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FORUM

GOMaP: A Matchless Resolution to Start the New Millennium

The world's ocean floor, which is almost equal in area to two moons plus two Mars-sized planets, is one of the most poorly mapped "terrestrial" surfaces in our solar system (Figure 1) [*Vogt and Tucholke*, 1986]. We propose a multiyear international effort to map the entire ocean floor using hull-mounted or towed sidescan/swath bathy-metric systems. The Global Ocean Mapping Project (GOMaP) would produce a seafloor backscatter image whose lowest spatial resolution, in the deep trenches, would be at least 100 m, comparable to that returned by the Magellan radar mission to Venus or Clementine's optical imaging of Earth's moon. GOMaP would simultaneously recover the bathymetry, a tight grid of water depths, as the second kind of ocean floor "image" but at slightly lower spatial resolution than the backscatter image. A GOMaP mission would collect numerous additional "piggy-back" data, from seismic reflection profiles of the subbottom to whale counts, at little extra cost.

The inner solar system's planets and moons—as well as most moons of the outer solar system and all the asteroids—have crisply defined rocky, muddy, or icy outer surfaces. These surfaces can be either exposed nakedly to outer space (for example, the Moon and asteroids), totally hidden from optical view by a thick atmosphere (for example, Venus), partially obscured by a hazy and cloudy atmosphere (the terrestrial Earth), or hidden below liquid water seas (70% of the Earth, perhaps also the Galilean moon Europa).

The nature of the media enveloping these planets and moons has dictated the methods of "imaging" their surfaces. Here we use "imaging" in its broadest sense, including quantitative topographic mapping and both passive and active techniques.

Stunning images have been returned from most of the terrestrial planets and moons in the last quarter century. For example, the Magellan mission mapped the nearly Earth-sized planet Venus at spatial resolutions of ~70–200 m, and similar radar imaging by RADARSAT of the subaerial Earth is ongoing; resolution for broad swaths is 100 m and as fine as 12.5 m for detailed swaths [*Mahmood et al.*, 1998].

Earlier this year, the NASA/National Imagery and Mapping Agency Shuttle Radar Topography Mission (SRTM) used synthetic aperture radars to map over 80% of Earth's land mass on a 30 x 30 m sampling grid, to a 16 m absolute height accuracy. The entire Moon was imaged multispectrally in sunlight by the Naval Research Laboratory's (NRL) Clementine mission [*Nozette et al.*, 1994], at ~100–200 m (in some areas 20 m) pixel resolution (Figure 2d). Still sharper in resolution, by up to an order of magnitude, are some of the most recent extraterrestrial images, such as those from the Mars Global Surveyor mission (2–3 m) and the Galileo flybys of Callisto, Io, Europa, and Ganymede (10–200 m; *Showman and Malhotra* [1999]). The Mars Orbiter Laser Altimeter (MOLA) maps the entire planet's topography to less than 5 m vertical accuracy, at an along-track resolution of 330 m. This accuracy is at or better than what multibeam bathymetry can achieve in deep-ocean areas. The NEAR multispectral imager is currently resolving features as small as 10 m across on the asteroid 433 Eros.

While Earth's deep ocean floors can be acoustically imaged from the sea surface at roughly comparable resolution in both topography (Figure 2a) and backscatter (Figure 2b), the existing data coverage at this resolution, from tens to hundreds of meters, is embarrassingly sparse and inconsistent (Figure 1). Only a small portion of the ocean floor has been systematically mapped with both sidescan and swath bathymetry. Our home planet's ocean floors are falling ever farther behind not only our dry lands, but extraterrestrial moons and planets. Admittedly, survey ships only travel at kilometers per hour, versus kilometers per second for orbiting spacecraft, but there are many ships, and detailed seafloor maps would arguably be at least as valuable to mankind as those from extraterrestrial bodies!

The global ocean floor data that do exist (Figure 1) are largely scattered near the margins of the industrialized nations, and in patches along the mid-oceanic ridge, or were collected along transit lines from ports to survey areas. It would probably be cheaper and more practical to begin GOMaP fresh instead of surveying around and among the existing surveys, and would certainly produce a more homogeneous image and database. Some mapping efforts in shallow-water [e.g., *Gardner et al.*, 1998] might be checked off as "done" in the GOMaP context, however.

The highest resolution of a relatively homogeneous, global ocean floor image is only 20-30 km, which was achieved by orbiting microwave altimeters mapping the ocean surface. This surface is approximately a gravity equipotential, to first order a smoothed representation of oceanfloor topography [*Sandwell and Smith*, 1997]. The spectacular world ocean altimetric image is still an order of magnitude

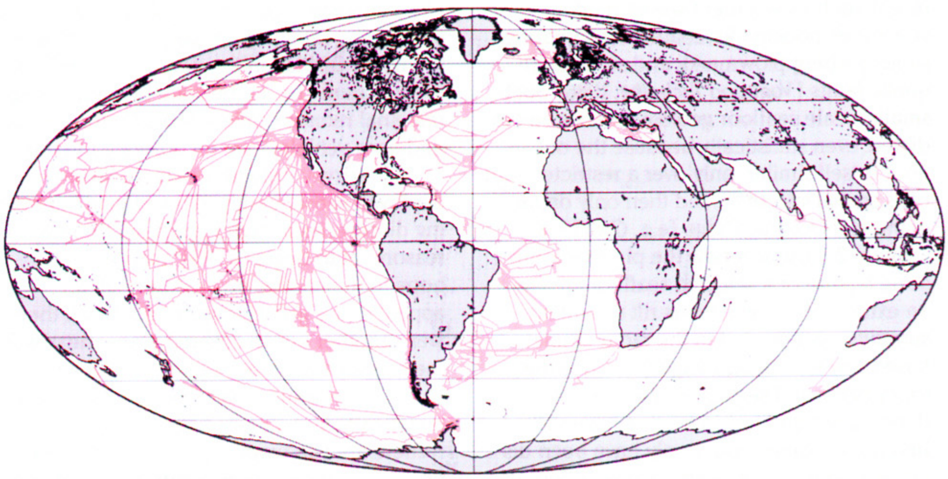

Fig. 1. Ship tracks (in red) along which swath bathymetry was collected, for data currently held by the National Geophysical Data Center (NGDC). Note that lines are many times wider than actual data swaths. Mollweide Projection, with 45°W the center meridian; latitude lines are spaced 15° apart, and longitude lines 45°.

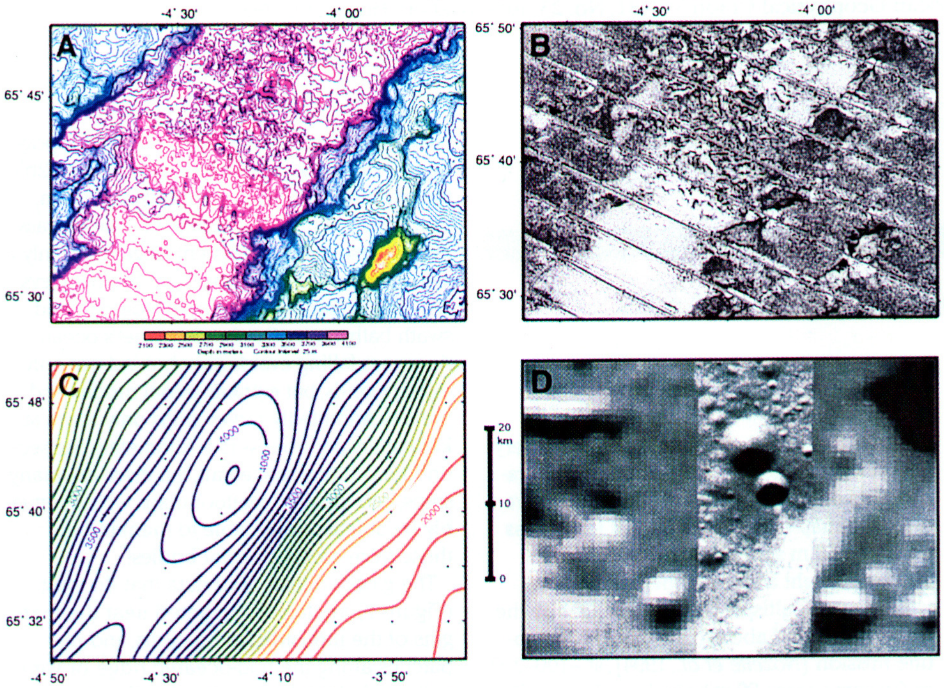

Fig. 2. a) 16 kHz multi-beam (HYDROSWEEP) bathymetry for part of the extinct Aegir Ridge rift valley, Norway Basin (NRL data). b) 11–12 kHz SeaMARC II side-scan sonar image of same area. Darker shades indicate stronger returns. (NRL data). c) ERS-1/GEOSAT-derived predicted bathymetry for same area [Sandwell and Smith, 1997]. d) Clementine solar-illuminated image of part of Schroedinger lunar crater, with area of same dimensions as in images a) and c). The central swath (20–40 m pixel resolution) is comparable in resolution to a 12 kHz ocean-floor side-scan image at 500–1000 m range, while outer areas of the image have spatial resolution comparable to that of 12 kHz sonar in the deep (~7 km) ocean.

lower in spatial resolution than the optic images obtained from Mercury in the early 1970s! The oceanic geoid reveals the main plate-tectonic "fabric" of the oceanic crust; for example, fracture zones, rift valleys, and large seamount chains. However, even the largest abyssal hills are barely resolved in the geoid, and there is no hint of the myriad smaller features that 100-m resolution imagery would reveal, such as sediment waves, mud volcanoes, pockmarks, channels, submarine slides, iceberg plowmarks, and small earthquake faults [*Vogt and Tucholke*, 1986]. Such smaller-scale seafloor geology cannot be predicted, even statistically, because the ocean floor is "self-similar" only over a restricted part of its spatial spectrum, and then only on flanks of the Mid-Oceanic Ridge [e.g., *Goff*, 1998].

Figure 2 illustrates how the plate-tectonic-scale feature of a selected seafloor area—an extinct rift valley and its rift mountain summits—is revealed in the radar altimetric-based low-resolution image (c), while the topography and sediment character of the debris flows and turbidites that have spilled into the rift valley could only have been discovered in the multibeam (a) and sidescan sonar (b) images. And, while correspondence is high between the bathymetric contours (a) and the backscatter imagery (b), the latter is clearly of still higher resolution and reveals features not seen in the topographic contours alone; for example, the "white" areas in the rift valley, which indicate the presence of very weak-backscatter turbidites. Clearly, the seafloor must be mapped in sonar imagery—the analogue of radar imagery of land—as well as topographic contours. And ideally, the sonars should produce more than seafloor "pictures;" full sonar calibration is required to extract actual values of backscatter strength from the measurements.

The acoustic and GPS-based (global positioning satellite) navigation technologies to initiate GOMaP in the near future are relatively mature (i.e., in the zone of diminishing marginal returns), unless AUVs (autonomous undersea vehicles) are incorporated in the GOMaP survey instead of—as we favor—deployed subsequently to investigate interesting discoveries at high resolution. There is no reason not to begin GOMaP planning. We hope to initiate this process through an appeal to the geoscience community. If there were another ocean-covered planet nearby in the solar system, robot survey vessels would surely be swarming over the planet's seas, systematically mapping its bottom!

There are two ways to swath-map the ocean floors acoustically from a surface vessel. The mapping can either be done from transducer banks mounted around the sides of the survey vessel—"hull-mounted" mapping—or from transducers mounted on "fish" towed behind the vessel. Each method has certain advantages, but we favor a hull-mounted approach. To date, seafloor mapping has used single-frequency systems, but future progress may make multifrequency sidescan practical.

Although the resolution of bathymetry returned by towed systems is not quite as good as from hull-mounted systems, the backscatter imagery is superior. However, as the location and attitude of a vessel can be more accurately determined than those of a "fish" towed behind the vessel, a pixel of hull-mounted data can be more accurately positioned; this advantage probably outweighs other considerations. With modern GPS navigation, seafloor features can be routinely located in absolute coordinates to spatial accuracies of 100 m or better with a hull-mounted system [*deMoustier*, 1993].

While towed systems are more mobile, making them more suitable for GOMaP projects involving a variety of ships perhaps contributed "in kind" by the international seafaring community, it is difficult and at times dangerous and time-consuming to launch and retrieve deep-water towfish, which are by necessity large and cumbersome. For this and other reasons, it also requires a larger complement of watch-standers and technicians to conduct a towfish-based mapping operation. Such extra manpower drives up the survey cost.

How big a project would GOMaP be? To land in the right ball park, we used the existing gridded (5′ latitude x 5′ longitude) global ocean bathymetric database and the data swath widths of several current state-of-the-art systems. Our fundamental requirement is 100% coverage of the entire ocean floor for both bathymetry and sidescan. Additional coverage—that is, overlapping swaths—will result at least from the transit tracks and would be valuable, particularly for sidescan, for which backscatter strength depends on grazing-angle and azimuth. In general, data swath widths for 9-15 kHz systems are limited by the water depths, ranging from about 20 km at 6000 m depth to 10 km at 3000 km and 1 km at 300 m depth. Higher-frequency systems can be used in still shallower water. Even though swaths from three to ten times water depth can be achieved, complete mapping still requires a very large track mileage.

However, smaller, cheaper vessels can be used in coastal regions, and the actual return in information is great, despite the narrow swath widths, due to the high resolution afforded by proximity to the seafloor and the higher acoustic frequencies. Waters 25–500 m deep cover less than 10% of the oceans yet require more than twice the survey distance and three times the survey time. But they will return an order of magnitude more pixels of information compared to the deeper water. In shallow areas of high water clarity, aircraft laser bathymetry and hyperspectral scanning may replace acoustics as the mapping tools of choice.

A shallow water (25–500 m) acoustic GOMaP will require about 58 million km of ship track, which equals about 166,000 ship days or 665 ship years. Comparable figures for the much larger deep-water ocean are a "mere" 25,800,000 km of ship track, about 54,000 ship days or 215 ship years. If U.S. UNOLS (University-National Oceanographic Laboratory System) vessels were used, the approximate cost for deep water would be $30 to $35 per square kilometer mapped, a figure that includes bathymetry, side-scan imagery, and geophysical data. Economy-of-scale factors could reduce this cost.

Simply comparing the cost of ocean floor mapping with NASA extraterrestrial missions per unit area obscures the difference in data types and relative value to mankind. For example, GOMaP seismic reflection profiles, which can "look" up to a kilometer or more below the seafloor, have no counterpart in extraterrestrial imaging missions. The latter cannot claim to help assess fishery stocks, assist in locating hydrocarbon and other mineral resources (at least for the foreseeable future), or show where to lay fiberoptic communications cables. Seafloor mapping discoveries can be followed up with ground-truthing expeditions and submersible visits whose extraterrestrial equivalents would be literally astronomical in cost. Few of today's extraterrestrial geologists will live to see their geological maps ground-truthed.

A complete GOMaP mission initiated using the present research fleet would cost about $10 to $20 billion, about half the cost of the International Space Station and much cheaper, in constant dollars, than the Apollo mission to the Moon. Spread out over a decade and divided among the major seafaring nations, a GOMaP "mission to the seafloor" would cost each no more than about $200 million annually. Economies of scale and use of ships from nations with lower labor costs would reduce the cost and spread research and development know-how.

Admittedly, GOMaP seems less glamorous than putting astronauts on the Moon or returning images of volcanoes on Io, but who can say what discoveries still await us on the ocean floor? As is true for extraterrestrial bodies, we won't know until we look!

The above discussion presupposes surface ships with towfish or hull-mounted systems. Other possibilities are fleets of radio-controlled survey "torpedoes," like the NRL's Oceanographic Remotely Controlled Automaton system [*Harris*, 1999] or fleets of AUVs launched by a GOMaP mother ship and skimming a few tens of meters above the seafloor, mapping it at high spatial resolution (0.1–1 m). The AUVs would surface to recharge their batteries at the mother ship or, in low latitudes, perhaps by solar power.

Manned submarines could also be pressed into GOMaP service, as demonstrated by the Seafloor Characterization and Mapping Package (SCAMP) sidescan/swath bathymetric system attached to U.S. Navy STURGEON-class nuclear submarines during the Arctic field seasons 1998 and 1999. Submarines can survey below the pack ice, and with much less vessel motion and lower acoustic noise and at higher speeds. However, navigation accuracy is reduced, and the true costs of operating a nuclear submarine, not to speak of the construction costs, are an order of magnitude higher than that of a survey vessel operating on the ocean surface.

The NRL will host a small, invited "pilot" GOMaP workshop this month. This workshop will address the technical issues raised above in more detail, and a White Paper will be made available to the world ocean geoscience community. Based on the response, a larger, more international workshop will be planned for 2001. Please contact the authors if you wish to be involved in some way.

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