John Orcutt standing on the fantail of R/V *Melville*.

THE EARTH *Beneath the Sea*

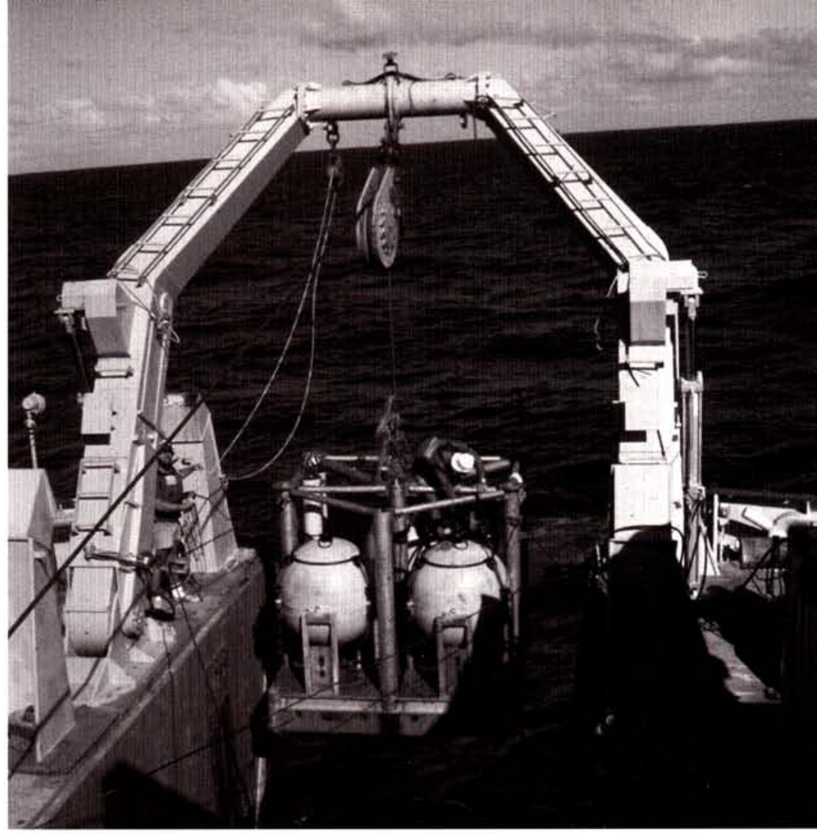
Researchers Explore Hidden Planetary Processes

BY CHUCK COLGAN

Consider the plight of marine geophysicists. Not only is their area of interest hidden within the earth's interior, it is also beneath the oceans, mostly in remote locations of the globe where the seafloor often is uncharted in significant detail. Going there requires long-range scheduling of large research ships, developing specialized instruments capable of penetrating through deep water and into the seafloor, and securing funds for experiments and personnel. "The sea makes marine geophysics a lot more difficult and a great deal more expensive than it would be if we could just go there on land," said Scripps Professor John A. Orcutt, director of the Cecil H. and Ida M. Green

Institute of Geophysics and Planetary Physics (IGPP). "There is a world of difference between our detailed knowledge of the continents and the oceans. Only very specific, small patches of the seafloor have been examined to the extent found on a standard topographic map."

The global seafloor is far larger than the continents, yet few data have been collected there, so scientists' studies of planetary processes are severely handicapped. The ocean basins hold valleys and mountains that dwarf any on land and contain the earth's single largest geophysical feature. It is a 30,000-mile-long submerged volcanic range called the mid-ocean ridge that spans the globe much like the seam of a baseball. Since its discovery in the late 1950s, the ridge system has become critical to understanding the earth as a whole and the processes of plate tectonics.



A substantial amount of earth's seismic activity, as well as most of the world's volcanism, is found along the crest of the mid-ocean ridge. Both heat and energy are transferred into the oceans, and new earth crust is created by upwelling magma. The recently formed seafloor pulls away perpendicular to the ridge in both directions, a process called seafloor spreading. This spreading moves the gigantic tectonic plates of the earth aside and, over eons, changes the face of our planet.

Marine geophysical investigations are much more than just academic pursuits. Some 70 percent of the earth's current crust was created at mid-ocean ridges, including significant ore deposits. Hidden in the seafloor are clues to the way useful and valuable minerals are formed and where they may be found on land.

(Top) The recording package for an ocean bottom borehole seismometer is recovered during a geophysical experiment at sea from R/V *Melville*. (Above) John Orcutt on R/V *Melville* while oceanographic equipment is loaded aboard for a recent cruise. (Right) Orcutt examines a bathymetric map of an area to determine the cruise destination. The map was prepared using satellite altimetry. See story page 24.

Heavy seas break over the bow of R/V *Melville* as seen from the ship's bridge during the Westward Expedition in November, 1994. Marine geophysicists on board were headed for an area of the seafloor known as the Australian Antarctic Discordance, some 1,200 miles southwest of Melbourne, Australia.

"Satellite maps are particularly useful in the Southern Ocean where the weather and sea conditions are so bad."

In addition, the volcanic activity at the ridges vents hot hydrothermal fluids that act as natural geochemical factories, emitting huge amounts of materials and adding significantly to global chemical cycling among the oceans, air, and land.

Marine geologists usually work on land because exploring the ocean bottom is expensive. Ship time alone can run $20,000 a day. A new survey tool is helping to reduce costs by improving scientists' ability to pinpoint specific locations prior to a cruise.

While planning the 1994 Westward Expedition on Scripps's 280-foot research vessel *Melville* to study the earth's structure deep beneath the seafloor near the Antarctic Circle south of western Australia, Orcutt and his colleagues began looking for a research site from an unexpected viewpoint–space. Maps of the region are sketchy, as it is out of normal ship tracks; and the weather and seas are so rough year-round that few venture that far south. But instruments on earth-orbiting satellites enabled Orcutt to locate a prospective site from the comfort of his La Jolla office.

The remote-sensing instruments, called radar altimeters, are used to measure the height of the sea surface to fractions of an inch. Sea-surface height is controlled by two factors: physical effects, such as waves and currents, and gravitational attraction created by geological structures on the seafloor. As a result, mountains cause the water to rise, and valleys create sea-surface depressions. Because the movement of the ocean and the effects of gravity create distinctively different and measurable signals, it is possible to filter out the oceans by using computer algorithms. What remains is a map of the surface gravity field that closely matches the large-scale features of the seafloor miles below.

"Satellite maps are particularly useful in the Southern Ocean where the weather and sea conditions are so bad, even in summer, that you can't spend a lot of time there doing general surveys to locate areas of interest," Orcutt said. "When we arrived at the coordinates we selected using the satellite data, the ship was not more than 3,000 feet from where we actually found the ridge crest–much better than we expected."

Submariner to Scientist

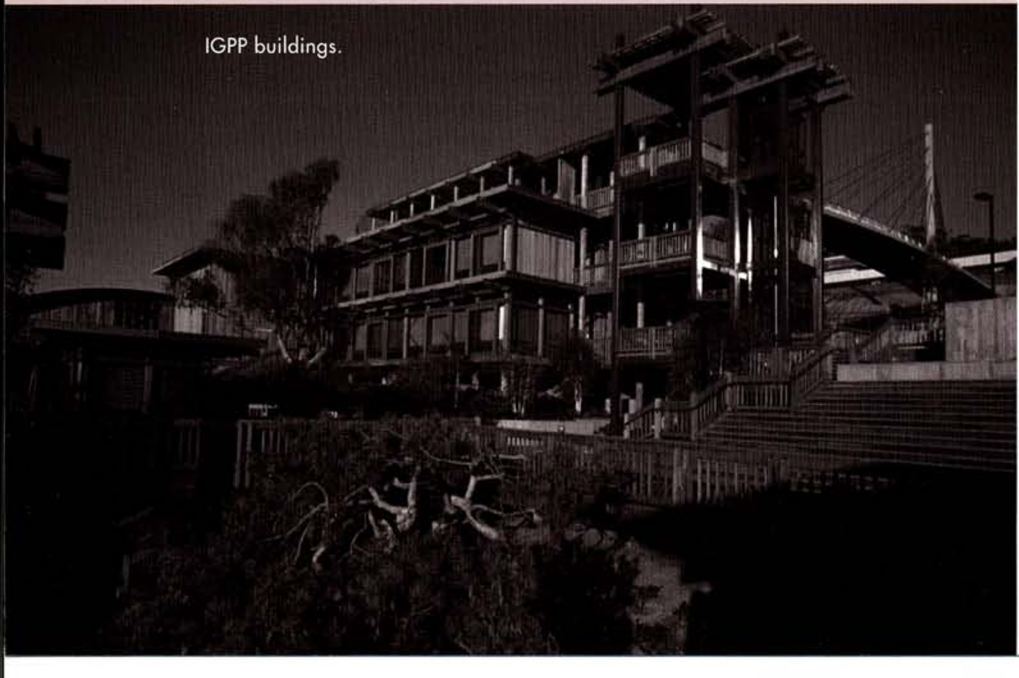
As director of the UCSD Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics (IGPP), John A. Orcutt oversees the largest academic research division at Scripps Institution of Oceanography with 175 faculty and staff members supported by a $21 million budget.

Orcutt is a 1976 Scripps graduate who came to oceanography via the U.S. Naval Academy and seven years of active duty, during which he served as a chief engineer on nuclear submarines. His areas of research include ocean-bottom seismology and the interpretation of acoustic waves to probe beneath the seafloor.

During the 1990s, Orcutt has averaged two ocean expeditions per year, but like most scientist-administrators, much of his time is spent in meetings, serving on advisory panels, and lobbying for funding. He would like to spend more time at sea, but reality dictates that he spend more time doing business in Washington, D.C., often with the Office of Naval Research and the National Academy of Sciences.

Orcutt thinks that within the next five years marine geophysists will be able to install and maintain a wide range of instruments and benchmarks on the seafloor to greatly increase geophysical measurements. He cites new technologies developed for large-volume data recording, global positioning, and acoustic remote sensing as innovations to research.

"I think we are on the edge of another substantial change in the way we work at sea with technology that will allow us to do longer term, less expensive experiments," Orcutt said. "So much of this is new that there have not been opportunities to try things out at sea, but we're making a good start."



IGPP buildings.

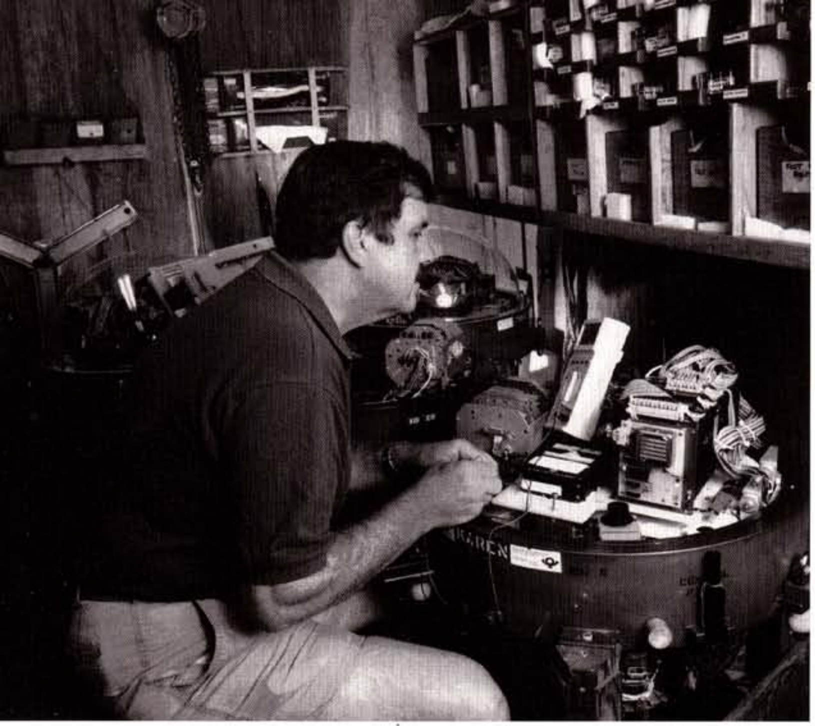
The expedition traveled to a section of the ridge that is different from other areas in that it is very deep, some 12,000 feet. Mid-ocean ridge crests normally are about 7,500 feet deep, because the rock material at the ridge is hot and thus, lighter than the surrounding seafloor.

Getting to the research site proved to be a high-seas adventure with gales gusting to 65 knots and waves more than 50 feet at times. *Melville's* weekly report understated, "this considerably slowed our transit to the site." According to Orcutt, it was a true test of sea legs and a testament to the crew's abilities to operate in rough seas. By the time they reached the site, the weather had improved, allowing the experiment to go smoothly.

Aboard *Melville*, the research team used sound waves to probe the seafloor structure. They placed seismic measuring instruments on the bottom and used large compressors to rapidly fire "air guns" to produce acoustic impulses that penetrated the rocky bottom. By measuring the return rates of the sound and the way its characteristics had been modified, they were able to produce three-dimensional computer images of the hidden ridge structure in much the same way as a CAT scan reveals details within the human body.

"What we are doing is looking at the same type of seismic signal that you would find from an earthquake, but because they are unpredictable natural phenomena, we bring our own source of energy," Orcutt said.

So far, analysis of the data has provided some intriguing evidence that the section of ridge crest surveyed is evolving differently. Orcutt reports that for some unknown reason, the mantle is cooler than elsewhere beneath the ridge, so the material is not as buoyant. The crust in this region is also thinner than expected. The findings offer only clues, not answers, as to why this ridge section is so deep.



"What we need is to record in the oceans continuously over long periods of time–something you can't do from a ship or a satellite."

Orcutt makes adjustments to a seismometer that will be deployed on the seafloor to record earthquake data for up to six months. After that time, it will be retrieved by means of an electronic release triggered from shipboard that causes the positively buoyant instrument to surface.

"It takes an awful lot of patience to do marine geophysics," Orcutt lamented. "The more we investigate the seafloor, the more questions arise. What we need is to record in the oceans continuously over long periods of time–something you can't do from a ship or a satellite."

Orcutt and other principal investigators have scheduled an expedition on *Melville* next year off Hawaii to test a system that promises to increase ocean bottom seismic data collection. The research team will place a seismograph into a previously drilled bore hole in the deep seafloor, and then leave the instrument there for three months to collect data. If that works well, the plan is to locate about 20 instruments in various remote areas over the next five years, creating the first ocean-bottom seismic network.

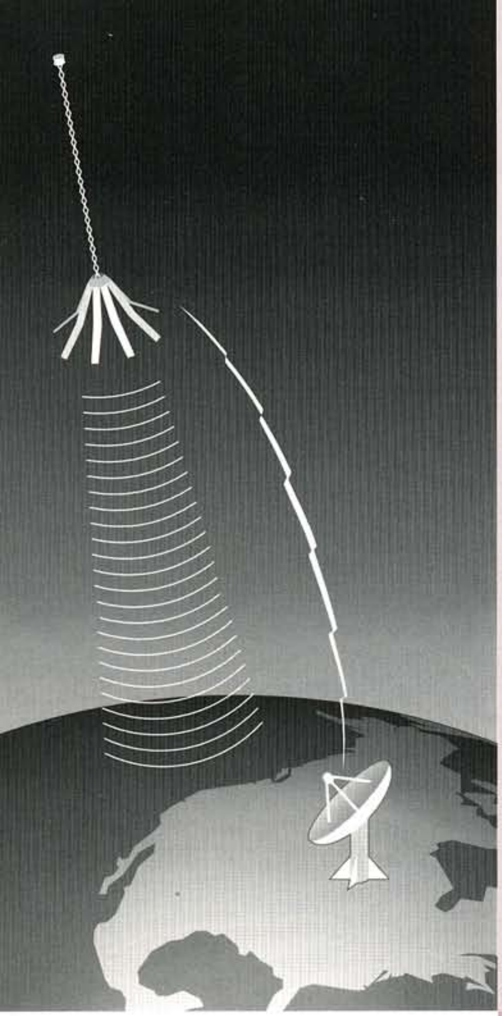
Ultimately, a surface buoy outfitted with data recorders will be tethered to each seafloor seismograph, which will allow the scientists to collect data without removing the instrument. An experimental buoy system, humorously named L-Cheapo, for Low-Cost Hardware for Earth Applications and Physical Oceanography, is being tested at IGPP. L-Cheapo could hold up to two years of seismic data on a nine-gigabyte computer hard drive. L-Cheapos cost about $11,000 each, a bargain when you consider the reduced ship time required to collect these simple, light buoys.

Another approach to long-term seafloor measurements is being undertaken by a team at Scripps's Marine Physical Laboratory. The group, including Professors Fred Spiess and John Hildebrand, and Dr. David Chadwell, are placing acoustic transponders–instruments that both transmit and receive signals–on the seafloor in an arrangement that spans a segment of the ridge crest. Transponder locations are determined with great precision, and then measured on a regular basis to an accuracy of a fraction of an inch. The results will enable geophysicists to understand better how ridges actually move and to document the pattern by which the motion takes place. The first such instruments were placed along a section of the Juan de Fuca Ridge off the coast of Oregon during an expedition last year.

"We examine the seafloor away from the ridge crests and see distinct patterns in the rocks that tell us the spreading rates, but these are simply averages of the movement over decades and centuries," Spiess said. "We really don't know details of how the system moves, only that it is moving."

The nation's basic science research in marine geophysics is funded primarily by the National Science Foundation, much of it under the Ridge Inter-Disciplinary Global Experiments (RIDGE), a long-term program of mapping, sampling, and measuring seafloor and crustal processes at the mid-ocean ridges. Orcutt is optimistic that the program will continue to fare well among priorities for science funding, even with the current climate of budget reductions.

"The funding levels for RIDGE have increased over the years and continue to increase regularly, because it has accomplished some extremely good science that has led to a better understanding of how the earth works," Orcutt said. "Because Scripps has one of the largest complements of ocean geologists and geophysicists in the world, who are among the very best as well, the institution plays an increasingly major role in many aspects of the earth sciences."



The Seafloor from Space

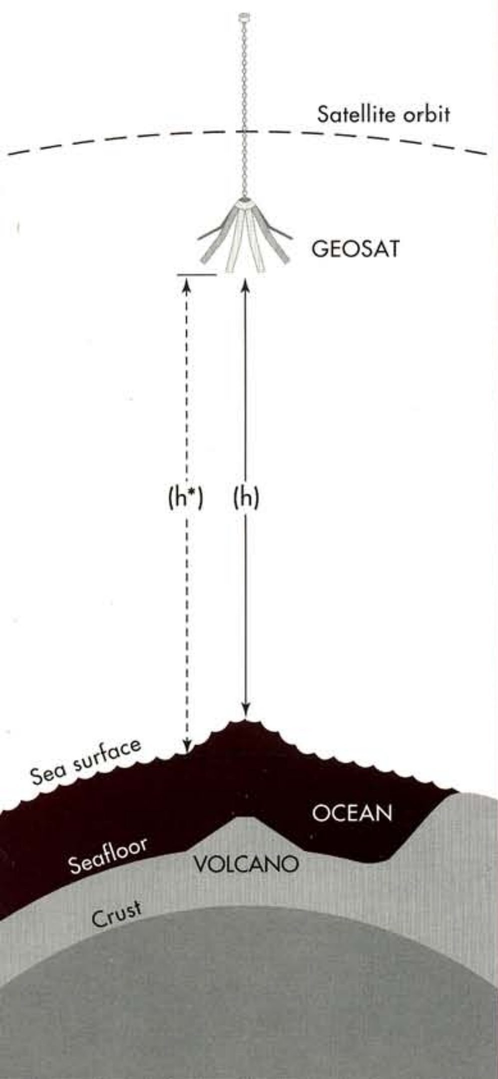
Satellites orbiting the earth provide marine geophysicists with a new way to look at the ocean bottom.

The satellites have remote sensing instruments that bounce a radar pulse off the ocean to measure the height of the sea surface. Because geological features create their own gravity, seamounts create bumps in the surface and valleys cause depressions. Thus the satellite data yield a detailed map of the sea-surface gravity field that shows the geology below.

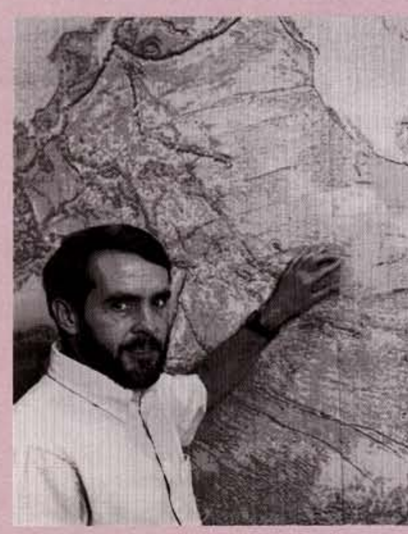
The processing and interpretation of satellite gravity data is a specialty of Institute of Geophysics and Planetary Physics Professor David T. Sandwell. Working with IGPP Research Associate Walter Sullivan of the National Oceanic and Atmospheric Administration's Geodynamics Laboratory and graduate student Mara Yale, Sandwell has translated data from remote regions of the oceans into three-dimensional maps that show unexplored segments of the seafloor in rough detail.

Until recently, much of the ocean gravity data collected over the years remained classified by the U.S. Navy and unavailable for academic research. The sensitivity stems from the fact that this information can also be used to guide submarine-launched missiles.

"There were very good national security reasons in the past to have the data classified, but fortunately those reasons now have largely disappeared, which allows us to create satellite maps for marine studies," said John A. Orcutt, a marine geophysicist who uses the maps in studies of seafloor structure.

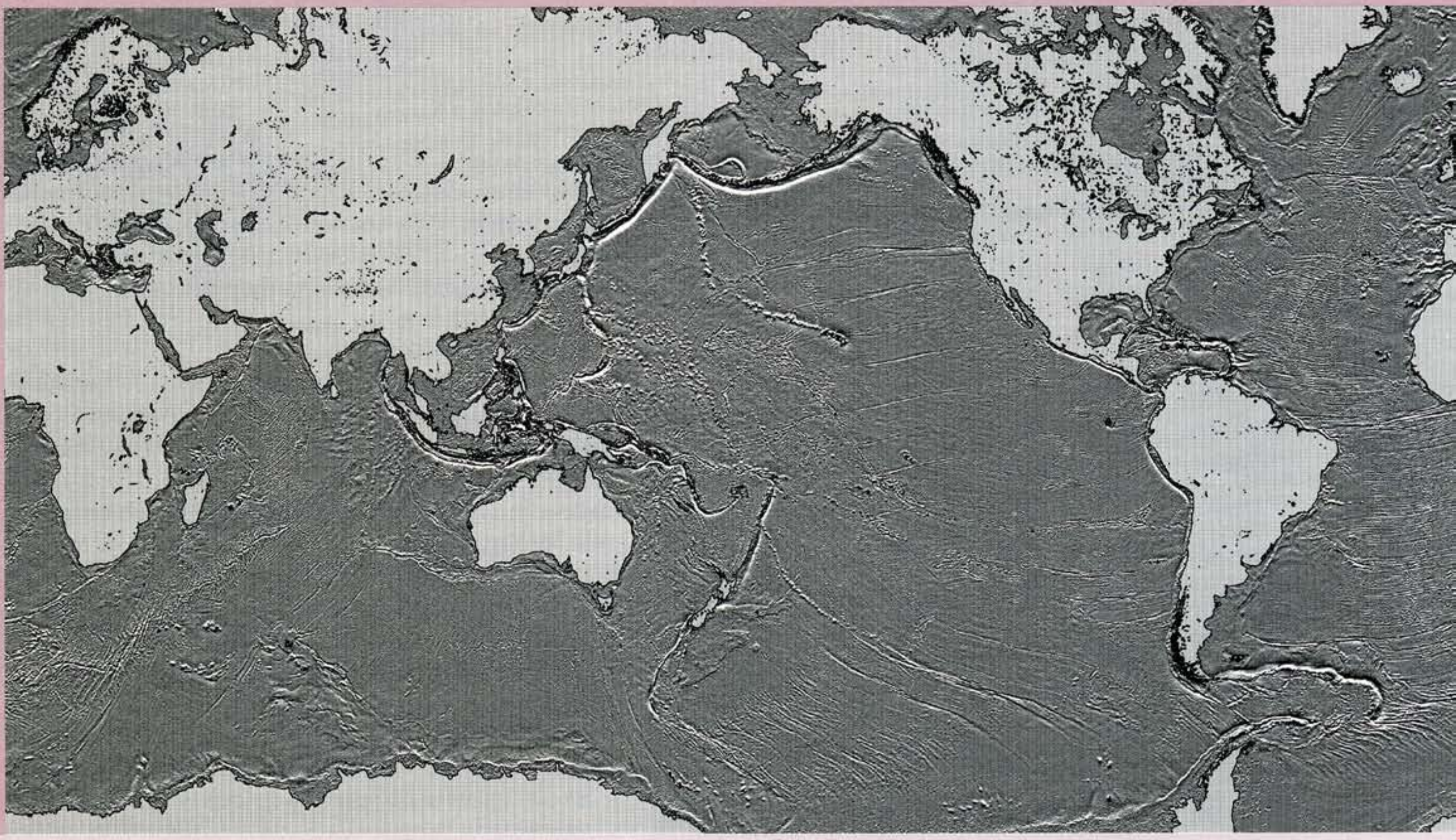


The GEOSAT satellite (Illustration above left) was launched by the U.S. Navy to map the ocean surface topography in great detail for submarine and space applications. GEOSAT was built by Johns Hopkins Applied Physics Laboratory and houses an instrument called an altimeter. In addition to military applications, GEOSAT yields information important to marine geophysics and physical oceanography.



Professor David Sandwell explains remote sensing of the sea surface at an exhibit at the Stephen Birch Aquarium-Museum.

The gravitational attraction of a large volcano (Illustration left) on the seafloor produces a bump in the ocean surface—typically 3 feet high and 30 miles across. A satellite altimeter (GEOSAT) determines the topography of the ocean surface by measuring the travel time of a radar pulse (h). The height of the satellite (h^*) must also be measured by using a global tracking network, such as the Global Positioning System (GPS).



For the first time, this map (above) reveals details of the global seafloor topography by displaying tiny variations in the pull of gravity (gravity anomalies) as measured by instruments on the GEOSAT (U.S. Navy) and ERS-1 (European Space Agency) satellites. Geophysicists are particularly interested in places where the seafloor spreads away from ridge crests and where the earth's tectonic plates meet.

This section of the gravity anomaly map shows the seafloor south of Australia. It discloses a ridge crest oriented roughly east to west parallel to the Australian coastline at 50° S that is segmented by fault lines running north to south. The traces of these faults on older pieces of the seafloor tell scientists details of how the Indo-Australian and Antarctic plates have moved apart over the eons. The white line depicts the ship track for the Westward Expedition in 1994 during which John Orcutt led a study of the structure of the crust associated with an abrupt change in seafloor height (Australian Antarctic Discordance) near 127° E longitude.