arndt et al., 2013).

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

1. An Editorial Board consisting of members with interest in the ocean region in focus should be established and form the broad base of a Regional Mapping Project. The Editorial Board should be led by a chairman.
2. A committed "home" institute/center should be established for a Regional Mapping Project. The selected home should have a strong capacity within the field of ocean mapping and be internationally recognized.
3. There must be human capacity assigned to work on the Regional Mapping Project at the home institute/center. This include leadership, networking with data providers, database administration, bathymetric cleaning, merging and compilation as well product evaluation.

## 5.2. Seabed 2030 structure

### *5.2.1. Regional Mapping Centers*

Based on GEBCO's the successful experiences of working with Regional Mapping Projects, Seabed 2030 is based on the establishment of eight Regional Mapping Centers, each having a defined ocean area of responsibility (Figure 5.1). These Regional Mapping Centers should have committed personnel that are responsible for championing and coordinating regional mapping activities within their prescribed region as well as for compilation of the region's bathymetric data into final products that will be merged to comprise GEBCO World Ocean bathymetric portrayal. Seabed 2030 aims to establish the regional mapping centers in sequence, based on current activity and maturity.

### *5.2.2. Program Office*

A Program Office will be established that is responsible for overall co-ordination of the program including: merging together all regional bathymetric compilations, acting as bridge across the Regional Mapping Centers, distributing the final bathymetric product to end users. The Program Office will administer seed project funding that will accelerate and facilitate the Seabed 2030 activities at the regional level.

### *5.2.3. Management Board and Strategic Advisory Group*

A Management Board will be established to be responsible for defining the overall Seabed 2030 strategy and operational activities and which will be responsible for financial governance. This board in turn, receives independent strategic advice from a Strategic Advisory Group. The Management Board reports to the GEBCO Guiding Committee. The Management Board consist of:

1. Chair: Seabed 2030 Director.
2. Participants: Regional Mapping Centre Leads
3. Admin support: Program Office Administrator

*Figure 5.1. Structure of Seabed 2030.*

## 5.3. Seabed 2030 Milestones

TO BE CONTINUED AFTER GC MEETING IN CHILE

# 6.0. References

Arndt, J. E., Schenke, H. W., Jakobsson, M., Nitsche, F. O., Buys, G., Goleby, B., Rebesco, M., Bohoyo, F., Hong, J., Black, J., Greku, R., Udintsev, G., Barrios, F., Reynoso-Peralta, W., Taisei, M., and Wigley, R., 2013, The International Bathymetric Chart of the Southern Ocean (IBCSO) Version 1.0 – A new bathymetric compilation covering circum-Antarctic waters: Geophysical Research Letters, v. 40, p. 3111-3117.

Becker, J. J., Sandwell, D. T., Smith, W. H. F., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls, S., Kim, S.-H., Ladner, R., Marks, K., Nelson, S., Pharaoh, A., Sharman, G., Trimmer, R., vonRosenburg, J., Wallace, G., and Weatherall, P., 2009, Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS: Marine Geodesy, v. in press.

Hell, B., and Öiås, H., 2014, A New Bathymetry Model for the Baltic Sea: International Hydrographic Review, no. 12, p. 21-31.

Holland, D. M., Thomas, R. H., Young, B. d., Ribergaard, M. H., and Lyberth, B., 2008, Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters: Nature Geoscience, v. 1, p. 659-664.

Jacobs, S. S., Jenkins, A., Giulivi, C. F., and Dutrieux, P., 2011, Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf: Nature Geosci, v. 4, no. 8, p. 519-523.

Jakobsson, M., Cherkis, N., Woodward, J., Macnab, R., and Coakley, B., 2000, New grid of Arctic bathymetry aids scientists and mapmakers: EOS, Transactions American Geophysical Union, v. 81, p. 89, 93, 96.

Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J. A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebesco, M., Schenke, H. W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R. M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J. V., Hall, J. K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S. V., Pedrosa, M. T., Travaglini, P. G., and Weatherall, P., 2012, The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0: Geophysical Research Letters, v. 39, no. 12, p. L12609.

Macnab, R., and Grikurov, G., 1997, Report: Arctic Bathymetry Workshop: Institute for Geology and Mineral Resources of the Ocean (VNIIOkeangeologia).

Mix, A. C., Jakobsson, M., and Petermann-2015 Scientific Party, 2015, Petermann-2015 Expedition Launches International Collaboration in Arctic Science, Witness the Arctic: https://www.arcus.org/witness-the-arctic/2015/3/article/24490, Arctic Research Consortium of the Unites States.

Mouginot, J., Rignot, E., Scheuchl, B., Fenty, I., Khazendar, A., Morlighem, M., Buzzi, A., and Paden, J., 2015, Fast retreat of Zachariæ Isstrøm, northeast Greenland: Science, v. 350, no. 6266, p. 1357-1361.

Münchow, A., Padman, L., and Fricker, H. A., 2014, Interannual changes of the floating ice shelf of Petermann Gletscher, North Greenland, from 2000 to 2012: Journal of Glaciology, v. 60, no. 221, p. 489-499.

Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B., 2013, Ice-Shelf Melting Around Antarctica: Science, v. 341, no. 6143, p. 266-270.

Smith, W. H. F., and Marks, K. M., 2014, Seafloor in the Malaysia Airlines Flight MH370 Search Area: Eos, Transactions American Geophysical Union, v. 95, no. 21, p. 173-174.

Smith, W. H. F., and Sandwell, D. T., 1997, Global seafloor topography from satellite altimetry and ship depth soundings: Science, v. 277, p. 1957-1962.

Weatherall, P., Marks, K. M., Jakobsson, M., Schmitt, T., Tani, S., Arndt, J. E., Rovere, M., Chayes, D., Ferrini, V., and Wigley, R., 2015, A new digital bathymetric model of the world's oceans: Earth and Space Science, v. 2, no. 8, p. 331-345.