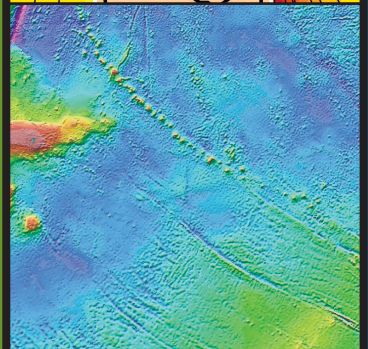
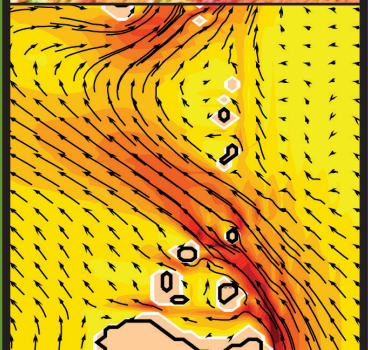
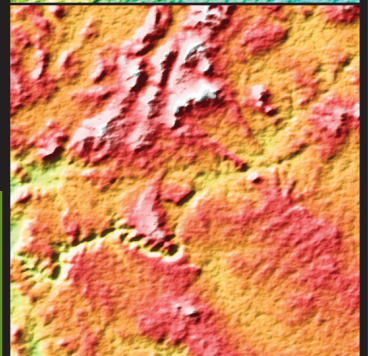
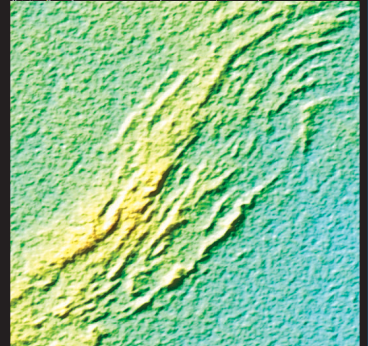
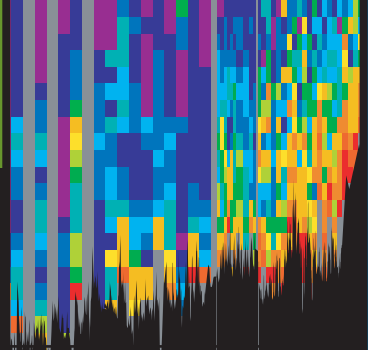
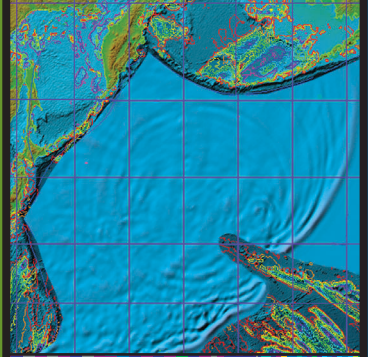


Bathymetry from Space

Oceanography, Geophysics, and Climatology



Funding for the workshop was provided by the National Science Foundation, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, ConocoPhillips Inc. and the Cecil H. and Ida M. Green Institute for Geophysics and Planetary Physics.

Draft

Bathymetry from Space

Oceanography, Geophysics, and Climatology

May 2003

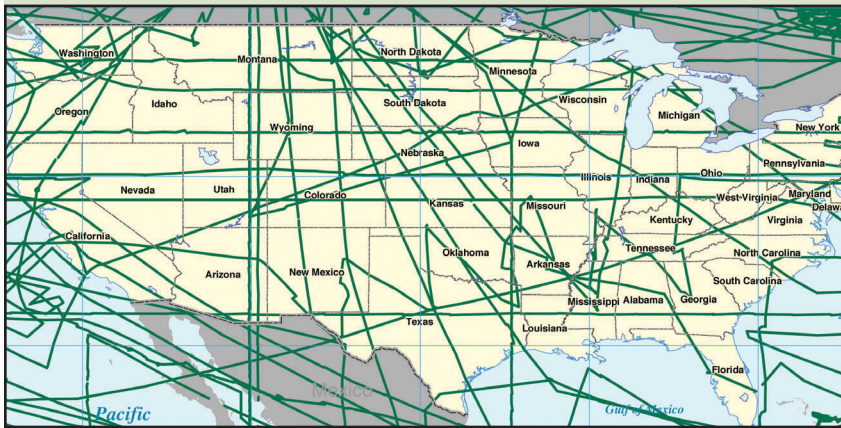
This report summarizes written and oral contributions from many interested scientists, including 46 participants (Appendix 1) at a workshop held in La Jolla, California on October 24-26, 2002. Sarah Gille, David Sandwell, and Walter Smith convened the workshop, with Sandwell serving as Chair. The conveners prepared the document with the assistance of Ellen Kappel and Johanna Adams of Geosciences Professional Services. Critical reviews were provided by Steven Jayne, Walter Munk, John Orcutt, Dale Sawyer, and Paul Wessel.

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the need for bathymetry from space

The topography of the United States would be very poorly known if surveyors took data only along the Interstate highways. Our knowledge of the topography of remote ocean basins is similarly limited because the distribution of survey lines is just as sparse. Shown here are the bathymetric survey lines in the South Pacific (top) mapped at the same scale as the Interstate highway system (bottom).



executive summary

Bathymetry is foundational data, providing basic infrastructure for scientific, economic, educational, managerial, and political work. Applications as diverse as tsunami hazard assessment, communications cable and pipeline route planning, resource exploration, habitat management, and territorial claims under the Law of the Sea all require reliable bathymetric maps to be available on demand. Fundamental Earth science questions, such as what controls seafloor shape and how seafloor shape influences global climate, also cannot be answered without bathymetric maps having globally uniform detail.

Current bathymetric charts are inadequate for many of these applications because only a small fraction of the seafloor has been surveyed. Modern multi-beam echo sounders provide the best resolution, but it would take more than 125 ship-years and a billion dollars to complete the job. Fortunately, the seafloor topography can be charted globally, in five years, and at a cost under \$100M. A radar altimeter mounted on an orbiting spacecraft can measure slight variations in ocean surface height, which reflect variations in the pull of gravity caused by seafloor topography. A new satellite altimeter mission, optimized to map the deep ocean bathymetry and gravity field, will achieve a resolution threshold that is critical for both basic science and practical applications including:

- Determining the effects of bathymetry and seafloor roughness on ocean circulation and mixing, on climate, and on biological communities, habitats, and mobility.
- Improving tsunami hazard forecast accuracy by mapping the fine-scale topography that focuses or scatters tsunami wave energy.

- Understanding the geologic processes responsible for ocean floor features unexplained by simple plate tectonics, such as abyssal hills, seamounts, micro-plates, and propagating rifts.
- Mapping the marine gravity field to improve inertial navigation and reveal the subseafloor structure of continental margins for both geological research and offshore resource exploration.
- Providing bathymetric maps for numerous other practical applications, including planning submarine cable and pipeline routes, improving tide models, and defining international boundaries on territorial claims to the seabed under the United Nations Convention on the Law of the Sea.

Because ocean bathymetry is a fundamental measurement of our planet, there is a broad spectrum of interest from government (DoD, NASA, NIMA, NOAA, and NSF), the research community, industry, and the general public. Public opinion polls favor ocean exploration over space exploration by two to one.¹

¹American Attitudes toward the Ocean, SeaWeb, 900 Adult Americans interviewed, May 10-15, 1996. American Attitudes toward the Ocean II, SeaWeb, 1014 Adult Americans interviewed, August 21-24, 1997.

mission requirements

The need for ocean bathymetry is already acute and will become more so as ocean and climate modeling capabilities advance, and as marine resources become harder to find and manage. The resolution of the altimetry technique is limited by physical law, not instrument capability. Everything that can be mapped from space can be achieved now, and there is no gain in waiting for technological advances.

Mission requirements for Bathymetry from Space are much less stringent and less costly than typical physical oceanography missions. Long-term sea-surface height accuracy is not needed; the fundamental measurement is the slope of the ocean surface to an accuracy of $\sim 1 \mu\text{rad}$ (1 mm per km). The main mission requirements are:

- **Improved range precision.** A factor of two or more improvement in altimeter range precision with respect to current altimeters is needed to reduce the noise due to ocean waves.
- **Fine cross-track spacing and long mission duration.** A ground track spacing of 6 km or less is required. A six-year mission would reduce the error by another factor of two.
- **Moderate inclination.** Existing satellite altimeter data lie along orbits inclined near Earth's poles, thus their resolution of East-West components of ocean slope is poor at low latitudes. The new mission should have an orbital inclination close to 60° or 120° so as to resolve North-South and East-West components almost equally while still covering nearly all the world's ocean area.
- **Near-shore tracking.** For applications near coastlines, the ability of the instrument to track the ocean surface close to shore, and acquire the surface soon after leaving land, is desirable.

mapping the ocean floor

The depth to the ocean floor and the roughness of the bottom vary throughout the oceans as a result of numerous geologic processes. This seafloor topography influences the ocean circulation and mixing that moderate Earth's climate, and the biological diversity and food resources of the sea. The ocean floor records the geologic history and activity of the ocean basins, revealing areas that may store resources such as oil and gas, and generate earthquakes and tsunamis. Despite the importance of Earth's ocean floor to our quality of life, we have made much better maps of the surfaces of other planets, moons, and asteroids (see back cover).

the need for bathymetry from space

After five decades of surveying by ships carrying echosounders, the majority of the ocean floor remains unexplored and there are vast gaps between survey lines; the remote basins are covered as sparsely as the Interstate Highway system covers the United States (see box opposite Executive Summary). The primary reason for this lack of data is simply that ships are slow and expensive to operate. The chief advantage of satellites is their relatively higher speed and lower cost. A systematic survey of the oceans by ships would take more than 125 years of survey time at a cost exceeding one billion U.S. dollars. A complete satellite survey can be made in five years for under \$100M.

Satellites have another advantage in comparison to the present database of echosoundings, which is globally uniform resolution. By carrying the same sensor all over the globe, a satellite makes measurements of the same quality everywhere, a requirement for mapping the global distribution patterns of small bathymetric features. Ships have not done this. The era of frontier exploration, when

scientists could take ships into remote areas merely for curiosity's sake, was an era of single-beam echosounders and relatively poor navigation. The last two decades have seen great technical advances in echosounding (multi-beam swath mapping systems, Figure 1) and navigation (Global Positioning System), but these have been deployed over only a few percent of the ocean's area. The focus

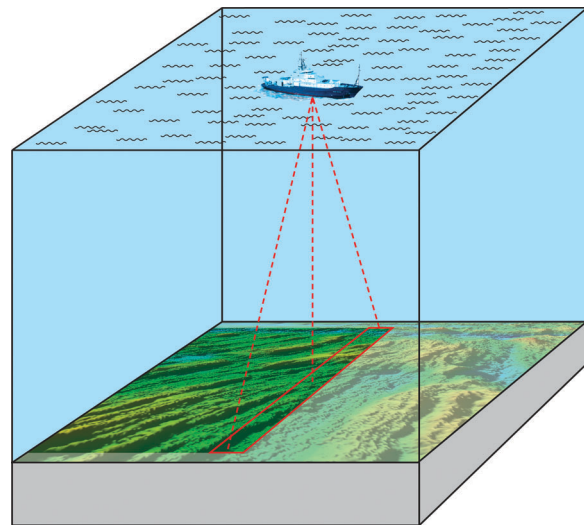


Figure 1. Swath-mapping bathymetry uses sound waves to map 10-20 km wide swaths in deep water at 200 m horizontal resolution. Complete mapping of the oceans using this technology would take 125-ship-years at a cost of one billion U.S. dollars.

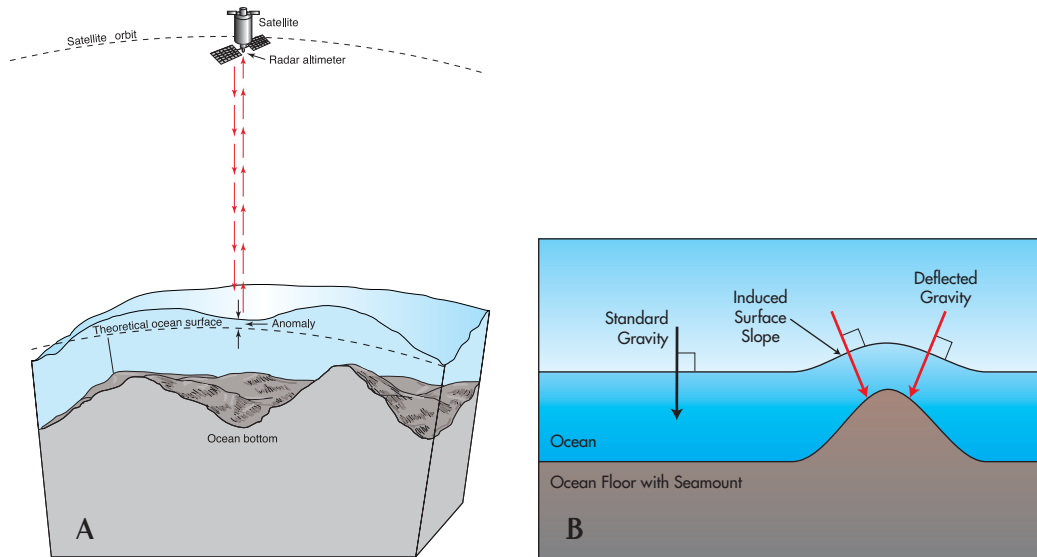


Figure 2. Satellite-derived bathymetry. A. An Earth-orbiting radar in space cannot see the ocean bottom, but it can measure ocean surface height variations induced by ocean floor topography. A mountain on the ocean floor adds to the pull of Earth's gravity and changes its direction subtly, causing extra water to pile up around the mountain. For example, a mountain on the ocean floor that is 2000 m tall produces a sea surface bump only 20 cm tall. Though small, this is measurable from space. The ultimate resolution of this method is limited by regional ocean depth. B. The tilt in the direction of gravity, called a "deflection of the vertical," is equal to the slope of the sea surface, and is measured in microradians. One microradian of deflection appears as a 1 mm change in sea surface height per 1 km of horizontal distance.

has been on coastal regions and Exclusive Economic Zones, and research emphasizing "hypothesis testing," which requires ships to revisit previously surveyed areas. The result is that even today, the majority of data available in the remote oceans are the old-style, low-tech data.

A third advantage of satellites is that they can go everywhere, without making noise. Some countries prevent ships from surveying in their territorial waters. Concerns have been raised recently that the use of acoustic devices may harm marine life, and it is now becoming more difficult to get permission to use acoustic systems. These concerns may ultimately make global surveys by ships impossible.

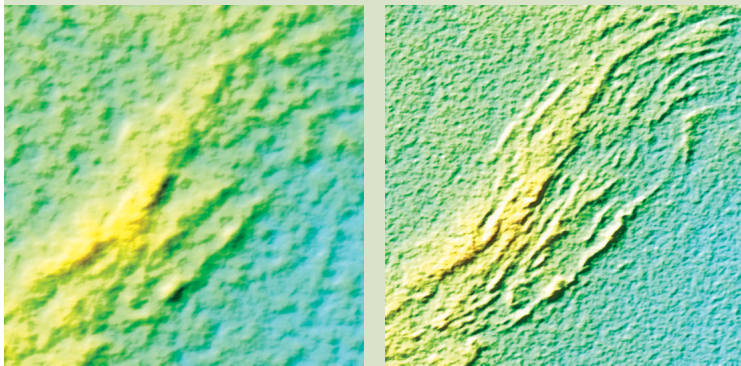
sensing bathymetry from space

The ocean's surface has broad bumps and dips that mimic the topography of the ocean floor. The extra gravitational attraction of seafloor features such as seamounts produces minor variations in gravity, which in turn produce tiny variations in ocean surface height (Figure 2). As tiny as they may seem, these bumps and dips can be mapped using a very accurate radar altimeter mounted on a satellite. In the deep ocean basins, where sediments are thin and seabed geology is simple, space radar data may be used to predict bathymetry. Existing satellite altimeter data have proved the feasibility of the technique and revealed the overall, large-scale tectonic features of the ocean basins. A properly designed mission using existing technology could bring significant new resolution (see box on opposite page), capturing a critical scale of features, and facilitating new science and applications.

what we mean by resolution

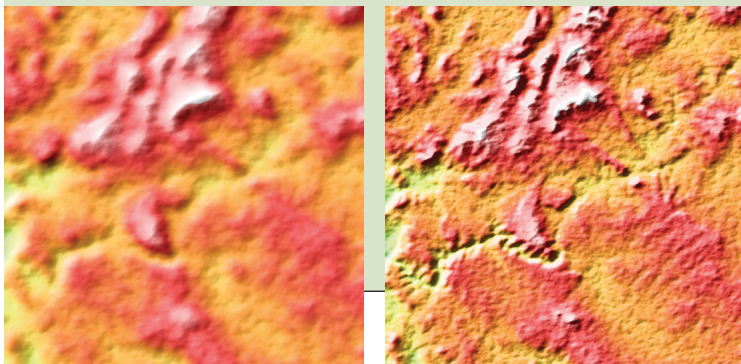
A feature is “resolved” if it stands out clearly above the background noise caused by measurement errors. “Resolution” is a function both of instrument error and of feature size. A physical law (“upward continuation”) prevents a space bathymetry mission from resolving objects much narrower than twice the regional depth of the ocean water (~8 km in the deep basins). The resolution of existing maps are suboptimal by about a factor of two to three in feature width (four to nine in area) because of the high noise in the satellite data caused by ocean waves. It is now possible for a low-cost, low-risk mission to reduce the noise by a factor of five, achieving feature resolution to the limit set by physical law.

Appalachia



To illustrate the improvement possible, these maps show how Appalachia and the Grand Canyon would look if the topography had been generated by the space bathymetry technique using existing data (left box), and data that are less noisy by a factor of four (right box). The better data show faults and drainage patterns in the Grand Canyon, and individual ridges and valleys and their curvature in the Allegheny Mountains.

Grand Canyon



new science

A new space bathymetry mission would furnish—for the first time—a global view of the ocean floor at the proper scale to enable important progress in basic and applied science. Ocean and climate modelers and forecasters would be able to account for how the ocean bottom steers currents and how bottom roughness controls the mixing of heat, greenhouse gases, and nutrients. The details of the tectonic and volcanic processes that shape the ocean floor could be studied in their full complexity, beyond the over-simplified view given in the plate tectonic theory. The hazards to coastal communities posed by tsunamis could be more realistically assessed, as fine-scale bathymetry determines the likelihood of undersea earthquakes and landslides, the propagation of tsunami waves generated by these sources, and the height of the wave that ultimately arrives at the coast.

ocean circulation, mixing, and climate

Bathymetry defines the bottom boundary of the ocean. At large scales it determines basic flow patterns of ocean circulation. At small scales it controls the transport of water between ocean basins, and seafloor roughness converts energy from horizontal flows to mix the ocean vertically. Both ocean circulation and mixing play major roles in climate.

The sun fuels Earth's climate system, supplying most of its energy near the equator. The tropics would be painfully hot and high latitudes uninhabitably cold were it not for the atmosphere and ocean, which spread the sun's energy poleward. Both the atmosphere and ocean contribute roughly equally to the poleward transfer of heat, but the ocean has vastly greater heat storage capacity. The

energy required to heat the entire atmosphere by 1°C would warm the ocean by less than 0.001°C. Because the ocean is slow to heat and cool, it moderates climate change.

To evaluate how the ocean influences climate, oceanographers try to understand how the ocean transports and stores climatologically important properties such as heat and carbon dioxide. This requires identifying the routes that water follows as it flows in deep currents along the seafloor, as well as how it mixes with other waters as it moves along. The deepest, densest water in ocean basins results from sinking at high latitudes. Water that has sunk recently contains the most recent signature of the current state of the climate: high concentrations of carbon dioxide, for example, or slightly warmer temperatures than less recently

ventilated water. State-of-the-art ocean models investigate the impact of mixing from overflows over sills and in deep ocean basins through direct simulation and parameterization (Figure 3). Because ocean currents interact with the bottom of the ocean, detailed knowledge of seafloor bathymetry will help improve predictions of the global ocean circulation and heat transport, and thus their effect on climate.

predicting ocean circulation

Numerical models of the ocean's circulation forecast currents for shipping and military operations, predict climate, provide early warnings for natural disasters, and help us understand the fundamental physics that governs ocean circulation, which in turn helps develop improved forecast models. Bathymetry provides the bottom boundary condition for all types of ocean models.

Ocean circulation models are remarkably sensitive to small perturbations in bathymetry. In high-resolution models used to predict oceanic flows, small topographic features can steer major currents (Figure 4). Other ocean models run for climate prediction (Figure 3) show how changes in bathymetry influence poleward heat transport. Ocean climate modelers looked at the impact of changing the depth of the ridge separating the high-latitude Norwegian Sea from the North Atlantic Ocean. In their model, the ocean transports nearly twice as much heat northward when the ridge contains deep passageways. This difference implies significantly different climate regimes. These results show that accurate representation of ridges and canyons is important even for low-resolution climate models, and that topographic features in the deep ocean can steer upper ocean and surface level flows, even when the flow does not intersect topography.

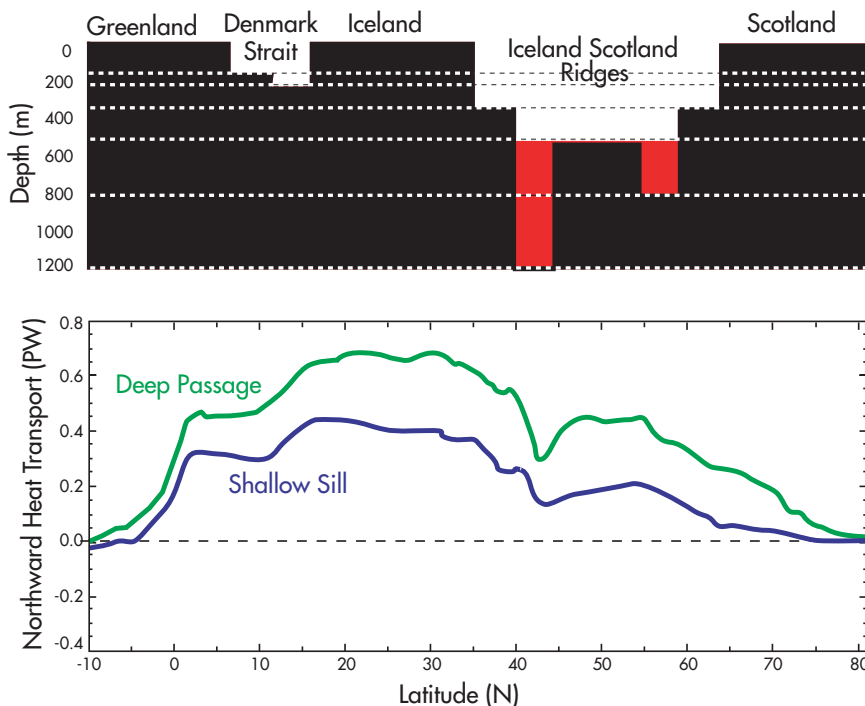


Figure 3. Accurate bathymetry is important even for the low-resolution ocean models used in global climate change studies. Including deep passageways (shown in red) in the sill that connects the Greenland-Iceland-Norway Sea with the North Atlantic results in twice as much poleward heat transport in the UK Meteorological Office's 1° by 1° ocean climate model. This difference predicts significantly different modeled climate regimes. Adapted from Roberts, M. J. and R. A. Wood, 1997, *J. Phys. Oceanogr.*, 27, 823-836.

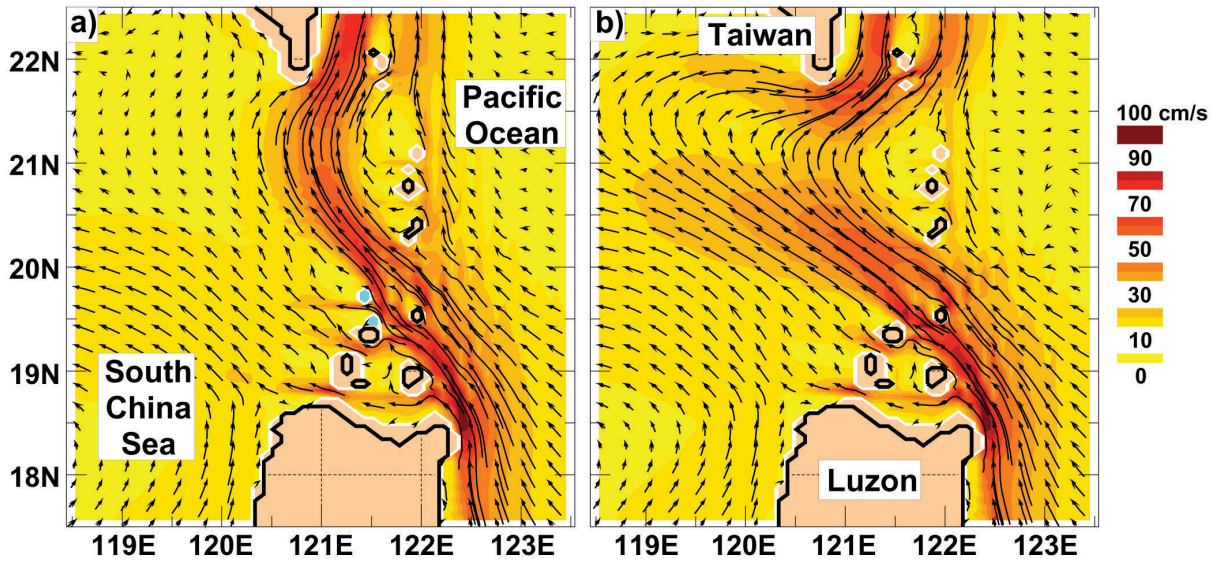


Figure 4. The availability of accurate bathymetric data is critical for modeling major current systems such as the Kuroshio in the North Pacific. The simulation in the left panel properly represents the islands and shoals within Luzon Strait and the intrusion of the Kuroshio into the South China Sea. If the three model grid points representing small topographic features are removed (marked in blue on the left panel), the Kuroshio intrudes farther west (right panel) than indicated by observations. From Metzger, E.J. and H.E. Hurlburt, 2001, *Geophys. Res. Lett.*, 28, 1059-1062.

In the future, accurate high-resolution bathymetry is expected to become a more pressing requirement, as other modeling challenges are solved. In the next ten years, projected increases in computer power will permit global models to simulate eddies and currents with scales of 10 km or less. With new satellite-derived bathymetry, modelers will be able to resolve bathymetry at the same resolution as the currents and eddies. This will help to make more reliable ocean circulation models and better predictions of how heat and other water properties move through the ocean to influence climate.

understanding ocean mixing

Small-scale bathymetry has a large impact on ocean circulation because it influences how water mixes. Understanding how the ocean mixes is crucial for understanding Earth's climate because

vertical mixing determines how quickly heat and carbon dioxide can penetrate into the deep ocean. Predictions of global sea level rise over the next century differ by 25% or more depending on the rate of vertical mixing. Most deep-ocean mixing can be attributed to two processes, both of which depend on bathymetry.

As water flows through tightly constrained passageways (Figure 5) and over sills it rapidly mixes with surrounding water. This mixing affects the concentrations of heat and dissolved gases in sea water and the total quantities that can be stored in the ocean. As a result, in models containing these passageways, small changes to the topography can lead to significant changes in ocean circulation and in the way that heat is transported through the ocean.

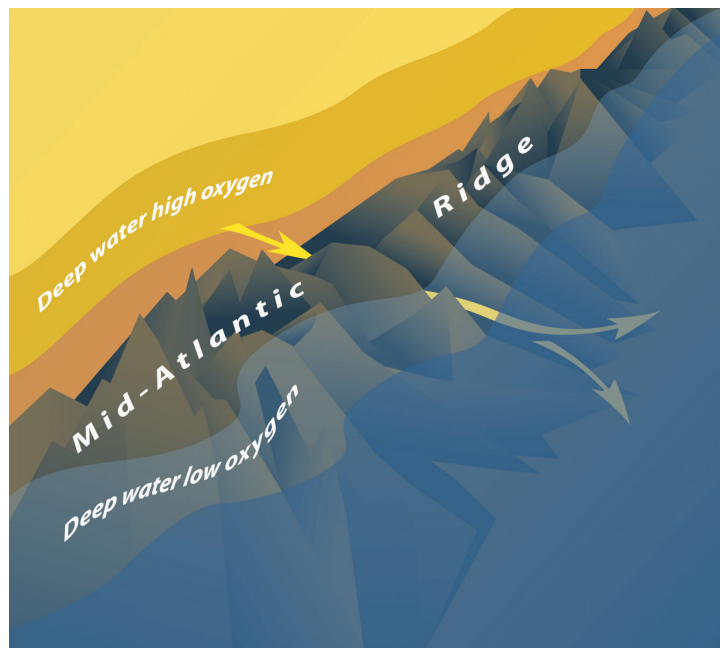
Vertical mixing in the deep ocean also controls aspects of the horizontal circulation. Both wind-driven and tidal currents generate internal waves when they flow over abyssal topography. These waves subsequently mix the ocean vertically through wave breaking or other mechanisms. Measurements of vertical mixing in the Brazil Basin indicate that mixing rates vary with geographic location and depth, and the energetics of dissipation depend on fine-scale topography in the deep ocean (Figure 6). Models that predict future climate will require accurate bathymetry in order to predict spatially varying mixing rates.

Unfortunately, the best global bathymetry that is currently available does not resolve seafloor topography at all length scales. Theoretical studies suggest that bathymetric features as small as 1 km

may influence mixing. A new mission could map the length scales constraining 50% to 70% of the tidally driven mixing. Some features that generate internal waves are too small to be visible from space, but they may be predicted statistically, provided that bathymetry is resolved down to lengths where the statistics of roughness may be extrapolated from fractal models (8 km).

There are still unknown circulation pathways in the ocean, and the best bathymetry cannot yet determine where critical mixing is happening. A factor of two increase in resolution and factor of five increase in the signal to noise ratio, possible with the proposed satellite mission, will permit many of these currently unknown pathways to be mapped, and areas with topographically enhanced mixing to be found.

Figure 5. Mid-ocean ridges constrain flow and mixing in a way similar to the blocking and steering of winds by mountain-pass topography. The Mid-Atlantic Ridge generally prevents mixing between the basins on its east and west flanks. In the South Atlantic, the deep water is higher in oxygen on the western side, allowing oceanographers to observe that some flow does cross the ridge where it is cross-cut by deep troughs associated with fracture zones. Rapid and climatically important mixing takes place in such passages, and so mapping their locations is an important step in realistic climate modeling.



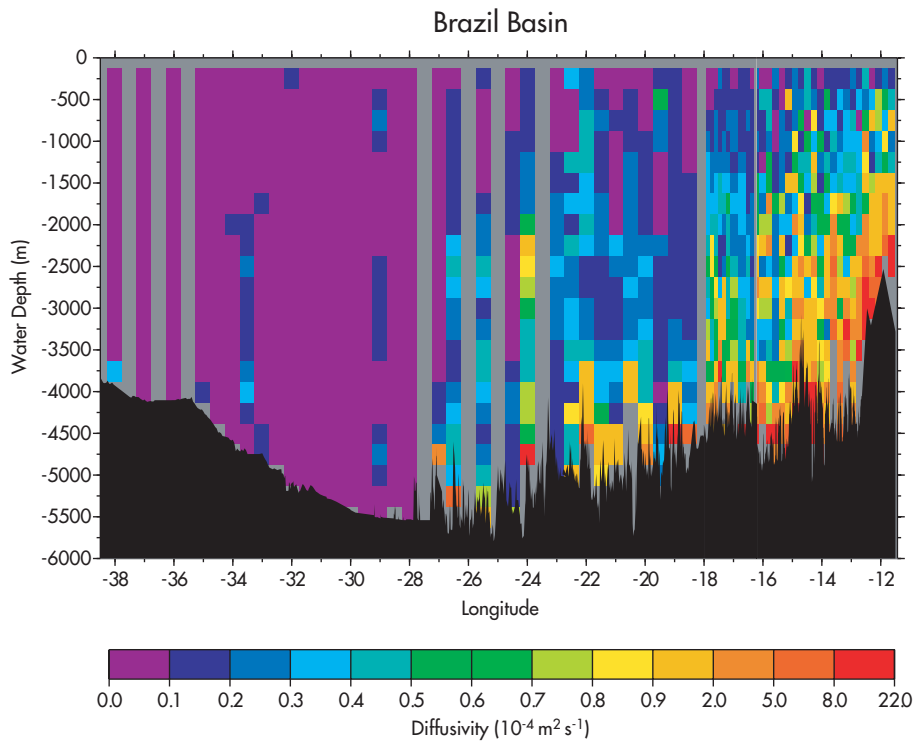


Figure 6: Knowledge of mixing rates in the ocean are needed to better forecast Earth's climate. Mixing rates measured at sea in the Brazil Basin (left) indicate that they vary geographically depending on bottom roughness. Mixing rates are low over the smooth topography to the west (nearly solid purple) and high over the rough topography to the east (multiple colors). Modified from: Mauritzen et al, 2002, *J. Geophys. Res.*, 107(C10), 3147.

beyond plate tectonics

The broad architecture and geologic history of the ocean basins can be elegantly explained by plate tectonic theory (Figure 7): Earth's outer rocky layer is divided into a number of rigid blocks called plates; these plates move slowly over Earth's surface; the plate's interiors should be geologically stable and inactive; and earthquakes, volcanoes, and mountain building occur only near plate boundaries. This theory grew up in the 1960s when seafloor bathymetry was relatively crude, and so the evidence came primarily from the geographical pattern of seafloor magnetic anomalies, and the global distribution of earthquakes, volcanoes, and fossils.

In the mid-1990s, satellite altimeter measurements of the marine gravity field provided the first globally uniform and detailed view of ocean floor architecture. This new view seemed to both confirm and complicate plate tectonic theory. The satellite perspective displayed a globally continuous pattern of mid-ocean ridges and fracture zones, as the theory predicted. The data, however, also revealed many features that the theory did not anticipate—mid-ocean ridges propagating into old, thick oceanic lithosphere; spreading centers that overlapped; and a very complex pattern of volcanic seamounts in the interiors of plates. These new features pro-

vide clues to the changing forces applied to the tectonic plates. The improved resolution of a new space bathymetry mission will reveal hundreds of small structures on a global basis. Understanding these second-order plate tectonic features is a primary focus of marine geological research today.

A key attraction of a new space bathymetry mission is that it will resolve enough of the abyssal hill fabric (see Abyssal Hill box on p. 12) to reveal changes in hill orientation, indicating when and where tectonic regimes have changed, whether or not these changes are synchronous along the global spreading system, and whether or not the plates transmit stress rigidly, as plate theory supposes.

These observations will enable scientists to better understand the strength of the plates, an important question in earthquake physics.

A global map of abyssal hill orientation will also be important in other applications. The direction of the hills with respect to bottom currents will be a key factor in modeling deep ocean flow and mixing. New research in locations where plates bend as they approach subduction zones suggests that the long direction of the hills with respect to the trench axis may determine whether old faults are reactivated or new faults are cut as the plate is flexed. Thus, it is possible that in some regions, the earthquake and landslide potential of the deep ocean floor depends, in part, on abyssal hill orientation.

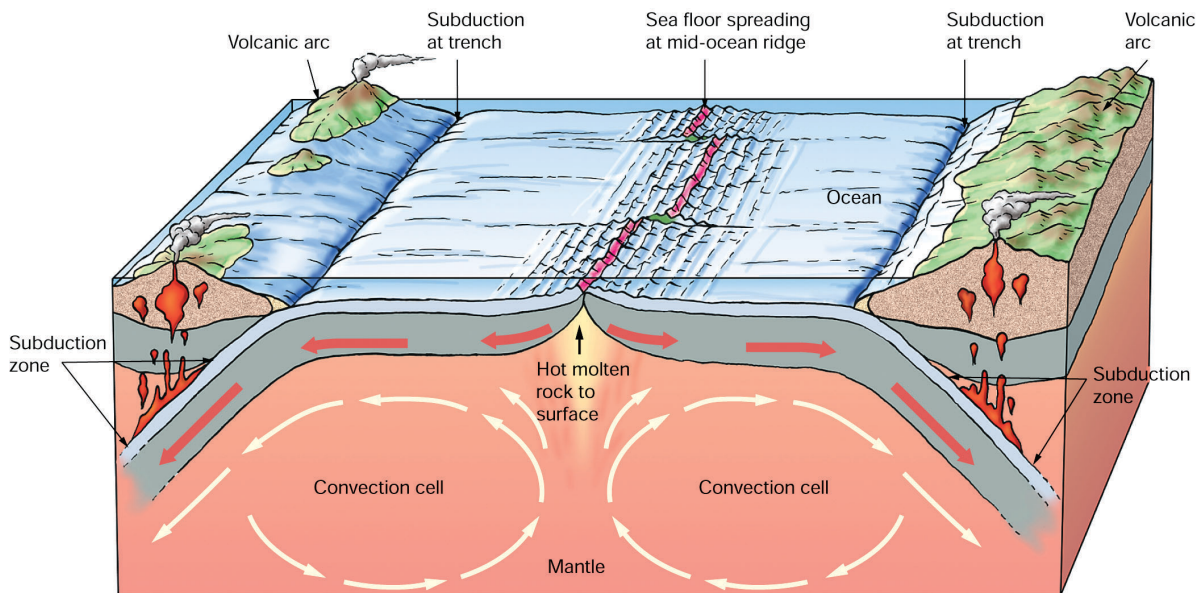
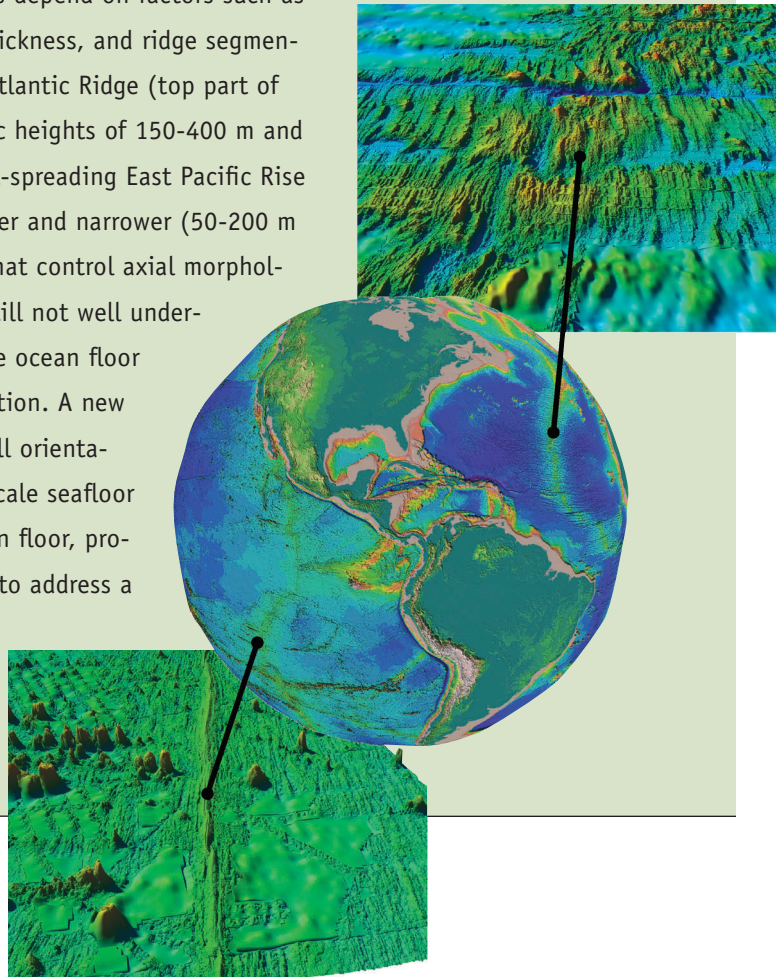


Figure 7. The global-scale variations in the depth of the ocean basins are explained by the plate tectonic theory as manifestations of a heat transfer process called convection. Radioactive decay generates heat in Earth's rocky interior, the mantle. Hot mantle material wells up at spreading ridges to form new oceanic crust and rigid plates. As the plates age they cool and contract causing a deepening of the seafloor with distance from the spreading ridge. Eventually, the dense, cold plates descend into the mantle at subduction zones. According to the theory, seafloor topography generated at mid-ocean ridges consists of ridge-parallel abyssal hills and ridge-perpendicular fracture zones. During the plate's journey from the ridge axis to the subduction zone, seamounts are created and sediments blanket the abyssal hills. Image courtesy of Alan Trujillo and Prentice Hall, Inc.

abyssal hills:

the most common landform on earth

Abyssal hills are the most pervasive landform on Earth. They are formed at mid-ocean ridges through a combination of surface faulting and constructional volcanic processes (Figure 7). Over time, as they ride the tectonic plates across the deep ocean basins, they are modified by landslides and sedimentation. The size and shape of abyssal hills depend on factors such as spreading rate and direction, crustal thickness, and ridge segmentation. Along the slow-spreading Mid-Atlantic Ridge (top part of image), abyssal hills have characteristic heights of 150-400 m and widths of 4-14 km, while along the fast-spreading East Pacific Rise (lower, left image) they are much smaller and narrower (50-200 m height, 1-5 km width). The processes that control axial morphology and abyssal hill development are still not well understood because only a few percent of the ocean floor has been mapped with sufficient resolution. A new satellite mission would yield abyssal hill orientation and other parameters of the fine-scale seafloor roughness spectrum for the entire ocean floor, providing significantly more data required to address a broad range of problems from plate tectonics to climate change.



origin of undersea volcanoes

Seamounts are active or extinct undersea volcanoes. They sustain important ecological communities, determine habitats for fish, and act as obstacles to water currents, enhancing tidal energy dissipation and ocean mixing. For all these reasons, it is important to map them. Seamounts come in a range of sizes, and the smaller ones are much more common than the larger ones. Analysis of the size distribution suggests that a new space-based mapping should increase the number of charted seamounts 18-fold, from roughly 3000 to nearly 60,000 (Figure 8).

The map pattern of seamount locations may settle a debate about the fundamental relationship between volcanism and plate tectonics. In basic

plate theory, plate interiors are geologically inactive, and so a “hot spot” theory was added to explain linear volcanic chains in the middles of plates, such as at Hawaii. Although this theory is now enshrined in all introductory textbooks, many scientists are questioning its validity, some believe it cannot explain all seamount chains, and a few scientists do not believe hotspots exist at all. Alternative explanations include excess magma supply spilling beyond mid-ocean ridges, stretching and cracking of plates, or small-scale convection under plates. A space-based mapping will be required to settle the debate, as the seamount distribution pattern can only be revealed by a systematic mapping with a globally uniform resolution of seamount sizes.

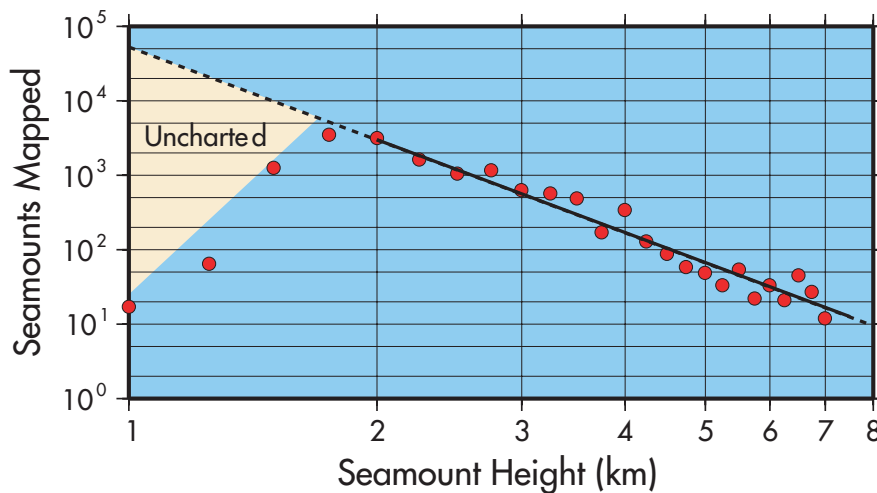


Figure 8. Seamounts—undersea volcanoes that deflect currents and create habitats—come in a range of sizes. A new Bathymetry from Space mission should increase the total number of seamounts mapped by 18-fold, if the relationship shown here can be extrapolated. The new-found seamounts will have important ramifications for physical oceanography, marine ecology, fisheries management, and fundamental science questions on the Earth’s magma budget and the relationship between volcanism and tectonics.

forecasting tsunamis

Tsunamis are waves triggered by earthquakes and landslides or, rarely, an unusually large seafloor volcanic eruption. A large tsunami can drive huge waves against the coastlines, endangering people and damaging property in low-lying areas. Since 1990, tsunamis have caused \$100 million in damage, killed more than 4,500 people, and left more than 145,000 homeless. Early warning systems for tsunamis can save lives by allowing people to evacuate, but tsunami forecasts have to be done quickly since tsunamis can traverse the entire Pacific Ocean in just a few hours.

Tsunami simulations have shown that relatively small-scale details of deep-ocean bathymetry have a significant impact on tsunami heights because of the cumulative effect of refraction (Figure 9). In many parts of the North Pacific, the predicted maximum tsunami height differs dramatically depending on the resolution of the bathymetry. Further improvements in bathymetry are expected to produce significant improvements in tsunami forecasts, facilitating mitigation in shoreline regions that are frequently endangered and allowing targeted evacuations of at-risk populations.

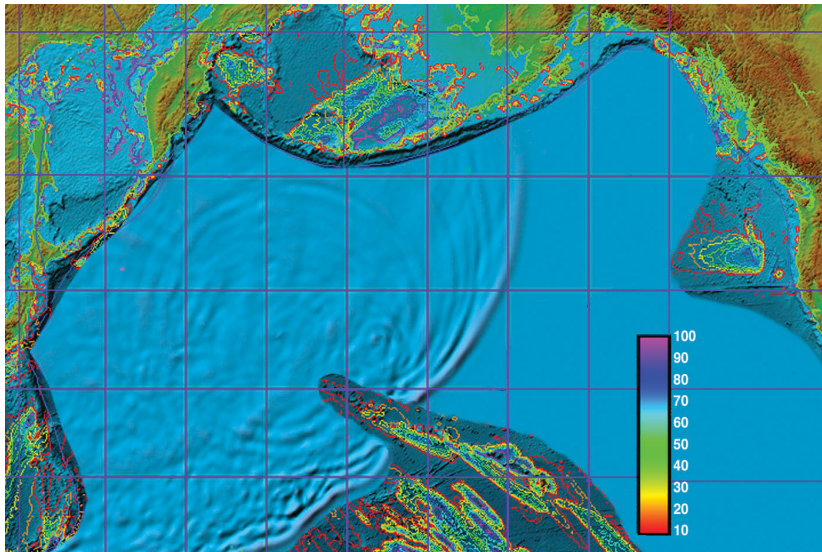


Figure 9. Tsunamis (popularly called “tidal waves”) are catastrophic shock waves that can flood coastal areas after a submarine earthquake or landslide. A submarine event on one side of an ocean basin can flood the coasts on the other side in a matter of hours. Careful modeling of the propagation and refraction of these waves is a key component of hazard mitigation. Model studies have shown that lack of information about the small-scale bathymetry of the ocean floor makes the estimated height of the flooding wave uncertain by 100% or more. Shown here is a model of the tsunami generated by the December 5, 1977 earthquake in Kamchatka. Blue regions in the open ocean show the tsunami spreading outward, like a wave that forms after dropping a pebble into a pond. Rainbow colors indicate the percent change in amplitude attributed to fine-scale bathymetry. Image courtesy H.O. Mofjeld, NOAA PMEL.

tsunami generated by the April 1, 1946, Aleutian Islands, Alaska earthquake



Before and after pictures of the Scotch Cap Lighthouse on Unimak Island, Alaska (left). A magnitude 8.0 earthquake to the south of Unimak Island generated a tsunami that destroyed the five-story lighthouse, located 10 m above sea level. Only the foundation and part of the concrete sea wall remained. All five occupants were killed. The waves deposited debris as high as 35 m above the sea. Although little damage occurred in Alaska, except at Scotch Cap, the tsunami was one of the most destructive ever to occur in the Hawaiian Islands. Photo credit: U.S. Coast Guard.

Wreckage of a political party clubhouse (right), Kamehameha Avenue, Hilo, Hawaii, resulting from a tsunami generated by the same Alaska earthquake. Every house on the main street facing Hilo Bay was washed across the street and smashed against the buildings on the other side. Houses were overturned, railroads ripped from their roadbeds, coastal highways buried, and beaches washed away. The waters off the island were dotted with floating houses, debris, and people. Property damage in Hawaii was \$26 million (1946 dollars). Photo credit: U.S. Army Corps of Engineers.



other applications of improved bathymetry

continental margins and hydrocarbon exploration

Geologists call the outermost layer of rocky earth the “crust.” Both continental and oceanic geological processes create crustal rocks, but of distinctly different physical and chemical types. The transition from oceanic to continental crust is at the continental margins. It is structurally complex and often obscured by thick layers of sediment shed from the continent. Understanding the margins and their sedimentary basins is important because most of the world’s mineral, oil, and gas wealth is formed in basins at the continental margins, and because new international law allows new territorial claims in this area.

In the deep ocean, the crust is formed by oceanic processes, overlying sediments are thin, and the subseafloor geology is simple enough that ocean surface gravity anomalies observable from space are easily correlated with bathymetry. This is the principle that allows bathymetric mapping from space by satellite. The situation is different at a continental margin where the various sedimentary layers and underlying rocks are of variable thickness and contrasting composition and density, producing gravity anomalies uncorrelated with bathymetry. The continuous high-resolution data set of altimetric gravity anomalies that would be collected during a high-resolution space bathymetry mission would be used to map

bathymetry in the deep ocean and also geologic structure on the continental margins. The lack of direct correlation between bathymetry and gravity at a margin is not a problem, as margins are usually well-enough covered with conventional bathymetric data, allowing geophysicists to interpret the gravity anomalies in terms of sub-seabed structure.

The gravity data obtained from a new space bathymetry mission would dramatically improve our understanding of the variety of continental margins:

- An image of the gravity field is useful for the study of mass anomalies (e.g., sediment type and distribution) and isostatic compensation at continental margins.
- A uniform, high-resolution data set continuous from the deep ocean to the shallow shelf will make it possible to follow fracture zones and other structures out of the ocean basin onto the adjacent continent, to define and compare segmentation of margins along their length and identify the position of the continent-ocean boundary.
- Rifted fault-bounded blocks of continental crust often have dimensions of 5-25 km by 20-100 km. One must be able to constrain the shapes of

Figure 10. Major offshore sedimentary basins around the world (green) contain much of the world's hydrocarbon resources. Future exploration will focus on largely unexplored areas up to 3-km deep. In many of these areas, gravity anomalies derived from satellite altimetry provide the only reconnaissance information to guide seismic and other detailed surveys.



these blocks in three dimensions to understand rifting tectonics. These individual blocks are not resolved in current data but would be mapped by the proposed space bathymetry mission.

Improved mapping of structures and sediment deposits on rifted margins has economic as well as academic value. Sedimentary basins are the low-temperature chemical reactors that produce most of the hydrocarbon and mineral resources upon which modern civilization depends (Figure 10).

While current altimeter data delineate the large offshore basins and major structures, they do not resolve some of the smaller geomorphic features and they cannot be used to detect some of the smaller basins. Spatial scales shorter than 20 km in the presently available data cannot be interpreted with confidence close to shore, as the raw altimeter data are often missing or unreliable near the coast. The exploration industry would like to have altimeter data with as much resolution as possible and extending as near-shore as possible.

law of the sea definition of the continental shelf

One of the many objectives of the United Nations Convention on the Law of the Sea is to subdivide ocean space into zones under the jurisdiction of a Coastal State or of the International Seabed Authority. Coastal States may claim territorial rights to the seabed and its resources beyond their traditional Exclusive Economic Zones by submitting a claim to a Juridical Continental Shelf. This shelf

represents a seaward prolongation of a State's territory and must delineated according to a complex legal formula prescribed in Article 76 of the Convention. Bathymetry from space can potentially contribute to resolving one element of the formula, namely the 2500 m isobath. It is also likely that altimetry can contribute to the problem of determining the location of the foot of the slope. Such uses of altimetric data are consistent with the view

expressed by the Commission on the Limits of the Continental Shelf that altimetric data will be considered admissible as supporting information in a submission.

Although publications on space bathymetry caution that the technique may not be most accurate in continental slope and rise areas, it seems to be accurate enough for the purpose of determining a Juridical Continental Shelf under Article 76. A joint U.S.-Canadian study compared the location of the 2500 m isobath as measured by acoustic swath bathymetry from a GPS-navigated ship sur-

vey and as estimated from the space bathymetry technique using existing satellite data. The study found that the location discrepancies between the two techniques were small enough to be within International Hydrographic Organization guidelines for errors in bathymetric surveys. To maximize the territory claimed, the Convention allows Coastal States to select data emphasizing seaward protrusions of their shelves. Thus, it is likely that space bathymetry will be used for initial reconnaissance of areas where a State might profitably invest in more detailed ship surveys.

inertial navigation

A passenger in a moving vehicle can close her eyes and perceive changes in the vehicle's velocity (direction or speed) because they cause her body to lean in the direction opposite the change. Inertial navigation systems work the same way, computing the motion of a vehicle by sensing accelerations on it. Precise inertial navigation systems require knowledge of gravity anomalies, for otherwise a tilt of the direction of gravity (Figure 2) is mistaken for a turn of the vehicle.

Advanced integrated navigation systems now in use on some ships and aircraft require knowledge of anomalies in the direction of gravity at the 0.5 arc-second (2 microradians) level for optimum performance. Data supporting this requirement were

collected over limited areas of Earth during the cold war, and remain classified. A systematic global data set of this quality does not yet exist. The measurements that a new bathymetry from space mission would obtain, sea surface slopes to 1 microradian, will allow computation of the gravity deflection angles at sufficient precision to support precise inertial navigation at sea over nearly all the globe. The improved spatial resolution of a new mission will be particularly useful to slow-moving vehicles such as submarines. Inertial navigation systems are very sensitive to errors resonant at an 84 minute period; vehicles moving slowly enough (around 4 knots) take this long to cover the length scales not yet mapped but resolved by the new mission.

implementation

Current space bathymetry can resolve 12 km on rough seafloor and only 20 km on smooth seafloor. A new mission with sufficient accuracy to resolve 8 km would capture most of the interesting geophysics of seafloor spreading and the statistical properties of the finer-scale roughness.

current limitations and future requirements

The laws of physics impose a fundamental limit on the resolution of the recovered topography to about twice the regional ocean depth, which is ~8 km in the deep ocean. This physical limit has not yet been achieved from satellite altimetry because the ocean surface is roughened by waves that are typically 2-4 m tall. Conventional radar altimeters illuminate a spot on the ocean surface that is large enough to average out some of the local irregularities due to ocean waves. The noise is further reduced by averaging a thousand pulses over a 6 km distance along the satellite track. Attaining the physical limit will require a factor of five improvement in the accuracy of the global sea surface slope, which can be achieved through a combination of improved radar technology and multiple mappings. We envision a new mission with the following characteristics:

Altimeter precision. The most important requirement is improvement in ranging technology to achieve at least a factor of two enhancement in range precision (with respect to older altimeters such as GEOSAT and TOPEX) in a typical sea state of 3 m. In shallow water, where upward continuation is minor, and in calm seas where waves are

not significant, it will also be important to have an along-track footprint that is less than one-half of the resolution. This footprint is smaller than the standard pulse-limited footprint of GEOSAT or TOPEX so new technology must be used.

Mission duration. The GEOSAT Geodetic Mission (1.5 years) provided a single mapping of the oceans at ~5 km track spacing. Since the measurement noise scales as the square root of the number of measurements, a six-year mission could reduce the error by an additional factor of two.

Moderate inclination. Current non-repeat orbit altimeters have relatively high inclination (72° GEOSAT, 82° ERS) and thus poor accuracy of the East-West slope at the equator. A new mission should have an inclination of ~60° to improve East-West slope recovery. This, combined with the other improvements, will meet the factor of five requirement.

Near-shore tracking. For applications near coastlines, the ability of the instrument to track the ocean surface close to shore, and acquire the surface soon after leaving land, is desirable.

It should be stressed that the basic measurement is not the height of the ocean surface but the slope of the ocean surface to an accuracy of better than 1 microradian (6 mm height change over 6 km horizontal distance). The need to resolve height differences, and not heights, means that the mission can be much cheaper than other altimeter missions and can take advantage of a spacecraft platform that is less stable than other missions require. The 1 microradian slope precision can be achieved without measuring radar propagation delays in the ionosphere and troposphere, as the slopes of these corrections are negligible. These factors reduce the cost and complexity of the spacecraft with respect to a typical altimeter optimized for recovery of ocean currents.

Delay-Doppler altimeter technology. A delay-Doppler radar altimeter can deliver the required height precision and spatial resolution. This innovative satellite altimeter uses signal processing strategies borrowed from synthetic aperture radar to improve height measurement precision by a factor of two, and to reduce along-track footprint size by a factor of five or more, in marked contrast to a conventional radar altimeter. The signal processing can be performed on-board in real-time, resulting in a modest data downlink rate. The delay-Doppler altimeter has been built by the Johns Hopkins University Applied Physics Laboratory (JHU APL) and flight-tested on Naval Research Laboratory (NRL) and National Aeronautics and Space Administration (NASA) P-3 aircraft. A preliminary design study by JHU APL for the National Oceanic and Atmospheric Administration (NOAA) suggests that a delay-Doppler space bathymetry mission could be completed for approximately \$60 M, plus launch costs.

Swath altimeter technology. The Wide-Swath Ocean Altimeter (WSOA) was designed by NASA's Jet Propulsion Laboratory (JPL) to measure changes in ocean topography over a 200 km swath, with height postings every 15 km and height accuracy better than 5 cm. These measurement characteristics were selected to sample ocean mesoscale phenomena and tides, and have the potential to greatly improve our understanding of ocean circulation. However, as currently designed, the WSOA will not meet the 1 microradian slope requirement for seafloor bathymetry. Moreover, the 15-km postings are inadequate for achieving 8-km resolution. Finally, since the proposed WSOA must follow the ground track of the TOPEX/Poseidon and Jason altimeters to provide long-term stability for monitoring global climate, it will not provide complete ocean coverage. In principle, one could design a WSOA that would meet bathymetric accuracy and resolution requirements, but at a much higher cost and much greater complexity than the delay-Doppler technology. Bathymetric coverage would require deviation from the standard TOPEX-Jason ground track, which would mean that a bathymetric WSOA mission would not contribute to the long-term record of sea level that is critical for understanding ocean climate. Thus, the WSOA oceanography mission and the space bathymetry mission have conflicting goals and it is not possible, let alone cost effective, to try to meet both goals with one mission or technology.

partners

The *Bathymetry from Space* concept serves the needs of, and will be supported by, federal agencies, corporations, educators, and individuals.

- The National Aeronautics and Space Administration's Earth Science Enterprise program requires bathymetry and seafloor roughness to understand the earth climate system—in particular, the effects of ocean circulation and mixing on temperature, CO₂, and sea level.
- The National Oceanic and Atmospheric Administration requires gravity and bathymetry for many of their functions including geodesy, environmental prediction, fisheries management, and coastal charting, including issues related to the Law of the Sea.
- The National Science Foundation's basic science programs such as RIDGE2000 and MARGINS programs examine specific localities. Bathymetry from space will provide the global framework and context for these local studies.
- The National Imagery and Mapping Agency and the Department of Defense require high-resolution deflections of the vertical (marine gravity) to support real-time inertial navigation of their vehicles.
- The petroleum exploration industry requires high-resolution gravity anomalies for deep-water exploration along the global continental margins.
- Educators and the general public use global bathymetric maps to increase the public understanding of the deep oceans—the last unexplored regions of our planet.

appendix 1

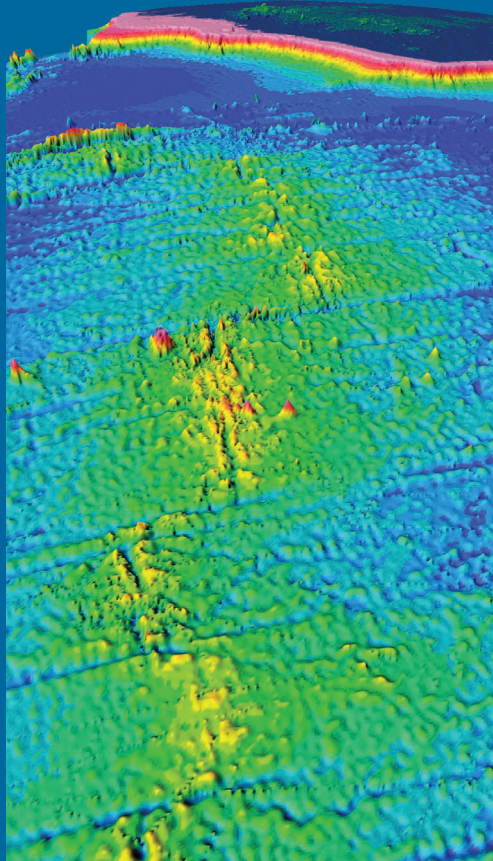
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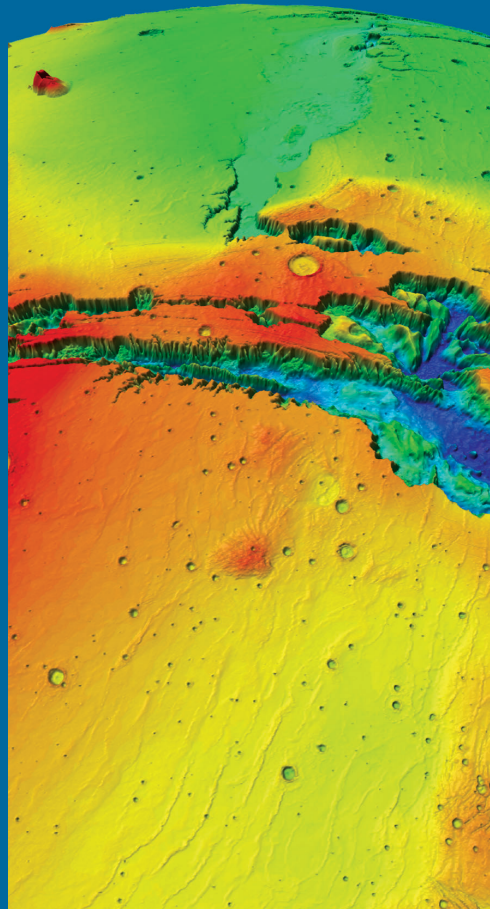
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Earth vs. Mars

mapping the surface of planets from space



Ocean Floor



Mars

The surfaces of Mars, Venus, and the Moon are much better mapped than Earth's ocean floors. Topography of Earth's Mid-Atlantic Ridge (left) derived from sparse ship soundings and satellite altimeter measurements reveals the large-scale structures created by seafloor spreading (ridges and transforms) but the horizontal resolution (15 km) and vertical accuracy (250 m) is poor. Topography of Valles Marineris on Mars (right) reveals both the large-scale structure of the canyon as well as the smaller impact and fracture features. These images have the same horizontal and vertical scale. The horizontal resolution of the Mars data (1 km) is 15 times better than that of the Earth data, while the vertical accuracy (1 m) is 250 times better.