ONE THE PLATE TECTONICS

REVOLUTION

Who can avoid wondering at the force which has upheaved these mountains.

—CHARLES DARWIN, *Voyage of the Beagle*

Our fascination with earthquakes likely dates back to the dawn of human awareness, but efforts to understand them were doomed to failure prior to the 1960s. Although key aspects of seismology were understood before this time, seeking a deep understanding of earthquakes in the context of forces that shape our planet was, for a long time, a little like trying to fathom heart attacks without knowing anything about the body's circulatory system. Prior to the plate tectonics revolution of the 1960s, humans had struggled for centuries to understand the earth, to reconcile its obviously restless processes, such as seismicity and vulcanism, with its seemingly ageless geology.

This book must therefore begin at the beginning, with an exploration of the theory that provides the framework within which modern earthquake science can be understood. We know this theory by a name that did not exist prior to the late 1960s—the theory of plate tectonics. In a nutshell, the theory describes the earth's outermost layers: what their components are and, most critically for earthquake science, how the components interact with one another on our dynamic planet.

THE HISTORY OF A THEORY

Geology is by no means a new field; indeed, it is one of the classic fields of scientific endeavor. By the third century A.D., Chinese scientists had learned how to magnetize pieces of iron ore by heating them to red hot and then cooling them

in a north—south alignment. Such magnets were widely used as navigational compasses on Chinese ships by the eleventh century A.D. Important discoveries in mineralogy, paleontology, and mining were published in Europe during the Renaissance. Around 1800, an energetic debate focused on the origin of rocks, with a group known as Neptunists arguing for an Earth composed of materials settled from an ancient global ocean, while an opposing school, the Plutonists, posited a volcanic origin for at least some rocks. Investigations of rock formations and fossils continued apace from the Renaissance on. In 1815, geologist William Smith published the first maps depicting the geologic strata of England.

The introduction of a geologic paradigm that encompassed the earth as a whole, however, required nothing short of a revolution. Revolutions don't come along every day, in politics or in science, and the one that changed the face of the Earth sciences in the 1960s was an exciting event. Plate tectonics—even the name carries an aura of elegance and truth. The upshot of the plate tectonics revolution—the ideas it introduced to explain the features of the earth's crust—is well known. The story behind the revolution is perhaps not. It is a fascinating tale, and one that bears telling, especially for what it reveals not only about the revolution itself—a remarkable decade of remarkable advances—but also about its larger context. Revolutionary advances in scientific understanding may be exciting, but they are inevitably made possible by long and relatively dull, but nevertheless critical, periods of incremental, "evolutionary" science.

No schoolchild who looks at a globe can help but be struck by an observation as simple as it is obvious: South America and Africa would fit together if they could be slid magically toward each other. Surely this is not a coincidence; surely these two continents were at one time joined. Upon learning the history of the plate tectonics revolution, one cannot help but wonder why on earth (so to speak) scientists took so long to figure out what any third-grader can see?

One answer is that the idea of drifting, or spreading, continents has been around for a long time. In the late 1500s, a Dutch mapmaker suggested that North and South America had been torn from Europe and Africa. In 1858, French mapmaker Antonio Snider published maps depicting continents adrift. In 1620, philosopher Francis Bacon commented on the striking match between the continents.

Early maps of the world reveal that humankind viewed the earth as a violently restless planet. Such an outlook, which came to be known as *catastrophism* in the mid—nineteenth century, seemed only natural to people who

sometimes witnessed—but could not begin to explain—the earthquakes, volcanoes, and storms that provided such compelling and unfathomable displays of power. Such ideas were also consistent with, indeed almost a consequence of, prevailing Western beliefs in a world inexorably shaped by catastrophic biblical events.

By the mid-1800s, however, the paradigm of catastrophism, which described an Earth shaped primarily by infrequent episodes of drastic change, had given way to a new view of the planet, first proposed by James Hutton in 1785 and later popularized by Charles Lyell, known as *uniformitarianism.* Based on recognition of the nearly imperceptible pace of geological processes and the earth's considerable age, the principle of uniformitarianism holds that geologic processes have always been as they are now: at times catastrophic, but more often very gradual. If continents are not being torn apart now, proponents of the new school of thought argued, how could they have been ripped from stem to stern in the past?

By the nineteenth century, moreover, the technical sophistication of the scientific community had grown, and scientists became more concerned than they had been in the past with understanding physical *processes.* The mid—nineteenth century was an extraordinary time for science. Charles Darwin's *On the Origin of Species* was published in 1859 (Sidebar 1.1). Seven years later, Gregor Mendel laid out his laws of heredity, which established the basic principles of dominant and recessive traits. At nearly the same time, Louis Pasteur's germ-based theories of disease gained wide acceptance. Advances were by no means restricted to the biological sciences. In 1873, James Maxwell published the four equations that to this day form the backbone of classic electromagnetism theory.

In this climate of growing scientific sophistication, advocating a theory of continental drift without providing a rigorous physical mechanism for the phenomenon became untenable. If the continents moved, how did they move? In 1912, a German meteorologist named Alfred Wegener presented the basic tenets of continental drift in two articles. He introduced a name for the supercontinent that existed prior to the break-up that separated Africa from South America, a name that remains in use today: Pangaea. Wegener's ideas were scarcely flights of unscientific fancy; they were instead based on several types of data, primarily from paleobotanical and paleoclimatic investigations. Wegener pointed to evidence that tropical plants once grew in Greenland and that glaciers once covered areas that are at midlatitudes today; he proposed continental drift as a mechanism to account for these observations.

When challenged over the ensuing decades to produce a physical mechanism to go with the conceptual one, Wegener put forward the notion that the continents plow their way through the crust beneath the oceans. The image conveyed, that of continental barges adrift on the oceans, had intuitive appeal. The mechanism, however, was easily dismissed by geophysicists, who understood enough about the nature of the earth's crust to know that continents could not push their way through the floor of the oceans without breaking apart.

For nearly two decades the debate raged on. Tireless and determined by nature, Wegener published a book and many papers on his theory. Yet he was not to see vindication during his own lifetime. Tragically, Wegener died from exposure during a meteorologic expedition to Greenland in 1930. In the annals of Earth science, few deaths have been quite as badly timed as Alfred Wegener's at the age of fifty. He died just as oceanic research vessels were beginning to acquire high-quality seafloor topography (bathymetric) data that would provide scientists a vastly better view of the character of the ocean floor and pave the way for the revolution to begin in earnest.

WEGENER'S HEIRS

Harry Hammond Hess, born in 1906, was a scientist whose timing and luck were as good as Wegener's were bad. A geologist at Princeton University in the late 1930s, Hess was well poised to build upon Wegener's continental drift hypothesis, as well as a hypothesis, proposed in 1928 by British geologist Arthur Holmes, that material below the crust circulated, or convected, much like wa-

ter in a boiling pot (but far more slowly). Hess, a member of the U.S. Naval Reserves, was pressed into service as captain of an assault transport ship during World War II. Military service might have been nothing more than an unfortunate interruption in a sterling research career, but Hess was not a man to let opportunity pass him by. With the cooperation of his crew, he conducted echo-sounding surveys to map out seafloor depth as his warship cruised the Pacific. Marine geophysics is an expensive science, primarily because of the high cost of operating oceanic research vessels. There is no telling how long it might have taken the geophysical community to amass the volume of seafloor topography data that Hess collected while he happened to be in the neighborhood, but the data set was a bounty on which Hess himself was able to capitalize almost immediately.

Back at Princeton after the war, Hess turned his attention to the character of the ocean floor as revealed by his extensive surveys. Struck by the nature of the long, nearly linear ridges along the seafloor—the so-called mid-ocean ridges—away from which ocean depth increased symmetrically, Hess prepared a manuscript presenting a hypothesis that would become known as seafloor spreading. A first draft prepared in 1959 circulated widely among the geophysical community but was not published. Hess's ideas were met with skepticism and resistance, just as Wegener's theories had been earlier. To argue that the structure of the ridges and ocean basins implied a mechanism of spreading was little different from arguing that the striking fit between Africa and South America implied continental drift. Both hypotheses failed to provide a physical mechanism, and both were inherently descriptive.

Hess, however, had his remarkable data set and the framework for a geophysical model. In 1962, he published a landmark paper titled "History of Ocean Basins," which presented a mechanism for seafloor spreading. Hess's model described long, thin blades of magma that rise to the surface along the mid-ocean ridges, where they cool and begin to subside as they get pushed away bilaterally as more oceanic crust is created. Millions of years after being created at a mid-ocean ridge, the crust encounters trenches along the ocean rim, where the crust then sinks, or *subducts,* descending back into the earth's mantle in the granddaddy of all recycling schemes. These trenches, also imaged by Hess's seafloor surveys, were a critical element of the hypothesis because they explained how new crust could be created continuously without expanding the earth. Some of Hess's ideas about subduction were incomplete, however, and were superseded by later studies and models.

Still, Hess's 1962 paper was remarkable for its prescience and its insights into physical processes. Although it was what scientists consider an "idea paper" (that is, one whose hypotheses are consistent with but cannot be proven by the data in hand), the 1962 paper was distinguished from its predecessors by its presentation of nineteen predictions derived from the model. Ideas may be the seeds of good science, but testable hypotheses are the stuff of which it is made. Scientific hypotheses are accepted not when they offer a satisfactory explanation of empirical observations but when they allow predictions that are borne out by new, independent data. Of Hess's nineteen predictions, sixteen would ultimately be proven correct.

The true Rosetta stone of plate tectonics—the key that won over a skeptical community—involved something considerably simpler than hieroglyphics: the geometry of the linear, magnetic stripes on the ocean floor. That the oceanic crust was magnetic came as no surprise; by the 1950s, scientists knew that it was composed predominantly of basalt, an iron-rich volcanic rock well known for its magnetic properties. Basalt was moreover known to serve as a permanent magnetometer, locking in a magnetism reflecting the direction of the earth's magnetic field at the time the rock cooled (not unlike the ancient Chinese magnets).

As early as 1906, scientists investigating the magnetic properties of the earth's crust recognized a tendency for rocks to fall into one of two magnetic orientations: either aligned with the earth's present-day magnetic field or aligned in the diametrically opposite direction (normal polarity and reversed polarity, respectively). The earth's magnetic field is similar the field generated by a bar magnet with its north end nearly aligned with the geographic North Pole. Yet the earth's field is the result of a more complex, dynamic process: the rotation of the planet's fluid, iron-rich core. Although the process gives rise to a field that appears fixed on short timescales, scientists have known for centuries that the earth's magnetic field is dynamic and evolving. At a rate fast enough to be measured even by the slow pace of human investigations, the magnetic field drifts slowly westward at a rate of approximately 0.2 degrees per year. Over tens of thousands of years, the field undergoes far more dramatic changes known as *magnetic reversals.* During a reversal, south becomes north and vice versa, apparently in the blink of an eye, at least from a geologic perspective—perhaps over a period of a few thousand years. Basaltic rocks lock in the field that existed at the time the rocks were formed, and they remain magnetized in that direction, insensitive to any future changes in the earth's field.

The subfield of geology known as *geomagnetism*—the study of the earth's magnetic field—has long been an intellectually lively one. The study of earthquakes was hampered for years by the slow pace of seismic events (in Europe especially) and the lack of instrumentation to record them. The earth's magnetic field, by contrast, is considerably more amenable to investigation with simple instruments. Documentation of the magnetic field—its direction and intensity—dates back nearly 400 years, to William Gilbert, physician to Queen Elizabeth I.

Beginning in the 1950s, geomagnetism found its way to the forefront of Earth sciences in dramatic fashion. The journey began, as so many scientific journeys do, serendipitously. When the ocean floor was surveyed with magnetometers designed to detect submarines during World War II, a strange pattern gradually came into focus. The oceanic crust was no mottled patchwork of normal and reversed polarity; it was striped. In virtually every area surveyed, alternating bands of normal and reversed polarity were found (Figure 1.1).

A report by U.S. Navy scientists in 1962 summarized the available magnetic surveys of oceanic crust. Just a year later, British geologists Frederick Vine and Drummond Matthews proposed a model to account for the observations in the navy report. They suggested that the oceanic crust records periods of normal and reversed magnetic alignment, in the manner that had been documented earlier for continental crust. To interpret the spatial pattern, Vine and Matthews applied an equation from high school physics: velocity equals distance divided by time. In September of 1963, the team of scientists published a paper in the journal *Nature* in which they proposed that the magnetic stripes resulted from the generation of magma at mid-ocean ridges during alternating periods of normal and reversed magnetism; the scientists' proposal was consistent with the predictions from Hess's seafloor-spreading hypothesis.

Vine's and Matthews's work paralleled that of another scientist working independently, Lawrence Morley of the Canadian Geological Survey. Such coincidences are neither unusual nor remarkable in science. The collective wisdom of a scientific field is built slowly, not so much in leaps of extraordinary genius as in a series of steady steps taken by individuals who possess both a thorough understanding of the current state of knowledge and the talent to take the next logical step. In the case of ocean floor magnetism, the 1963 publication of Vine and Matthews was actually preceded slightly by a paper that Morley had submitted twice, a paper that had been rejected twice, once by *Nature* and once by one of the seminal specialized Earth sciences journals, the
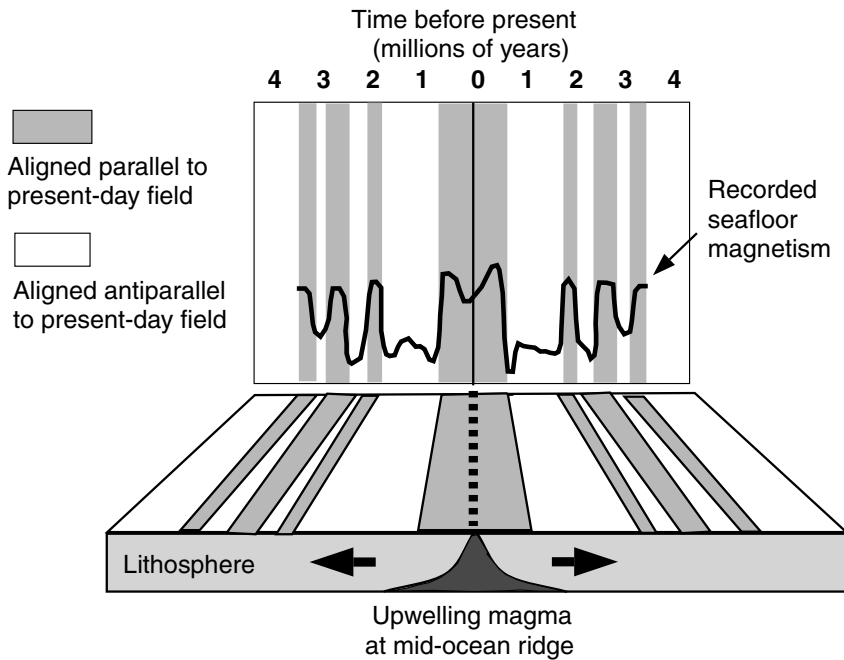
Figure 1.1. Magnetic striping of oceanic crust compared to the magnetic record established from continental crust. Dark and light bands correspond to magnetic alignments that are parallel and antiparallel to the present-day field direction, respectively. The recorded seafloor magnetism *(dark line in top panel)* reveals the alternating orientations.

Journal of Geophysical Research. In a remark that has become famous in the annals of the peer-review publication process, an anonymous reviewer commented that Morley's ideas were the stuff of "cocktail party conversation" rather than science. Historians of science—and scientists—do generally give Morley his due, however, when they refer to the "Vine-Matthews-Morley hypothesis."

In 1963, Canadian geophysicist J. Tuzo Wilson introduced another "cocktail party" concept that was critical to the development of plate tectonics theory (Sidebar 1.2). Focusing his attention on volcanic island chains like Hawaii, Wilson suggested that the characteristic arc shape of these islands resulted from the passage of the crust over an upwelling of magma that remained stationary in the mantle. Wilson dubbed these upwellings "hotspots," a term (and con-

cept) that has long since been accepted into the scientific lexicon but was so radical in its day that Wilson's paper, like Morley's, was rejected by several major geophysical journals before seeing the light of day in a relatively obscure Canadian geological journal.

Wilson continued to work on critical aspects of plate tectonics theory after 1963, as did Vine and Matthews, who continued their investigations of magnetic stripes. To better understand the time frame for the formation of the stripes, Vine and Matthews looked to the very recent work of U.S. Geological Survey and Stanford scientists Allan Cox, Richard Doell, and Brent Dalrymple. This team had succeeded in using the slow radioactive decay of elements within basalt to construct a history of the earth's magnetic field dating back 4 million years. By dating rocks from around the world and measuring their magnetization, the scientists produced a 4-million-year timeline indicating periods (epochs) of normal and reversed magnetic field alignment. Comparing the record from continental crust with established observations of magnetic striping in the oceans, Vine and Matthews showed that the two were remarkably consistent if one assumed a seafloor-spreading velocity of a few centimeters a year. Their work was published, again in *Nature,* in 1966.

By the mid-1960s, the revolution was in full swing; the geophysical community was ignited by the exciting ideas that circulated like a firestorm in

many, if not quite all, Earth science departments. Some of the ideas might have been old, but the data and theories in support of them were shiny and new. Like so many puzzle pieces, other aspects of plate tectonics were pieced together in a series of seminal papers published in the latter half of the decade.

In a 1965 paper—this one accepted by *Nature*—Tuzo Wilson presented an explanation for the great oceanic transform faults. Long, linear fractures running perpendicular to ocean ridges, these transform faults represented a paradox until Wilson, a scientist fond of using simple cardboard constructions to explore complex geometrical ideas, showed how they fit neatly into a seafloor-spreading model (Figure 1.2).

Although the plate tectonics revolution began at sea, it spread almost instantly to incorporate continental tectonics as well. In 1965, Cambridge University professor Teddy Bullard showed that for continental drift to be a viable theory, the continental plates themselves must be rigid, characterized by very little internal deformation. In 1967, Dan McKenzie and Bob Parker published a paper that worked out the details of rigid plate motion on a spherical earth. A 1968 paper by Jason Morgan of Princeton used the geometry of the oceanic transform faults to show that, like the continents, oceanic plates behave as rigid plates.

At this point in the story it is appropriate to pause and reflect on another great technical revolution of the twentieth century: the computer revolution. With a computer in every classroom and e-mail giving regular ("snail") mail and telephones a run for their money as the preferred means of communication, it is perhaps easy to forget just how new a phenomenon these computing machines are. The first all-electronic computer, ENIAC, made its debut in 1946. It contained eighteen thousand vacuum tubes, could perform a few hundred multiplications per minute, and could be reprogrammed only by manual rearrangement of the wiring. Transistors, which allowed for the development of much smaller computers with no unwieldy vacuum tubes, debuted only in the late 1950s. Silicon chips, which paved the way for the microprocessors we have come to know and love, arrived on the scene two decades later.

Because computer technology was in its infancy in the mid-1960s, making a detailed scientific map was no easy matter, and an early critic of plate tectonics, noted geophysicist Harold Jeffreys, suggested that perhaps a measure of artistic license had been used in the diagrams and mechanical models illustrating plate motions and reconstructions. Geophysicist Bob Parker will cheer-
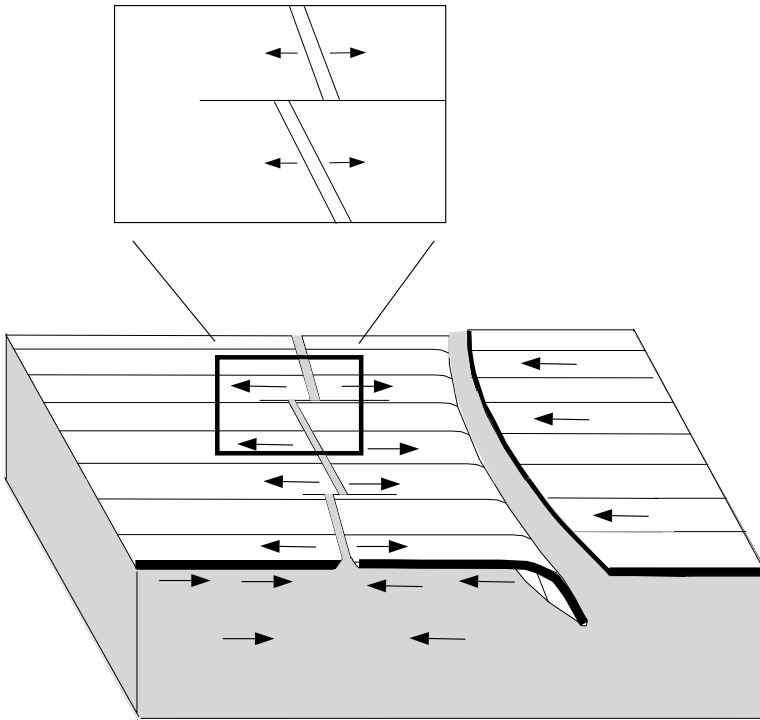
Figure 1.2. Model of transform faults in oceanic crust proposed by J. Tuzo Wilson. Transform faults are depicted by horizontal lines that connect segments of spreading centers, where new crust is created.

fully admit that his contribution to the plate tectonics revolution had less to do with geophysical insight than with his talent for exploiting the newfangled tools of the geophysical trade. Having written a computer program to plot coastlines (Super Map, affectionately named for the then prime minister of England, Harold "Super Mac" Macmillan), Parker teamed up with Dan McKenzie to produce computer-generated three-dimensional reconstructions that bore no trace of artistic license. Even with Super Map, the work was no easy task. McKenzie worked on the reconstructions at Princeton but could not generate maps because the university had no plotter at the time. He tried to make his maps at the Lamont-Doherty Geological Observatory of Columbia University (now the Lamont-Doherty Earth Observatory); the observatory had a plotter but, unfortunately, insufficient computer memory to handle the large (for their

day) files. To finally generate the maps for the paper that was published in *Nature* in 1967, McKenzie had to send his files across the ocean to Cambridge University.

Another small handful of landmark papers, perhaps half a dozen, were published between 1965 and 1968 as the pieces of a maturing, integrated theory fell into place. A special session on seafloor spreading was convened at the 1967 annual meeting of the American Geophysical Union; 30 years later the special session would be recognized as a watershed event in the development and acceptance of global plate tectonics theory. Resistance to the theory of plate tectonics persisted through the mid-1960s, with eminent scientists among the ranks of both the latest and the earliest converts. By the late 1960s, however, there was too much evidence from too many different directions; notwithstanding a trickle of continued objection from the most determined quarters, the theory passed into the realm of conventional wisdom (Figure 1.3).

If the pieces of the plate tectonics puzzle had largely fallen into place by 1967 or 1968, the name for this grand new paradigm emerged, curiously enough, rather gradually. Although the papers by McKenzie and Parker (1967) and Morgan (1968) were credited in a 1969 "News and Views" summary in *Nature* as having established the theory of "plate tectonics," neither article had proposed that particular name. McKenzie and Parker perhaps get the close-but-no-cigar award with the title "The North Pacific: An Example of Tectonics on a Sphere" and an opening sentence that read, economically, "Individual aseismic areas move as rigid plates on the surface of a sphere."[4] However, throughout the text they referred to their theory by a name that was not destined to catch on: "paving stone tectonics." Perhaps the earliest official use of the name "plate tectonics" came in the title of a small geophysical meeting convened in Asilomar, California, in 1969 so that participants could present and discuss the exciting new ideas in seafloor spreading and continental drift.

SEISMOLOGY AND PLATE TECTONICS

Seismology might not have been the first subfield of Earth science to arrive at the plate tectonics ball, but it did arrive in time to make its share of critical contributions. In 1968, Xavier Pichon, then a graduate student at Lamont-Doherty Geological Observatory, published a paper that used catalogs of large earthquakes worldwide to help constrain the geometry of the plates. Just a year earlier, another Lamont scientist, Lynn Sykes, had also made a critical seismo-
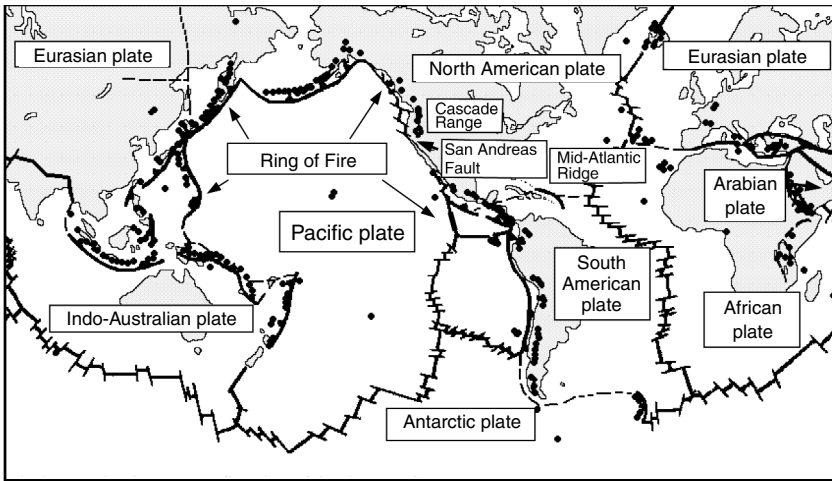
Figure 1.3. The earth's major tectonic plates. The so-called Ring of Fire includes both transform faults such as the San Andreas Fault in California and, more generally, subduction zones around the Pacific Rim. At mid-ocean ridges such as the Mid-Atlantic Ridge, new crust is created. The dots in the figure indicate active volcanoes.

logical contribution to the development of plate tectonics theory. Whereas other seismologists had successfully investigated the forces that were inferred to drive earthquakes, Sykes focused on the inferred fault motions and showed them to be consistent with the motions predicted for Wilson's transform faults.

To understand why earthquake motions do not necessarily reflect driving forces directly, imagine a book on a table. Push on one edge and it will slide across the table in a direction parallel to the direction of the applied force. Now push the book downward into the table and forward. The book will still slide forward, not because that is the direction parallel to the force but because the book is not free to move vertically. The earth's crust behaves in a similar manner when subjected to a driving force. Faults represent pre-existing zones of weakness in the earth's crust, zones along which movement will tend to be accommodated, even if the faults are not perfectly aligned with the driving forces. (The direction of earthquake motions can generally be determined with fewer assumptions than can the direction of the actual driving forces.)

Just as an explosion in the quantity and quality of geomagnetic and topographical data presaged the giant leap in our understanding of oceanic crust,

so too did the seismological contributions to plate tectonics theory depend critically on enormous improvements in observational science. Oddly enough, the enmity of nations once again proved to be among the greatest, albeit entirely unwitting, benefactors to science. The Worldwide Standardized Seismograph Network (WWSSN) was launched in the early 1960s to monitor underground nuclear weapons tests and to provide support eventually for a comprehensive ban on all nuclear testing. For the first time, humankind had developed weapons powerful enough to rival moderate to large earthquakes in terms of energy released: both nuclear weapons and earthquakes generate seismic signals large enough to be recorded worldwide. At large distances, earthquakes and large explosions generate what seismologists term *teleseismic waves,* which are vibrations far too subtle to be felt but which can be detected by specially designed seismometers.

It is often difficult to find financial support for scientific inquiry that requires expensive and sophisticated scientific instrumentation. Like commercial electronics, scientific instruments became enormously more sophisticated in the latter half of the twentieth century. Unlike consumer electronics, however, scientific instruments are not subject to mass-market pressures that drive prices down. Prior to the 1960s, a standardized, well-maintained, global network of seismometers would have been a pipe dream for a science that generally runs on a shoestring. Financed not by the National Science Foundation but by the Department of Defense, the WWSSN sparked the beginning of a heyday for global seismology. In the decades following the launch of the WWSSN, data from the network allowed seismologists to illuminate not only the nature of crustal tectonics but also the deep structure of our planet.

The tradition of symbiosis between military operations and academic geophysics continues today. Seismology's contribution to the critical issue of nuclear-test-ban-treaty verification has resulted in substantial support for seismological research and monitoring that would otherwise not have been available.

The military provided yet another boon for geophysics—especially for the study of global tectonics—with the development and implementation of the Global Positioning System (GPS). Initiated in 1973 by the Department of Defense as a way to simplify military navigation, the GPS now relies on dozens of satellites and associated ground-based support. Instrumented with precise atomic clocks, each GPS satellite continuously broadcasts a code containing the current time. By recording the signal from several satellites and processing

the pattern of delays with a specially designed receiver on the ground, one can precisely determine the coordinates of any point on Earth. Conceptually, the procedure is nearly the mirror image of earthquake location methods. To locate earthquakes, seismologists use waves generated by a single earthquake source recorded at multiple stations to determine the location of the source.

Within a decade of the inauguration of the GPS, geophysicists had begun to capitalize on its extraordinary potential for geodetic surveys. The dictionary defines *geodesy* as the subfield of geophysics that focuses on the overall size and shape of the planet. Geodesists have historically employed precise ground-based surveying techniques such as triangulation and trilateration. By measuring the transit time of a light pulse or a laser beam between precisely oriented markers on the earth's surface and applying simple geometrical principles, geodesists can determine relative position.

Geodesy has enormous practical applications. We need precise knowledge of location to build roads, to make real estate transactions, and to draw maps, to name but a few applications. Geodetic surveys have contributed to our understanding of the earth's landforms (for example, the size and shape of mountains), to the determination of permanent deformation caused by large earthquakes and volcanic eruptions, and to our knowledge of long-term, slow crustal movements. Efforts to understand slow crustal deformation were hampered for decades by three factors: the intrinsically slow nature of such movements, the imprecision of surveying techniques, and the enormous number of hours required for large-scale geodetic surveying campaigns. The last factor was especially critical because a triangulation or trilateration survey of an area is done by leapfrogging instruments between locations for which there is direct line-of-sight. Covering an area of geophysical interest typically required weeks or months of effort on the part of teams that made their way at a snail's pace, sleeping in mobile encampments.

Although the modern GPS offers significant improvements in both precision and ease of measurement, early geophysical GPS campaigns were arduous. They required teams to observe satellite signals during the limited hours of the day or night when satellite coverage was sufficient to obtain the coordinates of any given location (Sidebar 1.3). By the 1980s, though, satellite coverage had improved and instruments could monitor GPS signals continuously. By the mid-1990s, the geophysical community had begun to implement continuous GPS networks that ran alongside their seismic counterparts. Whereas seismic instruments record ground motions that occur over seconds, minutes,

and sometimes hours, GPS networks record ground motions that occur over
days, months, and years.

GPS data have been used to address a wide range of unresolved questions in
geophysics, including several questions related to earthquake prediction. The
primary geophysical application of these data, however, has been to document
the plates' motion, including their internal deformation. Several decades after
the revolution swept in the grand new ideas, the basic paradigm is clear, but
the devil remains in the details. GPS, a boon to the geophysical community
provided by the defense industry, is one of the most valuable tools for ad-
dressing those devilish details.

The symbiotic relationship between the Earth sciences and the military con-
tinues to this day. As the twentieth century drew to a close, Earth scientists be-
gan to make use of yet another technology originally developed with military
applications in mind: Synthetic Aperture Radar, or SAR. SAR is a technique
that uses reflected microwave energy from satellites to create high-resolution
images of the earth's surface.

In the early 1990s, scientists realized that the differences between two SAR
images of the same region could be used to study earthquakes. This technique,
known as InSAR, was first applied by geophysicist Didier Massonnet and his
colleagues, who studied the 1992 magnitude 7.3 Landers, California, earth-
quake. In an InSAR image such as the one on the cover of this book, fault dis-
placement can be inferred from a pattern of fringes. Each fringe—a suite of
colors from violet to red, or shades of gray—corresponds to a certain change

in the distance from each point on the ground to the satellite. Typically the change is on the order of a few centimeters per fringe.

The details of InSAR processing and analysis are somewhat complicated, but estimating fault rupture from an InSAR image is basically akin to estimating the age of a tree by counting its rings. A ruptured fault appears as a bull's-eye—or an elongated bull's-eye—in an InSAR image, and the amount of fault motion is given by the number of fringes that make up the bull's-eye.

Unlike GPS measurements, which are available as point measurements from individual stations, InSAR has the potential to image the entire surface of the earth. In some cases, then, it provides far more detailed information than can be obtained using GPS. But GPS is by no means obsolete, as it can provide results in certain areas, such as those with heavy forestation, where InSAR often doesn't work. InSAR also captures only snapshots taken by repeat passes of a satellite, whereas GPS data can be collected continuously. The two techniques are therefore highly complementary, with InSAR providing another nifty (and sometimes delightfully colorful) tool in the Earth scientist's bag of tricks.

THE FRAMEWORK OF PLATE TECTONICS THEORY

By the time the revolutionary dust had settled at the end of the 1960s, a basic understanding of the earth's crust had been established. The "crust" is broken into about ten major plates, each of which behaves for the most part as a rigid body that slides over the partially molten "mantle," in which deformation occurs plastically. The quotation marks around "crust" and "mantle" reflect a complication not generally addressed by the most elementary texts. Geophysicists determine what is crust and what is mantle on the basis of the velocity of earthquake waves. At a depth of approximately 40 kilometers under the continents, wave velocities rise abruptly at a boundary known as the *Mohorovicic discontinuity,* or simply the Moho, which is thought to reflect a fundamental chemical boundary. The Moho separates the crust from the mantle below. Except for those that occur in subduction zones, earthquakes are generally restricted to the upper one-half to two-thirds of the crust, the brittle upper crust. The thickness of the crust ranges from a few kilometers under the oceans to several tens of kilometers for the thickest continents.

Although earthquakes are generally restricted to the crust, the depth of the crust does not coincide perfectly with the depth of the tectonic plates. Conti-

nental plates in particular are much deeper, perhaps 70 kilometers on average. Geophysicists know the earth's relatively strong upper layer as the *lithosphere,* only the uppermost layer of which is, in a strict sense, the crust.

Underneath the lithosphere is a layer scientists know as the *aesthenosphere,* which is a zone of relative weakness. Earth scientists categorize layers as weak or strong, often relying on the speed of earthquake waves through a zone as a proxy for its strength. The lithosphere is strong as a unit; wave velocities are high (shear wave velocities of 4.5–5 kilometers/second) over most of its 70-kilometer extent. Below the lithosphere, shear wave velocities drop by about 10 percent, and seismic waves are strongly damped out, or attenuated. Because laboratory results show that zones of partial melting are characterized by slow wave velocities and high attenuation, the aesthenosphere is thought to be a zone of partial melting. That is, the aesthenosphere is not a liquid per se but rather a saturated matrix. The basaltic magma that rises to the earth's surface at the mid-ocean ridges is thought to be derived primarily from the 1–10 percent of the aesthenosphere that exists as a melt.

The weak aesthenosphere, extending to a depth of about 370 kilometers, accounts for the mobility of the solid overriding lithospheric plates. The mantle, as strictly defined, incorporates the aesthenosphere and the solid lower mantle. Deeper still, a chemical and physical boundary marks the transition from the magnesium—iron silicate mantle to the mostly iron core.

The study of the earth's deep interior is a fascinating one and one that is critical to a full understanding of the processes that affect the earth's surface. Many questions remain unanswered. Does the mantle convect, or turn over, as a whole, like one big, slowly boiling cauldron, or does it convect in layers? Where does the magma source for hotspots originate, and how do these features remain fixed in a convecting mantle? What becomes of oceanic crust once it subducts? Do dynamic processes within the mantle help buoy mountain ranges to their present gravity-defying heights?

Sidestepping such questions now to return to the phenomenology of the crust as we understand it—and as it concerns earthquakes—let's focus on the boundaries between the plates. Three types of plate boundaries are defined according to their relative motion: zones of spreading, zones of relative lateral motion (transform faults), and zones of convergence, where plates collide. Simplified examples of faults associated with the three plate-boundary types are shown in Figure 1.4. As already noted, plates pull apart at the mid-ocean ridges, where basaltic magma from the aesthenosphere rises and creates new
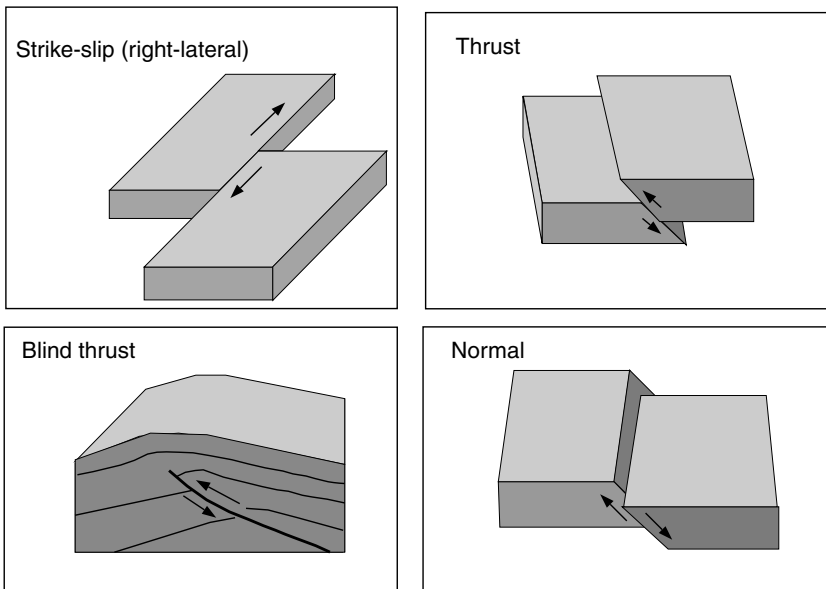
Figure 1.4. The basic types of faulting: *top left,* strike-slip; *top right,* thrust; *bottom right,* normal; and *bottom left,* blind thrust. The different types of plate boundaries are characterized by different types of faulting; strike-slip faulting dominates at transform boundaries, thrust faulting dominates at subduction zones, and normal faulting dominates at zones of spreading.

oceanic crust. Plates converge along subduction zones, where oceanic crust subducts beneath the continents. And plates sometimes slide past one another without any creation or consumption of crust, as with the San Andreas Fault in California and the North Anatolian Fault in Turkey, which produced a devastating magnitude 7.4 (M7.4) event in August of 1999 and a subsequent M7.2 temblor three months later.

Readers will likely not be surprised to learn that the earth is more complicated than the images often depicted in simple drawings. Although mid-ocean ridges are the most conspicuous and active zones of spreading, they are not the only ones. In some cases, deep earth processes conspire to tear a continent apart. The East African rift zone, stretching from Ethiopia south toward Lake Victoria and beyond into Tanzania, is one such zone that is active today. Sometimes continental rifting gets started but then fizzles out, creating what geo-

physicists regard as failed rifts. These fossilized zones of weakness can be important players in the earthquake potential of continental crust away from plate boundaries.

Convergence is another process that is not always simple. Sometimes one oceanic plate subducts underneath another; and sometimes one continent collides with another, in which case neither can sink because continental crust is too buoyant. If material can't be internally compressed and can't subduct, only two options are open: the material can rise, or it can push out sideways if the material on both sides is amenable to being pushed. Continental collision is a fascinating and complex process, especially because it creates mountains. The highest mountain range on Earth, the Himalayas, is the result of a collision between a once separate Indian land mass and the Eurasian plate. Scientists estimate this collision to have begun perhaps 40 million years ago, and convergence continues to this day.

If the slow convection of the aesthenosphere is the engine that drives plate tectonics, earthquakes are in a sense the transmission. Again, simple diagrams of plate boundaries are inadequate in another important respect: the smoothly drawn boundaries between plates do not accurately represent the complicated geometries and structure of real plate boundaries. An oceanic plate that subducts under a continent is lathered with sediments and possibly dotted with underwater mountains known as seamounts. To descend into an oceanic trench, a plate must overcome significant frictional resistance from the overriding continental crust. Oceanic crust sinks beneath the continents because the former is more dense, but it does not go quietly into the night. Although magma and crustal generation at mid-ocean ridges is relatively continuous, a plate usually stalls out at the other end of the conveyor belt until enough stress accumulates to overcome friction. Oceanic real estate disappears piecemeal, in parcels up to 1,000 kilometers long and 300–500 kilometers deep. By virtue of their enormous area, subduction zones produce the largest earthquakes anywhere on the planet.

Zones of continental convergence are also, not surprisingly, characterized by significant seismic activity. The seismicity associated with the India—Eurasia collision is more diffuse and complicated than that associated with classic subduction zones, but it is no less deadly. Very large earthquakes—the equal of those on the San Andreas Fault and then some—occur over vast regions within Eurasia, including India, Tibet, Mongolia, and mainland China, all a consequence of a collision that began 40 million years ago. The M7.6 earthquake

on January 26, 2001, in Bhuj, India, was a consequence of the India—Eurasia collision, and it happened several hundred kilometers away from of the active plate boundary.

Earthquakes are by no means restricted to convergence zones. Crustal generation at mid-ocean ridges is also accompanied by earthquakes. Although generally of modest size, a steady spattering of earthquakes clearly delineates these plate boundaries. At spreading centers, the plates' total motion is greater than the component contributed by the earthquakes: because the spreading process does not involve as much frictional resistance as subduction does, some of the motion occurs gradually, without earthquakes. Along transform faults, however, long-term motion is also accounted for predominantly by the abrupt fits and starts of earthquakes.

The circum-Pacific plate boundaries—sometimes known as the Ring of Fire because of the relentless and dramatic volcanic activity—alone account for about 75 percent of the seismic energy released worldwide. A trans-Asiatic belt, stretching from Indonesia west to the Mediterranean, accounts for another 23 percent or so. That leaves a mere 2 percent of the global seismic energy budget for the rest of the world, including most of the vast interiors of North America, Australia, South America, and Africa. Although 2 percent might not sound like much, it is nothing to sneeze at. The devastating earthquakes that struck midcontinent in the United States near Memphis, Tennessee, in 1811 and 1812 occurred far away from active plate boundaries, in what geologists term *intraplate crust.* Another noteworthy North America event, perhaps as large as magnitude 7, struck Charleston, South Carolina, in 1886. Other events with magnitudes between 6 and 7 have been documented during historic times in the northeastern United States and southeastern Canada.

These intraplate events, which have been attributed to various forces, including the broad compression across a continent due to distant mid-ocean spreading and the slow rebound of the crust upward following the retreat of large glaciers, are considerably less frequent than their plate-boundary counterparts. These events are also potentially more deadly because they strike areas that are considerably less well prepared for devastating earthquakes.

A RETROSPECTIVE ON THE REVOLUTION

Before we explore earthquakes in more detail, it is worth pausing briefly to look back on the plate tectonics revolution as a phenomenon unto itself. Scientific

revolutions are indeed uncommon and therefore interesting events; to understand them is to understand the nature of scientific inquiry in general. Although the basic ideas of continental drift might have been obvious, the data and theoretical framework required for the formation of a mature and integrated theory required a technical infrastructure that was unavailable in earlier times.

What do we make of Alfred Wegener? Should we decry the treatment his visionary ideas received and honor him posthumously as the father of plate tectonics? He did, after all, argue tirelessly and passionately for continental drift some 30 or 40 years before it passed into the realm of conventional wisdom. Or should he be dismissed as a nut, having championed ideas he fervently believed even when doing so meant relying on less-than-definitive data and invoking explanations that the experts of the day dismissed as total bunk?

Both arguments have been made in the decades following the 1960s. For those predisposed to viewing the scientific establishment as a monolithic, territorial, and exclusionary entity, Alfred Wegener is nothing short of a poster child. Just look at the derision that his ideas met, the argument goes, because he was an outsider to the field of solid earth geophysics, an outsider who challenged the conventional wisdom of his day.

In the final analysis, however, one must always remember that science is about ideas alone. Having drawn on data from many different sources in support of his ideas, Wegener's contributions to plate tectonics exceed those of Francis Bacon and Antonio Snider. Indeed, by the 1980s, Wegener was frequently credited as being the father of continental drift theory, and rightly so.

But was the treatment of Alfred Wegener in his own time unconscionable? Was the establishment monolithic? Exclusionary? It is easy to conclude that it was, and this conclusion fits neatly with many of our preconceptions. Yet the fossil and climatological data on which Wegener relied were suggestive but scarcely conclusive; paleontologists were themselves divided in their interpretations and conclusions. Moreover, if we attribute the skepticism of Wegener's ideas to his status as an outsider, what then should we make of the early treatment of Lawrence Morley? Harry Hess? Tuzo Wilson? Although they were established insiders within the field of geophysics, their ideas also met with harsh criticism, their papers with rejection. It is a truism in science that the papers that present the most radical—and perhaps ultimately the most important—scientific ideas of their day are often the ones that meet with the harshest reception during peer review. And, again, rightly so. Within any field of science,

the body of collective wisdom is hard won, based on data and inference that have themselves survived the intense scrutiny of review. Scientists whose quest for truth upsets the apple cart will likely chafe at the resistance they encounter but will ultimately accept the responsibility to persevere.

In 1928, geologist Arthur Holmes proposed a model for mantle convection and plate motions that was not far off the mark. Applying the standards of scientific advancement to his own theories, Holmes wrote, "purely speculative ideas of this kind, specifically invented to match the requirements, can have no scientific value until they acquire support from independent evidence."[6] That is, testable hypotheses that future data can prove or disprove are essential before a hypothesis can pass from the realm of cocktail party conversation to good science.

What Wilson and Morley had that Wegener (and, indeed, Holmes) lacked was not acceptance in the club—or even a willingness to persevere—but rather the good fortune to have lived at the right time. Had Wegener not agreed to the expedition that claimed his life in 1930, he would have been in his early seventies when the great bounty of bathymetric data was collected in the early 1950s. Those who portray Wegener as a victim of the scientific establishment sometimes gloss over the fact that Wegener became part of the academic establishment in the 1920s, when he accepted a professorship at the University of Graz in Austria. It requires no great stretch of the imagination to suppose that, as a tenacious and energetic individual with the security of a tenured academic appointment, Wegener might have remained active in science well into his seventies. He might have been well positioned to be among the first to recognize the significance of the bathymetric data and to capitalize on it.

But he wasn't. And it wasn't a matter of fault, his or anybody else's. It was sheer happenstance that Wegener died just as Harry Hess, Lawrence Morley, and Tuzo Wilson emerged on the scientific scene. In politics, one person can perhaps a revolution make, but if and only if world events have first set the stage. In science the stage itself is more important than the intellect, personality, vision, or charisma of any single individual. The birthright of scientists is the state of understanding at the time that they take their places in their chosen field. The legacy of any scientist is the additional contributions he or she provides. The advancement of scientific understanding is a little like the building of a transcontinental railroad. The work to be done at any given time depends on the lay of the land. Even with tremendous scientific insight and acumen, it's hard to build a bridge if the tracks haven't reached the river yet.