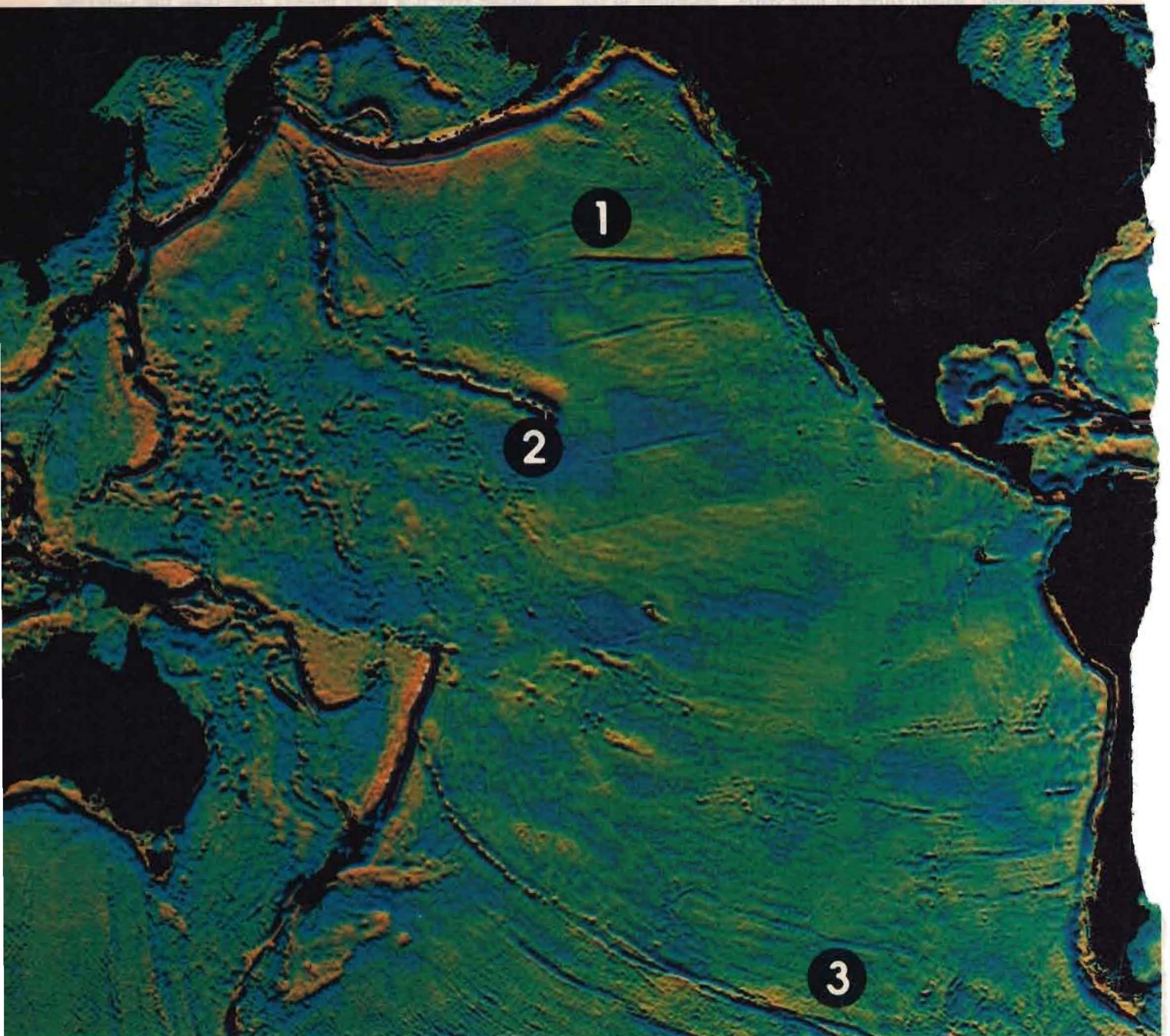


Mapping the sea

● The ridges and trenches on the ocean bottom cause corresponding humps and valleys on the surface because of variations in the pull of gravity. In 1978 the radar altimeter of a satellite called Seasat precisely measured the distance to the ocean surface over most of the globe. Now, using computer processing, geophysicist William Haxby has transformed that raw satellite data into color maps of the ocean floor. His maps help confirm both ancient and ongoing movements of tectonic plates and raise intriguing new questions.

Color relief map of ocean floor was created by computer processing of billions of satellite measurements. Primary

features include: Mendocino Fracture Zone (1); Hawaiian Emperor Seamount chain (2); Eltanin Fracture Zone (3); Mid-



floor from space

By **MARCIA BARTUSIAK**

“It’s as if he pulled a giant plug out of the sea bottom and all the water in the oceans of the world drained away.”

That’s the general reaction these days at Columbia University’s Lamont-Doherty Geological Observatory when inquisitive visitors ask Lamont scientists what they think of their colleague William Haxby’s latest endeavor.

The response doesn’t end there. Interest in Haxby’s work

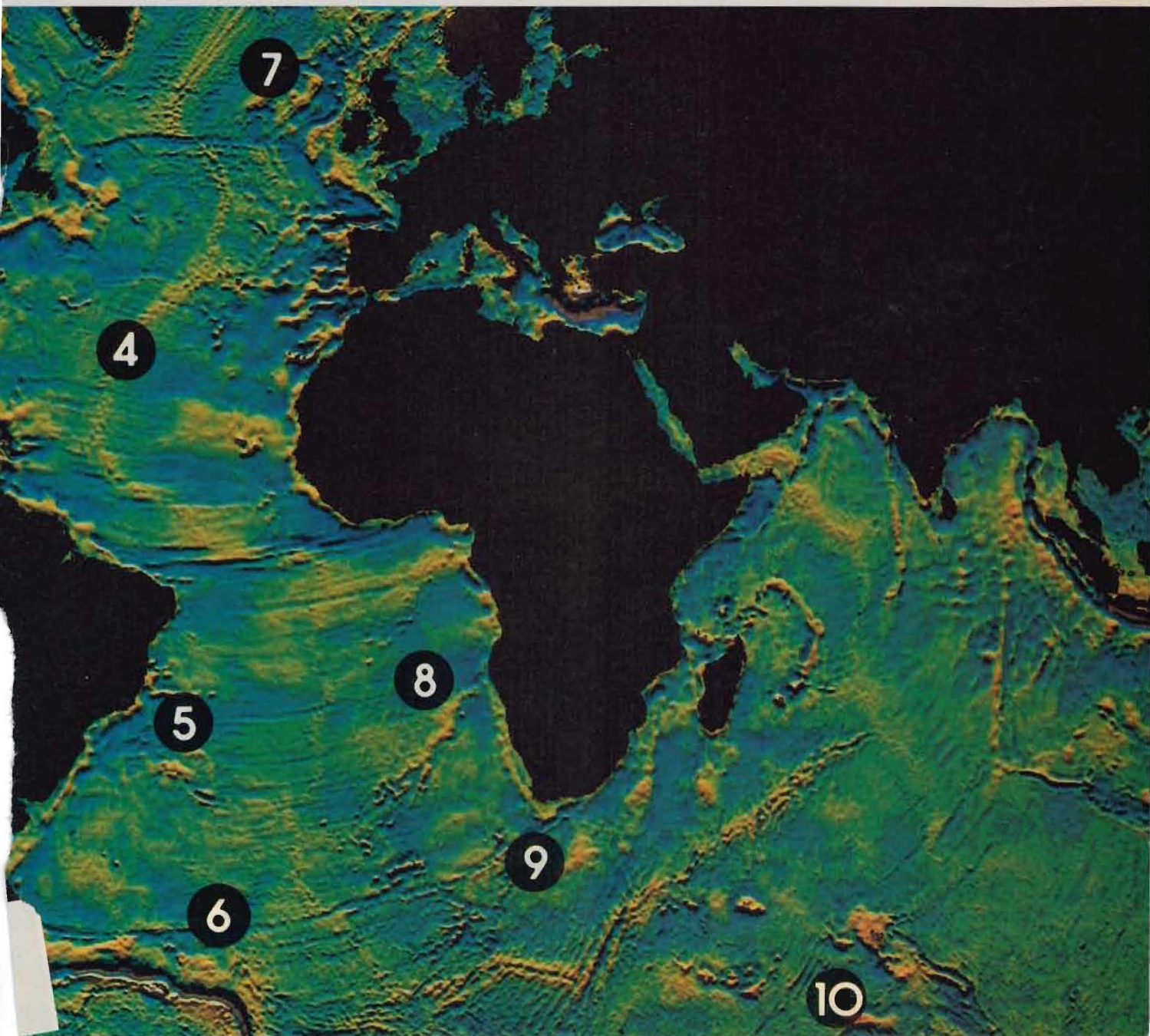
has quickly spread beyond the gates of the sprawling observatory complex that lies along the scenic banks of the Hudson River in Palisades, N.Y. At a recent meeting of the American Geophysical Union, Haxby’s presentation created a sensation among the conferees.

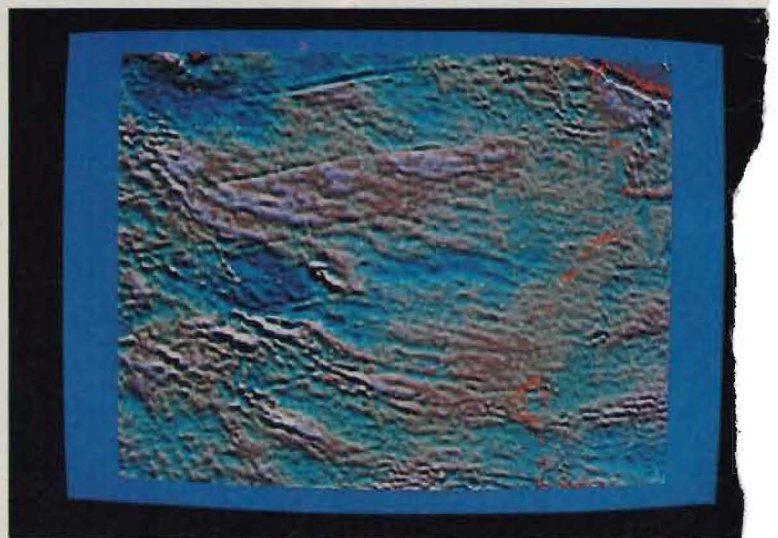
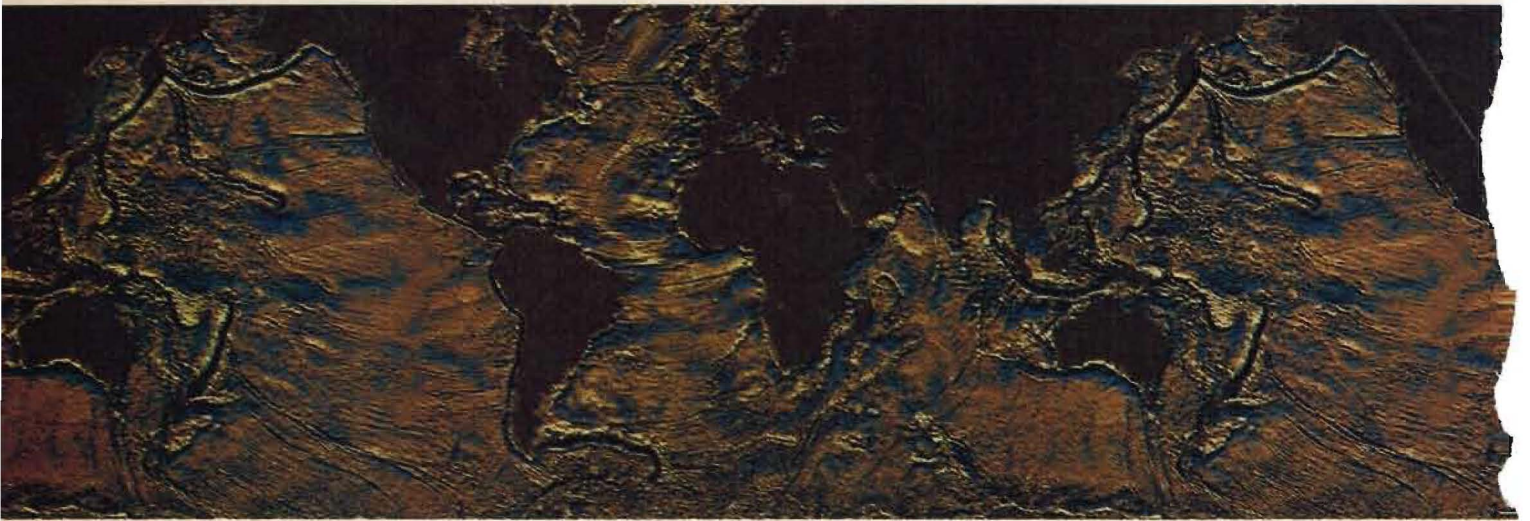
What has Haxby done to engender all this excitement? After 18 months of painstaking computer processing, the 33-year-old Lamont geophysicist has converted reams of satellite data into an exquisitely detailed panorama of the ocean floor—an elaborate color map that identifies under-

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Atlantic Ridge (4); Rio Grande Rise (5); Falkland-Agulhas Fracture Zone (6); Reykjavik Ridge (7); Walvis Ridge (8);

Agulhas Basin Ridge (9); newly discovered India-Antarctica Fracture Zone (10). Continents are the solid dark areas.





Satellite gravity map (top) filled in gaps that remained from bathymetric surveys from ships. Bathymetric map (middle) shows finer detail but not fractures beneath sediment; gravity map does. Close-up of the Eltanin Fracture Zone

from Haxby's gravity map (top of frame, above left) has red spots added to pinpoint past earthquakes. Bottom frame is a bathymetric map of the area. Above: Gravity map reveals sea floor east of Hawaii (upper left of frame).

"Gravity piles water over seamounts"

water structures as small as 20 miles across. He did this by calculating how the sea-floor topography gravitationally tugged at the water above, causing variations in the height of the sea surface that had been measured by satellite. The geophysics community views the feat with astonishment.

Although still in its infancy, such satellite-aided gravity mapping has become a powerful and multifaceted tool for oceanographers and marine geologists. Researchers Timothy Dixon and Michael Parke at NASA's Jet Propulsion Laboratory in Pasadena, Calif., for example, have already generated similar maps from the same data. Their independent venture is enhancing the larger-scale features of the ocean floor.

Sea-floor mapping, of course, is not a new endeavor. For decades, mariners have charted the submarine landscape by taking echo-soundings of the depths below as their vessels crisscrossed the ocean surface. Even gravity maps of limited areas have been made from shipboard with precision instruments called gravimeters. But until the Lamont and Jet Propulsion Lab maps came spewing out of computers, the worldwide picture was far from complete. Large regions of the South Pacific and South Atlantic sea floors remained very sketchy. Many geologists have remarked, only half-jokingly, that the arid landscape of Mars was better known than that 70 percent of Earth's surface hidden beneath a watery veil.

"Let me put this into context," explains geophysicist John LaBrecque, Haxby's colleague at Lamont. "It would take several billion dollars and centuries of time for a research vessel to acquire the amount of knowledge contained in Bill's maps. They're virtually a television scan of the ocean bottom."

Crustal collisions

Indeed, Haxby's maps of the world's sea floors reveal a terrain as diverse as any found on the seven continents and reinforce geology's most unifying concept: plate tectonics, an idea forged more than a decade ago ["Plate Tectonics—A Startling New View of Our Turbulent Earth," *PS*, June '72]. This revolutionary theory says that Earth's crust is divided into some 20 plates. Propelled by the turbulent motion of Earth's scorching interior, some of these giant slabs collide, thrusting mountains upward and digging trenches deeper. The miles-deep trenches that rim the western Pacific, for instance, mark where the huge Pacific plate is diving into the mantle with a vengeance. Other plates move apart, giving molten magma deep within Earth the chance to rise and form new sea floors. Such a process is going on right now at the prominent Mid-Atlantic Ridge, where the North American plate is inexorably separating from the Eurasian and African plates by about one inch each year.

Haxby's successful reproduction of these familiar sea-floor landmarks gave him confidence in his technique, which he has dubbed "geotectonic imagery." But the real excitement grew when his relentless effort to sharpen the resolution of his maps began to reveal long-hidden features, especially in poorly charted sections of the ocean floor. New ridges, rifts, and underwater volcanoes (or seamounts) seemed to pop up everywhere. Needless to say, such discoveries are of more than academic interest. "The Navy is certainly interested in discovering new seamounts so their submarines won't run into them," quips Haxby.

More intriguing were the long, dark streaks cutting across many of the sea floors, as if the muddy bottoms

had been raked by a giant pitchfork. These are fracture zones, the scars left behind as the edges of the plates scrape past and away from one another. Costly ship surveys have tracked them before, but never so many or so clearly. "They're like railroad tracks," explains LaBrecque, "that now enable us to trace the past movements of the continents more accurately than ever before." Adds Haxby, "You can actually follow the motions back to Pangea," that single land mass that existed some 200 million years ago when the Americas, Africa, Antarctica, and Australia were fastened together.

"Take the fracture zone extending from the tip of Africa to the Falkland Islands off the coast of Argentina," suggests Haxby. "If you rotate the African continent along this fracture, you can see how Africa once tucked in quite nicely next to South America."

Haxby credits the Seasat satellite for this astounding clarity. With the launching of the instrument-packed probe in the summer of 1978, oceanographers were obtaining their first worldwide monitor of ocean activity. Unfortunately, an electrical short circuit terminated the Seasat mission after only three months, but not before an on-board radar altimeter had measured the distance between the spacecraft and the ocean surface to an accuracy of two to four inches over most of the globe.

"The altimeter sent out a thousand pulses each second and recorded the time it took for those radar pulses to bounce off the sea surface," says Haxby. "It did this continuously until the satellite failed." The resulting data—some eight billion readings in all—enabled Haxby virtually to X-ray the ocean bottom. How? The answer begins with gravity's varying strength, determined by local variations in Earth's mass, both on the continents and beneath the seas.

Scientists have long known that the sea would not be perfectly level even if the wind stopped blowing and the waves ceased rolling. Instead, the surface would subtly mimic the contours of the landscape below. This is because gravity tends to pile water above massive underwater structures such as mountains and ridges because its strength is greater near such large concentrations of mass. Conversely, the seas subside over objects of lesser mass, such as trenches and basins. "A 1,600-foot seamount, for example, elevates the sea surface by about eight inches," notes Haxby. A miles-deep trench, on the other hand, causes the ocean to drop by dozens of feet. But don't look for these roller-coaster effects on your next voyage; such bulges and dips are spread out over many miles. Fortunately for Haxby, the Seasat satellite, from its lofty perch 500 miles out in space, was able to discern the broad variations quite easily.

The Seasat data arrived at Lamont more than two years ago on 24 computer tapes. "My original intention," recalls Haxby, "was to map only a small area, the poorly surveyed South Atlantic between Africa and South America." His method: converting the varied sea-surface heights recorded on the tapes into their corresponding gravity "signatures," the variations in the force of gravity due to the presence of underwater structures. Gravity "highs" would pinpoint the mountains and ridges; gravity "lows," the trenches and fractures.

In fact, Haxby's processing revealed much more. His gravity maps also identified many features hidden beneath hundreds of feet of sediment, because the sediment has relatively little mass. This enables researchers to detect

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"Tectonic plates can bend like rubber"

long-buried fracture zones not seen on conventional sea-floor maps.

Focusing the image

Haxby displayed his first results in a standard but very crude form, as black-and-white contour maps only comprehensible to experts. Even then, the Lamont scientists sensed the power of the technique. LaBrecque remembers one night of computer processing in particular: "Bill was sitting at his terminal, cranking in finer and finer contouring. We asked him to crank it up some more. He replied, 'Well, there might be a lot of noise in there.' But to everyone's surprise, more resolution emerged. It was like focusing a microscope. Things came out of the ocean floor that we never had hoped to see."

The most exciting event for Haxby and LaBrecque during that all-nighter was finding a thin, sinuous line snaking southward in the Agulhas Basin, several hundred miles southwest of the tip of Africa. For the first time, geologists were viewing the ancient mid-ocean ridge that formed when South America, Africa, and Antarctica started to spread apart more than 100 million years ago, a time when dinosaurs still roamed the earth. The buildup of sediment had kept this fossilized sea-floor-spreading center well concealed.

"The boundary between the plates later jumped somewhere farther west, so this ridge was left behind to subside," explains Haxby. But it continues to rest on the sea bottom as a vital piece of evidence that will help researchers trace the evolution of the oceans, a process crucial to the development of climatic patterns.

Such revelations in the South Atlantic prompted Haxby to expand the scope of his project. "We were perfectly happy with the contours," recalls LaBrecque, "but Bill went around mumbling, 'Maybe I can make a picture out of this.'"

Indeed he could. Soon he was producing a single map of all the world's ocean floors, using a sophisticated color-graphics system. He chose to form his photo-like image out of eight million picture elements (pixels). Each of these pixels was assigned one of 15 colors to depict the gravity strength at that particular point, from dark blue (gravity

low) to yellow or pink (gravity high). Haxby also used 256 degrees of shading to highlight the relief. "It acts as if there is a light source to the north," he points out.

Such touches are more than sheer theatrics. "Color and shading add a whole new dimension. They bring out features not seen in standard contour maps," says Haxby. Already, certain textures in the color image may provide a glimpse into Earth's interior. Haxby and Lamont geophysicist Jeff Weissel suspect that the faint lines running like a comb through the central Pacific sea floor may be the result of convection currents churning 30 to 90 miles beneath the ocean bottom in the upper mantle. In their model, each circulating loop consists of hot material rising and cooler material sinking back into the depths. "A single ship measuring this area would barely notice this feature," contends Haxby. Analyzing this relatively small thermal process might lead to better understanding of the monstrous convective cells suspected to be driving the plates themselves.

Accordion squeeze and a rubber plate

A recent newsletter put out by Lamont described geotectonic imagery as providing marine geologists with "a quantum leap in mapping power." It's an apt description. The inventory of structures that have been either discovered or better resolved with the observatory's maps increases daily:

- A newly revealed fracture zone in the southern Indian Ocean promises to shed light on India's break from Antarctica 200 million years ago. This 1,000-mile-long gash, located southwest of the Kerguelen Islands, was gouged out of the sea floor as the Indian continent inched northward. India's cataclysmic meeting with Asia 160 million years later forged the Himalaya mountains.

- A strange series of east-west wrinkles in the ocean crust just south of India and Sri Lanka verifies that the Indian plate continues to push northward, resulting in earthquakes and surface deformations. "The entire crust is being squeezed in like an accordion," says Haxby. "This is something that is not well understood, since the plate was expected to be more plastic."

- The intense gravity low surrounding the distinctive Hawaiian Emperor Seamount chain in the mid-Pacific clearly indicates how a tectonic plate can bend like a rubber mat under the massive weight of a seamount. The crust beneath Hawaii (the southeast tip of the chain) deflects by as much as six miles.

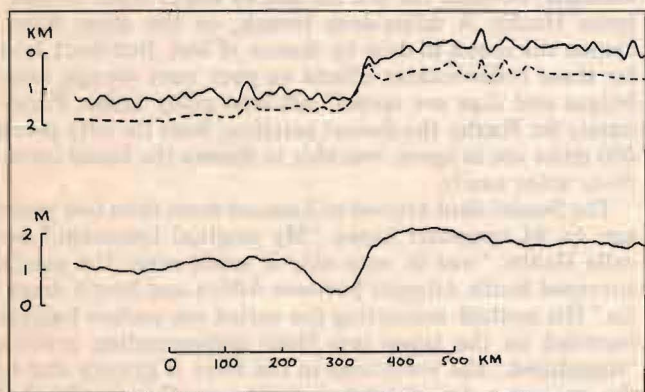
- The sharp bend in the lengthy Mendocino Fracture Zone that juts out of northern California confirms that the Pacific plate abruptly changed the direction of its motion millions of years ago. This may be one of the resounding effects of India slamming into Asia.

- The darkened area off the coast of Somalia in northwest Africa outlines what may be the oldest oceanic crust on Earth. This gravity low has formed as the aged plate sinks into the mantle.

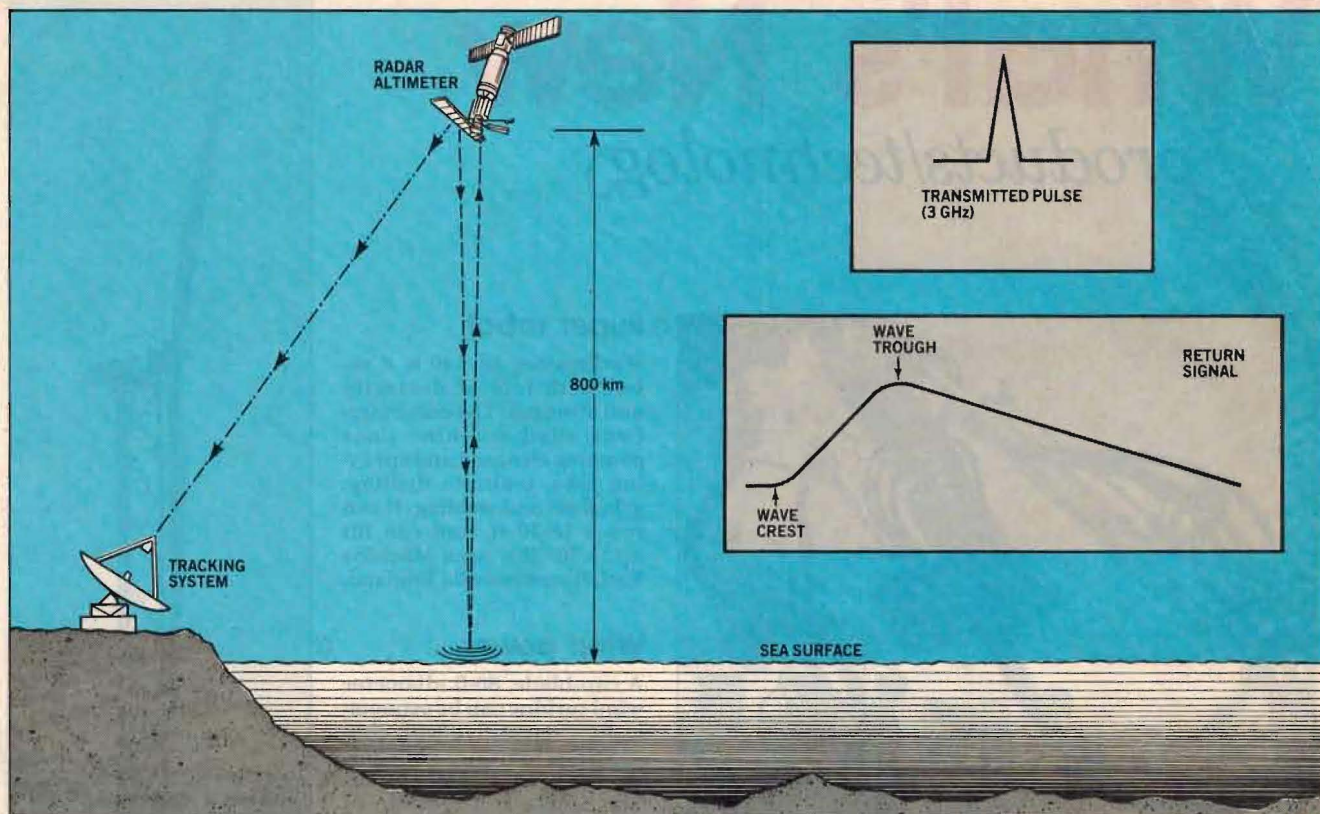
- The gravity map confirms that the Reykjavik Ridge, southwest of Iceland, is indeed V-shaped, a matter of some controversy. This wedge seems to be forming as hot magma pulses up from Earth's interior.

Missing high

Even a missing feature is very telling. The prominent East Pacific Rise—the long ridge system that separates the Pacific, Antarctic, and Nazca plates off the west coast of South America—barely shows up on the gravity map.



Raw data from Seasat (bottom solid line) show how the sea surface dips by one meter (3.3 ft.) for a few hundred kilometers over the Mendocino Fracture Zone off the coast of northern California. Haxby fed this data into a computer and profiled the topography of the sea floor (top solid line). To confirm its accuracy, he compared results with measurements of the sea-floor topography done by shipboard depth soundings (dotted line). The two are a close match.



Radar altimeter aboard Seasat sent 1,000 three-GHz pulses each second. Pulses traveled 500 miles to the sea surface and bounced back to the spacecraft. The exact round-trip travel time of each pulse gave the sea-surface height to an

accuracy of two to four in. Return signal reflects characteristics of sea surface. Each pulse sampled an area five miles long and one mile wide. The altimeter averaged each 100-pulse group and transmitted result to tracking stations.

"This is because the ridge is spreading relatively quickly, on the order of six inches a year—three times faster than the Mid-Atlantic Ridge," explains Haxby. "With this rapid spreading, the materials formed get distributed in such a way that the gravity signature gets smoothed out."

Scientists around the country are starting to use these gravity maps of the world's ocean floors to assess and refine certain geological theories. LaBrecque claims that the images have already made him change his mind about the evolution of two prominent features on the South Atlantic ocean floor.

Geologists have long believed that the Rio Grande Rise, a massive underwater plateau off the southeast coast of Brazil, and the Walvis Ridge near southwest Africa were built up long ago when both the South American and African plates moved over a "hot spot" beneath the ocean crust—a region near the Mid-Atlantic Ridge where molten magma could easily gush out of the mantle below. But the gravity map, contends LaBrecque, tells another story. It suggests that the Rio Grande Rise and Walvis Ridge were once joined, part of a fledgling mid-ocean ridge system that burgeoned as South America and Africa started to spread apart.

"The boundary between the plates jumped to the east, and these structures started to move apart some 100 million years ago," ventures LaBrecque. "That intense gravity low on Bill's sea-floor map, south of the Rio Grande Rise, is the scar that was left behind." As the scenario goes, the Walvis Ridge continued to rift, "a rift that broke the African plate apart like a tear in a piece of paper," says LaBrecque. On the gravity map this rifting, seen as a long rivulet of yellow, makes Angola look as if it had sprung a leak.

No one expects these new satellite charts of the ocean floor to replace on-site measurements. Most likely the sat-

ellite gravity maps will be used for reconnaissance, cheaply and efficiently identifying regions where detailed ship surveys of the ocean bottom are most needed. "The accuracy of a satellite radar altimeter will never match the accuracy of a shipboard gravimeter [an instrument that directly measures the force of gravity]," says Haxby. "Gravimeters can measure a millionth of the force that we normally feel pulling on us."

Topex: accurate to an inch

Haxby expects his maps to be updated and improved as new radar altimeters are launched into space by both NASA and the European Space Agency. He's the first to admit that his initial effort was far from perfect: "There were fairly large gaps in Seasat's orbital path; some of the gaps were as much as 120 miles wide." To compensate, Haxby had to identify dominant topographic trends and interpolate the data along those trends.

The Navy's Geosat satellite, scheduled for launch in the fall, will provide the first opportunity to fill in the missing pieces. Detailed altimeter information from the first phase of Geosat's mission will be classified (gravity variations can affect the flight of missiles), "but the second phase shows promise of improving the Seasat data," notes Haxby. And at the end of the decade, NASA plans to orbit a satellite called Topex (Topographic Experiment), which will be designed to sense sea-surface variations of less than an inch. With such capabilities at hand, researchers should be able to produce gravity maps distinguishing sea-floor features as small as eight miles across.

For now, however, Haxby is anxious to put his computer "hacking" to rest so that he can concentrate on more interesting matters: joining his colleagues in interpreting the many intriguing features being revealed for the first time in these remarkable maps.

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