From: P. Bowler, I.R. Morus, Making Modern Science (CUP: 2005)

CHAPTER 10

CONTINENTAL DRIFT

The 1960s witnessed a dramatic revolution in the earth sciences. Within a decade or so, principles that had been accepted since the "heroic age" of geology in the nineteenth century were overthrown and replaced by a new model of the earth's interior. The surface was now seen to be composed of interlocking but mobile plates that were constantly being renewed by volcanic action at one edge and destroyed by subduction into the interior at another. As a consequence of this new theory of "plate tectonics," the idea that the continents may drift horizontally across the face of the earth—which had been rejected or ridiculed for decades—now seemed perfectly plausible. The continents are like rafts of lighter rock carried along by the motion of the underlying plates on which they rest.

Not surprisingly, historians and philosophers of science have sought to use this episode as a case study to test theories of scientific change (Frankel 1978, 1985; Le Grand 1988; Stewart 1990). Was this a "revolution" in T. S. Kuhn's sense, in which a long-established paradigm entered a crisis state and was then replaced by another? Many of the participants certainly saw it in this light. Or was something more complex going on, perhaps requiring explanation in sociological terms related to the formation of research groups and new disciplines? According to Robert Muir Wood (1985), the revolution was actually a successful takeover bid for the earth sciences in which the newer discipline of geophysics displaced the more traditional science of geology. Much of the knowledge established by the geologists was retained, but the underlying principles were reformulated in the light of the new understanding of the earth's interior provided by geophysics. The sequence of geological formations established by nineteenth-century geologists (see chap. 5, "The Age of the Earth") was still valid, but their explanations of mountain building were abandoned. At the same time, one of the most controversial axioms of earlier geology, Charles Lyell's principle of uniformity, was triumphantly vindicated. The motions postulated by plate tectonics were slow and gradual and are still going on today. In part, the theoretical transformation had been made possible by new technologies allowing exploration of the deep-sea bed, revealing geological agencies that Lyell's generation had been unable to observe.

The situation is complicated by the fact that the idea of continental drift was suggested by Alfred Wegener as early as 1912 but was largely repudiated until the revolution of the 1960s. Was Wegener a pioneer of the theory that would later be accepted, and if so, why did a whole generation of geologists resist his arguments so vehemently? Or was his insight only a superficial anticipation of plate tectonics, a lucky guess that just happened to hit on one key aspect of the later theory while totally failing to anticipate the more fundamental revolution in our understanding of the earth? Wegener did not foresee the reformulation of ideas about the mechanisms going on within the crust that are integral to plate tectonics. Yet even when similar mechanisms were proposed in the 1920s, as a consequence of the new understanding of radioactive heating, the majority of geologists remained skeptical. Perhaps the fact that Wegener was himself a geophysicist, not a geologist, helps us to understand why his ideas were not taken seriously by those trained in the older way of thinking. In this case, we may want to think carefully about Wood's suggestion that the revolution was a consequence of the belated triumph of geophysics, prompted by the emergence of new techniques for studying the earth's crust.

The Crisis in Geology

Alfred Wegener was not the first to notice that the apparent "fit" between the coastlines of Africa and South America makes it look as though the Atlantic Ocean had been created by the continents being pulled apart. But he was the first to build this insight into a whole theory that sought to explain a wide range of geological phenomena in terms of continental drift. His theory was greeted with widespread skepticism, in part because he suggested no plausible mechanism by which continents could move horizontally across the earth's surface. Yet he did articulate a number of serious objections that had begun to plague the existing theories of geological change and hinted that a "mobilist" alternative might resolve these problems. In this sense, Wegener can be taken seriously as an architect of the downfall of the previous paradigm in the earth sciences, even if his anticipation of the

new theory was limited in its scope. It is worth remembering that neither Copernicus nor Kepler was able to foresee the explanation of planetary motions offered by Newton, and Wegener himself saw his drift theory as a preliminary outline that would await future vindication by a generation that would reformulate ideas about the earth's underlying structure.

To understand the crisis to which Wegener was responding, we need to go back to the theories of the earth proposed during the nineteenth century (Greene 1982). As we saw in the chapter on the age of the earth (chap. 5), the predominant theory was that the earth is cooling down, with a consequent diminution in the rate of geological activity such as earth movements. Charles Lyell's uniformitarian alternative had been resisted largely because it implied that the earth had been in a "steady state" for an uncountable period of time. Lyell had some success in persuading the catastrophists to scale down the upheavals they postulated in earlier periods, but very few abandoned the basic claim that the earth was a more violent place in the distant past. Nor was Lyell able to explain away the evidence for dramatic, if not actually catastrophic, events in the geological record. The divisions between the geological periods did indeed seem to mark punctuation marks between periods of relative calm and episodes of massive mountain building and mass extinction caused by the resulting climatic transformation. By the later part of the century, most geologists believed that these episodes were caused by relatively sudden crumplings of the crust needed to relieve the pressure built up as the interior as the earth cooled and hence reduced in volume. Even the continents themselves were formed by such large-scale warping of the crust, so even they were relatively impermanent—any part of the earth's surface might be pushed down to form ocean bed or pushed up to form continents and mountains, depending on the precise location of the weaknesses that gave way to the pressure caused by contraction. The timescale of the whole sequence was defined by how long it had taken the earth to cool from an initially molten state.

By the end of the century, many aspects of this theory had been called into question, in part by the emergence of a new approach to the study of the earth that came to be known as geophysics. This new breed of earth scientists was not interested in the geologists' efforts to provide a relative dating for the sequence of events in earth history: they wanted to understand the actual physical processes that drove the activities going on deep in the planet's interior. Lord Kelvin's efforts to work out a timescale for the earth's cooling were part of this initiative, and Kelvin was certainly interested in the processes by which heat would be conducted up to the surface. One consequence of his work was the realization that the amount of heat reaching the surface from the interior was insignificant compared to that received from the sun. So even an advocate of the cooling earth would not expect the climate to cool down, at least in the later phases.

But some of the calculations performed by the geophysicists were more serious for the prevailing theory. Most important, it turned out that even if the earth were cooling and hence contracting, the amount of contraction was not enough to produce the enormous amounts of folding and faulting observed in the crust. By the early twentieth century, the cooling-earth model itself had come under fire, as the theory of radioactive heating suggested that the internal temperature could be maintained over thousands of millions of years. The contraction mechanism of mountain building was dead, and to Wegener it seemed obvious that horizontal movements of the continents would provide an alternative explanation.

Equally suggestive was evidence coming from new studies of the actual nature of the rocks making up continents and oceans. In his *Physics of the Earth's Crust* of 1881, the British geophysicist Osmond Fisher collected evidence suggesting that the continental rocks were composed of lighter material than those from the deep ocean bed. The continents were composed mainly of silicates of aluminum (later abbreviated to "sial") while the ocean floor was mostly silicates of magnesium ("sima"). The implication was obvious: the continents are not formed by uplift from the ocean but are better visualized as rafts of the lighter sial floating on an underlying global crust of sima. This concept was built into the theory of "isostasy" proposed in 1889 by the American geophysicist Clarence Dutton. On this model, the continents floated in hydrostatic equilibrium, rising and falling as material was eroded or deposited at one point or another.

By this time, the majority of geologists had accepted that the continents were extremely ancient, but many still believed that areas of land had been sunk beneath the sea at certain points in geological time. The present continents had once been linked by "land bridges" or even more extensive areas of land, now vanished beneath the waves. These land bridges explained certain anomalies in the fossil record, including the fact that the populations of Africa and South America seemed to have been identical up to the Mesozoic era, after which they steadily diverged. The assumption was that a land bridge linking the continents had been submerged at that point. But in the model proposed by Fisher and Dutton, such land bridges were implausible—it would be physically impossible for lighter continental rock to be forced down to a level where it could form the bed of the South Atlantic or any other ocean. Continents might occasionally be invaded by very shallow seas, but they could never form deep ocean bed. Here again

Wegener was able to seize on a weakness in the existing theory that, he claimed, could be overcome by postulating a horizontal motion of the continental rafts themselves.

Wegener and the First Theory of Drift

Wegener's theory was thus an attempt to provide an alternative to a paradigm that, he was able to argue, was already defunct. The problem was that most of his contemporaries thought the new idea was even more implausible than the old. There were certainly some important lines of evidence pointing to the possibility that the continents had moved, including some that had once been used to justify the postulation of land bridges. But Wegener did not move forward to a complete reformulation of ideas about the earth's internal structure, and his theory thus lacked any plausible explanation of how the continents could be dragged across the face of the earth against the enormous frictional force that would resist any such movement. Equally serious, Wegener himself was an outsider to the community of traditional geologists. He was a meteorologist whose original interests lay in paleoclimatology (Schwarzbach [1989]; for more general discussion, see Hallam [1973]). Along with his father-in-law Wladimir Köppen he supported the theory that the onset of ice ages was triggered by fluctuations in the amount of heat received from the sun. This interest in ice ages led him to do research in Greenland, where he eventually died on an expedition in 1930. His work on continental drift was thus, in a sense, peripheral to his main career in the meteorological aspects of geophysics. Historians have argued that Wegener's lack of training in orthodox geology may have given him the flexibility of mind needed to invent a completely new idea about earth movements, but it also alienated him from the professional community of geologists, who saw him as an outsider and a dilettante.

Wegener conceived his theory in 1910 when he noticed the relationship between the coastlines of Africa and South America, and he immediately began a search of the geological literature looking for arguments that would support the idea. Two years later, he began lecturing on the topic, and his book *The Origin of Continents and Oceans* appeared in 1915 (not translated into English until 1966). The book presented an effective summary of all the evidence that had built up against the old theory of mountain building and then went on to make the case for drift as an alternative. Few now doubted that the continents could be seen as rafts of lighter material resting on a denser layer of crust exposed on the ocean bed. Wegener's point was that if the continents were somehow pushed horizontally across the surface, friction would cause the leading edge of the continental plate to crumple, thus generating mountain ranges. If America were moving away from Africa and Eurasia, this would explain the ranges of mountains that run down the western edges of both North and South America. Wegener argued that all the continents had once been joined in a single great landmass he called Pangaea, which had begun to split up in the Mesozoic (fig. 10.1). This explained why the inhabitants of South America and Africa had only begun to diverge after that point. It also explained why the early geological structure of the two areas was also very similar. The argument from the fit of the coastlines was based on more than mere geography—the actual geological formations would also be continuous if one imagined them joined together. Wegener used an effective analogy: "It is just as if we were to refit the torn pieces of a newspaper by matching their edges and then check whether the lines of print run smoothly across. If they do, there is nothing left but to conclude that the pieces were in fact joined this way" (Wegener 1966, 77). In his eyes, the evidence for a splitting apart of the continents in the Mesozoic was inescapable.

Wegener also used his knowledge of paleoclimatology to provide other lines of evidence. The fossil record suggested that many continental areas had experienced an ice age during the Permian period. This was hard to explain if the continents had then been positioned as they are today but would make sense if they had once been united to form a larger landmass located near the South Pole. The warm conditions enjoyed by other regions at the same time could be explained if they had been located in the tropics. Much less reasonably, Wegener tried to argue, in addition, that Europe and North America had also been linked in the last ice age. Since this was very recent in geological terms, this theory would imply a very rapid opening of the North Atlantic. Wegener even cited some very dubious measurements suggesting that Greenland and Europe are currently separating at the rate of ten meters per year.

Moreover, Wegener had to explain how the continents were moved across the surface, and here his efforts proved much less convincing. He still thought of the underlying crust of sima as static, so the continental rafts would have to be pushed across this surface against a tremendous frictional resistance. To make the idea seem more plausible, he argued that the crust was not absolutely rigid. Like pitch, it resisted a sudden blow but would flow gradually when subjected to a continuous pressure. But even so, the resistance to a moving continent would be enormous, and to supply the necessary pressure Wegener had only two suggestions. One was a hypothetical "flight from the poles" caused by centrifugal force stemming

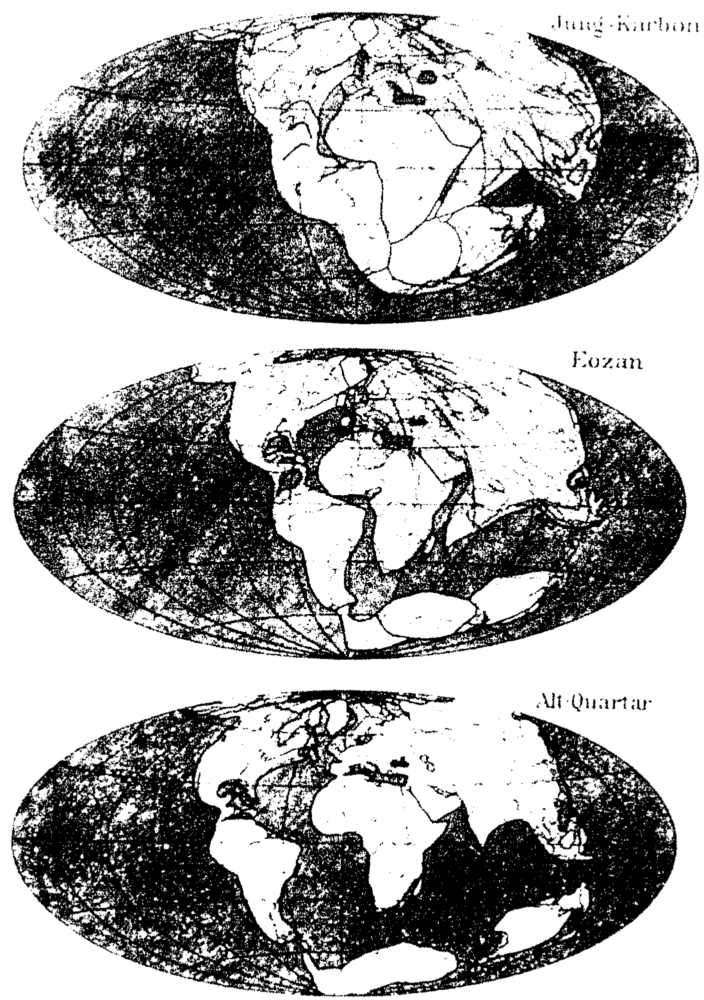

FIGURE 10.1 Alfred Wegener's maps showing continental drift, from his *Die Entstehung der Kontinente und Ozeane,* 3d ed. (1922), 4. The *upper* map shows the earth in the late Carboniferous period, with most of the land united in a single supercontinent, Pangaea. The *lower* maps show the fragmentation in the Eocene and finally in the early Quaternary period, by which time the modern distribution is becoming apparent.

from the earth's rotation. The other was a westward pressure caused by tidal forces generated by the moon. The problem was that these forces not only seem inadequate to most geophysicists but also failed to explain why Pangaea had broken up in the Mesozoic. Presumably the flight from the poles had been in effect since the continents were formed, so they should all have moved steadily to the equator and stayed there. And if the tidal force was pushing America westward, why was it having no effect on Eurasia and Africa? Wegener had seen the superficial evidence for continental drift, but he had not appreciated that to make this theory work one would have to develop a mobilist model for the whole underlying crust of the earth.

Reaction to Wegener

The response to Wegener's theory was muted at first, but in the English-speaking world it soon built up into almost universal hostility. German geologists were more sympathetic, treating the idea as potentially interesting, although in need of much further evidence if it were to be taken really seriously. In Germany, there was a tradition of theoretical work in the earth sciences done by armchair geologists who did no fieldwork of their own but, instead, assembled their evidence from the literature. In Britain and America, though, it was assumed that anyone presuming to advance a new theory must first have paid their dues in the field, so Wegener was seen very much as an outsider venturing into territory already claimed by others (Oreskes 1999). At a now notorious meeting of the American Association of Petroleum Geologists in 1926, the drift theory was widely rejected and in some cases openly ridiculed. The old idea of sunken land bridges was still used to explain the fossil evidence, despite its incompatibility with the geophysical evidence. Wegener was depicted as an uncritical enthusiast who combed the literature looking for evidence favorable to his cause, while ignoring a mass of contrary arguments. It was also felt that the theory undermined the logic of uniformitarianism because it seemed to imply that there was an arbitrary starting point for the whole process of drift in the Mesozoic.

Even the geophysicists proved hard to convince, and here the weakness of the actual mechanisms suggested by Wegener proved crucial. In his influential textbook *The Earth*, first published in 1924, the British geophysicist Harold Jeffreys argued that the forces postulated by Wegener were many orders of magnitude too small to overcome the friction that must occur if the continent were to be pushed across an underlying static crust.

A few geologists did take the theory seriously, although for several de-

cades they were voices crying in the wilderness. The Harvard University geologist R. A. Daly postulated a mechanism for drift based on the continents sliding down from a polar "bulge" in the earth's surface. Most enthusiastic of all was the South African geologist Alexander Du Toit, who appreciated the similarities between the structure of his homeland and of South America. In his 1937 *Our Wandering Continents,* he toned down some of the more excessive claims that Wegener had made about the rapidity of drift and postulated two ancient supercontinents, Laurasia and Gondwana, instead of one.

For those historians seeking to understand why a theory so close to the modern one was rejected at the time, the most interesting line of support came from the geophysicist Arthur Holmes, who had a substantial reputation based on his work on radioactive dating of the earth (Frankel 1978). Holmes calculated that the amount of heat produced by radioactivity deep in the earth was so great that some mechanism in addition to conduction was needed to bring it to the surface. Extensive vulcanism was an obvious possibility. In 1927, Holmes argued that there might be convection currents in the earth's crust, in which hot material rose to the surface while cool material was subducted into the interior elsewhere. In effect, new crust was created from molten rock over a "hot spot" and old crust destroyed by subduction, and in between the crust would move horizontally. Holmes soon realized that such convection currents would provide a mechanism for continental drift because if the continental raft floated on an area of crust in motion, it would move with it. The arguments against Wegener based on the level of friction between continent and underlying crust were undermined by this new model of what was going on within the crust itself.

Holmes suspected that hot spots would tend to build up under continents and thus fragment them by drift. He did not realize that the implications of this are that most hot spots will now be found beneath the oceans created by the breakup of the original continent. In this respect his idea did not anticipate the notion of seafloor spreading that became central to the theory of plate tectonics, yet the theory of convection currents in the earth's crust was an uncanny anticipation of later developments. Even so, no one paid any attention, and Holmes's suggestions did nothing to boost the fortunes of Wegener's theory. Historians are thus led to ask why a theory that, by this stage, had come very close to that which would be accepted in the 1960s, continued to be rejected for another generation. One suggestion is that Holmes's early version of the theory was untestable and hence could not be used as the basis for a viable research program. Even if he had realized that the place to search for hot spots was in the middle of the oceans, there were no techniques available for studying the deep-sea bed at the time. More serious, though was the continuing influence of the old geological community, which was still not willing to allow the upstart geophysicists to dictate its worldview.

Plate Tectonics

The developments that revolutionized the earth sciences in the 1950s and 1960s were in part a spin-off from military technology developed during World War II and the Cold War. The threat posed by submarines made it vital for the world's navies to know more about the deep-sea bed, and it was to the geophysicists that they turned for information. Improved instruments were developed for mapping the magnetic structure of the ocean floor, and from this emerged new insights that would transform scientists' theoretical models of the earth's crust. This would allow the idea of continental drift to enjoy a belated triumph as it rode in on the coattails of the new theory of plate tectonics. But it was not just an existing paradigm that was replaced. As a result of its new level of funding and influence, the younger science of geophysics was able to overturn the power balance that had so far kept it subordinate to traditional geology. The triumph of the new order was proclaimed by the International Geophysical Year (actually July 1957–December 1959) that brought it wide publicity even outside the scientific community. Over the next decade or more, university geology departments began to rename themselves as departments of "earth sciences," acknowledging that the subject was no longer dominated by old-style geology. The revolution that created the theory of plate tectonics was not a transformation occurring within a single discipline; it was a by-product of a newer research community's bid for control of an area that had hitherto been dominated by the older geological tradition. According to one recent study, what changed—at least for American scientists—was the definition of what counted as good science in this area (Oreskes 1999).

The most important additions to the technology available to geophysicists were those that allowed detailed study of the earth's magnetic field. There were major controversies among the physicists over the nature of magnetism and hence over the constancy of the earth's field. The British physicist P. M. S. Blackett had helped to produce an extremely sensitive magnetometer to detect magnetic mines during World War II and he now used these skills to trace minute magnetic fields locked into the rocks of the earth's crust. It was assumed that these fields were imprinted onto the rocks when they were formed, in effect providing a record of the earth's magnetic

field throughout geological time. To everyone's surprise, when details of the remnant magnetism from rocks in different areas were compared, it was clear that they were not all aligned with the current state of the earth's field or with each other. Either the rocks had moved since they were formed, or the magnetic poles had shifted. Since the remnant fields were different in rocks from different parts of the world, the most likely explanation was that the continents were no longer in the position they had occupied in earlier geological periods.

Equally puzzling was the fact that in many rocks the remnant magnetism had the reverse polarity to that now observed. Geophysicists began to suspect that the earth's magnetic field must reverse from time to time, the north and south magnetic poles swapping positions. By putting a mass of observations together it was possible to build up a timetable of these geomagnetic reversals. At the same time, more refined techniques of radiometric dating were allowing the construction of a more fine-grained timetable of rock formation through the Pleistocene era. By putting the two lines of evidence together, a team at Berkeley led by Richard Doell, Alan Cox, and G. Brent Dalrymple were able to work out a sequence for the magnetic reversals correlated with the existing geological timescale. The last reversal was pinned down from tests on rocks at Jaramillo, New Mexico, and published in 1966 (Glen 1982). It would soon play a vital role in the case for continental drift.

A parallel line of development took place in oceanography. During World War II and then the Cold War, detection of enemy submarines became of primary importance to the military. Better information about the nature of the ocean floor was crucial if concealed submarines were to be detected, and efforts were made to extend the range of the new, more sensitive magnetometers so they could produce detailed magnetic maps of the seabed. This research completely overturned expectations based on the idea of a static earth because the rocks of the seafloor turned out to be remarkably uniform and extremely recent in geological terms. Research with sonar and other techniques revealed a pattern of mid-ocean ridges, underwater mountain ranges stretching down the middle of otherwise flat seabeds. The ridges were sites of extensive seismic and volcanic activity. When rocks from the ridges were dredged up, they were found to be younger than any of the others, only recently solidified from a molten state. Here, in a totally unexpected location, were Holmes's predicted hot spots.

A leading figure in this transformation of ideas about the ocean bed was the American geophysicist Harry Hess. He had commanded a naval vessel in the Pacific war against Japan and had used its sonar system to map the

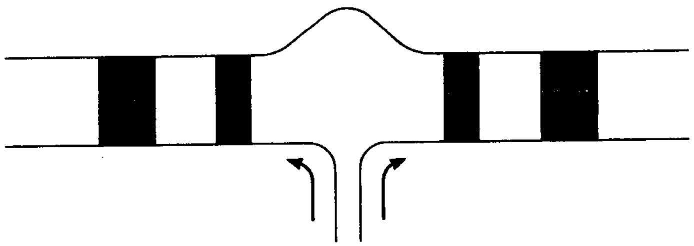

FIGURE 10.2 Cross section of the deep-ocean bed at a mid-ocean ridge, showing the effect of seafloor spreading. Hot material upwelling at the ridge spreads out equally on either side. The light and dark bands represent the magnetism of the earth's magnetic field imposed on the rock as it cools, either normal (*white*) or reversed (*black*). The effect is to produce parallel bands of normal and reverse magnetism on either side of the ridge, as shown in fig. 10.3. The continents form slabs of lighter rock lying on top of the denser, deep-ocean crust. As the crust spreads outward from the mid-ocean ridge, the continents are pushed apart.

ocean floor. In the mid-1950s he began to suggest that the mid-ocean ridges were the sites at which hot rock welled up from the interior of the earth. Here was where new crust was being produced, and the deep oceanic trenches were where old crust was being thrust down into the depths. The seabed was young because it was constantly being renewed — only the continents, riding high because of their lighter density, preserved evidence of the distant past. Holmes's theory of convection currents in the crust was right, but all the activity was taking place on the seafloor, where no one had been able to observe it before. The term "seafloor spreading" was coined by Robert Dietz in 1961.

At first Hess's ideas were greeted with skepticism, but he fired the enthusiasm of Fred Vine and Drummond Matthews of Cambridge University. They were trying to make sense of the patterns of magnetism being revealed on the seabed and were puzzled by the existence of parallel stripes of normal and reversed magnetism alongside the mid-ocean ridges. In 1963 they published a paper arguing that this pattern was exactly what would be expected if new seafloor were constantly being produced at the ridge and then forced away from it in either direction. As new rock upwelled, it would be imprinted with the current direction of the earth's magnetic field, but when the field reversed a new strip of reverse-magnetized rock would begin to form, steadily pushing the original strip further away from the ridge. The ridge should thus be surrounded on either side by a pattern of normal and reversed magnetic strips (figs. 10.2 and 10.3).

Vine and Matthews already had some evidence for this striping effect,

but it was too indistinct to convince most of their fellow geophysicists. Workers at the Lamont Geological Observatory were skeptical, and it was their survey ship *Eltanin* that was producing the best magnetic maps of the seabed. In 1965 they were surveying the region of the Juan de Fuca ridge off the west coast of North America (the notorious San Andreas Fault in California is linked to this ridge). One magnetic sweep, *Eltanin* 19, demonstrated the parallel stripes so clearly that opinion now began to shift in favor of seafloor spreading (fig. 10.4). Vine was able to show that the sharper timescale of magnetic reversals provided by the Jaramillo event fit the pattern of magnetic stripes perfectly. At the same time, the Canadian geophysicist J. Tuzo Wilson developed the concept of "transform faults," which explained why the mid-ocean ridges and their associated magnetic patterns were occasionally shifted bodily to one side or another, creating an apparent zigzag effect.

The final version of the theory of plate tectonics was worked out in the mid-1960s by Jason Morgan, Dan McKenzie, and Xavier Le Pichon. They realized that the earth's spherical shape imposed constraints on the shape of the plates defined by mid-ocean ridges and associated subduction zones, explaining many effects that were confusing when viewed on a two-dimensional map. Le Pinchon produced a simplified version of the theory in which there were six major plates, each in constant motion because it was defined by the horizontal section of a convection cell in the underlying

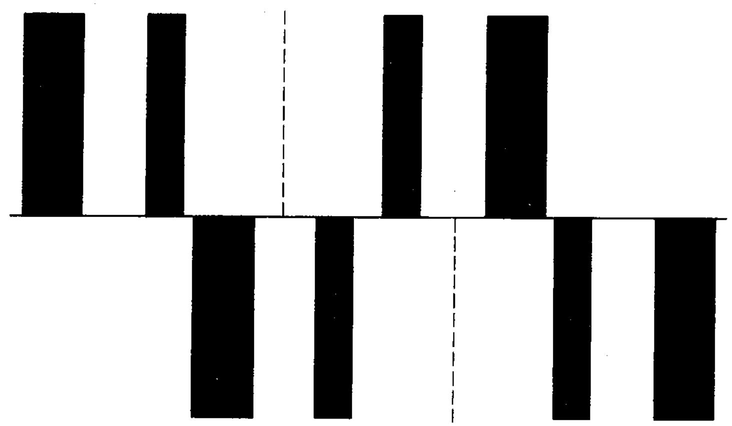

FIGURE 10.3 The parallel bands of normal and reverse magnetism produced by the process shown in fig. 10.2. The horizontal split in the middle of the pattern is a transform fault, where the whole ridge and its associated pattern of rocks are displaced at right angles to the ridge.

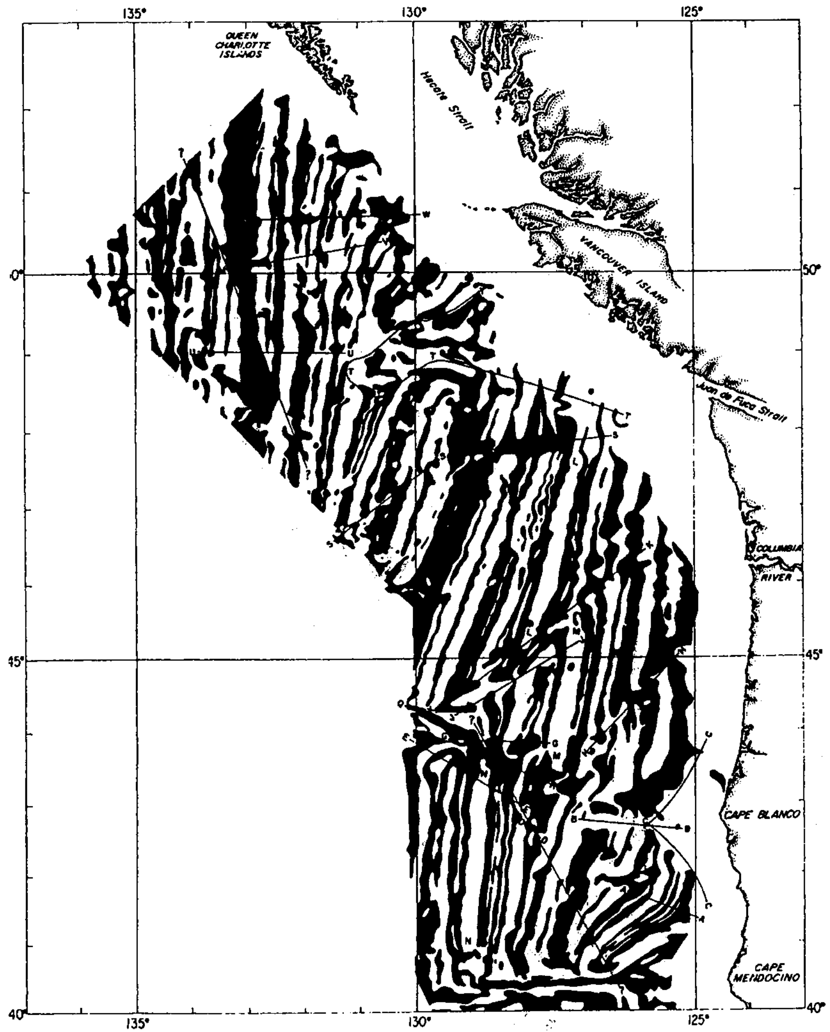

FIGURE 10.4 Map showing the magnetic anomalies on the ocean floor around the Juan de Fuca Ridge off the coast of Vancouver Island, produced by the survey vessel *Eltanin* in 1961, from R. Masson and A. Raff, in *Bulletin of the Geological Society of America* 72 (1961): 1267–70. Compare this with the idealized patterns shown in figs. 10.2 and 10.3. It was this survey that convinced many geophysicists that the hypothesis of seafloor spreading, coupled with the discovery of magnetic reversals, provided an explanation of continental drift.

crust. The continents, as in Holmes's theory, were simply carried along by the motion of the plates—America is separating from Eurasia and Africa because the Atlantic Ocean is expanding as the activity of the mid-Atlantic ridge continues to produce new crust. Mountains are formed either where a continent is riding up over a subduction zone, as in the case of the Rockies and the Andes, or where two continental masses are being forced together by the motion of separate plates, as in the Himalayas.

Conclusions

The widespread acceptance of the theory of plate tectonics in the late 1960s certainly marked a revolution in the earth sciences. Wegener's long-ridiculed idea of continental drift now made perfect sense, thanks to a complete reformulation of ideas about what was going on deep underneath the earth's crust. But this was not a paradigm shift within an established science. Orthodox geologists had focused on reconstructing the history of the earth but had not been very adventurous in seeking to explain the earth movements on which their theories relied to explain phenomena such as mountain building. It was the geophysicists who began to ask new kinds of questions about the structure of the earth and to seek new lines of evidence that would answer those questions. Although seen as junior partners by the established geological community of the late nineteenth and early twentieth centuries, they began to undermine the logic on which much of the older theorizing was based. To begin with, however, they had no serious alternative to offer, and even when the first hints of such an alternative were provided by Wegener, the geologists remained unwilling to admit that their existing ideas were vulnerable. To be fair, even some geophysicists were unimpressed, because without a much more radical rethinking of ideas about the earth's interior Wegener's idea was implausible. The revolution occurred when geophysics gained a new lease on life thanks to the oceanographic technology made available in the 1950s and 1960s. Simultaneously, the new evidence both precipitated a theoretical revolution and reduced the influence of the older community that would have been least likely to accept it.

In one sense, however, the revolution helped to reinstate a once-controversial principle of geological methodology. In the nineteenth century, Charles Lyell's uniformitarianism had gained only limited influence because few were prepared to believe that the earth was not cooling down. The massive expansion of the geological timescale made possible by the theory of radioactive heating rendered the idea of a steady state earth plausible at last. Plate tectonics reinforced this message by showing that the forces that drove the continents apart were still at work in the mid-ocean ridges today. All earth movements were slow and gradual, exactly equivalent to those we still observe. It is against this background that we must assess the later revolution of the 1980s, outside the scope of our study here, in which uniformitarianism was challenged once again by the advocates of mass extinctions caused by asteroid impacts (Glen 1994). Even if the earth's internal processes are slow and uniform, there is clear evidence of catastrophes caused by external, astronomical events. In addition, there are growing indications that vulcanism was so active at certain periods in the past that it generated environmental traumas as great as anything attributed to impacts. Modern science has been forced to take seriously some of the more alarming ideas promoted in the earliest days of catastrophism.

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