

Bathymetry from Space is Now Possible

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A new satellite altimeter mission to map the deep ocean bathymetry and gravity field five times better than existing global maps is being considered. This mission, which would be 16 times faster and cheaper than mapping the sea floor with conventional multibeam systems, would be used to probe the internal structure of the continental margins, and estimate sea floor topography and roughness spectra for geological, oceanographic, and climatological purposes (see boxed sidebar). Of course, the highest-resolution bathymetry maps come from shipboard systems, but so far, only 10% of the sea floor has been surveyed, and it will take 125 ship-years to map the deep oceans at a cost of about one billion dollars.

The accuracy of current altimeter-derived maps is limited by ranging noise and short mission duration. A new altimeter with improved technology and a non-repeating orbit could provide accuracy to 1 mGal within 6 years (<http://fermi.jhuapl.edu/abyss>). In the deep ocean, where there is little sediment cover, gravity and topography are highly correlated, so that gravity can be used to predict topography, but there is a fundamental resolution limit of π times the mean ocean depth, which is ~ 12 km full-wavelength, due to upward continuation. On the shallow continental margins, the gravity field reveals variations in sediment and crustal structure.

A workshop was held at Scripps Institution of Oceanography in California last October to examine the science that lies in the wavelength band that can be mapped from space, and to document the rationale and requirements for a high-resolution altimeter mission. Forty-seven experts in marine geology and geophysics, physical oceanography, satellite geodesy, space radar, education, and outreach participated. A list of participants and abstracts of some presentations are available at <http://topex.ucsd.edu/workshop>. A more complete report will be forthcoming.

Marine Geology

What ocean floor geology is revealed at these length scales, and why does it matter? Satellite altimetry has revealed the large-scale manifestations of plate tectonics such as sea floor spreading ridges, transform faults, fracture zones, and linear volcanic chains. However, shipboard multi-beam surveys—which are largely guided by altimetry—have shown that many complex details of plate tectonics are poorly understood. In the deep ocean, these features include abyssal hills and other spreading fabric, seamount chains, volcanic ridges, and outer rise fractures. The roughness spectrum of the ocean floor varies considerably from one place to another, and the tectonic controls on this texture are poorly understood.

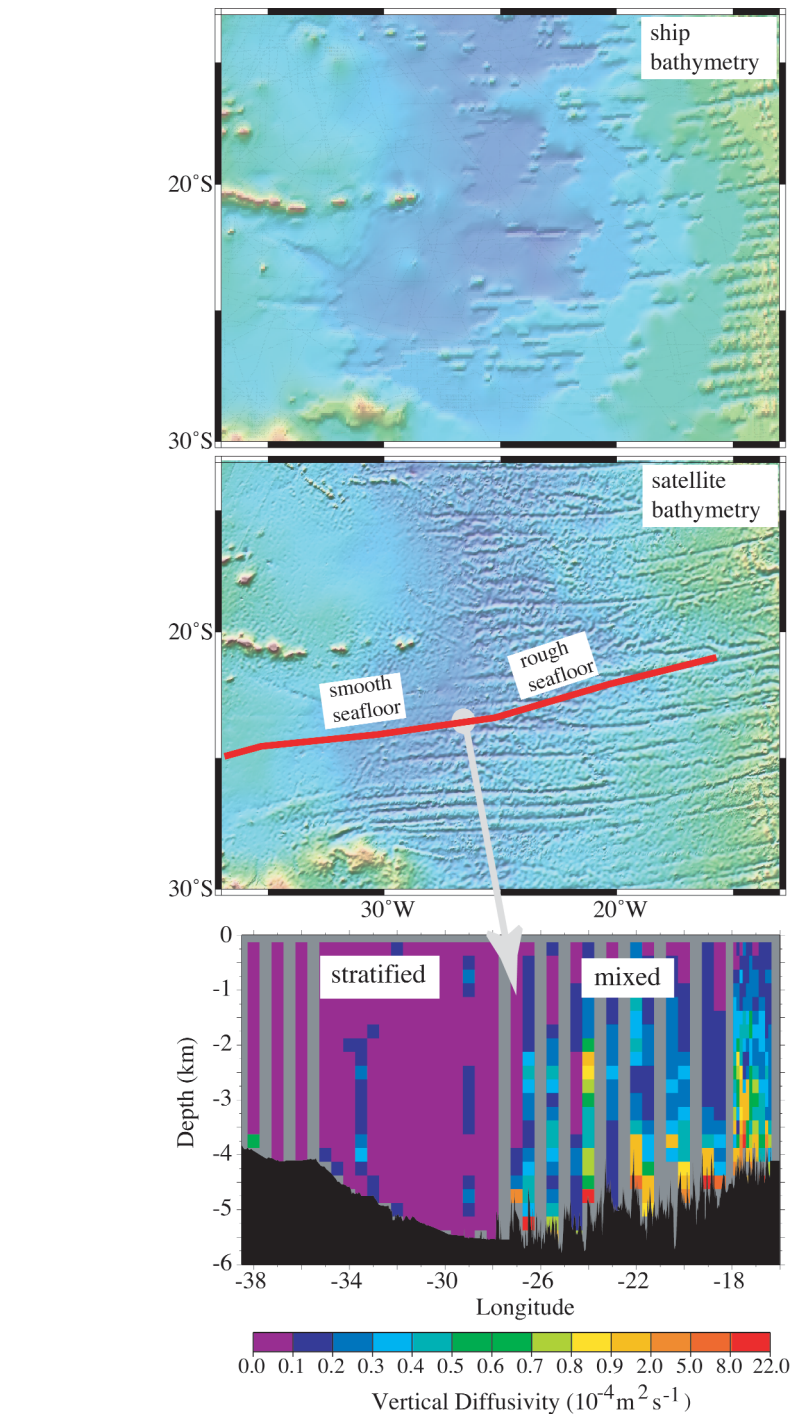


Fig. 1. (upper) Bathymetry of Brazil Basin, South Atlantic, derived from ship soundings, lacks the resolution needed to distinguish between rough and smooth sea floor; (center) Bathymetry derived from satellite altimetry and ship soundings resolves the rough sea floor associated with fracture zones, but not abyssal hills; (lower) Vertical diffusivity represents vertical mixing of stratified seawater. Mixing rates are an order of magnitude greater over rough topography (abyssal hills and fracture zones) than they are over smooth topography. Enhanced mixing over rough topography extends from depths of about 1500 m to the bottom of the ocean (> 4000 m). Mixing affects the vertical stratification, which in turn influences deep currents.

Sea floor spreading ridges and their flanking abyssal hill topography can be broadly divided into two categories. Smooth ridges—which are usually fast-spreading; for example, the East Pacific Rise—have a small axial summit that is infrequently offset by transform faults, narrow and highly elongate abyssal hills on the ridge flanks, and overall roughness amplitudes away

from seamounts generally under ~ 200 m. Rough ridges—usually slow-spreading; for example, the Mid-Atlantic Ridge—have a deep axial valley that is frequently offset by transform faults, broader and less elongate abyssal hills, and overall roughness amplitude that is two or more times larger than that of smooth ridges. Current satellite altimetry shows large-scale

roughness variations that appear correlated with smaller-scale sea floor fabric variations, but cannot directly resolve abyssal hill topography.

A new mission would yield abyssal hill orientation and other parameters of the fine-scale sea floor roughness spectrum. A global map of abyssal hill orientation would reveal new details in plate reorganizations and non-rigid plate behavior over the past 200 Ma of Earth history, and provide important clues about the causes and mechanisms of "second-order" plate tectonics.

Seamounts are ubiquitous undersea volcanoes that form in two separate tectonic environments. Most smaller seamounts form near mid-ocean ridges, most likely due to excess magma supply. Most larger seamounts are believed to be formed over mantle plumes at so-called hotspots, although Earth scientists still debate this issue. Extrapolation of seamount statistics derived from current satellite altimetry data suggests that there may be as many as 100,000 seamounts on the ocean floor with heights exceeding 1 km, although this estimate is highly uncertain, since it is based on only 15,000 seamounts in the 2–7 km height range. Combined, these undersea volcanic features represent a significant fraction of the volcanic extrusive budget (perhaps as much as 10–20%), and their distribution gives vital information about spatial and temporal variations in intra-plate volcanic activity.

Seamounts also act as obstacles to water currents and thus enhance tidal dissipation. Finally, seamounts sustain important ecological communities and determine habitats for fish. Thus, complete mapping of the world's seamounts has important ramifications for marine geophysics, physical oceanography, marine ecology, and fisheries management. A new altimeter would resolve perhaps 85,000 new seamounts.

Ocean Circulation

Is bathymetry at these scales important for oceanography or climate modeling? Bathymetry steers ocean currents and blocks the flow of deep and bottom waters between ocean basins. Observational physical oceanographers often rely on global bathymetric data to indicate the locations of canyons and fracture zones. Numerical models simulating present and future ocean circulation depend on bathymetric data to provide an accurate bottom boundary condition.

Current bathymetry is sufficient for climate models and is just adequate for current ocean general circulation models. However, sensitivity studies indicate that small changes in bathymetry can have major impacts on circulation. For example, in the Naval Research Lab model, a change in the depth of only three points in a $1/16^\circ$ grid altered the Kuroshio path in the Luzon Strait region. As computers grow faster, model resolutions are increased, and errors in bathymetry may soon limit model performance.

Ocean Mixing

Small-scale bottom roughness appears to be directly related to tidal dissipation, internal wave generation, and vertical mixing of the ocean.

Applications of High Spatial Resolution Satellite Altimetry

Topography Applications:

- fiber optic cable route planning
- tsunami propagation and hazard models
- hydrodynamic tide models and tidal friction
- coastal tide model improvements
- ocean circulation models
- tidal role in ocean mixing
- understanding sea floor spreading ridges
- identification of linear volcanic chains
- education and outreach for geography of the ocean basins
- law of the sea
- fisheries management

Gravity Applications:

- inertial guidance of ships, submarines, aircraft, and missiles
- planning shipboard surveys
- mapping sea floor spreading ridges and microplates
- continental margin structure
- petroleum exploration
- plate tectonics
- strength of the lithosphere
- search for meteorite impacts on the ocean floor

Observations of ocean microstructure carried out as part of the Brazil Basin Experiment show that mixing is enhanced by an order of magnitude above rugged abyssal topography compared with smoother sea floor (Figure 1). The Hawaii Ocean Mixing Experiment is examining the specific processes governing tidal dissipation at the Hawaiian Ridge. As results from the field programs are fully analyzed, investigators will require the best possible global bathymetry to extrapolate their findings globally and provide mixing estimates that can be used in climate studies.

Theoretical and observational studies suggest that tidal flow over abyssal topography generates internal waves, which mix the ocean vertically. These waves can be generated from abyssal hill topography with full wavelengths of 1–30 km, even if the topographic slopes are small. Current altimeter data do not resolve sea floor topography at mixing-controlling scales. A new mission could map length scales that may control 50–70% of the energy conversion from barotropic to baroclinic tides, but some features responsible for generating individual mixing events will never be visible from space. However, the spectrum of abyssal hill topography depends on a relatively small number of statistical parameters. If a new altimeter mission resolves ~15 km full wavelengths, these parameters may be captured, allowing roughness spectra to be extrapolated over the entire band of wavelengths important for internal wave generation.

Climate and Sea Level Forecasts

Ultimately, global estimates of vertical mixing are likely to influence ocean circulation and climate models. Recent model experiments indicate that the circulation is sensitive to regional variations in vertical mixing rates that are linked to topographic roughness. Vertical mixing rates also influence climate and sea

level by governing heat transfer from the atmosphere to the ocean.

What about the continental margins? The transition from oceanic to continental crust is structurally complex and often obscured by thick layers of sediment shed from the continent. Changes in the thickness and elevation of these layers can be tracked with gravity anomaly data. Current altimeter-derived gravity provides the plate tectonic framework for continental margins and resolves the transition from continental to oceanic crust and the larger scale (~40 km) sedimentary basins on rifted margins. However, many of the economically important basins and their controlling fault blocks have characteristic wavelengths of between 10 and 50 km and are poorly resolved by current altimetry. A new mission would dramatically improve our understanding of the variety of continental margins, facilitate comparisons between margins, assist reconnaissance exploration for oil and gas, and guide the interpolation of widely spaced, two-dimensional seismic survey lines.

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