EXPLORING

ELECTROMAGNETIC TECHNOLOGY ADAPTED TO DETECT OFFSHORE OIL

For decades, scientists have studied Earth's structure, on land and deep in the ocean, aided by the power of the sun and the force of lightning. Using the magnetotelluric (MT) method, geophysicists trace variations in the planet's magnetic field created by solar winds and lightning storms. These variations cause electrical currents to course deep into the planet's crust.

Marine geophysicists at Scripps are revising existing electromagnetic technology to explore the resource-rich sediments of the continental shelf. These technological advances give scientists another tool for understanding the forma-

NEW FIELDS

BY PAIGE JENNINGS

tion and structure of the planet, and the oil industry acquires access to potential new reserves of oil and natural gas.

An industrial collaboration began in 1994 when Scripps geophysicist Steven Constable met with Arnold Orange, a scientist and oil-industry consultant. Orange knew that Constable and his colleagues in the Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics had successfully mapped deep-ocean rocks by measuring electrical conductivity, and that Constable was familiar with the MT method, which was frequently used on land for oil exploration. The consultant wanted to know if it would be possible to survey geologic structures less than one mile deep, as well as in depths up to three miles, using the MT method. Constable immediately took up the challenge. Eventually his Scripps group joined a team that included researchers from Ernest

Orlando Lawrence Berkeley National Laboratory and scientists and industrialists with several of the world's leading oil companies.

"I said yes without thinking about it," recalled Constable, "but as we started to discuss it more, I realized that the traditional method, which is to measure very low frequency electromagnetic fields, wasn't going to work in the areas of the ocean where oil might be found."

First developed in 1957, the MT method exploits a basic physical phenomenon: as the planet's relatively constant magnetic field is altered by variations from solar winds and electrical storms, electric currents form within the earth that work to counteract the magnetic field variations. These currents are stronger in good electrical conductors, such as sandstone and shale, and weaker in resistive materials, including limestones, ancient lava flows, and salt structures.

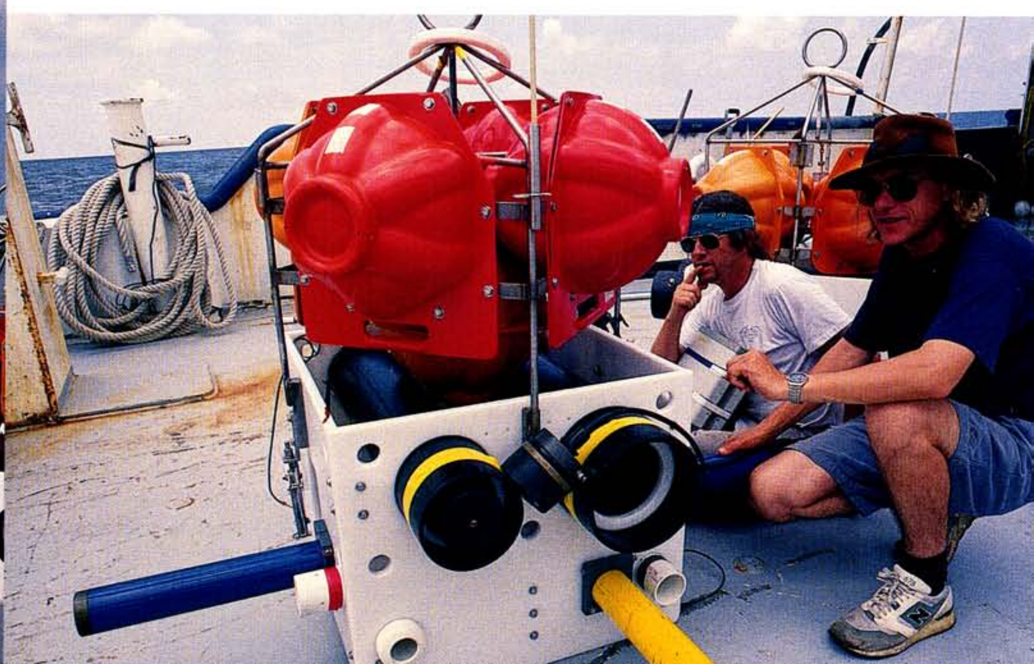
To monitor these currents, a magnetometer records the magnetic field along the surface, and a voltmeter gauges the flow of electric currents through the ground. Traditional seafloor methods rely on low-frequency waves, usually with periods of 1,000 seconds or more, to study Earth's mantle (or deep structure). But, to study the relatively shallow sediment layers of the continental shelf, scientists need to focus on periods between 1 and 1,000 seconds. Designing equipment to read very small, high-frequency electric fields in the magnetically noisy, highly conductive ocean environment atop the continental shelf was a bit tricky. Fortunately, Scripps has a long history of developing magnetic and electric sensors for marine exploration.

With the resources and knowledge available at the institution, Constable modified existing technology and created a spidery looking instrument package sturdy enough to survive ocean conditions, compact enough to easily transport, and sensitive enough to detect faint, small-scale variations through the earth's upper layers. His alterations included adding a special amplifier to bolster weaker electric signals and an autonomous seafloor data logger capable of gathering information rapidly at each deployment. This allowed for the shorter and more frequent instrument deployments necessary for compiling a comprehensive survey. Each package was linked to a detachable cement anchor and affixed with a compass to record its orientation on the ocean floor. Magnetic readings from land-based magnetometers set up near the offshore survey site provided a remote reference to help process noisy underwater measurements.

To test his initial modifications, trials were conducted off the San Diego coast. The results were

R/V *Pelican* (left) awaits the loading of Steve Constable's stock of MT instrument packages. Constable (pictured below, right) and members of his team (right and below) assemble and test each instrument package before deployment.

FACING PAGE A specially designed compass (above) records the orientation of the instrument package on the seafloor. The instrument package is deployed in one of two configurations: either with magnetometers (left), or with electrodes housed in the ends of four long, black plastic arms (right).



advertised to the oil industry. One company, AGIP, was aggressively exploring the Mediterranean Sea and in 1995 asked Constable and Orange to conduct surveys on their behalf off the coast of Italy. They surveyed 20 sites with limited success.

During this time, researchers with the Earth Sciences Division at Berkeley Lab were working on developing computer-generated models of salt structures in the Gulf of Mexico. They were interested in utilizing Constable's developing technology to gather data for their project, thus an academic collaboration between the two research centers was struck.

With support from Berkeley Lab's model studies of the Gulf of Mexico, Constable and Orange began forming a consortium of oil companies to sponsor the first field trials off the coast of Louisiana.

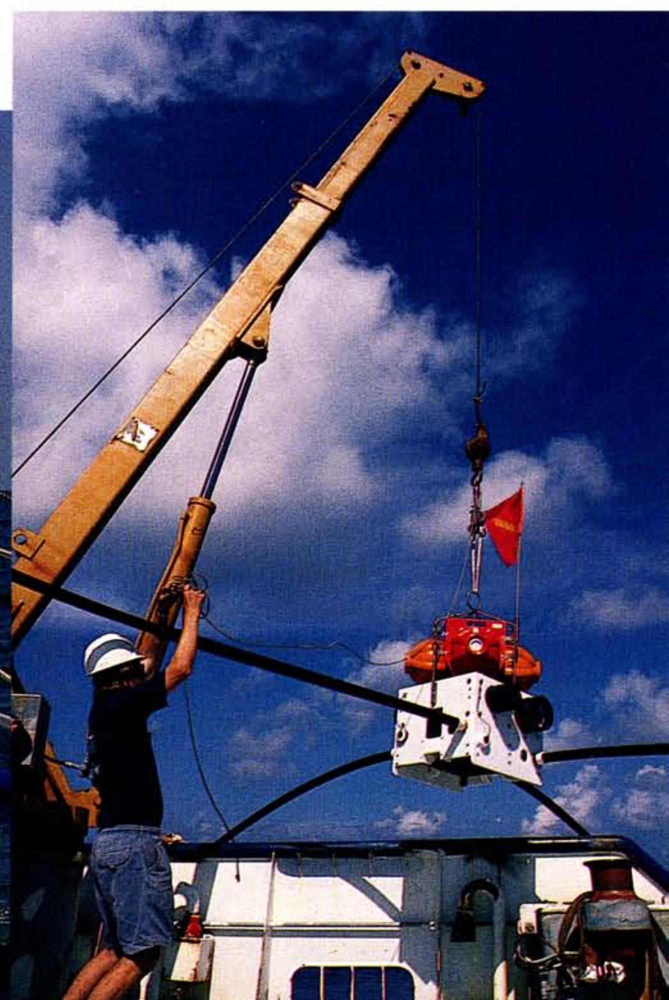
"Now began a three-legged operation—Arnold Orange representing industry applications, Scripps providing the methodology, and Berkeley Lab working on their modeling theories," described Constable.

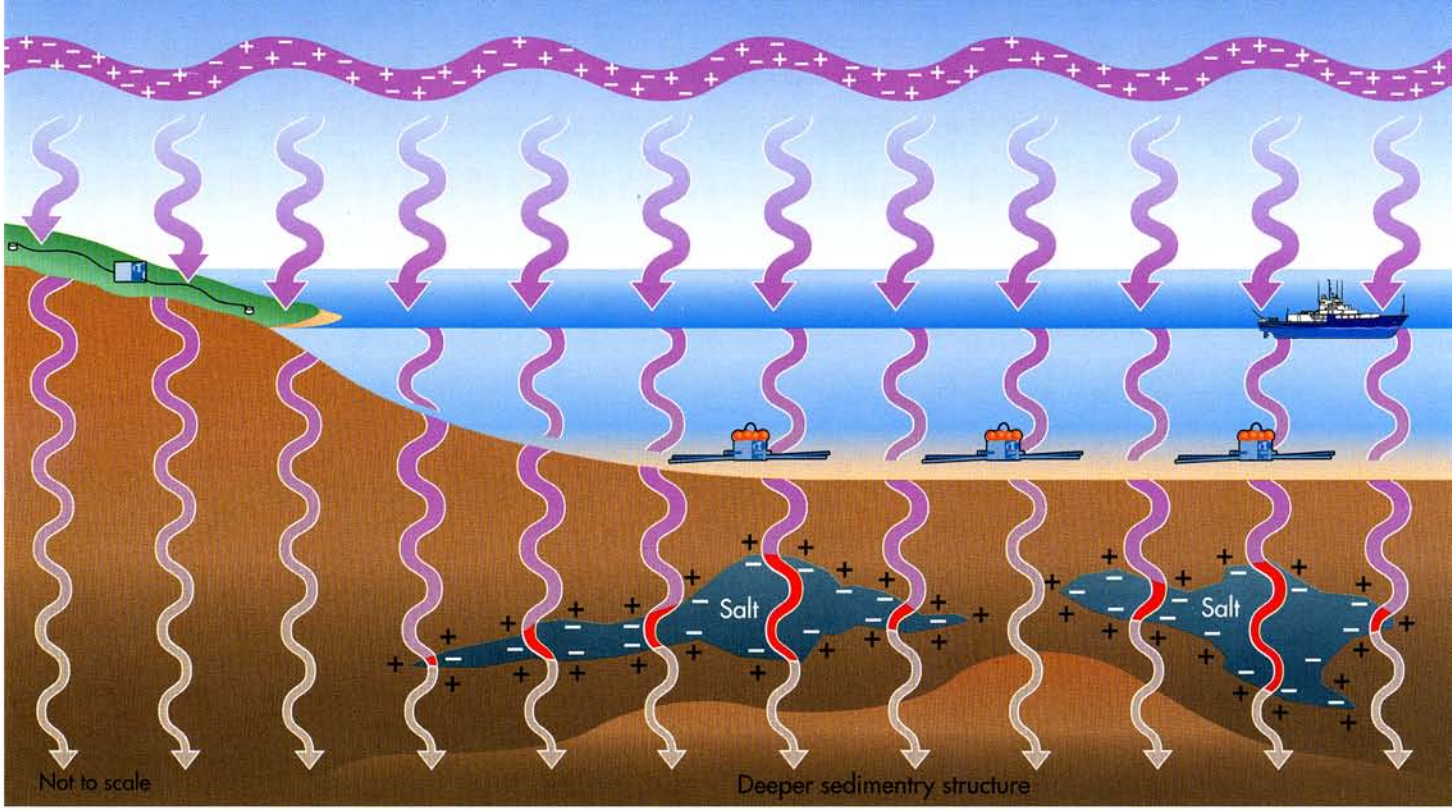
Six oil companies joined the consortium and operations were quickly organized to begin field trials in the gulf. During August of 1996, Constable made approximately 40 gulf surveys for academic purposes using consortium funding. Two months later he was back in the Mediterranean assisting AGIP with an extensive 100-site commercial survey.

This past summer Constable spent nearly the entire humid month of June in the small fishing and recreational community of Cocodrie, Louisiana, and amidst the cobalt blue waters of the Gulf of Mexico conducting more academic research for Scripps and Berkeley Lab.

From the stern of the 105-foot (32 m) research vessel *Pelican*,

"I SAID YES WITHOUT THINKING ABOUT IT, BUT AS WE STARTED TO DISCUSS IT MORE, I REALIZED THAT THE TRADITIONAL METHOD, WHICH IS TO MEASURE VERY LOW FREQUENCY ELECTROMAGNETIC FIELDS, WASN'T GOING TO WORK IN THE AREAS OF THE OCEAN WHERE OIL MIGHT BE FOUND."





Electromagnetic energy (descending arrows), generated by Earth's ionosphere (horizontal wave, top), propagates with almost no attenuation in the non-conductive atmosphere, but quickly dissipates in the electrically conductive ocean and sediments. The rate at which the energy decays depends on seafloor electrical structure and on an electrical charge that builds up on the edges of conductive boundaries, such as the salt structures pictured in gray. An array of seafloor instruments, with a land instrument for reference, maps the influence of the deeply buried conductors.

Constable and a team representing Scripps, Berkeley Lab, and Arnold Orange Associates deployed 46 instrument packages. On land and at sea, their efforts were supported by the Louisiana Universities Marine Consortium, which operates two research vessels, including R/V *Pelican*, from a marine research center nestled in the heart of estuarine wetlands between the Mississippi and Atchafalaya Rivers.

Prior to the first shakedown cruise, Constable's team headed for the town of Thibodaux to establish a land-based station. In a muddy field of knee-high grass sandwiched between an early season sugarcane field and the overgrown tangles of a bayou, they aligned and buried several magnetometers and hooked up the monitoring equipment in a camping tent purchased from the local Wal-Mart. While in the field, Constable and his team were warned to watch out for poisonous snakes, chiggers, mosquitos, fire ants, and swamp rats, making their upcoming work at sea sound almost hazard-free by comparison.

After the first land station was up and running, one person was left on land to monitor it, and the rest of the team boarded the ship in search of salt structures.

The salt structures found in the Gulf of Mexico developed during the Jurassic period when the

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Constable tests the magnetometers before they are delivered to the land station.

FACING PAGE Oil platforms (above) are a common sight for Constable's team while working in the Gulf of Mexico. (below) During the establishment and maintenance of the land station, the equipment must be checked periodically, and the data downloaded for analysis.

continents were separating. It is believed that as a rift formed between North and South America, seawater spilled over from the Pacific. As the water evaporated, salt deposits were laid down in what is now the Gulf of Mexico and on land throughout Texas, Louisiana, and Mexico. Over time some of the salt sheets protruded up through heavier marine sediments as domes and formed pockets that now harbor rich oil reservoirs. Geologists are interested in how these structures formed, and oil explorers are interested in the resources that might lie in the sediments below.

In most industrial surveys, the seismic method is the preferred mode of exploration. This technique measures the sounds from small explosions as they bounce off the differing sediment layers. But the reliability of this method decreases when used with certain geologic structures, such as salt.

"Salt is a problem for the seismic method," explained Constable. "The oil industry wouldn't be interested in MT if the other method worked all of the time. In materials

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Innovative Technology Makes Data Affordable

Tucked neatly inside Steve Constable's magnetotelluric (MT) instrument package is an autonomous data logger appropriately named L-CHEAPO by its developers at Scripps. It is described as Low-Cost Hardware for Earth Applications and Physical Oceanography, and it provides geophysicists with an affordable and reliable method for gathering digital information from many types of Earth monitoring instruments, including undersea hydrophones and Constable's MT system.

Although based on decades of technological development at Scripps, L-CHEAPO was designed, built, tested, and deployed in just four months. The process began in 1993 when Scripps geophysicist John Orcutt and his engineers, David Willoughby, Paul Zimmer, and Crispin Hollinshead, found themselves in urgent need of an affordable system with which to compile seismic data from ocean-bottom hydrophones. Commercially available systems were not considered suitable because they required massive power to operate, were too bulky to transport easily, and did not always keep accurate time. With the tools, knowledge, and experience all available at Scripps, Orcutt's team decided to create smaller, more efficient and reliable loggers.

Constable collaborated with Orcutt's team by providing the acoustic navigation and release systems that allow scientists to remotely locate, communicate with, and retrieve seafloor instruments. The acoustic system involved—the result of years of work by Constable and two other Scripps scientists, Chip Cox and Spahr Webb—also was more affordable than similar commercial products.

In an impressive development cycle, design of L-CHEAPO began in December 1993 and six new instruments were assembled by March 1994. In that same month, as five of the loggers were in transit to Orcutt's research team in Barbados, Constable was testing the sixth instrument in the waters off San Diego.

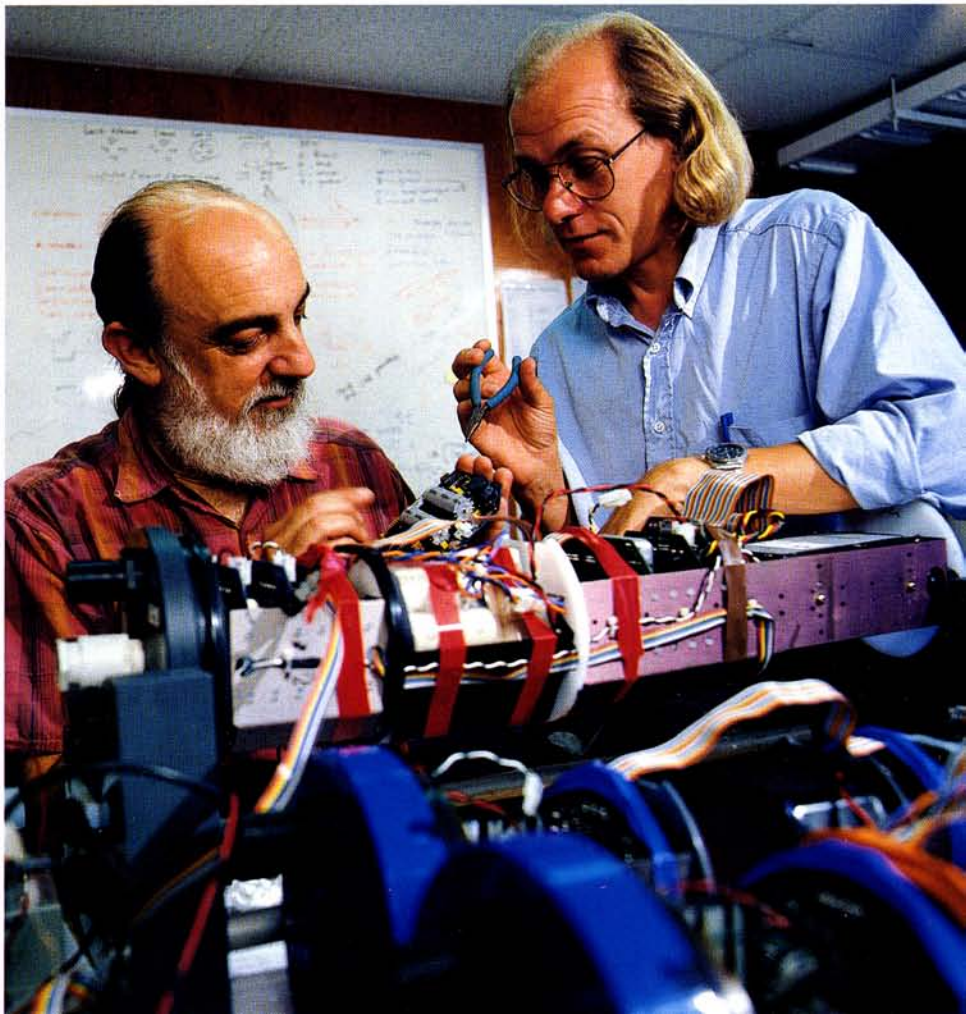
"The instrument worked," said Constable. "We actually recorded some aftershocks of the Northridge, California, earthquake, and were able to e-mail corrections of minor bugs to Orcutt's group in Barbados. His experiment was a great success."

The next year the U.S. Navy sponsored further improvements to L-CHEAPO with a specific goal of extending its endurance to one year deployments collecting up to 10 gigabytes of data.

"L-CHEAPOs have not pioneered the use of any new or exotic technologies," explained Willoughby of the new research tool. "They simply combine state-of-the-art components from the computer and oceanographic industries to make a small, simple, and cheap package that can be used to record any kind of data on the seafloor."

To date, nearly 50 L-CHEAPOs have been built at Scripps and used for numerous projects including passive and active marine seismology, marine MT, ocean acoustic studies, and monitoring of whale vocalizations.

David Willoughby and Constable ready a team of L-CHEAPOs, prior to embarking on the latest research cruise in the Gulf of Mexico.



such as salt, basalt, and carbonates, there is too much reverberation within the structure to get an accurate seismic reading."

These formations reflect so much of the sound that lower-lying sediment layers can't be detected with explosions. This problem is averted using the marine MT method.

"Rocks such as basalt, limestone, and salt domes, are usually less electrically conductive than surrounding sediments of sandstone and shale, because they have less water trapped in pore spaces, and it is the water that usually conducts electricity in the ground," said Constable. Using the new modified MT instrumentation, the electrical contrast between sediments buried beneath the reflective layers of rock can be measured.

The results from Constable's Louisiana expedition were successful. The data, when processed, allowed them to accurately image the salt structure with enough detail to be useful to the oil industry. The positive outcome of the latest expedition has heightened Constable's confidence in the effectiveness of the marine MT method as a tool for natural resource exploration. He also is encouraged by the strengthening ties, both academic and industrial, that his improving technology is helping to form.

Multifaceted collaborations involving the oil industry are rare at Scripps; but with a growing need for alternative academic funding sources and the decreasing availability of petroleum products from existing sites, relationships such as these may become more common.

Constable explained further, "What we are doing is a mixture of academically funded field trials and commercial surveys. The funding we are receiving is important. It generates money to purchase equipment, to hire engineers to develop new instruments, and to support the education of graduate students and postdocs. Plus, it's given me experience very quickly that is invaluable to my academic work."

Constable envisions that the work that has gone into developing the new MT method for research in shallow waters may improve existing techniques for mapping crustal structures, such as mid-ocean ridges, in the deepest parts of the ocean. One of his new instruments was tested to depths of approximately 2.5 miles off Hawaii as part of a traditional marine MT survey last April.

"From an industrial point of view, the new MT will probably never be as widely used as the seismic method," concluded Constable. "But I think it has the potential to change the way scientists conduct offshore exploration."

Of the 46 instrument packages deployed, all were recovered, and nearly all supplied useful data for Constable's survey.