MEETING AMERICAN GEOPHYSICAL UNION

Of Ocean Weather And Volcanoes

SAN FRANCISCO, CALIFORNIA—The 8500 attendees of last month's meeting of the American Geophysical Union had some interesting poster presentations to choose from. Particular attractions for the perambulatory set included a possible volcano aborning, old sea-floor volcanoes, and predictions of next month's ocean storms.

Next Month's Ocean Weather

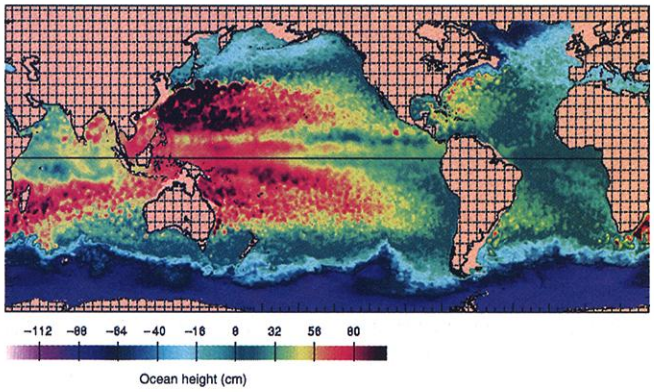
Drilling for oil in the deep Gulf of Mexico? Fishing on the Grand Banks? Looking for unfriendly submarines playing cat and mouse in the Gulf Stream? Then the U.S. Navy has just what you need. In a first, it is routinely making computer forecasts of the swirlings and churnings of the world ocean in enough detail to realistically render ocean "weather." Similar numerical forecasting of atmospheric weather went operational in the late 1950s, but oceanographers had to await far faster computers to simulate the smaller scale "storms" within the ocean. Now, the position of Japan's mighty Kuroshio current or next month's ring current peeling off into the Gulf of Mexico is just a few clicks away (www7320.nrlssc.navy.mil/global_nlom/).

The ocean forecasting milestone comes courtesy of the Naval Research Laboratory's (NRL's) Layered Ocean Model (NLOM), as described in a meeting poster by Ole Smedstad of Planning Systems Inc. and NRL colleagues, all located at the Stennis Space Center near Bay St. Louis, Mississippi. NLOM produces a 30-day forecast of ocean behavior with enough detail to portray 50- to 100-kilometer-wide eddies, the oceanic equivalent of atmospheric storms that typically span thousands of kilometers.

Researchers first barely resolved ocean eddies in global models in the early 1990s by dividing the ocean into blocks 0.5 degree on a side and calculating the average properties of a block of water (*Science*, 2 April 1993, p. 32). NLOM now divides the ocean into one-16th-degree blocks, yielding a resolution of 6 to 7 kilometers at midlatitudes that clearly renders eddies.

The next trick is to make a forecast quickly. NLOM does that using a computationally efficient scheme for creating a snapshot of water movements globally and projecting those motions into the future. It also takes some shortcuts, such as not dealing with shallow waters over the continental shelf. And it relies on an IBM WinterHawk 2, a massively parallel computer that achieves speeds of 35 gigaflops using 216 processors. A decade ago, oceanographers had to settle for eight processors working in parallel to achieve speeds of little more than 1 gigaflops.

Like atmospheric weather forecasting models, NLOM needs to be told what's going on at the moment, plus how wind and heat are driving ocean circulation. In place of weather stations, the model turns to satellites, taking in data on sea-surface temperature and the shape of the sea surface. (The sea-surface shape reflects the pattern of ocean currents the way highs and lows of atmospheric pressure reflect the way the wind must blow.) The model also takes in data on how the wind is blowing water at the ocean surface and how heat is flowing in and out of the ocean.



Going global. Computers now allow for 30-day forecasts of ocean behavior (here, ocean height).

Each day, the model creates a snapshot of the world ocean and then a 4-day forecast. On Wednesdays, it produces a 30-day forecast. It has been running since October 2000 and in an operational mode with public distribution of results since last October. Although the forecasts are useful out to at least 30 days in most areas, says Smedstad, in more dynamic regions, such as the area of the Gulf Stream, they are useful for only about half a month.

That's long enough to pique the interest of a variety of forecast users. An oil company would like to know if a powerful eddy is about to sweep by its deep-sea drill rig. Fishing companies want to know where eddies of particularly warm or cold water might be harboring fish. Even researchers keeping tabs on whales in the northwest Pacific check forecasts. "What they have achieved—running a quite high-resolution model on a routine basis—is an important contribution," says ocean modeler Allan Robinson of Harvard University, "but there's a great deal of work to be done yet." Weather forecasters are still 40 years ahead of oceanographers.

Oregon's Bulging Unabated

Last spring, volcanologists studying satellite radar measurements were startled to find a 15-kilometer-wide swelling of the ground just west of central Oregon's Three Sisters volcanoes that threatened an eruption (*Science*, 18 May 2001, p. 1281). The bulge continues to grow, according to an instrument volcanologists installed on it to track the doming. But they are relaxing a bit after seeing signs that similar events may have occurred before without triggering eruptions. Although magma may yet break through to the surface, giving volcanologists a start-to-finish record of an eruption, they aren't holding their breath.

The continued bulging has been confirmed by the Global Positioning System (GPS) receiver installed last May near the center of the uplift. Geodesist Michael Lisowski of the U.S. Geological Survey's (USGS's) Cascades Volcano Observatory in Vancouver, Washington, reported at the meeting that GPS has recorded a rise of about 30 millimeters per year, about the rate indicated by interferometric synthetic aperture radar (InSAR) up to last year.

Taking the total uplift of 150 millimeters since bulging began in late 1997, Lisowski and his colleagues calculate that about 21 million cubic meters of magma has risen into a chamber located 6 to 7 kilometers beneath the bulging surface. That volume is equivalent to a sphere 350 meters in diameter, or one-tenth the volume of magma injected into the heart of Mount St. Helens before its cataclysmic eruption.

Although some of the hundreds of small volcanic vents in the area have erupted as recently as 1200 years ago, volcanologists aren't betting on any fireworks soon. Experience at Northern California's Long Valley, which is the scar of an ancient caldera-forming eruption, provides some reassurance. A central bulging there has totaled more than 750 mil-

CREDIT: U.S. NAVAL RESEARCH LABORATORY, STENNIS SPACE CENTER limeters since 1979. That bulging was often accompanied by earthquakes as large as magnitude 6 or swarms of smaller quakes indicative of pressurized fluids breaking through rock a few kilometers down. Yet there's been no eruption, and the valley is quiet again. And chemical analyses of springs on the Oregon bulge suggest that there have been earlier magma injections. Warm springs there contain elevated sulfate, chloride, and helium-3, confirming that water has percolated down near deep-seated magma and returned to the surface. But analyses made in the 1980s in the course of exploration for geothermal energy also show elevated sulfate and chloride in the area, suggesting that one or more pulses of magma injection preceded the current episode without triggering an eruption.

"We wouldn't be surprised if this died out," says geodesist Charles Wicks of USGS in Menlo Park, California. But then again, no one's turning off the GPS yet.

Plate Tectonic Benchmarks Adrift

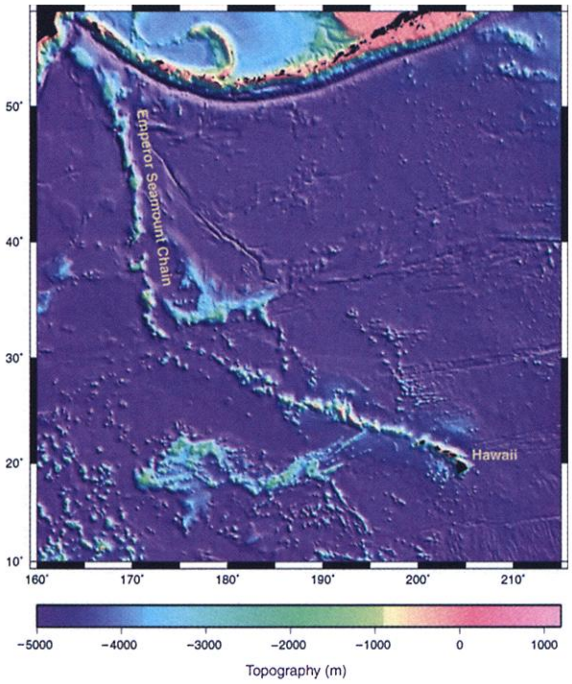
The founders of plate tectonics considered the fount of molten rock that feeds Hawaii's volcanoes to be immobile, a fixed marker on a planet where everything but volcanic hot spots like Hawaii shuffles about endlessly. In the plate tectonics canon, great plumes of hot rock rising from deep in the mantle feed the 40 or so hot spots such as Hawaii, Yellowstone, Iceland, Pitcairn, and the Galápagos. But doubts about the fixity of hot spots eventually arose. Now, deep-ocean drilling into the string of volcanic seamounts trailing away from Hawaii confirms that this hot spot, at least, has moved, at times as fast as some drifting continents. That suggests that reconstructions of long-past arrangements of plates around the Pacific require correction—including those supporting far-traveled bits and pieces of continent being plastered onto North America. It also implies that if plumes do feed hot spots, they are being buffeted by the "wind" of a vigorously churning mantle.

The job of testing hot-spot fixity has fallen largely to paleomagnetists. In principle, they can decipher where on Earth—or at least at what latitude—a volcanic rock formed: They measure the orientation of Earth's magnetic field frozen into a rock when it solidified from lava. Because Earth's field is horizontal at the equator, vertical at the magnetic pole, and tilted in proportion to its latitude in between, determination of the inclination of a rock's locked-in field can yield its latitude at the time it was formed. That means a core of rock drilled from one of the now-submerged seamounts—built one at a time in a string across the Pacific plate as it moved over the Hawaiian hot spot—should tell a paleomagnetist whether that volcano formed over the present location of the hot spot, 19°N.

Researchers did just that in the 1970s and 1990s at two seamounts in the northern North Pacific—Suiko and Detroit—and found that they had formed more than 1000 kilometers north of the present location of the Hawaiian hot spot. But the limited data didn't convince most researchers that the hot spot had moved.

Paleomagnetist John Tarduno of the University of Rochester, New York, wanted to convince his colleagues that hot spots can move, so he arranged to do the job right. He and colleagues persuaded the Ocean Drilling Program to send its drill ship *JOIDES Resolution* to the Emperor chain of seamounts northwest of Hawaii for a full 2 months of drilling. Last summer, he, co–chief scientist Robert Duncan of Oregon State University in Corvallis, and the shipboard scientific party of Leg 197 drilled four seamounts, penetrating a total of 1200 meters of volcanic rock beneath the bottom sediments. That was enough to average out short-term variations in the orientation of the magnetic field, something earlier, less ambitious drilling had not done convincingly. With these higher quality data from more sites, preliminary shipboard analyses suggest that the Hawaiian hot spot moved southward at rates as high as 30 and 50 millimeters per year—faster than North America is moving—between 81 million and 43 million years ago.

"It's a very nice result," says Tarduno, who presented his findings on his poster. "It's pretty hard to argue against hot-spot mobility now." Tectonophysicist Seth Stein of Northwestern University in Evanston, Illinois, agrees. "His results raise a very major question about the long-term fixity of hot spots," he says. "You're talking about hot-spot motion at the speed of plates. A lot of questions about mantle dynamics and plate motions will need rethinking."



Hawaii marks the hot spot. Both plate motion and a moving hot spot shaped the string of volcanoes trailing Hawaii.

SOURCE: J. TARDUNO AND R. COTTRELL/UNIVERSITY OF ROCHESTER

Geophysicists have already been rethinking plumes and why their hot spots might move. Richard O'Connell of Harvard University and Bernhard Steinberger of the University of Colorado, Boulder, have modeled how the slow churning of the mantle might drive hot-spot motion. When they put Pacific plumes into their simulation of mantle motions, most plumes swayed toward the south the way a rising smoke plume would bend in the wind. That would move the upper end of the plume and thus the hot spot about 10 millimeters per year, slower than Tarduno has it but clearly moving. If the Hawaiian plume is blowing in the wind, the sharp bend in the Hawaiian-Emperor chain that had been attributed to a postulated change in the direction of the Pacific plate's motion—something no one has been able to find—may mark an abrupt shift in the mantle wind.

Moving hot spots would also require rethinking how plates moved in the past. Paleomagnetist Robert Butler of the University of Arizona in Tucson notes that if the Hawaiian hot spot did move rapidly southward, then the long-vanished Kula ocean plate would not have moved northward along western North America as fast as calculated under the assumption of stationary hot spots. It was the Kula plate that supposedly carried chunks of continent from the latitude of Baja California and plastered them where British Columbia is today (*Science*, 12 September 1997, p. 1608). If the Kula plate didn't move as fast as assumed, says Butler, the Baja–British Columbia scenario won't work because the bits of continent couldn't be moved as fast as required.

Hot-spot motion could also allow paleomagnetists to invoke little or no "true polar wander" to explain certain observations. True polar wander is theoretically possible, but researchers have long debated whether it has ever happened (*Science*, 10 April 1987, p. 147). One contingent sees the paleomagnetic data requiring the entire solid Earth to tumble like a rolling ball beneath the pole, making the pole move over millions of years. Others see hot-spot motion contaminating the paleomagnetic data. Perhaps seamount rock can settle that one too.

—RICHARD A. KERR