

Bathymetry: Features and Hypsography

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Abstract

The study of the distribution of elevations on the Earth or hypsography shows how more than half of the world ocean is dominated by deep basins (4–6.5 km) covered with abyssal plains and hills. Seafloor from 2 to 4 km depth is primarily comprised of oceanic ridge systems that spread over ~30% of the seafloor. The shallow seas and continental margins from sea level to 2 km depth cover the least amount of area and represent only ~15% of the seafloor. Superimposed on the primary features of the seafloor landscape are secondary features such as the median valley, seamounts, and submarine canyons. Fine-scale geomorphology of the underwater landscape and discontinuities in bathymetry are increasingly being used to assess distributions of marine organisms. New terminology and computational methods identify seafloor features that enhance marine biodiversity and allow for better management of vulnerable marine ecosystems.

INTRODUCTION

Up until the mid-20th century, the seafloor was thought to be featureless consisting of bits of rock and sediment eroded from the continents and flushed into the ocean reservoirs.^[1] However, we now know that ocean bathymetry encompasses a varied seascape including vast mountain ranges, deep trenches, fracture zones extending for thousands of miles, the flattest plains on Earth, and a plethora of lesser meso- and microscale features ranging from individual seamounts to individual ripples and tidal channels. Comprehension of this landscape is a key component of the theory of plate tectonics, an intrinsic part of marine ecology, and a significant component of ocean circulation on global scales to individual estuaries. Indeed bathymetry and ocean science are intricately intertwined and one cannot be understood without the other.

Hypsography is the study of the distribution of bathymetric features across the Earth's surface and provides the percentage of the seafloor covered by large-scale features, such as continental shelves and abyssal plains. Fine-scale oceanic features can also be mapped at high resolution using new technology.^[2] Assessing the geomorphology or shape of underwater landforms is now an important component in developing marine reserves to protect sensitive marine ecosystems. Many organisms aggregate at

discontinuities in the bathymetry that can also affect local eddies and current features that shape aspects of local water properties. Bathymetry of coastal estuaries and bays must also be evaluated in terms of tidal currents driven by the gravitational influence of the moon that can change bathymetry on hourly time scales. In a little over a century, the vast underwater landscapes from large- to small-scale features have been revealed, and this knowledge has contributed to the fundamental understanding of the Earth's processes.

BATHYMETRIC FEATURES AND HYSOGRAPHY

The large-scale primary and secondary features of the deep seafloor and fine-scale features on the marine and coastal seafloor are discussed further.

Large-Scale Features

Covering 3.6×10^8 km², or 71% of the Earth's surface, the oceanic basins are dominated by three major physiographic features: 1) deep basins covered with abyssal plains and hills covering ~53% of the seafloor; 2) the world-girdling oceanic ridge system covering ~31% of the seafloor; and 3) continental margins and shallow seas comprised of

continental shelf, slope and rise covering over 16% of the seafloor (Fig. 1). Undulating abyssal hills and gently sloping to flat abyssal plains lying between 4 and 6.5 km spread across the vast ocean floor. Very large features of significant linear extent include the great *trenches* and *fracture zones* of the world ocean that can extend for thousands of miles either along the margins of ocean basins as in the case of trenches or across ocean basins as in the case of fracture zones. The ridges and rises associated with fractures zones predominantly occur at depths from 2 to 4 km across the world ocean (Fig. 1). Oceanic trenches from 6.5 to ~11 km in depth cover 0.2% of the world ocean. Continental margins are made up of continental shelves, continental slopes, and continental rises. *Continental shelves* border the continents and vary in size and shape across the world ocean. Comprised of continental crust, they are relatively flat containing thick layers of terrigenous sediments from riverine input. The widest continental shelves tend to occur along passive margins where considerable sediment can build up over time. In active continental margins with converging plates, there can be little to no

shelf at all. The depth limit describing the continental shelf is often considered to be <200 m, but deeper shelves extending to 500 m commonly occur in polar regions north and south of 60° latitude including Antarctica and Greenland. The *shelf break* indicates the point where the continental shelf abruptly ends and the slope steepens dramatically in what is referred to as the *continental slope*. At the base of the slope, the *continental rise* is characterized by a gentle slope of accumulated sediment that merges into the abyssal plain on passive continental margins.

Superimposed on the primary features of the seafloor landscape are secondary features such as the *median valley* associated with the mid-ocean ridge system, mountain ranges, and ridges not associated with the mid-ocean ridge system. The abyssal hills and plains are interrupted by a spectrum of larger hills, knolls, and cones with varying elevations culminating with the higher underwater mountains having relief >1000 m called *seamounts*. With over 100,000 estimated to occur on the seafloor, seamounts are typically formed from volcanic activity in association with diverging plates, hot spots, or converging plates.

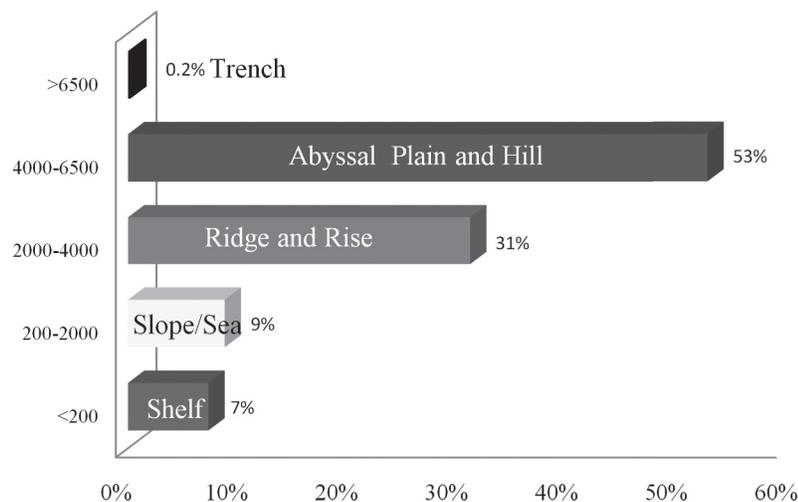
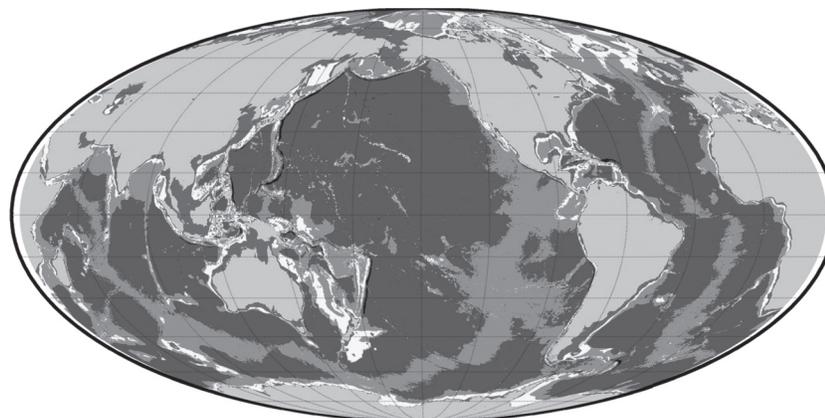


Fig. 1 Depth distribution of seafloor in the global ocean translating roughly to trenches (>6500 m, black), abyssal plains and hills (4000–6500 m, purple), ridges and rises (2000–4000 m, blue), continental slope and shallow seas (200–2000 m, yellow), and continental shelf (<200 m, red).

Source: Data from ETOPO1.^[14]

1 Tablemounts or *guyots* are flat-topped seamounts formed
2 by wave erosion which has been transported to deeper
3 water and submerged on a moving plate. Volcanic activity
4 forming mountains (either undersea or continental)
5 commonly occurs on the back side of the trench feature
6 where the downthrust subducting plate heats and melts.
7 *Volcanic island arcs* are formed in this manner and run par-
8 allel to a trench at a distance of ~200 km from the trench
9 axis. *Submarine canyons*, generally extensions of large riv-
10 ers or formed by turbidity flows, periodically cut through
11 the continental slope and transport considerable sediments
12 from the shelf to the deep sea. Other secondary features
13 include individual basins, troughs, deeps, holes, escarp-
14 ments, benches, terraces, regional and local plains, great
15 canyons, and lesser valleys found on the continental slopes
16 of the world.

17 Virtually all of the primary and many of the secondary
18 features of the world ocean were discovered by either line
19 and sinker technology or by single-beam echo sounding.^[1]
20 However, because the introduction of multibeam sounding
21 systems coupled with the global positioning system,^[2]
22 many additional deep-sea features have been discovered
23 including hydrothermal vents and vent fields, mud volca-
24 noes, mud wave and dune fields, individual lava flows,
25 landslide scars, and diapiric structures including commer-
26 cially valuable salt domes.

27 Comprehension of the significance and inter-relationships
28 of the primary and secondary features of the seafloor has
29 come about only since the formulation of the theory of
30 plate tectonics. Plate tectonics describes the surface of the
31 Earth in terms of numerous plates that either move away
32 from each other at divergent plate boundaries, collide at
33 convergent plate boundaries, or slide past each other along
34 great faults known as transform faults. The median valleys
35 of mid-oceanic ridges are the primary location of divergent
36 boundaries, also known as seafloor spreading centers,
37 where new seafloor is being produced from upwelling
38 magma. Sites where plates collide with one plate being
39 thrust under another consuming the seafloor, known as sub-
40 duction zones, are marked by the great oceanic trenches,
41 while colliding plates with no subduction form the great
42 terrestrial mountain ranges of the world such as the Alpine-
43 Himalayan belt of Europe and Asia. Sites where plates
44 slide past one another are marked primarily by the numer-
45 ous offsets on the mid-oceanic ridge system and are known
46 as transform faults or fracture zones.

47 The presence of the abyssal plains and hills can also be
48 explained from tectonic processes in combination with
49 sedimentary processes. As new seafloor is formed and then
50 pushed away from the median valley, parallel trains of
51 abyssal hills are formed. With the passage of time, these
52 hills are draped with sediment. When completely covered,
53 the resulting surfaces are termed abyssal plains. Lineal
54 chains of islands and seamounts can also be formed over
55 long-lived stationary “hot spots” that provide conduits for
56 magma to come to the surface. As the seafloor moves over

these hot spots, lineal chains of islands and seamounts are
formed trending in the direction of seafloor motion. The
Hawaiian Islands and Emperor Seamount chains are exam-
ples of this phenomenon.

Fine-Scale Features

Marine geomorphology—the study of underwater
landforms—is becoming an important component of man-
agement of marine ecosystems. Increasingly, the fine-scale
ridges and troughs of the underwater landscape are being
used to assess and define biological habitats for fish and
other marine organisms. In Long Island Sound (Fig. 2A),
the largest urban estuary in the United States, a concen-
trated mapping program has characterized the physical
character of the seafloor using multibeam sonar for depth
and “sidescan” sonar for a qualitative view of seafloor
reflectivity characteristics.^[3] Such high-resolution images
showing sand ripples, uplifted ridges, and small depres-
sions in bathymetry (Fig. 2B) are valuable for assessing
benthic habitats, current modeling, and evaluating sedi-
mentary processes.

Many species aggregate at locations with particular geo-
morphic features, such as reef promontories, uplifted
ridges, and shelf edges, that are associated with abrupt dis-
continuities in surrounding structure.^[4] When related to the
seafloor, the terms “habitat heterogeneity” and “keystone
structures” are applied to seafloor features that may enhance
biodiversity by providing refugia from predation, enhanced
or alternative food resources, spawning areas, stress gradi-
ents and substratum diversity.^[5,6] Not only do undersea
landforms provide three-dimensional structure, but they
can also influence eddies and currents and create oceanog-
raphic conditions important for the growth and survival of
marine communities.^[7] Submarine canyons, for example,
are sites of organic enrichment and benthic productivity
due to sinking of particulate materials from the shores.^[5]

Modern techniques allow for mapping of the seafloor
with higher precision than ever before and assessment of
benthic structures at meter scales or less. Because of link-
ages between bathymetric features, biodiversity, and bio-
geochemistry, new methods for classifying the seafloor
have been developed. A benthic location can be classified
according to a terrain ruggedness index^[8] or more specifi-
cally the bathymetric position index (BPI), for example,
which identifies the sloping nature of a region or “neigh-
borhood.” A positive BPI denotes ridge features; zero val-
ues indicate flat terrain or region with a constant slope; and
negative values correspond to valleys. Bathymetric data
tends to be spatially autocorrelated where locations closer
together are more related than those further apart, and
thereby the value of the BPI is related to the scale of data
under investigation and the type of topography within the
selected region.^[9] Often BPIs are estimated at different
scales to define different scales of features from small sand
ripples to large-seascape features such as channels.

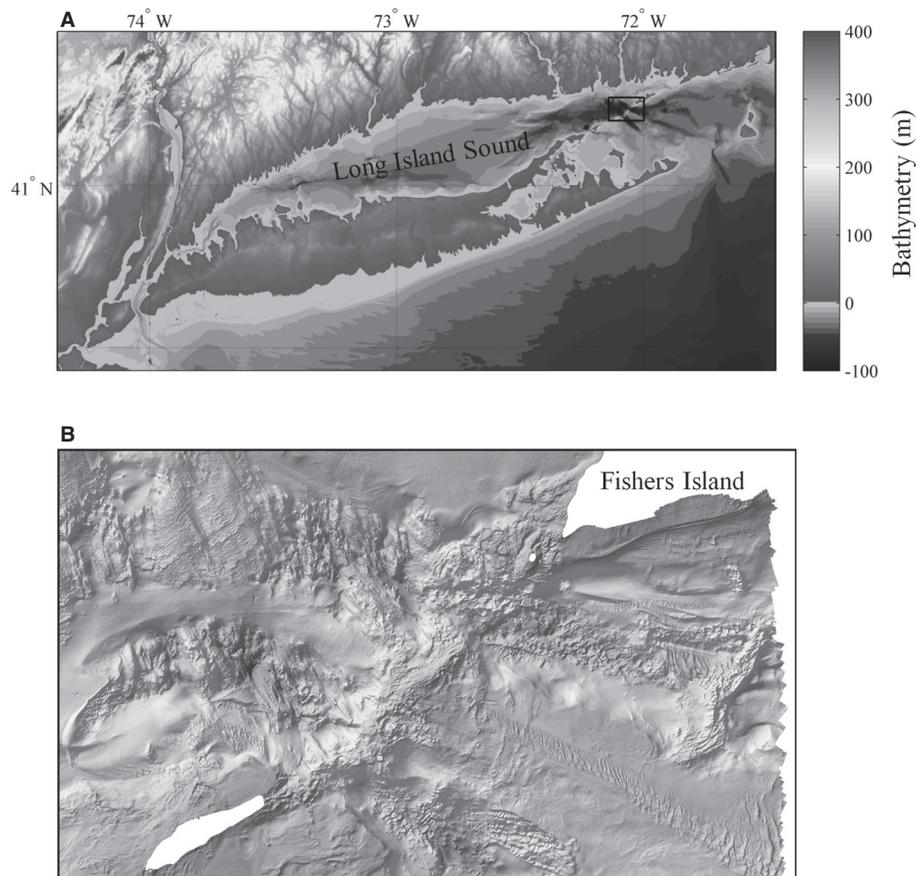


Fig. 2 (A) Bathymetry of Long Island Sound, the United States as mapped from NOAA digital high-resolution coastal gridded data (Amante^[14]). (B) High-resolution bathymetry from multibeam sonar of the area around Fishers Island, outlined in black in Panel A, highlights a variety of detailed seafloor features (Poppe and Polloni^[3]).

Source: Image courtesy of Long Island Sound Resource Center.

Fine-scale benthic features are also characterized by their “rugosity,” which is a measure of the bottom complexity or “bumpiness.” It is often parameterized as the surface area in relations to the planar area. A rugosity of 1 indicates a smooth, flat surface and values >1 indicate higher relief. Regions with higher rugosity have been linked to higher biodiversity.^[10]

Ongoing efforts are underway to organize and define coastal and marine environments in meaningful units that can be compared across different temporal and spatial scales. The Coastal and Marine Ecological Classification Standard (CMECS) is one such effort that defines a habitat using five different components: water column, benthic biotic, surface geology, sub-benthic, and geform component^[11](Fig. 3A). The geform component classifies the major geomorphic or structural characteristics of the seafloor and is often assessed with bathymetric data. The classifiers tend from large- to small scale and begin with coastal region, physiographic setting, geform (natural), and subform, with an additional category called geform (anthropogenic). The physiographic setting is defined from many of the primary oceanic features described earlier (e.g., mid-ocean ridge, abyssal plain, etc.)

and also includes the “coast” defined as the land–water interface. Geform classifies features from centimeter to kilometer scale and has been separated into structures that are natural and anthropogenic in origin. Anthropogenic geforms cover jetties, piers, artificial reefs, and other man-made structures and seafloor areas where human activities have changed the landscape (e.g., trawling and prop scars). Within the natural geforms are definitions to describe marine features (e.g., seamounts, guyots, banks, boulder fields, and megaripples) and those structures in coastal regimes (e.g., fjord, beach, delta, coral reef, and lagoon). Finally, the subform category describes smaller features within the geform and can include walls, escarpments, and also such factors as substrate orientation which can impact the availability of light and wave energy. Hence, many layers of complexity are required to describe the bottom topography itself, not to mention the additional components describing the type of substrate and biota associated with these features.

In a reef system, these techniques can be used to define zones corresponding to the geomorphology of the coral reef community. A recent analysis mapped the reef structures according to the following categories: shoreline intertidal,

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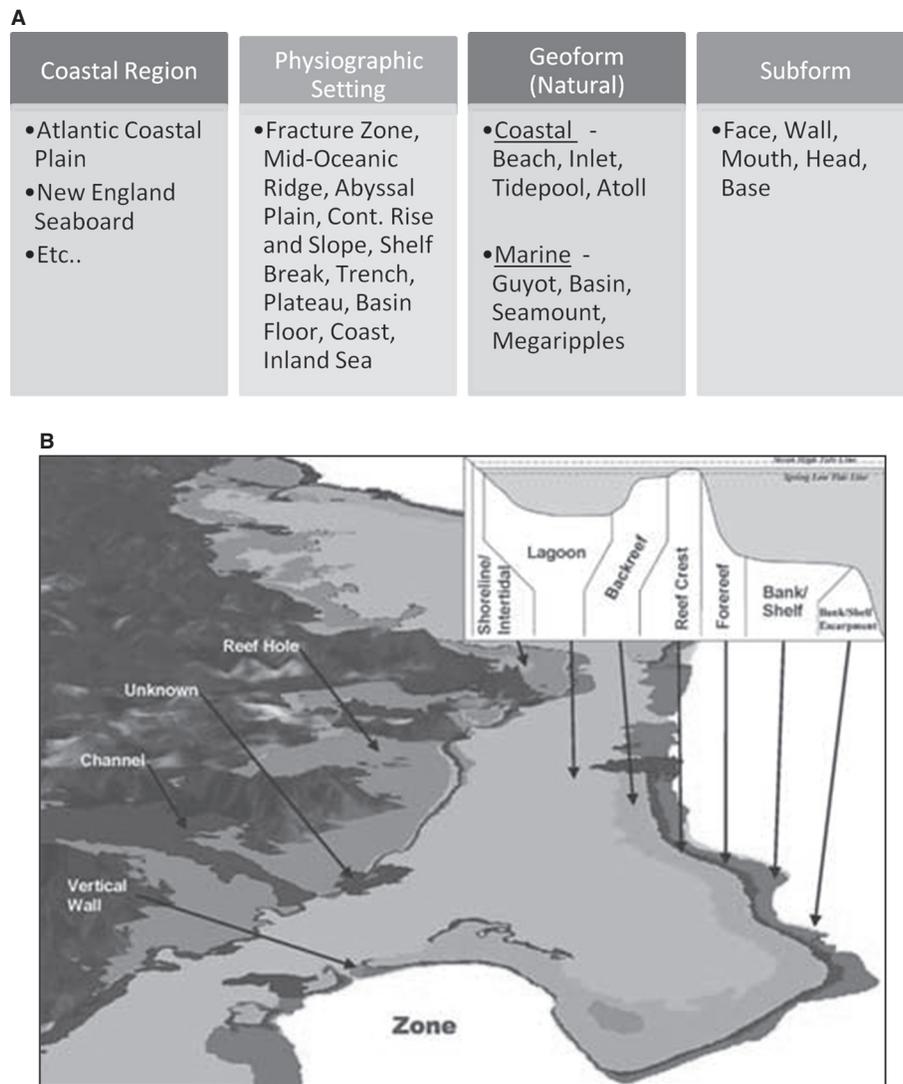


Fig. 3 (A) Geomorphologic classification scheme proposed by the Coastal and Marine Ecological Classification Standard (CMECS) categorize features from large (coastal region) to small (subform) spatial scales. (B) A classification of a coral reef demonstrating the different bathymetric features mapped from a bathymetric grid (Battista^[12]).

Source: Image from NOAA, NOS, NCCOS Biogeography Branch.^[12]

vertical wall, lagoon, back reef, reef flat, reef crest, fore reef, bank/shelf, bank/shelf escarpment, channel, and dredged area^[12] (Fig. 3B). These geomorphologic zones can be comprised of different benthic substrate or cover types. The “lagoon,” for example, may be covered by patch reefs, sand, and seagrass beds. Integrating and assessing the biota and geomorphology is important for managing these sensitive coastal resources.

HYPISOGRAPHY OF THE OCEAN

The bathymetry of each of the five ocean basins varies considerably (Fig. 4). Ridges and rises associated with seafloor spreading can be found in all five of the ocean basins. As mapped in the 1800s,^[1] the Mid-Atlantic Ridge extends

from the north of Iceland to the Southern Ocean boundary. Wide continental shelves (<200 m depth) are visible along much of the western Atlantic Ocean. The vast Pacific Ocean contains mostly broad expanses of deep ocean floor including abyssal hills, chains of seamounts, and lineal scars of great fracture zones. Prominent bathymetric features also occur along the margins of the Pacific Ocean. The Pacific Ocean is bounded by the “Ring of Fire” consisting primarily of subducting plates on the western, northern, and eastern margins with deep trenches and considerable earthquakes and volcanic activity. The southern boundary is defined by the Pacific–Antarctic Ridge and the southern portion of the East Pacific Rise. The Indian Ocean is crossed by ridges and volcanic island structures where the African, Indian, Australian, and Antarctic crustal plates all converge. With the exception of Western Australia, the Indian Ocean has

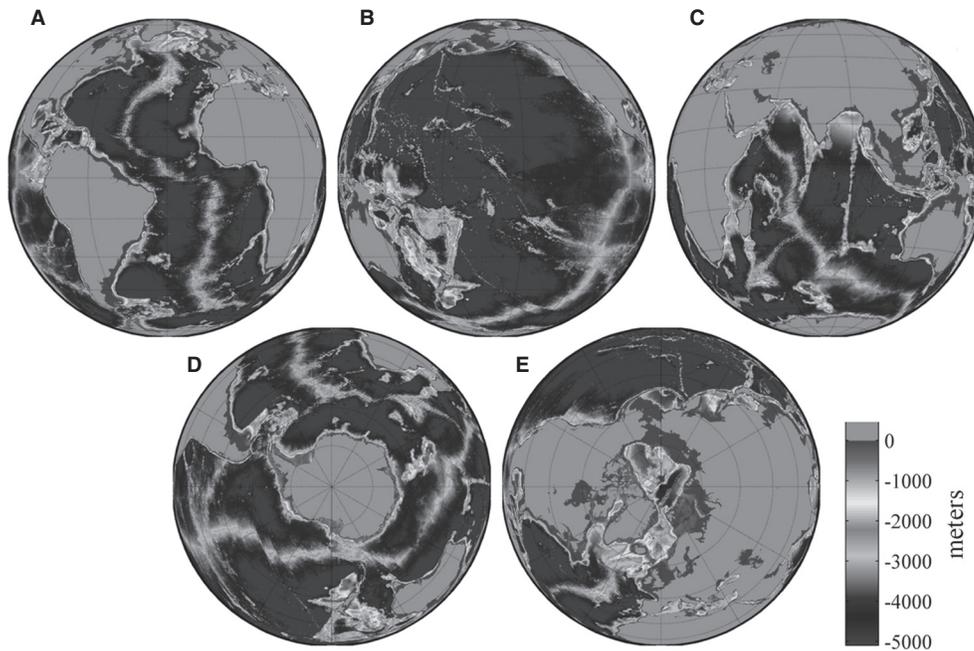


Fig. 4 Gridded bathymetric data are a compilation of satellite gravimetric data and sonar data from throughout the global ocean.^[14] These plots show bathymetry (m) for each ocean basin in orthographic projection: (A) Atlantic, (B) Pacific, (C) Indian, (D) Southern, and (E) Arctic. Land surfaces are shown in gray.

limited continental shelf area. In contrast, the Arctic Ocean represents the shallowest of ocean basins and is characterized by broad expansive deep (500 m) shelves and shallow seas. The Southern Ocean also contains deep continental shelves (500 m), large expanses of abyssal plains, and prominent ridge features bordering the Pacific, Atlantic, and Indian Oceans.

Taken from the Greek word “hypsos,” meaning height, hypsography is the study of the distribution of elevations on Earth and is used to relate bathymetry to the projected two-dimensional surface area of a region or feature. The “hypsographic curve” of Earth shows the cumulative percentage of the Earth surface area at different elevations from above and below sea level (Fig. 5). As shown, the ocean represents ~71% of the Earth’s surface and most of this surface area is quite deeply submerged at close to 4 km below sea level. Based on our current and still limited knowledge of bathymetry, the average depth of the oceans is calculated to be 3.7 km. The prevalence of deep sea-floor is related to the heavier elemental composition of oceanic crust that makes it much denser than terrestrial crust. Along the perimeters of the ocean basins, the ocean slopes rapidly and very little of the Earth’s surface occurs between the continental shelves (<500 m) and the deep sea (4 km). Metaphorically, the ocean basins can be considered like deep bowls with thin rims and steep sides. However, the bowl bottoms are not smooth, but littered with abyssal hills and seamounts, as well as spreading ridges that appear as jagged seams laced across a baseball.

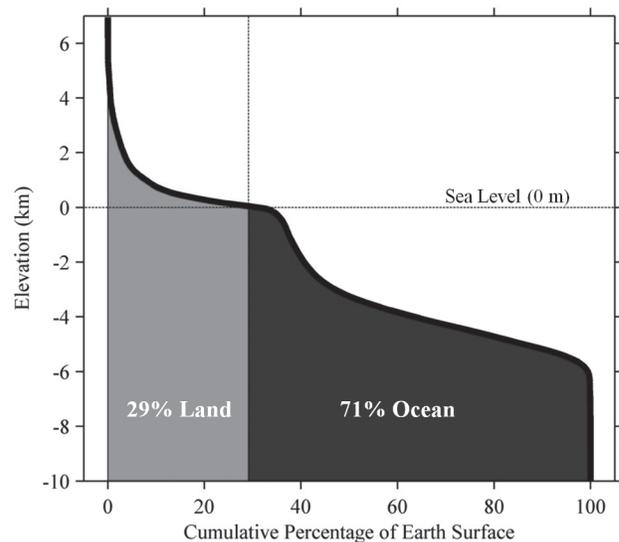


Fig. 5 Hypsographic curve modeled from ETOPO1 gridded bathymetric data^[14] shows the cumulative percentage of Earth’s surfaces above and below sea level. Land represents a smaller depth range and comprises 29% of Earth’s surface; whereas, ocean has nearly an 11 km depth range and covers 71% of the Earth’s surface. Over 50% of Earth falls between 4 and 6 km below sea level comprised predominantly of abyssal plains and hills.

CONCLUSION

Representing less than a third of the Earth’s surface, the land is dwarfed by the enormity of ocean. The ocean has more relief with deep 11 km trenches compared to

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1 maximum peaks of 7 km on land. The large-scale features
 2 of the underwater landscape span the five ocean basins
 3 from the Southern Ocean northward to the Arctic Ocean.
 4 Describing and classifying coastal and marine geomor-
 5 phology at fine scales is still an area of active research that
 6 requires more data and enhanced computational methods.
 7 Bathymetry is not static and the percentage of ocean is
 8 likely to increase in the next century as sea-level rises due
 9 to thermal expansion of ocean water and melting of land-
 10 based glaciers.^[13] Ocean bathymetry will need to be revised
 11 particularly in the near-shore environment as the oceans
 12 get deeper and coastal regions become submerged. While
 13 islands and seamounts are continually being formed by
 14 volcanic activity, many islands will become submerged by
 15 tectonic activity and projected sea-level rise.

17 ACKNOWLEDGMENTS

18 Funding was provided from the U.S. Office of Naval
 19 Research, U.S. National Aeronautics and Space Adminis-
 20 tration (Dierssen), and U.S. National Oceanographic and
 21 Atmospheric Association (Theberge).
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