PART I

THE HISTORICAL BACKGROUND

The idea that continents move was first seriously considered in the early 20th century, but it took scientists 40 years to decide that it was true. Part I describes the historical background to this question: how scientists first pondered the question of crustal mobility, why they rejected the idea the first time around, and how they ultimately came back to it with new evidence, new ideas, and a global model of how it works.

Chapter 1

From Continental Drift to Plate Tectonics

Naomi Oreskes

Since the 16th century, cartographers have noticed the jigsaw-puzzle fit of the continental edges.[1] Since the 19th century, geologists have known that some fossil plants and animals are extraordinarily similar across the globe, and some sequences of rock formations in distant continents are also strikingly alike. At the turn of the 20th century, Austrian geologist Eduard Suess proposed the theory of Gondwanaland to account for these similarities: that a giant supercontinent had once covered much or all of Earth's surface before breaking apart to form continents and ocean basins. A few years later, German meteorologist Alfred Wegener suggested an alternative explanation: continental drift. The paleontological patterns and jigsaw-puzzle fit could be explained if the continents had migrated across the earth's surface, sometimes joining together, sometimes breaking apart. Wegener argued that for several hundred million years during the late Paleozoic and Mesozoic eras (200 million to 300 million years ago), the continents were united into a supercontinent that he labeled *Pangea*—all Earth. Continental drift would also explain paleoclimate change, as continents drifted through different climate zones and ocean circulation was altered by the changing distribution of land and sea, while the interactions of rifting and drifting land masses provided a mechanism for the origins of mountains, volcanoes, and earthquakes.

Continental drift was not accepted when first proposed, but in the 1960s it became a cornerstone of the new global theory of plate tectonics. The motion of land masses is now explained as a consequence of moving "plates"—large fragments of the earth's surface layer in which the continents are embedded. These plates comprise the upper 45 to 60 miles (80 to 100 kilometers) of the earth's surface (now called the lithosphere), and move at a rate of 1 to 4 inches (3 to 10 centimeters) per year. Earthquakes, volcanoes, and mountains are concentrated on plate margins where two plates collide, split apart, or slide past one another. Moreover, the global configuration of continents and oceans is constantly changing. As Wegener suggested, the breakup of Pangea produced the configuration of continents and oceans that we have today.

BEFORE CONTINENTAL DRIFT: VERSIONS OF CONTRACTION THEORY

One of the central scientific questions of 19th-century geology was the origin of mountains. How were they formed? What process squeezed and folded rocks like putty? What made the earth's surface move? Most theories invoked terrestrial contraction as a causal force. It was widely believed that Earth had formed as a hot, incandescent body, and had been steadily cooling since the beginning of geological time. Because most materials contract as they cool, it seemed logical to assume that Earth had been contracting as it cooled, too. As it did, its surface would have deformed, producing mountains.

In Europe, Austrian geologist Edward Suess (1831–1914) popularized the image of Earth as a drying apple: as the planet contracted, its surface wrinkled to accommodate the diminished surface area. Suess assumed that Earth's initial crust was continuous, but broke apart as the interior shrunk. The collapsed portions formed the ocean basins; the remaining elevated portions formed the continents. With continued cooling, the original continents became unstable and collapsed to form the next generation of ocean floor, and what had formerly been ocean now became dry land. Over the course of geological history, there would be a continual interchange of land and sea, a periodic rearrangement of the land masses.

The interchangeability of continents and oceans explained a number of other perplexing geological observations, such as the presence of marine fossils on land (which had long before puzzled Leonardo Da Vinci) and the extensive interleaving of marine and terrestrial sediments in the stratigraphic record. Suess' theory also explained the striking similarities of fossils in parts of India, Africa, and South America. Indeed, in some cases the fossils seemed to be identical, even though they were found thousands of miles apart. These similarities had been recognized since the mid-century, but they had been made newly problematic by Darwin's theory of evolution. If plants and animals had evolved independently in different places within diverse environments, then why did they look so similar? Suess explained this conundrum by attributing these similar species to an early geological age when the continents were contiguous in an ancient supercontinent called Gondwanaland.[2]

Suess' theory was widely discussed and to varying degrees accepted in Europe, but in North America geologist James Dwight Dana (1813–1895) had developed a different version of contraction theory. Dana suggested that the continents had formed early in earth history, when low-temperature minerals such as quartz and feldspar had solidified. Then the globe continued to cool and contract, until the high-temperature minerals such as olivine and pyroxene finally solidified: on the moon, to form the lunar craters; on Earth, to form the ocean basins. As contraction continued after Earth was solid, its surface began to deform. The boundaries between continents and oceans took up most of the pressure—like the seams on a dress—and so mountains began to form along continental margins. With continued contraction came continued deformation, but with the continents and oceans always in the same relative positions.[3] Although Dana's theory was a version of contraction, it came to be known as permanence theory, because it viewed continents and oceans as globally permanent features.

In North America, permanence theory was linked to the theory of geosynclines: subsiding sedimentary basins along continental margins. This idea was developed primarily by James Hall (1811–1889), state paleontologist of New York and the first president of the Geological Society of America (1889). Hall noted that, beneath the forest cover, the Appalachian mountains were built up of folded layers of shallow-water sedimentary rocks, thousands of feet thick. How did these sequences of shallow-water deposits form? How were they folded and uplifted into mountains? Hall suggested that materials eroded off the continents accumulated in the adjacent marginal basins, causing the basins to subside. Subsidence allowed more sediments to accumulate, causing more subsidence, until finally the weight of the pile caused the sediments to be heated, converted to rock, and then uplifted into mountains.[4] (The process of uplift, or mountain-building, is called *orogeny.*) Dana modified Hall's view by arguing that thick sedimentary piles were not the cause of subsidence but the result of it. Either way the theory provided a concise explanation of how thick sequences of shallow-water rocks could accumulate, but was vague on the question of how they were transformed into mountain belts.

Continental Drift as Alternative to Contraction Theory

In the early 20th century, contraction theory was challenged by three independent lines of evidence. The first came from field mapping. Nineteenth-century geologists had worked in great detail to determine the structure of mountain belts, particularly the Swiss Alps and the North American Appalachians. When they mapped the folded sequences of rocks in these regions, they found the folds to be so extensive that if one could unfold them the rock layers would extend for hundreds of miles. Impossibly huge amounts of terrestrial contraction would have to be involved. Geologists began to doubt contraction theory as an explanation for the origins of mountains.

The second line of evidence came from geodesy—the science of the shape (or figure) of the earth. While field geologists were unraveling the structure of the Alps and Appalachians, cartographers with the Great Trignometrical Survey of India were making geodetic measurements to produce accurate maps of British colonial holdings.[5] In the early 1850s, Colonel (later Sir) George Everest, the surveyor-general of India, discovered a discrepancy in the measured distance between two stations, Kaliana and Kalianpur, 370 miles (600 kilometers) apart. When measured on the basis of surveyor's triangulations, the latitude difference was five seconds greater than when computed on the basis of astronomical observation. Everest thought the difference might be due to the gravitational attraction of the Himalayas on the surveyors' plumb bobs, and enlisted John Pratt (1809–1871), a Cambridge-trained mathematician and the archdeacon of Calcutta, to examine the problem. Pratt calculated the expected gravitational effect of the mountains, and discovered that the discrepancy was *less* than it should have been: it was as if part of the mountains were missing. Pratt proposed that the observed effects could be explained if the surface topography of the mountains were somehow compensated by a deficit of mass beneath them—an idea that came to be known as *isostasy,* or "equal standing." In the early 20th century, isostasy was confirmed by detailed geodetic and gravity measurements across the United States. John Hayford (1868–1925) and William Bowie (1872–1940), working at the U.S. Coast and Geodetic Survey, demonstrated that the distribution of gravity was most consistent with the assumption of isostasy, not just in mountain belts, but across the continents. Isostasy could be achieved either if the continents were less dense than the layers of rock beneath them, or if they had deep roots, like icebergs. Either way, they "floated" in the substrate beneath them, and therefore they could not sink to become ocean basins. Continents and oceans were not interchangeable.

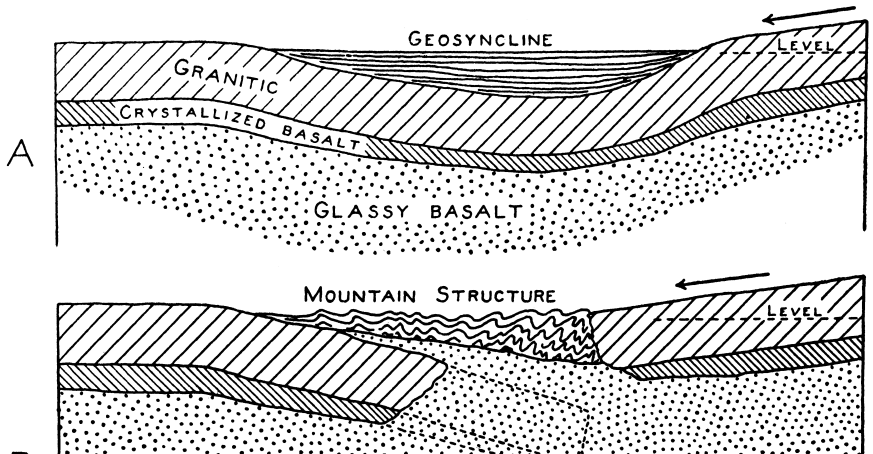
Third, and most fundamental, physicists discovered radiogenic heat, which contradicted the basic assumption of contraction theory that the earth was steadily cooling. With contraction no longer assumed, earth scientists were motivated to search for other driving forces of deformation. By the 1920s, many considered the science to be in a state of crisis: with contraction theory discredited, how were geologists to account for the evidence of prior continental connections? How were they to reconcile the evidence from historical geology for the changing configuration of land masses with the apparent permanence of continents and oceans? This crisis was felt most acutely by European geologists who had accepted Suess' theory, but Americans also realized that they faced a dilemma. A number of scientists began to put forward alternative theories of continental fragmentation or migration. Alfred Wegener (1880–1930) is the most significant, for his theory was the most widely discussed at the time, and the one that was later vindicated.

A pioneering meteorologist and author of an early text on the thermodynamics of the atmosphere, Wegener realized that paleoclimate change could be explained if continents had migrated across climate zones and the reconfiguration of land masses altered Earth's climate patterns.[6] However, continental drift was more than just a theory of paleoclimate change. Wegener explicitly presented his theory as a means to reconcile historical geology with isostasy: on the one hand, paleontological evidence that the continents had once been connected; on the other, geodetic evidence that they could not be connected in the way European contractionists had supposed by now-sunken crust. Wegener's answer was to reconnect the continents by moving them laterally.

Wegener's theory was widely discussed in the 1920s and early 1930s. It was also hotly rejected, particularly by geologists in the United States, who labeled it bad science. The standard explanation for the rejection of continental drift is the lack of a causal mechanism, but this explanation is false. There was a spirited and rigorous international debate over the possible mechanisms of continental migration, which ultimately settled on the same explanation generally accepted today for plate tectonics: convection currents in the earth's mantle.

The debate over the mechanism of continental drift centered on the implications of isostasy. If continents floated in a denser substrate, then this substrate had to be either fluid or plastic, and continents could at least in principle move through it. There was good evidence that this was indeed the case: in Scandinavia, geologists had documented a progressive uplift of Finland and Scandinavia since the end of the Pleistocene epoch (10,000 years ago), which they called the *Fennoscandian rebound.* The accepted explanation for this phenomenon was that during the Pleistocene epoch, the region had been depressed under the weight of a thick sheet of glacial ice; as the ice gradually melted, the land surface gradually rebounded. This provided empirical evidence that continents could move through the substrate in which they were embedded, at least in the vertical direction and at least during the Pleistocene. However, in Scandinavia the cause of motion was generally agreed: first the weight of glacial ice, then the pressure release upon its removal. What force would cause horizontal movement? Would the substrate respond to horizontal movement as it did to vertical movement? Debate over the mechanisms of drift concentrated on the long-term behavior of the substrate and the forces that could cause continents to move laterally.

In the United States, the question was addressed by Harvard geology professor Reginald A. Daly (1871–1957), North America's strongest defender of continental drift. Daly argued that the key to tectonic problems was to be found in the earth's layered structure. Advances in seis-

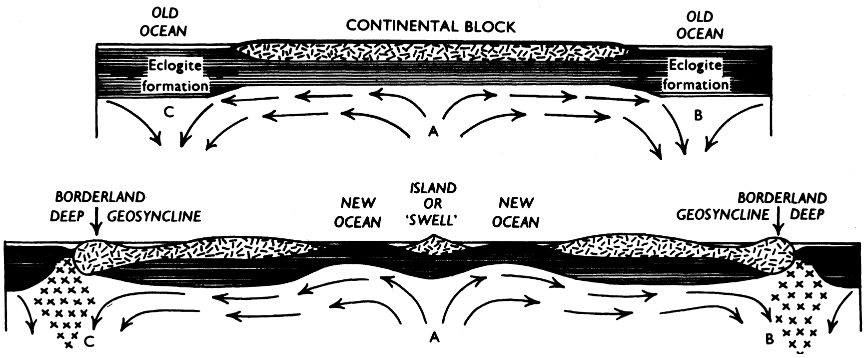


Reginald Daly's mechanism of continental drift by gravity sliding. Reprinted with permission of Scribner, a Division of Simon and Schuster, from *Our Mobile Earth* by Reginald A. Daly, copyright © 1926 by Charles Scribner's Sons, renewed 1954 by Reginald A. Daly, on p. 269.

mology suggested that the earth contained three major layers: crust, substrate (or mantle), and core. The substrate, he suggested, might be glassy, and therefore could flow in response to long-term stress just as old plates of glass gradually thicken at their lower edges and glassy lavas flow downhill. Continents might do the same. Building on the geosyncline concept of Dana and Hall, Daly suggested that sedimentation along the continental margins resulted in subtle elevation differences, which in turn produced gravitational instabilities. Eventually, the continent could rupture, sliding down over the glassy substrate under the force of gravity. The sliding fragment would then override the other half—an early suggestion of subduction—and, over time, the accumulation of small increments of sliding would result in global continental drift.[7]

Daly urged his American colleagues to take up the question of drift, but few did. Reaction in Europe was more favorable. Irish geologist John Joly (1857–1933) linked the question to discoveries in radioactivity. Trained as a physicist, Joly had demonstrated that the commonly observed dark rings in micas—so-called pleochroic haloes—were caused by radiation damage from tiny inclusions of uranium- and thorium-bearing minerals, such as apatite. Radioactive elements were therefore ubiquitous in rocks, suggesting that radiogenic heat was also ubiquitous. If it was, then it could be a force for geological change. Joly proposed that as radiogenic heat accumulated, the substrate would begin to melt. During these episodes of melting, the continents could move under the influence of small forces, such as minor gravitational effects, that would otherwise be ineffectual.[8] Periodic melting, associated with magmatic cycles caused by the build-up of radiogenic heat, would lead to the periods of global mountain-building that many geologists saw evidence of when they compared the geology of Europe and North America.

Joly's theory responded to a geophysical complaint against a plastic substrate, voiced most clearly by Cambridge geophysicist Harold Jeffreys (later Sir Harold), that the propagation of seismic waves indicated a fully solid and rigid Earth. Jeffreys argued on physical grounds that continental drift was impossible in a solid, rigid Earth; Joly noted that although Earth was solid now, it might not always have been. More widely credited was the suggestion of British geologist Arthur Holmes (1890-1965) that the substrate was partially molten or glassy—like magma. Underscoring arguments made by Wegener, Holmes emphasized that the substrate did not need to be *liquid,* only plastic, and that it might be rigid under high strain rates (during seismic events) yet still be ductile under the low strain rates that prevailed during orogeny (mountain-building). If it was plastic in response to long-term stress, then continents could move within it.



Arthur Holmes' model of continental drift driven by mantle convection currents, from Holmes (1929), Radioactivity and earth movements, *Transactions of the Geological Society of Glasgow* 18: 579 (1929), used by permission of the Geological Society of Glasgow.

Holmes' driving force was convection currents in the mantle. He argued that radiogenic heat would generate the convection: the mid-ocean ridges were fragments of continental crust left behind after continents had split apart above upwelling convection currents; the ocean deeps (geosynclines) were the sites of downwelling currents where continents deformed as the substrate descended. Between the ridges and the trenches, continents were dragged along in conveyor-belt fashion.[9]

THE REJECTION OF CONTINENTAL DRIFT

Arthur Holmes' papers were widely read and cited; many geologists thought he had found the cause of continental drift. However, opposition was nonetheless strong, particularly in the United States, where reaction to Wegener's theory was vitriolic.

Three main factors contributed to the American animosity to continental drift. First, Americans were widely committed to the method of multiple working hypotheses—the idea that scientific evidence should be weighed in light of competing (multiple) theoretical explanations, which one held provisionally until the weight of evidence was sufficient to compel assent. This provisional stage was thought to require a long time—certainly years, perhaps even decades. Most closely associated with the University of Chicago geologist T. C. Chamberlin (1843–1928), who had named it, the method of multiple working hypotheses reflected American ideals expressed since the 18th century linking good science to good government. Good science was anti-authoritarian, like democracy; good science was pluralistic, like a free society. Americans going back to Thomas Jefferson and Benjamin Franklin promoted the idea that good science provided an exemplar for good government; Jefferson advocated scientific study in large part for this very reason. And if good science was a model for a free society, then bad science implicitly threatened it.[10] Consistent with the methodology of multiple working hypotheses, Americans believed good scientific method was empirical, inductive, and modest, holding close to the objects of study and resisting the impulse to go further. Alfred Wegener's work was interpreted as violating these principles on several counts. It put the theory first and then sought evidence for it. It settled too quickly on a single interpretive framework. It was too large, too unifying, too ambitious. Features that were later viewed as virtues of plate tectonics were attacked as flaws of continental drift.[11]

Second, continental drift was incompatible with the version of isostasy to which Americans subscribed. While John Pratt had suggested that isostatic compensation could be achieved by subsurface density variations, British Astronomer Royal George Biddell Airy (1801–1892) had pointed out that the same surface effects could be produced by differences in crustal thickness. In Pratt's view, the mountains would be underlain by low-density crust, but the depth of isostatic compensation would be the same everywhere. In Airy's view, the depth of compensation would be variable, with the highest mountains underlain by the deepest roots. When Hayford and Bowie set out to investigate isostasy, they based their test on Pratt's model. By making the assumption of a uniform depth of compensation, they were able to predict the surface effects of isostasy very accurately throughout the United States—that is, to show that the data were consistent with the predictions of the model. Therefore, they concluded that the model was correct. Hayford and Bowie used Pratt's model because it was simpler and therefore easier to use. What began as a simplifying assumption evolved into a belief about the structure of the crust. This belief had consequences for the reception of the theory of drift, for if continental drift were true, then the large compressive forces involved would squeeze the crust to generate thickness differences, ultimately ending up with the Airy version of isostasy. Continental drift seemed to refute Pratt isostasy, which had worked for Americans so well. Rather then reject Pratt isostasy, they rejected continental drift.

Third, Americans rejected continental drift because of the legacy of uniformitarianism. Uniformitarianism was the principle, articulated most famously by British geologist Sir Charles Lyell (1797–1875), that the best way to understand the geological record was by reference to presently observable processes. To understand how sandstones formed, study beach processes. To understand volcanic rocks, study modern volcanoes. To understand fossils, study modern organisms in similar habitats. And so on. Lyell proposed uniformitarianism in part as an intellectual response to the difficulties of interpreting the rock record, and in part as a reaction against an earlier generation of natural historians who had looked to the Bible as a basis for interpreting earth history. So uniformitarianism was associated in many geologists' minds with the exclusion of religious arguments from geology and the consolidation of geology as a science.

Whether or not Lyell's arguments were correct, by the early 20th century the methodological principle of using the present to interpret the past was deeply embedded in the practice of historical geology. Historical geologists routinely used fossil assemblages to make inferences about climate zones. According to drift theory, however, continents in tropical latitudes did not necessarily have tropical faunas, because the reconfiguration of continents and oceans might change matters altogether. Wegener's theory raised the specter that the present was not the key to the past—that it was just a moment in earth history, no more or less characteristic than any other. This was not an idea that Americans were willing to accept.

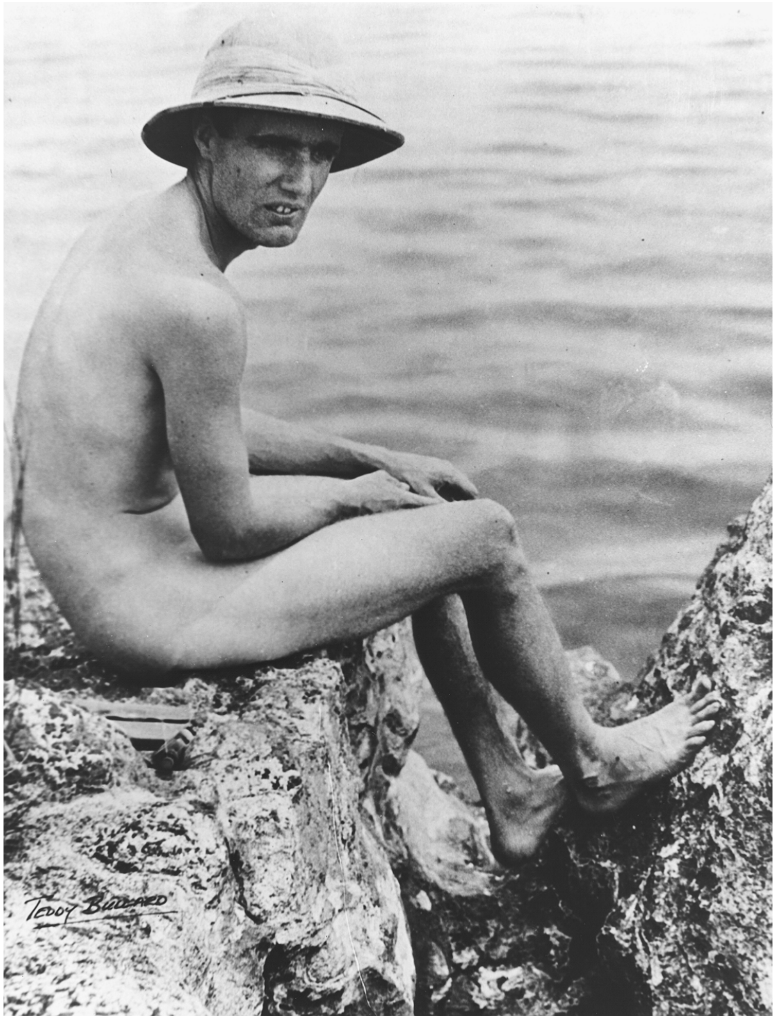
In North America, the debate over continental drift was quelled by an alternative account of the faunal evidence. In 1933, geologists Charles Schuchert (1858–1942) and Bailey Willis (1857–1949) proposed that the continents had been intermittently connected by isthmian links, as the isthmus of Panama presently connects North America and South America and the Bering Land Bridge recently connected North America and Asia. The isthmuses had been raised up by orogenic forces, then subsided under the influence of isostasy. This explanation was patently ad hoc—there was no evidence of isthmian links other than the paleontological data they were designed to explain (away). Nevertheless, the idea was widely accepted, and it undercut a major line of evidence of continental drift. In 1937, South African geologist Alexander du Toit (1878–1948) published *Our Wandering Continents,* a comprehensive synthesis of the geological evidence of continental drift, but it had little impact in North America. Elsewhere, particularly in South Africa and Australia, some geologists continued to advocate drift and to use it to interpret their geological data, but these individuals were mostly isolated. The consensus of scientific opinion was against continental drift. There the matter rested for two decades, until the debate was reopened on the basis of entirely new evidence.

FROM LAND TO SEA: GRAVITY ANOMALIES AND CRUSTAL MOTIONS

Schuchert and Willis' alternative theory satisfied most North American geologists that continental drift was no longer something they needed to worry about, but the issue did not quite stop there. In the 1920s, a group of American scientists led by William Bowie had begun a program in cooperation with the U.S. Navy to measure gravity at sea. Bowie and Hayford had demonstrated that isostasy applied over the continents, but did it also apply over the oceans? What *was* the structure of the crust under the ocean basins? What was the ocean floor made of? The answers to these fundamental questions were unknown, and one's view of the earth might change dramatically according to what the answers turned out to be.

Measuring gravity at sea was extremely difficult, because wind and waves disturbed the sensitive apparatus used. The world's expert on the subject was a Dutch geodesist, Felix Vening Meinesz (1887–1966), who had invented a novel gravimeter that was resistant to external disturbance. In 1923, he demonstrated its efficacy in a series of Dutch submarine expeditions to Indonesia, where he had discovered major gravity anomalies associated with the Java Trench. Supporters of Wegener had proposed that the Java Trench was the site of convergence of two giant crustal slabs, and Vening Meinesz became interested in the possible connection among gravity anomalies, ocean trenches, and crustal movements. In 1928, Bowie invited Vening Meinesz to the United States, and a series of gravity expeditions followed, focused on the Caribbean Sea and the Gulf of Mexico. Among the scientists who participated in these expeditions were two assistant professors, Harry H. Hess (1906–1969), a young petrologist at Princeton, and Maurice Ewing (1906–1974) a fledgling geophysicist at Lehigh who was rapidly becoming known for his pioneering work on refraction seismology (using explosives to send shock waves through the earth's crust to determine its structure). On the 1937 *Barracuda* expedition, they were joined by another rising star, British geophysicist Edward ("Teddy") Bullard (1907–1980).[12]

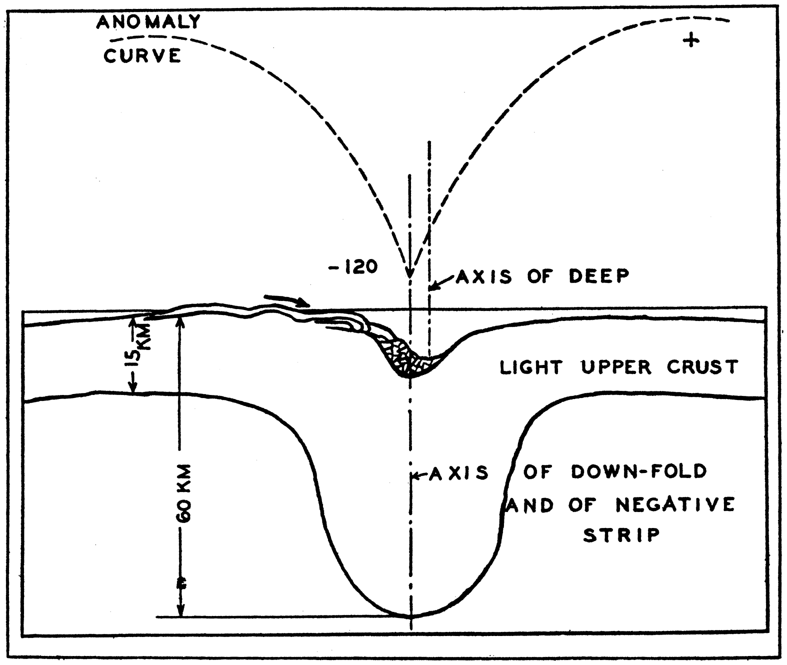
These expeditions confirmed Vening Meinesz's earlier discoveries: gravity measurements in the Caribbean and the Gulf of Mexico demonstrated an association between negative gravity anomalies (regions of lower than normal gravity) and regions where the ocean was particularly deep. Hess discussed these results with Vening Meinesz, and both agreed that they indicated some form of crustal disturbance or deformation. Apparently the ocean basins were not static, but actively deforming, at least in certain zones.



Teddy (later Sir Edward) Bullard, taking a break from gravity measurements somewhere in the Caribbean, ca. 1937. Photo courtesy of Robert Parker, Scripps Institution of Oceanography.

Familiar with European arguments over continental drift, Vening Meinesz proposed that convection currents might be dragging the crust downward into the denser mantle below, explaining both the ocean deeps and the negative gravity anomalies associated with them.[13] Hess imagined vertical buckles in the crust, expressed on the surface as ocean trenches or deeps, and in gravity measurements as negative anomalies. Borrowing a term from German geologist Erich Haarmann, he called these downwarpings *tectogenes*.[14]

The tectogene concept received support from Vening Meinesz's



Harry Hess' tectogene concept explaining the origins of ocean deeps associated with negative gravity anomalies, from Hess (1933), Interpretation of geological and geophysical observations, in *The Navy–Princeton Gravity Expedition to the West Indies in 1932*, edited by R. M. Field. Washington, D.C., U.S. Government Printing Office, p. 30.

Dutch colleague, Philip Kuenen, who undertook a series of experiments to show that the idea was at least physically possible, and from University of California professor David Griggs, who created a laboratory model of continental drift using a layer of paraffin over a tank of oil, in which convection currents were simulated by the action of two rotating drums.[15] While his experimental apparatus was very small, Griggs argued that the scale of mantle convection currents could be very large, perhaps "covering the whole Pacific basin, comprising sinking peripheral currents localizing the circum-Pacific mountains and rising currents in the center."[16] He noted that seismologists such as Caltech's Beno Gutenberg and Charles Richter had noticed that the earthquakes around the edges of the Pacific basin were concentrated in zones that dipped about 45 degrees toward the continents; perhaps these quakes were "caused by slippage along the convection current surface."[17] Hess was excited by these suggestions, which helped to link his Caribbean work to global theory. In 1939 he began to put the pieces together, writing:

> Recently an important new concept concerning the origins of the negative strip [of gravity anomalies] . . . has been set forward by David Griggs. It is based on model experiments in which . . . by means of horizontal rotating cylinders, convection currents were set up in a fluid layer beneath the "crust," and a convection cell was formed. A down-buckle in the crust, similar to that produced in Kuenen's experiments, was developed where two opposing currents meet and plunge downward. So long as the currents are in operation, the down-buckle is maintained. . . . The currents which Griggs suggested would have velocities [in nature] of one to ten centimeters [1/2 to 4 inches] per year.[18]

The year was 1939, and Griggs and Hess had hit upon what scientists would later affirm as the rate of plate motions. But before they could go any further, World War II broke out.

A New Age of Exploration

In the 1920s the Navy had been cautious about funding basic scientific research, concerned about the appropriate expenditure of Navy funds and doubtful that work such as gravity measurement was likely to be of operational use. World War II changed the situation, largely because of submarine warfare. Allied forces suffered heavy losses in the early part of the war from attack by German U-boats, and the U.S. Navy realized that geophysics and oceanography might provide means to detect or avoid submarines. Particularly salient were two lines of research: magnetics, which might provide direct means of submarine detection, and physical oceanography, which might guide evasive maneuvers.

In the early 1940s, the U.S. Navy was experiencing difficulties with its sonar equipment, which tended not to work well in the afternoon. Thinking that marine organisms were interfering with transmissions (or that operators were dozing off after lunch), the Navy asked Maurice Ewing, then working at the Woods Hole Oceanographic Institution, to investigate. Together with colleague J. Lamar (Joe) Worzel, Ewing discovered that temperature effects were bending the sound waves in such a way as to create a "shadow zone"—a region in which sonar transmissions went undetected. This discovery had enormous implications for submarine warfare: if a submarine commander could accurately locate the shadow zone, he could hide his ship within it. Moreover, Ewing and Worzel discovered that under certain conditions sound waves would be focused into a narrow region, in which they traveled for great distances.

They called this phenomenon *sound channeling,* and it became the basis for SOFAR (SOund Fixing and Ranging), which the Navy used during the war to locate downed airmen, and SOSUS (SOund SUrveillance System), the Navy's Cold War underwater acoustic array established to detect Soviet submarines.[19]

While Ewing worked on underwater sound in a civilian capacity, Hess joined the Naval Reserve and in 1941 was called to active duty. He became the captain of an assault transport, the USS *Cape Johnson,* and among her tasks was the echo-sounding of the Pacific basin. This was a project with both military and scientific significance: for the Navy, an accurate topographic map of the sea floor would provide captains with an independent check on their navigation; for scientists, understanding of the sea floor would be greatly enhanced by knowing its shape and structure. This latter hope was fulfilled by Hess' discovery of "guyots"—flat-topped mountains, which he named after Arnold Guyot, the first professor of geology at Princeton. Hess interpreted these mountains as ancient volcanoes whose tops had been eroded by wave action as they gradually sank on a subsiding ocean floor.[20] Guyots were strong evidence that the ocean basins were not fossils of an early stage of earth history, but were geologically active throughout time.

By war's end, the U.S. Navy was convinced of the value of geophysical research. Through the newly established Office of Naval Research (ONR), funds began to flow generously into American laboratories.[21] Three institutions particularly benefited from ONR support: Woods Hole, the Scripps Institution of Oceanography, and the newly created Lamont Geological Observatory at Columbia University, now directed by Ewing. Work at these institutions focused on physical oceanography for its relation to underwater sound, magnetics for its relevance to submarine detection, and bathymetry for mapping the sea floor. At Scripps and Lamont, seismology—the study of earthquakes and how shock waves travel through the earth—was also developed, first as means to investigate the structure of the sea floor and the nature of earthquakes; later to detect underground nuclear explosions.

The years 1945–1970 may well have been the most exciting time in the history of American earth science, as abundant funding led to a new age of scientific exploration—not to get across the oceans, but to spend time within and under them, and ultimately to understand them. Woods Hole, Scripps, and Lamont launched a series of major oceanographic expeditions, collecting an enormous quantity of diverse data on the bathymetry and structure of the sea floor, the physical and chemical properties of the water column, the air-sea interaction and generation of waves and currents, the sediments on the sea floor, and the magnetic and gravity signatures of the solid rocks at the bottom of the sea. More was learned about the oceans during these 25 years than in the entire previous history of science. But there was one downside: much of the data gathered was classified.

In the United Kingdom as in the United States, many scientists worked during the war on military-scientific problems, among them Teddy Bullard and P. M. S. Blackett (1897–1974). In the late 1920s, Bullard was a graduate student at the Cavendish Laboratory at Cambridge University, directed by Nobel Laureate Ernest Rutherford. Blackett was also a member of the lab and Bullard was assigned to work under Blackett on the scattering of electrons in gases; Bullard soon discovered diffraction patterns that supported recent theoretical advances in quantum mechanics.[22] Bullard's career was off to an outstanding start, but the year was 1931, the Depression was at its nadir, and there was no work to be had. Rutherford advised him to take whatever job he could find; that turned out to be teaching surveying under Cambridge geodesist Colonel Sir Lenox-Conyngham. Bullard became a demonstrator in the newly established Department of Geodesy and Geophysics—now consisting of two men.

Over the next eight years, Bullard worked on gravity measurements, including a 1937 trip to the United States where he met Hess and Ewing. Through Ewing, he also learned about refraction seismology, and began studies of the continental shelf on the British side of the Atlantic Ocean to parallel Ewing's studies of the North American side. Meanwhile Blackett was continuing work he had begun under Rutherford on the origin of cosmic rays, for which he would win the 1948 Nobel Prize in Physics.

In 1939 both Bullard and Blackett became involved in war work. Among other things, Bullard concentrated on magnetic minesweeping and demagnetizing ships. After the war, both Bullard and Blackett turned to questions of geomagnetism. For Blackett, the decision was a conscious move away from nuclear physics, with its connections to the atomic bomb.[23] In 1947, now working at the University of Manchester, Blackett proposed a theory to explain the earth's magnetic field: that magnetism arose as a fundamental property of rotating matter. When the planet rotated, it generated a magnetic field. To test his theory, Blackett designed an astatic magnetometer, a highly sensitive device in which he would rotate a massive object in an attempt to generate a detectable magnetic field. Drawing on rich political connections from his war work and a distinguished family background, Blackett arranged to borrow 37.4 pounds (17 kilograms) of pure gold from the Royal Mint, which he rotated at high speed to simulate the effects of the more massive earth moving at lower speed.[24] The experiment failed—no discernable field was generated.

Meanwhile, Bullard had become an advocate of an alternative view: that the earth's field resulted from transient factors such as convection currents in a liquid iron core—the so-called dynamo theory.[25] This led Bullard to conceive a test of the two theories. If Blackett were correct, and the magnetic field arose from the total mass of the earth (like gravity), then it would be a distributed property and the intensity of magnetism would decrease with depth (as does gravity). On the other hand, if Bullard were correct, the strength of the planetary magnetic field would be unaffected by depth. This suggestion was taken up by Blackett's Manchester colleague, S. K. (Keith) Runcorn (1922–1995), who began taking magnetometers down the shafts of coal mines. He found no depth effect, and by 1951 it was clear that Blackett's theory was wrong.

At this point, Runcorn and Blackett turned their attention to magnetism in rocks. If the magnetic field was transient, then the history of variations in the magnetic field might be recorded in rock remanent magnetism—the ancient magnetic signatures of rocks. In the early 20th century, Pierre Curie had discovered that rocks cooled in a magnetic field take on the polarity of that field (the temperature at which this occurs eventually became known as the Curie point). Therefore, if the magnetic field varied, these variations might be recorded in rocks, particularly volcanic rocks that began life as magmas at temperatures above the Curie point. There was evidence that this was so dating back to the early 20th century; more recently the idea had been revived by Jan Hospers, a Dutch graduate student who had entered the Ph.D. program at Cambridge in 1949 trying to use remanent magnetism to correlate lava flows in Iceland, and by John Graham, working in the United States at the Carnegie Institution of Washington.[26] Runcorn, now back at Cambridge, borrowed Blackett's magnetometer and began to develop a geomagnetic research group. He also hired a field assistant, a recent geology graduate named Edward (Ted) Irving. Runcorn and Irving began a program of collecting samples of rocks from different age strata (rock layers) in the United Kingdom.

In 1953, Blackett moved to Imperial College, London, where he set up his own remanent magnetism group. He also encountered geology professor H. H. Read, the man who inspired Arthur Holmes to make geology his professional focus. During the war years with few students to teach, Holmes had written a comprehensive textbook that had an extensive discussion of continental drift, including the evidence of it and the possible role of convection currents to drive it. Years later at Imperial College, it was said that when Blackett turned to Read to learn about rocks, Read sent Blackett to the library to read Holmes. Whatever the truth of the matter, by the mid-1950s both Blackett and his group at Imperial and Runcorn and his group at Cambridge were convinced that remanent magnetism held a record of the variations in the earth's magnetic field, and that these variations showed that rocks had not remained stationary relative to Earth's magnetic field over the course of geological history.[27]

There were two possible interpretations of their data: either the earth's poles had moved relative to the land masses (true polar wander), or the land masses had moved relative to the poles (continental drift). Runcorn realized this ambiguity could be resolved by comparing magnetic variations in rocks of the same age on different continents. By compiling remanent magnetism of rocks of varying ages, one could construct a record of how the poles had seemed to move over time, an "apparent polar-wandering path." If all the continents produced the same apparent polar wandering path, it would mean that the poles had moved. If they varied, it would indicate continental drift. Irving left Cambridge for the Australian National University, where he began to compare apparent polar-wandering paths for Australia, India, North America, and Europe. The result? The paths were distinctly different among the continents. By 1956, both Irving and Blackett's group—now working on rocks from India—were arguing for the paleomagnetic data as evidence for continental drift, and Runcorn soon accepted their views.[28] So did Teddy Bullard, and so did Harry Hess.

Inspired by these developments, Hess revisited the question he had set aside when he had gone off to war 20 years before: whether mantle convection currents might drive continental drift. In a paper written in 1960, although not published until 1962, Hess argued that the British paleomagnetic work had reopened the question, and the answer was drift. Moreover, heat flow measurements by Bullard, working with Scripps scientists Arthur Maxwell and Roger Revelle, showed that heat flow through the oceanic crust was greatest at the mid-ocean ridges, consistent with rising convection currents.[29] Hess therefore suggested that mantle convection might be driving the crust apart at mid-ocean ridges and downward at ocean trenches, forcing the continental migrations in their wake. "One may quibble over the details," he wrote, "but the general picture on paleomagnetism is sufficiently compelling that it is more reasonable to accept than to disregard it."[30] He interpreted the oceanic crust as an upper layer of the mantle that had been altered by interaction with sea water; Scripps geologist Robert Dietz (1914–1995) modified the hypothesis by arguing that the ocean crust was formed by submarine basalt eruptions, and gave it the name it holds today: *sea floor spreading*. Dietz's interpretation was later confirmed by direct examination of the sea floor.

Hess referred to his paper as an "essay in geopoetry," no doubt to deflect criticism from the many North Americans who were still hostile to continental drift.[31] While the British had generally viewed the outcome of the 1920s debate as a stalemate, and therefore open to reconsideration on the basis of new data, Americans generally believed that drift had been refuted.[32] It would take more work to convince North American scientists to reconsider. Moreover, while Hess grew convinced of continental drift on the basis of the apparent polar-wandering paths, others doubted the paleomagnetic data. While it was true that some rock sequences produced highly coherent patterns, others were less coherent, and some were *reversely* magnetized. That is, the polarity of the magnetic field recorded in the rock was opposite to Earth's magnetic field. Most people interpreted this as a sign that the data were unstable: some rocks accurately recorded the surrounding magnetic field, others didn't. Perhaps some minerals did not record the surrounding field, but somehow reversed the direction. Or perhaps the polarities were altered by later events.

Or perhaps Earth's magnetic field periodically reversed its polarity. Early in the 20th century, French physicists B. Brunhes and P. L. Mercanton had suggested this idea: that reversed remanant magnetism in rocks might be recording reversed polarity in the planetary field. But the origin of the earth's field was then unknown; to postulate reversals in a field of unknown origin was speculative in the extreme.[33] In the 1920s, Japanese geophysicist Motonari Matuyama undertook a detailed study of magnetism in volcanic rocks in Japan and found a very consistent pattern: recently erupted lavas were consistently polarized in line with the present field, but reversed rocks were all Pleistocene in age or older (more than 10,000 years). Matuyama argued for a Pleistocene field reversal: that sometime around 10,000 years ago, Earth's magnetic field reversed its polarity. But his work appears to have been largely ignored by European and American scientists.[34] Working in Iceland in the early 1950s, Jan Hospers found similar results: basalt flows there were alternately normally and reversely magnetized.[35]

The question was taken up by a group in the United States at the University of California at Berkeley: geophysics professor John Verhoogen, his postdoctoral fellow Ian McDougall, and graduate students Allan Cox

(1923–1987), Richard Doell, and Brent Dalyrymple. They wanted to determine whether reversals reflected the ambient magnetic field or were a consequence of the physical properties of the minerals involved. Cox began a project analyzing hundreds of samples from the Snake River basalts in the northwest United States, and found results that confirmed the work of Matuyama and Hospers: the patterns were coherent, and they appeared to depend upon the age of the basalt flows. To pin this down, Cox needed accurate ages for the flows.

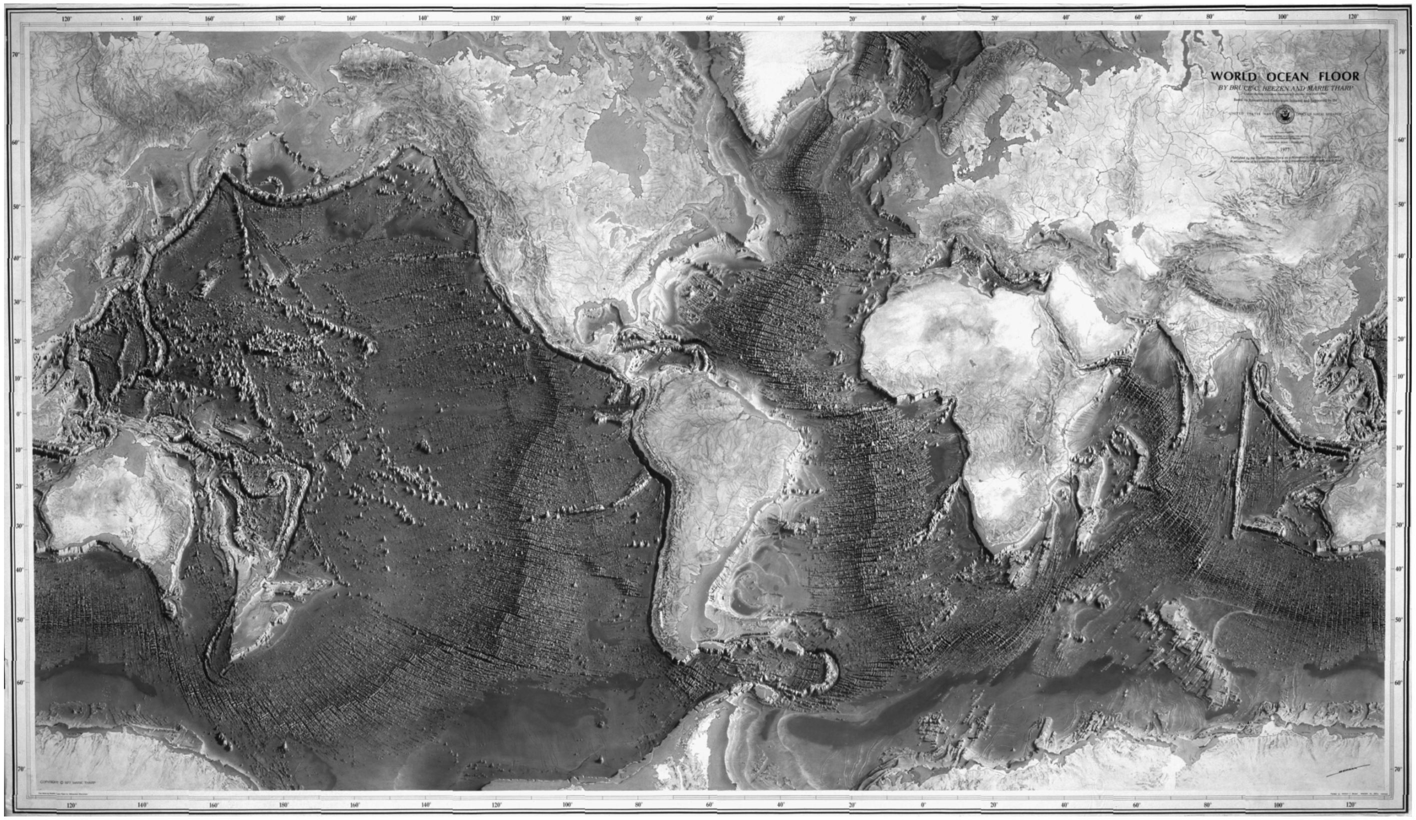
At this point, a key instrumental development emerged. The radiometric uranium-lead (U-Pb) method for dating rocks had been around since the 1910s, but given the long half-life of uranium, it was accurate only for very old materials. However, Berkeley geochemists had developed the potassium-argon (K-Ar) dating technique to the point where it was accurate for very young rocks, including basalts that might be only a few hundred thousand years old. By this time, Cox, Doell, and Dalrymple had been hired as scientists at the U.S. Geological Survey, and McDougall had moved to the Australian National University, where he established a K-Ar laboratory with colleagues Don Tarling and François Chamalaun. The two groups were now working concurrently on the same problem: accurate K-Ar dating of the magnetic reversals in rocks to prove whether they recorded time-specific events in earth history, and, if so, when they had occurred. By 1963, the combined work of the two groups led to the establishment of a paleomagnetic timescale, with four clearly dated reversals extending over the past four million years. Scientists named the first two of these periods after Brunhes and Matuyama: we live in the Brunhes normal epoch, which was preceded, starting around 700,000 years ago, by the Matuyama reversed epoch.[36]

Meanwhile, throughout the 1950s, researchers at Scripps and Lamont had been collecting sea floor magnetic data, with funds and logistical support provided by the U.S. Navy. In 1961, Scripps scientists Ronald Mason and Arthur Raff published a widely read paper documenting a distinctive pattern of normal and reversely magnetized rocks off the northwest coast of the United States. The anomalies formed a series of stripes, roughly parallel to the shoreline. Published in black and white, they looked a bit like zebra stripes—slightly irregular, but stripes nonetheless. Magnetic reversals plus sea floor spreading added up to a testable hypothesis, proposed independently by Canadian geophysicist Lawrence Morley and Cambridge geophysicists Frederick Vine and Drummond Matthews (1931–1997). If the sea floor spreads while Earth's magnetic field reverses, then the basalts forming the ocean floor will record these events in the form of a series of parallel "stripes" of normal and reversely magnetized rocks. Both Morley and Vine and Matthews realized that Mason and Raff's zebra stripes might be the tangible evidence needed to convert Hess' geopoetry into geo-fact.

The group best situated to examine the evidence was at Lamont, led by James Heirtzler. Throughout the 1950s, Ewing had made sure that magnetometers were towed behind every ship, and that the data collected were catalogued systematically. For some years, Heirtzler and his students had been studying sea floor remanent magnetism, and they had inadvertently amassed the data needed to confirm or deny sea floor spreading. Very quickly they did.[37] In 1965, Heirtzler and Xavier Le Pichon published the first of several articles documenting the magnetic patterns of the Atlantic Ocean; by 1967–1968, Lamont scientists, including Walter Pitman, proved that the sea floor magnetic stripes were consistent with the predictions of the Vine and Matthews model.[38] Meanwhile Neil Opdyke, also working at Lamont, showed that marine sediments recorded the same magnetic events as terrestrial and sea floor basalts, linking the continents with the oceans.[39]

Another group at Lamont had focused on bathymetric data—measurements of the depth of the sea floor—primarily in the Atlantic. These data were highly classified, but Bruce Heezen (1924–1977) and Marie Tharp had found a creative means around security restrictions: a physiographic map, essentally an artist's rendition of what the sea floor would look like drained of water, based on quantitative measurements, but without actually revealing them. In one glance, a geologist could see the most important feature: a mountain chain running down the middle of the Atlantic Ocean floor, crosscut by an enormous series of east-west bearing fractures that dislocated the ridge all along its length. A fracture zone also ran down the middle of the mid-ocean ridge, and Tharp noted that the shape of this central fracture zone suggested it was a rift, a place where the ocean floor was being pulled apart. Heezen interpreted the medial rift as evidence in support of the expanding earth hypothesis, an idea that had been promoted in the mid-1950s by Australian geologist S. Warren Carey. But other Lamont scientists now saw it as strong evidence of Hess' theory. The sea floor was split down the middle, the two sides were moving apart, and the rocks on either side preserved a symmetrical pattern of the periodic reversals of Earth's magnetic field.

One more piece in the puzzle would help to bring the whole picture together: the recognition of transform faults by Canadian geologist J. Tuzo Wilson (1908–1993). An unusually creative and insightful scientist, Wilson had been studying Pacific oceanic islands, such as the Hawaiian

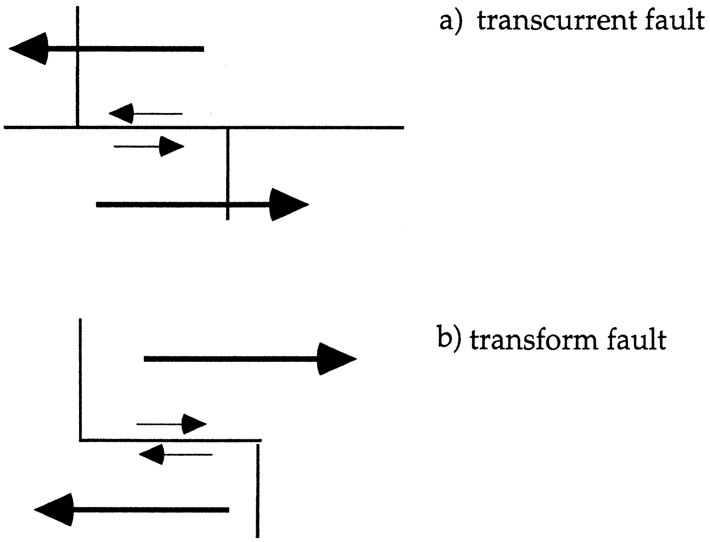


World Ocean Floor, Bruce C. Heezen and Marie Tharp, 1977. Copyright Marie Tharp, 1977.

chain, and found that the ages of the islands increased as one moved farther from the East Pacific Rise—a mountainous region on the eastern side of the Pacific. He realized this could be explained if the rise were a volcanic center above an upwelling convection current and the islands were moving progressively from that center by sea floor spreading.[40] The weight of geological data, together with the fit of the continents, revealed that the earth's surface was "divided into rigid blocks separated by zones of weakness," and that the "periodic break-up of continents and then their slow progression to a new pattern may have happened several times."[41] In 1965, Wilson visited Cambridge, where he spoke at length with Teddy Bullard, Fred Vine, Dan McKenzie, and others interested in continental mobility, including Harry Hess, who also visited Cambridge that year.[42]

Wilson now realized that the fracture zones that displaced the mid-Atlantic ridge—and similar fracture zones mapped by Scripps scientist W. H. (Bill) Menard (1920–1986) in the Pacific—provided a clear test of the idea that the two sides of the ridge were moving apart as solid blocks. Most people assumed that these fracture zones were strike-slip faults, because the ridges were displaced across them. But Wilson had a new idea. Normally, when geologists look at blocks of rock disturbed by an earthquake, they can determine which direction the land has moved based on the observable features that are displaced: a fence, a road, a bridge, or a distinctive rock layer. If the fault is a strike-slip (or transcurrent) fault, where two blocks slip alongside each other as they do along the San Andreas Fault, then geologists look across the fault to see which way things have moved: if objects have moved to the right, then it's a right-lateral fault; if they have moved to the left, then it's a left-lateral fault. But if the mid-ocean ridges were rifts, with the ocean floor splitting apart along them, then the slip directions on the faults that displaced the ridges—what Wilson now called *transform faults*—would be the opposite of what they would be along conventional strike-slip faults.[43]

This was a clear and unequivocal test, and developments in seismology, hastened by the U.S. government's funding of a world wide standard seismograph network (WWSSN), had recently made it possible to accurately determine the slip directions on faults. Once again, Lamont scientists were positioned to perform the test. In 1967, seismologist Lynn Sykes demonstrated that the slip directions on the fracture zones that cut across the mid-Atlantic ridge were consistent with Wilson's interpretation. The offsets were not transcurrent faults, but, in Wilson's new terminology, transform faults, where a mid-ocean rift was locally transformed into a zone of crustal sliding, and then back again into another



The difference between transcurrent and transform faults. (a) In a transcurrent (or strike-slip) fault, the direction of movement can be determined from the offset of a feature intersecting the fault. If the feature is moved to the left, it is a left-lateral fault, as shown here. The north side of the fault has moved to the left (west), the south side of the fault has moved to the right (east), and the fault may continue indefinitely. (b) In a ridge-to-ridge transform fault, a section of the mid-ocean ridge is fractured perpendicular to its length. In this case, the right side of the ridge is moving to the right (east), the left side is moving to the left (west), and the sense of motion is opposite of that illustrated in (a). Note also that the fault does not extend indefinitely, but terminates against the north-south running ridge segments.

rifting ridge segment. There was no longer any doubt that the oceans were splitting apart.

Sykes and co-workers Jack Oliver and Bryan Isacks also examined the slip directions on earthquakes associated with the edges of ocean basins. These edges are characterized by zones of deep-focus earthquakes, either beneath volcanic island chains like the Aleutians on the northern edge of the Pacific, or beneath continental margin mountain belts such as the Andes on the eastern edge of the Pacific. Sykes, Oliver, and Isacks found that the slip directions were consistent with the overlap of one crustal plate onto another, with the lower one slipping downward; the zones of deep-focus earthquakes marked the position of the down-going slab.[44]

A global picture now emerged. Oceans split apart at their centers, where new ocean floor is created by submarine volcanic eruptions. The crust then moves laterally across the ocean basins. Ultimately, it collides with continents along their margins (edges), where the ocean crust sinks underneath, back into Earth's mantle. As it does, it compresses the continental margins, generating folded mountain belts and magmas that rise to the surface as volcanoes, and deep earthquakes as the cold, dense ocean slab sinks farther and farther back into the earth.[45]

In 1967–1968, this picture was integrated into a synthetic, quantitative theory. Working independently, Daniel P. McKenzie and Robert L. Parker at Scripps and Jason Morgan at Princeton established the plate tectonic model: that crustal motions could be understood as rigid body rotations on a sphere.[46] Building on Morgan's work, Xavier Le Pichon summarized the relevant data in a map of the world divided into plates, and calculated their rates of movement on the basis of paleomagnetic data.[47] The result became known as plate tectonics, and it was now the unifying theory of the earth sciences. By the early 1970s, geologists were working out its meaning for continental tectonics.[48] After nearly a century, scientists had finally answered the question of the origin of mountains: they form when plates collide.

This has been a very broad overview. We turn now to how these events looked at the time, to the people who made them happen.