From: K. O'Hara, A Brief History of Geology (2018, Cambridge University Press, Cambridge).

6 Continental Drift

Thus the theory of continental drift is a fairytale.

– Bailey Willis, 1944[23]

As early as the 1870s, geologists working in Africa[1] and India[2] had concluded there was once continuity between Africa and India, and also Australia, based on the similarity of plant and reptile fossils on these three continents in Permo-Carboniferous times. At the time it was commonly assumed that the ocean basins were simply foundered continents, so it seemed plausible that continental connections once existed between now separate continents. Recall, for instance, from Chapter 5 that the French geologist Bertrand correlated mountain belts across the north Atlantic Ocean from Europe to North America believing that these same mountain belts underlay the present day Atlantic; the fact that continental crust and oceanic crust were of entirely different chemical compositions was not yet fully appreciated. As an alternative to foundering continents, Darwin's coral reef map of 1842 suggested to others that there were shallow underwater mountains throughout the Indian Ocean (Maldives, Seychelles, etc.), so that a land bridge may have existed between India and southern Africa.[2]

Edward Suess, in his *Face of the Earth*, coined the term *Gondwanaland* to describe this southern continent, named after Permian to Jurassic formations from India (his Gondwanaland also included South America east of the Andes and Madagascar). He stated that because *Glossopteris* (a Permian-aged fern) was common to all the Gondwana continents and that all its Permian sediments were non-marine, that it was a contiguous continent at that time and only began to break up with the appearance of Jurassic marine sediments. Suess rarely ventured into tectonic mechanisms and, apart from subsidence of ocean basins, he left them vague.

In Chapter 5 we saw that horizontal thrust and nappe displacements on the order of tens of kilometers (up to 100 kilometers in the case of the Caledonian of Scandinavia) were by now widely accepted, but large-scale horizontal displacements of the continents themselves had not yet been seriously proposed. This changed at the beginning of the twentieth century with the publication of a paper by the American geologist Frank B. Taylor in 1910,[3] followed by Alfred Wegener's book on Continental Drift in 1915.[4] Taylor's paper might be termed Continental Drift light: he allowed for continental displacements of hundreds of kilometers, whereas Wegner's hypothesis called for horizontal displacements of thousands of kilometers.[5]

In the *Face of the Earth*, Suess had used trend lines, or map-view trends of mountain belts and island arcs, to analyze tectonic patterns of Asian mountain belts. In Asia he recognized a series of arcs that are convex toward the Pacific Ocean, and he interpreted them as indicating tectonic transport toward the south. In the case of the Himalayas, he saw that the Indian continent acted as a rigid indenter causing a reentrant into Asia, a geometry that is visible on any physical geography map of the region. Taylor applied this approach of using tectonic trends to Tertiary mountains belts in Europe and also North America. He concluded that all of the northern hemisphere continents were transported southward to lower latitudes (despite the fact that many of the mountain belts showed northward tectonic transport, such as the Alps and the Carpathians) or eastward transport (the Rocky Mountains). He then applied the same method to the southern hemisphere, where he concluded that South America and Australia indicated tectonic transport to the north to lower latitudes (despite the fact that the Andes indicate tectonic transport to the west). He interpreted the tectonic displacements in the two hemispheres as due to flattening of the Earth at the poles, which gave the Earth its oblate shape, thereby causing the continental lithosphere to move toward the equator. Although his tectonic analysis does not stand up to even cursory scrutiny, he did make some original suggestions regarding rifting along the mid-Atlantic ridge and suggested that it was the site along which Africa and South America fragmented.

THE ORIGIN OF CONTINENTS AND OCEANS

Alfred Wegener was born in Berlin in 1880 and died in 1930 on his third expedition to Greenland.[6] He received a Ph.D. in astronomy in Berlin in 1905, but spent most of his career studying meteorology and the physics of the atmosphere. On his first expedition to Greenland (1906–1908), he undertook atmospheric investigations using balloons and kites. On return from Greenland he took a teaching job in meteorology at the Physical Institute at Marburg, Germany, and from 1909 to 1912 he published more than forty papers on atmospheric physics that he later collected into a book.

While examining a new atlas of the Atlantic in 1910 based on data collected on the Challenger voyage (1873–1876), Wegener noticed the similar bathymetry on the opposite coastlines of Africa and South America. As he explains in the introduction to his book, the following year he came across geological and paleontological data showing that the two continents were probably connected at one time as Suess and others before him had suggested. In 1912 he wrote a paper on his theory of horizontal displacement of the continents (later called Continental Drift). During a prolonged sick leave from action in World War I, he wrote the book for which he is now most famous: *The Origin of Continents and Oceans* in 1915. The war meant it did not receive the attention it deserved, and it was not translated into English and other languages until 1924 (from the third German edition), after which it aroused great interest worldwide.[5] A fourth edition was published in 1929 in which Wegener placed greater emphasis on geodetic measurements of present day continental movements. What follows is a brief outline of Wegener's book (first English edition).

The first chapter of Wegener's book is a brief synopsis of the hypothesis of horizontal displacement of the continents, what Wegener called his "displacement theory" (Figure 6.1). Chapter 5 in this book summarized why the contraction theory of mountain-building is

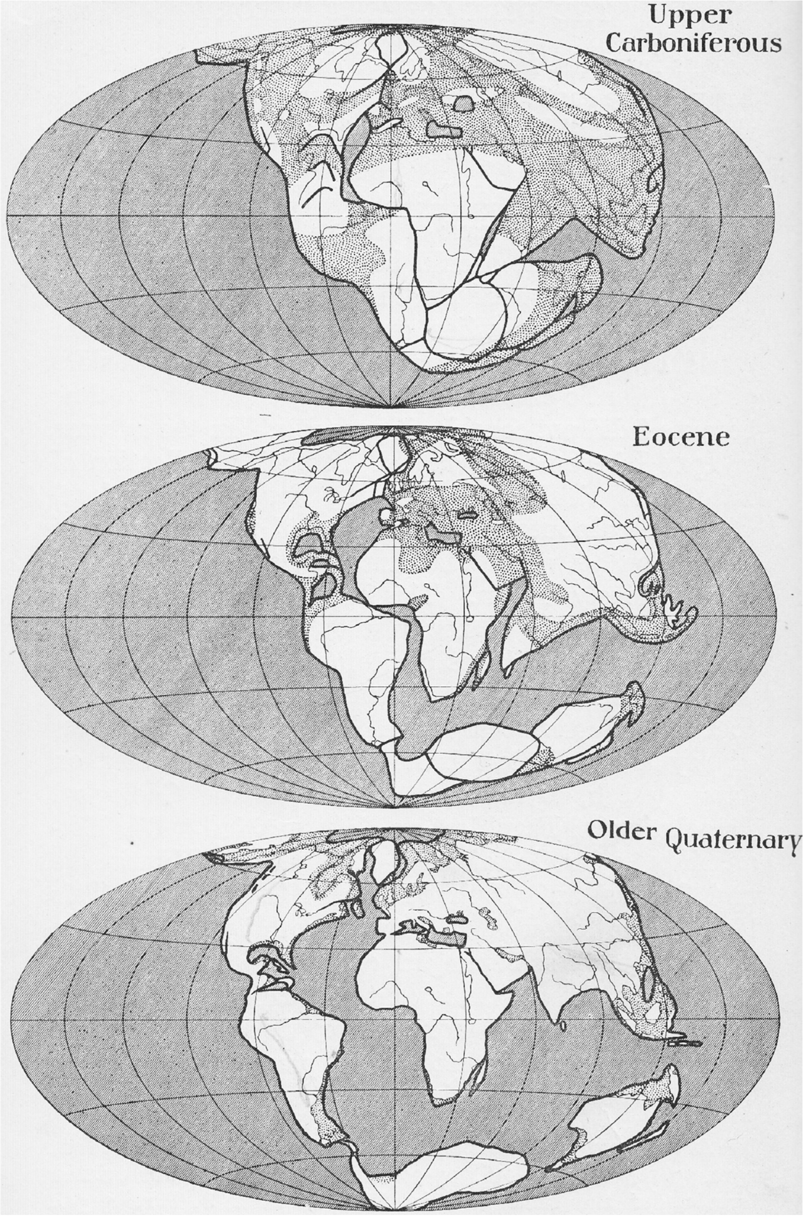

FIGURE 6.1 Reconstruction of the world geography according to Wegener for three periods: upper Carboniferous (~290 million years ago), Eocene (~45), and lower Quaternary (~2). Stippled areas are shallow continental seas. Continental outlines include the submarine continental shelf. Wegener called the Carboniferous supercontinent Pangaea. The Atlantic Ocean is still quite narrow by Eocene time. The north Atlantic is still nearly closed by the lower Quaternary, making the north Atlantic basin much too young.

Source: Wegener, A. 1924. *The Origin of the Continents and Oceans*. Methuen, London. Trans., J. G. A Skerl. First published in German 1915.

insufficient to explain mountain shortening and why isostasy precludes the foundering of continents into ocean basins. The absence of deep sea sediments on the continents also argued against continental foundering and the only alternative was narrow land-bridges across oceans to explain the fossil similarities on opposite sides. Wegener did not deny the existence of continental shelf land bridges (such as the Bering Straits) along continental margins, but did deny the existence of deep sea land bridges across oceans and maintained his displacement theory is a better explanation for similar flora and fauna on different continents. Long distance land bridges would cross different climate zones, he maintained, and would therefore show differences in flora and fauna; but the Permian fern *Glossopteris*, for example, is identical on the various parts of Gondwanaland.

Chapter 3 of Wegner's book advances geophysical arguments in favor of displacement theory, focusing mainly on the different physical properties (seismic, magnetic, density, and topographic features) of the oceanic realm versus the continental realm, using Suess's terminology of sima (silicate- and magnesium-rich crust) versus sial (silicate- and aluminum-rich crust), respectively. Based on isostasy, Wegener estimated the continents are about 100 kilometers thick with about 5 kilometers above sea level, and the rest is below sea level floating on the sima (oceanic) substrate.

In Chapter 4 of his book, Wegener presents the geologic arguments in favor of his theory. He begins with the Atlantic and notes that the south Atlantic is wider than the north Atlantic, so that the south Atlantic was the first to open up (we now know this to be incorrect). He points out various geologic features that join up across the Atlantic, such as the east-to-west trending Cape Mountains of South Africa, which can be followed again in South America south of Buenos Aires, and that the Precambrian gneisses of the Brazilian shield match gneisses on the west coast of Africa. Moving northward, he summarizes Bertrand's correlation of older mountain belts across the North Atlantic with Europe (see Chapter 5). Wegner uses the analogy of torn newspaper fragments matching up with each other for the opposite sides of the Atlantic and the various geologic features, such as older mountain belts also lining up, so that not only did the shape of the torn fragments align, but the lines of print could be read across the torn newspaper.

In the north Atlantic, Wegner follows Taylor's ideas on the rifting of Greenland from Labrador in the west and from Norway to the east. Turning to connections between India, Madagascar, and Africa, Wegener summarizes the evidence presented earlier by Suess for the existence of Gondwanaland. In Chapter 5 he summarizes a previously published survey of twenty paleontologists regarding the timing of the disappearance of land bridges based on the paleontological evidence. The paleontological data indicate a breakup of Gondwanaland between the Jurassic and Cretaceous. However, Wegener apparently over-interprets the data in the case of Europe and North America where he concludes a Quaternary breakup is indicated, when in fact most of the data indicated a Jurassic breakup. This mistake explains why Wegener includes, in his first chapter, a correlation of terminal glacial moraines in Europe and North America as geological evidence of a connection as late as the recent Pleistocene glaciations (this was a major mistake). It also explains why in his reconstruction the geography of today does not occur until the Quaternary period only a few million years ago (see Figure 6.1), when in fact our present-day geography becomes quite recognizable by the late Cretaceous, 65 million years ago. These mistakes played a large role in the criticisms of his theory as it implied the Atlantic Ocean was much younger than the Pacific Ocean, which many geologists were not ready to accept.

In Chapter 6, Wegener summarizes paleoclimatic arguments. The glacial deposits (tillites) in the various parts of Gondwana are strong evidence that Gondwanaland was centered over the South Pole in Carboniferous time. The Permian fern *Glossopteris* generally overlies these glacial formations. At the same time in equatorial regions, tropical coals and evaporate deposits are present and these observations do indeed support the existence of Gondwanaland. In Chapter 7 of his book, Wegener attempts to present geodetic measurements based on astronomical measurement of longitude to indicate present day rates of drift, but the method is not sufficiently accurate to provide an answer. This chapter is considered to be Wegener's weakest. In the fourth edition of his book, he provides additional geodetic data, but most commentators gave them little credence.

The final chapter discusses the driving forces for drift. Wegener saw a westward drift of the continents (e.g., South America) and, like Taylor before him, he also saw a drift toward the equator. He attributed the westward drift to tidal forces of the sun and moon, and the equatorial drift as due to the Earth's equatorial bulge. The Cambridge geophysicist Harold Jeffreys (1891–1989) showed these forces to be hopelessly inadequate to move the continents (see Box 6.1).[7]

The possible reasons for the rejection of Continental Drift are many and may have included Wegener's nationality at the time of World War I, as well as his outsider status as a nongeologist. Continental Drift was more strongly rejected in America compared to Europe. The exhaustively researched book *The Rejection of Continental Drift* by Naomi Oreskes specifically addresses this differential response.[8] She concludes that American geologists compared to Europeans had a different view of how science should be practiced. A simpler explanation, however, is that most of the evidence in favor of drift was on the continents in the southern hemisphere, with which most American geologists (excepting Reginald A. Daly) were unfamiliar, but which European geologists were more familiar.

The structure of Wegener's book itself may have been also part of the problem; the first chapter presents the hypothesis and the subsequent chapters provide the supporting evidence, which may have raised the ire of some observers. The influential American geologist Thomas Chamberlin (1843–1928), who is best known for his studies of Pleistocene glaciations, published an influential paper entitled "The Method of Multiple Working Hypotheses"; the paper has no references, a testament to its originality.[9] This paper is still influential in the United States, and it was reprinted in 1966 by

BOX 6.1 Geophysicist Harold Jeffreys (1891–1989)

Because of his fame as an authoritative geophysicist, Harold Jeffreys's opinions against drift were given great weight by many. Jeffreys was born in Durham, England, and died in Cambridge, aged ninety-eight. He attended Durham University (now University of Newcastle) where he graduated in 1910 with a first-class degree with distinction in mathematics; he also studied chemistry and physics, plus a year of geology.[31] He was awarded a scholarship to read mathematics at Cambridge, where he received first-class marks, and his scholarship was extended to four years while he developed research focused on astrophysics. In 1922 he returned to Cambridge as a lecturer in mathematics. While in London he met Arthur Holmes when Holmes was working on radiometric dating, and Jeffreys then became interested in the age of the Earth and its thermal history and other geophysical problems. The results of these studies were brought together in his great treatise *The Earth: Its Origin, History and Physical Constitution* (1924), which ran six editions The sixth edition lists 170 publications of his and is a small fraction of his total output in other fields.[32] His main achievements lie in the fields of seismology, planetary geodynamics, meteorology, applied statistics, and Earth's gravity anomalies. He showed, for example, from seismology that the Earth's metallic outer core is liquid, leading to new ideas concerning the origin of the Earth's magnetic field. However, in geology, he was on the wrong side of several major debates.

As outlined in Chapter 5, the idea that long-term cooling of the Earth leads to contraction of the crust and formation of mountains chains (contraction theory) was dismissed as inadequate on quantitative grounds. Jeffreys, however, revived (resurrected might be a more appropriate word) the theory in his book *The Earth* (second edition) by taking into account radioactivity and pronounced the shortening as being adequate (100–400 kilometers) to explain Tertiary mountain belts. In answering objections to the theory, he said, with detectable ire: "Some objections have been answered several times already, but appear to be capable of indefinite

BOX 6.1 **(cont.)**

repetition however often they are answered."[7] He did not answer a major objection to contraction theory, however, namely that it could not explain the asymmetry of mountain belts. Although in the sixth edition, where he still supported contraction theory, he invoked James Dana's old theory of mountain-building, which attempted to explain the asymmetry.

Jeffreys was not a fan of continental land bridges because isostasy precluded their foundering (for once, here he agreed with Wegener). He noted that many were opting for Continental Drift as an alternative, and commented: "If ever there was a migration from the frying pan into the fire it is this."[7] His two main geophysical arguments against drift in the second and sixth editions of his book are the same: lack of a driving force, and the strength of the sima (oceanic crust) would not allow the sial (continental crust) to drift through it. These ideas are summarized throughout this chapter, and are not repeated here. Jeffreys also rejected that the sima was a viscous fluid as Wegener proposed – the topography of the ocean basins would have decayed to become a flat surface, which in 1976 was known to have highly variable topography.[32]

Regarding convection models, he complains that the rheology is not specified in the various models and therefore they cannot be evaluated, and this presumably applies to Holmes's 1929 paper. He concluded convection would lead to a steady state rather than episodic mountain-building events. Regarding the paleomagnetic results that had been accumulating since the 1950s that showed large continental displacements, he was suspicious of the stability of the magnetic field in minerals, saying: "I have been told that the magnetic minerals, magnetite and hematite, stand ill-treatment better than steel. But I remain doubtful."[32] By 1976 (sixth edition of *The Earth*), the basic rudiments of plate tectonics were in place, but Jeffreys rejected both sea-floor spreading and the concept of subduction, saying that the mantle was too strong to digest the slab. At this time he was eighty-five years old. He published his last

BOX 6.1 **(cont.)**

technical publication at age ninety-six. It might be said that Harold Jeffreys was to geologists of the twentieth century what Kelvin was to nineteenth century geologists: a thorn in their sides. Recall that Kelvin was also on the wrong side of several major geological debates, including Darwin's evolution and the age of the Earth.

Science Magazine as a tribute to its importance. After its original publication, it may have influenced the reception to scientific hypotheses in general, and more specifically, Wegener's drift hypothesis. Chamberlin recognized three intellectual states: the ruling theory, the working hypothesis, and the method of multiple working hypotheses. Wegener, in his book, by stating his hypothesis upfront in the first chapter followed by supporting evidence, may have alienated the American scientific community at that time who favored Chamberlin's multiple hypothesis approach. Several critics noted that Wegener was an advocate for his own hypothesis rather than an impartial investigator, and that his was an unscientific approach; this argument is consistent with Oreskes's conclusion that American and European scientists had different approaches to science.[8] Wegener did, however, have a few influential supporters.

WEGENER'S SUPPORTERS

Three early and strong supporters of Wegener were the English geologist Arthur Holmes, the South African geologist Alexander du Toit, and Émille Argand, a Swiss Alpine geologist. The American igneous petrologist Reginald A. Daly and John Joly of Ireland also supported their own versions of Drift.

Arthur Holmes, who we met in Chapter 2 for his work on the geologic timescale and in Chapter 3 for his work on the age of the Earth, was a strong advocate of convection in the mantle as the driving force for Continental Drift as early as 1929. Holmes was born in Tyne, England, in 1890, and died in London in 1965.[10] He gained an interest in geology in high school and entered Imperial College London and studied physics for his first degree under Robert Strutt (later Lord Rayleigh). He later studied geology under W. Watts at Imperial College. He undertook graduate studies under Strutt based on the recently developed uranium-lead method of dating of minerals, and produced the first geologic timescale based on this work at the age of twenty-one (Chapter 2). Two years later, his book *The Age of the Earth* appeared.[11] He later went on expedition to Mozambique, where he gained field experience and studied mainly igneous rocks. He took a teaching job at Imperial College during the period 1912–1920, then became chief geologist for an oil company in Burma (now Myanmar) from 1920 to 1924, after which he became professor of geology at the University of Durham in 1925. He married for the second time in 1939 to a well-known geologist at that time, Doris Reynolds. He became chair of geology at the University of Edinburgh in 1943. He started writing his textbook *Principles of Physical Geology* while at Durham during World War II, and it was published in 1945.[12] The final chapter is a review of Wegner's Continental Drift theory, where he points out some of its errors but nevertheless acts as a strong supporter of the hypothesis; he also restates convection as the driving mechanism for Continental Drift. The second edition of his *Principles* was published in 1964, a year before his death, which ran to nearly 1,300 pages and covered a wide range of disciplines from geophysics to geomorphology. It became very popular, and was also my first undergraduate geology textbook at college and certainly an intimidating one. His writing was clear and lucid, and he had skill at illustrating his ideas. Holmes received many awards, including the Penrose Medal from the Geological Society of America, its most prestigious award, on his retirement in 1956. His main contributions to the Earth sciences were in geochronology, the geologic timescale, the origin of igneous rocks, and convection in the mantle.

Holmes's 1929 paper entitled "Radioactivity and Earth Movements" is remarkable for how close it comes to modern plate tectonics

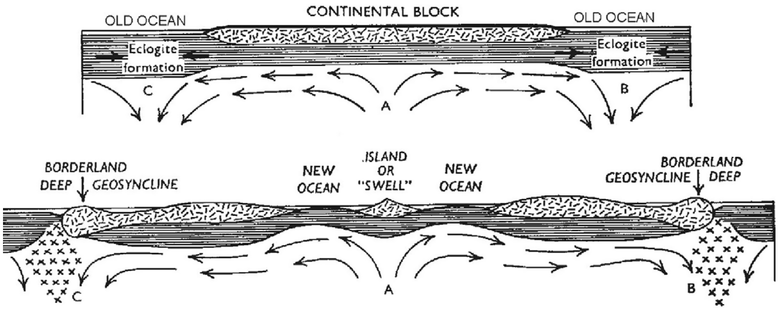

FIGURE 6.2 **Upper panel**: Convection currents in the mantle rise beneath continental crust (A) and down-going currents convert basalt (horizontal lines) to heavier eclogite (B and C). **Lower panel:** Continent is thinned and extended, creating new ocean between continental fragments (A). The eclogite joins down-going convection currents at the edge of the continents, forming borderland geosyncline deeps.
Source: Holmes, A., 1929. Radioactivity and Earth movements. Transactions Geological Society Glasgow, v. 18, 559–606. Courtesy Geological Society of London.

(Figure 6.2).[13] In it he shows how radioactivity is a sufficient energy source for convection to occur in the mafic substratum (the mantle), upon which the continents float isostatically. He assumed the mafic substratum to be a viscous fluid with no yield strength. Upwelling convection currents caused continents to drift apart, forming new basaltic ocean crust, and down-going limbs of convection currents caused continent collisions, formation of geosynclines, and compressional mountain belts (Figure 6.2). He estimated the continents moved at about 5 cm/year, which is the correct order of magnitude. Convection in the mantle provided a driving mechanism for Wegener's Continental Drift, and the lack of strength of the mantle allowed the continents to plow through the mafic substratum, thereby removing two of the chief objections to Wegner's ideas. Collisional mountain belts were produced by converging convection currents. Perhaps because Holmes's arguments were only semi-quantitative, they did not gain substantial support.

Émile Argand, another supporter of Wegner, was born in Geneva in 1879 and died in Neuchâtel in 1940.[14] Because of his artistic skills, his father apprenticed him to an architect, but his mother wanted him to study medicine. While at the University of Lausanne, he met the Alpine geologist Maurice Lugeon, and under his direction Argand decided to devote himself to geology, specifically Alpine structural geology. He was a good mountain climber, having spent his youth in Geneva in the foothills of the Alps. He unraveled the structure of several Alpine nappes, and his excellent ability at drawing complex shapes in three dimensions from different perspectives allowed him to present accurate cross-sections of these structures.[15] The latter publication contains thirteen cross-sections on the same page, showing the development of the nappes of the western Alps from the original paleo-geography through the various tectonic stages, and is a work of art in itself apart from its scientific significance. He was appointed professor of geology at Neuchâtel in 1911. Argand read Wegener's book in the original German in 1915 (during World War I it was illegal to read German in private or in public in Switzerland),[16] and was convinced of the "mobilist" view of the Earth, a term he coined himself. Figure 6.3 shows the complex nappe structure of the Alps due to collision of Africa with Europe, in keeping with Wegner's drift hypothesis. Argand's most important work is his *La Tectonique de l'Asie*, (The Tectonics of Asia), published in 1922.[16] The title is somewhat misleading as the book covers not just the tectonics of Asia, but also of Europe; it was translated into English in 1977.[17] Argand knew at least six languages, and whenever his review of the world literature required a new language he learned that language, sometimes in as little as a few days.[17] Argand's work was influential in French-speaking Europe, but less so in the United States.

Alexander du Toit was born in South Africa (1878–1948).[18] The American geologist Reginald Daly called him the "world's greatest field geologist."[18] It is estimated he mapped 256,000 kilometers (100,000 square miles) during his lifetime using a plane table with a bicycle for transport. He graduated from the University of Cape Town and spent two years studying mining engineering in Glasgow, Scotland, where he met his wife, and he also studied geology at the Royal

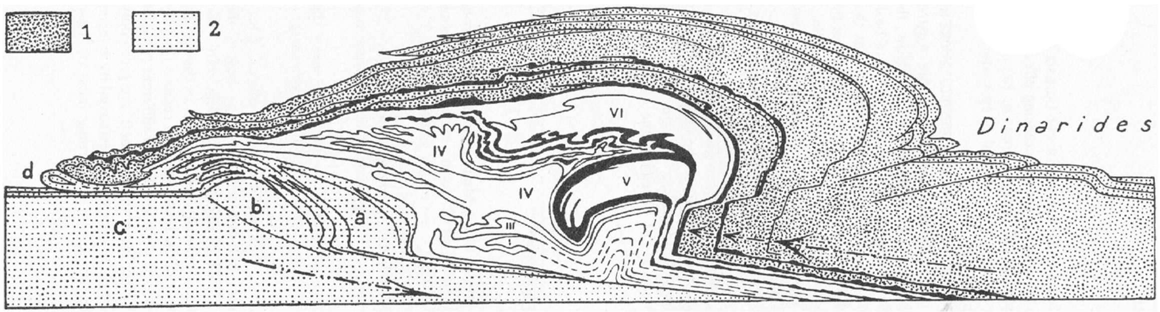

FIGURE 6.3 Diagram showing the development of nappes in the western Alps due to the collision and thrusting of Africa over Europe. 1: Africa; 2: Europe. Mafic rocks are shown in black. Nappes: IV, Great Saint Bernard; V, Monte Rosa; VI, Dent blanche. Scale: 1:1,000,000.

Source: Argand, É. 1922. La tectonique de l'Asie. Conférence faite á Bruxelles, le 10 août. *Congres géologique international, Belgique*.

College, London. He became lecturer at both the Royal Technical College, Glasgow, and the University of Glasgow. In 1903 he returned to South Africa where he was a field geologist for the Geological Commission of the Cape of Good Hope and spent nearly all of his time in the field over the next seventeen years. In 1923 he received sponsorship from the Carnegie Institution of Washington (USA) to compare the geology of South America with South Africa, with a focus on testing Wegener's hypothesis.

He spent five months studying the geology of Brazil, Paraguay, and Argentina traveling by train and steamer, hosted by the various heads in charge of geological resources of their respective countries which cover a vast area on a continental scale. Not surprisingly, he noted little coordination between countries over this large continent and his synthesis of South American geology is a triumph. The results of his work were published in *A Geological Comparison of South America with South Africa* in 1927, in which he concluded the numerous similarities between the two continents favored the theory of Continental Drift.[19] He published his well known-book *Our Wandering Continents: A Hypothesis of Continental Drifting* in 1937, in which he displays his knowledge of global geology and paleontology, especially that of Gondwanaland.[20]

One of the few well-known American geologists (born in Canada) to support Continental Drift was Reginald Daly. In his 1926 book, *Our Mobile Earth*, he largely accepted Wegner's ideas and proposed the driving mechanism was gravity whereby continents slide off topographic highs on the Earth's surface,[21] which is somewhat similar to Joly's model, which is outlined later in the chapter. Daly also played a role in helping du Toit get support for his South American trip from the Carnegie Institution.

CRITICS OF DRIFT

Petroleum geologists were very interested in the Wegener hypothesis; the breakup of Gondwanaland in Jurassic to Cretaceous times created new passive continental margins where thick, carbon-rich sediments were likely to develop into hydrocarbon reservoirs. Today we know that most of the giant oil fields discovered in the 1980s and 1990s were formed in this tectonic setting. So it is not surprising that the American Association of Petroleum Geologists convened a symposium in New York in February of 1928 to discuss Continental Drift.

The international meeting was convened by van Waterschoot van der Gracht, vice president of Marland Oil Company at that time, and the results of the meeting were published by the University of Chicago Press.[22] The vice president provided an informed introduction to the volume and at the end he addressed the concerns of those who objected to Wegener's Drift hypothesis. Of fourteen participants in the Petroleum Geologist's meeting, four were European and the remainder American. Alfred Wegener's contribution was short and was presented by a surrogate; Wegener himself was preparing for his third and last trip to Greenland. Frank Taylor was a Wegener supporter and largely repeated his 1910 paper described above. Seven Americans were *against* and only one was *for* the Continental Drift hypothesis.

Among the Americans who rejected drift were world-class geologists Bailey Willis of Stanford University; Thomas Chamberlin of the University of Chicago; and Charles Schuchert and C. H. Longwell, both of Yale University. John W. Gregory of the University of Glasgow, who wrote a book on the tectonics of Asia himself,[23] was also against drift. One critic, E. Berry (University of Baltimore) called the hypothesis unscientific because Wegener was selective in his use of evidence and that he was an advocate for his own theory.

The main arguments against drift were twofold: 1) geophysical, involving the rheological behavior of the continental crust versus the oceanic crust and the absence of a driving force; and 2) geological, paleontological, stratigraphic, and tectonic. Wegener put himself in a bind by proposing that the continents (sial) plowed through the ocean realm (sima), while at the same time the resistance of the sima caused fold and thrust belts in the front of the solid continents by resistance to the sima – the westward drift of the Americas and their western mountain ranges being the main examples. Wegener countered this problem as follows in later editions of his book: "The solution of this apparent contradiction lies in the great dimensions of the Earth and in the long periods of time."[4] Citing Maxwell on viscous fluids, he noted that a substance (for example sealing wax) may behave as a solid under a rapid impulse (e.g., an earthquake), but under a slow impulse it behaves as a viscous fluid. Nevertheless, under a slow impulse, a viscous sima still cannot crumple the front of an advancing solid continental block and at the same time flow. The fact that he ignored the oceanic crust as consisting of solid basalt made matters worse.

A second objection was that mountain-building was episodic in time, while the drifting of the continents does not produce episodic events. In a similar vein, if part of Gondwanaland broke up in the Cretaceous, why is this period tectonically quiet, with no mountain-building events? Wegener's drift hypothesis implies mountain-building events should occur continuously during drift, but this is not observed.

The physicist and geologist John Joly of Trinity College, Dublin, who we met in Chapter 2 for his work on the chemical age of the oceans, gained much support among the participants of the meeting. He suggested a modified version of Wegener's hypothesis involving episodic melting and episodic Continental Drift due to heating by radioactivity. In this hypothesis, continents acted as a thermal blanket over the sima causing melting and topographic highs. The continents then slid down off the topographic highs allowing the heat to escape by conduction causing cooling, and so on cyclically, producing episodic tectonic events. Many of the participants thought this idea deserved further work.

The objection by Bailey Willis was that the eastern side of westward drifting continents should also show tensional features, just as the western side shows compressional features. This argument can be overcome, however, if convection of the underlying sima is invoked so that the continents are floating on a convecting substratum, as Holmes had suggested in his 1929 paper.

Another major objection was that Continental Drift had no viable driving force. Wegener attributed the westward drift to tidal forces of the sun and moon, and the equatorial drift as due to the Earth's equatorial bulge. Others have pointed out that the emplacement of Alpine nappes and repeated glaciations were two examples of phenomena that were accepted at the time without known mechanisms or causes, so that Continental Drift could be recognized as valid without a causal mechanism; du Toit was of this opinion.

Geological and paleontological objections were many.[22] If the Atlantic opened in the Quaternary glacial period, where were the young fold belts of this age? Chamberlain was blunt on this point, saying, "The matching of the glacial moraines is ludicrous." Wegener did unfortunately match European and American glacial moraines in his first chapter, implying Europe and North America were recently connected. Similarly for the drifting away of Australia: Where were the young fold belts in Australia? More than one commentator suggested that a 50 percent to 75 percent similarity of species on the various continents would be expected if they formed a single continent, but only 5% showed such similarity. They suggested land bridges were a better explanation (even though isostasy ruled out sinking land bridges).

Charles Schuchert used plasticine outlines of the continents on a globe to show that if North America and Europe were juxtaposed that a large gap opens up between Alaska and Siberia, which had been joined since Cambrian time. Wegener replied that if North America was rotated rather than translated, no gap appears. Schuchert also noted a poor correlation of the geology between Ireland and Newfoundland that Wegener had placed together. Today that geology is regarded as consistent with the Wegener fit.

These are just a sample of the objections that came to light at the American Petroleum geologists' symposium of 1928. The debate was interrupted by World War II, but continued until 1944 when the *American Journal of Science* published several discussions against

Wegener's Hypothesis.[24, 25] One of these contributors was by Bailey Willis with a discussion entitled: "Continental Drift, Ein Märchen" (A Fairytale).[24] Alexander du Toit answered these objections in the *American Journal of Science* in 1944.[26]

In Europe a similar but less damning discussion of drift played out in the pages of *Nature Magazine*,[27] the *Geological* Magazine,[28] and the *Geographical Journal.*[29] A meeting in 1923 of the British Association in Hull, England, discussed the Wegener hypothesis, which produced a lively but inconclusive discussion.[30] All participants, however, agreed that Wegener's north Atlantic was much too young.

PALEOMAGNETISM

William Gilbert, born in Colchester, England (1544–1603), was physician to Queen Elizabeth I., and of whom Galileo said "great to a degree that might be envied." He wrote *De Magnete* in 1600, the first scientific book on magnetism and possibly the first book in all of experimental science.[33] In it he recognized the Earth had a dipole field as if a giant bar magnet was embedded in it, aligned roughly with the Earth's spinning axis. He saw that the inclination (the angle from the horizontal) of a magnetic needle varied with latitude on the Earth, the magnetic field being horizontal at the equator and vertical at the poles. The Earth's magnetic field is now thought to be a dynamo that originates in the convection of the molten core.[34]

Paleomagnetism is the study of the Earth's magnetic field in the geological past and is undertaken by the study of the magnetization of rocks. In the simplest case, for example, when volcanic lava erupts at the surface and cools down below the Curie temperature (about 600°C), iron-rich minerals in the lava lock in the Earth's ambient magnetic field at the time of eruption. However, subsequent metamorphic or weathering events can superimpose new magnetic fields on the original field corresponding to younger times, leading to possibly erroneous interpretations. Secondary hematite (Fe_2O_3), for example, might overprint the primary field due to original magnetite (Fe_3O_4). Today there are laboratory techniques to detect these complications and remove these overprints.

Oriented rock samples of known age are collected in the field and the direction of the rocks' remnant magnetization is measured in the laboratory with a magnetometer. The latitude of the rock at the time of eruption can then be calculated (using the formula $\tan \theta = \frac{1}{2} \tan I$, where θ is latitude and I is inclination), and a magnetic pole can also be calculated which is close to the geographic pole. This is done for rocks of different age and the change in magnetic pole is plotted for different times. The resulting curve is called an apparent polar wandering path because it is not clear whether the continent to which the samples belong to actually moved or the magnetic poles moved; the magnetic data alone cannot distinguish between the two.

It was the French scientist P. Mercanton in 1926 who suggested that rock paleomagnetism could be used to test Continental Drift, but it was not until the 1950s that this was actually accomplished.[35] Keith Runcorn (1956) showed that the apparent polar wandering paths for Europe and North America were different so that the two continents must have moved relative to one another (Figure 6.4).[36] Shortly thereafter results from the southern hemisphere showed that Gondwanaland was united in the Carboniferous and its constituent parts fragmented in the Mesozoic. Studies of the Indian Deccan trap volcanics showed that India moved northward about 4,000–5,000 kilometers in early Tertiary (Eocene) time.[37] The authors of the latter study were, however, noncommittal in their review of the paleomagnetic results. They concluded the paleomagnetic results might be explained more plausibly by a rapidly changing magnetic field rather than by large-scale Continental Drift. These authors did, however, redeem themselves of their faulty conclusion later on when they constructed a paleomagnetic timescale (see Chapter 7).[38]

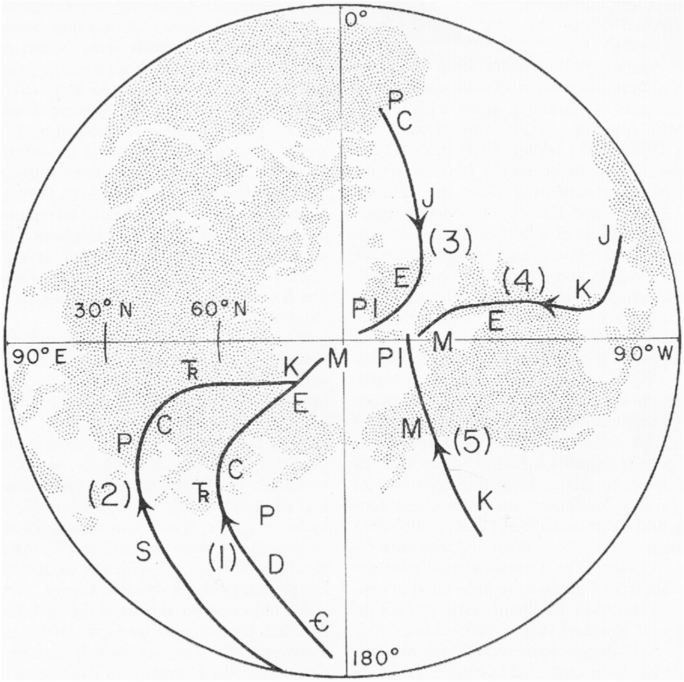

FIGURE 6.4 Apparent paleomagnetic polar wandering curves for several different continents indicate major displacement of the continents relative to one another during the Paleozoic, Mesozoic, and Cenozoic. 1. Europe; 2. North America; 3. Australia; 4. India; 5. Japan. S: Silurian; D: Devonian; C: Carboniferous; P: Permian; T: Triassic; J: Jurassic; K: Cretaceous; E: Eocene; M: Miocene; Pl: Pliocene.

Source: Cox, A. and Doell, R. 1960. Review of Paleomagnetism. *Bulletin of the Geological Society of America*, v. 71, 645–768. Courtesy Geological Society of America.

A symposium organized on Continental Drift as late as October 1965 by the Royal Society shows that both in Europe, and more so in North America, many geologists and geophysicists were still not onboard with the drift concept.[39] Tectonics was still in crisis mode. In Part II of this book, we will see that paleomagnetism of a different sort would lead to a new revolution in the study of Earth sciences. Continental Drift had its day, and it would soon be replaced by New Global Tectonics.

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7 Plate Tectonics

I shall consider this to be an essay in geopoetry.

– H. Hess, 1962.[1]

INTRODUCTION

While patrolling the northwest Pacific during World War II, the commander of the U.S.S. *Cape Johnson*, Harry H. Hess (1906–1969) often left the echo transponder on continuously as he crossed the Pacific Ocean in random traverses. Normally the sonar was only used while leaving and entering port, but as a geologist Hess was interested in the topography of the deep ocean floor. He later published a paper in the *American Journal of Science* (1946) stating that during service in the Navy he had discovered over one hundred flat-topped volcanoes that stood thousands of meters above the sea floor; he called them *guyots*, named after a flat-topped building on his campus (which in turn was named after a Swiss geographer).[2] He inferred the flat tops were due to wave erosion when sea level was lower. As an example of how little was known about the ocean floor at the time, Hess concluded that the guyots were Precambrian in age because no reefs were present, in contrast to Darwin's younger atolls (Chapter 1). We now know that the oldest rocks in the Pacific Ocean basin are Jurassic in age, about 170 million years old, not Precambrian. Over a decade later, Hess proposed the idea of sea-floor spreading, which was subsequently confirmed by the Vine-Matthews hypothesis based on magnetic stripes at mid-ocean ridges.[1]

The discovery of plate tectonics involved three narratives that were going on at approximately the same time in the 1960s, namely: the study of the magnetic signature of the ocean crust, the study of deep-focus earthquakes around the northern Pacific rim, and recognition of transform faults in ocean basins. Only a relatively few institutions were involved in the fundamental discoveries of plate tectonics, and they included Cambridge University, England; Princeton University, New Jersey; the Lamont Geological Observatory (now Lamont–Doherty Observatory), Columbia University, New York; and Scripps Institution of Oceanography, California.[3] In 1965 the paths of several individuals involved in plate tectonics crossed at Cambridge. Harry Hess visited from Princeton, as did Tuzo Wilson from the University of Toronto. Research students at Cambridge who were to make important contributions included Fred Vine, Dan McKenzie, Robert Parker, and John Sclater. Drummond Matthews was already on the faculty (or staff, as they say in England) and was to become Vine's doctoral thesis advisor. Three seismologists at Lamont would later crystallize the plate tectonic synthesis in an amazingly short period of time.[3]

Earlier, Hugo Benioff of the California Institute of Technology worked on deep crustal earthquakes[4] in the late 1950s which would later lead to discovery of destructive plate boundaries (subduction zones) by two seismologists Jack Oliver and Bryan Isacks at Lamont in 1968.[5] Together with constructive oceanic plate boundaries (seafloor spreading ridges) recognized by Hess[2] and Dietz[6] in the early 1960s and by Vine and Matthews in 1963,[7] these discoveries led to the New Global Tectonics. Tuzo Wilson described a third type of plate boundary: transform faults.[8]

Two instrumental or technological advances greatly aided in the discovery of plate tectonics. The first was the fluxgate magnetometer invented in 1936, which when airborne was used to detect submarines during World War II. After the war the first oceanic magnetic anomalies were discovered using this type of magnetometer towed behind a ship.[7] The second important advance came with the installation of the World-Wide Standardized Seismograph Network which commenced operation in 1962.[3] This network included calibrated seismographs of both long and short periods with high sensitivity and global coverage. The network was originally set up to monitor nuclear explosions during the ban on the testing of nuclear weapons. This network greatly improved the ability of seismologists to determine the sense of shear and orientation of the fault that caused an earthquake. These so-called first-motion studies allowed the determination of the type of stress at the three principal types of plate boundaries and played a very important role in understanding global tectonics. Data provided by the Deep Sea Drilling Project (DSDP) also yielded important information to support plate tectonics.[9]

OCEAN FLOOR RIFTS

In the late 1920s three research vessels, the *Carnegie*, the *Meteor*, and the *Dana* (American, German, and Danish in origin, respectively), made discoveries of ocean ridges in three different oceans using echo soundings; these ridges represented submarine mountain ranges that were topographically several kilometers above the surrounding ocean floor and hundreds of kilometers in length, but they were thought to be isolated features. By the 1960s a substantial amount of new geophysical data had been collected in the ocean basins worldwide including gravity, seismic, and heat flow data. Bruce Heezen of Lamont published a paper for a general audience in *Scientific American* in 1960 describing a worldwide system of connected oceanic rifts 64,000 kilometers (40,000 miles) in length that showed high heat flow and shallow earthquake foci largely confined to the rift zone.[10] The rifts were now recognized to be a global feature and not isolated phenomena. Henry William Menard, in his book *The Ocean of Truth*, provides a detailed account of early research on ocean basin geology in which Menard himself was deeply involved.[11,12]

Because subduction zones had not yet been discovered and because all the rifts were undergoing extension, Heezen suggested the Earth must be expanding. He attributed the cause of the high heat flow and topography at the ridges to the upwelling limbs of convection currents in the mantle. Robert Dietz in 1961 also tied mantle convection to upwelling at ocean ridges and down welling at Pacific-type continental margins, without the necessity for earth expansion.[6]

In 1961 Henry Menard of the Scripps Institute, California, described in substantial detail the high heat flow and shallow seismicity of the East Pacific Rise (rise and ridge are here interchangeable terms) and noted the low heat flow of deep ocean trenches supporting the idea that these were the down going limbs of the convection cells.[12] Menard, in his book, also discusses those who supported expansion of the Earth over geological time as an explanation for the present-day distribution of the continents.[11]

Harry Hess in his 1962 paper did not like the earth expansion idea, and agreed that the down going limbs of the convection currents took care of the material balance produced at the expanding ridges including their sedimentary cover that was eventually accreted to the continents.[1] Hess probably overemphasized the role of hydration of mantle peridotite to produce serpentine at the axes of the ridges (his doctoral thesis was on the hydration of ultramafic rocks). He recognized that sea-floor spreading (the term was first used by Dietz) "wiped the slate clean" on a relatively short geological time scale which explained the absence of Paleozoic-aged ocean ridges and of old oceanic sediments.[1] Who took priority over the sea-floor spreading concept is discussed by Menard in his book, and he favors Hess; Hess had earlier circulated a preprint of his manuscript in 1960, but Dietz had no recollection of this or of discussing the idea with Hess.[11]

In the 1950s several paleomagnetic studies showed magnetic polar reversals in volcanic rocks where the magnetic field direction appeared to be flipped by 180 degrees so that magnetic north became magnetic south; one of these early studies was on basalt flows in Iceland by a student at Cambridge.[13] Initially these reversals were interpreted as due to the instability of the magnetic signature in individual rock samples (called self reversals), but when enough data was collected, the reversals were seen to be global in extent and also contemporaneous. These data were attributed to reversal of the Earth's entire magnetic field, even though a good explanation for the reversals did not yet exist.[3] Workers at the United States Geologic Survey identified four major reversals and about a dozen or so short reversals over a period of 4.5 million years. This allowed the youngest part of the ocean floor close to the spreading center to be dated.[14] One of these reversals occurred during the Pleistocene and is named the Matuyama anomaly after the Japanese scientist who showed that a large number of Pleistocene-aged volcanic rocks from Japan indicate reverse polarity. This reversal ended about 0.8 million years ago, and since then the Earth has been under normal polarity, called the Brunhes period, named after the French physicist. The magnetic reversals were dated using the potassium-argon (K-Ar) radiometric decay system (see Chapter 8) on volcanic lava flows from around the world. Gradually, the age of the reversals was established for oceanic rocks as far back as 160 million years ago, corresponding to some of the oldest rocks in the oceans. The recognition of global magnetic polar reversals led the way to explain magnetic anomalies at mid-ocean ridges, thereby confirming the reality of sea-floor spreading as suggested by Dietz (1961) and Hess (1962).

Two English scientists working at Cambridge University, Fred Vine and Drummond Matthews, interpreted positive and negative magnetic anomalies centered on mid-ocean ridges that produced linear magnetic stripes parallel to the ridges as due to the magnetic reversals just described above.[7] Some of the data they used was produced aboard the H. M. S. *Owen* in 1962 by criss-crossing the northern Indian Ocean at the Carlsberg Ridge, towing a magnetometer behind the ship; they also used similar data from the Mid-Atlantic Ridge. According to the sea-floor spreading hypothesis, new basalt was extruded at the seafloor at mid-ocean ridges due to the upwelling of convection currents in the mantle. As the basalts cooled below their Curie temperature (~600°C), they locked in the ambient magnetic field of the Earth (whether normal or reversed) and gradually moved away from the rift zone at the rate of centimeters per year to be replaced by new basalt at the ridge axis. If the Earth's magnetic polarity changed, these new basalts would record the new magnetic field producing the reversed and normal anomalies observed in stripes parallel to the ridge. As Fred Vine noted, the oceanic crust acted as a tape recorder of the Earth's magnetic history. This eventually would allow a magnetic stratigraphy to be constructed for the entire history of the ocean basins. That the sediments deposited in the ocean basins should become older toward their margins is a corollary of the Vine-Matthews hypothesis, which was later confirmed by deep-sea drilling.

The Deep Sea Drilling Project (DSDP) began in 1968 with the launch of the *Glomar Challenger*, a drilling ship outfitted to obtain cores of sediment from the deep oceans; it also had a satellite global positioning system, novel for that time. Funded by the United States National Science Foundation, it was a highly successful scientific project over a fifteen-year period.[9] The *Glomar Challenger* logged 600,000 kilometers (375,000 miles) and sampled 19,000 cores from 624 sites. One of its most successful projects was Leg 3, which sampled seventeen cores in the south Atlantic Ocean from Rio de Janeiro to the Mid-Atlantic Ridge at about 30°S latitude. The results of the study showed that the sediments became older from zero at the ridge to 75 million years old with distance from the axis of the ridge (indicating a half spreading rate of 2 cm/yr), strongly supporting the Vine-Matthews hypothesis (Figure 7.1).

The near perfect symmetry of the magnetic anomalies detected immediately south of Iceland on the Reykjanes Ridge, which is reproduced in many introductory geology textbooks in the context of the Vine-Matthews hypothesis, was not published until 1966, three years after the Vine-Matthews paper appeared, so these authors were unlikely to have been aware of the Icelandic data (and it should be noted that they don't mention these data in their paper). The Icelandic aeromagnetic data were collected by a magnetometer suspended from a plane and were much more accurate than the data collected at sea by Vine and Matthews in the Indian Ocean. The Icelandic data therefore do not appear to have contributed to the Vine-Matthews hypothesis, but those data supplied strong additional confirmation afterward.

In 1963 a Canadian geophysicist (Lawerenc W. Morley) was working with previously collected aeromagnetic anomalies in the

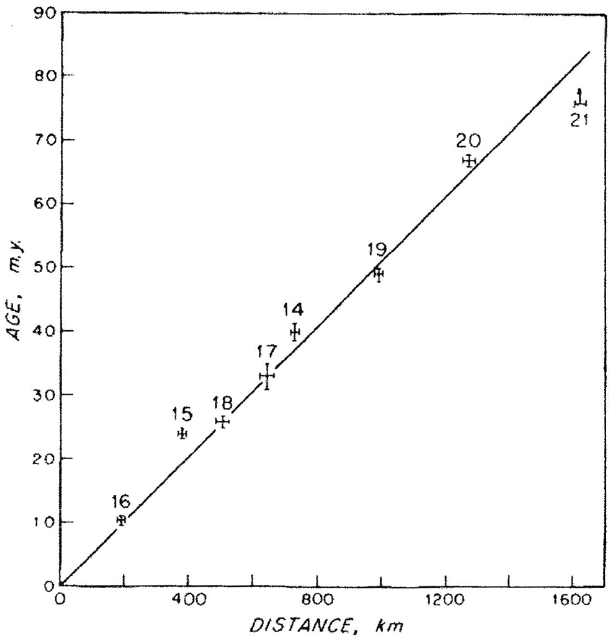

FIGURE 7.1 Leg 3 of the Deep Sea Drilling Project in the south Atlantic (about 30°S latitude) showed a linear relationship between distance from the Mid-Atlantic Ridge and the age of sediments immediately above basement. These data strongly supported the Vine-Matthews hypothesis. *Source:* Maxwell, A. E. et al. 1970. *Initial Reports of the Deep Sea Drilling Project*, v. 3. U.S. Government Printing Office, Washington D.C.

eastern Pacific Ocean offshore Vancouver Island that showed similar zebra stripes to those offshore Iceland, but were much more complex and less symmetric (Figure 7.2).[15] Morley had essentially the same idea as Vine and Matthews in interpreting these anomalies. Unfortunately for him, his paper was rejected by two journals (*Nature* and the *Journal of Geophysical Research*) in 1963 for being too speculative. One possible reason for Morley's rejection is that he was not using newly acquired data (the data he used was collected earlier by others),[15] whereas Vine and Matthews were using newly collected data. In addition, the anomalies were not symmetrical about a single spreading axis. Some writers now refer to this hypothesis as the

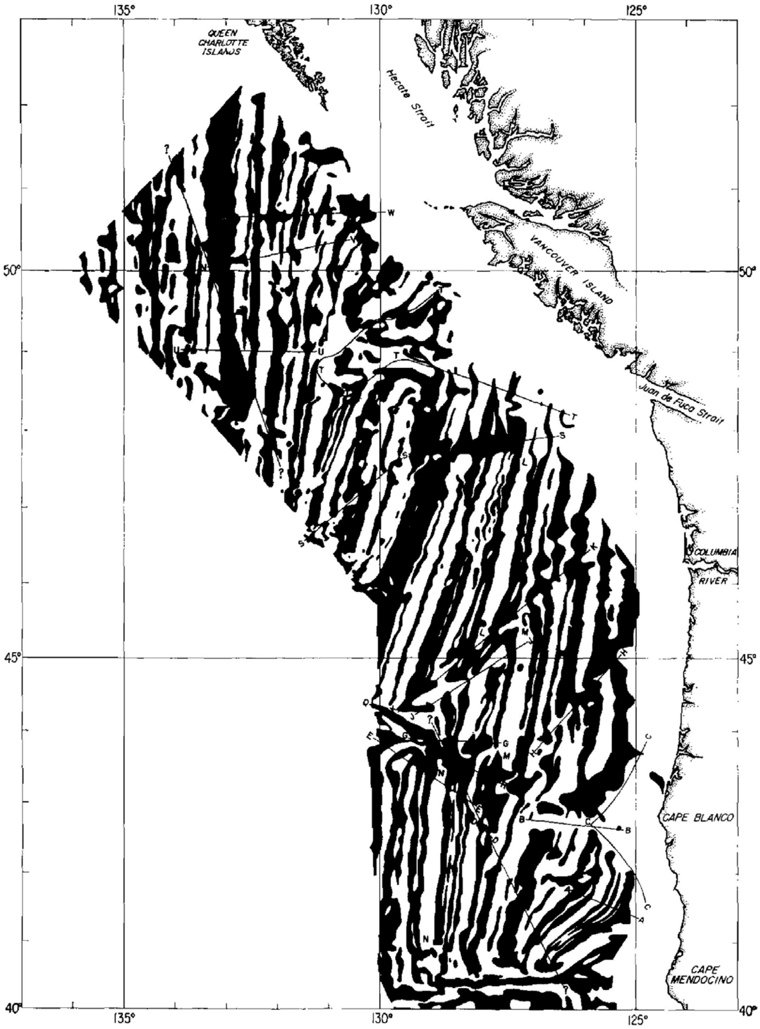

FIGURE 7.2 Aeromagnetic survey offshore Vancouver Island in the eastern Pacific ocean. The positive anomalies are black and negative anomalies white. The anomalies are offset by transform faults showing a complex pattern.

Source: Raff, A. D. and Mason, R. G. 1961. Magnetic survey off the west coast of North America, 40° N latitude to 50° N latitude. *Geol. Soc. Am. Bull.*, v. 72, 1267–1270. Courtesy Geological Society of America.

Vine-Matthews-Morley hypothesis. Morley's paper is discussed in detail by Frankel,[16] and is partly reproduced in Cox[3].

TRANSFORM FAULTS

Henry Menard showed the existence of east-west trending fracture zones that offset the East Pacific Rise (or Ridge) by several hundred kilometers (such as the Mendocino, Galapagos, and Easter fracture zones).[11] These offsets of mid-ocean ridges are global in extent and were later explained as a new type of plate boundary that Tuzo Wilson called transform faults.[8] They differ from transcurrent (or strike-slip) faults in fundamental ways. In oceanic transform faults, the sense of motion along the fault is (confusingly) opposite to the offset of the ridge itself because new crust is being created at the ridge axis (Figure 7.3A). Several types of transform faults exist: they can connect offsets of ocean ridges, such as the mid-Atlantic fracture zones (ridge-ridge type), or they may connect ocean ridges to island arcs (ridge-arc type). Wilson showed that six types of transform faults are possible (twelve if you reverse the sense of motion). He interpreted the San Andreas fault as a transform fault connecting the East Pacific Ridge in offshore southern California to the Juan de Fuca Ridge in offshore northern California.

Seismic studies undertaken by Lynn Sykes at Lamont at about the same time (1963) showed that the seismic activity on transform faults was confined to the segment of the transform fault *between* the ridges – the fault segments outside the ridges were aseismic, supporting Wilson's interpretation (Figure 7.3B).[17] Furthermore, using first motion or focal mechanism seismic studies, Sykes subsequently showed that the motion on the faults was as Wilson described, namely opposite to the offset of the ridge.[18] These seismic studies confirmed Wilson's interpretation of transform faults, leaving few doubters as to the reality of these counter-intuitive faults. Transform faults will continue to confound introductory geology students for generations to come. The understanding of the geometry of transform faults would later provide the key to understanding the relative motion of the tectonic plates.

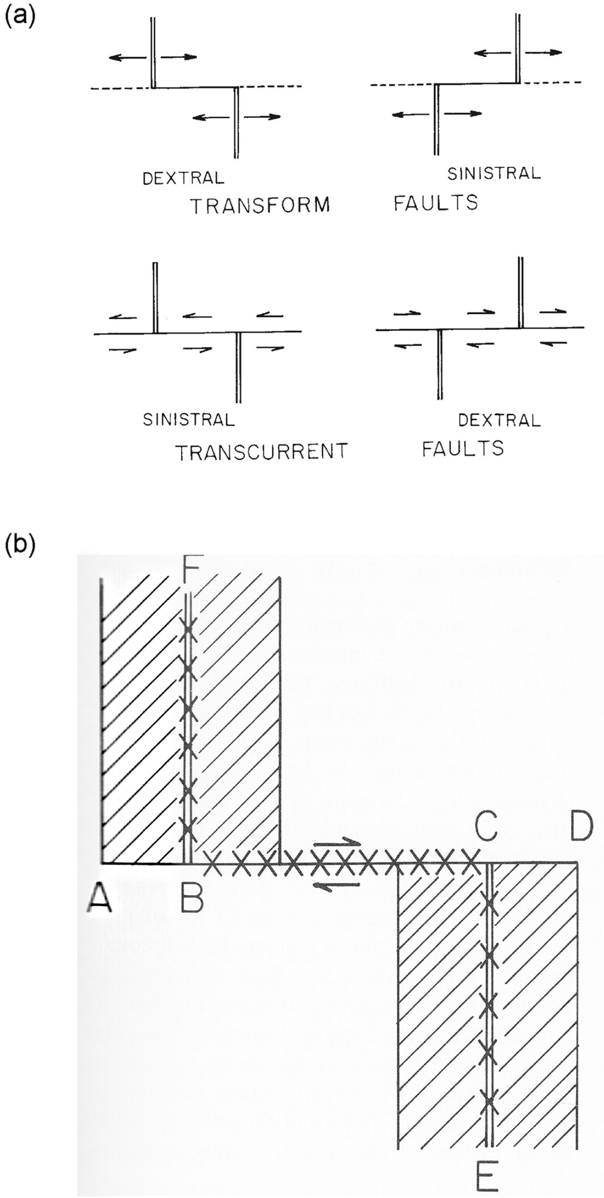

FIGURE 7.3 (a) Top: Transform faults (dextral and sinistral). The sense of motion on the fault is opposite to the offset of the ridge axis. Bottom: Transcurrent faults (sinistral and dextral). The sense of motion on the faults agree with the ridge offset.

Source: Sykes, L. R.1963. Seismicity of the South Pacific Ocean. *Journal Geophysical Research*, v. 68, 5999–6006. Courtesy Wiley.

(b) Seismic activity (X) on a spreading center is confined to the ridge axis and the transform segment between the offset ridge axis (BC). Fault segments beyond the ridge axis (AB; CD) are aseismic. These relationships confirm Tuzo Wilson's predictions for transform faults.

Source: Sykes, L. R.1967. Mechanisms of earthquakes and nature of faulting on mid-ocean ridges. *Journal of Geophysical Research*, v. 72, 2131–2153. Courtesy Wiley.

SUBDUCTION ZONES

Arthur Holmes in his 1929 paper (Chapter 6) on convection discusses down going convection currents: "Evidence of foundering blocks may be forthcoming from the occurrence of deep earthquakes (100 kilometers or more) off the coast of Japan." It was indeed deep earthquakes that established the existence of subduction zones where oceanic crust and the upper mantle (which together are referred to as oceanic lithosphere) descended into the deep mantle. Hugo Benioff at the California Institute of Technology in 1954 summarized the existing data on deep earthquakes by plotting their horizontal distance from volcanic arcs and deep ocean trenches (Figure 7.4).[4] Although he did not explicitly associate these deep earthquakes with down-going slabs, it would not be long before geophysicists associated these earthquakes with destructive plate margins (now called Benioff zones), complementary to the constructive ocean ridge plate boundaries described earlier.

The concept of tectonic plates had not yet emerged in 1954. The first mention of rigid tectonic plates, including ocean ridges and island arcs, appears to be Tuzo Wilson's paper in 1965 on transform faults already referred to; in that paper, arrows show the direction of motion of the plates. Seismometers installed in the Tonga trench showed that deep-focus earthquakes occurred on the upper surface of the descending slab (about 100 kilometers thick) within the Fiji region of the Pacific Ocean by Lamont researcher Bryan Isacks, which allowed the first lithospheric subduction zone to be delineated by Oliver and Isacks.[5] These authors suspected a similar pattern of seismicity beneath other deep-sea trenches for which data existed. Enough was now known that a new global synthesis could be attempted.

THE NEW GLOBAL TECTONICS

Two important papers entitled *Seismology and the New Global Tectonics*[19] and *Sea-floor Spreading and Continental Drift*[20] were published in 1968 by researchers all working at the Lamont

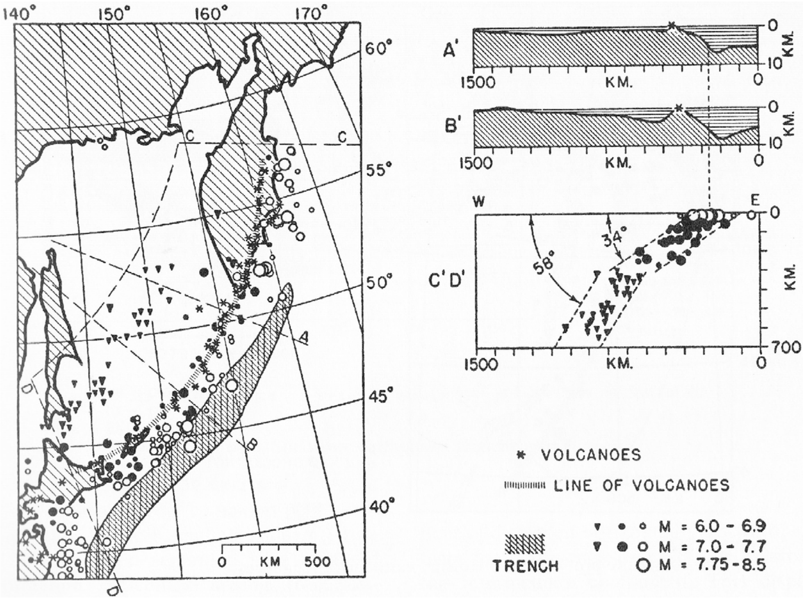

FIGURE 7.4 Left: Map of the Kurile-Kamchatka region that connects northern Japan and the Kamchatka Peninsula, showing epicenters of shallow (circles), intermediate (dots), and deep-focus earthquakes (triangles). The deep-sea trench is shown (crosshatch). Right: Composite profile of earthquake foci to 700 kilometers depth. The zone of deep and intermediate earthquakes dips toward the continent at two different angles. The stars represent active volcanoes.

Source: Benioff, H. 1954. Orogensis and deep crustal structure: additional evidence from seismology. *Geological Society of America*, v. 65, 385–400. Courtesy Geological Society of America.

Observatory. The latter paper by the French scientist Xavier Le Pichon identified six large rigid "blocks" (now called tectonic plates), namely: India, Antarctica, Africa, Pacific, America, Eurasia. Using the geometric principles for tectonics on a sphere and ocean floor magnetic anomalies, Le Pichon showed how the six rigid plates moved relative to one another together with their velocities on the globe. He used numerical methods on a digital computer with various types of Mercator projections for a visual display of the different plates. The geometrical principles he used were developed earlier by Jason Morgan at Princeton University[21] and Dan McKenzie and Robert Parker at the Scripps Research Institute,[22] and are briefly outlined here.

The relative motion between two plates on a sphere can be described by an axis of rotation, a line through the center of the Earth that can be simply specified by its latitude and longitude at the point it pierces the surface; this is referred to as Euler's theorem, after the eighteenth-century Swiss mathematician. It was Cambridge University scientists who first applied Euler's theorem in their fit of Africa and South America.[23] If three plates meet at a point, then the relative motion between two plates determines the relative motion of the third. McKenzie and Parker used earthquake first motion studies around the Pacific to find the pole of rotation for the Pacific plate relative to Asia.[22] Jason Morgan at Princeton developed the method of using transform faults to determine poles of rotation.[21] He saw that transform faults lie along small circles (those not passing through the center of the Earth), and that great circles (those that do pass through the center of the Earth) intersect these small circles at a right angle at the pole of rotation of two plates. This is the most accurate way to determine poles of rotation. Robert Parker also showed that the Mercator map projection was especially useful in determining the axis of rotation between two plates. As geography students know, the Mercator projection is a cylindrical projection and is normally thought of as a projection onto a vertical cylinder touching the Earth at the equator. But the cylinder can have any orientation, and Robert Parker had written a general computer program to do just that. He then recognized that if the pole of the Mercator projection was the same as the pole of rotation between two plates, then transform faults became horizontal lines on the projection – if the pole of rotation was correct.[22] Le Pichon used these geometric principles to solve the motion of his six plates on a sphere together with ocean floor magnetic anomalies.[20] His results agreed with those based on seismic first motion studies in the paper by Isacks, Oliver, and Sykes.[19] It was only 1968, and the basic geometry of plate tectonics was already in place.

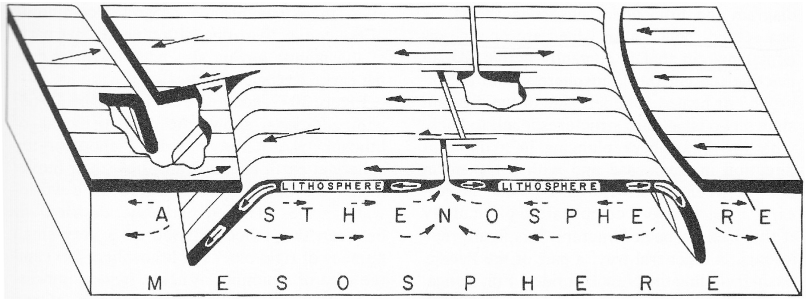

FIGURE 7.5 The now iconic cartoon figure from the paper entitled "Seismology and the New Global Tectonics" by Isacks, Oliver, and Sykes. It is notable for the absence of continents. The pattern of circulation in the asthenosphere is also unusual because it is opposite to the motion of the overlying plates.
Source: Reference 19: Isacks, Oliver and Sykes, 1968.

Perhaps the most iconic diagram of New Global Tectonics is a figure by Isacks and colleagues reproduced here in Figure 7.5. It is noteworthy for two reasons: First is the absence of continents, which underscores the point that plate tectonics was essentially a theory developed solely on evidence from the ocean basins but d later proved powerful in also explaining continental tectonics. The second unusual feature of the figure is that the motion in the asthenosphere (the weak layer beneath the lithosphere) does not conform to normal thermal convection – in fact, the motion in the asthenosphere is *opposite* to that in the overlying plates – and there is no return circulation pattern in the asthenosphere; the arrows point in the same direction at both deep and shallow levels. The authors suggest that the plates themselves may determine the circulation in the asthenosphere. They presented data suggesting a relationship between the velocity of the plates and the length of the attached subduction zone. Subsequent workers examined the gravitational forces that act upon the plates and did indeed show that subduction zones acted to pull the plate into the mantle (slab pull), and also that the topographic highs of the ridges acted to push the plates away from the ridge (ridge push).[24,25]

Isacks, Oliver, and Sykes also showed that the Earth's plate boundaries are largely defined by the distribution of both shallow-focus earthquakes (at ocean ridges) and deep-focus earthquakes (at subduction zones). They also show that the stress within down-going slabs is compressive parallel to the slab, an issue which was in dispute at the time. Both Bryan Isacks and Lynn Sykes were graduate students of Jack Oliver at Lamont where most students and faculty at the time were "fixist" and did not take Continental Drift seriously. The historical details of this remarkably successful small research group and their conversion to mobilism is recounted by Henry R. Frankel.[16]

As noted, the majority of Earth scientists (geologists, geophysicists, and oceanographers) readily accepted plate tectonics as a valid theory, with scientists in the former Soviet Union being the notable exception.[26] The influential Cambridge geophysicist Harold Jeffreys was also a notable exception. In the sixth edition of *The Earth*, published in 1976, he did not accept the Vine-Matthews sea-floor spreading hypothesis. He also maintained that the lithosphere was too strong to bend into subduction zones.[27]

The American Association of Petroleum Geologists (AAPG) was interested in Wegener's drift hypothesis (Chapter 6), and, not surprisingly, they were also interested in the new plate tectonics theory and published a memoir in 1974 entitled *Plate Tectonics: Assessments and Reassessments*, which grew out of a symposium held in 1971.[28] A large number of contributing papers expressed doubts about the theory, including the Russian scientist Vladimir Beloussov, Harold Jeffreys himself, and several papers by Arthur Meyerhoff and Howard Meyerhoff and one by J. C. Maxwell. Some of the doubts expressed by these authors are briefly outlined here.

Arthur Meyerhoff and Howard Meyerhoff rejected the young age of the ocean floor magnetic anomalies.[29] They plotted the locations of known oceanic magnetic anomalies and noted that over half of them were concentric to ancient cratons, claiming that they intersect the continents and so are Precambrian in age. They went on to list radiometric age determinations of rocks from the ocean basins. Out of approximately 140 radiometric dates, all are Cenozoic in age with only four aberrant dates ages giving Precambrian ages. They reiterated their conclusion that the ocean basins are Precambrian in age, ignoring the far more numerous Cenozoic dates. They further examined the results of Leg 3 of the Deep Sea Drilling Project shown in Figure 7.1. Because the drill cores stopped at the sediment-basement interface, these authors maintain the linear relationship between distance from the ridge and sediment age "prove nothing."[29] It would be easy to dismiss these authors as fringe cranks, but Jeffreys in *The Earth* (sixth edition) quotes extensively from these authors' papers in his own rejection of plate tectonics, indicating they had substantial influence at least on Jeffreys, who was more of a mathematician than a geologist.

More plausible objections were made by J. C. Maxwell.[30] He noted the absence of strong deformations in trench sediments and that normal faults predominated rather than thrusts, as would be expected. Isacks et al. however had already explained the normal faulting was due to bending of the down-going plate causing local extension (normal faulting) in the sediments. Maxwell also noted the East Pacific Rise magnetic anomalies were not symmetric about a single spreading center. But Vine (1966) had shown earlier that there were three short offset ridges associated with the East Pacific Rise (Figure 7.2).[31] Beloussov questioned the width of magnetic anomalies as being inconsistent with the then known ages of recent magnetic reversals.[32] But it appears he was using the earlier magnetic stratigraphy that was preliminary and later improved by discovery of additional short reversals which eliminated the inconsistencies.[13] Beloussov published a more detailed rejection of sea-floor spreading in a 1970 paper in *Tectonophysics*, which would have had a wider readership compared to the AAPG memoir.[33]

IMPLICATIONS FOR MOUNTAIN BUILDING

A paper entitled *Mountain Belts and the New Global Tectonics* by John Dewey (Cambridge University) and John Bird (New York

University at Albany) appeared in 1970 only two years after the seminal paper by Isacks et al., so that geologists lost no time in applying plate tectonic principles to the evolution of the continents.[34] Finally, a viable theory of mountain-building had arrived and the long-standing tectonic crisis outlined in Chapter 5 came to an end. The 1970 paper is notable for its numerous excellent illustrations and the fact that it conceptually makes several breakthroughs in geology. The paper focused on continent-ocean boundaries, as this is the locus of mountain-building either due to continent-continent collision or continent-island arc collision as a result of subduction.

The long standing problem of geosynclines, the long linear belts of exceptionally thick sediments, first identified in the Appalachians by James Hall (Chapter 5), and how and why they become the locus of intense folding and igneous activity was solved by the Dewey and Bird paper. The authors first show the sediments of the Appalachian miogeosyncline and eugeosyncline of Marshall Kay (see Figure 5.5) are very similar to the inner and outer margins of the present-day passive Atlantic margin. This passive margin is transformed into a subduction zone as the Iapetus (Ordovician aged) oceanic crust gets older and gains in density and sinks into the mantle. This leads to shortening of the passive-margin sediments and melting of the down-going slab, focusing igneous activity on the former geosyncline. The result is a mountain belt marginal to the continent, such as the Appalachians where the geosynclinal sediments become accreted to the continental margin and intruded by island arc volcanics. Readers familiar with northern Appalachian geology will recognize the Bronson Hill Anticlinorium in New England as an Ordovician island arc that formed over a closing Iapetus Ocean. The role of subduction at continental margins in producing Cordillera-type orogenic belts (e.g., the Andes) is also addressed in the Dewey and Bird paper, particularly with regard to emplacement of thrust sheets onto the continental interior, in which basement may or may not be involved. Continent-continent collision is also discussed in the context of the only modern example: the India-Asia collision. Plate tectonic models of all the major mountain belts quickly appeared in the geologic literature, including models of orogenic belts going back into early earth history.[35]

IMPLICATIONS FOR IGNEOUS ACTIVITY AND TECTONIC SETTING

Plate tectonics also revolutionized our understanding of the evolution of igneous rocks. This occurred mainly in three different tectonic settings, with increasing complexity in terms of petrogenesis, namely mid-ocean ridges, ocean-ocean subduction zones, and ocean-continent subduction zones. Sampling of the ocean floor showed that the dominant igneous rock there is tholeiite basalt, also known as mid-ocean ridge basalt (or MORB), and is remarkably uniform in composition and consists largely of pyroxene and calcic feldspar (in the ratio of 60–40 percent) with occasional olivine. This led to a simple two-stage model for the origin of MORB: partial melting of the upper mantle, leading to a magma chamber at the mid-ocean ridge, followed by fractional crystallization of pyroxene and feldspar during cooling leading to the MORB composition.[36] Some of the best evidence for the structure of the oceanic crust comes from the study on land of mafic and ultramafic rocks (called ophiolite suites), seen in several mountain belts including the Alps (e.g., Troodos in Cyprus) and the Appalachians of western Newfoundland (e.g., Bay of Islands), where they are interpreted to represent tectonic slices of oceanic crust that was obducted (as opposed to subducted) onto the continental margin.[37] These rock suites commonly consist, from bottom to top, of ultramafic rocks overlain by gabbro injected by dikes, further overlain by pillow basalts and sediments that correspond to the upper mantle and seismic layers 3, 2, and 1, respectively identified at mid-ocean ridges (Figure 7.6). That the oldest ophiolites known are about two billion years old suggests plate tectonics has been operative since that time.[38]

The igneous rocks in oceanic island arc settings are more complex and range in composition, with increasing silica (SiO_2), from basalt to andesite to rhyolite – referred to as the calc-alkaline trend. In the case of several Pacific island arcs, the volcanic rocks become

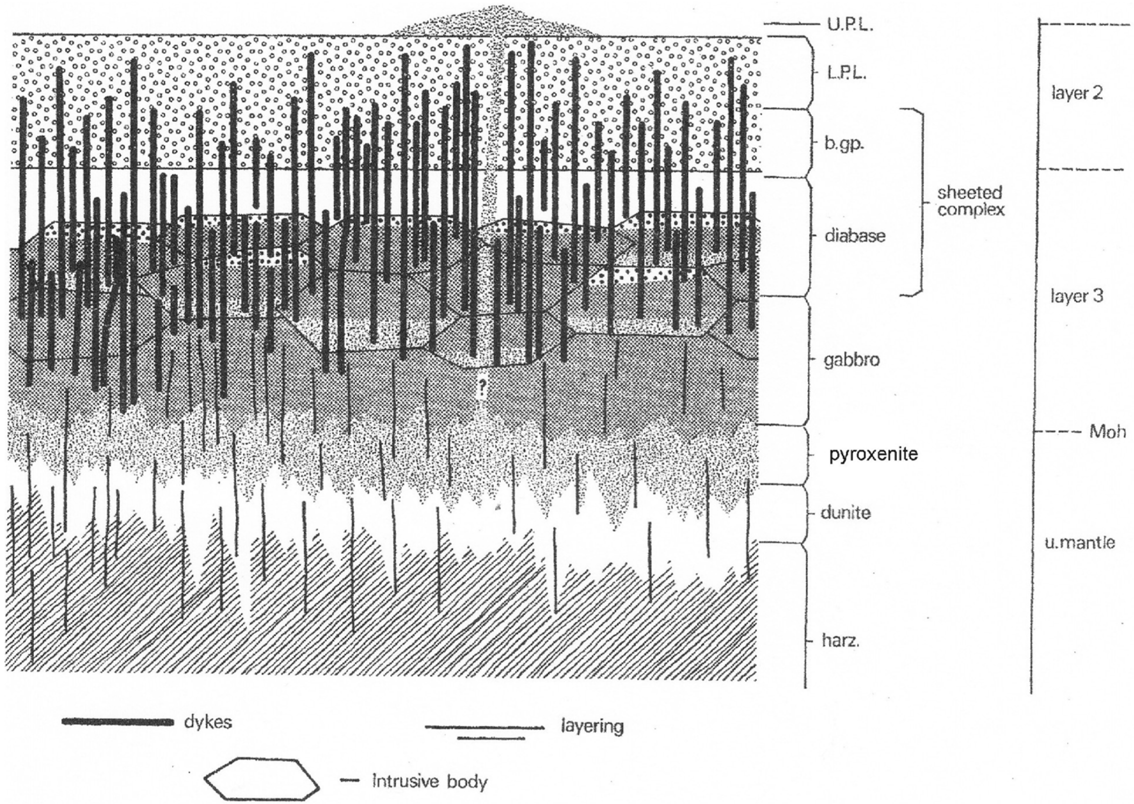

FIGURE 7.6 A stratigraphic sequence for the Troodos ophiolite complex, Cyprus, is thought to be a model for the structure of a mid-ocean ridge spreading center. Column at right indicates layers determined by seismic studies of mid-ocean ridges. UPL: upper pillow lavas; LPL: lower pillow lavas; BGP: basal group; Harz: harzburgite (olivine-pyroxene upper mantle rock); Moh: Mohorovicic boundary (crust-mantle interface).

Source: Moores, E. M. and Vine, F. J. 1971. The Troodos Massif, Cyprus and other ophiolites as oceanic crust: Evaluation and implications. *Philosophical Transactions of Royal Society, A*, v. 268, 443–467. Royal Society London with permission.

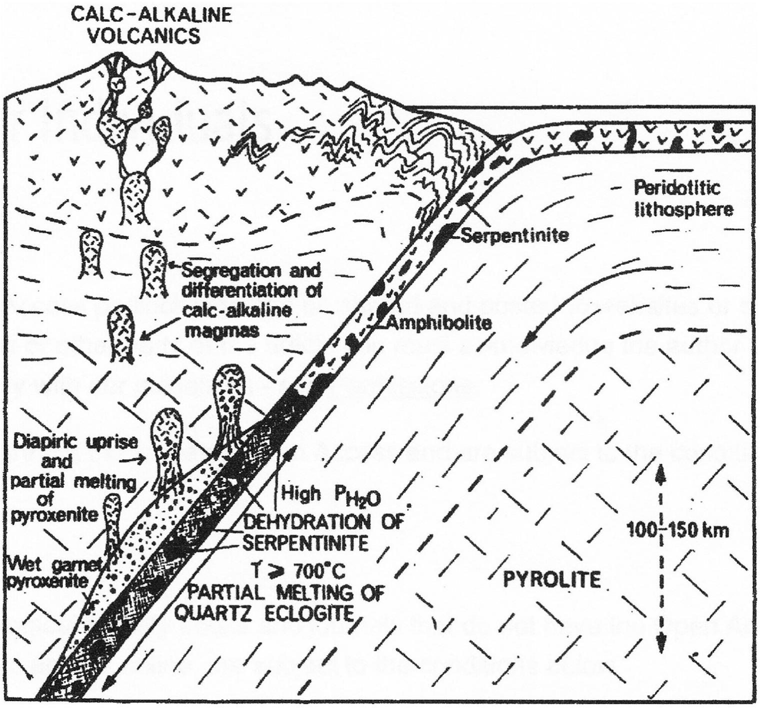

FIGURE 7.7 Igneous activity at a destructive plate boundary indicates partial melting of a down-going slab (after conversion of basalt to eclogite) produces calc-alkaline magmas that are accreted to the overlying plate to form a volcanic island arc.

Source: Ringwood, A. E. 1974. The petrological evolution of island arc systems. *Journal of Geological Society of London.*, v. 130, 183–204. Courtesy Geological Society London.

more potash (K_2O) and silica rich with increasing depth to the Benioff zone.[39] Australian experimental petrologists have also shown that partial melting of the down-going slab, after basalt is converted to eclogite (pyroxene and garnet-bearing rock) at a depth of between 100 kilometers and 300 kilometers, yields a calc-alkaline magma, which can in turn produce sialic crust such as diorite or granodiorite (Figure 7.7).[40]

A more complex tectonic setting is that of subduction at a continental-ocean plate boundary, where the additional variable is the potential involvement of the continental crust itself in the melting process together with any sediments involved in subduction. The question of the origin of granite batholiths is central to this problem, and was briefly addressed in Chapter 4. The origin of the granatoid rocks of the Sierra Nevada batholith of the western United States (most of which are diorite and granodiorite, as opposed to granite), and those of the Andes, for example, are still a significant scientific problem for geologists despite the tectonic framework provided by plate tectonics. The experimental work of Tuttle and Bowen outlined in Chapter 4 showed that in the presence of water, granitic melts can be produced at temperatures as low as 650°C, so that some granites can be produced by melting of sediments in the continental crust. Two Australian geologists (Bruce Chappell and A. J. R. White) in 1974, working in the Tasman orogenic belt of eastern Australia, proposed a classification of granitic rocks into two types: S-type (sedimentary source) and I-type (igneous source).[41] The S-type is mainly granite in composition and has accessory minerals rich in aluminum, such as micas and garnet, and is also rich in silica. The I-type has a wider range in composition from felsic to mafic (e.g., granite to diorite), and often contains the mineral hornblende. The two types also have distinct strontium isotopic compositions, reflecting different sources (see Chapter 8). The I-type granitic rocks could be produced by the subduction processes outlined in this chapter at a continental margin or island arc, and the S-type could be produced simply by metamorphism of a thick sedimentary pile. The English geologist Wallace S. Pitcher has discussed granite type and tectonic environment in considerable detail.[42]

CONCLUSIONS

Plate tectonics is a theory that crystallized over a very short period of time between 1961 and 1968, and gained widespread acceptance shortly thereafter. How could such a major scientific revolution have occurred over such a short period? Thomas Kuhn's book *The Structure of Scientific Revolutions* coincidentally appeared at about the same time the theory of plate tectonics was developing, and some have compared the plate tectonic revolution to a paradigm shift equivalent to that of the Copernican revolution in astronomy – although that is probably an overstatement.[43] But the acceptance of plate tectonics is an example of a paradigm change as described by Kuhn in his 1962 book (Chapter 12). It might be argued, however, that Wegener's continental drift hypothesis had been fomenting among the geological and geophysical community for forty years or longer (Wegner's ideas became widely known in several languages around 1925). The minds of Earth scientists may have been preconditioned by Wegener's radical ideas, so that when additional evidence became available in the form of sea-floor spreading and subduction zones, scientists were ready to get onboard. The problem of a mechanism for plate tectonics still existed (as it did for Wegener), but plate tectonics did not require plowing of continents through a strong sima, which was one of the main objections to Continental Drift. Plate tectonics was now acceptable to the majority of scientists, with or without a causal mechanism. Those who rejected plate tectonics were relatively insignificant in number, although some were prolific and famous. It may be suggested that in reality the acceptance by the majority of Earth scientists of large-scale continental mobility took at least forty years to ferment, requiring Wegner's ideas first, followed by continental paleomagnetic results, before plate tectonics could be accepted. The evidence presented by the proponents of plate tectonics was nevertheless overwhelming.

Dietz, in his important 1961 paper, stated: "The concept proposed here, which can be termed the spreading sea-floor theory, *is largely intuitive*, having been derived through an attempt to interpret sea-floor bathymetry"[6] (emphasis added). Hess, in his equally important 1962 paper, said: "I shall consider this paper to be an essay in geopoetry."[1] Apparently two of the most important papers leading to plate tectonics in the early 1960s are based on intuition and poetry. This is surely a long way from Chamberlin's multiple working hypothesis method that he encouraged all scientists to follow and which Menard said he tried to follow.[11] It is even farther away from Sedgwick's earlier inveighing against Lyell's uniformitarianism (quoted in Chapter 1). Wegener did not indulge in geopoetry or intuition, but rather marshalled a scientific hypothesis with solid evidence, yet he was still rejected. Clearly a major shift over time had occurred in how scientists were allowed to undertake science. World War I and World War II had intervened between Wegener's hypothesis and plate tectonics theories in the early 1960s. That little progress was made on tectonic issues, such as the origin of mountain belts, since the late eighteenth century may have convinced many that intuition and poetry were worth a try, since apparently Chamberlin's approach had not worked. A more prosaic explanation is that in the counter-culture environment of the 1960s, it was popular to espouse intuition and poetry as guiding forces – particularly in the context of Mother Earth.

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