

# BEYOND DISCOVERY™

THE PATH FROM RESEARCH TO HUMAN BENEFIT

## WHEN THE EARTH MOVES SEAFLOOR SPREADING AND PLATE TECTONICS

**E**arly on the morning of Wednesday, April 18, 1906, people in a 700-mile stretch of the West Coast of the United States—from Coos Bay, Oregon, to Los Angeles, California—were awakened by the ground shaking. But in San Francisco the ground did more than shake. A police officer on patrol in the city's produce district heard a low rumble and saw the street undulate in front of him, "as if the waves of the ocean were coming toward me, billowing as they came." Although the Richter Scale of magnitude was not devised until 1935, scientists have since estimated that the 1906 San Francisco earthquake would have had a 7.8 Richter reading. Later that morning the disaster of crushed and crumbled buildings was compounded by fires that broke out all over the shattered city. Some 700 people were killed, another 250,000 were left homeless, and 28,000 buildings were destroyed. Financial losses were estimated at \$500 million, almost \$9 billion today.

The earthquake that struck San Francisco that morning would go down in history not only for its destructiveness but also for what seemed at the time to be its inexplicable characteristics. Scientists of the period knew about the nearby San Andreas fault and were familiar with the idea that one side of such a crack in the planet's crust could shift up or down against the other to cause a localized earthquake. But as geologists began examining this event, they were at a loss to explain its magnitude. A very long section of

the fault had moved, spanning nearly 300 miles, from San Juan Bautista in San Benito County to the south of San Francisco to the Upper Mattole River in Humboldt County to the north, as well as westward some distance out to sea. The scale of this movement was unheard of. The explanation would take some six decades to emerge, coming only with the advent of the theory of plate tectonics.

One of the great achievements of modern science, plate tectonics describes the surface of Earth as being divided into huge plates whose slow movements carry the continents on a slow drift around the globe. Where the plates come in contact with one another, they may cause catastrophic events, such as volcanic eruptions and earthquakes, which in turn can trigger the destructive ocean waves known as tsunamis. Plate tectonics became widely accepted by earth scientists starting only in the 1960s. As the following article relates, investigators pursuing basic questions in ocean and terrestrial science gradually arrived at an understanding of how the planet's crust works, an understanding that now allows us to prepare for times when the very ground beneath our feet undulates like waves on the ocean.



Shattered by a powerful earthquake on April 18, 1906, the ruins of San Francisco's City Hall stand surrounded by thousands of tons of brick rubble. (Photo courtesy of the Museum of the City of San Francisco.)



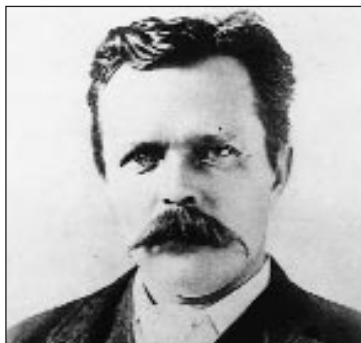
## From Earthquakes to Continental Drift

In the early 1890s, John Milne, a geologist teaching at the Imperial College of Engineering in Tokyo, developed with colleagues the first accurate seismograph, an instrument used to record ground shaking, a frequent and sometimes devastating occurrence in Japan. A few years later a fire destroyed Milne's home, his scientific observatory, and the earthquake data he had collected over more than a decade while working in Japan. Discouraged but not defeated, Milne returned to his native Britain, where by the turn of the century he had established a bigger and bolder approach to the study of earthquakes—a network of 27 instruments throughout the British empire. By the time Milne died in 1913, 40 stations around the world were beginning to define the global pattern of earthquake location.

A seismograph records vibrations produced by sudden motion along a fault that generates several kinds of seismic, or “shaking,” waves—vibrations back and forth, side to side, and up and down. The first seismologists could distinguish two kinds of seismic waves, which move at different speeds. Primary, or P waves, which alternately compress and dilate the matter in their path, arrive at the instrument first, inscribing a wavy line on a chart. Secondary, or S waves, which tend to oscillate snakelike, at right angles to their direction of motion, travel more slowly and have a more ragged seismographic signature. The interval between the arrival of the two types of waves can be used to calculate the distance of the monitoring station from the earthquake's epicenter, the point on Earth's surface above the subterranean hypocenter, or source of the shock. The distances from three seismographic stations can be used to triangulate the hypocenter and place it precisely on the map.

Milne's network ushered in the ability to detect and locate earthquakes by remote sensing, a significant contribution to science and society in itself.

*In the early 1890s, British geologist John Milne was instrumental in developing an accurate seismograph for recording the vibrations produced by earthquakes. (Photo courtesy of the Science and Society Picture Library.)*



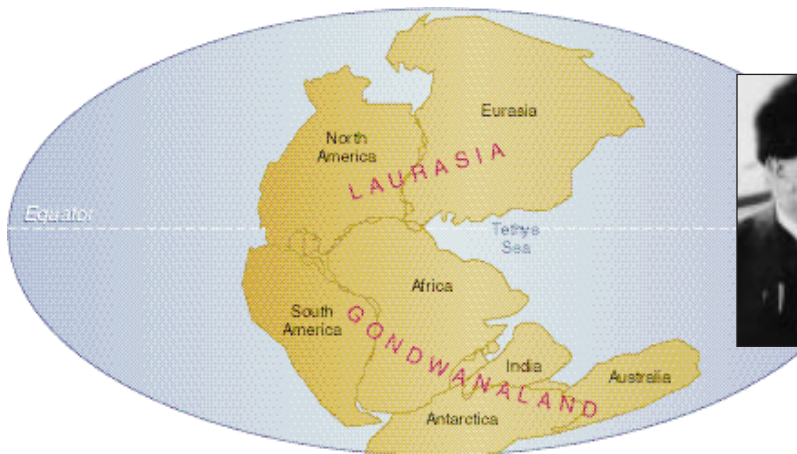
But seismologists soon realized that the instruments also offered a way to probe the mysterious interior of the planet. By the start of World War I, a succession of researchers had studied the behavior of seismic waves to infer a planetary structure composed of concentric layers: an inner core (although there was disagreement as to whether it was solid or fluid) covered by an intermediate layer of dense rock, the mantle, that began about 30 miles beneath the outermost surface crust.

Against this background of knowledge, a German meteorologist caused an uproar in the world of geology with his bold theory about the nature of Earth's surface. In 1915, Alfred Wegener published *The Origins of Continents and Oceans*, in which he addressed the puzzling match-up between the bulge of Brazil and the dent of southwestern Africa. He argued that the two continents had once been joined and had drifted apart. As additional evidence for continental displacement, or continental “drift” as the original German word was translated, Wegener cited fossils of the Mesosaur, a 270-million-year-old reptile found only in eastern South America and western Africa. Most geologists of his generation explained these similarities by postulating a connecting land bridge that had later sunk out of sight into the ocean. Wegener postulated, rather, that the Mesosaur bones were found in these distant places because those regions had come apart about 125 million years ago, slowly separating the groups of Mesosaur fossils. The continents of today drifted apart from a super-continent, which he called Pangaea.

The meteorologist was unsure as to how these huge slabs move around, but suggested that they were propelled through the oceanic crust by Earth's centrifugal force and the gravitational pull of the Sun and Moon. Many influential geophysicists argued convincingly that such mechanisms were insufficient to the task. However, in 1929, one supporter, Arthur Holmes of England, suggested that convective flow of heated rock in the mantle beneath the crust might provide the required driving force—that is, as rocky material deep in the mantle heats, it becomes less dense and rises toward the surface, where it cools and sinks, to be reheated and rise again. Without more evidence of such a mechanism, however, the theory of continental drift gained few adherents.

## Magnetic Clues

Evidence was hard to come by, but in the mid-1950s clues began accumulating in studies of magnetism in



*In 1915, German meteorologist Alfred Wegener published what came to be called the theory of continental drift, in which he suggested that the continents had once been part of a supercontinent he named Pangaea. But without a convincing mechanism for moving the continents around the globe, Wegener's theory had few champions for more than 40 years. (Figure adapted from Earth: Past and Present by Graham R. Thompson, Jonathan Turk, and Harold L. Levin, copyright 1995, by Harcourt, Inc., reproduced by permission of the publisher. Photo courtesy of the Alfred Wegener Institute of Polar and Marine Research.)*

rocks. Patrick M. S. Blackett (who received the 1948 Nobel Prize in physics for his work on nuclear physics and cosmic rays) at Imperial College, Stanley Keith Runcorn at Cambridge University, and Edward Bullard at the National Physical Laboratory in England were studying magnetism in rocks as part of their research into the nature of Earth's magnetic field. Scientists knew that newly formed crustal rock would record an imprint of the strength and orientation of Earth's magnetic field at the time of the rock's formation. Looking to see whether the rock's magnetism varied directionally, Blackett, Runcorn, Bullard, and their students found considerable evidence that throughout geological history rocks had somehow moved relative to the planet's magnetic poles. Two interpretations of this evidence were possible: either Earth's poles had wandered relative to the continents or the continents had moved relative to the poles.

By the mid-1950s, bolstered by paleomagnetic data gathered by Edward Irving at the Australian National University in Canberra, Blackett, Runcorn, and Bullard were convinced that Wegener had been right. The rocks showed distinctly different apparent polar wandering paths for different continents, paths that were consistent with the positions of the continents as suggested by Wegener's drift theory.

## Insights from the Ocean

Despite the magnetic evidence that the continents had moved over geological history, proponents of the theory were still lacking proof of a mechanism. However, additional support was gathering on the high seas.

With the help of war-driven improvements in the technique of echo location, or sonar (for sound navigation and ranging), for submarine detection, Harry

Hess, a geologist at Princeton University, aided the U.S. military with one hand and geoscience with the other. As the commander of an attack transport during World War II, Hess had the most powerful model of an echo sounder available, and he ran it almost constantly during his Pacific missions, intent on expanding on what little was known about the configuration of the seafloor. By sending out pulses of sound and listening for return echoes from the seafloor, a sonar instrument can measure the distance between a ship and the ocean bottom. Hess combined measurements from several passages to produce a rough contour map of the seafloor and in the course of his war service discovered and mapped about 100 flat-topped underwater mountains. Later, back at Princeton, Hess theorized that these mountains originated as pointed-top volcanoes that subsequently had been flattened by erosion. This led him to consider the life cycle of underwater mountains, an interest he pursued throughout the 1950s.

Meanwhile, Columbia University had become the home base for a vigorous marine geology research program, headed by Maurice Ewing. During the early 1950s, the research ships of Columbia's Lamont Geological Observatory (now named Lamont-Doherty Earth Observatory) collected numerous depth soundings taken across the Atlantic Ocean, and in 1952 the Lamont researchers began assembling a map derived from these soundings.

One of the features of the Atlantic seafloor known since the mid-1870s was an undersea mountain range called the Mid-Atlantic Ridge. Rising from a broad flat plain to either side, the range had peaks that jutted up 10,000 feet from the ocean floor. The Lamont researchers discovered startling new information about it, however. Not only was the Mid-Atlantic Ridge high, it was long. Running some 9,000 miles, nearly the full length of the ocean from north of Greenland



to south of Africa, the ridge stretched farther than the Rocky Mountains and the Andes combined. The Lamont researchers also found that the crest of the ridge system is virtually bare of sediments, as compared with the thick layer of sediment on the plains near the continental margins, which can reach a thickness of several miles. Perhaps the most unexpected feature of the Mid-Atlantic Ridge was the deep valley running down its spine. This rift, as it is called, descended an average of 6,000 feet from the ridge crest and ranged in width from 8 to 30 miles—dimensions that could comfortably contain the Grand Canyon of the Colorado River, which is at most about 18 miles wide. Bottom samples taken from the rift revealed the seafloor there to be made of extremely young, dark volcanic rock.

A map of the North Atlantic showing features of the midocean ridge was published by Lamont researchers Bruce Heezen, Marie Tharp, and Maurice Ewing in 1959. As it happened, echo soundings made elsewhere had produced similar profiles of the seafloor throughout the world, and now an extraordinary pattern emerged. The soundings revealed the entire midocean ridge system to be 37,200 miles in length, long enough to circle the equator one and one-half times. It was one of the planet's three dominant physical features, along with the continents and the oceans themselves. Researchers had also mapped a system of deep trenches—the deepest parts of the ocean basins—

that nearly ring the Pacific Ocean and are found at the northeastern boundary of the Indian Ocean.

These were fundamental new discoveries, and Harry Hess, who had kept abreast of new data about the seafloor, was eager to explore their implications. In 1960, he gleaned from Bruce Heezen the idea that Earth was “coming apart at the seams”—that is, at the ridges. Given the youthful nature of the samples from the rift bottom, Heezen argued that volcanic rock—magma—was welling up from below the crust. From this hint of a mechanism that could explain the midocean ridges, Hess developed a new synthesis of earth science in his well-known 1962 paper, “The History of Ocean Basins.” Although he characterized the essay as “geopoetry,” as if to warn other scientists that not every concept could be proven, the work stimulated thinking in the field.

Echoing the insights of seismologists, Hess posited a multilayered interior for the planet. By this time researchers had refined their notions of Earth's innermost structure. Rather than a single iron core, they now described a solid inner core of iron and a fluid outer core of metal alloy, mostly iron. Surrounding this was the mantle, overlain by the outermost thin oceanic and thick continental crust. Hess then elaborated on the evolution of the planet's architecture. The crust was made up of iron-poor rock that had risen to the surface when radioactive decay heated and melted rocks in the interior of the newly condensed

## Discoveries in Plate Tectonics and Seafloor Spreading

*This chronology shows the chain of basic research that led to key insights about plate tectonics and related processes.*

### 1890s

John Milne develops the seismograph, establishes a network of seismographic stations in the British empire.

### 1915

German scientist Alfred Wegener publishes his then-radical theory of continental drift in *The Origin of Continents and Oceans*.

### 1959

Bruce Heezen, Marie Tharp, and Maurice Ewing of Columbia University publish the first detailed map diagrams of the globe-girdling midocean ridge system.

### 1963

Fred Vine and Drummond Matthews at Cambridge University conceive of a connection between seafloor spreading and the “stripes” of magnetic reversal in the seafloor.

### Early 1900s

Scientists use seismographic research to probe Earth's inner structure, developing a model of concentric layers of core, mantle, and surface crust.

### Mid-1950s

Patrick M. S. Blackett, S. Keith Runcorn, and Edward Irving produce paleomagnetic data from several continents showing apparent polar wandering consistent with Wegener's drift theory.

### 1962

In seeking to explain the midocean ridges, Harry Hess of Princeton University proposes that the seafloor is slowly spreading away from the ridges, driven by convection currents in the mantle.



planet; this crust had once formed a single continental land mass. In the presence of continued heating in the planet's interior, a convection "loop" of rising and sinking material would be created in the mantle—just as Arthur Holmes had suggested in 1929.

Hess theorized that once the planet had formed, this mantle convection subdivided into numerous separate circulating loops extending from the core. Where the currents rise to the surface, molten material oozes out, building up the midocean ridges and forming new oceanic crust; as magma continues to flow, older seafloor is carried away in either direction from the ridge by mantle convection. Where the convection currents descend, cooled older oceanic crust plunges back into the mantle at deep ocean trenches.

Hess thus subordinated the configuration of the oceans and continents to the motions of the spreading, moving seafloor. While seafloor spreading was a compelling vision, it seemed untestable. Hess was proposing that it occurred at about the rate at which a fingernail grows. The proof would have to come indirectly—from magnetism, as it turned out.

## Of Magnetism and Time

Scientists had known since the 1920s that rock from different geological times could show opposite magnetic polarities. Sometimes the orientation was

"normal," north-pointing, as it is today; at other times the geomagnetic field was reversed. In 1963, Allan Cox, Richard Doell, and Brent Dalrymple of the U.S. Geological Survey and Ian McDougall at Australian National University began to establish a quantitative timescale of reversals by measuring the magnetic directions in lava flows on land and determining their ages by radioactive methods. It was a painstaking process, but by 1966 researchers had charted the reversal timescale for the past 3.5 million years.

At sea, meanwhile, researchers were finding an intriguing pattern. Magnetic surveying of the seafloor had been developed during World War II as an outgrowth, like echo sounding, of the effort to improve detection of submarines. In 1961, Arthur Raff and Ronald Mason of the Scripps Institution of Oceanography noted magnetic anomalies in the pattern of stripes on the ocean floor off the coast of Washington state. One year later geophysicist Drummond Matthews of Cambridge University, who had gathered magnetic surveys of an undersea ridge in the Indian Ocean, also noticed a distinct and curious pattern of magnetic stripes—stronger and weaker magnetic signals in parallel bands on either side of the ridge crest. Back in England he talked over his findings with Fred Vine, a graduate student at Cambridge University who was focusing on marine geophysics. The two of them hypothesized that the seafloor had recorded Earth's magnetic field orientation at the

### 1965

Vine and J. Tuzo Wilson of the University of Toronto bolster the Vine-Matthews hypothesis with additional magnetic reversal evidence from the seafloor at the Juan de Fuca Ridge. Later that year deep-sea cores collected by Columbia's Neil Opdyke show a matching timescale. Seafloor spreading is confirmed.

### Late 1960s

Wilson coins the term "plate" in developing the concept of seafloor spreading into a new scientific worldview—plate tectonics.

### Late 1960s

Xavier Le Pichon, Dan McKenzie, and W. Jason Morgan define the shapes of the plates and how their movement and location on the globe could be described by elementary spherical geometry.

### 1963—1966

Allan Cox, Richard Doell, and Brent Dalrymple of the U. S. Geological Survey and Ian McDougall of the Australian National University determine the timescale of reversals of Earth's magnetic field from measurements of lava flows on land.

### 1977

The National Earthquake Reduction Program is established to reduce earthquake hazards throughout the United States.

### 1977

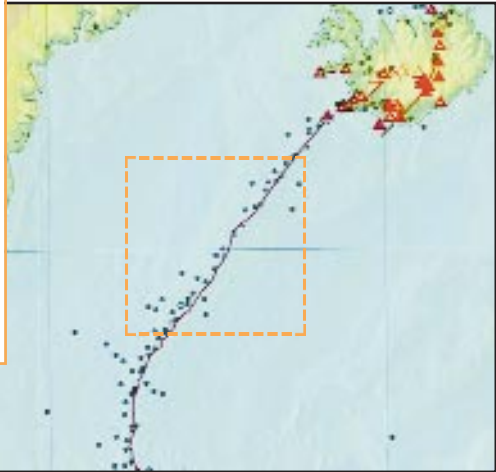
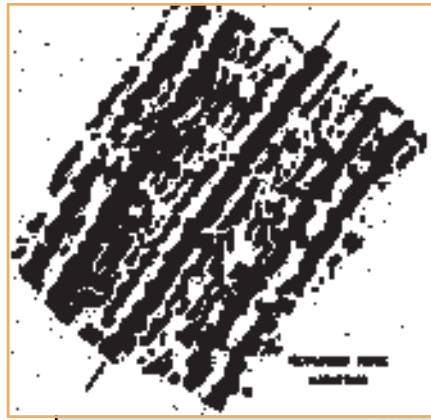
The first seafloor hot springs are discovered at the Galápagos Rift in an expedition led by Jack Corliss of Oregon State University and Robert Ballard of Woods Hole Oceanographic Institution. The scientists observe unique and unexpected animal communities living in the seafloor vents.

### 1968

Bryan Isacks, Jack Oliver, and Lynn Skyes recognize that slabs of material rigid enough to sustain earthquakes are descending into deep trenches, creating earthquake zones.



*Studies of seafloor magnetism in the early 1960s began establishing a timescale of reversals in Earth's geomagnetic polarity, from north-pointing to south-pointing. The reversals showed up as a striped pattern of normal and oppositely magnetized materials on either side of undersea ridges, such as Reykjanes Ridge off the southwestern coast of Iceland, an early clue to the movement of the seafloor. (Reprinted with permission from 1966, Deep Sea Research. 13: 427, as reproduced in Seibold and Berger, The Sea Floor, 2nd edition revised, 1993, and U.S. Geological Survey.)*



time the new molten rock oozed up from the mantle. If spreading of the ocean floor occurs as Harry Hess suggested, these blocks of alternately normal and reversely magnetized material would be carried away parallel to either side of the ridge.

The Vine-Matthews hypothesis, published in the fall of 1963, garnered little support in the geophysical community, partly because the magnetic reversal timescale was not yet complete, so the seafloor anomaly data matched their hypothesis only poorly. But two years later, in 1965, Fred Vine found himself in the company of Harry Hess, who had arrived at Cambridge on sabbatical leave, and J. Tuzo Wilson, there from the University of Toronto, continuing some of his own research on midocean ridges.

Wilson was examining Raff and Mason's maps of the seafloor area off the coast of Vancouver Island and south to California, and he suggested that the maps showed a seafloor spreading ridge. Vine and Wilson published a paper in October 1965 proposing a model for seafloor spreading in the northeastern Pacific, using as evidence bands of reversed magnetism that marched out from either side of the ridge. Shortly thereafter, a slight discrepancy between the seafloor reversal bands and the timing of known field reversals on land was smoothed out by a new land-based field reversal discovered by Doell and Dalrymple. With this addition, the two sets of data matched astonishingly well.

The confirmation of seafloor spreading was supported by other observations made in 1965 and 1966. Key among them were ocean sediment samples analyzed by Lamont's Neil Opdyke. The samples were from vertical cores, 16 to 40 feet long, taken from the ocean floor in the South Pacific. The timing and pattern of magnetic reversals in Opdyke's core

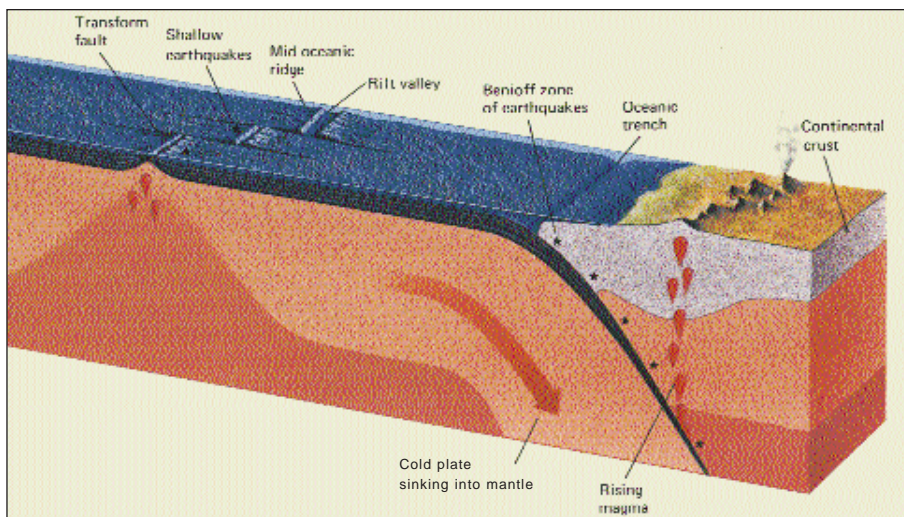
samples matched those determined from lava flows on land and from seafloor magnetic stripes.

## Plates in Motion

Scientists now held the key to a whole new way of understanding planet Earth. Tuzo Wilson, in an effort to explain seafloor fault lines, was the first to tackle the far-reaching implications of seafloor spreading.

Around the globe, researchers had noted faults—fractures perpendicular to the midocean spreading ridges that cross whole oceans and break the ridges up into segments. When Wilson took up the question, the favored interpretation was that the faults were evidence of the tearing of the ocean crust from edge to edge. The ridges were assumed to have started out as continuous features that were later fragmented and offset by the faults. Wilson disagreed. Yes, the faults were evidence of crustal tearing, but only between the spreading ridge segments, segments that had always been offset. This new view suggested that active deformation is concentrated at the ridges and along their connecting faults and that the rest of the ocean crust simply drifts along, unbroken. Wilson gave the name “plate” to these large masses of moving rock. He further proposed that Earth's surface was divided into about seven large crustal plates and several smaller ones.

Wilson's ideas about oceanic faults and plates were easily tested by the emerging earthquake location data set and Lynn Sykes, working at Lamont, was quick to try this test. Wilson's theories passed with flying colors. Sykes found that oceanic earthquakes were, indeed, concentrated along the midocean ridges and their connecting faults, and that the interiors of the oceanic “plates” were nearly aseismic or earthquake-free.



*New seafloor forms as molten rock rises up through layers of the mantle and spreads outward from crustal rifts at midocean ridges. Old seafloor descends back down into the mantle at deep trenches that occur where two tectonic plates collide—regions where earthquakes are common. Perpendicular to the midocean ridges are fractures called transform faults, where the ocean crust tears apart as tectonic plates move. (Figure adapted from Earth: Past and Present by Graham R. Thompson, Jonathan Turk, and Harold L. Levin, copyright 1995, by Harcourt, Inc., reproduced by permission of the publisher.)*

Earthquake studies also supplied a crucial step for our understanding of subduction zones. By the 1940s, Kiyoo Wadati in Japan and Hugo Benioff at the California Institute of Technology observed that deep earthquakes were on a plane dipping beneath the ocean floor and were concentrated in areas around the edges of oceans close to volcanoes on land. Studies in the 1950s showed that those ocean areas were also the location of deep trenches, which Harry Hess invoked in his model of seafloor spreading. The deep trenches and the quakes associated with them had puzzled seismologists. Some of these earthquakes occurred very deep in the mantle, where high temperatures should have softened anything rigid so that rocks would flow rather than being so hard and brittle that they fracture easily in earthquakes.

What changed that view was work by Lamont's Jack Oliver, Bryan Isacks, and Lynn Sykes, who examined earthquake activity in a trench near the South Pacific island of Tonga. Beginning in 1964, they collected seismic data to identify the subterranean sources, or foci, of earthquakes there. They observed, as had Benioff and Wadati, that the foci outlined a plane tilting down from the ocean floor at about 45 degrees. But the Lamont team was the first to recognize that this plane was a slab of descending material cool and hard enough to sustain earthquakes and, moreover, that the slab—containing the seafloor itself—was being bent down into the trench, creating the earthquake zone. The descending slab of seafloor, they determined, had considerable thickness, some 60 miles. What was moving was not just the surface of the seafloor, or the crust alone, but a thicker block. It seemed fair to call this moving block what Wilson had—a plate.

As the 1960s drew to a close, Xavier Le Pichon at Lamont, Dan McKenzie at Scripps, and W. Jason

Morgan at Princeton University went on to define the shapes of the contiguous plates and how their movement and location on the globe could be described by elementary spherical geometry, not only for the present but for the past and future, too. In a speech before a convention of his colleagues in 1967, Tuzo Wilson declared that seafloor spreading and plate tectonics “could be as important to geology as Harvey’s discovery of the circulation of the blood was to physiology or evolution to biology.”

## Putting Geophysical Insight to Work

Today, long-standing human concerns for public safety have benefited from an understanding of plate tectonics. For example, since the advent of plate tectonic theory in the late 1960s, scientists have recognized that the San Andreas fault in California is the boundary separating two plates that are slowly sliding past each other. The Pacific plate, the largest in the world, is moving in a northwesterly direction past North America, dragging the rim of the continent with it. Californians have long known that their land was earthquake-prone. The understanding that they are living on a major plate boundary clarifies that earthquakes are inevitable, that it is only a question of “when,” not “if” they will occur.

Although scientists cannot yet predict when earthquakes will occur, understanding the rate of plate movement and the pattern of earthquakes associated with the San Andreas fault has prompted the California state government to take specific precautionary measures. In 1975, California established a Seismic Safety



Commission, which, among other responsibilities, reviews and updates the state's earthquake hazard mitigation plan.

On a national level, the Earthquake Hazards Reduction Act in 1977 established the National Earthquake Hazards Reduction Program (NEHRP) to reduce earthquake hazards throughout the United States, something that earthquake specialists had been calling for since the great Alaskan earthquake of 1964. Research carried out by NEHRP participants influences not only programs of public education but also the development of seismic standards for the design and construction of buildings and other structures. One significant design change to the Uniform Building Code, for example, involves the principle of base isolation, in which a structure is supported by a number of bearing pads that are placed between the structure itself and its foundation, or base. As the ground moves in one direction, a structure on a fixed base lags behind, effectively going in the opposite direction; given the nature of earthquake ground waves, this means a structure actually vibrates back and forth, in many directions. If its base is isolated by intervening bearing pads, however, the pads themselves absorb the vibration and the building essentially remains stationary. Because of similar geologic hazards both Japanese and Californians are leaders in developing strengthened construction codes for, among other things, public schools, bridges, hospitals, and dams.

In addition to its relevance to public safety, the advent of plate tectonics theory has been a boon to essential economic activities such as mining and petroleum exploration. Since the 1970s, prospecting for oil and natural gas, for example, has been enhanced by the development and continued refinement of paleogeographic (literally “fossil” geography) maps that can help identify ancient environments that were conducive to the formation and preservation of petroleum sources.

## Window on a New World

More unexpected, perhaps, is the new undersea world discovered at hydrothermal vents, the hot springs created where seawater seeps down into the heated crust at spreading zones. In 1977, an expedition to the Galápagos Rift discovered astonishing new ecosystems around the hot springs there; similar ecosystems were soon found in several oceans around the globe. Researchers using manned and unmanned

submersibles have now collected more than 200 entirely new species of worm, mollusk, and arthropod from these hydrothermal vents—a far cry from the barren desert that biologists had once imagined as the ocean floor. Thriving in the absence of sunlight, the vent creatures create their energy by oxidizing chemical compounds emerging from the interior of the planet—primarily hydrogen sulfide, a poison for most life on Earth. Among the most intriguing creatures to be discovered in the vent systems are “hyperthermophiles,” microorganisms adapted to temperatures sometimes exceeding the normal boiling point of water. Their peculiar metabolic properties have made them the subject of research in biotechnology.

Plate tectonics explains virtually all of Earth's major geological features and makes sense of otherwise inexplicable phenomena such as earthquakes, volcanic eruptions, and the formation of mountain ranges. Tuzo Wilson's claim for the significance of the theory would therefore seem to be well founded. But plate tectonics has also led to new discoveries—such as that of the hydrothermal vent organisms and their implications for our understanding of life on the planet—outcomes that investigators such as John Milne, Alfred Wegener, or Harry Hess could not have predicted as they followed their scientific curiosity.

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