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Chapter 3

The Hypothesis of the Spreading Ocean Floor: A Synthesis

Geopoetry

As the theory of continental drift regained momentum and as progress in deep-sea geophysics directed scientists' attention toward the significance of the mid-oceanic ridges, Holmes' suggestion that the continents are carried by convection within the mantle (Chapter 1) began to seem more interesting. It was at this time that the late H. Hess of Princeton published a daring paper that attempted to establish a new concept of the earth, discarding such fixed ideas as an immovable earth or an unchanging ocean. The paper, entitled "History of Ocean Basins," was widely circulated among scholars before its publication, so that by the time it was published in 1962 its hypothesis was already widely known. In his introduction Hess stated, "I shall consider this paper an essay of geopoetry." The earth as depicted by this geopoetry is schematically represented in Figure 3-1. The mid-oceanic ridges are outlets for the substances welling up from the mantle; in other words, they are regions in which the conveyor belt, originally proposed by Holmes (page 38), is exposed on the surface. It is precisely there that the new suboceanic crust is born. This new ocean floor spreads out on both sides of the oceanic ridges, and descends again into the mantle at the oceanic trenches.

The speed of the flow of the "conveyor belt" is considered to be several centimeters per year. This means that it takes no more than about two hundred million years for the ocean floor, welling up at the

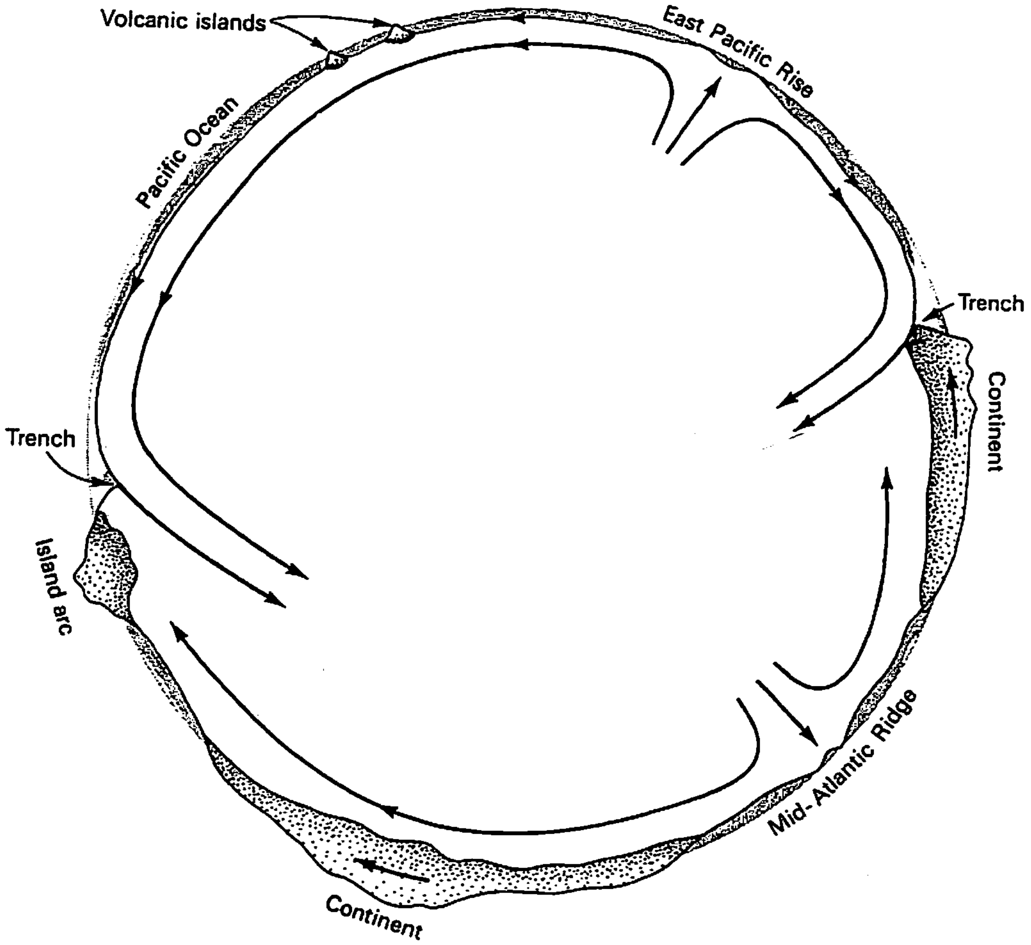

FIGURE 3-1
Schematic cross section of the earth based on the sea-floor spreading hypothesis.

mid-oceanic ridges, to move across the ocean, and sink into the oceanic trenches. It would thus appear that the ocean floor is not permanent, but is constantly being renewed. Continents, however, cannot sink as readily into the earth's interior on the conveyor belt because they are much too light. Therefore they are semipermanent. This idea explains the two riddles that had haunted marine geologists for decades: (1) Why have rocks older than 150 million years never been found on the ocean floor? (2) Why are the sediments of the ocean floor so thin? The ocean itself is several thousand millions of years old, but its floor has been continually changing!

Hess, in his paper, stressed one of his original ideas, that the oceanic crust is probably composed of serpentinized peridotite. The upper mantle is considered to be composed mainly of peridotite that contains water. It has been proved experimentally that, under high temperatures, peridotite and water are separate, but at temperatures below about 500°C, peridotite reacts with water and becomes serpentinite. Hess maintained that peridotite, ascending from the depth of the mantle, is serpentinized as it nears the surface and forms the oceanic crust at mid-oceanic ridges. When it descends into the mantle at the oceanic trenches, as it is reheated to above 500°C, water is released. Hess considered this released water to be the source of sea water.

This remarkable and now widely accepted theory is known as "sea-floor spreading," but the true originator of the idea was for a while the subject of some controversy. Shortly before the publication of the Hess paper on geopoetry, another well known American scientist R. Dietz (1961) published a similar hypothesis. Although it was Dietz who coined the intriguing term "sea-floor spreading," some debate on which man first came up with the hypothesis ensued, because the Hess paper had been read extensively before its publication. Later Dietz himself freely acknowledged Hess's priority. To me, Dietz's paper was just as enlightening as Hess's; and, in some respects, Dietz provided a clearer explanation of the hypothesis than Hess did, though perhaps with less geopoetry.

In fact, in retrospect, it seems to me that quite a number of scientists were nursing similar ideas around 1961 and 1962. This fact makes the controversy seem less important and perhaps its resolution should be left to the professional historians of science. I personally would like to see more credit go to Holmes who proposed his conveyor-belt hypothesis thirty years earlier.

Dietz, in his paper, supported the prevailing assumption that the oceanic crust is composed of basaltic gabbro, but departed from the accepted view in his assertion that the mantle is composed not of peridotite but of eclogite, which is formed from gabbro at very high pressures. Assumptions like this are made in an attempt to answer very basic questions: What is crust? What is mantle? What is the nature of the Mohorovičić discontinuity, or Moho? Opinions are still divided on these questions.

The more common view is, as explained in Chapter 1, that the Moho is the boundary between two layers of different chemical compositions, gabbro and peridotite, gabbro constituting the lower crust and peridotite the upper mantle. Another school of thought, however, holds that it is the boundary *not* between different materials, but between different *states* of the same material. It is interesting to observe that, though their models were different, both Hess and Dietz regarded the Moho as a boundary between states rather than between materials. This common point of view might have been a mere coincidence, but certainly it reminds us of our inability to answer such a basic question, "What is the Moho, which lies just a few kilometers below the sea bottom?"

Dietz attached little significance to the Mohorovičić discontinuity in the context of sea-floor spreading. He chose to call the earth's surface layer, to a depth of about 70 kilometers, the *lithosphere,* a term that had been used by earlier geologists to refer to the earth's outer layer of solid rock. Dietz regarded the lithosphere as a dynamic unit that moved as a single entity. He also maintained that underneath this layer was a slightly softer layer, the *asthenosphere,* which allowed the lithosphere to move. This argument, put forward in 1962, contained a foreshadow of the concept of plate tectonics that emerged five years later.

It Is the Sea Floor That Moves

J. Tuzo Wilson of Canada was an enthusiastic supporter of the hypothesis of sea-floor spreading. Wilson had espoused many original and startling ideas in the past, at one time supporting the theory of a contracting earth and later supporting that of an expanding earth. In the early 1960s, he began to maintain that the theory of convection within the mantle would explain many phenomena, including that of continental drift. Scholars who change their opinions too often usually lose the respect of their colleagues, but Wilson's insight and originality appear to have made him an exception. He seems to operate on the principle that everything should start as a hypothesis; once adopting a hypothesis, he pursues its consequences so thoroughly that finally some means of testing it emerges. If it stands the test, he pursues it further. If it is disproven by this process, he discards it. At this stage, usually another hypothesis has emerged to take its place.

Wilson approached the problem in this way. He proposed that—given that the Atlantic Ocean was a gigantic rift and that centers of volcanic activity were localized at or near the center of the rift—the ages of the islands scattered throughout the Atlantic, all volcanic in origin, should increase the further they had migrated from the Mid-Atlantic Ridge. Having gathered and assessed all the data available at the time (in the early 1960s), he concluded that this assumption was in fact correct. As Figure 3-2 shows, the longer the distance of an island from the Mid-Atlantic Ridge, the greater the age. For example, the island of Ascension, close to the Mid-Atlantic Ridge, is no more

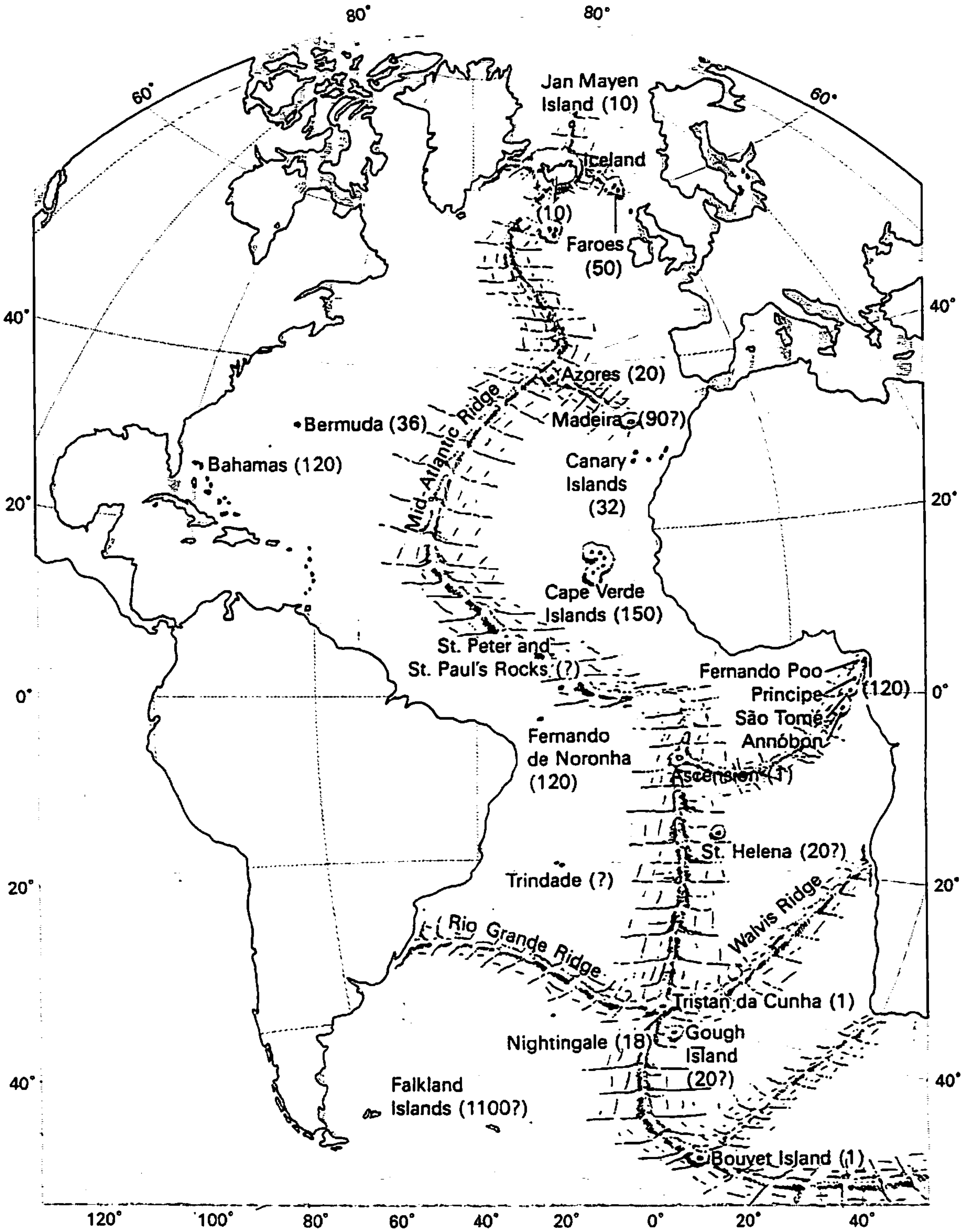

FIGURE 3-2
Ages of the Atlantic islands, as indicated by the ages of the oldest rocks found on them. The numbers in parentheses give the ages in millions of years. [After J. T. Wilson, "Continental Drift." Copyright © 1963 by Scientific American, Inc. All rights reserved.]

than a million years old, St. Helena, further from the same ridge is thought to be around 20 million years old, and the islands near the west coast of the African continent, such as Fernando Poo and Principe, are 120 million years old. This pattern coincides beautifully with the assumption, based on the theory of continental drift, that the Atlantic began to form during the Jurassic period about 200 million years ago. A similar examination of the chains of volcanic islands in the Pacific (see Figure 2-2) reveals that they too conform to this pattern, having gradually migrated from their points of origin. For example, the islands of the Hawaiian Archipelago, which line up northwest of the Island of Hawaii, have been shown to increase in age northwestward. The magma source for this archipelago is believed to be not a ridge but the point at which the Island of Hawaii is presently located. This source is an example of a "hot spot," which will be described in Chapter 5.

As these and other pieces of evidence accumulated, the concept of "the moving sea floor" gradually gained general acceptance. Wilson once pointed out, "If indeed the Earth is, in its own slow way, a very dynamic body, and we have regarded it as essentially static, we need to discard most of our old theories and books and start again with a new viewpoint and a new science."*

The Riddle of the Striped Patterns

One of the significant events in marine geophysics during the late 1950s was the discovery of the striped patterns of geomagnetic anomalies on the ocean floor and their offsets, discussed in Chapter 2. Why these spectacular striped patterns existed at all, however, was still unknown. The anomalies are 20 to 30 kilometers wide and hundreds of kilometers long with an amplitude of several hundred gammas.† We have seen that the source or cause of a magnetic anomaly may be either a current flowing in the earth's core or a body of magnetic rock within some 50 kilometers of the earth's surface. In order for the striped anomalies to be produced, the sources would have to lie directly beneath the striped belts—probably at a shallow depth; if the source were deep, the surface anomalies would not be as distinct as observed. Thus it seemed likely that the source consisted

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*J. Tuzo Wilson, "A Reply to V. V. Beloussov," *Geotimes*, December 1968, p. 22.

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†The gamma is a unit used in measuring the geomagnetic fields. The geomagnetic field in Tokyo is about 46,000 gammas and that in New York about 57,000 gammas.

of long, linear bodies of magnetic rock. One possibility was that the positive anomalies, where the field was unusually strong, were underlaid by prisms of strongly magnetized intrusive or volcanic rocks, whereas the negative anomalies, where the field was weak, were underlaid by steep-walled valleys filled with sediments, which are only weakly magnetic. Yet no one was really able to explain the origin and nature of the rocks that had caused the stripes, or even able to prove that such sources existed.

In 1963, two young British scientists, F. Vine and D. Matthews came up with an enlightening explanation. They proposed that the pattern of magnetization in the crust that causes the anomalies to be striped is due not to variations in the *intensity* of magnetization, but to changes in the *direction* of that magnetization. Beneath the positive anomalies the rocks are *normally* magnetized in a direction parallel to the present field. Beneath the negative anomalies the rocks are *reversely* magnetized in the opposite direction. They further maintained that this phenomenon calls for *no* new hypothesis. According to Vine and Matthews, the striped pattern of geomagnetic anomalies is a logical consequence of the combination of two fundamentally important but independently established phenomena—first, the spreading of the ocean floor that wells up at the crest of the mid-oceanic ridges and, second, the changes in polarity of the geomagnetic field, which reverses every several hundred thousand years or so (see the discussion on geomagnetism, page 30). Let us examine this hypothesis in further detail.

According to the sea-floor spreading hypothesis, magma from the hot mantle, as it ascends to the oceanic ridge to form the new ocean floor, cools through its Curie point. This is the moment at which the newborn crust is magnetized in the direction—either normal or reversed—of the geomagnetic field prevailing at that particular period or epoch. As the ocean floor slowly spreads away from the oceanic ridge, it is inevitable that a strip of ocean floor formed during a normal polarity epoch will be adjacent to a strip in which the magnetization is reversed, producing in a striped pattern. The spreading ocean floor—likened by Holmes to a conveyer belt—can now be described as a type of tape recorder as well. The oceanic crust ascending from the mantle is the magnetic tape that records the history of geomagnetic reversals.

L. Morley of Canada published an identical but independently developed explanation for the striped pattern of magnetic anomalies at almost the same time as Vine and Matthews. It is now fairly well known among earth scientists that Morley's paper, which had been submitted earlier to leading British and American scientific journals, was rejected at the time as being too speculative. It is a sad story. In all fairness, perhaps the hypothesis should be called the Vine-Matthews-Morley hypothesis.

The Ocean Floor as a Tape Recorder

The idea of a spreading ocean floor as proposed by Hess, Dietz, Wilson, and others, although it appealed to many scientists, was originally regarded with some suspicion. The reason was probably that so simple an explanation of such a complex set of natural phenomena tends to invite skepticism. It seems that there are always people who unconsciously think (and perhaps even hope) that nature is too complicated to be explained by a simple idea. The Vine-Matthews-Morley hypothesis—an attempt to explain the striped pattern of magnetic anomalies on the basis of a combination of two hypotheses that were themselves questionable—was also shunned at first by many scientists. The depressing fate of Morley's paper shows how widespread this rejection was. However, the skepticism was overcome in 1966 when a great many findings in support of these new concepts were reported that same year.

Vine reported that he and Wilson had succeeded in interpreting the magnetic anomaly lineations within the framework of the tape-recorder model—not only qualitatively, as Vine and Matthews had done, but also quantitatively. Vine assumed that the speed with which the ocean floor spreads from a given ridge remains constant. Given this constant rate, the width of each magnetic stripe on the ocean floor should be proportional to the length of the duration of each normal and reversed polarity epoch. This quantitative relationship between the known reversal time scale and the width of the magnetic stripes convinced a number of scientists that the idea of sea-floor spreading did indeed have some validity.

How did Vine arrive at his remarkable conclusions? For one thing, he had some very useful and reliable data to work with. A. Cox, R. Doell, and B. Dalrymple had by 1966 worked out the history of geomagnetic field reversals for the past four million years. Using the potassium-argon method,* they had dated magnetic rocks from all

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*This method of determining the absolute age of rocks is based on the following. The radioactive potassium isotope, K^{40}, contained in rocks, disintegrates into the argon isotope, A^{40}; it has a half life of 1.42×10^8 years. Therefore, if the amounts of K^{40} and A^{40} now existing in a rock are determined, the date when A^{40} began to accumulate can be inferred. This date is considered to be the age of the rock.

over the world and had determined exactly how many millions of years ago different geomagnetic field reversals had occurred. Anyone who was a regular visitor to the laboratory of Cox and his colleagues during that period would find that the history of geomagnetism was continually being unraveled, for something new invariably awaited each visit. Figure 3-3a shows the chronology of these geomagnetic field reversals as they were determined from the paleomagnetic research on volcanic rocks on land. In this figure, the center indicates the present time, and the dates on either side, from the most recent to the oldest, are given in units of a million years. The periods during which the polarity was fixed were called *epochs* by Cox and his colleagues, and each epoch was named after one of the pioneers of geomagnetism. The present epoch is called the Brunhes normal epoch, after the French scientist who, as early as 1906, postulated the possibility of the reversal of the geomagnetic field in the past. The preceding epoch, ending about 700 thousand years ago, is called the Matuyama reversed epoch after the Japanese scientist M. Matuyama, mentioned in Chapter 1. Cox and his colleagues also found that, superimposed on the normal and reversed epochs, there were short intervals of less than about 100 thousand years, during which the polarity was opposite from that of the epoch in which they occurred. These intervals are called *events* and are named after the localities in which the evidence of their existence was first discovered. For instance, one of the events is named Olduvai—after the gorge in Africa so well known as the site of spectacular anthropological findings.

Vine undertook the task of comparing the observed profiles of striped magnetic anomalies with the reversal time scale. Assuming reasonable rates for ocean-floor spreading, he came up with the excellent agreement demonstrated by the two curves in Figure 3-3b. The upper curve represents the profile of geomagnetic anomalies that has been theoretically calculated from the model sea floor as shown in Figure 3-3c. This model sea floor was constructed on the basis of (1) the history of geomagnetic field reversals, as demonstrated by Cox, Dalrymple, and Doell (1967), and (2) the theory of sea-floor spreading with a reasonable speed assumed for the rate of spreading. The lower curve is the observed anomaly profile of the East Pacific Rise. It is hard to imagine that the agreement between the computed and the observed profiles is accidental. Similar agreement has been demonstrated for other oceanic ridges such as the Reykjanes Ridge south of Iceland, the Mid-Indian Ridge, and some Antarctic ridges. Although the degree of agreement varies from ridge to ridge, it is usually possible to identify all of the longer epochs. Knowledge of the precise chronology of the geomagnetic field reversals has enabled us to de-

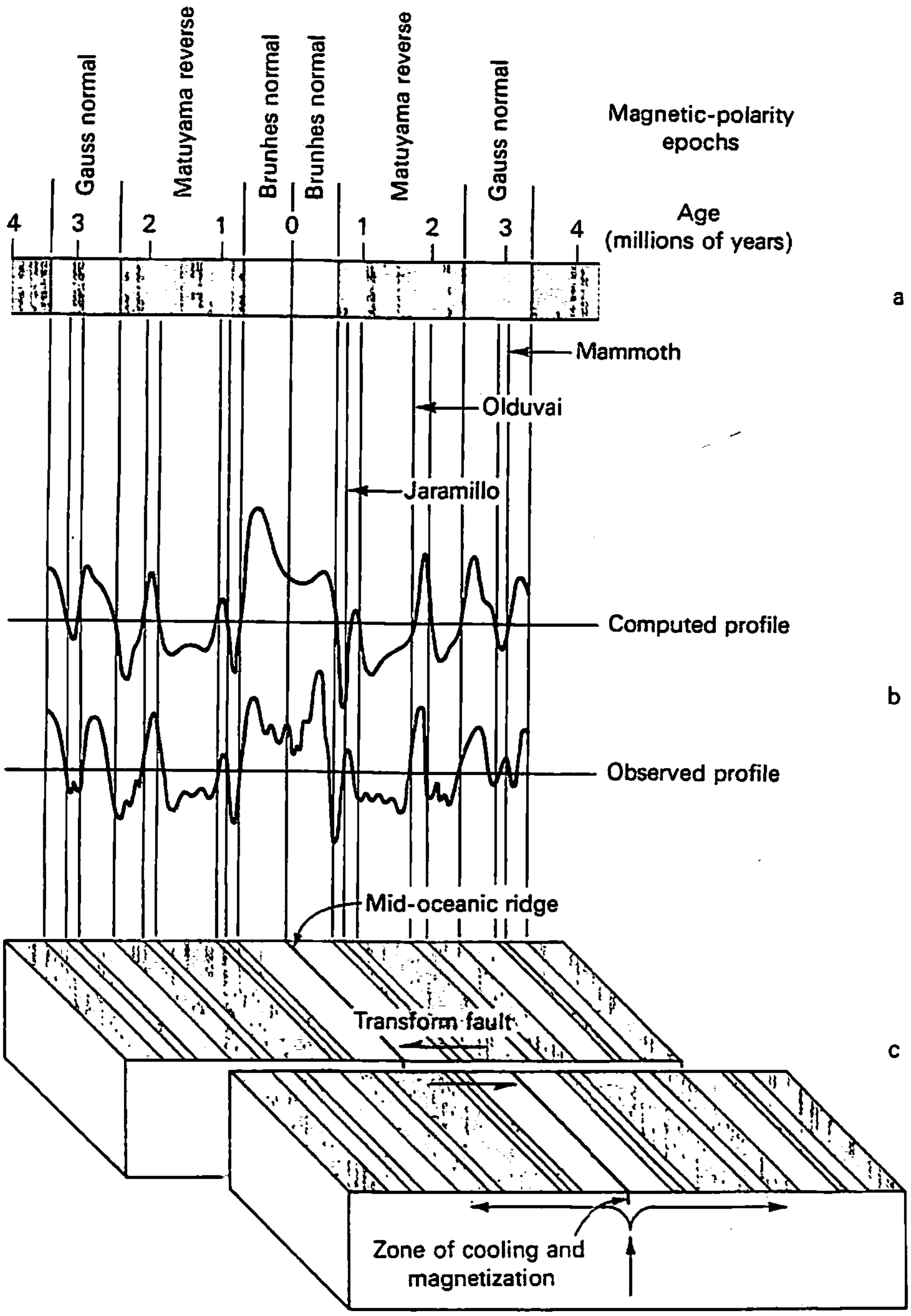


FIGURE 3-3

(a) The geomagnetic polarity epochs and events. Ages are given in millions of years. [After A. Cox, B. Dalrymple, and R. Doell, "Reversals of the Earth's Magnetic Field." Copyright © 1967 by Scientific American, Inc. All rights reserved.]

(b) Comparison of the observed geomagnetic anomaly profile Eltanin-19 (lower curve) with the computed profile (upper curve) for the East Pacific Rise. [After F. J. Vine, "Spreading of the Ocean Floor; New Evidence." *Science* **154** p. 1405. Copyright 1966 by the American Association for the Advancement of Science.]

(c) Model sea floor with the magnetic anomaly stripes produced by the Vine-Matthews-Morley mechanism. A fracture zone, represented by the displacement zone of the two blocks, cuts the ridge and the magnetic stripes, producing a transform fault (see page 74).

termine the absolute rate of the speed of sea-floor spreading. According to Vine and Wilson, the spreading rate is 4 to 5 centimeters per year for the East Pacific Rise, and about 1 centimeter per year for the Reykjanes Ridge. At the end of 1966 Vine published a masterful paper that left little room for doubt about the origin of the magnetic stripes and the rate of sea-floor spreading. Subsequently Vine was asked at a symposium whether he had checked his results statistically. "I never touch statistics," he answered, displaying his total confidence in his work, "I just deal with the facts."

By the end of 1966, J. Heirtzler, W. Pitman, and their colleagues at Lamont-Doherty Geological Observatory had accepted the interpretation of Vine, Matthews, and Wilson, and were beginning to use the width and spacing of the magnetic stripes to determine the rate of sea-floor spreading. In fact, the Lamont-Doherty group and Vine worked on the same anomaly profile across the East Pacific Rise taken by the National Science Foundation ship *Eltanin*—the now classical *Eltanin*-19 profile shown in Figure 3-3b—and both groups arrived at the same velocity of sea-floor spreading. The use of magnetic stripes to measure spreading velocities quickly transformed a speculative idea unworthy of publication into an established technique.

Yet another remarkable report was made in the same year. It was on the research on the remanent magnetism found in sea-floor sediments. Remanent magnetism exists within the sedimentary strata of the ocean floor. As fine particles of magnetic minerals—minute magnets—are deposited on the ocean floor, they tend to settle down, with their magnetization directions aligned with the prevailing geomagnetic field. This gives rise to the remanent magnetism of sediments. However, measurement of the direction of magnetization of ocean sediments is difficult because the magnetization is very weak. Also the sediments are soft and difficult to handle. Scientists at Cambridge University and the Scripps Institution of Oceanography had been attempting to take these measurements since 1957, but without much success. Finally, in 1966, N. Opdyke, B. Glass, and others of the Lamont-Doherty Geological Observatory succeeded in measuring the remanent magnetism in samples from the Antarctic and the North Pacific Oceans with spectacular results. Since sedimentation on the ocean floor is an extremely slow process, a continuous history of geomagnetism during the past several million years can be obtained by measuring the magnetization of sedimentary material only some 10 meters below the sea bottom. The sample material for the measurement, or core sample as it is called, is taken

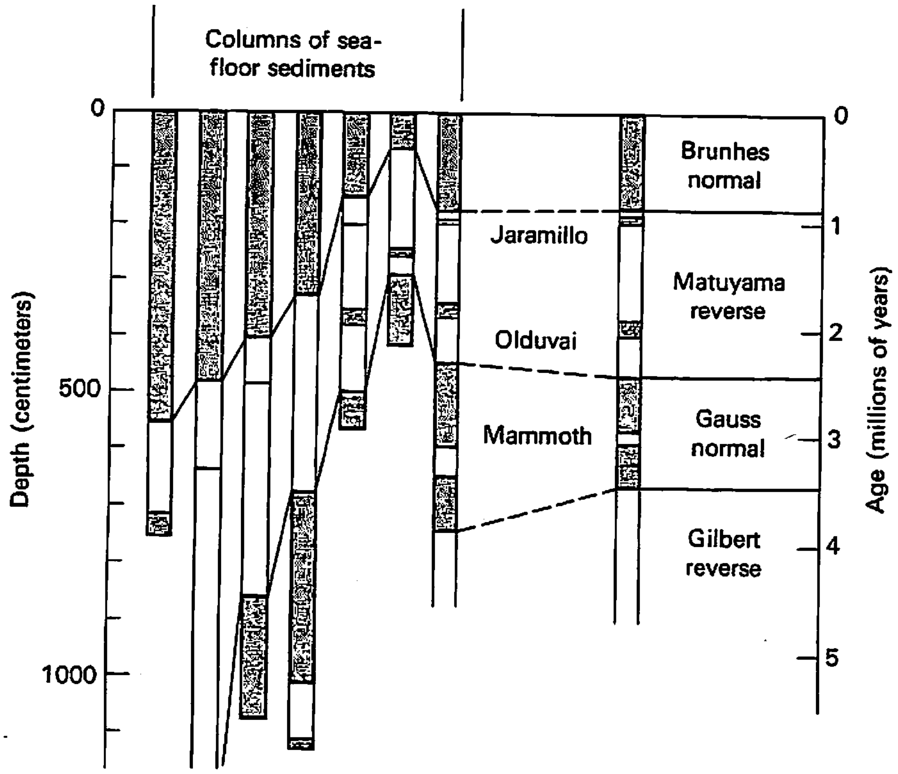


FIGURE 3-4
Normal and reverse magnetization of ocean sediments. The shaded areas in the columns represent normal magnetization; the white areas represent reverse magnetization. [After N. D. Opdyke, B. Glass, J. D. Hayes, and J. Foster, "Paleomagnetic Study of Antarctic Deep Sea Cores." *Science* **154**, p. 349. Copyright 1966 by the American Association for the Advancement of Science.]

from the ocean floor in the form of a vertical column by a pipe, called a corer, which is driven into the sediment. The results from such samples (diagrammed in Figure 3-4) distinctly demonstrate the alternation of normal and reversed magnetization. The major epochs are revealed by these measurements and even some of the events, but the events are not recorded consistently because the sediments are sometimes disturbed by burrowing organisms.

These results have justified the development of a new field of geology known as paleomagnetic stratigraphy. Precise identification of strata can now be accomplished by the examination of the direction of remanent magnetism, another valuable technique for dating rocks. Thus the history of geomagnetic field reversals was established quantitatively through three independent phenomena—the remanent magnetism of volcanic rocks from all of the continents, the magnetic stripes of the ocean floor, which are several tens of kilometers in width and several hundred kilometers in length, and the feeble remanent magnetism of ocean sediments collected from a stratigraphic thickness of 10 meters or less. The remarkable agreement of the results obtained from these three lines of investigation has established conclusively that the ocean floor is a high-fidelity magnetic tape recorder.

The Transform Fault— A Concept of Great Originality

As mentioned toward the end of Chapter 2, Vacquier and his colleagues discovered spectacular offsets, or displacements, in the geomagnetic stripes off the west coast of North America. These offsets profoundly impressed other scientists because they appeared to signify that large-scale displacements between adjacent segments of the ocean floor—some as large as 1000 kilometers—had taken place. Keeping in mind the cause of the striped pattern as explained by Morley, Vine, and Matthews, let us now examine the reason for the offsets of the magnetic stripes. Do these offsets really represent the slippage of adjacent segments of the oceanic crust?

It was J. Tuzo Wilson (1965) who proposed the following interpretation. He suggested that these offsets were not ordinary "transcurrent" faults but an entirely new type of fault, which he called a "transform fault." Figure 3-5 illustrates the difference between the two. In a transcurrent fault (a), the blocks on either side of the fault move in the directions of the arrows, thus causing the whole structure—the mountain range in Figure 3-5a, for example—on either side of the fault to be displaced. This type of fault is widely observed on land and had been the conventional explanation of the observed displacement of magnetic stripes and of oceanic ridges. In the transform fault (Figure 3-5b) the displacement bb′ of the mid-oceanic ridge, ab and b′c, does not appear to differ from the displacement caused by the transcurrent fault. But in the sea-floor spreading hypothesis, the mid-oceanic ridges are viewed as dynamic rather than static because the new ocean floor is constantly flowing forth and spreading in the direction of the arrows. If we accept this concept, then it becomes apparent that the transform fault is quite different from the ordinary transcurrent fault. First of all, in the transcurrent fault displacement BB′ will increase with time as the faulting activity continues; however, if we consider the mid-oceanic ridge sections ab and b′c to be producing sea floor with equal speed, the displacement

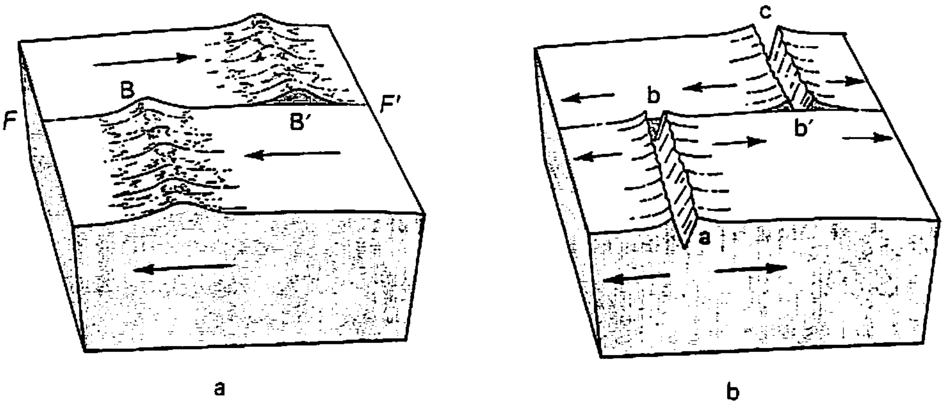


FIGURE 3-5
Two types of faults: (a) transcurrent fault; (b) transform fault.

bb′ will not change at all. Moreover, the displacement between the blocks on either side of the fault occurs only along the portion bb′; in the portions outside bb′ no displacement occurs across the fault. This has an important implication for seismology. If earthquakes are caused by displacement between blocks on opposite sides of a fault, they will occur along the entire length, FF′, of the fault in the transcurrent fault (Figure 3-5a), but only along the length bb′ between the ridges in the transform fault (Figure 3-5b). Furthermore, whereas the *apparent* displacement of the ridge axis is in the same direction in each type, the actual direction of movement across the fault is different. If it is a transcurrent fault, and you are standing on the south side of the fault, the earth on the opposite side is moving to your *right*. If it is a transform fault, however, and you are standing on the south side of the fault between the ridges, the earth on the opposite side is moving to your *left*. Wilson realized that the faults that commonly sever mid-oceanic ridges would have to be of the transform type (see Figure 3-3c). Figure 3-5 illustrates a fault only between one oceanic ridge and another, but faults can also exist between an oceanic ridge and a trench, or between two trenches.

Wilson's significant insight about transform faults occurred because he found it very hard to believe that a large-scale fault causing an apparent displacement of a thousand kilometers could be a transcurrent fault. Indeed, he found it inconceivable because there was no explanation for the disappearance, at the ends of the fault, of the crustal rocks on either side of it. Where do the displaced portions go? They can't simply vanish without violating the law of conservation of matter. Wilson found that fracture zones, which had long been

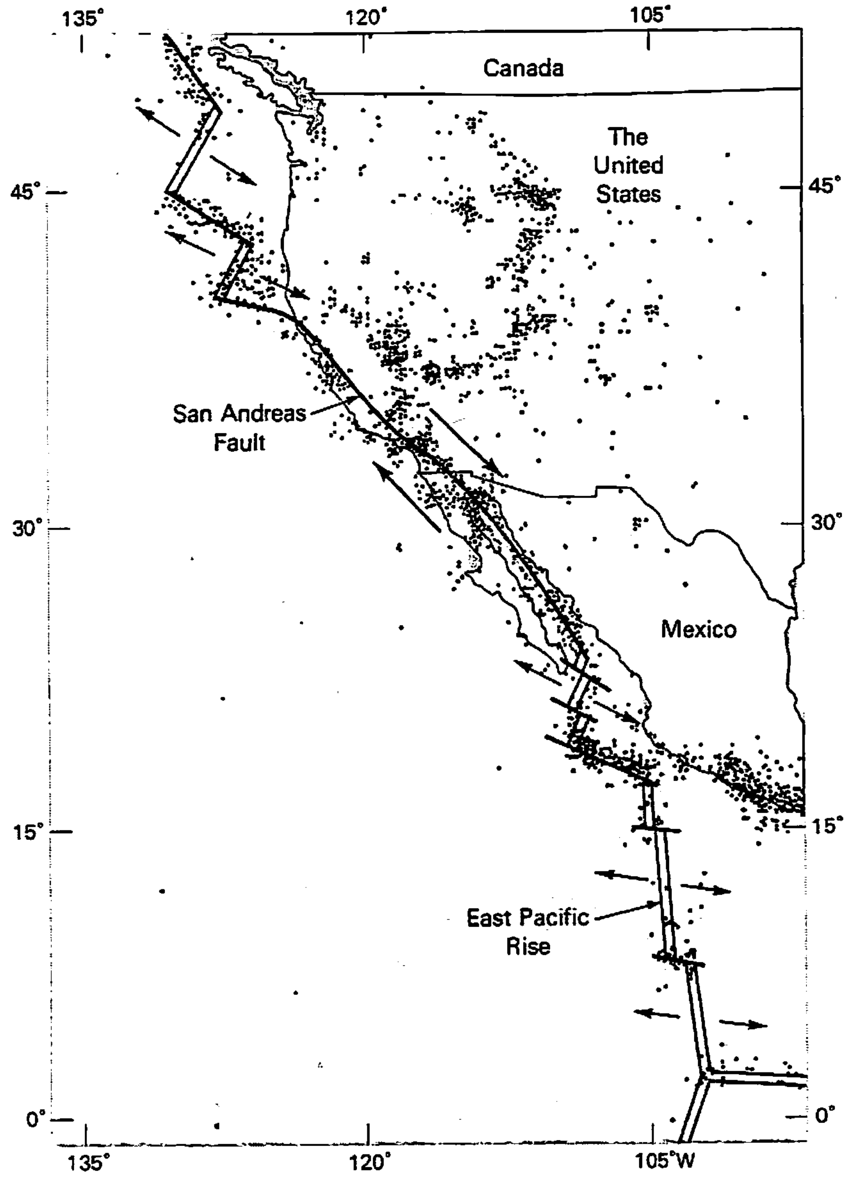


FIGURE 3-6
The San Andreas Fault as a transform fault. The double line represents the spreading ridge; the thick line, the transform fault. The shorter arrows on opposite sides of the East Pacific Rise show the movement of blocks on opposite sides of the rise *away* from each other. Along the San Andreas Fault the long arrows show the movement of the two sides of the fault past each other. The dots designate the earthquake epicenters.

known to oceanographers, provided the key he needed to answer these questions. Between offset ridges, the fracture zones mark the trace of still active transform faults. Away from the offset ridges the fracture zones are no longer active but are scars marking the trace of former transform faults.

The concept of transform faults suggested the possibility that the famous San Andreas Fault (Figure 3-6) might be such a fault. The occurrence of earthquakes on the East Pacific Rise suggested to Wilson that this was a mid-oceanic ridge from which the sea floor was diverging. The East Pacific Rise extends into the south end of the Gulf of California, and the San Andreas Fault emerges from the north end of it. The San Andreas Fault is known for the presence of shearing motion parallel to the fault rather than tensile motion diverging away from the fault. Why should the tensile forces in the East Pacific Rise suddenly change into the horizontal shearing forces of the San Andreas Fault? This question had long been an enigma to scientists. If the San Andreas Fault were considered a transform fault, however, Wilson showed that this enigma could easily be explained as demonstrated in Figure 3-6. To complete his explanation, Wilson needed another mid-oceanic ridge at the north end of the San Andreas transform fault. To prove the actual existence of such a fault, Vine and Wilson began scrutinizing the pattern of geomagnetic anomalies off Vancouver Island. One can imagine their elation when they discovered the symmetry in the geomagnetic stripes between the axes of the two shown in Figure 2-8. Profiles of geomagnetic anomalies across these axes showed an almost perfect agreement with the history of geomagnetic reversals, based on the assumption that the speed of sea-floor spreading is 2.9 centimeters per year. The topographic high along BC in Figure 2-8 was named the Juan de Fuca Ridge, and that along DE the Gorda Ridge.

Wilson once told me that he hit upon the idea of the transform fault while he was cutting out a model of a spreading mid-oceanic ridge from a piece of paper. It should be noted here that this idea occurred to him only after he had carefully examined an enormous amount of data that had already been compiled. Thus although it was his acute insight that brought the immense past efforts of other scientists to fruition, the accomplishment of Vacquier and his colleagues, who produced accurate data on geomagnetic anomalies, must not be overlooked. Their data proved to be most valuable for checking the validity of many theoretical inferences.

Verification of the Transform Fault

The direction of faulting can be estimated from the analysis of the initial motion of earthquake waves generated by the faulting. Earthquakes occur when a fracture takes place within the earth's interior,

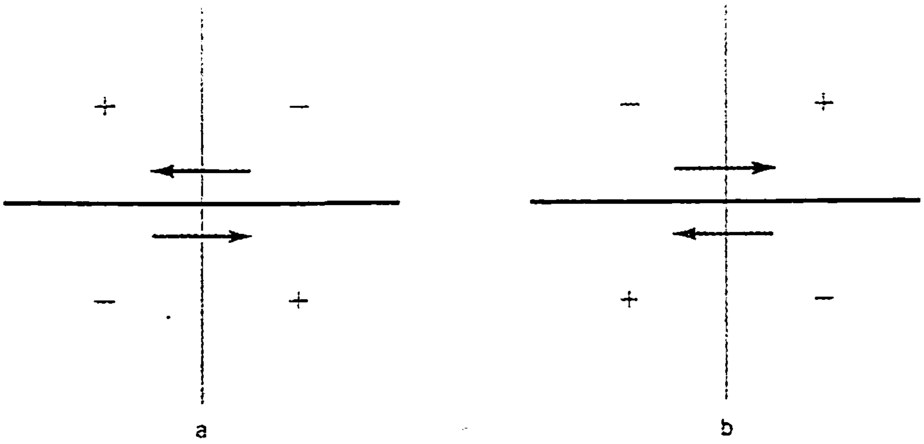


FIGURE 3-7
Radiation patterns for initial P-wave motions. The faults are shown by the thick lines, and the arrows indicate the direction of faulting. In regions marked (+), the initial motion is away from the source; in regions marked (−), it is toward the source.

which causes elastic waves to be generated. By analyzing the direction of the initial motion of an earthquake wave, with the aid of seismometers placed around the epicenter, seismologists can estimate the direction of the forces along the fault that has caused the earthquake. This is called the study of earthquake-source mechanisms and was developed by J. Shida and H. Nakano in Japan and P. Byerly in the United States in the 1910s to 1920s, and in the 1930s by H. Honda in Japan.

If faulting occurs in the direction shown in Figure 3-7a the initial motion of the P wave (see Figure 1-4a) radiated by the faulting pushes the matter away from the source in the regions designated by a plus sign, and in those marked with a minus sign, the motion pulls the matter toward the source. If the direction of the faulting is reversed, as in Figure 3-7b, the radiation pattern is naturally reversed. By examining the mechanism of the earthquake source and then analyzing the direction of faulting, one should be able to deduce whether the fracture zone offsetting an oceanic ridge is a transform fault or not. In other words, one needs only to decide whether the actual faulting that takes place when earthquakes occur on the fracture zone is in the direction shown in Figure 3-5a or Figure 3-5b.

The progress that has been made in this field of study is due in great part to the data gathered by the World Wide Standard Seismograph Network (WWSSN), which the United States has set up throughout the world. After World War II, both the USSR and the

United States immensely improved their seismometer networks in order to be able to detect underground nuclear explosions. As a result, the field of seismology in both countries has made great progress. Actually, such seismological observation systems are contributing mostly to pure seismological studies rather than to the detection of nuclear explosions. The seismological data on oceanic ridges throughout the world, gathered for the first time by such a standardized observation system, provided L. Sykes of the Lamont-Doherty Geological Observatory with much of the material for his research in earthquake-source mechanisms.

It was already known that earthquakes in fracture zones occur only in the zone of displacement represented by bb′ in Figure 3-5b—a fact that in itself strongly supports the concept of a transform fault. Sykes sought to clarify further the source mechanism of earthquakes in fracture zones. The result of his study was reported in 1966. It verified Wilson's prediction perfectly. For earthquakes that occurred along fracture zones between ridges, the direction of the faulting agreed with that predicted by Wilson without exception. The earthquakes that occur at the crests of oceanic ridges, according to Sykes, generate the waves one would expect from faulting caused by tensile forces as the two sides diverge from the ridge. It is hard to imagine a more direct or convincing proof of Wilson's theory of the transform fault.

"Annual Rings" on the Ocean Floor: A Challenge to Geology

Supported by the Vine-Matthews-Morley hypothesis, which explained the striped geomagnetic anomaly pattern on the ocean floor, and by much additional evidence, the sea-floor spreading hypothesis became firmly established in the mid-1960s. It was at the Lamont-Doherty Geological Observatory that significant contributions to this development were made, for there, awaiting analysis and interpretation, were the results of decades of magnetic surveys covering all the oceans of the world. J. Heirtzler, W. C. Pitman, and others at the observatory undertook the arduous task of analyzing these data with computers. Soon, the geomagnetic anomaly profiles of all the earth's oceans had been systematically organized to provide a comprehensive description of the chronology of the sea floor.

The chronology of geomagnetic field reversals that can be deduced from paleomagnetic studies on land rocks covers only about four

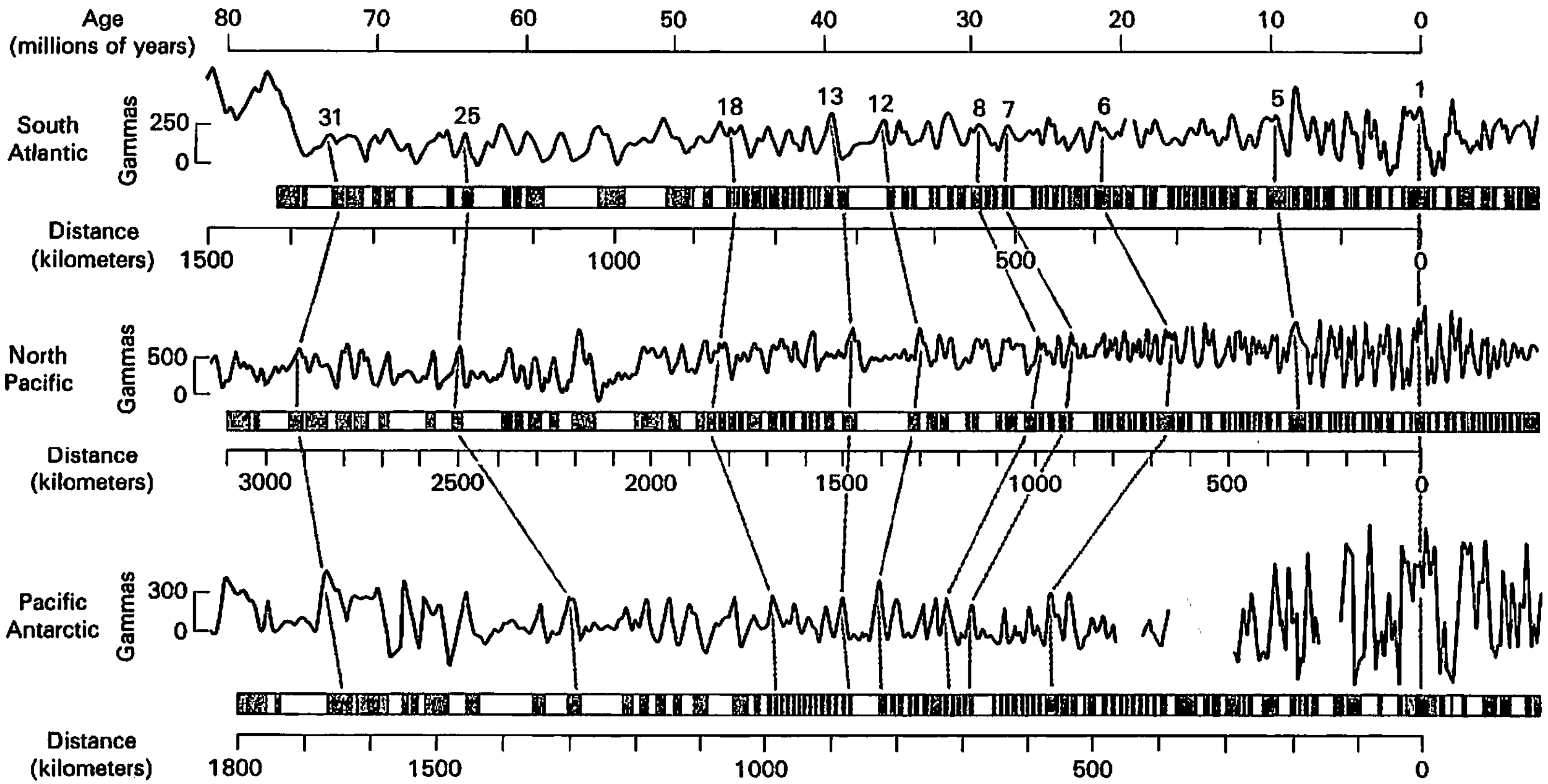


FIGURE 3-8
Geomagnetic anomaly profiles recorded over the floors of three oceans by ships traveling in a direction perpendicular to the mid-oceanic ridges. Note the similarity of the profiles, especially of the numbered peaks, which have easily recognizable shapes (each number refers to a particular lineation). The light and dark stripes along the horizontal bar beneath each profile indicate the succession of normally and reversely magnetized bodies of volcanic rock running parallel to the ridge. The spacing between magnetic bodies varies in each ocean because the spreading rates have been different (the rate in the South Atlantic is believed to have been the most constant), but each ocean has the same sequence of 171 reversals that extend back 76 million years, covering the entire Cenozoic period. [After J. R. Heirtzler et al., "Marine Magnetic Anomalies, Geomagnetic Field Reversals, and Motions of the Ocean Floor and Continents." *J. Geophys. Res.* 73, p. 2119, 1968. Copyrighted by American Geophysical Union.]

million years, and contains only several epochs of geomagnetic reversals. However there are dozens of magnetic stripes across the sea floor. How, then, were we to infer the chronology of geomagnetic stripes prior to the past four million years? Heirtzler and his colleagues set out to estimate it by assuming that the rate of sea-floor spreading had been constant in the South Atlantic. As exemplified for three oceans in Figure 3-8, the geomagnetic profiles of the different major oceans showed a similar sequence of peaks and troughs for each. Many of the peaks and troughs were found to be common to all the oceans. Some of the peaks that were distinctive enough to be recognizable almost everywhere were then numbered to facilitate comparison of different profiles. Scientists at Lamont-Doherty were able to trace the magnetic anomaly profiles as far back as 76 million years ago (Figure 3-9). They found that in the course of this time 171 geomagnetic field reversals had occurred. Once this method of estimating the geomagnetic time scale proved workable, the age of the ocean floor, wherever the floor displayed the striped geomagnetic anomaly pattern, could be traced as far back as one wished. The striped pattern, in other words, provides "annual rings" for the ocean floor. (Of course, on the ocean floor, each stripe represents growth that has taken place, not in the course of a single year but during periods of time varying from 20,000 to several million years.) Heirtzler's assumption that the rate of sea-floor spreading in the South Atlantic had been constant was subsequently supported by the evidence gathered by the Deep Sea Drilling Project (DSDP), to be described in the next section of this chapter.

By measuring striped patterns across the entirety of the vast spread of the ocean floor, it is possible in principle to construct magnetic lineations, or *isochrons*—which connect those points of the crust having the same age. The result is a geological map of the ocean floor. A geological map of the land may be more detailed in its description of such items as the nature of the rocks, but the mapping depends largely on the hammers, other manual equipment, and sheer physical endurance of large numbers of geologists who are dedicated to the step-by-step examination of the earth. By contrast, the geological mapping of the ocean floor can be done rapidly by research vessels with magnetometers trailing behind them. The results of such surveys are shown in the up-to-date compilation of marine magnetic findings plotted in Figure 3-10. The shaded areas represent those portions that Heirtzler and his colleagues succeeded in plotting as early as 1968. Explanations of lineations outside the shaded areas will be given in Chapter 4.

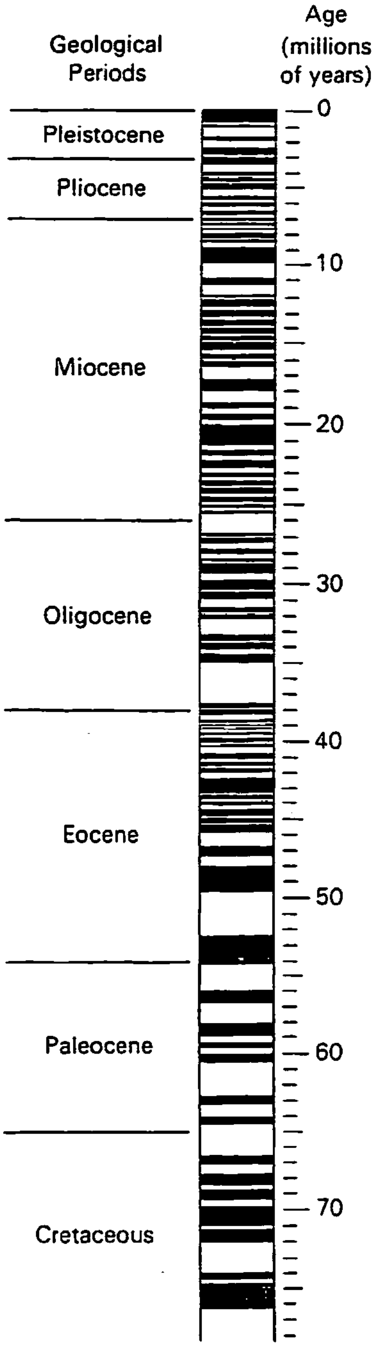


FIGURE 3-9
The chronology of geomagnetic field reversals for the past 76 million years. [After J. R. Heirtzler et al., "Marine Magnetic Anomalies, Geomagnetic Field Reversals, and Motions of the Ocean Floor and Continents." *J. Geophys. Res.* 73, p. 2119, 1968.]

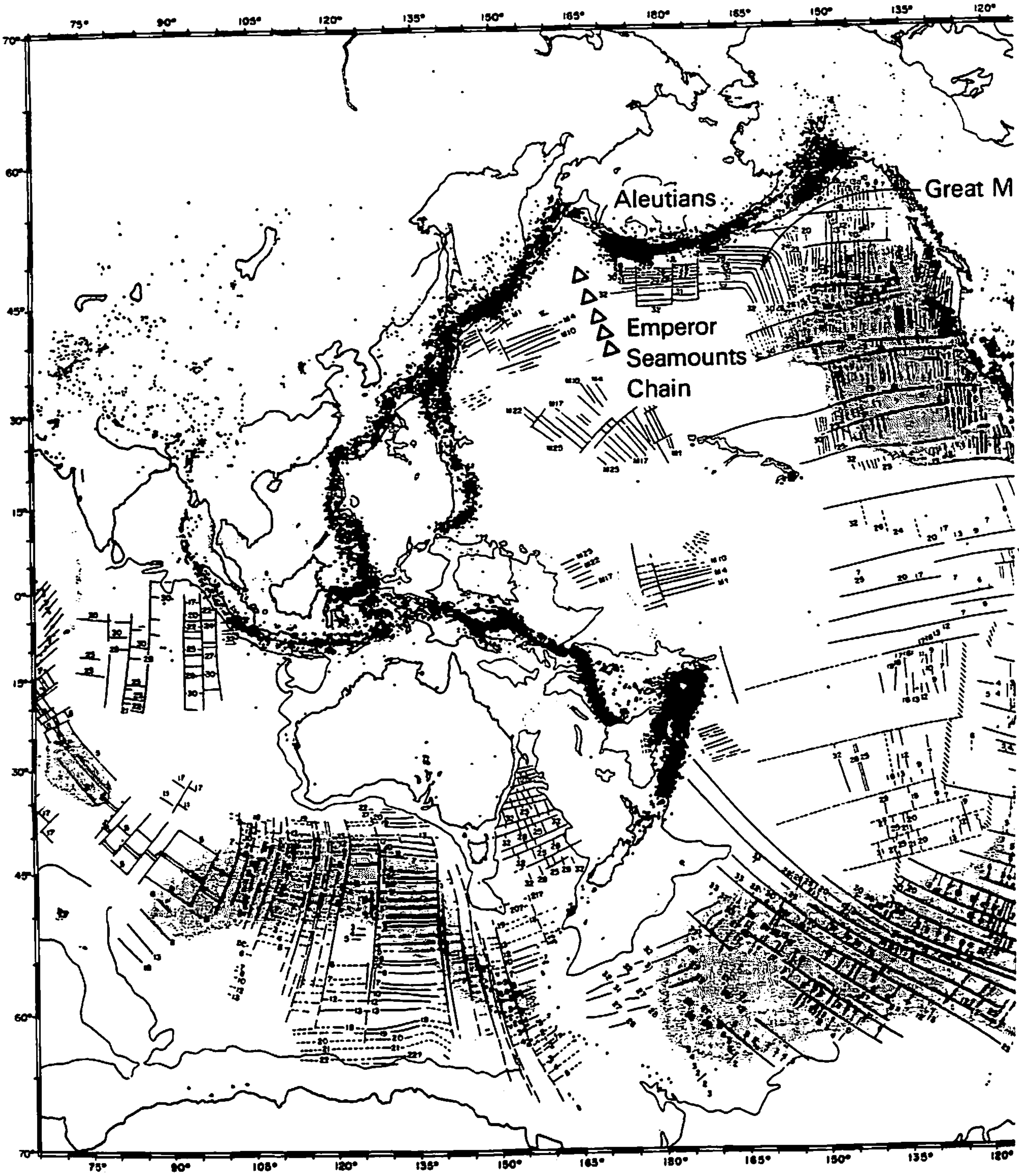
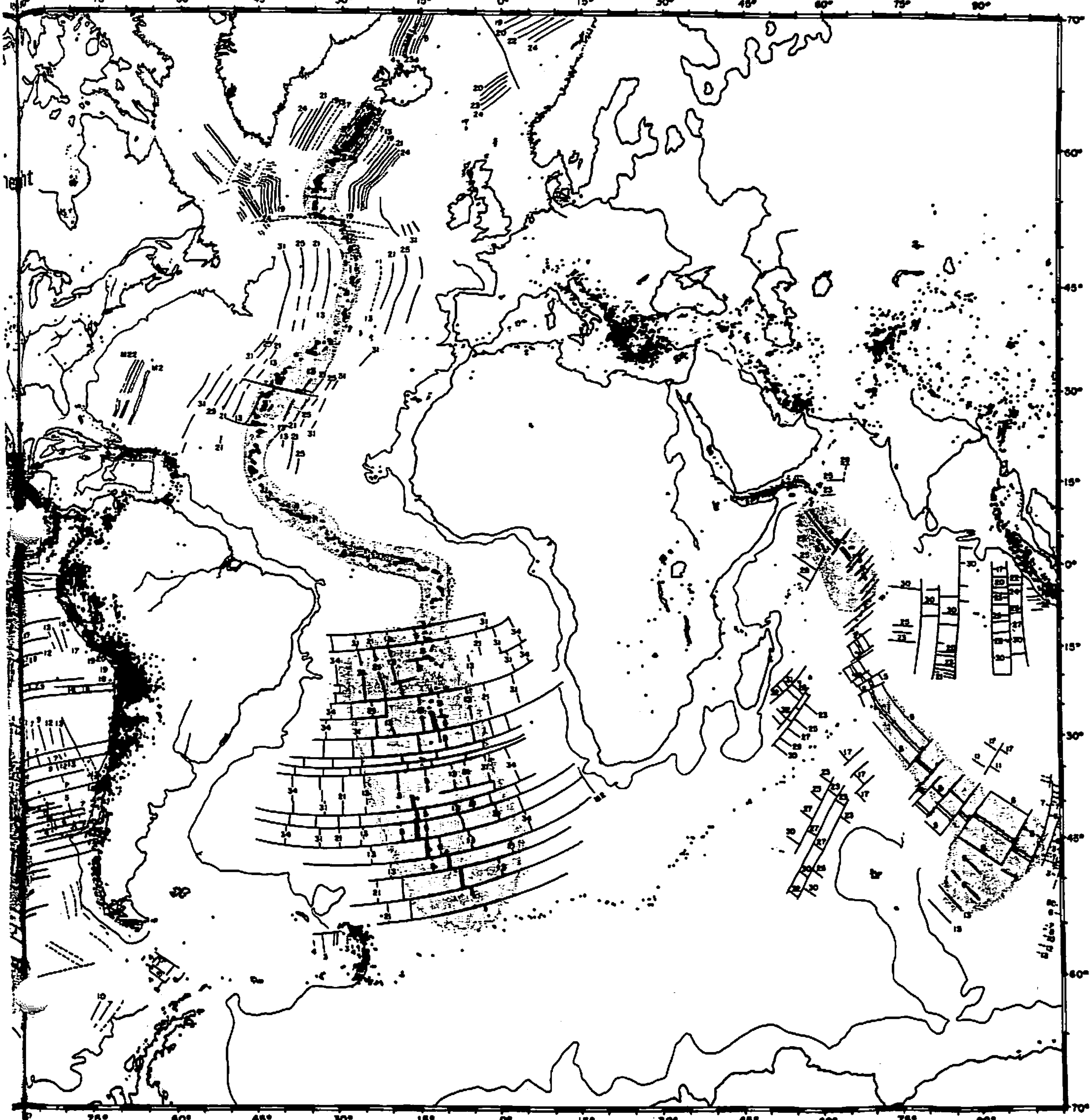


FIGURE 3-10
Isochron map of the ocean floor. The numbers along each isochron give the anomaly numbers (see text). Shaded sections represent the areas for which data were compiled in 1968 by J. Heirtzler and



colleagues. Also shown are the mid-oceanic ridges, transform faults, and the distribution of epicenters throughout the world. [Compiled by W. C. Pitman, III, R. L. Larson, and E. M. Herron, 1974. Reproduced with permission of the authors and the Geological Society of America.]

Although isochrons have been plotted for large portions of the ocean floor, other regions are blank, such as much of the central and western Pacific and regions in the northern Atlantic far from the oceanic ridges. The isochrons have not been plotted, either because detailed magnetic studies had not yet been made, or because magnetic surveys revealed no striped pattern of geomagnetic anomalies. Those areas revealing no magnetic patterns are called *magnetic quiet zones*, and the question of what caused them has several possible answers. It may be that the speed of sea-floor spreading was extremely rapid at the time, thus producing a larger area of sea floor while the geomagnetic field was facing in one direction. Or perhaps no geomagnetic field reversal occurred for quite a long period of time; paleomagnetic studies on land reveal that such periods, devoid of magnetic reversals, existed at the end of the Paleozoic era and in the Jurassic and Cretaceous periods. Other possible causes for quiet zones are that the ocean floor may have failed to record the geomagnetic reversals or lost its remanent magnetism because of secondary factors, or that the ocean floor of a magnetic quiet zone may have been produced by a process totally different from the sea-floor spreading process that is currently assumed. This problem was an important one throughout the late 1960s, and it was only after several years that a solution was attained, as will be explained in Chapter 4, where the riddle of magnetic lineations in the unshaded areas in Figure 3-10 is attacked.

The Deep Sea Drilling Project

Even the apparent success of the sea-floor spreading hypothesis did not stop man's desire for further endeavor. Since they were not entirely satisfied with the magnetic method of determining the age of the ocean floor (which, though logical, is based on a chain of hypotheses), scientists sought to develop a method of more direct sampling for this purpose. The Deep Sea Drilling Project (DSDP), initiated in the United States in 1968, fulfilled this goal. The objective was to gain direct information on the structure and history of the ocean floor by drilling to the basement rock and collecting samples of all the sediments covering the ocean bottom. Since this was to be a huge undertaking, too big for any single institution, a consortium of leading oceanographic institutions was formed. The consortium, consisting of Scripps Institution of Oceanography, Lamont-Doherty Geological Observatory, the University of Washington, the Univer-

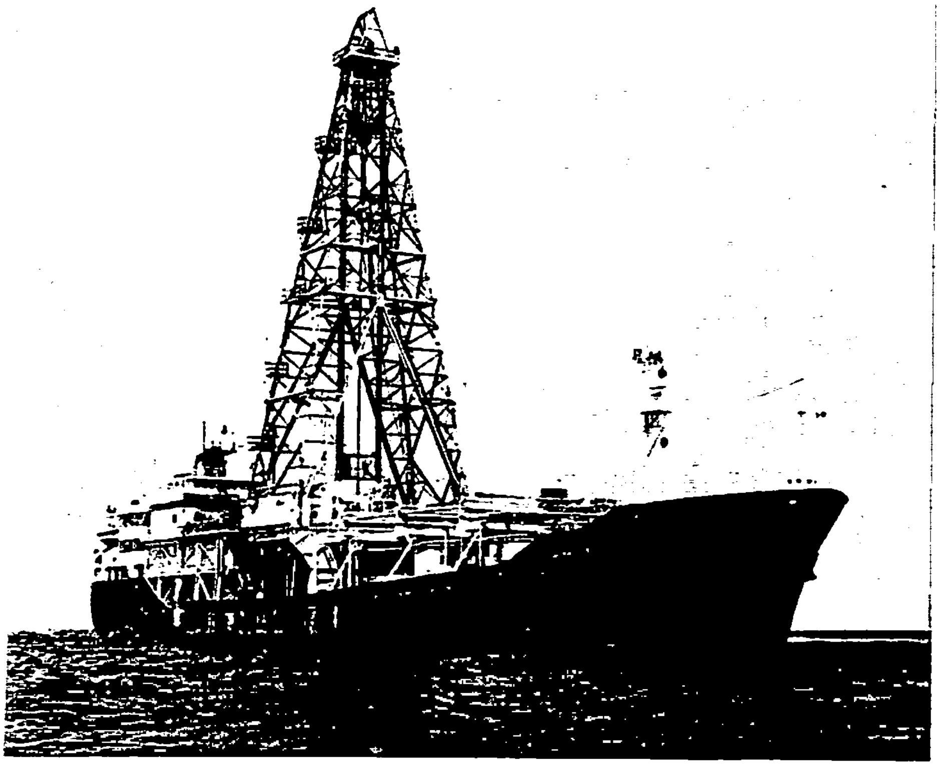


FIGURE 3-11
The Deep Sea Drilling Project vessel *Glomar Challenger* (10,500 tons). [Courtesy Deep Sea Drilling Project.]

sity of Miami, and the Woods Hole Oceanographic Institution, was called JOIDES (Joint Oceanographic Institutions Deep Earth Sampling). In order to accomplish the difficult task of boring holes in the sea floor, which lies several thousand meters below the surface of the ocean, scientists refined the boring technique used for offshore oil-well drilling and built a new drilling ship, the *Glomar Challenger* (Figure 3-11). The ship has conducted her drilling operations since August 1968, covering the Atlantic, Pacific, Indian, and Antarctic Oceans. Figure 3-12 shows the sites at which drilling was completed by October 1973. Each drilling cruise consists of a two-month "leg." When the DSDP terminated in 1975, 44 legs had been completed.

The most remarkable achievement in the early phase of DSDP was the set of results obtained in the Atlantic on the *Glomar Challenger's* Leg III. Holes were drilled through to the basaltic rocks thought to form the original volcanic sea floor. The sediments just above the basalts were believed to be only slightly younger than the

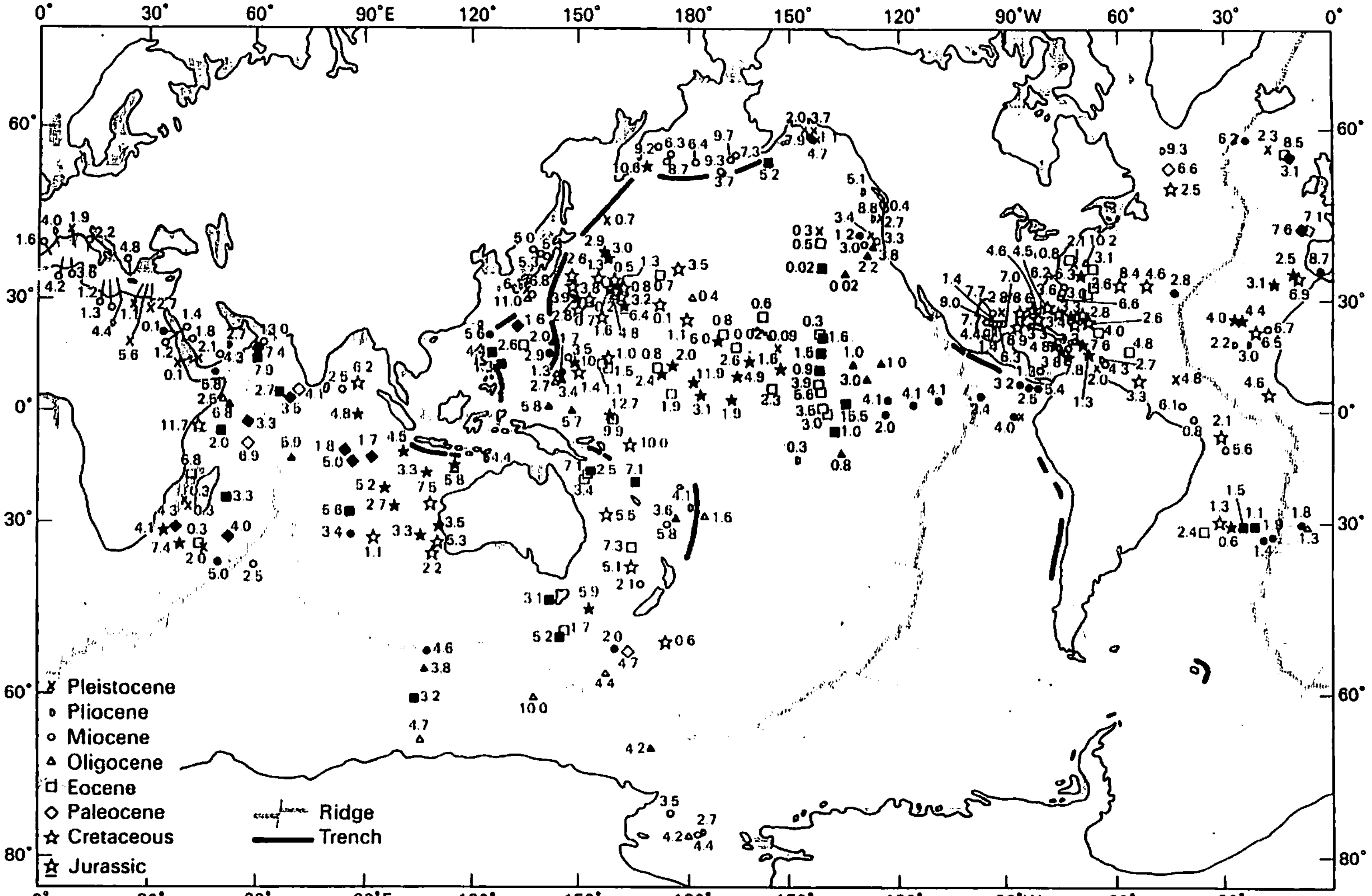


FIGURE 3-12
Deep Sea Drilling Project holes, legs I through XXXII. Numbers at the hole sites give the penetration depths in hundreds of meters. The symbols designate the age of the sediment by epoch or period. Black symbols at a site indicate that basalt was reached. The contour is for a depth of 4000 meters. [After K. Koizumi and S. Uyeda, "Earth Science and Deep Sea Drilling Project." Reproduced from *Kagaku* **44**, 4, p. 203, 1974. Copyright © 1974 by K. Koizumi. Courtesy of Iwanami Shoten Publishers, Tokyo.]

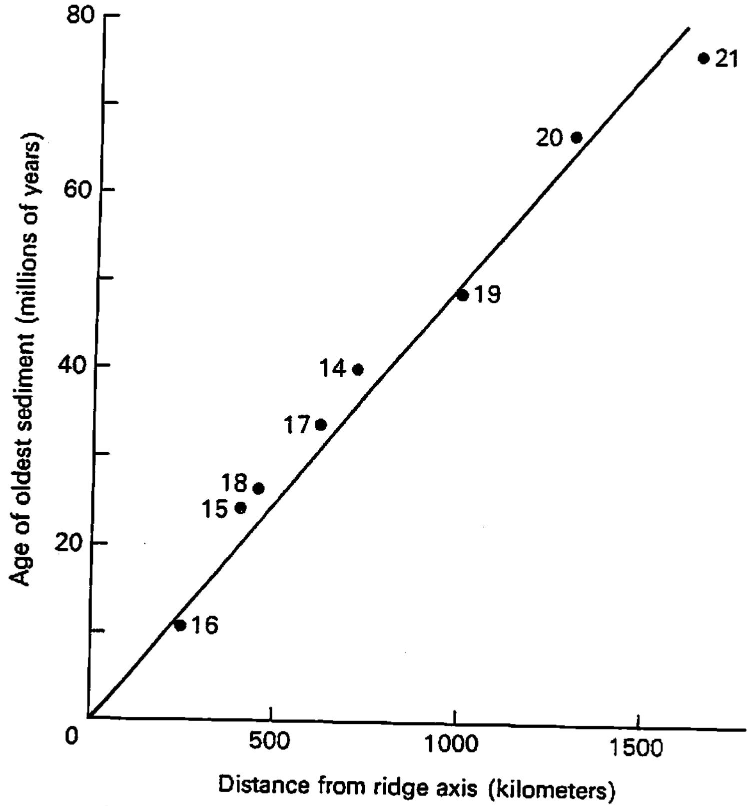


FIGURE 3-13
The results from the DSDP, Leg III, for sites 14 through 21 across the Mid-Atlantic Ridge at approximately 30 degrees south. The age of the oldest sediment at each site is plotted against the distance of the site from the ridge axis, revealing a strongly linear relationship between the two factors. This relationship suggests a constant spreading rate of 2 centimeters per year throughout the Cenozoic period. [After A. E. Maxwell and R. von Herzen, "The *Glomar Challenger* Completes Atlantic Track—Highlights of Leg III." *Ocean Industry* 4, 5, p. 64, 1969.]

basalt, and the ages of these sediments were determined from the fossils in them. These ages were found to be in excellent agreement with those one would infer from the distance of the site from the Mid-Atlantic Ridge (in accord with the sea-floor spreading hypothesis), as shown in Figure 3-13. The age of the sea floor of the Pacific Ocean, as indicated by the magnetic stripes, also coincided with that determined by the Deep Sea Drilling Project. Where the ages of magnetic lineations were unknown, holes drilled in critical areas provided the key information. It was confirmed that the youngest part of the Pacific Ocean floor is in the eastern Pacific and that the age generally increases toward the west, as shown in Figure 3-14.

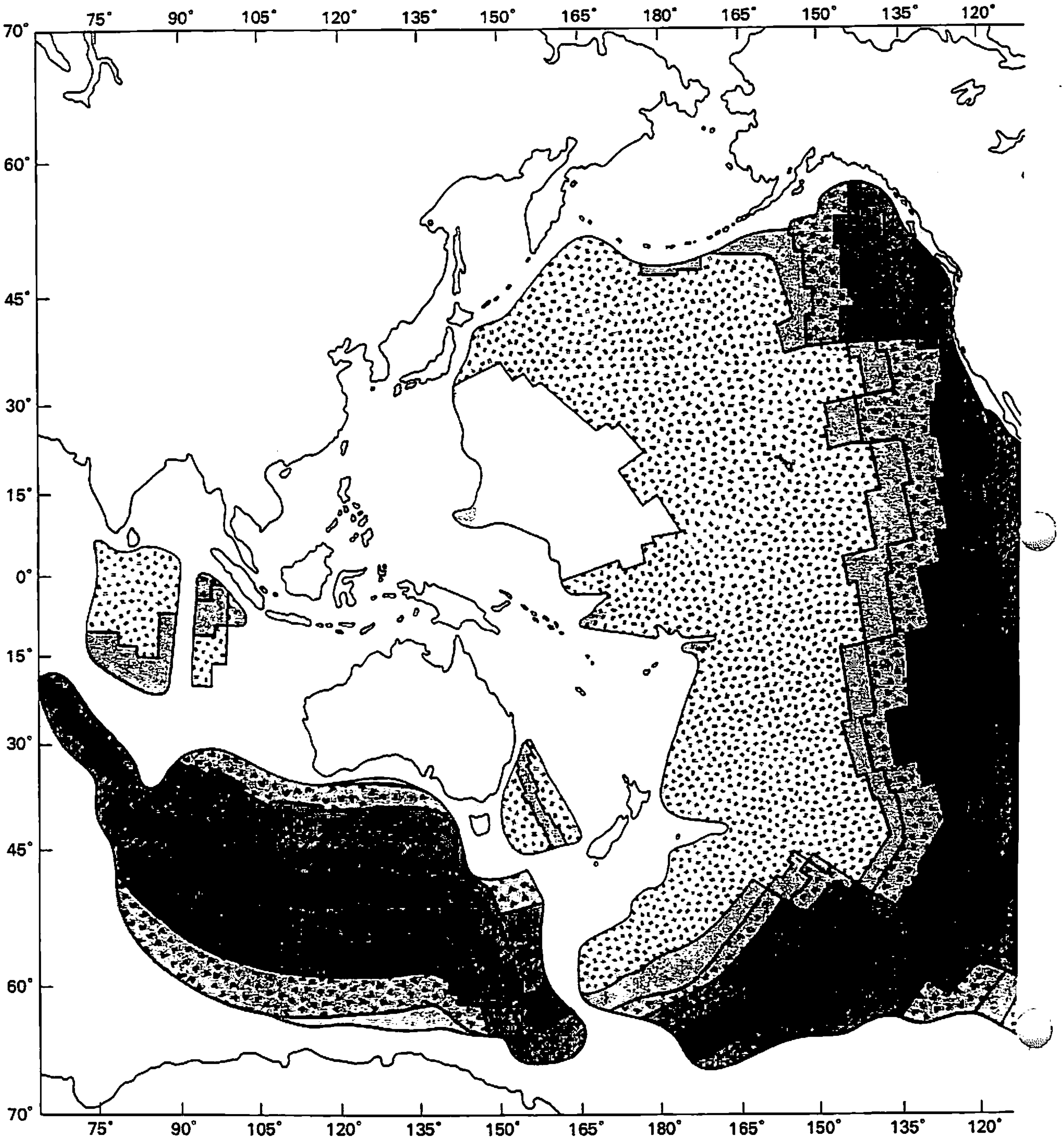
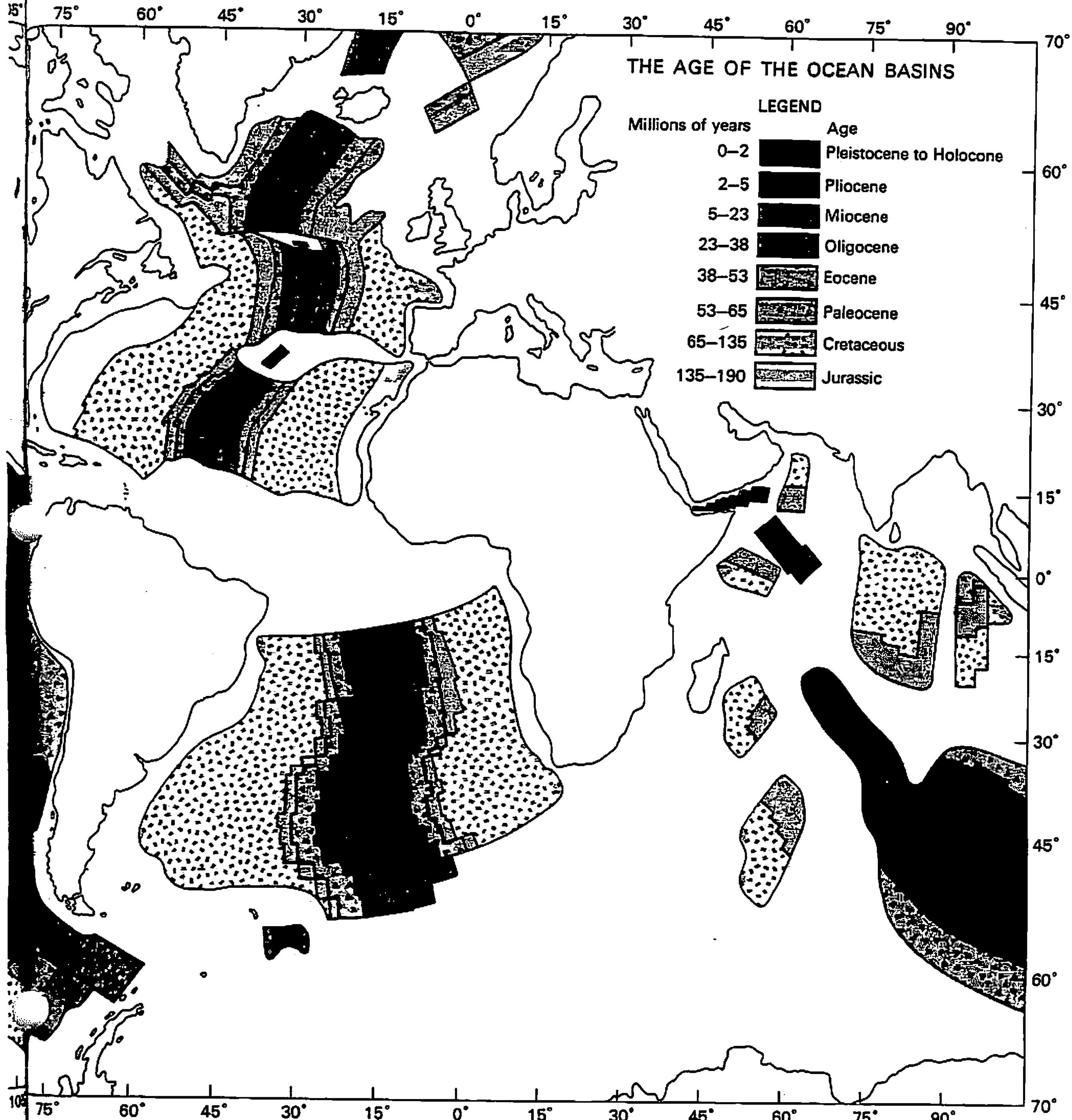


FIGURE 3-14
The age of the ocean basin. [Compiled by W. C. Pitman, III, R. L. Larson, and E. M. Herron, 1974. Reproduced with permission of the authors and the Geological Society of America.]


THE AGE OF THE OCEAN BASINS
LEGEND
Millions of years
Age
0–2 Pleistocene to Holocene
2–5 Pliocene
5–23 Miocene
23–38 Oligocene
38–53 Eocene
53–65 Paleocene
65–135 Cretaceous
135–190 Jurassic
75° 60° 45° 30° 15° 0° 15° 30° 45° 60° 75° 90°
70° 60° 45° 30° 15° 0° 15° 30° 45° 60° 70°

Although we will not go into more details here, the Deep Sea Drilling Project has provided an enormous amount of valuable information about the history of the oceans. Especially important from a geophysical perspective was verification that the second layer of the oceanic crust immediately beneath the layer of sediments is basalt, at least at the top. What, then, is the composition of the deeper part of the second layer, and of the third layer? Although the DSDP was terminated in 1975, scientific interest remained so keen that the project has been maintained as an international one called IPOD (the International Phase of Ocean Drilling). Thus very active drilling operations are still being conducted in an effort to understand the origin and evolution of the ocean bottom. JOIDES is now joined by institutions from the USSR, the Federal Republic of Germany, France, Japan, and the United Kingdom, as well as by several more American institutions. Man's desire for knowledge is boundless.

The Mysteries of the Pacific Ocean Floor

Figure 3-15 is a part of the map of magnetic anomalies around Japan that a group of us prepared in 1966. A distinct striped pattern is discernible in the areas east of the island arc of Japan—stripes that extend from northeast to southwest. At first we considered this striped pattern of magnetic anomalies to be the oldest one in the Pacific: born at the East Pacific Rise, it had moved across the vast Pacific Ocean and was about to descend beneath the Kurile Trench. This would mean the stripes should be progressively older to the north.

Such a simple assumption was challenged, however, as American scientists extended the survey of magnetic anomalies in the East Pacific northward to the area off the Canadian coast, the Gulf of Alaska, and the Aleutians. The magnetic stripes in the East Pacific, which extend from north to south in the southern areas, turn almost at right angles off the Alaskan coast to run from east to west (see Figure 3-10). In the northeast Pacific the magnetic stripes get progressively younger as they extend eastward, demonstrating that in this area the ridge that produced the ocean floor once existed to the east of those stripes. If we follow the same stripes northward around their bend to the point at which they run east-west off the Alaskan coast and the Aleutian Islands, it would seem logical that they would get older to the south and younger to the north.

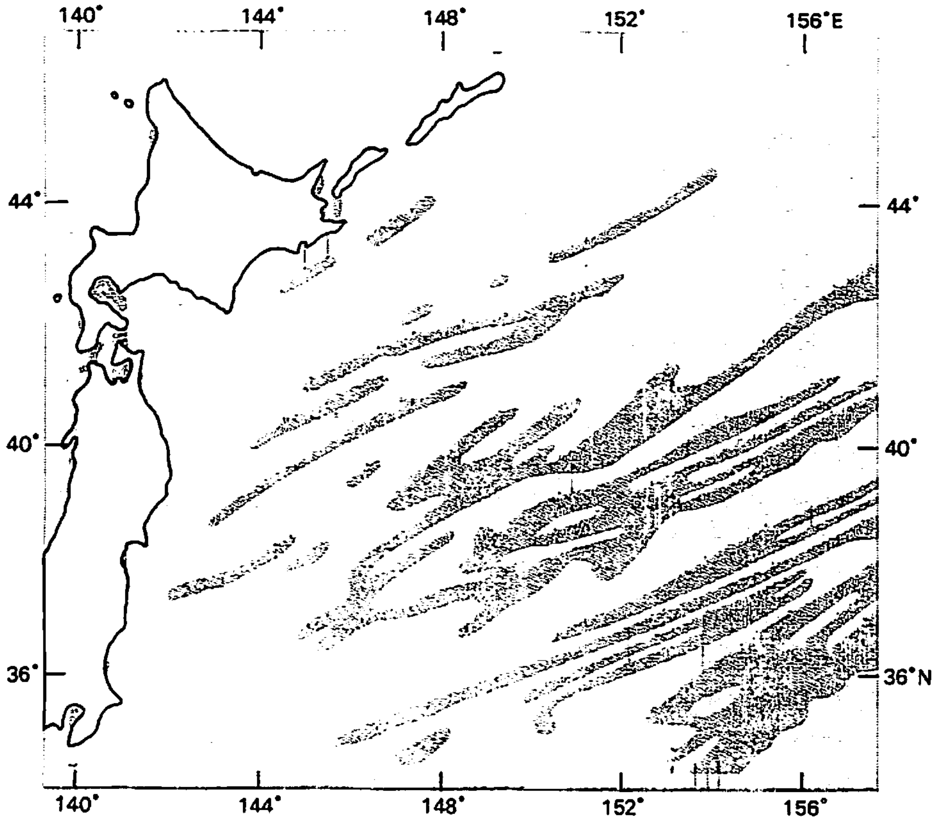


FIGURE 3-15
Total magnetic intensity anomalies in the northwestern Pacific. The shaded areas are positive in anomaly, and the white areas, negative. [After S. Uyeda et al., "Results of Geomagnetic Survey During the Cruise of R/V *Argo* in Western Pacific 1966 and the Compilation of Magnetic Charts of the Same Area." *Bull. Earthquake Res. Inst.* 45, p. 799, (1967).]

However, such a deduction seemed difficult to accept because to the north lies the Aleutian Trench, into which the sea floor is supposed to be descending. In contrast, the sea-floor spreading hypothesis would seem to require that the closer the ocean floor is to a trench, the *older* it should become. Therefore, shouldn't the stripes get younger toward the south and older toward the north, where the Aleutian Trench is? The east-west magnetic stripes south of the Aleutians extend westward until they almost join the magnetic stripes of the western Pacific off Japan. If the Japanese and Aleutian lineations are continuous, the problem mentioned above for the Aleutian area also applies to the Japanese area. Despite this difficulty, it seemed also unlikely that the magnetic anomalies, which form such a continuous striped pattern across all of the other ocean floors, should end so abruptly in the area between the Aleutians and

Japan (see Figure 3-10). More than one mystery, then, concerning the magnetic stripes in the northern Pacific remained to be solved.

The north Pacific was not the only area that posed unanswered questions, however; the age and area of the west Pacific were also still unknown by 1968, as indicated by the vast unshaded area in Figure 3-10. The west Pacific is known for its abundant flat-topped submarine mountains or seamounts (called *guyots*) and coral reefs (see Figure 2-2). For this reason the physiography of the sea floor of the western Pacific appears to be very different from that of the eastern Pacific. Did the two parts of the Pacific ocean floor originate from the East Pacific Rise by the same process of sea-floor spreading? Some scientists maintained that an extensive undersea rise had once existed in the area of the western seamounts. For example, the late H. Hess and H. W. Menard called this hypothetical rise the Darwin Rise. However the former existence of this rise would be evidenced by a large-scale depression in the same area, and the presence of such a depression has recently been subjected to serious doubt by the Deep Sea Drilling Project.

The sea-floor spreading hypothesis, then, was supported by observational data from the spreading-center areas—the ridges—in the 1960s. But sea floor away from the ridges and close to the trenches, such as the western Pacific, still posed a number of riddles. After introducing the concept of plate tectonics, we will come back to these questions in the following chapters.