OCEANS

Mysteries of the Deep

Douglas Faulkner/Photo Researchers

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Of all the areas on Earth scientists can explore, the deep seas are perhaps the least hospitable. But with advances in technology, the oceans have offered up some of their secrets.

Imagine what people knew about the seas 150 years ago. By that time, most land masses had been discovered and their coastlines mapped. But what of water, which covers nearly 71 percent of Earth? Navigating by the stars, sailors could ply the oceans, fishermen knew which areas were bountiful and whalers could follow the migrations of their prey. Our knowledge, in short, was limited to the surface waters and shallow seas. But in the past century or so, advances in engineering have enabled oceanographers to study even the ocean's deepest crevasses.

One of the earliest systematic studies began in 1872, when the *H.M.S. Challenger* left England for a four-year cruise on the world's oceans. The crew collected many new creatures — some that lived in waters more than three miles deep. They also measured the depth to the seafloor using soundings; that is, they lowered a hemp rope with a weight on the end and measured the depth. The expedition collected the first large set of biological samples and observations on the ocean, yet the 50 volumes of reports the expedition generated still barely scratched the surface of what is to be learned.

Ocean waves crash off Schoodie Point at Acadia National Park in Maine. The advent of submersibles, sonar, radar and satellite imagery has enabled scientists to peer into the depths of the sea.

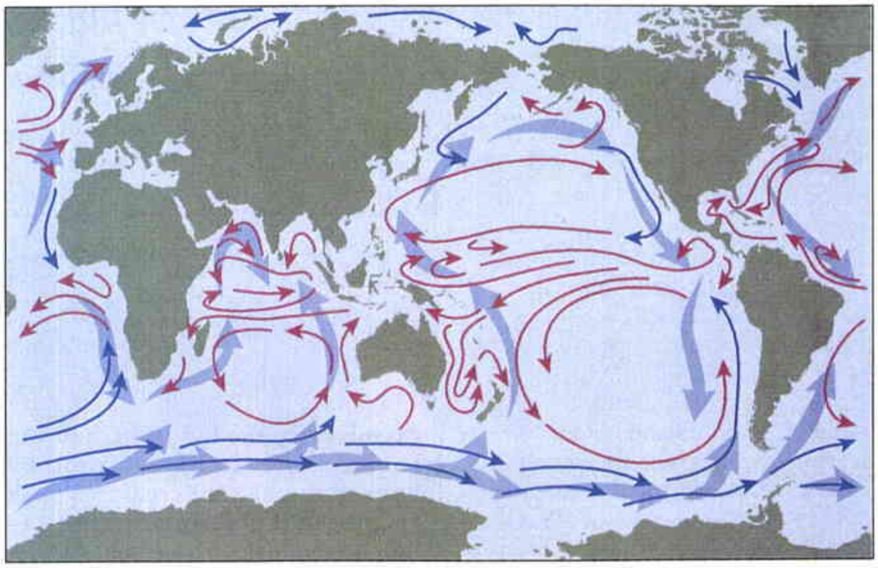
It wasn't until the development of sonar (sound navigation and ranging) that ocean depth measurements became more common. The technology was invented in 1915, primarily as a way for ships to detect icebergs and later to hunt submarines.

Scientists use sonar to send sound pulses toward the ocean floor and listen for their echoes, knowing that sounds travels through seawater at an average speed of 1,641 yards per second. If the sonar equipment detects an echo four seconds after sending the sound, scientists know it took two seconds to reach bottom and two to return. The rest is simple math.

After World War II, scientists began collecting data on the magnetic patterns in seafloor rocks, including those in the Mid-Atlantic Ridge. The surveys examining this magnetic imprint across the Atlantic had a curious tale to tell: The pattern of magnetization preserved in the seafloor paralleled the Mid-Atlantic Ridge, which is the equivalent of an underwater mountain range stretching from north to south across the middle of the Atlantic Basin. Some portions showed the "normal" magnetic patterns (with the north magnetic pole pointing north) and others showed a reversed magnetic field (with the north magnetic pole pointing south). These normal and reverse patterns were symmetric on either side of the ridge.

Almost simultaneously, in 1963, researchers Fred J. Vine and Drummond H. Matthews in England and L. Morley and A. Larochelle in Canada understood what this meant. They knew that rocks seal in the direction of Earth's magnetic field at the time they are created. Therefore, because the magnetic fields of the seafloor rocks had different orientations, the rocks must have formed at different times. Thus, they reasoned, if the oceanic crust was created at the crest of the ridge and then spread away from it, the rocks further away from the ridge should be older than those near the ridge and thus have a different magnetic orientation.

A comparison of the orientation of the magnetic fields in the seafloor with that of rocks on land of known age sealed it: The seafloor was spreading, and new oceanic crust was being created all the time as molten rock oozed up through the seafloor at mid-ocean ridges. Scientists had finally found strong evidence that continents move as passengers on fragments of Earth's outer shell. Thus, the theory of plate tectonics, which had been proposed but not proven, was nailed down not by studying continents but the ocean floor.



EARTH; Elisabeth Rowan/Source: *The Random House Atlas of the Oceans*

Continents shape the global system of warm and cold currents that flow through the ocean. Oceanographers have sampled water from different depths to map the currents, which can entirely change direction with depth. In this diagram, red arrows indicate warm surface currents, blue indicate cold surface currents and light blue indicate deep currents.

Seeing the whole picture of ocean circulation has been another major advance in marine science. By sampling the water at different depths, we've learned that the oceans are layered according to their temperature, chemical makeup and motions. A global system of currents snakes through the oceans, their paths determined by the size, shape and location of the continents, the contours of the seafloor and the motions of Earth itself. These currents are part of the intimate link between the oceans and global climate. For example, they transport heated water from the equator to the poles, preventing the difference in temperature between the two regions from growing too large.

Eventually, advances in technology allowed marine scientists to begin exploring the oceans firsthand. In 1930, William Beebe designed the first bathysphere, which held one person and could descend more than 3,000 feet. It enabled scientists to observe weird new marine life but was kept on a restrictive leash —

UPI/Bettmann

Submersibles, both piloted and unpiloted, have contributed much to our understanding of the deep-sea realm. In this August 1934 photo, William Beebe (right) and fellow explorer Otis Barton stand next to Beebe's bathysphere, built in 1930 to carry one person to incredible depths at the end of a tether. Here, the two-ton steel chamber is about to make a record dive to 2,510 feet.

a tether connecting it to a support ship. Later, the U.S. Navy led efforts to develop deep-submergence vehicles. In the 1960s Al Vine, of the Woods Hole Oceanographic Institute, recognized the value to science of piloted, free-ranging submarines. Thus the birth of *Alvin*. The 23-foot-long submarine held three people, could stay underwater eight hours and could descend nearly two miles in its original form.

In 1977, Alvin made a major discovery during a dive at the Galapagos Rift: hydrothermal vents spewing hot water at temperatures up to 757 degrees Fahrenheit (403 Celsius). These hot vents were surrounded by life such as tube worms, clams and crabs. The water had been heated by volcanic hot rock beneath the seafloor, which infused it with sulfur-containing chemical compounds called sulfides. Certain bacteria metabolize hydrogen sulfide

The submersible research vessel Alvin (foreground) is readied for a piloted dive into the depths of the ocean. The submersible is carried out to dive sites by its support ship, the Atlantis II. In 1977, Alvin uncovered a community of creatures living off sulfur compounds in hot water escaping from vents in the ocean floor.

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dissolved in the hot fluid, and the bacteria are in turn eaten by hydrothermal-vent creatures such as galitheid crabs and limpets (a type of mollusk). These vents represented oases of life on the floor of the deep sea, which, like deserts, are sparsely populated.

In 1984, in a trench off Oregon, *Alvin* found another type of oasis of animal life on the seafloor. Here, fluid rich in hydrogen sulfide was leaking out of the seafloor, but the temperature was close to that of the surrounding seafloor. These vents have been dubbed "cold seeps" to distinguish them from hydrothermal vents.

Some of the animals on hydrothermal vents and cold seeps — some types of clams, for example — have evolved an intriguing method of gleaning energy from the hydrogen sulfide. Unlike the animals that eat the bacteria, these creatures host bacteria in their bodies that metabolize the sulfides. These bacteria produce energy in the form of enzymes, which the host animals live off directly. I and my colleagues at the Monterey Bay Research Institute are now using a robot submarine attached to a support ship by a tether — an ROV, or "remotely operated vehicle" — to study the ecology of cold seep creatures in the undersea Monterey Canyon.

The discovery of these creatures was one of the most startling in deep-sea research. In most of the ocean, the food web — the complex set of relationships between the eaters and the eaten — is based ultimately on phytoplankton (that is, on photosynthesis). But on vents and seeps, the food web is powered by chemosynthesis — on bacteria that live off chemicals in the absence of light. This discovery made an important contribution to exobiology, the study of how life could survive in the harsh conditions that might prevail on other planets in the solar system. Some day exobiologists will probably use what we have learned on the seafloor to identify traces of life, past or present, in chemical oases on Mars or on the other planets and moons of our solar system. The recent announcement of possible traces of bacterial life in a Martian meteor makes this seem more imaginable.

Marine scientists have learned a lot about the oceans by going out into the field with research ships and submersibles. But with the help of satellites, we can now stay on land and still explore the oceans. For example, satellites equipped with radar have enabled scientists to map the sea surface to an accuracy of half an inch.

Radar (radio detecting and ranging) is similar to sonar in its basic workings: Electromagnetic waves (rather than sound waves) are beamed toward a distant target and bounce back. The time it takes for the radar beam to return reveals the distance of the target. It doesn't matter whether the target is an enemy bomber or the sea surface.

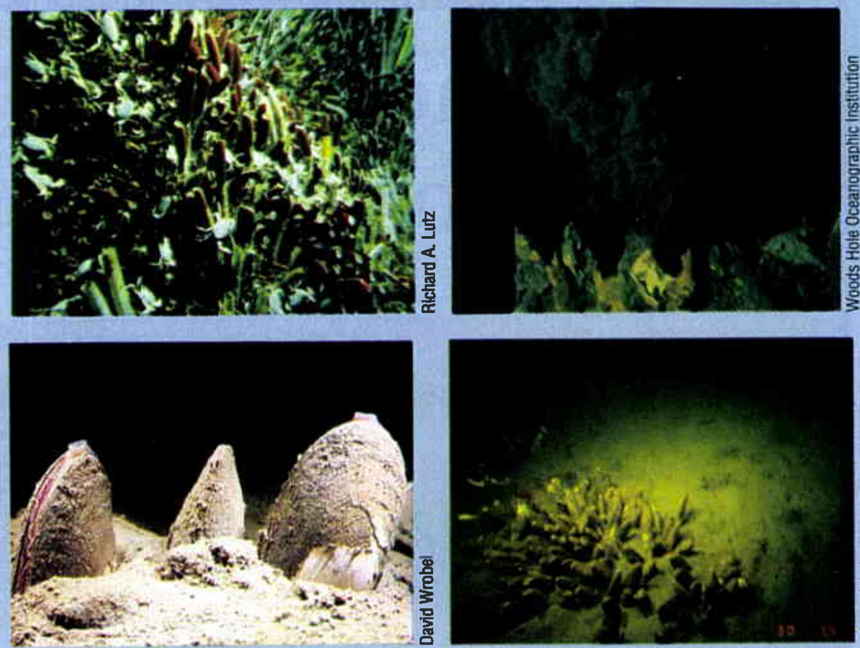
NASA launched the radar satellites Seasat in 1978 and Geosat in 1985. These satellites have shown us that because of differences in the force of gravity across Earth's surface, "sea level" is not level at all. Undersea mountains create slight bumps on the surface. The mass of the mountain draws the surrounding water toward it, causing the water to mound up on the sea surface. The converse is true for the trenches, where sea level can be depressed.

Satellites measuring temperature have shown what happens during an El Niño-Southern Oscillation, or El Niño. Normally, the equatorial winds blow from east to west, dragging warm surface waters to the western Pacific and allowing the cooler, nutrient-rich waters to rise on the west coast of South America. For reasons that remain unclear, every few years these winds relax, allowing the warm water to slosh back east. This change in atmospheric circulation affects weather and climate not only on the coast of Peru and Ecuador but other parts of the world as well. Scientists now use satellites to observe and forecast El Niño.

Satellites also help us keep an eye on the marine food web. Nutrient-rich areas of the ocean contain large concentrations of phytoplankton. These plantlike organisms contain the green, photosynthetic pigment chlorophyll, which they use to manufacture food. Satellites can detect the chlorophyll from space, and thus distinguish between areas of high and low biological productivity — akin to grassland versus deserts on the continents.

This important observation confronted marine scientists with a paradox. In ocean desert areas, such as the equatorial Pacific, there's very low biological productivity (that is, phytoplankton populations are low) despite warm water, lots of sunlight, and a supply of fertilizing nutrients. In two expeditions to the Pacific in recent years, ocean scientists tested the hypothesis of the late John Martin that a lack of dissolved iron in certain parts of the ocean is the cause of low productivity. The scientists seeded the ocean with iron and witnessed an immediate bloom in plankton. In some parts of the ocean, the availability of iron is an important limiter of primary production. The "iron experiment" proved that.

Despite the achievements I have briefly mentioned in this essay, important questions about the world's oceans are waiting for answers. For instance, we know that there is a strong coupling between changes in Earth's oceans and changes in climate — one drives the other and vice versa. But our understanding of this is imperfect. The challenge we have ahead of us is to figure out how the oceans and atmosphere interact as a system so we can fully understand and anticipate what effects we're having on the system by adding large amounts of carbon dioxide into the air.



Deep-sea explorers have discovered unique life-forms living near breaks in the ocean floor that spew sulphur-rich hot or cold water. Top left: Tube worms and crabs encircle a hydrothermal vent. Top right: A "black smoker" hydrothermal vent leaks chemical-rich fluids. Bottom row: Clams live near cold seeps in the undersea Monterey Canyon.

Other questions concern the ocean itself. How stable is it and what is the overall chemical budget for the ocean — which chemicals are being lost, which gained? We now know that immense amounts of seawater circulate through the mid-ocean ridges, but we don't know how much. Some scientists have calculated that the entire ocean circulates through the ridges every 8 million years. How does this affect the chemistry of ocean and ridge? We know huge amounts of fluid are squeezed out of sediments during subduction and accretion and bring an enormous amount of carbon back to the sea, but again we don't know how much.

Studying hydrothermal vents has led us to appreciate the subsurface biosphere. Bacteria thrive wherever chemical energy exists to fuel them: below the hydrothermal vents, in the sediments below cold seeps and even in oil fields. How much life exists in this unexplored world? Could it be greater than that above the surface? Satellite altimetry maps have provided new targets for seafloor research, and ocean drilling projects will address topics as diverse as the sub-seafloor biosphere and the evolution of continental margins.

Finally, we must address fisheries. The ocean supplies much of the food for this planet, and almost every fishery is over-harvested. The anchovy fisheries in Monterey Bay, the salmon in the Pacific Northwest, the cod on Georges Banks — all are threatened or have already crashed. We need to determine what natural and manmade processes regulate marine fisheries and then figure out how to harvest fish for long-term stability.

Advances in technology have helped us to lay bare the seafloor. New ones will help us learn more. But now, as our data has increased, the emphasis has shifted from cataloguing creatures to analyzing how our watery planet works. This is the challenge we present to the next generation of marine scientists. ⊕

Daniel Orange is a research scientist at the Monterey Bay Aquarium Research Institute (MBARI) in California. His recent research has focused on cold seeps. He also helps develop new deep-sea research technology. This past summer, he wrote this essay while aboard the Sonne, a German research vehicle participating in an international program to study cold seeps in the Aleutian Trench off Alaska.