海底を探る

## Chapter 2

# The Exploration of the Ocean Floor

### A New Frontier: The Science of the Ocean Floor

While paleomagnetism was bringing about the dramatic revival of the theory of continental drift, rapid progress was being made in an entirely different field—the science of the ocean floor. The fact that the ocean covers two thirds of the earth's surface makes research on the ocean floor crucial to the understanding of the earth as a whole. Even before World War II, scientists had already begun to appreciate its significance. But, as the study of oceanography progressed, it became clear that it was not the great extent of the oceans that makes marine geoscience important. It was the distinct *nature* of the oceans that was significant.

Vening Meinesz of Holland was one who began to suspect this as early as the 1930s. He had developed a technique for measuring gravity at sea that was amazingly advanced for that time. The measurement of gravity requires a precision higher than one part in a million. It requires precise leveling of the gravity meter and is extremely difficult even on land. It was almost an impossible feat to take such a measurement in the ocean, where no fixed or stable station is available. But Meinesz set up his sophisticated gravity meter on a submarine that remained reasonably stable while submerged deep beneath the waves, and he proceeded to measure the gravity at many spots in the ocean. His survey was particularly thorough in the waters around the Indonesian archipelago, then

Dutch territory. This method of gravity measurement was also employed by M. Matuyama and others of Japan, using a submarine of the Imperial Japanese Navy. These surveys revealed the remarkable anomalies in the distribution of gravity around the deep-sea trenches along Indonesian and the Japanese island arcs. These anomalous zones of gravity were entirely new discoveries. They simply do *not* exist on land. Thus earth science had a hint that something utterly new was to be found in the ocean. From these results, Meinesz came up with a hypothesis on the origin of trenches and island arcs, based on the theory of convection currents within the mantle.

It was obvious to those who had "insight" that research on the ocean floor was indispensable to the solution of basic geological problems such as the origin of continents, the origin of oceans, and the structure of the mantle. Both the technology and the financial support for such research, however, were still very scarce at that time. Despite much endeavor by a few enlightened scientists in the 1930s and 1940s, the real development of ocean-floor science had to wait for the end of World War II.

## Prerequisites for Studies of the Ocean Floor

The survey of the ocean floor, which is thousands of meters deep, cannot be made with the ordinary techniques used in land geology and geophysics. One needs special tools. First a research vessel is necessary. It must be provided with various kinds of special equipment in addition to that required for long-distance navigation. For example, special devices are needed for the exact positioning of the vessel and for measuring the water depth; wires and winches long enough and strong enough to lower the various instruments to a depth of many thousands of meters are also needed. Besides, research of this kind is a time-consuming process and requires a vessel that is reserved uniquely for this particular type of investigation. For these reasons, oceanic research immediately after the war was undertaken mostly by the victorious nations, such as the United States, England, and the USSR.

Ironically, once the techniques and methods were developed and research vessels secured, research on the oceanic areas progressed much faster than that on land. Whereas survey equipment must be hauled across valleys and over mountains, sometimes from nation to nation, the vessels can move easily to any ocean (and one does not have to contend with complicated visa-application procedures in order to cross an international border).

Although progress in sea-floor research was made possible by the ardent support of scientists, nobody could have predicted that, within a mere 20 years, it would reach such remarkable heights, nor that it would have such a significant impact on the theory of continental drift, which had been revived by the studies in paleomagnetism. Penetrating "insight" must have been at work, even though prediction of the exact future course of research was impossible.

A major contribution to the exploration of the world's oceans was made by the Lamont Geological Observatory of Columbia University, established in 1949. Its first director was the late Maurice Ewing, a man of outstanding leadership and an inquiring mind. The research projects he directed all over the world produced a number of new findings and theories. After more than 20 years of directorship, Ewing moved to the University of Texas in 1972 and died in early 1974, leaving behind important achievements in almost every aspect of ocean-floor studies. The Observatory is now called the Lamont-Doherty Geological Observatory and is still making important contributions under the directorship of Manik Talwani.

The Scripps Institution of Oceanography was established at the turn of the century. Roger Revelle, its director from 1948 to 1964, initiated its emphasis on ocean-floor research. Since the 1950s, the Institution has conducted a number of large-scale expeditions, largely in the Pacific and Indian Oceans and especially in the eastern Pacific.

I have had the privilege of spending considerable time at both these outstanding institutions. It was quite spectacular to observe both research groups making one new discovery after another. The oceanographic institutions of other countries, such as Great Britain, the USSR, Japan, France, Canada, and Germany, have also joined this dynamic effort, and groups of many countries have cooperated in a number of joint projects. For after all, oceans belong to all the nations!

## The Advent of New Techniques

The Japanese research vessel *Hakuho Maru* exemplifies today's modern vessel, fitted with highly advanced survey equipment (Figure 2-1). The most basic piece of equipment required for sea-floor research is a precision sonic depth recorder. In the past, the depth of the

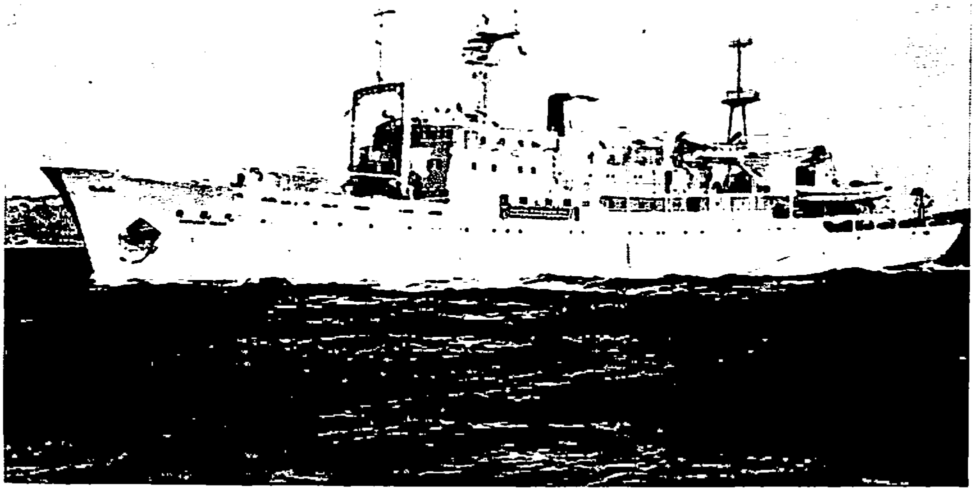

FIGURE 2-1
The research vessel *Hakuho-Maru* (3225 tons). [Courtesy Ocean Research Institute, University of Tokyo.]

ocean was determined by suspending a lead weight from a rope, and then measuring the length of rope needed for the lead to reach the bottom. This procedure required an enormous amount of time and energy. In the 1920s the so-called echo-sounding method was introduced, enabling us to measure the depth of the ocean by sending forth sonic waves from the vessel and recording the length of time they took to echo back. This technique was subsequently highly refined, and by the 1950s it was possible to measure ocean depths throughout the world to a depth of ten thousand meters. The resolving power of the modern precision depth recorder is better than one part in 5000, so that a change as small as one meter in the depth to the ocean bottom can be detected, even if the total depth is as great as 5000 meters. The mapping of the topography of the ocean floor with this device was one of the first developments in marine geology, and it is the first step in any individual project.

Based on the vast amount of data available, the late B. Heezen and M. Tharp of Lamont-Doherty Observatory compiled the now well known birds' eye view of the world's oceans with its spectacular overview of the sea-floor topography. A simplified view of the world ocean topography is shown in Figure 2-2.

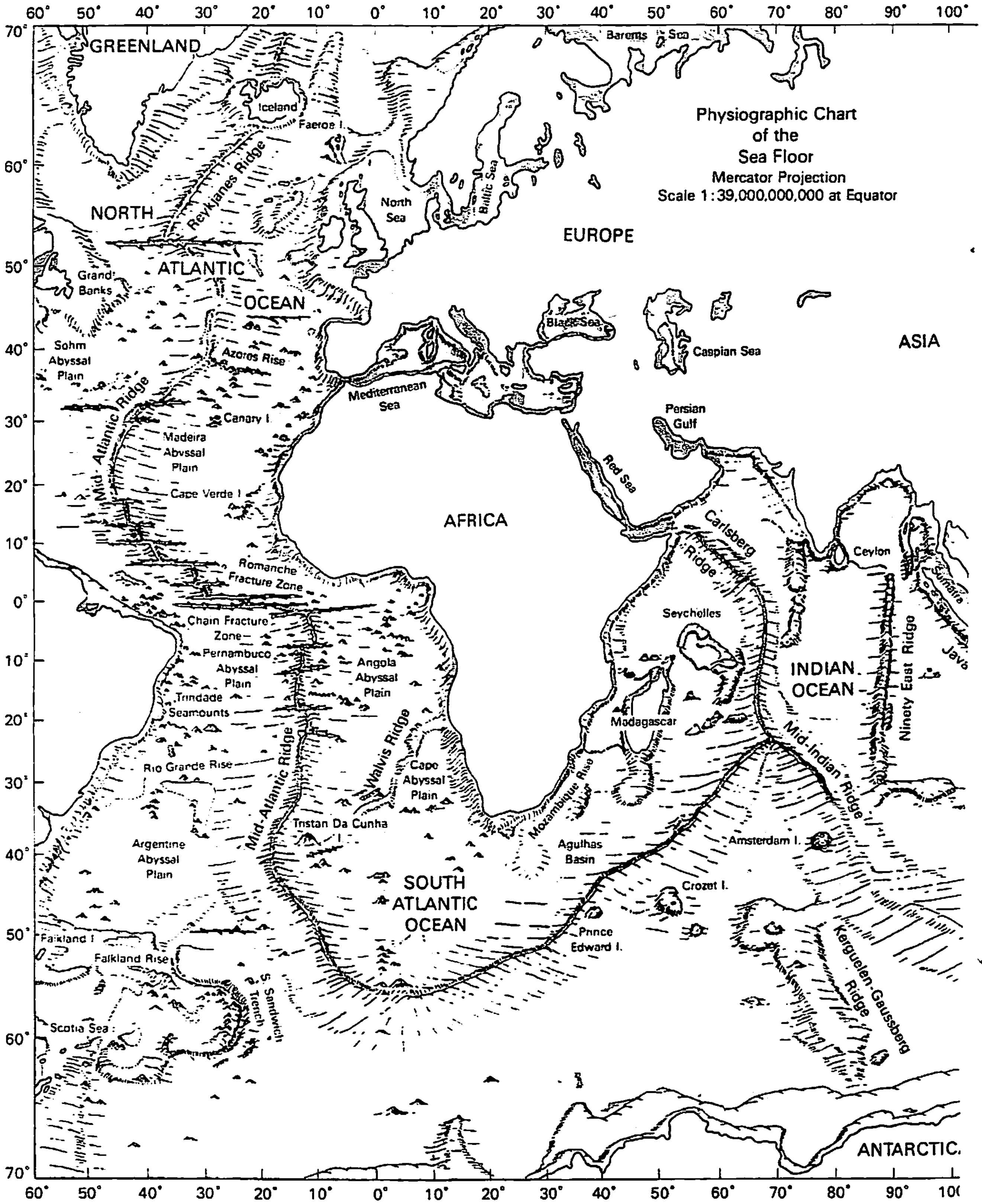

FIGURE 2-2
The floor of the oceans. [Courtesy Hubbard Scientific Company.]

Chukchi Sea
Bering Sea
Sea of Okhotsk
Aleutian Basin
Aleutian Trench
Aleutian Abyssal Plain
Emperor Seamount Chain
Kuril Trench
Sea of Japan
Japan
Japan Trench
Chinook Fracture Zone
Medocino Fracture Zone
Murray Fracture Zone
Molokai Fracture Zone
NORTH AMERICA
Hudson Bay
Burmuda Rise
Hatteras Abyssal Plain
Nares Abyssal Plain
Puerto Rico Trench
Caribbean Sea
NORTH PACIFIC OCEAN
Bonin Trench
Mariana Trench
Sea
Mariana Basin
Mid-Pacific Mountains
Clarion Fracture Zone
Middle America Trench
Line I.
Clipperton Fracture Zone
Galapagos Fracture Zone
Cocos Ridge
Galapagos I.
SOUTH AMERICA
Solomon Rise
New Guinea
Vitaz Trench
Samoa I.
Marquesas I.
Marquesas Fracture Zone
Coral Sea
Great B. Reef
Fiji I.
Cook I.
Society I.
Austral I.
Tuamotu Archipelago
East Pacific Rise
Galapago Rise
Nazca Ridge
Peru-Chile Trench
STRALIA
Tonga I.
Kermadec-Tonga Trench
Easter Fracture Zone
SOUTH PACIFIC OCEAN
Lord Howe Rise
Chile Rise
Chatham Rise
Campbell Plateau
Tasmania Rise
Eltanin Fracture Zone
Pacific-Antarctic Ridge
30°
140°
150°
160°
170°
180°
170°
160°
150°
140°
130°
120°
110°
100°
90°
80°
70°
60°
70°
60°
50°
40°
30°
20°
10°
0°
10°
20°
30°
40°
50°
60°
70°

For more sophisticated investigation, seismic waves are used, as on land. It is possible to observe the propagation of seismic waves artificially created by an underwater explosion near the surface of the ocean. This area of study is called marine-explosion seismology. The development of this technique in the 1940s and 1950s is due in great part to American and British scientists. It was this technique that made it possible to determine the suboceanic crustal structure. Recently, another method—the air-gun method—has been developed: a series of waves are generated by shooting an air gun from the ship. The structure of the upper part of the oceanic crust is revealed in remarkable detail by the continuous *reflections* of those waves from buried layers of sediment. Figure 2-3 is an example of the results obtained by this method. The conventional explosion method is now used largely to determine the deeper structure of the ocean crust and upper mantle.

Yet another basic method for determining ocean crustal structure is the measurement of gravity. Since Vening Meinesz's surveys were confined to the limitations of the submarine and consumed much time and energy, the development of a technique of marine-gravity measurement, which could be used on a surface ship, was highly desirable. Thanks to the endeavors of many scientists in various countries, several kinds of extremely intricate surface-ship gravity meters are in use today, producing large quantities of valuable data. C. Tsuboi led the research in Japan, and Y. Tomoda and others successfully developed a ship-borne gravity meter, now installed on the research vessel *Hakuho Maru*.

Measurement of the geomagnetism of ocean areas has become another important research area. The conventional method of geomagnetic field measurement on land had required the precise measurement of the delicate movement of a suspended magnet—a task almost impossible to perform on a rolling vessel. Then in the 1950s a technique for measuring oceanic magnetism, founded on an entirely new concept, was developed. The device is called a nuclear resonance type magnetometer, or *proton-precession* magnetometer. It is known that, in a substance such as water, each proton is constantly spinning like a top and in addition has its own magnetic moment; when the proton is placed in a magnetic field, it undergoes a *precessional* motion like that of a toy top when it is placed in a gravitational field. The working of the magnetometer is based on the fact that the frequency of this proton motion is precisely proportional to the intensity of the magnetic field. In taking measurements it is not necessary

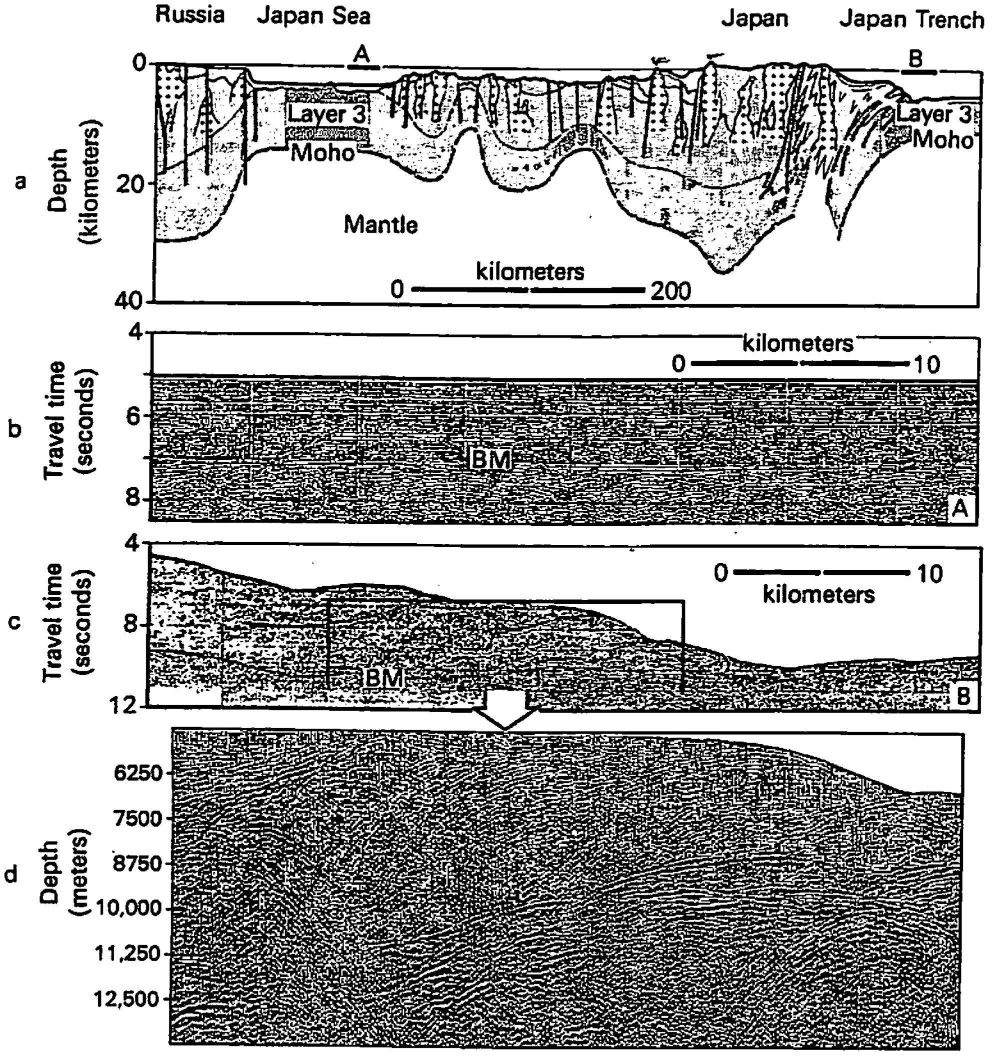

FIGURE 2-3
Example of modern seismic reflection records for the Japan Sea and Japan Trench. (a) The schematic cross section of the inferred crustal structure, with points A and B representing the sections at which seismic recordings were taken.
(b) The number of seconds required for a sonic wave to travel at point A in the Japan Sea. The symbol BM designates the sea-floor basement beneath the sediments.
(c) The seconds required for a sonic wave to travel at point B in the Japan Trench.
(d) The detail of the landward wall of the Japan Trench—designated by the rectangular outline in part (c)—and its depth in meters. [After R. H. Beck, P. Lehner, et al., "New Geophysical Data on Key Problems of Global Tectonics." *Proceedings of the Ninth World Petroleum Congress,* 1975.]

to level or align the magnetic sensor. Consequently it is now a routine operation to measure the total intensity of the geomagnetic field from a vessel cruising over the ocean surface. The sensor of the magnetometer is towed behind the vessel at a distance sufficient to avoid the effect of the magnetism of the vessel (most vessels being of steel and therefore highly magnetic). Surveys of geomagnetism, conducted with this method, have contributed greatly to research in the science of the ocean floor and to the development of the new view of the earth, as we shall see in this and the following chapters.

Another technique is to measure from a ship the heat that escapes from the earth's interior through the sea floor. Because of its high internal temperature, the earth constantly emanates a certain amount of heat. The quantity of this heat is called *terrestrial heat flow*. The rate of heat flow can be estimated from the measurement of the *geothermal gradient*, which is the rate at which the temperature increases with depth, and the *thermal conductivity* of the strata. The thermal conductivity of a material indicates how effectively heat is transferred by the material. The rate of terrestrial heat flow is obtained simply by multiplying the value of the geothermal gradient by that of the thermal conductivity. The measurement of terrestrial heat flow on land is made by measuring first the geothermal gradient in a mine or a deep well, and then the thermal conductivity of rock samples from the mine or well. Previously, however, measurement at sea posed a practical difficulty, since drilling a hole in the middle of the ocean floor is extremely difficult and expensive. This problem was solved in the 1950s by Bullard and his colleagues, who devised an instrument with a probe a few meters long that contained thermometers mounted along its axis. The probe is lowered until it penetrates the ocean floor and the temperatures at the different points along the probe are measured. From these temperatures the geothermal gradient is easily calculated. On land a deep hole is an absolute necessity for accurate measurement of the geothermal gradient, because the temperature near the surface is affected by the changes of air temperature. Thanks to the enormous thermal inertia of water, the water temperature in the depths of the ocean is constant, so that the necessity of drilling a deep well is eliminated.

Another development that has recently contributed greatly to the progress in marine geoscience is the use of satellites to determine the position of vessels at sea. If one does not know the exact position of the vessel, the measurement of gravity or magnetism means very little, no matter how precise it may be. Usually navigators estimate the position of the ship by taking readings of the sun and stars. Obviously this astronomical method is not applicable in bad weather. But even in fair weather, most estimates are inaccurate by a few miles. In recent years various methods have been developed to determine the position of ships by receiving electromagnetic waves from coastal stations. This method is accurate to within one or two miles under favorable conditions. Yet, as the measurements taken by various surveys became more and more precise, any inaccuracies, however small, came to be considered unsatisfactory. Satellite navigation is a method of determining the position of a ship by receiving the electromagnetic waves transmitted by a satellite. The ship's position can be automatically determined each time the satellite comes around (approximately once an hour) and it is accurate to within 100 meters. A significant improvement over earlier methods, this procedure is now widely used.

All of these new techniques have led to the discovery of important new facts; and the synthesis of these discoveries has molded a new science. Progress in the development of advanced techniques is unending. In the past several years, we have learned how to take various types of measurements by means of instruments set directly on the ocean bottom. *Ocean-bottom seismometers,* in particular, have been successful in providing us with information that is difficult to obtain otherwise. *Ocean-bottom magnetometers,* which will be useful in assessing the thermal state of the upper mantle under oceans, are also being developed. It is hoped that these new techniques will open up yet other new horizons in our science.

## The Ocean Floor

The map in Figure 2-2 shows the topography of the ocean floor. Note for example the long line of topographic highs stretching along the middle of the Atlantic Ocean. This is the great submarine mountain range called the *Mid-Atlantic Ridge.* The existence of such a ridge was already suspected at the end of the 19th century when the first submarine cable was being laid. It was then called the "Telegraph Plateau." A survey undertaken from the famous German vessel, the *Meteor,* from 1925 through 1927, led to the assertion that this "plateau" was a long one, extending practically the entire length of the Atlantic. Since then further studies have revealed that similar mid-oceanic ridges exist in the Pacific and Indian Oceans as the map also shows.

As is also evident in the map, a narrow chain of oceanic deeps lies in the circumferential regions of the Pacific near the island arcs. These deeps are called *trenches.* Between mid-oceanic ridges and continents or trenches, the ocean floor is spacious and quite flat, with numerous seamounts jutting up. If we consider the oceanic ridges and the margins as anomalous areas, the flatter basins between ridges and margins would represent the state of the average or normal ocean floor. The suboceanic crustal structure was first determined by explosion seismology in these basins.

As pointed out in Chapter 1, the oceanic crust in most places is thinner than 10 kilometers and lacks the thick granitic layer invariably found in the continental crust. Recall also that under a thin veneer of sediments, the main layers of the oceanic crust are composed of rocks like the basalts, which have a density and seismic-wave velocity higher than the granitic rocks. The lower layer of oceanic crust probably consists of such rocks as gabbro (the intrusive equivalent of basalts) and serpentinite (hydrated peridotite).

The first heat-flow measurements taken at sea were a surprise. We knew that the heat flowing out of the earth was generated by the decay of the radioactive elements uranium, thorium, and potassium. Chemical analysis had shown that these elements were much more highly concentrated in granitic rocks than in basalt, gabbro, and peridotite. Consequently, scientists expected that average heat flow from the ocean floor would be small, probably no more than one-tenth of the average flow from the continental crust. Those who conducted the early measurements of the heat flow of the ocean floor sought to confirm this point. The first of these measurements was undertaken in 1954 by Bullard and others. The result was unexpected. The heat flow of the average oceanic region was not as small as it was expected to be; in fact, it was about equal to that of the continental region. The similarities in the quantity of heat flow from both continental and oceanic regions, despite the great difference between them in the amount of crustal heat sources, would seem to suggest a greater supply of heat flow from *under* the crust in oceanic regions. The extra heat must be coming from the mantle. This was a significant discovery, as will be seen in the following chapters.

## The Mid-Oceanic Ridges

Among suboceanic topographic structures, the mid-oceanic ridges are the largest (Figure 2-2). The Mid-Atlantic Ridge, for instance, runs from the Arctic Ocean through the middle of the Atlantic, passes the African coast and the Cape of Good Hope, to the Indian

Ocean, from which it continues to the Pacific, practically encircling the entire earth. These mid-oceanic ridges are more than 3000 meters high and more than 2000 kilometers wide. In fact they surpass both the Alps and the Himalayas in scale. It was Ewing and Heezen who first realized that the earth is encircled by such grand-scale sub-oceanic ridges. This important discovery resulted from observations indicating that mid-oceanic ridges could be recognized as such not only because of their singular topography but also because of their seismic activity. Ewing and Heezen were able to predict the existence of ridges, even where a topographic survey had not yet been made, by the linear pattern of the occurrence of earthquakes in oceans. Figure 2-4 shows the world distribution of epicenters—the point on the earth's surface directly above an earthquake focus—demonstrating that most oceanic quakes occur along the mid-oceanic ridges.

In 1953, Heezen and Tharp made yet another important observation: a deep valley winds along the axial line of the Mid-Atlantic Ridge. From the cross-section of the ridge, shown in Figure 2-5, it would appear that this valley was formed by the splitting of the ridge. In contrast to the great mountain ranges on land, which consist mostly of *sedimentary* rock and show evidence of folding created by *compression* from both sides, mid-oceanic ridges are mostly of *volcanic* origin and show features that seem to have been caused by *tension.*

Yet another important discovery about mid-oceanic ridges was that the heat flow was considerably greater at their crests. During 1961 and 1962, I joined R. P. von Herzen of the Scripps Institution of Oceanography to launch a thorough survey of the East Pacific Rise, a feature analogous to the Mid-Atlantic Ridge. Previous surveys of this area had indicated that heat flow might be high at the ridge crest. At that time, in the areas around Japan, the survey of marine terrestrial heat flow was limited to a few sites, although the survey of heat flow on land was quite advanced (Chapter 5). Therefore, the three-month survey on board the research vessel *Spencer F. Baird* in the southeast Pacific, in which more than 300 measurements were taken, was a great revelation to me: today's marine geophysical work must be conducted with this kind of exhaustiveness. The days when conclusions could be drawn from a couple of measurements are over. Some of the results obtained during this cruise are shown in Figure 2-6. Notice the remarkably high terrestrial heat flow at the crest of the East Pacific Rise. We also found that the high heat flow occurs only within two very narrow zones situated on the crest of the East Pacific

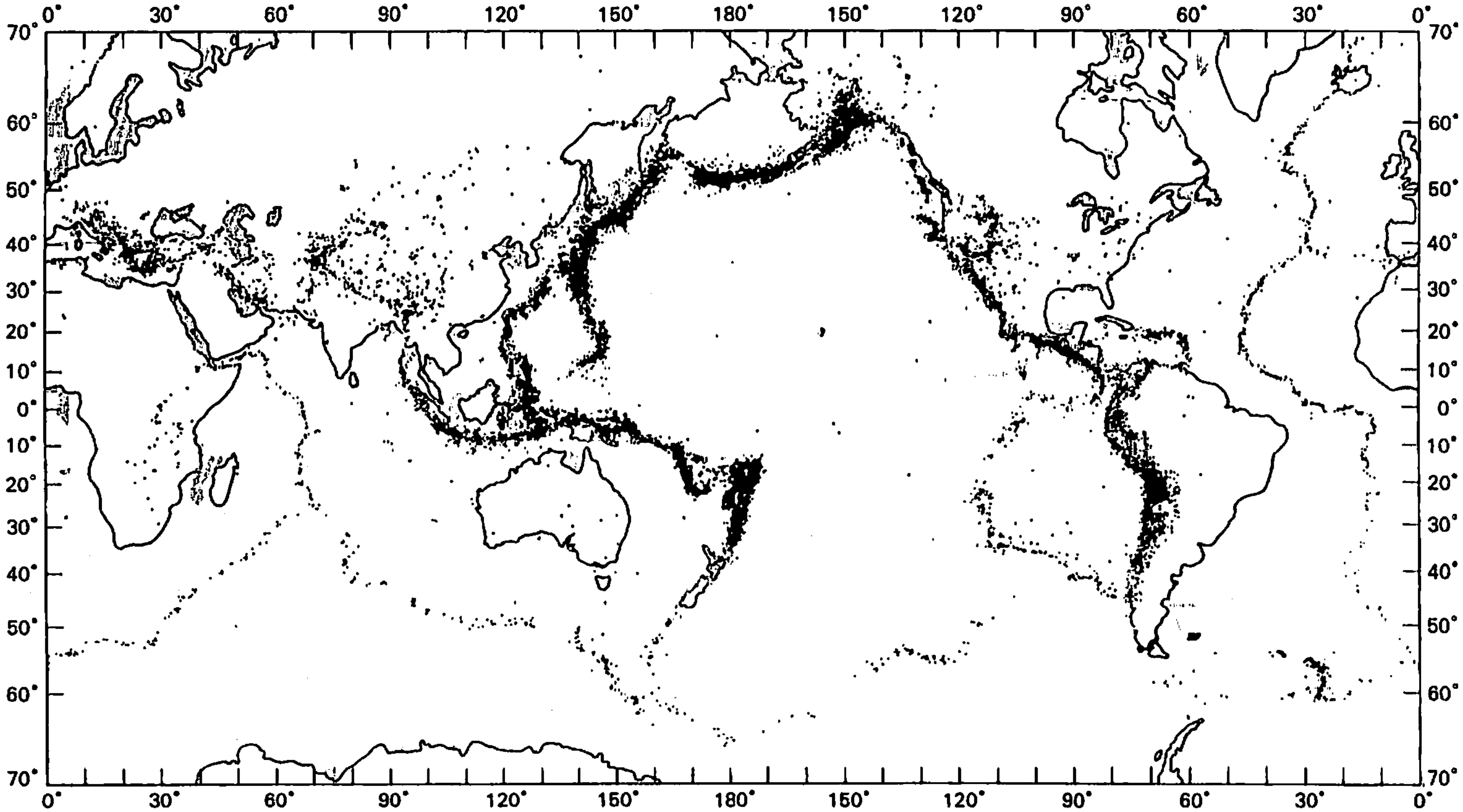

FIGURE 2-4
Diagram showing the distribution of earthquake foci. Notice that those in the oceans are concentrated in the mid-oceanic ridges. [After M. Barazangi and J. Dorman, "World Seismicity Map Compiled from ESSA Coast and Geodetic Survey Epicenter Data, 1961–1967." *Seismol. Soc. Amer. Bull.* 59, p. 369, 1969.]

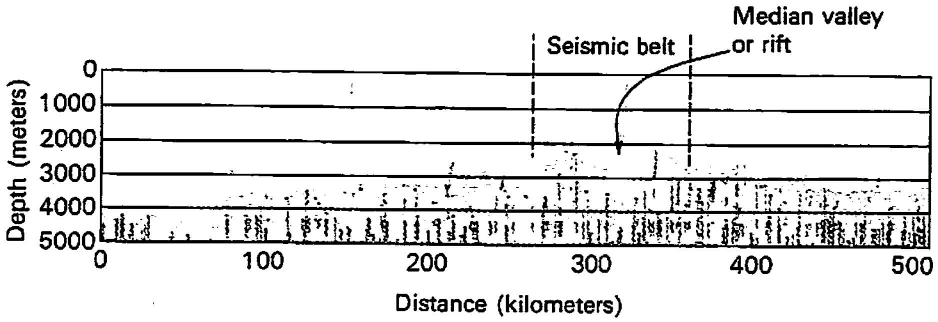

FIGURE 2-5
Profile of the Mid-Atlantic Ridge. [After B. C. Heezen, in S. K. Runcorn, Ed., *Continental Drift*. Academic Press, 1962.]

Rise. Immediately adjacent to these zones, curiously low heat flow values were observed. Such a juxtaposition of high and low heat flow values was later found to be a characteristic of active mid-oceanic ridges in general. This phenomenon is now interpreted as due to the hydrothermal activity in the crust at the crestal part of the ridges, and is under intensive investigation. The mid-oceanic ridges, then, are gigantic topographic highs where heat and tensional forces from the interior of the earth are at work.

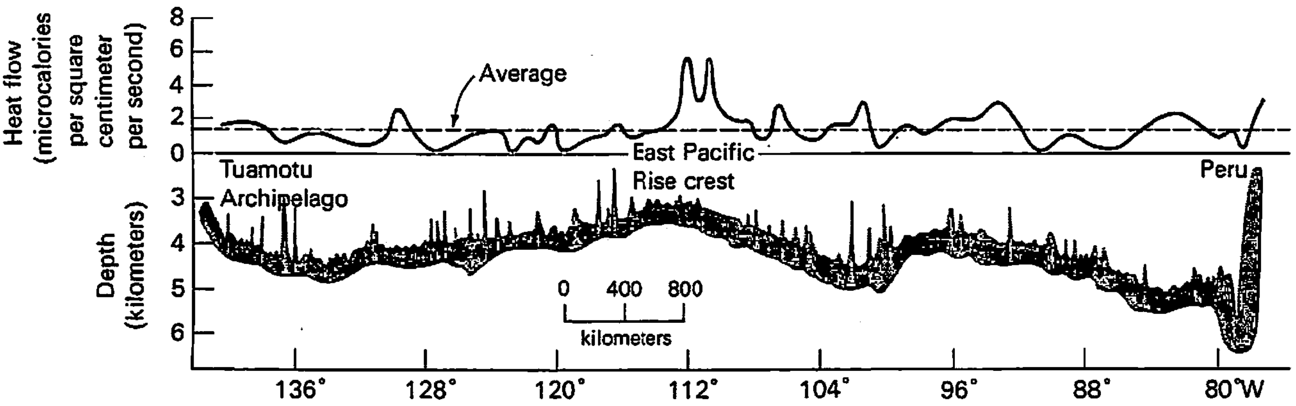

FIGURE 2-6
Profile of heat flow (in microcalories per square centimeter per second) and topography across the East Pacific Rise from the South American coast to Tuamotu archipelago. The horizontal dashed line shows the world average of heat flow. [After R. P. von Herzen and S. Uyeda, "Heat Flow Through the Eastern Pacific Ocean Floor." *J. Geophys. Res.* 68, p. 4219, 1963. Copyrighted by American Geophysical Union.]

As research progressed in the Atlantic and the Pacific, interest in the mid-oceanic ridges of the Indian Ocean also grew. The International Indian Ocean Expedition Project (1959–1965) materialized out of the cooperative spirit created by the International Geophysical Year (1957–1958) and the Upper Mantle Project (1962–1970). The United States, England, the USSR, France, Germany, and Japan all sent out scientists and research vessels to undertake extensive research.

The Indian Ocean floor is also shown in Figure 2-2. There too the system of mid-oceanic ridges is extensive. It is also quite complex. For example, the extension of the Mid-Atlantic Ridge circles the southern tip of Africa into the Indian Ocean, where it bifurcates. One of the branches extends eastward to the south of Australia and eventually reaches the Pacific Ocean. The other branch passes through the Gulf of Aden and enters the Red Sea. If we assume that something hot is welling up from beneath the mid-oceanic ridges and rending them apart, then it is logical to assume that the Gulf of Aden and the Red Sea currently constitute the now active rift that is causing the two continents to split (see Figure 2-7). In fact, we now have ample evidence showing that this inference is indeed true. As we will see later, the data collected by the International Indian Ocean Expedition and other expeditions proved to be extremely valuable, once the "new view of the earth" had shown us how to interpret these data in terms of the evolution of the world's ocean.

## The Oceanic Trenches

It might be logical to assume the deepest part of the ocean is in the middle of the ocean. But the actuality is quite the contrary. As the topographic map in Figure 2-2 shows, the deepest waters lie close to the land, in the margin of the ocean. The middle of the ocean is shallower, owing to the presence of the mid-oceanic ridges. This distribution is similar to that of the highest mountains on the continents. With a few exceptions, such as the Himalayas, most of the high mountain ranges are not in the middle of the continents but at their margins, facing the deep oceanic trenches.

The seemingly paradoxical distribution of ocean depths and shallows, and of mountain ranges, is closely related to the origin of the continents and the ocean floor. The trenches are highly developed in such areas as the western margin of the Pacific Ocean—from Alaska to the Aleutians, the Kuriles, Japan, Izu-Bonin and the Marianas, and Tonga-Kermadec—and the southeastern margin of the Pacific Ocean, the west coast of South America. Along the continental side of the oceanic trenches lie island arcs and continental arcs where the

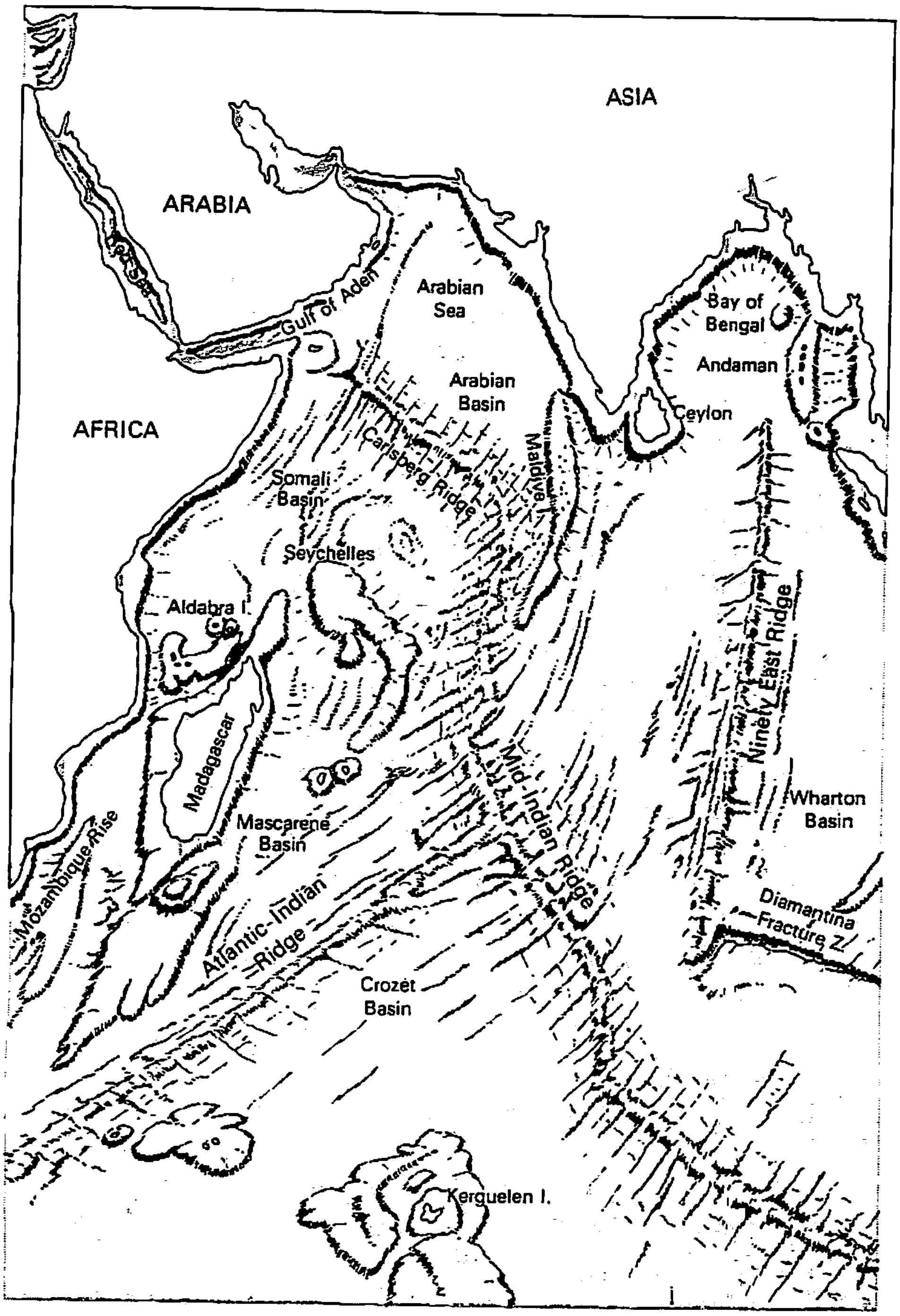

FIGURE 2-7
Portion of the sea floor, showing at the upper left the active rift between Asia and Africa, through the Gulf of Aden and the Red Sea. [Courtesy Hubbard Scientific Company.]

seismic and volcanic activity is vigorous. Since oceanic trenches and arcs always occur together, the two need to be considered as a pair. A system of island arcs and trenches is well developed in the Indonesian region also.

The pioneers of research on island arcs were the Dutch scientists who conducted investigations on the Indonesian archipelago as early as the 1920s. The measurement of gravity in the ocean by Meinesz, mentioned earlier, was one such pioneering investigation. The results of his measurements showed the gravity to be unusually low in the oceanic trenches. Since the trenches are filled with water (density of 1.0 grams per cubic centimeter) instead of rock (density of 2.6 to 3.0 grams per cubic centimeter), at first this finding appears only logical. And yet, we must not forget the principle of isostasy (see page 17) according to which material beneath the mountains must be lighter in order to maintain the buoyancy necessary to support them. By the same reasoning, heavy material must exist under the ocean trenches in order to maintain the depression. However, the low gravity readings in the trenches showed that the heavy material required for isostatic balance was definitely *not* present. Meinesz's discovery produced the following important question: what is it that holds down the oceanic trenches? Unless something were holding the trench floor down, it would be expected to rise and soon disappear, just as a mountain range not supported by a light root would sink and soon disappear.

Another feature of the oceanic trenches is their low heat flow, in contrast to the unusually high heat flow along the crests of submarine ridges. This characteristic suggests the following about the origin of the oceanic ridges and oceanic trenches: within the mantle there is a flow of material that ascends at the oceanic ridges and sinks at the oceanic trenches. Additional details of these geophysical measurements in the trench-arc areas and their geotectonic significance will be discussed in Chapter 5.

## The Geomagnetism of the Sea Floor: A Riddle

The new methods of measuring geomagnetism with ship-borne equipment (see page 48) spearheaded the research in deep-sea geophysics, yielding remarkable results on the distribution of geomagnetic anomalies in the ocean. Very active geomagnetic surveys in the East Pacific area were initiated by the Scripps Institution of Oceanography and U.S. Coast and Geodetic Survey and by such scientists as V. Vacquier, R. Mason, and A. Raff.

Figure 2-8 is a schematic representation of the distinct striped pattern of geomagnetic anomalies in the East Pacific extending north and south—a phenomenon never seen on the land. Although the earth's magnetic field forms a dipole pattern (see Figure 1-11), actual measurements reveal some deviations. These deviations are called *geomagnetic anomalies.* There are two general types of geomagnetic anomalies: (1) the large-scale anomalies with dimensions of thousands of kilometers, and (2) the more local ones. Large-scale anomalies are called *regional anomalies* and are believed to be caused by dynamo actions in the earth's core. The *local anomalies* are caused by the inhomogeneous magnetization of the crustal materials, and the anomalies of the ocean floor are definitely of this type. The striped pattern of the geomagnetic anomalies shown in Figure 2-8 therefore suggests that the oceanic crust is magnetized in stripes. When this remarkable striped pattern was discovered, the cause of it became an important riddle in marine geophysics.

There is another important feature shown in Figure 2-8 that is surprising. The stripes appear to be severed in several places. Closer examination of these lines of severance has indicated a displacement of the stripes of more than 100 kilometers; in a few places (not shown in the figure) displacement is so extreme that it is more than 1000 kilometers. These lines of severance are coincident with topographical discontinuities known as *fracture zones.* This displacement of magnetic stripes along fracture zones was a key observation in the theory of plate tectonics.

One of the reasons that many scientists rejected Wegener's ideas was that they could not accept the idea of the continents having moved thousands of kilometers. Yet it seemed clear that the distances that adjacent parts of the ocean floor moved from one another, as estimated by the displacement of geomagnetic stripes, were more than 1000 kilometers.* This indicated a more mobilist view of earth

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*The American Miscellaneous Society, which makes annual awards to people for extraordinary accomplishments, presented Victor Vacquier—a scientist who contributed to the monumental survey of geomagnetism in the East Pacific—their 1966 award, citing him as "The man who moved the ocean floor several thousand kilometers." Vacquier was visiting the University of Tokyo at that time and, as I remember it, the award was a stuffed albatross. This incident was evidence of oceanographers' interest in the displacement of the striped pattern in the marine geomagnetic anomalies.

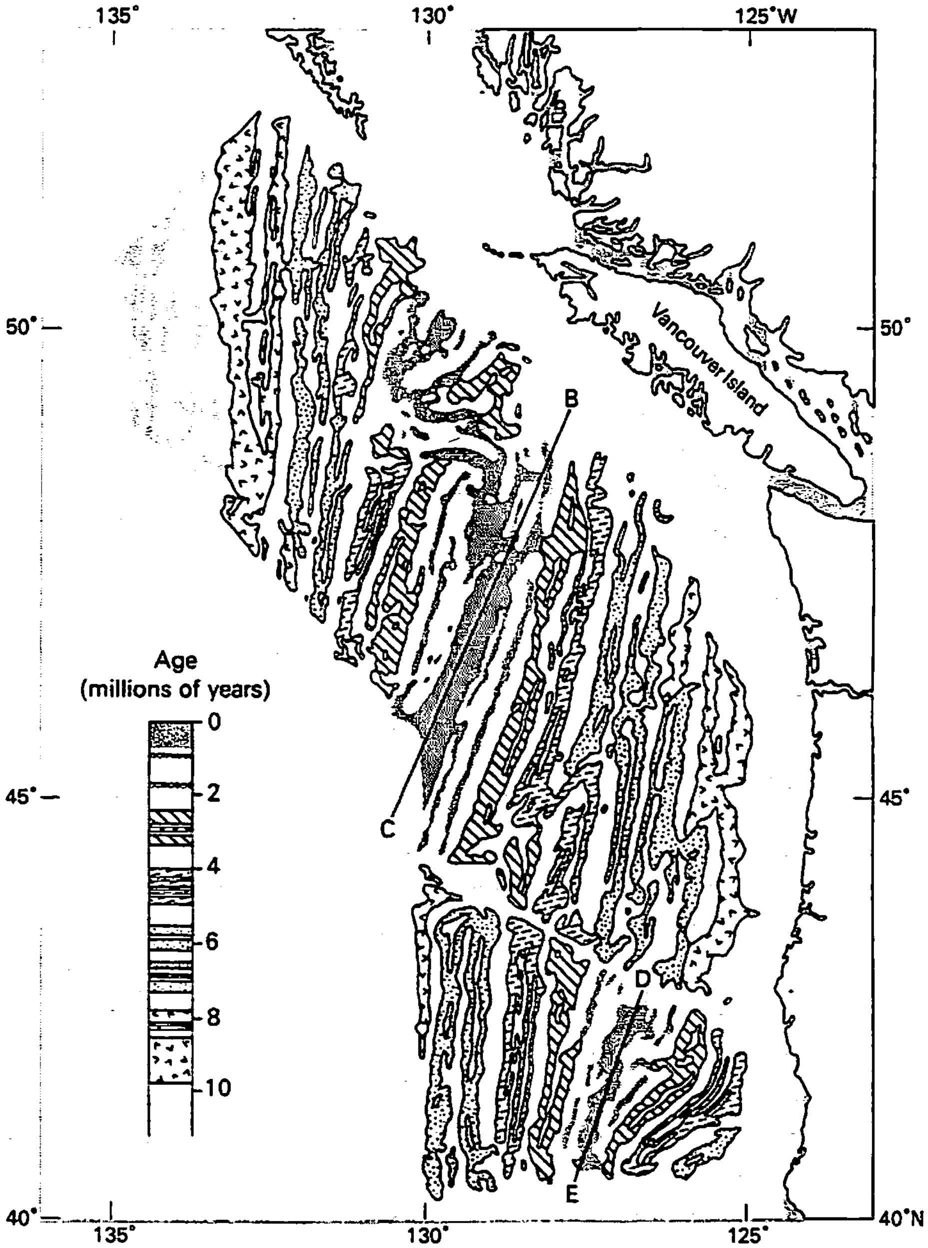

FIGURE 2-8
Summary diagram of total-field magnetic anomalies southwest of Vancouver Island. Areas of positive anomalies are shaded and are thought to approximate the areas of normal magnetization in the oceanic crust. The different patterns represent the different geological ages as shown on the vertical scale. The central anomalies (solid gray) coincide with the ridge crests—the Juan de Fuca to the north (BC) and the Gorda to the south (DE). Note that BC and DE are offset by a fracture zone CD. [From F. J. Vine, "Magnetic Anomalies Associated with Mid-Ocean Ridges," in R. H. Phinney, Ed., *The History of the Earth's Crust.* Copyright © 1968 by Princeton University Press. Redrawn by permission of Princeton University Press.]

history, but the question about the origin of the striped pattern itself remained. When it was finally answered, it was found that the displacement of magnetic stripes was due *not* to ordinary fault movement, but to something even more interesting. This revelation suggested a whole new concept of the earth—a topic we will discuss further in the next chapter.