Chapter 5

Island Arcs

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The Journey's End

Along the northern and western margins of the Pacific lies a series of arcuate island chains—the Aleutians, the Kuriles, Japan, the Ryukyus, and the Philippines. The Izu-Bonin-Marianas arc branches off to the south from Japan. Further south lie Indonesia, the Solomons, the New Hebrides, the Tongas, and finally the Kermadecs. These are all island arcs. Their arcuate form is not their only common characteristic, however. They all have trenches, more than 6000 meters deep; most lie on the ocean side of each arc (see Figure 5-1). The west coast of the South American continent is not an island chain but may be included in this list of island arcs, or at least in the list of arcs with Pacific-type active margins as defined in the previous chapter.

These island arc and trench systems are of vital importance in the new theory of plate tectonics. If the mantle wells up and forms mid-oceanic ridges, and if the oceanic plates produced at the crest of such ridges spread horizontally, there must be zones at which the spreading oceanic plate descends again into the depths of the mantle. Otherwise, the surface area of the earth must increase with time. In fact, some scientists, such as S. W. Carey of Tasmania and B. Heezen have proposed such a model of an expanding earth. But the evidence overwhelmingly contradicts such a hypothesis. The earth is not "inflating." As an examination of a world map reveals, island arc and

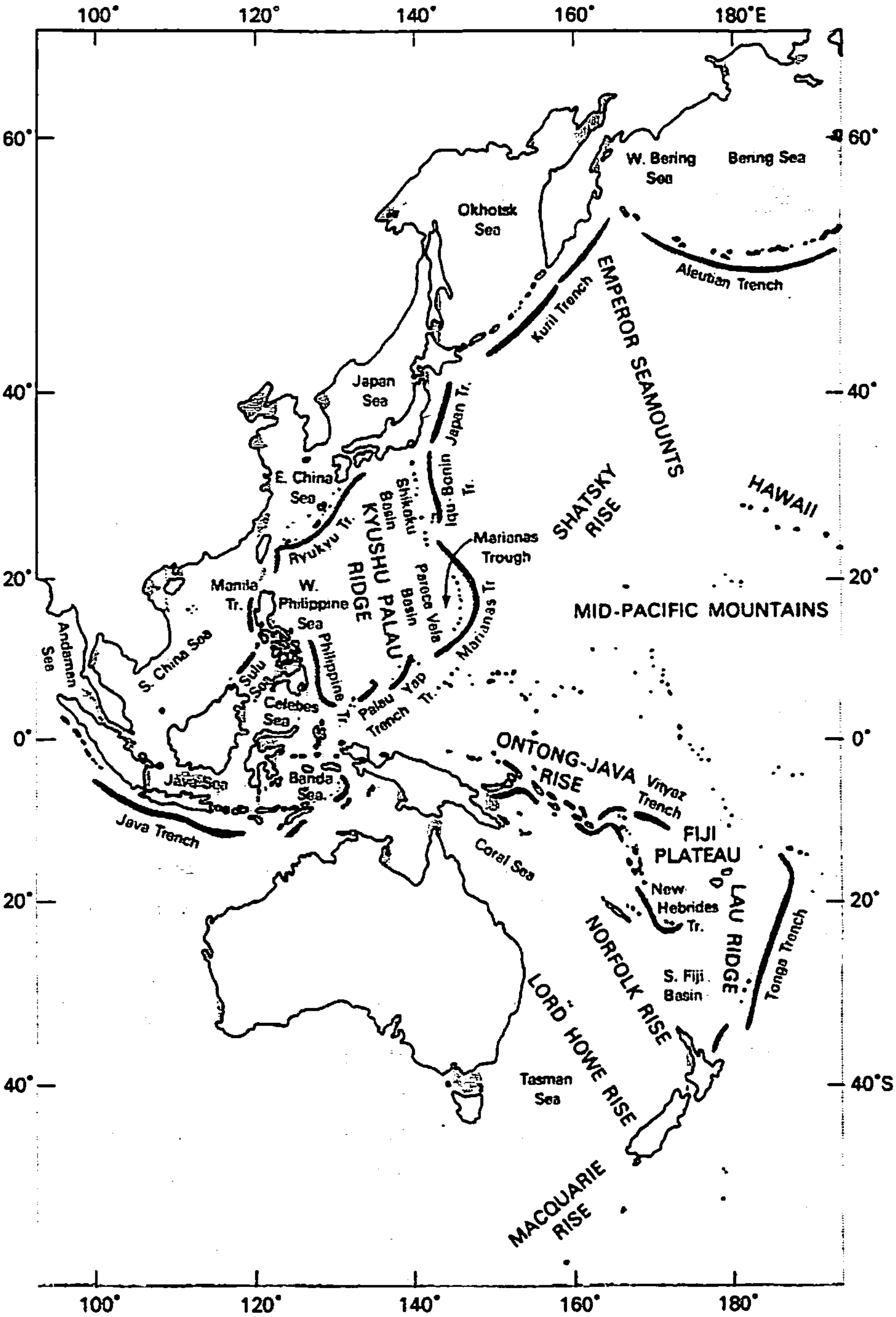

FIGURE 5-1
Island arcs in the western Pacific.

trench systems seem to be the most likely areas for the zones of subduction. A careful investigation of these systems is therefore critical to an understanding of the mobilist view of the earth.

The idea that island arc and trench systems are the journey's end for the ocean floor is not new. Although the theory of plate tectonics has been in existence only for several years, pioneering scientists such as A. Holmes, D. Griggs, and Vening Meinesz had already formulated a similar concept as early as the 1930s. Upon completing a famous experimental study of convection in the mantle, Griggs in 1939 pointed out that the geological features of island arcs could be explained if they were considered as developing on the downgoing zones of mantle flow. Meinesz reached a similar conclusion after measuring the gravity of oceanic regions in the 1930s. The Japanese earth scientists too—though traditionally reluctant to make sweeping hypotheses—accumulated a vast amount of data in their pioneering research, and the information they contributed was essential to the daring idea that was later to be expanded on such a grand scale.

The Japanese Islands

The Japanese islands* are typical of the world's island arcs and have received the most extensive study. For these reasons, and also because of my own familiarity with this particular island arc, it will be the main topic of discussion in this chapter. Many of its characteristics are common to the other arcs as well, however.

Let us begin with the most basic factor, the topography. As is evident in Figure 5-2, the Japanese islands are arcuate in form. If judged by the coastlines of the islands, they appear to comprise four arcs—the Kurile arc, the Honshu arc, the Ryukyu arc, and the Izu-Bonin-Marianas arc. (Figure 5-1). However, if the contours of the submarine topography are taken into consideration, it becomes apparent that the above grouping is not entirely appropriate. "Ocean" and "land" are simply names attached to areas according to their present position relative to the level of the sea. Submarine topography, however, provides us with a much more significant way of perceiving the meaning of the existence of island arcs. A good example of this is the Japan Trench. As the topographical contours in Figure 5-2 show, the highest mountains of the Japanese islands are only 2000 meters above sea level, whereas the topography of the Kurile Trench, the Japan Trench, and the Izu-Bonin-Marianas Trench is much more pronounced, all three trenches being more than 6000 meters deep. The topography would seem to indicate that the Japanese islands actually comprise two island arc systems: one links the Kurile, the northeast Honshu, and the Izu-Bonin-Marianas

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*This topic is discussed more extensively in a recent book by A. Sugimura and me (1973).

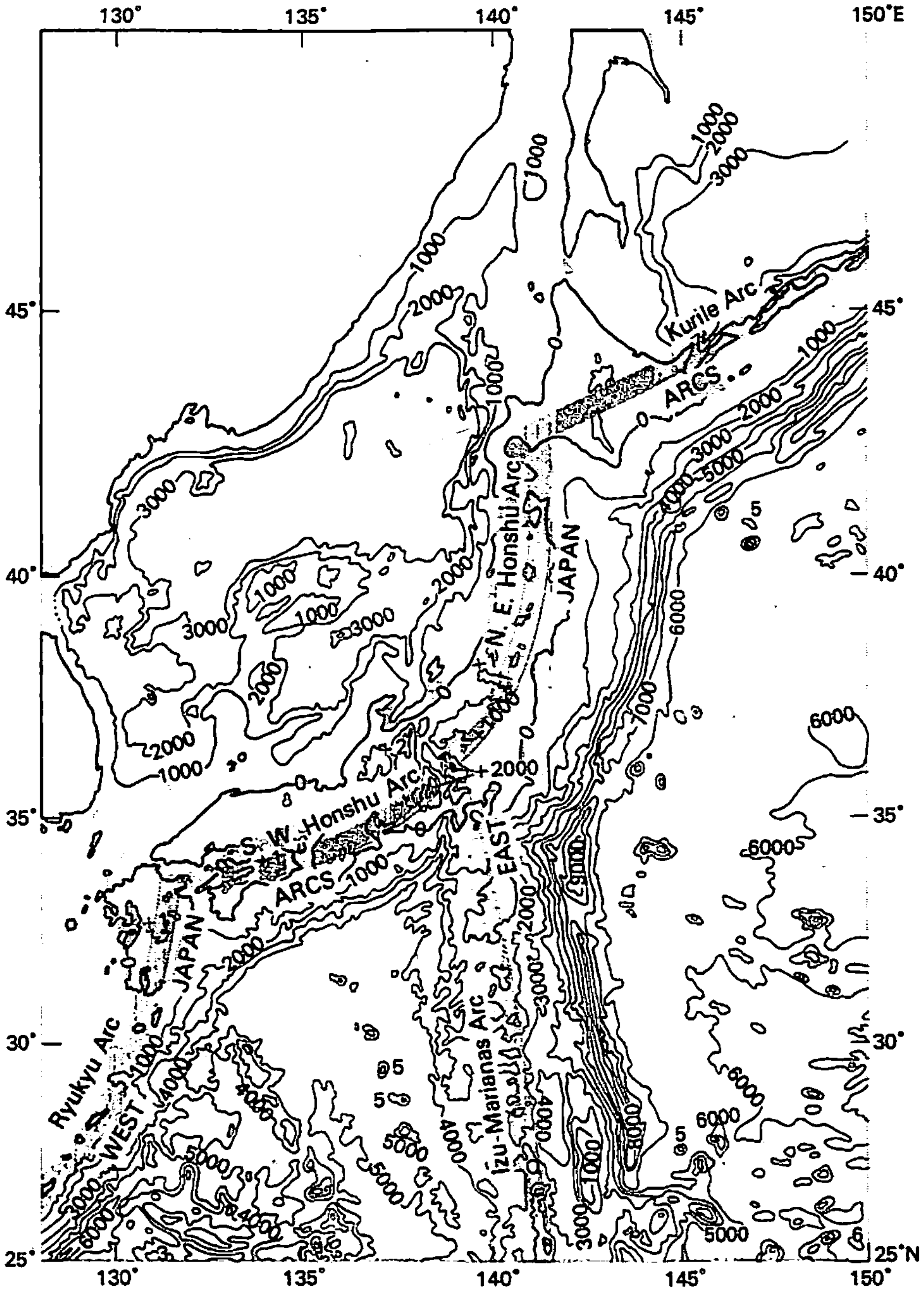

FIGURE 5-2
The topography of Japan and environs (as shown by 1000-meter contours) and the grouping of the island arc system. [After A. Sugimura and S. Uyeda, *Island Arcs: Japan and Its Environs*. Elsevier, 1973.]

Arcs (which we will call the *East Japan Arcs*), and the other links the Ryukyus, Kyushu, Shikoku and western Honshu Arcs (the *West Japan Arcs*). Thus, although Honshu looks like a single arc, it is now considered to be the place at which the two major arc systems meet.

A. Sugimura of the University of Tokyo was the first to conceive of grouping the Japanese islands into these two systems. Although the idea may seem slightly far-fetched, after we have considered all the geological and geophysical circumstances, it will be evident that it is quite valid.

One important feature island arcs have in common is a sea existing on the continent side of the chain of islands, such as the Sea of Japan, the Sea of Okhotsk, and the Philippine Sea (see Figure 5-1). These small seas are called *marginal seas* or, more specifically, *back-arc basins,* and their origin is considered to be critically related to the origin and development of island arcs.

Gravity Anomalies

As mentioned earlier, the gravity measurements undertaken by Meinesz revealed the significance of the island arcs. Gravity is the force that pulls terrestrial bodies toward the center of the earth by universal gravitational attraction. (In order to simplify the topic at hand, we shall disregard the small centrifugal force generated by the earth's rotation.) If the earth were a perfectly homogeneous spherical body, gravity would be identical at any given spot on the earth. Actual measurement, however, reveals that force is variable—stronger in some places, weaker in others. The difference between the actual magnitude of the gravity measured and the *expected* magnitude is called the *gravity anomaly,* and it displays the irregularity of mass distribution in the earth's interior. Rocks that constitute continents are much heavier than sea water, and thus have stronger gravitational pull. Consequently, if the topography of the land and the ocean floor is known, one can calculate how much weaker the gravity is over the ocean than over the land. But the magnitude of gravitational attraction also depends on the distance between the mass and the spot at which the measurement is taken. It is a well known fact that the force of gravitation weakens as distance from the earth's center increases. Thus the strength of the gravity measured on top of a mountain, for example, is the result of two opposing factors—the greater pull of gravity due to the fact that the mountain is made of rocks rather than air, and the smaller pull of gravity due to the greater distance of the mountain top from the earth's center. The factors are reversed if a measurement is taken at the ocean surface. This means that, before we try to use gravity anomalies to learn something about the earth's interior, some adjustments must be made to the raw result of the measurements.

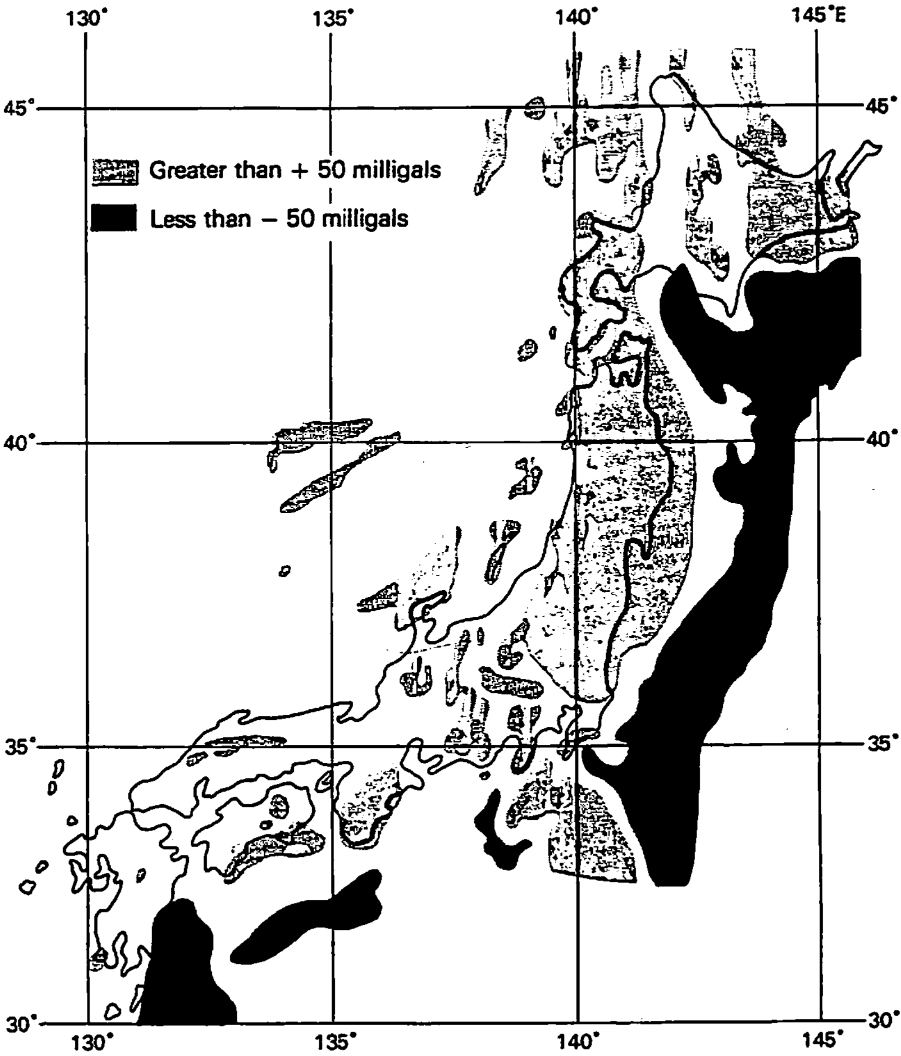

FIGURE 5-3
Free-air gravity anomaly in and around Japan. Positive gravity anomalies are indicated in light gray, and negative anomalies in dark gray. (The milligal is a convenient unit for measuring gravity anomalies. The earth's average gravity field is about 980 gals.) [After Y. Tomoda, "Gravity Anomalies in the Pacific Ocean," in P. J. Coleman, Ed., *The Western Pacific: Island Arcs, Marginal Seas, Geochemistry*. University of Western Australia Press, 1973.]

First of all, the height of the position at which the gravity was measured must be reduced to a standard level, usually to sea level. This adjustment is called the height or *free-air* correction. After this adjustment is made, standard gravity—the estimated gravity that would be present if the earth's structure were completely uniform—is subtracted. The difference is called the *free-air gravity anomaly*. Figure 5-3 illustrates the distribution of the free-air anomaly in and

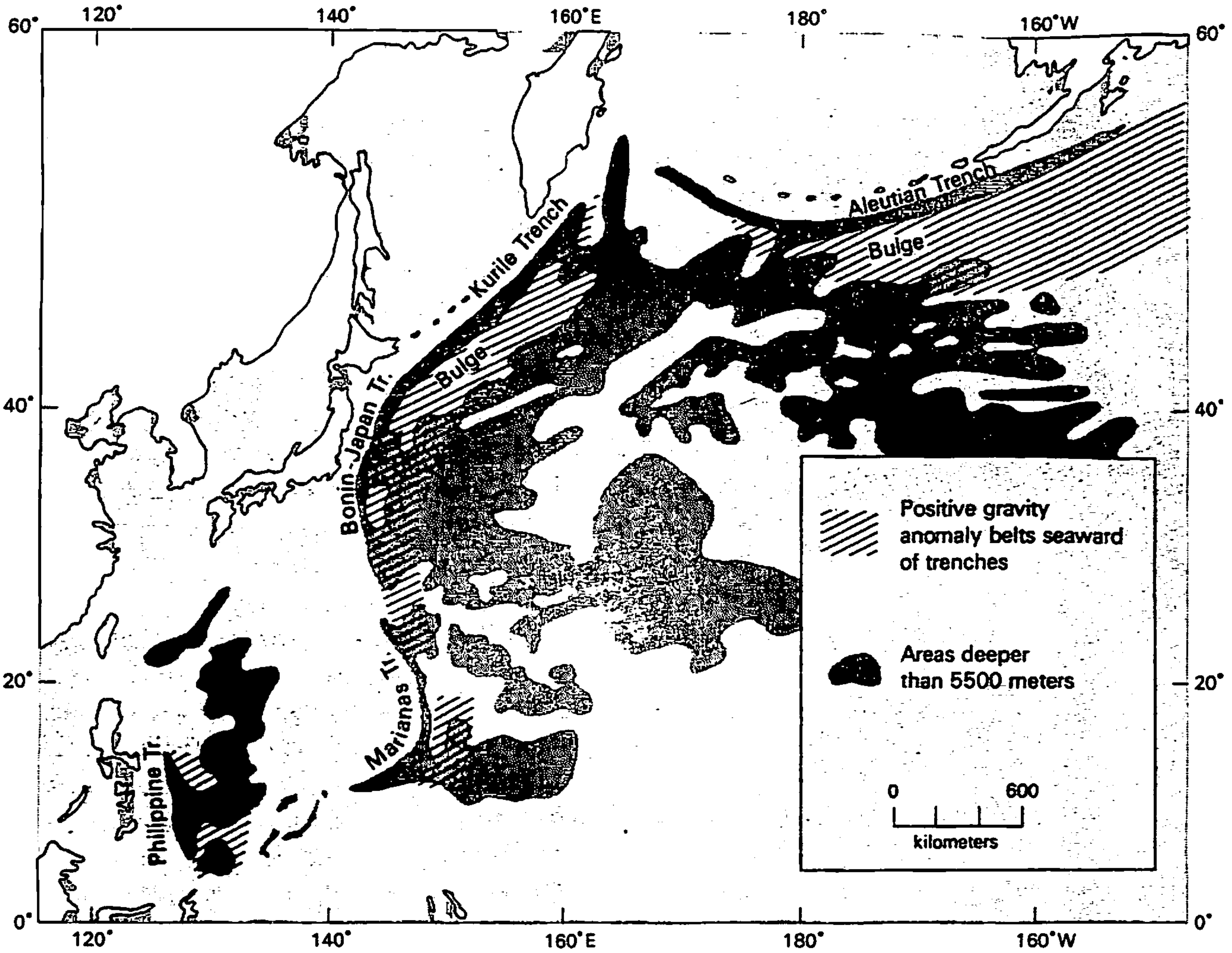

FIGURE 5-4
Positive gravity anomaly belts seaward of trenches, and general bathymetry of the northwest Pacific. Note that the positive anomalies are widest seaward of the central and eastern Aleutian Trench, and narrowest seaward of the Marianas Trench. [After A. B. Watts and M. Talwani, "Gravity Anomalies Seaward of Deep-Sea Trenches and their Tectonic Implications." *Geophys. J.* 36, p. 57, 1974.]

around Japan. Notice that an extensive negative gravity anomaly belt exists in the Japan Trench area. The position of the axis of this belt is displaced slightly toward the continent from the axis of the trench. Part of the negative anomaly is due to the fact that the trench is filled with water instead of rock. However, after allowance is made for this condition, some part of the negative anomaly remains. This indicates that material of low density is present beneath the sea floor.

This result is amazing because it violates the principle of isostasy, which as we saw in Chapter 1, describes the observation that almost everywhere in the world the oceanic crust and the continental crust appear to be floating on the mantle like icebergs floating on water. The negative belt suggests that gravitational equilibrium is not being maintained in the trench. Unless some downward force prevailed here, the deep trench bottom would rise and equilibrium would be restored. The requirement that such a downward force be present can be easily understood if we imagine trying to force a floating log beneath the surface of the water. The log must be either pushed from above or pulled from below. Since it is obvious that no force exists to push from above the trenches, we are left with only one alternative—a force that is pulling down on the ocean floor from the depths of the earth. The theory of mantle convection currents explains this force as the drag created by the downward flow of the mantle. Belts of negative gravity anomaly like that in the Japan Trench are common to all the trenches of the world.

Recently, A. Watts and M. Talwani made an interesting study of the gravity anomalies seaward of the trenches. On the ocean side of many trenches, there are long topographic bulges several hundred meters high. Watts and Talwani found that the gravity anomaly at the bulges too are out of isostatic equilibrium. Again, applying the same logic as we did to the trench anomaly, we can see that the bulge must be supported by some force, an upward force in this case. Watts and Talwani ascribed the positive anomaly to the bending of the oceanic plate, which is strongly compressed as it approaches the trenches. Their interpretation seems reasonable, at least qualitatively, when we consider that the oceanic plate must force its way into the mantle at the trenches (see Figure 5-4 on the preceding page).

Why Do Earthquakes Occur?

Another characteristic of island arcs is the seismicity. As we have seen in Figure 2-4, earthquakes do not occur just anywhere, but are concentrated in the circum-Pacific island arcs, the Alpine-Himalayan orogenic belts, and the mid-oceanic ridge systems. The detailed mechanisms aside, an earthquake is a phenomenon in which displacement occurs in the crust or in the upper mantle as a result of certain underground forces. The distribution of earthquake epicenters shown in Figure 2-4 would seem to suggest, therefore, that this process takes place mainly in the mid-oceanic ridge system, in the island arcs, and in the orogenic belts.

There are however, major differences between the earthquakes that occur in the island arc systems and those that occur in the mid-oceanic ridge systems: one is the depth of the foci.

Deep Earthquakes. Deep-focus earthquakes occur only in island arc areas.* This fact is evident if we compare Figure 5-5 (which shows the distribution of the epicenters of deep-focus earthquakes) on the next page with Figure 2-4 (which shows the distribution of all earthquake epicenters). Now let us consider the distribution of deep earthquakes in more detail by examining that in the Japanese area more closely. Figure 5-6a on page 136 shows the distribution of the epicenters of the earthquakes in the area. Except for the few in the Japan Sea area, almost all of these earthquakes occurred at foci shallower than 60 kilometers. Figure 5-6b shows the epicenters of intermediate and deep-focus earthquakes.† As both parts of the figure show, even in island arc areas the major earthquake activities originate from shallow focal depths.

In this section, we will first examine the deep-focus activity. Note in Figure 5-6a, b that the focal depths are greater closer to the continent. The deepest one (near Siberia) is about 500 kilometers. This variation in the depth of the seismic foci is one of the remarkable features of island arc earthquakes; in comparison, those of the mid-oceanic ridges are all shallow.

As is demonstrated in Figure 5-6b, the foci of deep earthquakes seem to lie on a plane that inclines downward from the oceanic region toward the continent. The existence and distribution of deep-focus earthquakes was discovered in the 1930s by K. Wadati of Japan and his colleagues. Later H. Benioff of the United States investigated them further and stressed their significance, so that the inclined plane of foci has come to be known as the *Benioff zone.* Personally, I

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*The Spanish deep-focus earthquake of March 29, 1954 (focal depth, 630 kilometers) is a notable exception.

†Earthquakes occurring at depths of more than 60 kilometers actually fall into two categories: intermediate-focus earthquakes, occurring at depths of 60 to 300 kilometers; deep-focus earthquakes, at depths of more than 300 kilometers. For the sake of simplicity, we will in some places refer to both types as *deep-focus,* where the distinction is not important.

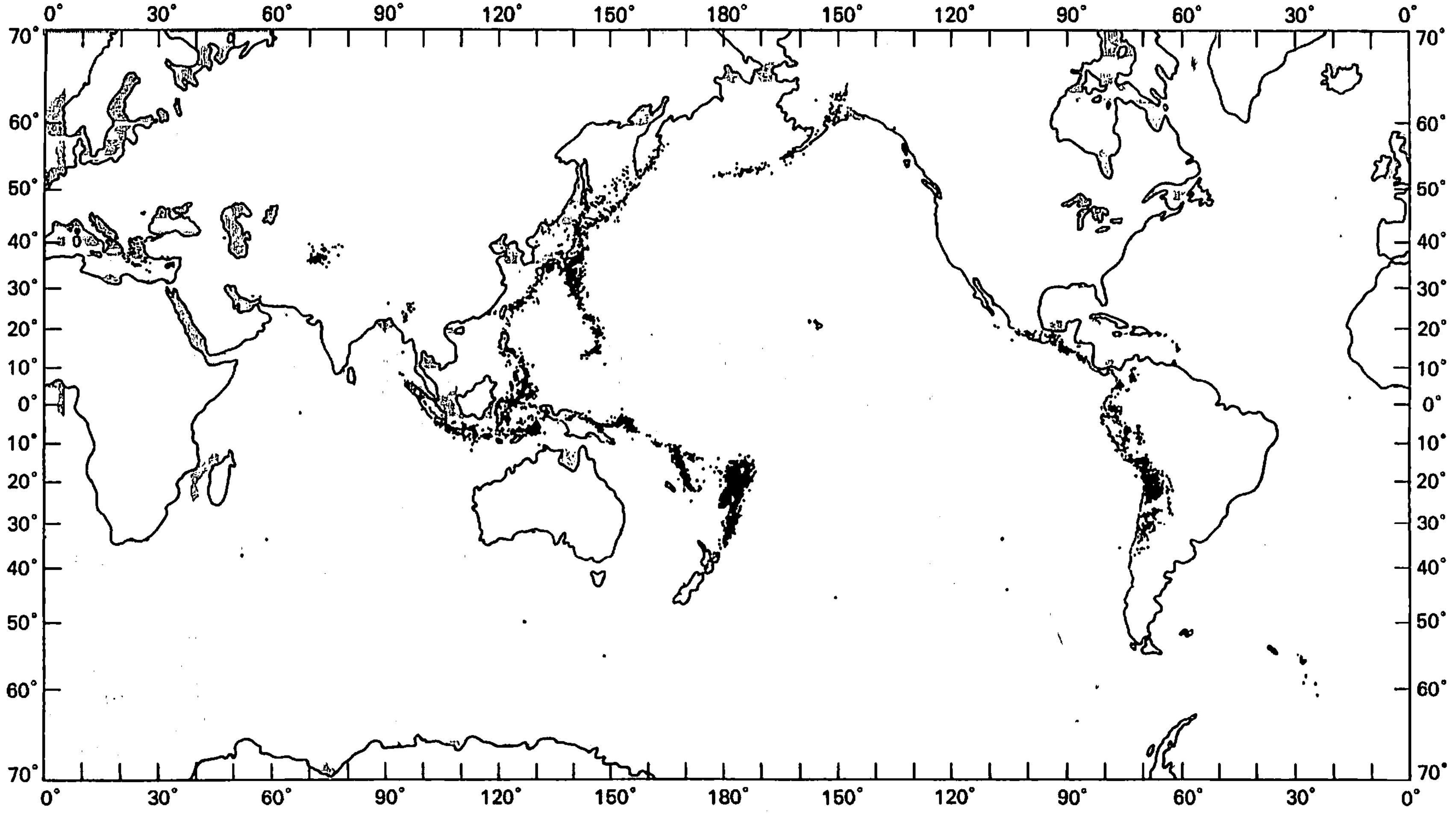


FIGURE 5-5
Distribution of epicenters of earthquakes deeper than 100 kilometers, 1961–1967. [After M. Barazangi and J. Dorman, "World Seismicity Map Compiled from ESSA Coast and Geodetic Survey Epicenter Data, 1961–1967." *Seismol. Soc. Amer. Bull.* 59, p. 369, 1969.]

prefer to call it the *Wadati-Benioff zone* to give due credit to my fellow countryman.

What is the significance of this inclined plane of deep-focus earthquakes? First of all, in order for a fracture to occur that is sudden enough to generate seismic waves, the material must be brittle. Experimental evidence has shown that at high temperature and pressure, rocks tend to lose their brittleness, and flow rather than fracture. So the fact that earthquakes occur at depths where the mantle is hot and under high pressure is an enigma. But it is known that at low temperatures rocks tend to preserve their brittleness even under pressure: therefore, it would be a reasonable inference that along the Wadati-Benioff zone temperature must be unusually low. But it is obviously impossible for the thin, inclined zone to remain at a temperature lower than that of the surrounding mantle for a long time, because the hot mantle that surrounds it will soon heat it up. Apparently it can remain cool only if it is constantly supplied with new cold material in the form of the descending slab of lithosphere. This point was first stressed by D. McKenzie in 1969 in his plate tectonic model. McKenzie found that, if a cold plate of reasonable thickness (70 to 100 kilometers) plunges into the mantle at a speed of several centimeters per year, the center of the plate can remain cool down to 600 or 700 kilometers, the depth of the deepest earthquakes. In contrast, under the mid-oceanic ridges, where hot mantle material continues to well up, only shallow earthquakes occur because the rocks there are quite ductile below the shallow depths.

Thus the very occurrence of deep earthquakes is evidence for the subduction of cold plates. Moreover deep earthquakes would be expected to take place at the central part of the sinking plate in McKenzie's model. Prior to the introduction of this model, it was generally believed that deep earthquakes occurred at the interface between the sinking plate and the mantle surrounding it. The implications of this difference in theory are explained on page 140.

Now in addition to brittleness, there must also be strong stress if earthquakes are to occur. Information on the stress that exists at seismic foci can be obtained from research on earthquake mechanisms. By examining the direction of the initial motions of earthquake waves, the direction of the stress that caused the fracture at the foci can be estimated (see page 78). H. Honda of Japan and his colleagues had made pioneering contributions to the study of earthquake mechanisms as early as the 1930s. At that time many western seismologists believed that earthquakes were caused by a pair of equal and parallel forces acting in opposite directions termed a *force*

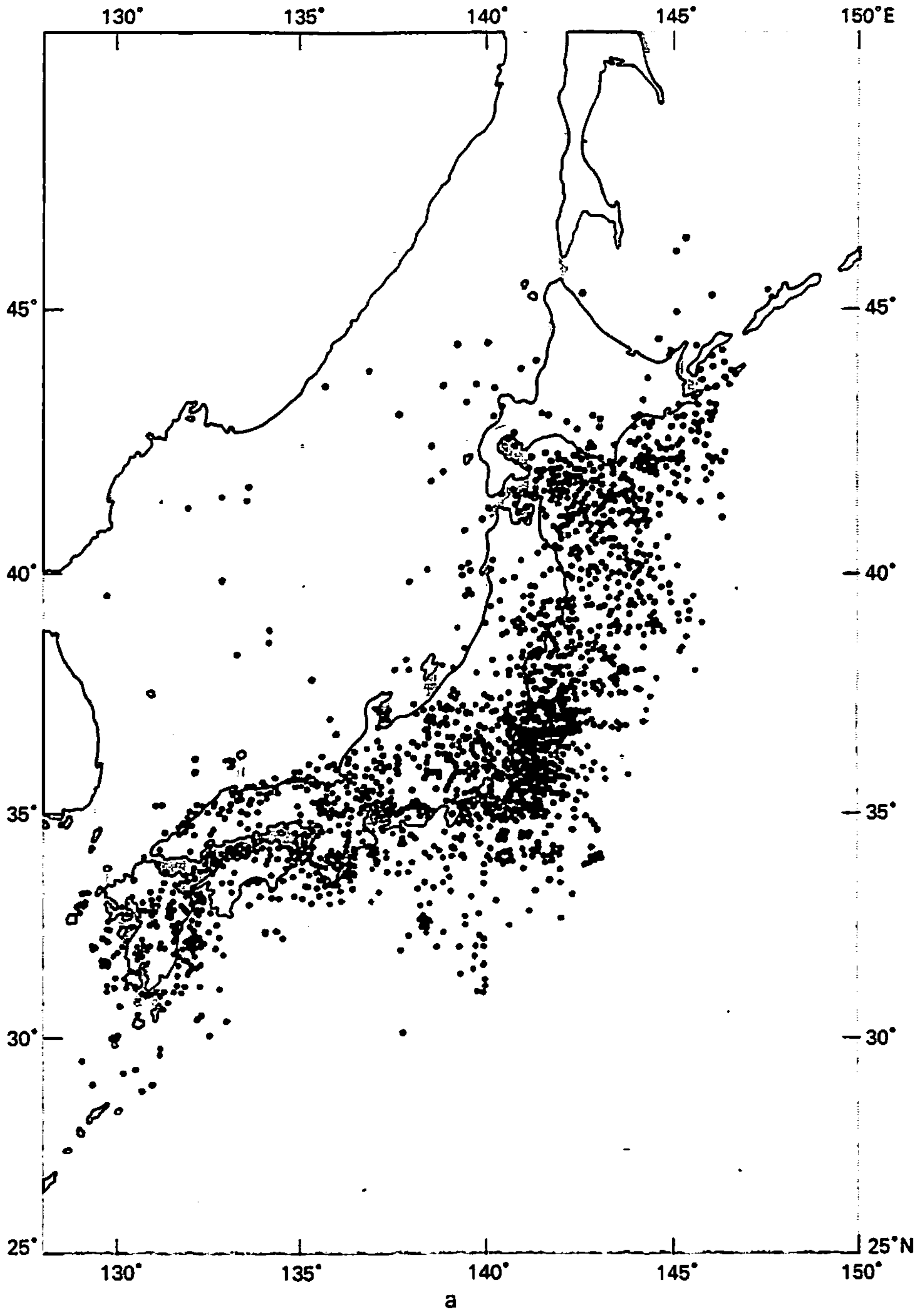
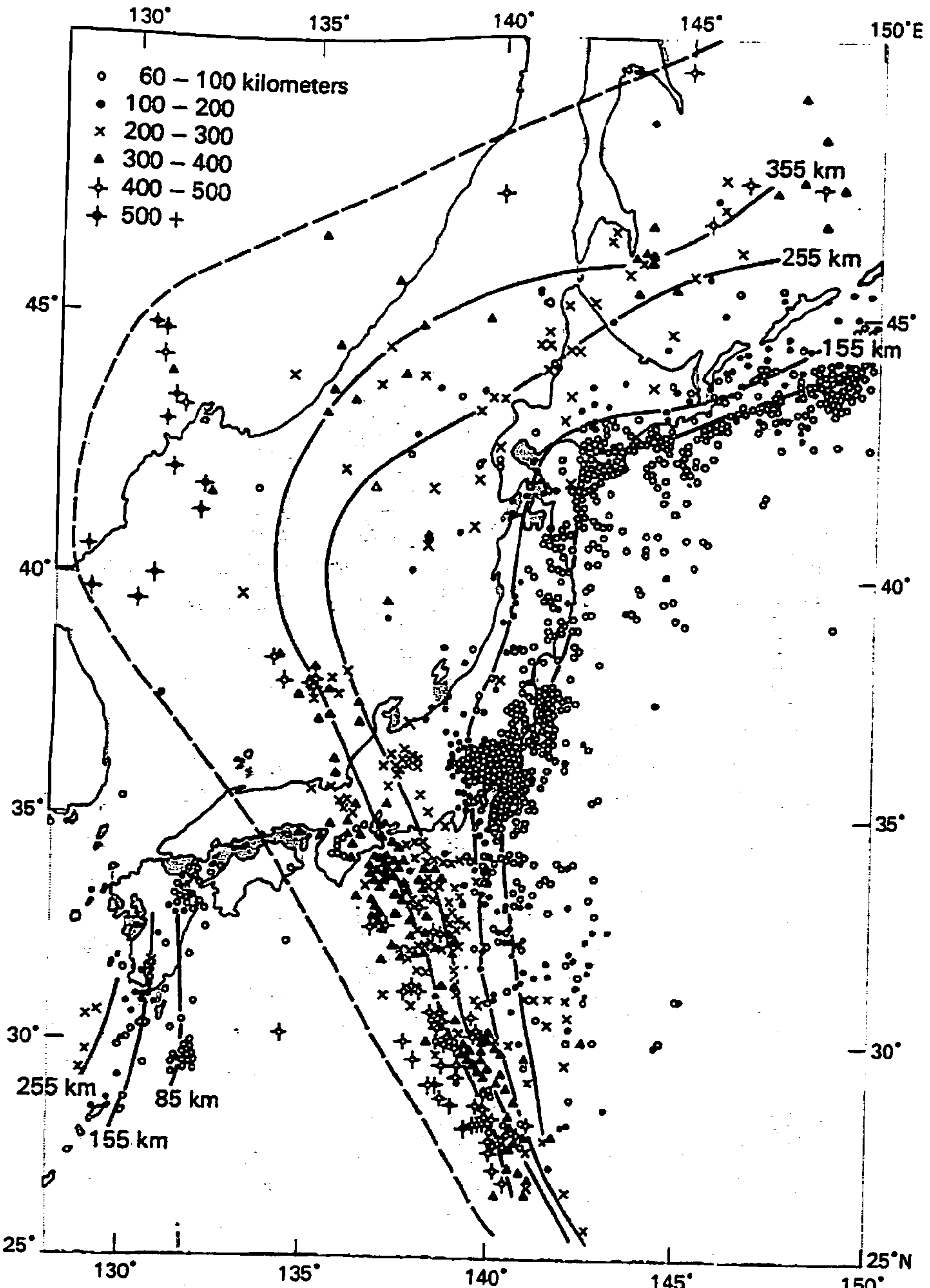


FIGURE 5-6
(a) Epicenters of earthquakes (of magnitude greater than 4) in the Japanese area, 1900–1950. The majority of these earthquakes were shallow-focus, except for those occurring in the Sea of Japan area. (For an explanation of magnitude, see page 142 in the text.)



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(b) Epicenters of intermediate and deep earthquakes, 1928–1962. [After Japan Meteorological Agency, 1958, 1966.]

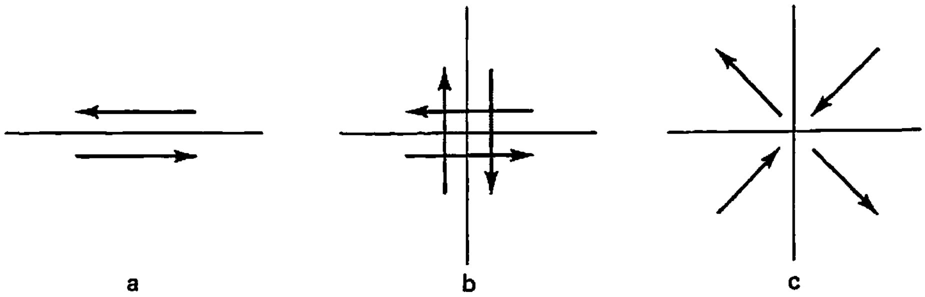


FIGURE 5-7
Proposed models of the forces operating at an earthquake focus.

couple (Figure 5-7a). But Honda and others showed that the cause was a *double couple* (Figure 5-7b)—that is, two force couples perpendicular to each other. The double couple in Figure 5-7b is mathematically equivalent to a pair of compressional and tensional forces as shown in Figure 5-7c. Theoretically, the double couple is more reasonable than the single couple, but it was only after a long period of controversy that Honda's concept was finally accepted. World recognition was delayed primarily because it was impossible to discriminate between the single-couple and double-couple models by observation of the first motion of *P* waves alone. The validity of the double-couple model was finally confirmed by examining the distribution of the initial motion of *S* waves. Detailed research on the initial motion of *S* waves was difficult because, by the time they arrive, *P* waves have already registered on the seismogram, thus making it hard to observe the arrival of the *S* waves clearly. Japanese seismologists may have had an advantage in this research, because frequent earthquakes have prompted the installation of seismometers all over Japan, thus enabling them to arrive at the correct solution.

The directions of the two couples, as determined from the study of seismic waves, delineate the direction of the forces acting at the focus at the moment of the earthquake, that is, the earthquake-generating forces. Figure 5-8 demonstrates the distribution of these forces in the area around Japan. It shows the directions of the compressional stress of deep-focus earthquakes projected on a horizontal plane. It is clear from this figure that there is a regularity in the geographical distribution of such forces. The direction of the compressive axis is perpendicular to the direction of the arc. This again would seem to provide evidence of stress conditions consistent with the theory of plate tectonics.

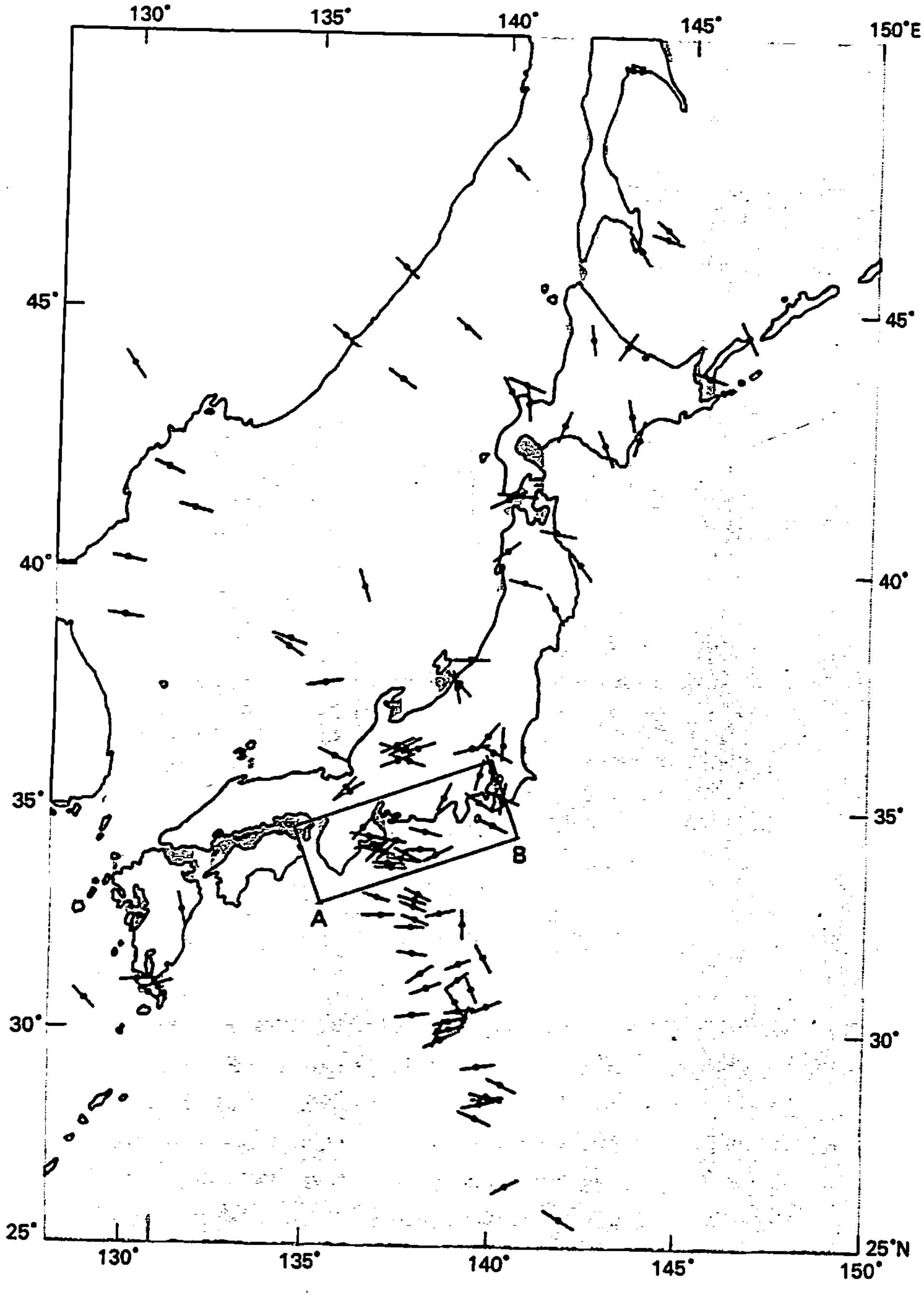


FIGURE 5-8
Directions of the maximum horizontal compressional stress for intermediate and deep earthquakes. The directions of the stress are indicated by the bars attached to each epicenter. For an explanation of the rectangle AB, see Figure 5-9. [After H. Honda, "On the Mechanism of Deep Earthquakes and the Stress in the Deep Layer of the Earth Crust," *Geophys. Mag.*, Japan Meteorological Agency, 8, p. 179, 1934; M. Ichikawa, "Mechanism of the Earthquakes in and near Japan, 1950–1962," *Papers Meteorol. Geophys.* 16, p. 201, 1966.]

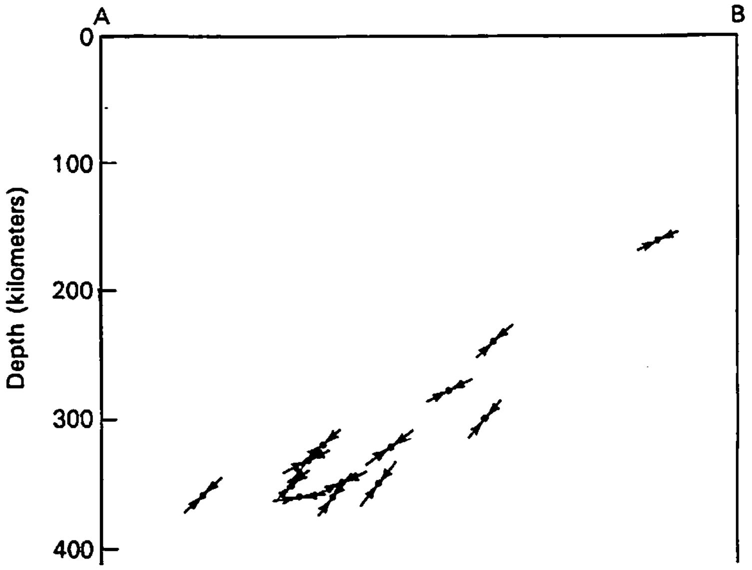
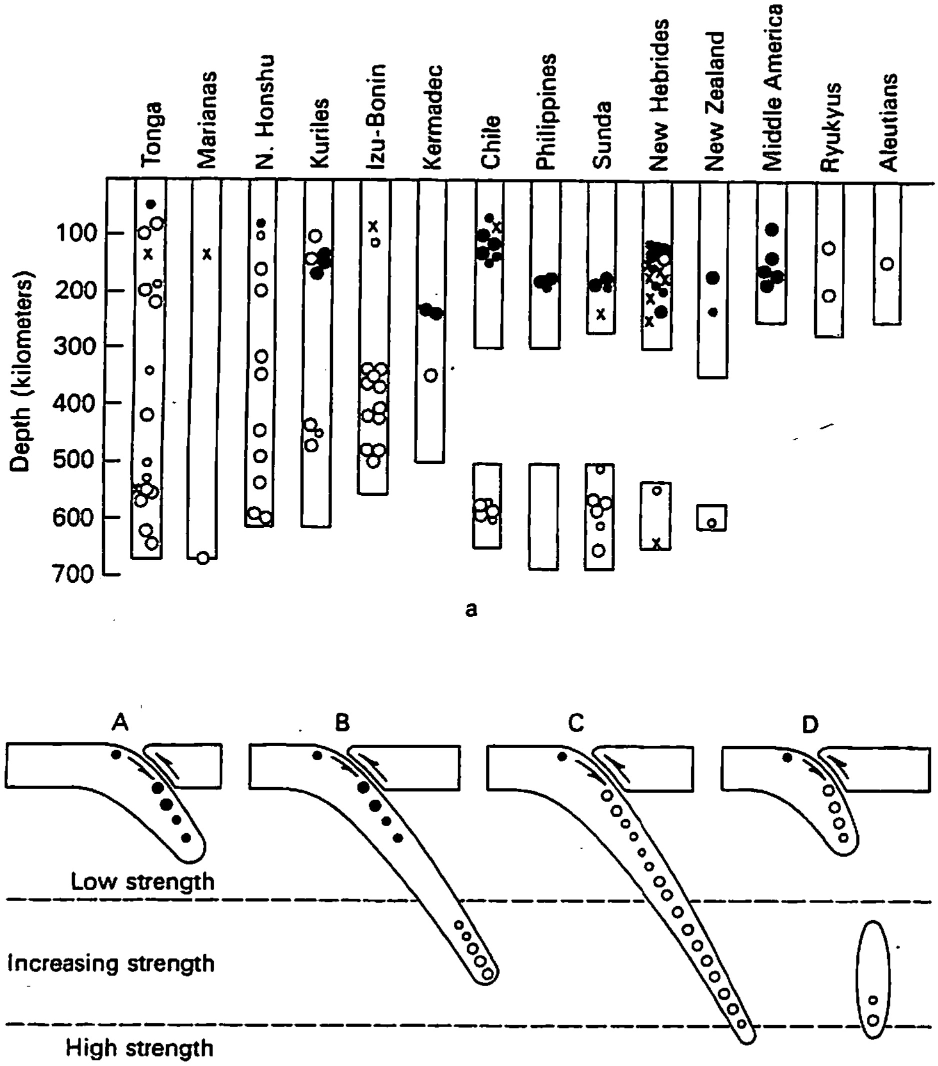


FIGURE 5-9
Directions of the principal compressional stresses for intermediate and deep earthquakes in a vertical plane. Symbols are the projections on the vertical plane passing AB in Figure 5-8. [Data after H. Honda et al., "On the Mechanism of Earthquakes and the Stresses Producing them in Japan and Its Vicinity." *Geophys. Mag.*, Japan Meteorological Agency, 33, p. 27, 1967.]

However the picture is not so simple when we look at the stresses seen in a vertical cross section through the descending slab. Figure 5-9 shows the direction of compressional stress between A and B in Figure 5-8 projected onto a vertical plane perpendicular to the trench. We see that the direction of the compressional axes is parallel to the plane of the descending slab as determined from seismology. What does this mean? If the sea and continent (right and left in Figure 5-9) are exerting stress on each other as they move together, wouldn't one expect the direction of the compressive stress to be horizontal? Instead it is a *down dip* stress—that is, one parallel to the seismic plane and directed down the direction of dip of the slab. Many people, myself included, were troubled by this apparent dilemma for some time. Then in 1969 B. Isacks and P. Molnar discovered that under many other arcs the stresses are also down dip, but that sometimes it was the tensional axis rather than the compressional axis that was aligned parallel to the dip of the slab (Figure 5-10a).



a

b

FIGURE 5-10
(a) Down-dip stress type plotted as a function of depth for fourteen regions. A filled circle represents down-dip extension; an unfilled circle represents down-dip compression; and the crosses represent orientations that satisfy neither of the preceding conditions. Smaller symbols represent stress types that have not been accurately determined. The enclosed rectangular areas indicate the approximate distribution of earthquakes as a function of depth by showing the maximum depth and the presence of gaps for the various zones.
(b) A diagram showing possible distribution of stresses in slabs of lithosphere that sink into the asthenosphere (A) and hit bottom (B and C). D represents a slab from which a piece has broken off. The symbols for the stress types are the same as in Figure 5-10a. In B and D gaps in the seismicity would be expected. Also shown are the underthrusting and the extensional stresses near the upper surface of the slabs due to the bending of the slab beneath the trenches. These features are inferred from the mechanisms of shallow earthquakes (to be explained in the text). [After B. Isacks and P. Molnar, "Mantle Earthquake Mechanisms and the Sinking of the Lithosphere," *Nature* 223, p. 1121, 1969.]

Plate tectonics provided a simple, clear-cut solution to this problem too. Isacks and Molnar explained the phenomenon as follows: when the plate sinks, it meets resistance from the deeper, hard mantle as illustrated in Figure 5-10b. Moreover, the earthquakes occur in the middle of the plate or slab rather than at its interface with the mantle (see page 135). It would thus be more natural to describe the resistive force against the sinking plate as parallel to the slab. Let us note here that the mantle is soft in the asthenosphere but becomes harder at a depth of, say, 500 to 700 kilometers. As we will see in the next chapter, the descending slab is considered to sink by its own weight, so that there will be a tensional force in it if the resistance from outside is small. This explains the distributions of stresses shown in Figure 5-10b (at A, B, and D).

Shallow Earthquakes. Shallow earthquakes are much more spectacular because the energy released is so much greater and consequently their impact on human society is much more significant.

The size of an earthquake is usually represented by its magnitude *M*. We tend to think of earthquakes with great tremors as big and those with weak tremors as small; but this is not quite accurate, because no matter how big the earthquake might be, one cannot feel much shaking if the earthquake has occurred a great distance away. Just as the brightness of two lamps can be compared accurately by an observer only if the lamps are at an equal distance from the eye, the magnitudes of two earthquakes can be compared in terms of the amount of perceived shaking of the ground only if the observations are made at equal distances from the focus.

Earthquake magnitudes are generally determined by a standard method devised by C. Richter and B. Gutenberg. On the *Richter magnitude scale,* when the magnitude goes up by one unit, the seismic energy increases 30 times. The famous San Francisco earthquake of 1906 had a magnitude of 8.25; the great Kanto earthquake of Japan in 1923, a magnitude of 8.2; the Chilean earthquake of 1960, a magnitude of 8.3; and the Alaskan earthquake of 1964, a magnitude of 8.4. There is no record of an earthquake with a magnitude greater than 8.7. The seismic energy that accompanies an earthquake with a magnitude of 8 is approximately 10^{25} ergs*, which equals the energy of 10,000 atomic bombs of the type dropped on Hiroshima!

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*The erg is the unit of energy: 10^7 ergs is equivalent to 0.239 calorie.

Earthquakes with a magnitude of more than 7.5 are called *great earthquakes*. All of them are shallow, and nearly all of them occur in the circum-Pacific seismic belt. No great earthquakes have been known to occur in the mid-oceanic ridge areas. This is another major difference in seismicity between island arc systems and mid-oceanic ridge systems.

How do shallow earthquakes in island arc systems originate? From an analysis of the seismograms of great earthquakes and application of recent advancements in seismological theory, one can estimate not only the direction of the faulting that caused the earthquake, but also the size of displacement at the fault and even the size of the fault itself. H. Kanamori and others exhaustively investigated the great earthquakes that have occurred in the circum-Pacific zones. He proved that most of them took place when the sea floor of the Pacific was underthrust beneath the crust on the land side of the trench, and that the relative displacements along the faults were several meters.

In the meantime, S. M. Fedotov of the USSR, K. Mogi of Japan and L. Sykes demonstrated that areas of rupture caused by great historic earthquakes form oval patches that are roughly parallel to the arc. These patches tend to form a belt, but one that is discontinuous with numerous gaps at which no rupture has taken place during the time for which we have records. Furthermore, they showed that as more recent earthquakes occur, their focal areas tend to fill in these gaps rather than overlapping one another (Figure 5-11). They also pointed out that the time interval between great earthquakes in one area is in the neighborhood of 100 years.

One other fascinating fact should be mentioned here. It has long been known that great earthquakes in Japan cause the Japan Pacific coast to lift up by a few meters. But during an interquake period the coast gradually subsides.

If we put the foregoing information together, the following view is not too far-fetched: during the interquake period, the Pacific sea floor continues to underthrust several centimeters per year, dragging the crust on the land side down into the earth. When the deformation caused by this dragging reaches a critical point, a slip occurs at the boundary between the land crust and the oceanic crust and, as a result, the land side rebounds and is uplifted (see Figure 5-12). Assuming the average underthrust rate to be 5 centimeters per year and the interquake period to be 100 years, the slip would be 5 meters. This figure is in excellent agreement with the order of magnitude of the fault displacement—believed to be several meters—estimated from the seismic waves at the time of great earthquakes.

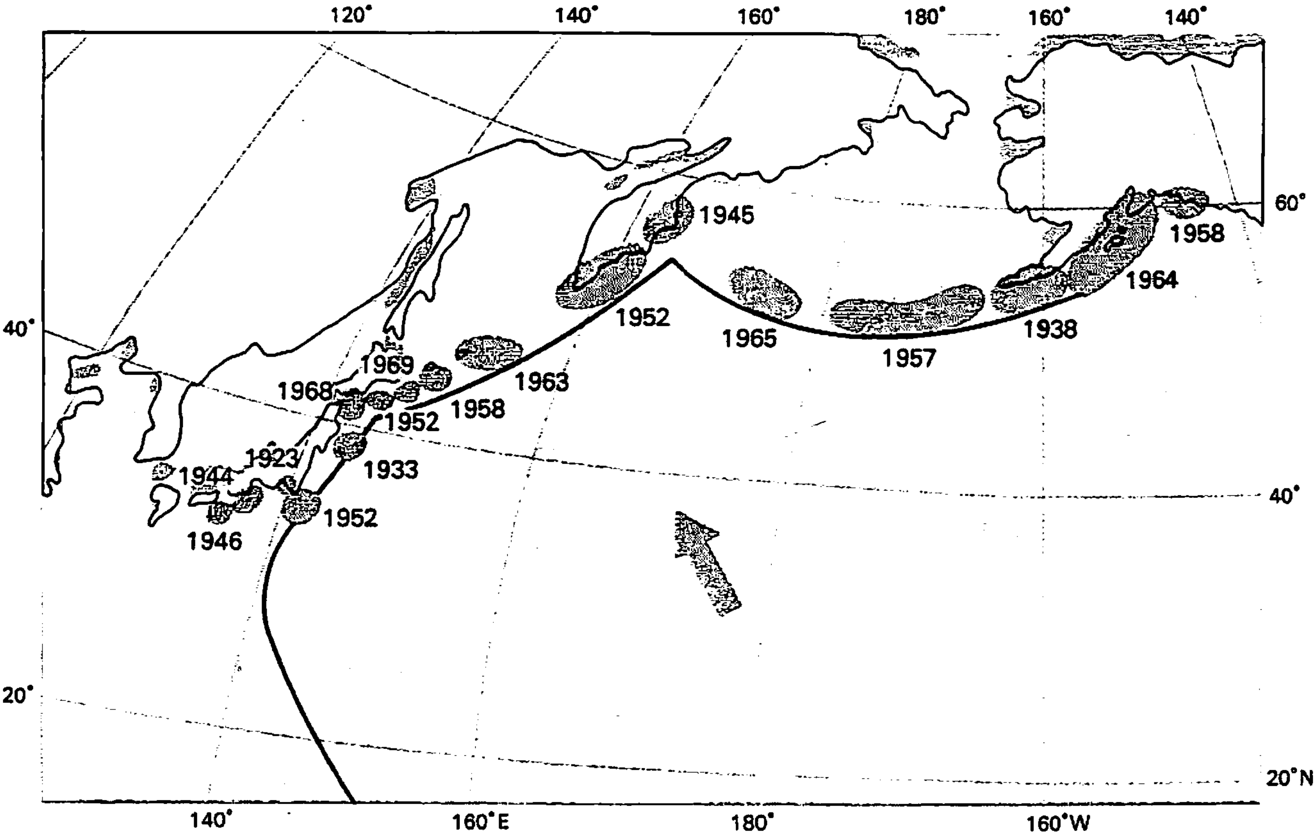

FIGURE 5-11
Distribution of focal regions as defined by after-shock areas of great earthquakes in the northwest Pacific margin. The year of the earthquake is indicated for each region. The arrow shows the approximate direction of motion of the Pacific Plate relative to the Eurasian and American Plates. [After K. Mogi, "Sequential Occurrences of Recent Great Earthquakes." *H. Phys. Earth* **16,** p. 30, 1968]

The fact that such fault areas are filling up the entire circum-Pacific zone also tends to support the plate tectonic theory, because it demonstrates that the entire rigid Pacific plate is subducting beneath the continental plate.

To summarize briefly the difference between shallow and deep earthquakes, the shallow earthquakes that occur in island arc regions are *inter*plate earthquakes that originate from the interaction of the oceanic and the landward plates—that is, the subduction of the first beneath the second; deep earthquakes, by comparison, can be termed *intra*plate earthquakes, because they occur within the subducting slab. The origin of earthquakes at other types of boundaries (diverging and transform fault boundaries) has already been discussed on pages 78–79.

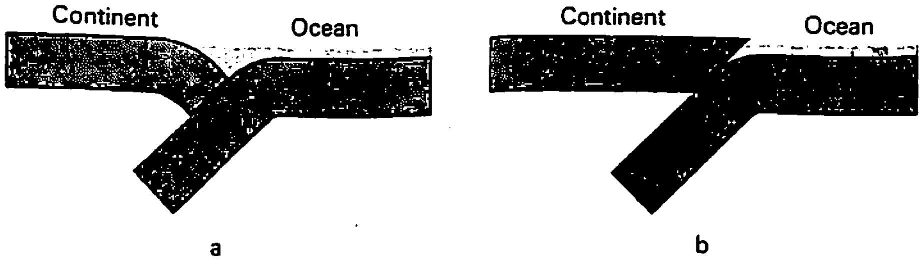

FIGURE 5-12
Movements assumed to take place under island arcs: (a) during the interquake period; (b) at the time of an earthquake.

The Underground Structure of the Japanese Islands

We have seen that the gravity anomalies seem to indicate that some force besides gravity is pulling the trench floor into the earth in the island arc regions. The testing of such an inference naturally requires another method of observation—the determination of crustal structure through observation of seismic waves. Unusual layers of rock underground can be detected by seismometers, because in such areas the seismic waves will show irregular propagation. This procedure is called seismic prospecting, and has long been used for the detection of oil and other mineral resources. Not until after World War II, however, was it widely used for the purely scientific purpose of studying the crustal structure to a depth of many tens of kilometers. In 1947 a vast quantity of German explosives were detonated on an island in the Atlantic in order to dispose of them. This occasion—presenting European seismologists with the opportunity to observe at the same time, from different points on the continent, the seismic waves generated from this explosion—turned out to be the world's first large-scale experiment in explosion seismology.*

In Japan, a Research Group for Explosion Seismology was organized in 1950 and has been actively engaged since then in exploring the crust and upper mantle. According to their studies, the crust under the Japanese islands seems to consist of the following layers:

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*As a result, for the first time they were able to obtain information on the deeper structure of the European continent, since this kind of information can be gained only by observing seismic waves from a distance: the further away the observer is from the seismic wave source, the deeper his observations can be.

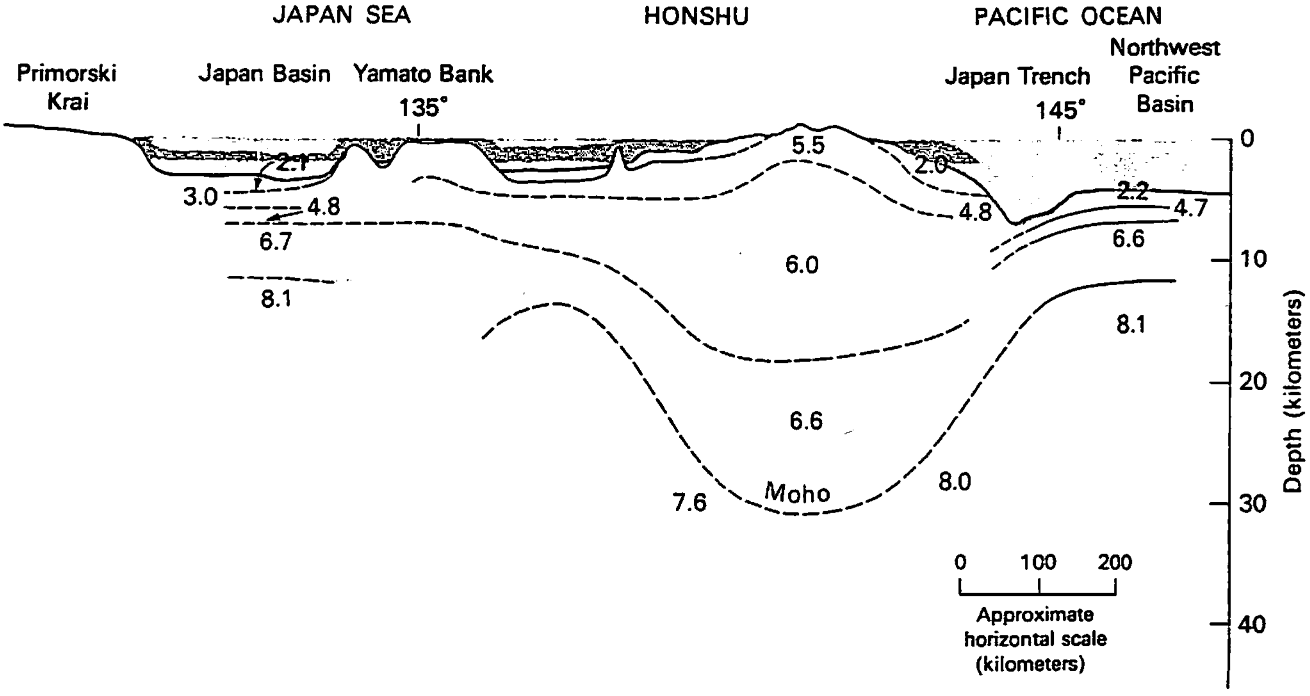

FIGURE 5-13
Crustal cross section across northeastern Japan. The numbers indicate P-wave velocity in kilometers per second. When there are breaks in the boundaries delineating the crustal layers, data were incomplete. [From S. Murauchi and M. Yasui, "Geophysical Investigations in the Seas around Japan." *Kagaku* 38, p. 196, 1968.]

an uppermost layer several kilometers thick with a P wave velocity of 5.5 kilometers per second, and a second layer 10 to 30 kilometers thick with a P wave velocity of 6.0 to 6.6 kilometers per second. This second layer may be composed of two distinct layers—one granitic and the other basaltic. The crust under the Japanese islands is thus almost continental. It was also found that the P wave velocity of the uppermost mantle (immediately below the Moho discontinuity) is about 7.6 to 8.0 kilometers per second. A velocity of 7.6 kilometers per second is significantly smaller than that of the world average (8.0 to 8.2 kilometers per second). These major results are illustrated in the crustal cross section of Figure 5-13. As can be seen in this figure, the crust under the Pacific Ocean is much thinner than the 30-kilometer crust under the Japanese islands. The crust under the Sea of Japan is also thin, especially in the region called the Japan Basin. There the sea is some 3500 meters deep and the crust is almost as thin as that of the Pacific Ocean. The area of the Yamato Bank, in the southwestern part of the Sea of Japan, has a thicker crust somewhat similar to the continental one.

Apparently the general tendency of the crust to become thin beneath the deep sea does not apply to trenches. Note in the figure that the crust under the Japan Trench is no thinner than that under the Pacific basin. This further verifies the inference derived from the results of gravity observation that isostatic equilibrium is not maintained in the oceanic trench areas.

Volcanoes and the Belt of Volcanic Rocks

As has been observed so far, the various geophysical features of island arcs—such as gravity anomalies and earthquake activity—show a certain set of regularities. Such regularities exist not only in the Japanese area but in all island arcs. This fact would lead one to postulate that island arcs may be created by a certain mechanism common to all of them. The theory of plate tectonics suggests this mechanism is the subduction of the cold slab into the mantle.

But some geophysical features, despite their regularity, are not so easy to explain within the framework of the basic concept of subduction. For example, consider volcanic activity. The distribution of volcanoes is quite similar to that of earthquake foci. Volcanoes, like the foci, are concentrated on island arcs and oceanic ridges. There are active volcanoes in the ocean basins also, such as those of the Hawaiian Islands, but only a few. More than 90 percent of the world's active volcanoes are situated on the circum-Pacific island arcs. Figure 5-14 shows the distribution of volcanoes in Japan. As can clearly be observed, they are concentrated along the two systems of island arcs, the East Japan and the West Japan Arcs that are shown in Figure 5-2.

Although both volcanoes and earthquake foci exist in island arc systems, the distribution of each varies, as can be seen when the distribution of earthquakes in Figure 5-6a is compared to that of volcanoes in Figure 5-14. Whereas the majority of foci are concentrated on the oceanward sides of the island arcs, no volcanoes exist on the oceanward sides of the island arcs. The distribution of volcanoes and earthquakes may seem to be similar when indicated on a world map. Under more careful scrutiny, however, it becomes clear that their belts of concentration are displaced from one another. The oceanward boundaries of the volcanic zones can be clearly determined. These boundaries were named the *fronts of the volcanic belts*

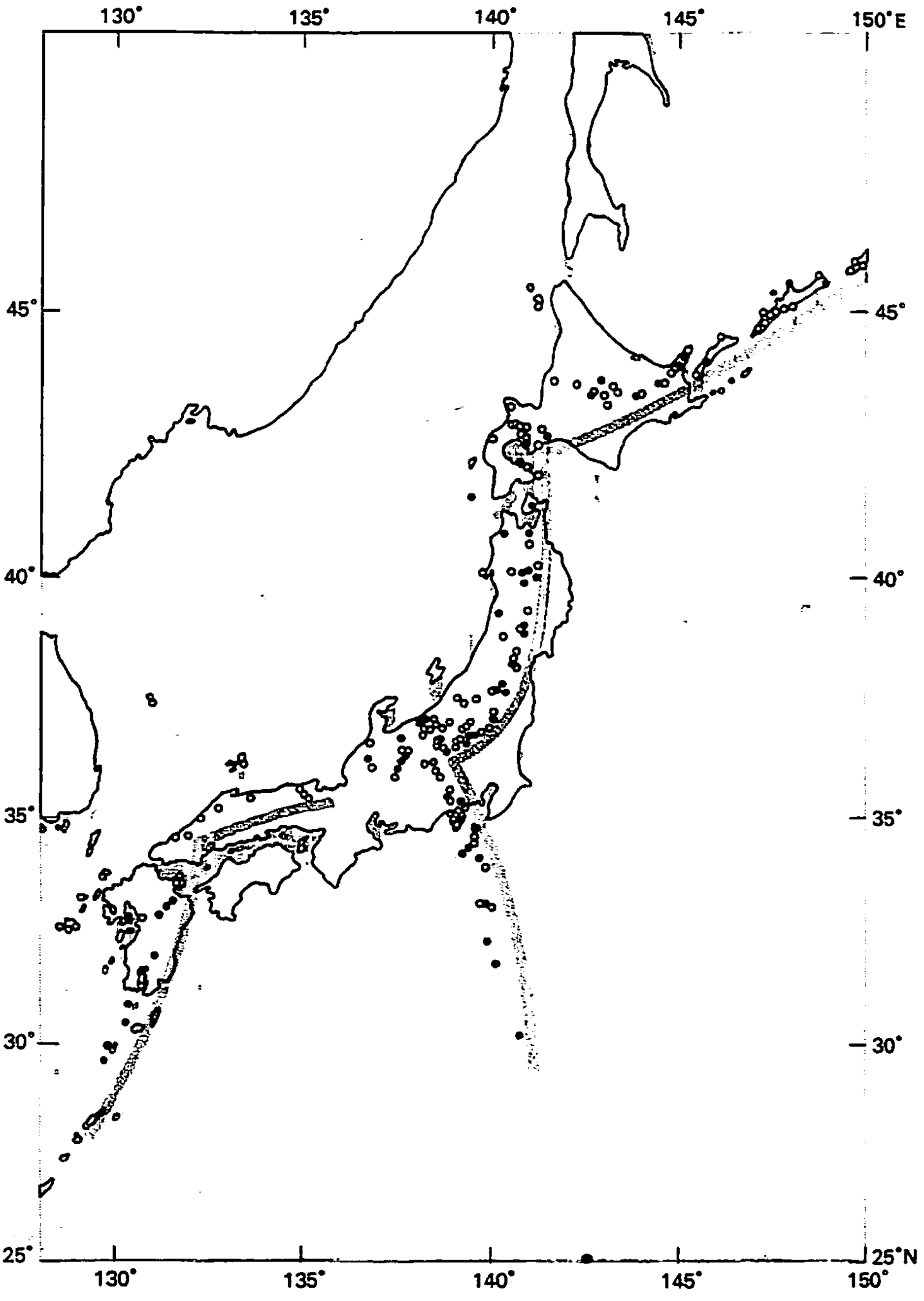

FIGURE 5-14
Distribution of volcanoes in Japan. Volcanic fronts are indicated by the gray shading. The closed circles indicate active volcanoes; the open circles, other Quaternary volcanoes. [After A. Sugimura and S. Uyeda, *Island Arcs: Japan and Its Environs.* Elsevier, 1973.]

or *volcanic fronts* by A. Sugimura in 1963. Why is it that not a single volcano exists on the oceanward side of the volcanic fronts?

Volcanic rocks are solidified lava that has been spewed out from volcanoes. The chemical composition and mineral assemblage of these rocks vary greatly, however, depending on the nature of the original magma—called the parental magma—at depth, and also on the various processes the magma has gone through before the eruption. For instance, if the temperature of the magma decreases, fractional crystallization takes place as minerals of certain composition crystallize and sink. Moreover, the remaining magma may react with the surrounding rocks. Both of these processes cause changes in the magma's composition. Modern petrology now enables us to estimate the chemical composition of the primary magma from the extruded lava, taking these complicated processes into consideration. Such estimates have revealed a regularity in the nature of volcanic rocks. The pioneering study in this field was conducted in Japan by T. Tomita in the 1930s, and more recently by the late H. Kuno. Their results showed a regularity in the chemical composition of primary magma. Among the various volcanic rocks, those exhibiting a chemical composition closest to the primary magma are basalts. For this reason, Kuno used basalt to determine the nature of parental magmas. Figure 5-15 shows the distribution of types of basaltic parental magmas in Japan, as proposed by Kuno. The magma that exists under the volcanoes near the volcanic front is called *tholeiite* basalt magma. The magma found farther from the volcanic front, and closer to the Asiatic continent, is called *alkaline* basalt magma, which is much higher in potassium and sodium content than tholeiite. Between these two regions of different types of magma lie basalts with high aluminum content. Kuno named such zones of magma *petrographic provinces.*

To explain the origin of these petrographic belts, which are parallel to the trench, Kuno proposed that the depth of magma production is shallower near the volcanic front and deeper near the continent. This hypothesis is based on findings from experimental petrology. H. S. Yoder of the Carnegie Institution and I. Kushiro of the University of Tokyo found that, the higher the pressure under which the magma is produced, the greater its content of potassium and sodium. The Geological Laboratory of the Carnegie Institution, with its excellent facilities for melting rocks under high pressure, is the mecca for experimental petrology. Since pressure is proportional to depth, the experimental finding of Yoder and Kushiro agrees, at least qualitatively, with Kuno's hypothesis—that the magma forms at greater depth near the continent. Kuno took the hypothesis one step further: he combined the depth of magma production with the Wadati-Benioff zone of deep-focus earthquakes, and postulated that magma production is related to the occurrence of deep earthquakes. At the time (in 1959), the concept of the subducting slab did not exist. Since its advent, a regularity in chemical composition of volcanic rocks has

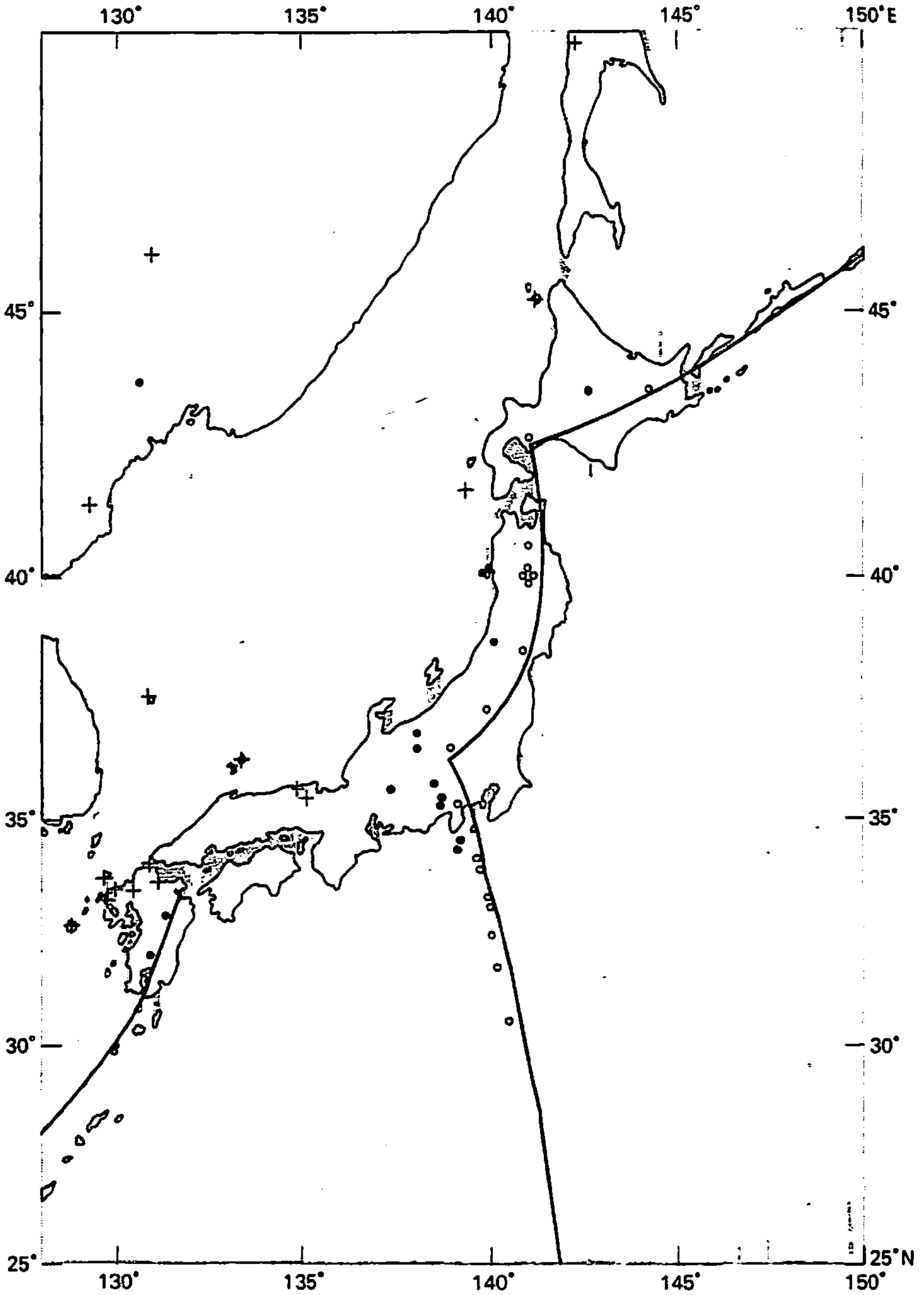

FIGURE 5-15
The distribution of types of parental magmas in Japan and environs: the open circles designate tholeiite magma; the closed circles, high-aluminum basalt magma; the crosses, alkaline basalt magma. The solid line indicates the volcanic front. [After H. Kuno, "High-Alumina Basalt." *J. Petrol.* 1, p. 121, 1960.]

also been found in rocks other than basalts. Thus it became one of the major problems of the new theory of plate tectonics to explain the observed regularities in the chemical composition of volcanic magma in the arcs. Many scientists have tried to synthesize the information into a theory. A. E. Ringwood of Australia and his colleagues, and W. Dickinson of the United States are among those who have made significant contributions to the subject. We will not treat this prob-

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lem in any more detail because an even more basic question requires our attention: how is magma produced under the island arcs in the first place?

The Thermal State Beneath Island Arcs

Magma, which is produced in the depth of the earth's interior, most probably in the upper mantle, appears on the earth's surface as a result of volcanic eruptions. It is obvious that volcanic activity is largely determined by the thermal state of the upper mantle. Magma production occurs when the underground temperature rises, causing a localized melting. What is the reason for this rise in temperature and why is it localized in certain zones? Assuming that hot mantle material is extruded at the mid-oceanic ridges, it is reasonable to assume that magma production takes place there. Thus, the presence of volcanoes on the mid-oceanic ridges is readily explained. They are even more abundant in the circum-Pacific zones, however, where the cold sea floor is believed to be descending. It is hard to explain why. In order to do so, scientists realized that it would be necessary to understand the thermal state of the earth and, in particular, its peculiarities under island arcs. One observational approach to the problem was to make an extensive investigation of terrestrial heat flow.

We began the measurement of terrestrial heat flow in the Japan area in 1957. This problem was my postdoctoral research project at the Earthquake Research Institute, University of Tokyo. Although the project had to be started from scratch, it soon benefited from the generous cooperation of K. Horai, M. Yasui, and T. Watanabe. In addition, our oceanic heat flow work was greatly enhanced by joint projects with Scripps Institution of Oceanography and Lamont-Doherty Geological Observatory.*

In more recent years a number of Japanese scientists—I. Yokoyama, H. Mizutani, K. Baba, Y. Kono, and others—have been measuring the heat flow in various areas. Measurement of heat flow conducted in Korea with the cooperation of the Geological Survey of Korea was another successful international project. As a result of these various combined efforts, the heat flow of Japan and its environs has been most thoroughly studied. It is our current hope to extend these measurements into the main Asiatic continent and

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*These projects were greatly benefited by funding under the United States-Japan Science Cooperation Program.

southeast Asia with the cooperation of scientists in the countries concerned.

The results of the observations on heat flow in the Japanese area up to 1970 are summarized in Figure 5-16. The regularity is remarkable. Terrestrial heat flow is low on the Pacific Ocean side of the island arcs or the trench areas, whereas that on the landward side is high: specifically, on the ocean side, where shallow earthquakes are frequent, the heat flow is less than 1 heat flow unit,* and on the landward side it is higher than 2 heat flow units. It should be mentioned that the seaward boundary of the high heat flow zone coincides rather well with the volcanic front shown in Figure 5-14. Most heat flow measurements are taken at stations that have been deliberately established away from the immediate vicinity of active volcanoes and hot springs. This way we can be sure that the higher heat flow registered on the landward side of island arcs is a regional state rather than a local one resulting from the proximity of individual volcanoes and hot springs. The findings demonstrate that the distribution of heat flow is closely and regionally related to the distribution of volcanoes and earthquakes.

Another notable feature in the distribution of heat flow (shown in Figure 5-16) is the fact that the high heat flow region extends toward the continent to include the marginal sea basins behind the arcs, such as the Sea of Okhotsk, the Sea of Japan, and the Okinawa Trough. The distribution of active volcanoes (Figure 5-14), however, shows a high concentration along the volcanic front and a decrease toward the continent. There are no active volcanoes in the Sea of Japan.

The regularity of heat flow distribution in island arc areas—low on the ocean side and high on the continent side or in marginal seas—applies to the Kurile Arc, the Northeast Honshu Arc, the Izu-Bonin-Marianas Arc and the Ryukyu Arc. But the Southwest Honshu Arc shows a high heat flow on the ocean side of the arc. Examination of Figures 5-6b and 5-14 will reveal that both deep earthquakes and active volcanoes are scarce in the area of the Southwest Honshu Arc; these observations support the view that it is not a typical active island arc. Further to the southwest, the Ryukyu Arc is more active and more typical.

How universal is this zonal distribution of high and low heat flow in the arcs of other parts of the world? Naturally we were eager to

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*The world average value of terrestrial heat flow is about 1.5 heat flow units. (1 heat flow unit = 1/1,000,000 calorie per square centimeter per second.)

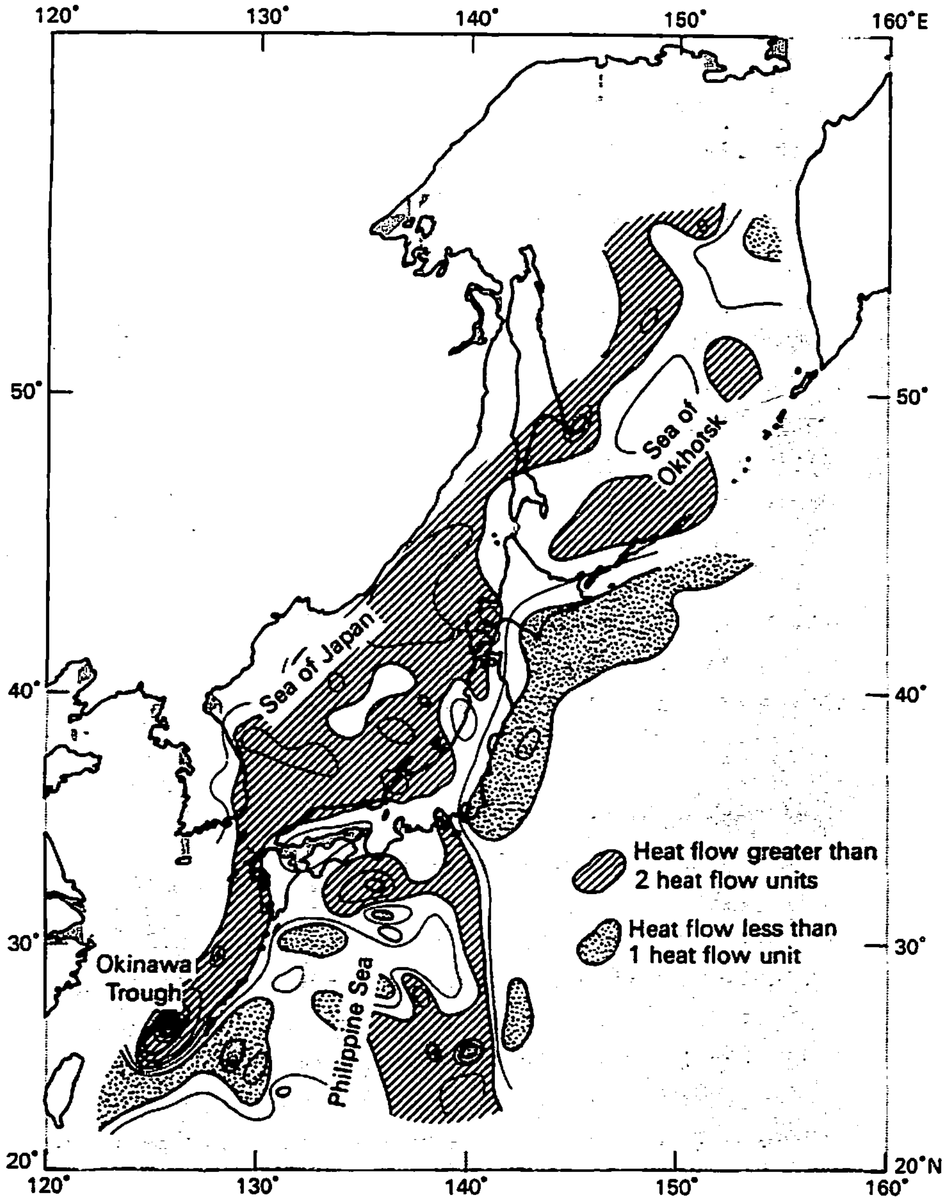

FIGURE 5-16
Heat flow distribution in and around Japan (in heat flow units). Contour interval is 0.5 heat flow unit.

compare the results of our observations with data obtained from other arc areas. At that time, however, not many data on other arcs were available. Thus an expedition was formed in 1969, to explore the arc systems on the other side of the Pacific—along the west coast of South America. T. Watanabe and I conducted heat flow measurements in the mines and oil fields of Ecuador, Bolivia, Peru, Chile, and Argentina, with the help of local scientists and authorities, and of mining geologists and scientists from various parts of the world who were working in these areas. The results of the measurements indicate the existence of a low heat flow zone seaward of the volcanic front, but the presence of a high heat flow zone landward of the front has not been verified. Certainly a more thorough survey remains to be carried out.

A number of surveys of other island arcs and back-arc marginal basins have been undertaken by various groups. So far measurements have been taken primarily in the oceanic areas around the arcs rather than on the islands themselves. The heat flow in the trench areas is almost always low, but that in the marginal seas behind the arcs is rather complex. In some, heat flow is high, and in others it is not. For instance, the North Fiji Basin (Fiji Plateau), the South China Sea, and the West Bering Sea exhibit high heat flow, whereas the South Fiji Basin, the West Philippine Basin and the East Bering Sea have either normal heat flow or heat flow of mixed high and low values. The heat flow in marginal basins seems to be closely related to the history of these basins, as we shall see later. Figure 5-17 is a schematic representation of heat flow in the Western Pacific area.

The Distribution of Electrical Conductivity and the Thermal State of the Upper Mantle

Another possibly significant factor that reflects the thermal state of the earth's interior is the distribution of underground electrical conductivity. The rocks that compose the crust and the mantle are electrical semiconductors (so that they have some conductivity but are not good conductors), and their weak electrical conductivity increases with increasing temperature. Hence the distribution of electrical conductivity within the earth provides information about the temperature distribution.

The method of estimating the underground electrical conductivity is rather complicated. It is deduced from the time variations in the geomagnetic field. The main cause of geomagnetism is believed to be the electric currents flowing in the earth's metallic core. These currents are maintained by a kind of dynamo action in the core. A small part of the geomagnetic field, however, is induced by the presence of electric currents outside the earth. This externally induced geomagnetic field undergoes changes that are much more rapid than the very slow changes brought about by currents in the earth's core, such

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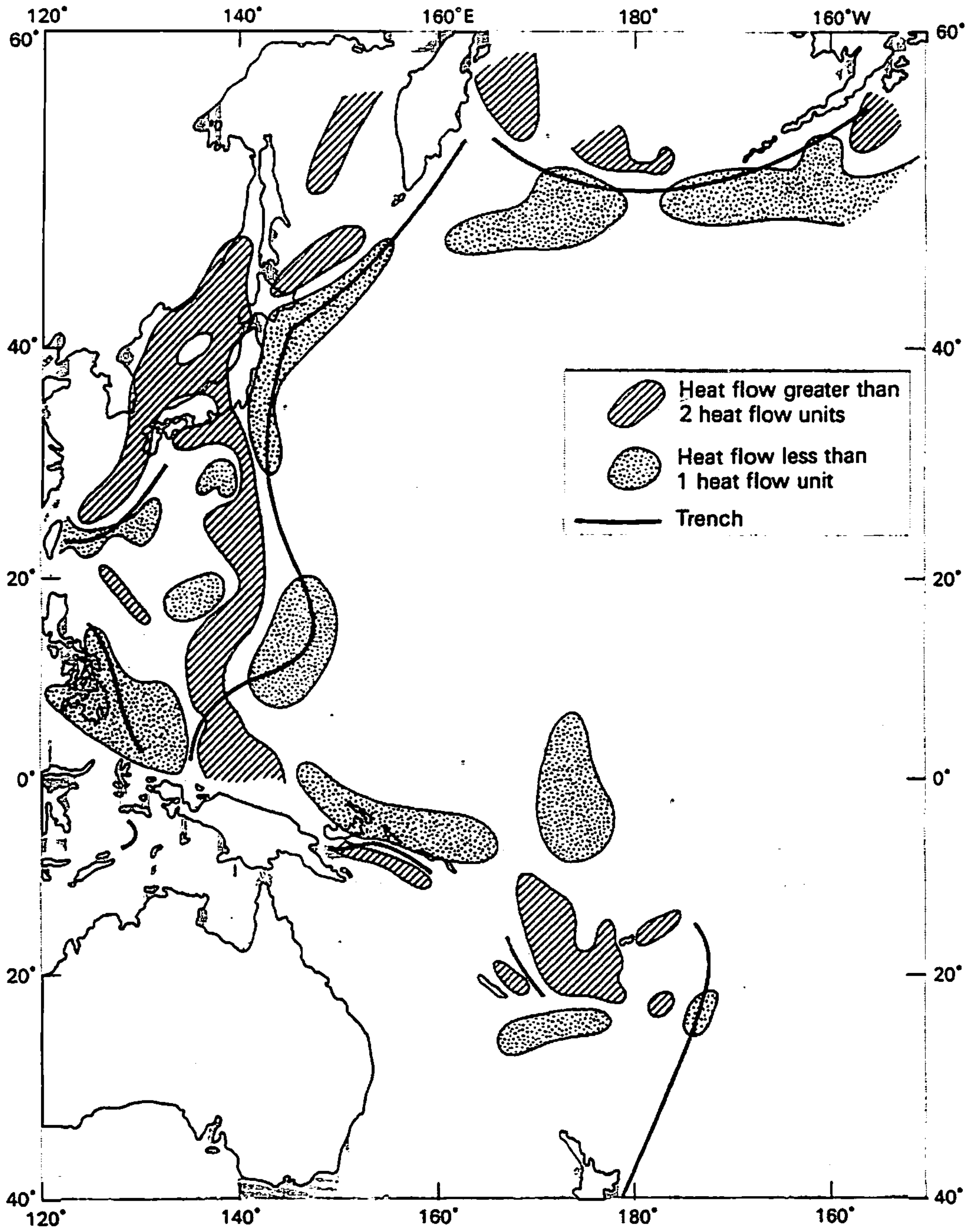

FIGURE 5-17
Simplified heat flow distribution in the western Pacific. [After T. Watanabe, "Heat Flow in the Western Margin of the Pacific," 1974. Redrawn with permission of the author.]

as the geomagnetic reversals (discussed in Chapter 3), whose duration is measured on a geological time scale. Time variations in the external field take place within hours or minutes, or even more rapidly. They are caused by changes in electrical currents in the upper atmosphere. These changes, in turn, are induced by changes in the flow of radiation and charged particles from the sun. It is well known, for example, that when a solar flare occurs, the geomagnetic field experiences especially large-scale disturbances called magnetic storms, but less dramatic changes also occur daily because the solar radiation at any given point on the earth changes daily.

Now, suppose that the magnetic field is changed by the electrical currents within the earth's upper atmosphere that are influenced by solar variations. The law of electromagnetic induction requires that a certain electric current will be induced in the earth's interior by this changing of magnetic field. This electric current will then produce a rapidly changing, though weak, secondary magnetic field. When we observe the geomagnetic field on the ground at the time of a magnetic storm, we measure, in effect, the sum total of the two kinds of variations. The first variation in the magnetic field is due to currents in the ionosphere; the second is due to the currents in the earth induced by the first. By isolating the secondary from the primary variations, one should theoretically be able to assess the strength of the electric current that has been induced in the earth. From this information one can further estimate the electrical conductivity of the earth. Estimation of underground electrical conductivity by this method was begun by the late S. Chapman of England and his coworkers more than 30 years ago. Then T. Rikitake and his colleagues discovered in 1955 that the mode of variations of the secondary geomagnetic field in the Japanese arc areas is quite anomalous compared to that in other areas of the world. From this they concluded that the electrical conductivity under the island arc of Japan was anomalous in comparison with other areas.

Anomalies in electrical conductivity suggest anomalies in temperature distribution, since electrical conductivity is an indirect indicator of the thermal state of a rock. According to subsequent detailed studies by Rikitake and his colleagues, the temperature distribution under Japan, as deduced from the study of the electrical conductivity anomaly, is in close agreement with that surmised from the distribution of terrestrial heat flow. This means that the temperature of the upper mantle underneath the Japanese islands, as deduced from the anomaly in electrical conductivity, is higher on the landward side and lower on the ocean side along the northeast Honshu Arc (Figure 5-2).

More interestingly, this condition does not apply to the southwest Honshu Arc, where the measured heat flow shows a pattern that is almost the reverse of that of the northeast Honshu Arc (Figure 5-16). Considering the long chain of inferences and the complex data processing employed in the assessment of temperatures from geomagnetic variation observations, the agreement with heat flow data is remarkable indeed.

Seismic Waves and Temperature Distribution

Another way of estimating subterranean temperature is from the seismic wave velocity, another property that changes with temperature. Seismic waves slow down as they go through hot rocks. As the temperature approaches the melting point, the velocity drops even more drastically. At this point we must introduce another category of seismic waves—*surface waves,* which travel along the surface of the earth (as opposed to *P* and *S* waves, which travel ***through*** it).

A typical example of surface waves might be the ripples on the surface of a lake. Seismic surface waves include waves of various wave-lengths. Theoretically the propagation characteristics of surface waves are determined by the physical properties of the medium to the depth that is comparable to their wavelength. High-frequency surface waves (short wavelengths) tell us about the crust. Low-frequency waves (the longer wavelengths) tell us about the mantle. It is possible to estimate the physical properties of the entire upper mantle as a function of depth by investigating surface waves of various wavelengths. Using this technique, H. Kanamori and K. Abe have investigated the conditions of the upper mantle in the Japanese area. The upper mantle temperature distribution, as estimated from the results of their studies, is also in remarkable agreement with the temperature distribution as deduced from the measurements of heat flow (Figure 5-16). Kanamori and Abe also believe that the temperature is very high in the upper mantle beneath such areas as the Sea of Japan and eastern Philippine Sea, so high, in fact, that partial melting might be occurring at an unusually shallow depth of 30 or 40 kilometers.

Another important piece of information on the structure of the upper mantle of island arcs has been provided by seismology. It has long been observed in Japan that the distribution of the intensity of seismic vibrations is often very strange. For instance, when a deep earthquake occurs under the Sea of Japan at a depth of, say, 400

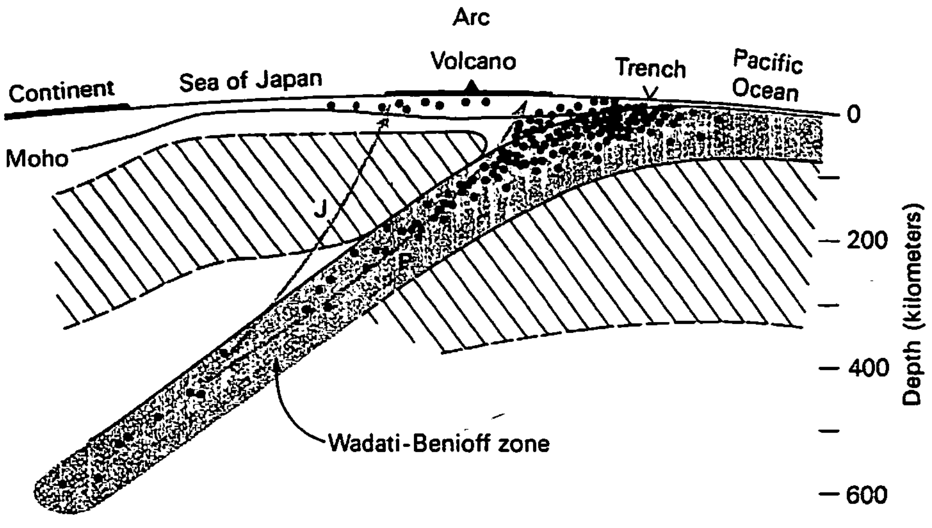

FIGURE 5-18
A model showing the various layers of the deep structure of the northern Japan arc. Dots represent earthquake foci. J is a typical path of seismic wave transmission from a deep-earthquake focus to the Sea of Japan side of the arc; P is the path of transmission from the same focus to the Pacific Ocean side. The light gray represents the cold layer in which seismic waves travel with high velocity and low absorption; the stripes represent the hot layer in which the waves travel with low velocity and high absorption. [After T. Utsu, "Seismological Evidence for Anomalous Structures of Island Arcs with Special Reference to the Japanese Region," *Review of Geophys. and Space Phys.* 9, p. 839, 1971. Copyrighted by American Geophysical Union.]

kilometers, the seismic intensity is often stronger on the Pacific Ocean side than on the Sea of Japan side. Since the distance from the focus is greater on the ocean side, this phenomenon is an unexpected one that must be explained. M. Katsumata and T. Utsu of Japan interpreted this phenomenon as follows: typical paths of transmission of the seismic waves from a deep earthquake to the two sides of the arc are shown in Figure 5-18. If the rocks along path P are capable of transmitting seismic waves while absorbing much less than the rocks along path J, the Pacific side will feel more intense vibration than the Sea of Japan side. They concluded that the Japanese islands are underlaid by an inclined layer with low seismic absorption that intrudes from the Pacific side along the Wadati-Benioff zone. It was further noticed that seismic waves traveling through this layer of low absorption propagate at greater speed than those traveling through the upper mantle outside the layer. It is known that seismic velocity is greater and absorption is lower in cooler rocks. These observations clearly suggest the existence of a colder slab along the Wadati-Benioff zone (Figure 5-18). Thus the central concept of plate tectonics is again supported. A strikingly similar situation in the Tonga Arc of the South Pacific was found by J. Oliver and B. Isacks.

The thermal state of the upper mantle underneath island arc systems, then is quite complex. The most significant issue here is whether these thermal conditions support the concept of a descending slab or not. At present, it is commonly assumed that the subduction of the slab occurs because the slab is cold and, therefore, heavy. Given this assumption, such dynamic phenomena as shallow and deep-focus earthquakes, and such conditions as low heat flow, which signifies a low temperature and results in an absence of volcanoes, all seem explicable. Additional seismic evidence for the existence of the cold slab mentioned above lends support to the entire concept of the subduction of the oceanic plate. Yet, how can we explain such anomalous phenomena as high heat flow and high temperature within the upper mantle, and the existence of volcanoes on the landward side of island arcs? Does this not squarely conflict with the model in which the descending slab is considered to be cold?

The Island Arc—An Orogenic Zone

Let us discuss briefly another observation before we explore the difficult problem of the conflict between the high temperatures in the upper mantle and the concept of the cold slab. One of the most significant features of the geological structure of the Japanese islands is the striking difference between northeast and southwest Japan. Northeast Japan exhibits pronounced features that are typical of active island arcs, such as a deep trench and a volcanic belt. This volcanic belt (see Figure 5-14) lies along the land side of northeast Japan and then turns to the south along the great geologic discontinuity called the *Fossa Magna* (see Figure 5-19) and extends into the Izu-Bonin-Marianas Arc. By contrast little present-day volcanic activity occurs in southwest Japan. This area is divided by the *Median Tectonic Line* shown in Figure 5-19. The geological structure there lies in belts that are generally parallel to the Median Tectonic Line. The most interesting feature of this structure is the distribution of regional metamorphic belts, also shown in the figure.

Metamorphic rocks are the secondary rocks that are formed when the original rocks undergo a transformation as a result of thermodynamic action. They can be roughly divided into two groups: those transformed by the presence of low temperature and high pressure, and those transformed by low pressure and high temperature. In

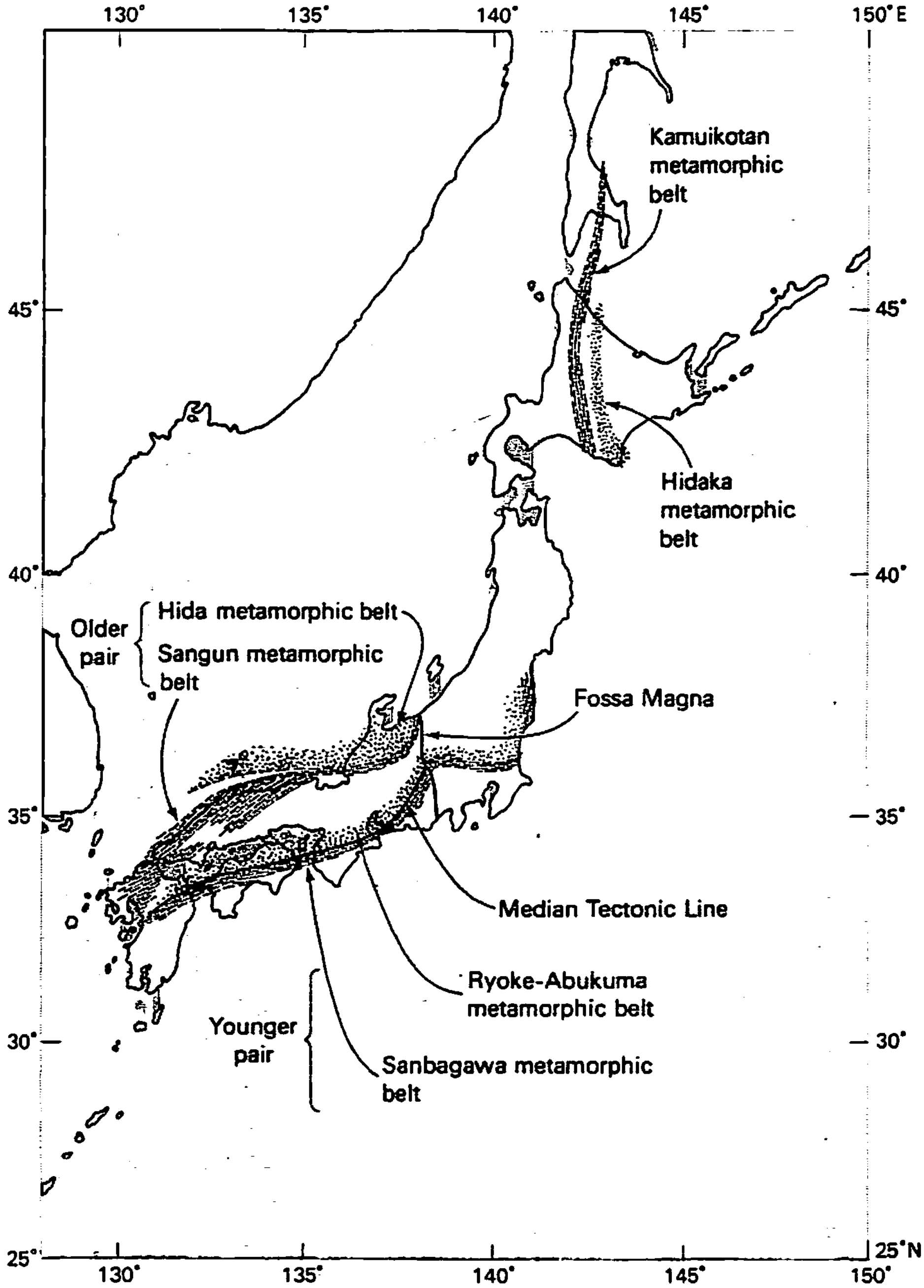

FIGURE 5-19
Regional metamorphic belts in Japan. The Median Tectonic Line and Fossa Magna are shown in solid lines. [After A. Miyashiro, "Evolution of Metamorphic Belts." *J. Petrol.* 2, p. 277, 1961. Redrawn with permission of the author.]

southwest Japan, these two kinds of metamorphic rocks are distributed with regularity, so that they form a pair of belts. The high-pressure low-temperature metamorphic belt (the Sanbagawa Belt) lies on the ocean side of the Median Tectonic Line while the low pressure-high temperature belt (the Ryoke Belt) runs along the land side of the Median Tectonic Line. These belts, then, are considered to be indications of the type of underground activity that took place at the time of metamorphism. (The Ryoke-Sanbagawa Belts are the result of a metamorphism that took place in the Jurassic and Cretaceous periods.) Notice in Figure 5-19 that the metamorphic belts extend to the southern part of northeast Japan, beyond the Fossa Magna. This indicates that in Mesozoic or earlier times, Honshu acted as an orogenic belt. This is in contrast to the present configuration of northeast and southwest Japan. Another pair of metamorphic belts lie alongside the Sea of Japan in southwest Japan. The high-pressure low-temperature belt on the ocean side is also paralleled here by a low-pressure high-temperature belt on the land side. These are called the Hida and Sangun metamorphic belts. This pair of metamorphic belts is considered to have been formed in the Paleozoic age and hence it is older than the Ryoke-Sanbagawa pair to the south. The two pairs would indicate that the thermal state of the area in Paleozoic and Mesozoic times might have been much the same as that of an active zone today—that is, the temperature was low on the ocean side and high on the land side. Since southwest Japan is considered to be a rather inactive island arc at present, it can give us some idea of what the condition of active island arcs will be several hundred million years from now. Although a number of scientists must have recognized this possibility (at least subconsciously) for a long time, the first ones to postulate it—in the late 1950s and early '60s—were A. Miyashiro, A. Sugimura and T. Matsuda. Their theory was as follows: presently active island arcs are the very places at which orogenesis—the phenomenon that produced extensive mountain belts and metamorphism such as those seen in southwest Japan—is now taking place.

Metamorphism and Heat Flow

What encouraged two of us—H. Takeuchi and me—to support the foregoing concept was the quantitative comparison illustrated in Figure 5-20. Line *A* shows the distribution of underground temperature on the ocean side of the northeast Japanese arc, that is, the low heat-flow zone; line *B* shows the temperature distribution on the land side, or the high heat-flow zone. These temperature distributions were deduced from the observation of heat flow by K. Horai and me in 1964. The horizontal axis in this figure shows the gradation of pressure and depth. The shaded area *a* shows the temperature and pressure ranges that probably existed when the high-pressure low-

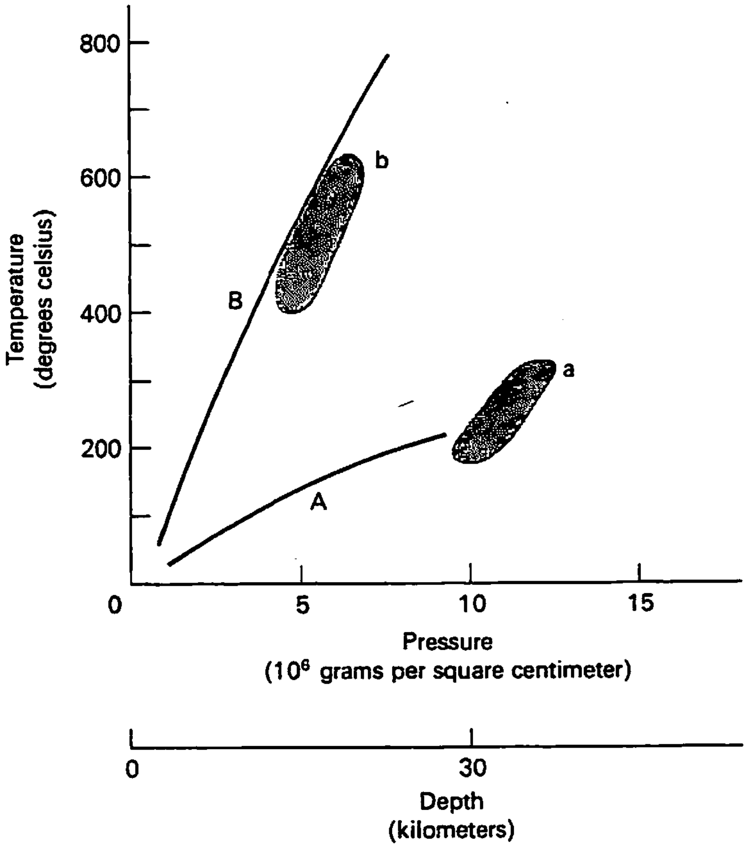

FIGURE 5-20
Temperature-depth relationships under present island arcs, and temperature-pressure ranges in metamorphic belts. Solid lines A and B represent the present temperature distribution in low heat flow and high heat flow zones. Shaded areas *a* and *b* are the temperature-pressure ranges for the high-pressure/low-temperature and low-pressure/high-temperature types of regional metamorphism. [After H. Takeuchi and S. Uyeda, "A Possibility of Present-Day Regional Metamorphism." *Tectonophysics* 2, p. 59, 1965. Redrawn with permission of the authors.]

temperature metamorphism took place in the Sanbagawa Belt, and the shaded area *b* shows the probable ranges prevailing when metamorphism took place in the Ryoke Belt. These ranges of pressure and temperature were estimated by comparing the mineral assemblages found in the metamorphic rocks with the minerals produced in the laboratory under known conditions of pressure and temperature. Thus the temperature/pressure ranges were estimated by two separate methods—one based on heat flow along the presently active arc in northeast Japan and the other based on the composition of metamorphic rocks along the former orogenic zone in southwest Japan. Takeuchi and I thought that the agreement between them as shown in Figure 5-20 was too close to be coincidental, and suggested that the two types of regional metamorphism may be taking place now beneath the island arc of northeast Japan.

Pacific-Type Orogeny

The similarity between our view about the activity of island arcs, which we consider to be orogenesis itself, and Dewey and Bird's revolutionary concept that all geological phenomena can be explained by plate tectonics (page 121) is readily apparent. But their view, though spectacular, is rather phenomenological. They seem to take it for granted that wherever the subduction of a plate takes place, earthquakes, volcanoes, and metamorphism will occur. The relationship between subduction and earthquakes is easy to accept, but the occurrence of volcanic activity and metamorphism (especially that of the low-pressure-high-temperature type) requires more explanation than they have given. Similarly, our postulation that the island arc represents a progressive stage in orogeny itself, demands more scrutiny of the physical mechanism involved. Again, the thermal aspect is especially difficult to explain.

In order to distinguish the orogenic process that creates great mountain ranges like the Himalayas from the process that takes place in island arcs, we will call the island arc process *Pacific-type* orogeny. The question of how melting and high temperature can occur at the same time that a cold plate is descending has long plagued the minds of scientists who are interested in the problems of "why."

A Model for Pacific-Type Orogeny

Insofar as we adhere to the present commonly accepted model that a cold slab of lithosphere is descending under the arc, it is necessary to assume the existence of some kind of unique heating mechanism in order to explain Pacific-type orogeny. At present we are considering the possibility that frictional heat is the source of the thermal energy in Pacific-type orogeny. But how friction provides enough heat is not yet clear. Primitive man knew how to make fire by rubbing pieces of wood together, but modern science cannot determine how a cold plate, descending at the slow rate of several centimeters a year, could generate a sufficient amount of heat to cause the orogeny. In an effort to solve this problem, my colleagues (K. Hasebe and N. Fujii) and I, in 1970, set for ourselves the task of defining the physical mechanism that produces the heat. As a first step, we attempted to figure out quantitatively how much heat would be necessary in order to cause the observed high heat flow and volcanism on the continent side of island arcs. We found that numerical experiments with the use of electronic computers were the best approach. First of all, a normal oceanic cross section of the earth was assumed for the initial state. Then we created a model in which plate subduction began at a certain time. As the subduction continued, we assumed that a certain quantity of heat was produced along the interface between the sinking plate and the surrounding mantle. Then we calculated how the temperature distribution changed with the passage of time in the cross section. The heat capacity, the velocity of the descending plate, thermal conductivity, and the melting point of the materials were the factors included in the calculation. By changing the values of these quantities, we sought to determine numerically the conditions necessary to produce the observed heat flow distribution. The principal features of our model are shown in Figure 5-21. The dotted area denotes the descending cold plate.

An important element in calculations like ours is the time that has elapsed from the onset of the phenomenon to the present. Such a period can be estimated from geological observations, but not determined with precision. Since the geological structure of the Japanese islands could not have been formed within a span as short as 10 million years, and since it is known that the present island arcs came into being after the Mesozoic period, it is assumed that the period from the beginning of the underthrusting to the present has been 100 million years. Hence, in our efforts to explain Pacific-type orogeny our main objective was to determine what conditions 100 million years ago produced the present state. The amount of heat generated on the upper surface of the obliquely descending plate was estimated as follows: first, although the heat flow anomaly observed on the surface is about one heat flow unit,* 5 heat flow units must be generated on the upper surface of the slab. This large amount of heat is required because the cold plate subducts and most of the heat generated would be carried down with the cold sinking plate.

We also found that the value of thermal conductivity needed to transmit the heat to the earth's surface through the mantle would have to be about 10 times greater than that of mantle rocks. Thus our calculations indicated that a large amount of heat would have to be

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*Recall that one heat flow unit equals $^1/_{1,000,000}$ calorie per square centimeter per second.

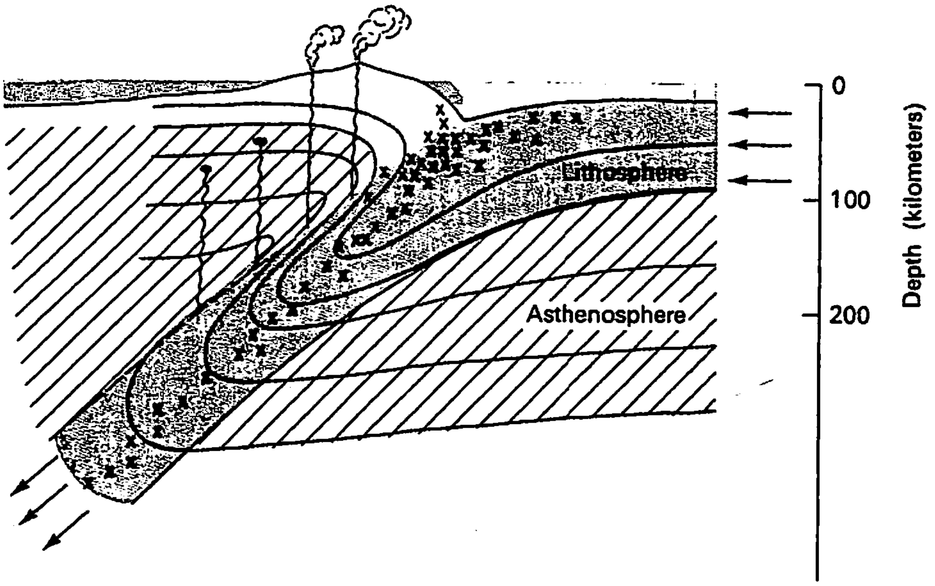

FIGURE 5-21
Model of a proposed heating mechanism under active island arcs that explains Pacific-type orogeny. The shaded area represents the descending cold plate (the lithosphere). Isotherms are represented by the curved lines. Arrows indicate the direction of movement, and the crosses indicate earthquakes. The wavy vertical lines indicate the ascent of magma. [After A. Sugimura and S. Uyeda, *Island Arcs: Japan and its Environs*. Elsevier, 1973.]

generated and that it would have to be conducted to the earth's surface very efficiently. At first such efficient heat transfer seemed impossible, but we found that it is possible if the heat is transferred not only by solid conduction but also by ascending magma. Quantitative examination, however, revealed that the lava actually found on the earth's surface is not enough—about ten times as much magma as the amount of existing lava would be necessary to transfer the heat. All these conditions are quite stringent and not very easily met. Some scientists believe that the high rate of frictional heating required by our model is not compatible with the assumed occurrence of melting needed for the transfer of heat, because melted rocks would act as a lubricant. This too is a major problem that remains to be solved!

The Origin of the Sea of Japan—A Suggestion

If massive amounts of magma, 10 times greater than the amount of lava found on the surface, continued to ascend for as long as 100 million years, what could result? This question suggests a rather convenient hypothesis. The substance that rises to the surface during the 100-million-year period is equivalent to a column some 300 kilometers tall. If this material were piled on the earth's surface, a spectacular mountain 50 times higher than Everest would appear on the inner side of island arcs above the deep seismic zone. Since this has not happened, we should consider the possibility that the upper mantle now underlying the Sea of Japan has come up from underground during the last 100 million years. What does this mean? It is absurd to imagine that this area was once a depression 300 kilometers deep, but it may not be totally unreasonable to surmise that the present Japanese islands were once the eastern margin of the Asiatic Continent (Figure 5-22a) and subsequently migrated toward the Pacific Ocean to allow space for the ascending material (Figure 5-22b). This model would explain marginal seas—one of the features of island arcs—as the inevitable result of island arc tectonic activity. In our model the Pacific Plate is consumed as it descends into the inner side of the island arc, but some of it then reascends on the continental side to form the plate under the marginal sea. As marginal seas—such as the Sea of Okhotsk, the Sea of Japan, the Philippine Sea, and the East China Sea—increase in area, the arcuate form of the islands that outline these seas will become more and more pronounced. N. Kawai and his colleagues have found from paleomagnetic studies that the Honshu Arc has gradually bent throughout geological time. This bending would be the logical result of the process of marginal sea formation.

The origin of marginal seas like the Sea of Japan has long been the subject of controversy. It is difficult for a geologist to consider such a sea to be very old. Because rivers carry large amounts of earth and sand from the adjoining land, such a small sea would be filled in "no time at all" in geological terms (that is, within a mere 200 or 300 million years). Yet at present, the layer of sediment on the floor of the Sea of Japan is no more than 2 kilometers thick. This leads us to suspect that the Sea of Japan, as a sea, is fairly new.

An earlier theory was that until quite recently the Sea of Japan had been land and that the depression of this land had created the sea. This theory too met with a logical objection because, according to Archimedes' principle, land must have a thick crust beneath it to support its buoyancy (page 17). This means that if the land suddenly transformed into a sea, the ensuing depression would create an enormous gravity anomaly, and such an anomaly has not been observed above the Sea of Japan or anywhere else. This theory, then, could be viable only if the continental crust were *replaced* by an

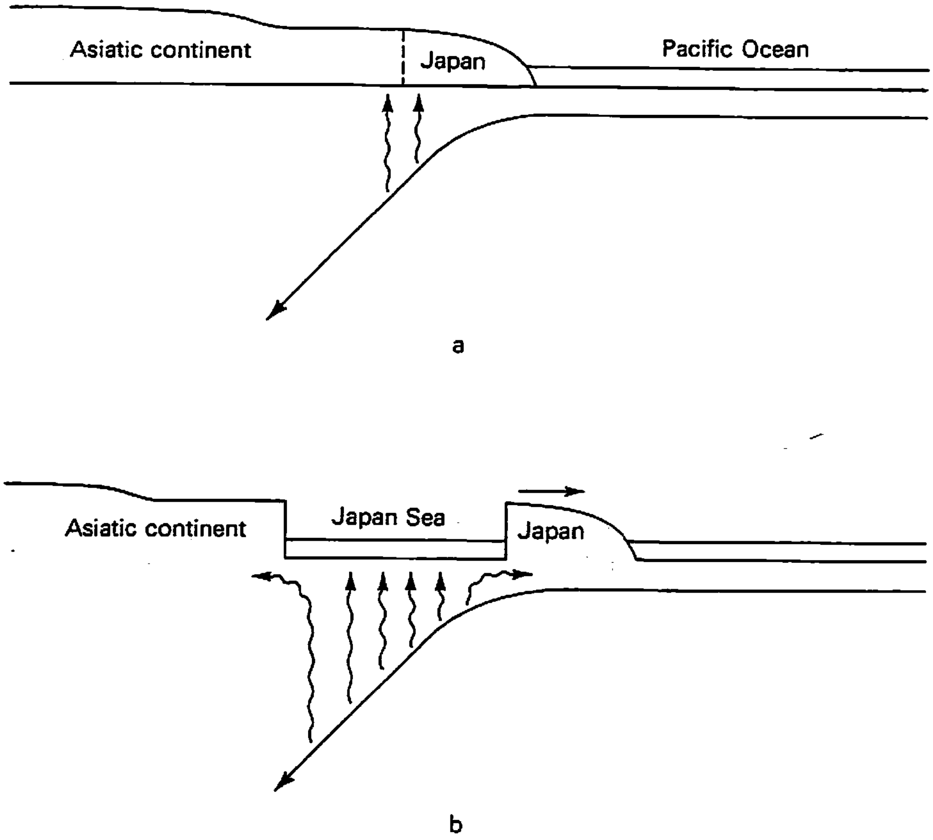

FIGURE 5-22
A model describing the way in which the Sea of Japan may have opened.

oceanic crust. Such "oceanization" of the continental crust has been espoused by V. Beloussov, the Soviet scientist, in an attempt to explain marginal seas. However, most modern petrologists find thermodynamically unacceptable the idea that the rocks constituting the continental crust could change into those making up the oceanic crust, although the reverse process—conversion of oceanic crustal material to continental material—is quite possible.

Given these considerations, I inferred that the Sea of Japan cannot be regarded as a depressed piece of continent. In our efforts to determine which conditions did explain the present distribution of heat flow and the mechanism of Pacific type orogeny (as described in the preceding section) my coworkers and I suggested that frictional heating and the ascent of magma might have caused island arcs like Japan to drift away from adjacent continents, creating marginal seas like the Sea of Japan. Indeed the assertion that the Sea of Japan was formed by the migration of the Japanese islands is not really new. As early as the 1930s, T. Terada, a unique physicist as well as a natural philosopher at the University of Tokyo, reached the same conclusion in his study of the topography of the Sea of Japan. In recent years, two more of my countrymen, S. Murauchi and K. Nakamura have supported this hypothesis. I emphasize these other contributions because, although I have been preoccupied with my own line of reasoning about the Sea of Japan, I want to be sure not to neglect the valuable investigations conducted by other scientists on marginal seas.

Three major hypotheses on the origin of marginal seas have been put forth. We have discussed two—the *oceanization* and the *drifting of the island arcs*. The third is the *entrapment* hypothesis, which proposes that a new island arc is formed off shore in such a way that the part of the ocean landward of the arc is entrapped to become a marginal basin. This means that the marginal sea would have to be older than the island arc. Therefore, the hypothesis cannot be applied when the arc is very old, for the small basin would be quickly filled up with sediments from the surrounding land. Recently, A. Cooper, M. Marlow, and D. Scholl of the United States have postulated that the Bering Sea may be a trapped and ancient part of the Pacific Ocean. They claim to have discovered magnetic lineations in the Aleutian Basin that appear to be part of the M-sequence lineations (see page 116), which were produced as a part of the Kula Plate, later to be entrapped by the formation of the Aleutian Arc. Another sea that may have been formed by entrapment would be the western Philippine Basin.

No example of an "oceanized" marginal sea has been convincingly demonstrated as far as I know, although the proponents of the oceanization hypothesis consider almost all the marginal seas to be good examples.

Of the three hypotheses of marginal sea formation, drifting and possibly (for some seas) entrapment appear to be more realistic than oceanization. The verification of these hypotheses lies in the direct investigation of the marginal seas themselves. D. Karig (1974), among others, has contributed significantly to the problem of marginal sea formation. From his study of bottom topography, sediment distribution, and other geological factors, Karig in 1970 postulated that marginal seas were opened by extensional forces that pushed the arcs oceanward. He also introduced the concept that, in the course of island arc formation, the rise of material from the upper surface of the descending slab will split the arc longitudinally in two, and that an interarc basin is then formed between the two halves. These two

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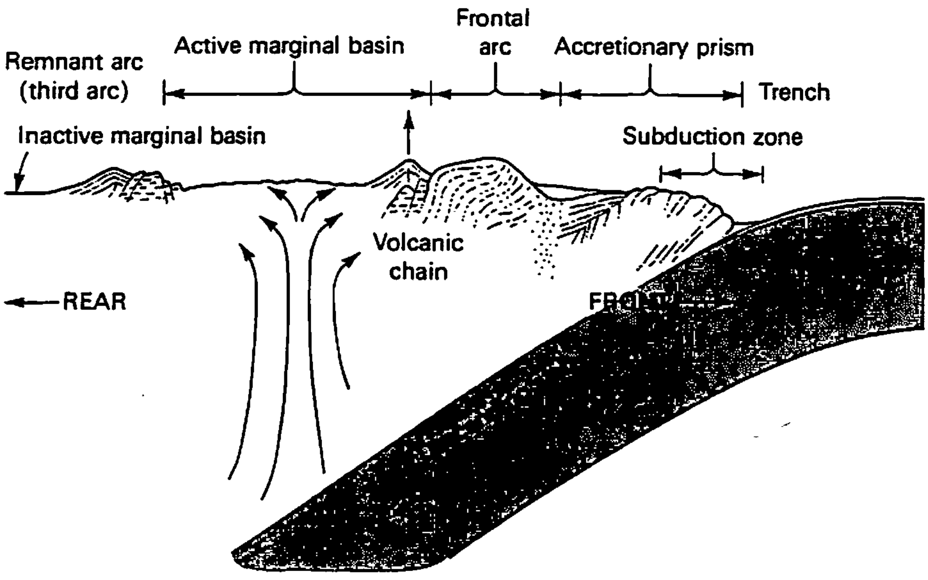

FIGURE 5-23
Model of a western Pacific island arc system, based on Karig's concept that an arc, in the course of its formation, is split into two parts—a frontal and a remnant arc—and that a marginal basin is thereby formed between them. The accretionary prism, on the landward wall of the trench, is a complex structure formed by ocean-floor sediment that has been scraped from the descending slab (it will be described in more detail in Chapter 6). [After D. E. Karig, "Evolution of Arc Systems in the Western Pacific." Reproduced with permission of *Ann. Rev. of Earth & Planet. Sci.*, Volume 2. Copyright © by Annual Reviews, Inc. All rights reserved.]

parts are called the *frontal* and *remnant* arcs. The frontal arc, having a volcanic chain just behind it, advances oceanward. For this reason the remnant arc is also called the *third* arc (Figure 5-23).

Karig was able to show that such a succession of events could explain certain features in various arc areas, including the Tonga-Kermadec, the New Hebrides, and the Marianas: he suggested that such extensional opening of marginal basins takes place episodically, producing a series of basins. Thus he contends that, within the Philippine Sea, the Marianas Trough, the Shikoku-Parece Vela Basins, and the West Philippine Basin are the successive results of increasingly older episodes of extensional opening (see Figure 5-1). As already mentioned, it is possible that the West Philippine Basin is an entrapped ocean. But the first two (the Marianas Trough and the Shikoku-Parece Vela Basins) may well be the results of two episodes, one presently active, and the other inactive now but formerly active in the Tertiary age. They are labeled as active and inactive marginal basins in Figure 5-23.

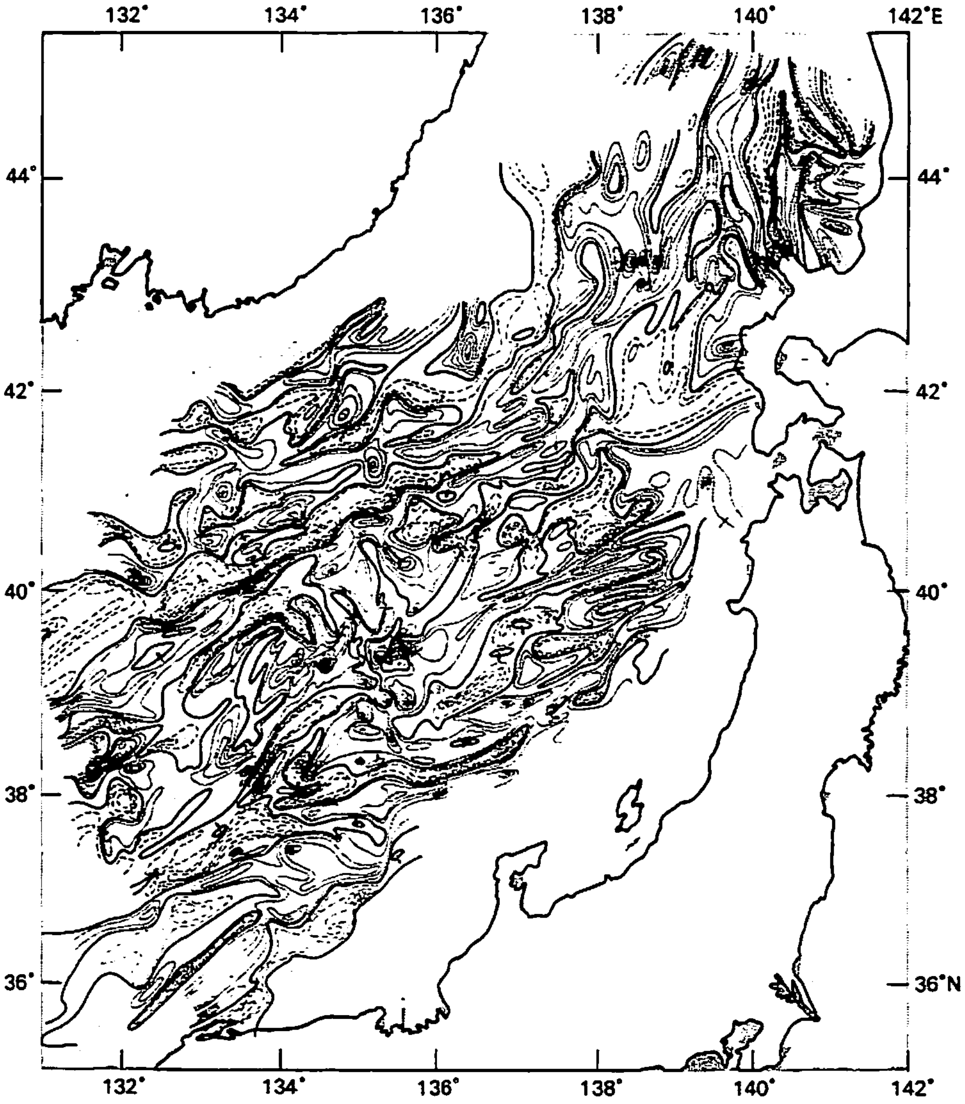

FIGURE 5-24
The magnetic anomalies of the Sea of Japan. Solid lines indicate the positive anomalies, and broken lines the negative anomalies. Although the anomalies are lineated in a northeast-southwest direction, the lineations are too irregular to permit their ages to be determined (compare with the lineations shown in Figure 2-8). The contour interval is 50 gammas. [After N. Isezaki and S. Uyeda, "Geomagnetic Anomaly Pattern in the Japan Sea." *Marine Geophys. Res.* 2, p. 51, 1973.]

Recently, magnetic lineations have been mapped in the Shikoku Basin by both Japanese and Lamont scientists—Y. Tomoda and colleagues, and A. Watts and J. Weissel. Some of these lineations have been identified as Miocene in age, a finding that generally supports Karig's idea. It now appears that the formation of these marginal seas may be similar to sea-floor spreading (if not exactly identical), since they too have Vine-Matthews-Morley type magnetic lineations.

In the Sea of Japan, a magnetic survey was undertaken from two research vessels, the *Seifu-maru* of the Maizuru Marine Meteorological Observatory, and the *Kofu-maru* of the Hakodate Marine Meteorological Observatory. Then in 1970 we were able to conduct a more detailed survey from a fishing boat, the *83rd Daiei-maru.* Figure 5-24 shows the anomalies obtained from these surveys. The lineations seem to exist, but they are weak in intensity, discontinuous, and irregular in shape; therefore it is very difficult to identify their age by the standard magnetic reversal time scale. It is possible that even if the Sea of Japan did open as a consequence of the drifting of the Japanese arc, it was not by a typical sea-floor spreading that took place around a ridge, but by an irregular emplacement of magma—a *diffuse* spreading. However, N. Isezaki has suggested, on the basis of an intricate mathematical treatment, the existence of an axis of symmetry in the stripes of the Sea of Japan. If there is indeed such an axis, Vine-Matthews-Morley type spreading could have occurred here too. The problem is yet to be solved.