U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

TO ACCOMPANY MAP SHEETS OF THE
CIRCUM-PACIFIC PLATE-TECTONIC MAP SERIES

Explanatory Notes for the Plate-Tectonic Map of the Circum-Pacific Region

By GEORGE W. MOORE

CIRCUM-PACIFIC COUNCIL
FOR
ENERGY AND MINERAL
RESOURCES

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DENVER, COLORADO 80225, USA

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THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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TULSA, OKLAHOMA 74101, USA

1992

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EXPLANATORY NOTES FOR THE PLATE-TECTONIC MAP OF THE CIRCUM-PACIFIC REGION

By GEORGE W. MOORE

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ABSTRACT

Publication of the seven sheets of the Plate-Tectonic Map of the Circum-Pacific Region was completed in 1992. This map series, the work of 48 specialists from 15 countries, is one of eight series being prepared by the Circum-Pacific Map Project, a cooperative international effort to produce new maps showing the geology, geophysics, and energy and mineral resources of the Pacific Ocean and surrounding continental areas.

The theory of plate tectonics constitutes one of the great revolutions in scientific understanding. It touches almost all aspects of the earth sciences: the origin of mountains, earthquakes and volcanoes, the distribution of fossils, the formation of metalliferous ores, and the generation of petroleum. It is the starting point for scientists and engineers striving to predict and minimize the consequences of natural disasters such as volcanic eruptions and earthquakes. Although the theory was only linked together in complete and coherent form in 1965, it has filled such a basic need in the science of geology that a majority of the world's geologists now understand the tenets of plate tectonics and are applying them.

Volcanoes and earthquakes around the Circum-Pacific "ring of fire" were important factors in developing the theory of plate tectonics. They are represented on the map sheets in several categories, along with major faults, plate boundaries, directions and rates of motion of the plates, and records of past plate motion that are registered on the seafloor by magnetic anomalies, parallel lines where the Earth's magnetic field differs from the expected field. These explanatory notes interpret the data shown on the map sheets and discuss the principles of the theory of plate tectonics on the basis of its historical development.

The Plate-Tectonic Map of the Circum-Pacific Region provides a framework for understanding the geologic information on which the theory of plate tectonics is based, and it serves as a starting point for research to apply and further develop the theory. It is a practical tool for solving geologic problems and directing the search for energy and mineral resources.

INTRODUCTION

CIRCUM-PACIFIC MAP PROJECT

The Circum-Pacific Map Project was established in 1973 to produce a comprehensive set of maps to combine the earth-science information of land areas with that only recently available from the deep sea. This international project, an activity of the Circum-Pacific Council for Energy and Mineral Resources, receives its direction from six regional panels of geologists and geophysicists who represent national earth-science organizations around the Pacific Ocean. The six panels and their chairs are: Northwest, Tomoyuki Moritani (Japan); Northeast, Kenneth J. Drummond (Canada); Southwest, R. Wallace Johnson (Australia); Southeast, José Corvalán D. (Chile); Arctic, George W. Moore (United States); and Antarctic, Ian W.D. Dalziel (United States). George

Gryc (United States) is general chair of the project.

Four complete seven-sheet map series have now been issued by the Circum-Pacific Map Project. They consist of the base, geographic, and geodynamic maps and the newly completed plate-tectonic maps. Still in the course of preparation and publication are the geologic, tectonic, energy-resources, and mineral-resources map series. The base map series (1977-1989) consists of 2-color sheets with closely spaced latitude and longitude lines to aid in the accurate plotting of data. The geographic series (1978-1990) consists of 4-color sheets showing cultural features and newly compiled submarine contours and topography, tinted in shades of blue and orange respectively. The geodynamic series (1984-1990) includes gravity anomalies, lithospheric stress, earthquake mechanisms, historical faulting, volcanoes, and crustal thickness.

PLATE-TECTONIC MAP OF THE CIRCUM-PACIFIC REGION

The Plate-Tectonic Map of the Circum-Pacific Region was issued 1981-1992 as a series of six 8-color overlapping equal-area sheets at a scale of 1:10,000,000, and one composite sheet at a scale of 1:17,000,000. All the sheets except the Arctic have been revised and reprinted at least once since they were first published.

The six 1:10,000,000 sheets are designated the Northwest, Northeast, Southwest, and Southeast Quadrants, and the Arctic and Antarctic Sheets. The centers of the azimuthal equal-area projections are at the centers of the sheets, so distortion at the margin of each sheet is only about 5 percent. Therefore, a variety of analyses can be undertaken on the sheets with almost the precision provided by a globe.

The 1:17,000,000 Pacific Basin sheet, also equal-area but with greater marginal distortion, shows the regional relations around the entire Pacific Basin. It covers 220° of longitude, or more than half the Earth.

The plate-tectonic map depicts active plate boundaries, major faults within the plates, present-day directions and rates of plate motion, earthquake epicenters, young volcanoes, and seafloor magnetic lineations. The map gives an overview of geologic processes that are presently active or have been active in the recent geologic past. It provides a background for further research on contemporary geologic processes, and also serves as a regional framework for extrapolating those active processes into the geologic past or into the future.

An explanation printed on the plate-tectonic map identifies the symbols used to depict the various map elements. This text explains the map elements further and relates them to plate-tectonic theory.

ACKNOWLEDGMENTS

Forty-eight people representing 15 nations have contributed unpublished material to the Plate-Tectonic Map of the Circum-Pacific Region. They are named on the map sheets together with their organizations. Maurice J. Terman served as chair of scientific coordination. For reviewing the first draft of the manuscript of these explanatory notes I am indebted to Campbell Craddock, H. Frederick Doutch, Kenneth J. Drummond, Vincent E. McKelvey, Ellen J. Moore, Paul J. Richards, and Seiya Uyeda. The final manuscript was reviewed by Warren O. Addicott and David G. Howell.

THEORY OF PLATE TECTONICS

Tectonics deals with the broadest aspects of the structure and development of the outer part of the Earth. Plate tectonics concerns about 20 shell-like plates at the surface of the Earth that move with respect to each other. The average thickness of these plates is approximately 100 km, which is about the length of Great Salt Lake, Utah. They include both the relatively light crust of the Earth (the uppermost 6 to 35 km) and the uppermost part of the underlying denser mantle. The mantle constitutes the largest part of the Earth. It surrounds a core that is believed to be metallic.

The 100-km thickness of the plates is equal to about five times the distance from the bottom of the Earth's deepest oceanic trench (the Mariana Trench) to the top of its highest mountain (Mount Everest). The individual plates on the surface of the Earth are like the tiles in a mosaic (fig. 1). Typical of the larger plates are the Pacific Plate, extending from New Zealand and Japan to California at the San Andreas Fault, and the North America Plate, extending from the San Andreas Fault to the Mid-Atlantic Ridge in the middle of the Atlantic Ocean.

The most active plates move at rates of 5 to 10 cm per year; that is about the rate at which a person's fingernails grow. The central parts of the plates are nearly rigid, and the plates slip along above the lower mantle. There is little evidence of this slippage at the Earth's surface, except at plate boundaries where many active geologic processes are clearly evident. Most of the world's earthquakes, volcanoes, and actively growing mountains occur at these boundaries. At many places in the world, rock layers are compressed and folded at rates fast enough that repeated land surveys, made after the elapse of only a few decades, can detect the changes. The plates have three different types of boundaries:

spreading axes, transform faults, and subduction zones.

Material from deeper in the mantle emerges to fill in the rift that is created where two plates move apart at a spreading axis, as occurs along the Mid-Atlantic Ridge and the East Pacific Rise. Most of the 100-km-thick gap between the plates is filled by the upward flow of solid mantle material, but the uppermost 6 km in the ocean basins is composed of basaltic lava and its noneruptive equivalents. The basalt forms as a partial melt of mantle material, selective in composition, and so differs chemically from the mantle. Its density is also less. The basalt comes directly to the seaflloor, where it is chilled by seawater. Even though the rate of plate movement is slow, and the formation of new basaltic seafloor at any given place is also slow, the great length of the world's spreading axes (55,000 km) results in the production each year of about 3 sq km of new rock at the Earth's surface along spreading axes.

Transform faults lie at the sides of plates where two plates slide past one another without significant divergent or convergent relative motion. They connect the plate boundaries that spread apart with those that converge. The San Andreas Fault of California is a famous example of a transform fault. At the San

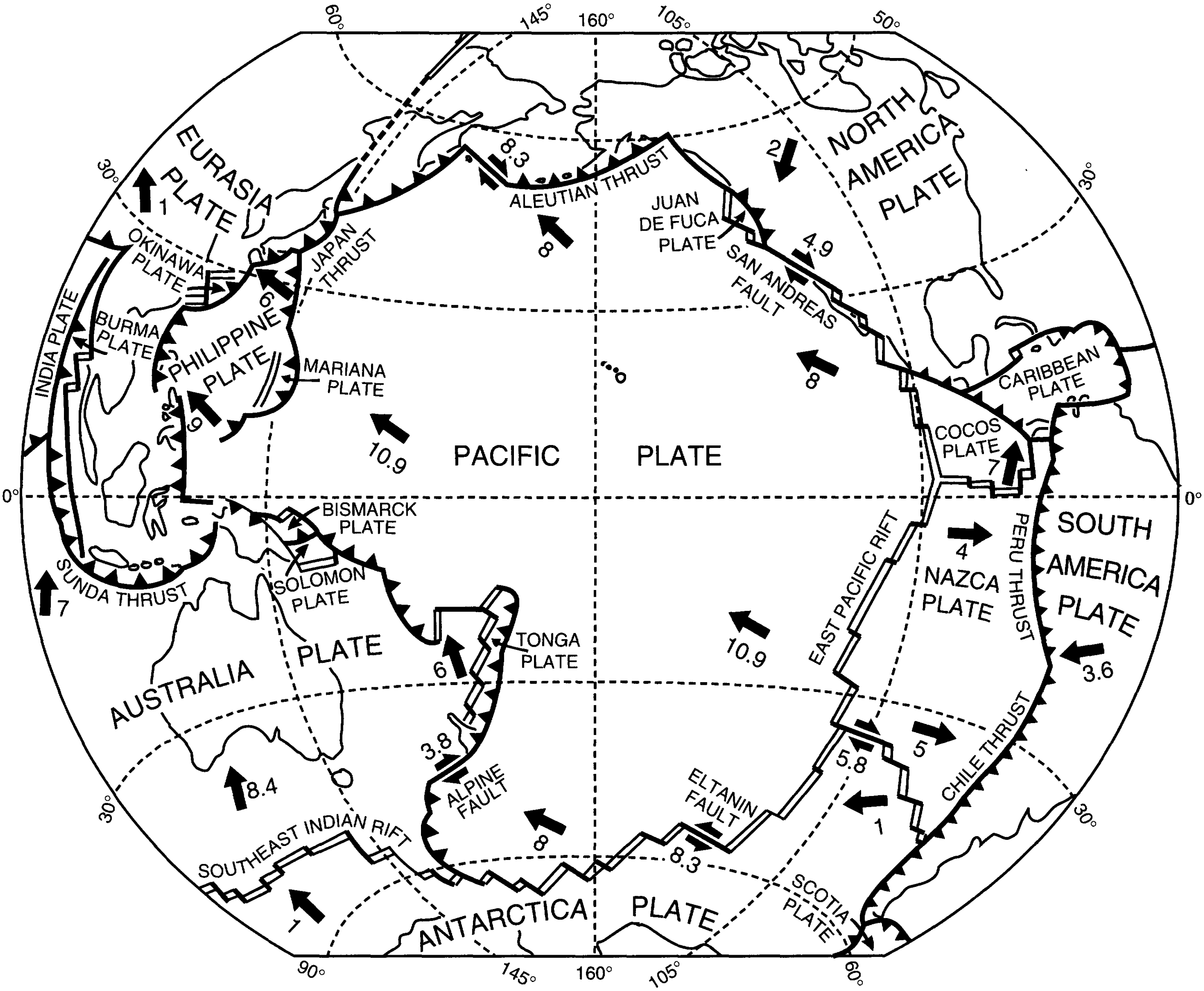

FIGURE 1.—Plates of the Circum-Pacific region, showing by full arrows the rate of plate movement in centimeters per year with respect to the body of the Earth, and by half arrows the relative movement between adjacent plates at major transform faults. Spreading axes are shown as double lines, transform faults as single lines, and subduction zones as barbed lines with the barbs pointing away from the downgoing plate.

Andreas Fault, the Pacific Plate moves toward the northwest with respect to the North America Plate, carrying with it coastal California and Baja California.

Subduction zones mark places where two plates converge along plate boundaries. At most subduction zones, the denser, more oceanic plate moves downward, and the lighter, more continental plate overrides it. This happens at the world's great oceanic trenches, such as at the Japan Trench. The greatest earthquakes occur at subduction zones. The earthquakes indicate that the downgoing plate may penetrate the mantle to a depth of as much as 700 km; that is a distance greater than 10 percent of the radius of the Earth. Arcuate volcanic belts lie above subduction zones, probably because oceanic crust and sediment at the top of a descending slab releases water that promotes partial melting in the overlying mantle. Basaltic melt moves buoyantly upward toward the surface where it and products from it are erupted as lava and volcanic ash. Although the area of the Earth's surface destroyed at subduction zones each year is more difficult to measure than is the area created at spreading axes, most geologists assume that the two areas are equal, about 3 sq km/year. That equality maintains a constant total area for the surface of the Earth.

On the basis of extrapolation downward of temperature measured in deep wells, and on laboratory studies of rock melts, the temperature at the base of the plates is estimated to be about 1,300°C. At the surface, rocks at this temperature would be molten. Under the great confining pressure that occurs at a depth of 100 km, however, the rocks are solid, but possess a high degree of plasticity.

Rock plasticity increases with higher temperature at depth, but it decreases with higher pressure. The two opposing effects interact to produce a maximum plasticity (that is, a minimum viscosity) at a depth of about 100 km. Therefore, the main plate motion takes place at that depth, rather than higher or lower.

The movement of the larger plates with respect to each other can be quite regular for long periods of time. For example, the North America Plate began to move away from the Africa and Eurasia Plates to create the Atlantic Ocean about 180 m.y. ago. Only minor changes in direction and rate have occurred during that time. But other kinds of change, both gradual and abrupt, do take place. Before the opening of the North Atlantic Ocean, an older ocean in the same area closed up, and when it did, the compression created the folded rocks that now lie along the Appalachian Mountains.

The decade of the 1970s was the main test period for the numerous hypotheses that compose the theory of plate tectonics. During this period, the deep-sea-drilling vessel *Glomar Challenger* made many important discoveries, including a verification that the seafloor rocks become systematically older as one moves away from spreading axes. The most revolutionary discovery by the *Glomar Challenger* was that the crustal rocks of the ocean basins are no more than about 180 m.y. old. That is a very short period in the 4,600-m.y. age of the Earth.

The subduction process is so rapid, and it is so effective in destroying previously formed oceanic crust, that no ocean-basin rocks older than the Jurassic Period have survived. All present oceanic rocks were created during the last 4 percent of geologic time.

MAP ELEMENTS

The map elements depicted on the plate-tectonic map, in addition to national boundaries and selected cities, consist of active plate boundaries, plate-motion vectors, active hotspots, volcanic centers, earthquake epicenters, seafloor magnetic lineations, selected intraplate structures, and underwater topography.

The plate boundaries (printed in red) are divided into subduction zones, spreading axes, and active transform faults. At the spreading axes, a red pattern shows the area of new oceanic crust formed within the past 1-million years. At broad plate boundaries where the movement is distributed over several faults, the principal fault is shown in red and subsidiary faults in black. We endeavored to portray the complete plate boundaries, dashed where approximately located, but a few gaps exist at very uncertain boundaries in the southwestern Pacific. In some places where a plate boundary seems to be covered by uncoupled crustal slabs, as in Colombia and Venezuela, the faults used as the boundary have been arbitrarily selected. Our rendering of the Scotia and Sandwich Plates on the Antarctic Sheet conforms with many known facts, but other investigators have published alternative interpretations. Also, some areas remain poorly known (for example, the Fiji area) and revision at such places is likely on future editions of the map sheets. New subplates also may be distinguished in the future. For example, a diffuse boundary probably lies between Mongolia and Russia along the Baikal-Okhotsk Shear Zone. If this boundary were added, it would separate southeast Asia from the remainder of the Eurasia Plate, thereby requiring another new plate.

Plate-motion vectors show the direction and rate of movement of the plates in two ways: as relative motions between adjacent plates, and as absolute motions of a single plate with respect to the body of the Earth. The absolute-motion vectors are laid out as curved lines of arrows that depict the curved paths of various parts of the plates at the spherical surface of the Earth. Relative-motion arrows lie close enough together at plate boundaries for map users to interpolate between them to determine the relative rate and direction at any desired place. Both relative and absolute arrows are labeled with the rate of movement in centimeters per year.

A hotspot is a place where lava believed to be derived from below a plate erupts to the surface. Because the plate is moving and the hotspot is essentially fixed, a hotspot leaves a linear trail of volcanic rocks at the surface of the Earth. Active hotspots are shown in red on the plate-tectonic map. A circle marks the present position of the hotspot, and a bar extends from the present position to a point along the volcanic trail where the plate is calculated to have overlain the hotspot 10 m.y. ago.

Volcanic centers are classified on the plate-tectonic map by the age of their last-known eruption (Simkin and others, 1981). All the volcanoes that are shown were active within the 10,000-year duration of the Holocene Epoch. Those that erupted during historic time, or generally during the past 1,000 years, are distinguished by a separate symbol, and those that were active since 1964 are named in color. Many volcanoes lie above subduction zones and help to define them. Others occur at hotspots such as Hawaii, and a few lie elsewhere within the interiors of the plates, marking places where the Earth's crust is under tension.

Earthquake epicenters are shown on the plate-tectonic map in colors that represent earthquake depth intervals. Circles mark earthquakes of magnitude 5.7 through 7.4 that occurred since 1964, and triangles labeled by date mark earthquakes of magnitude 7.5 or greater that occurred since 1899. At subduction zones, systematically displaced bands of earthquake epicenters of different depth colors clearly illustrate the inclination of the zones. Also, discrete lines of shallow earthquakes closely follow active transform faults. Taken together, the belts of earthquakes plotted on the plate-tectonic map faithfully outline the plate boundaries.

Magnetic lineations, believed to represent past positions of spreading axes, are shown in black on the plate-tectonic map. Labels for the individual lineations are keyed to a labeled plot of a newly revised geomagnetic polarity time scale printed on the map sheets. The lineations are particularly useful in preparing reconstructions of past positions of the plates.

Intraplate structures, shown in black, include subsidiary faults at plate boundaries and major inactive faults ranging in age from Jurassic to the present, the same age range as the oceanic crust in the present oceans. On the seafloor, the intraplate structures indicate inactive transform faults, subduction zones, and spreading axes. The belts of intraplate structures depicted on the continents indicate areas that were being deformed at the same time that the present oceans formed.

Underwater topography on the plate-tectonic map is tinted in shades of blue. Deep-sea trenches, closely related to subduction zones, are clearly delineated, as are the broad areas of shallow submarine topography that lie along spreading axes. Submerged micro-continents and other oceanic plateaus are especially conspicuous on the map. These plateaus have a thickness of low-density crust intermediate between that on normal continents and that in the deep sea. Therefore, in analogy with icebergs, they "float" higher than the ocean basins but lower than the continents. Also, unlike oceanic crust of normal thickness that is readily carried downward at subduction zones, they commonly are too buoyant to be subducted. The Ontong-Java Plateau, for example, seems to have choked a former subduction zone east of the Solomon Islands, causing the present Solomon Subduction Zone to develop west of the islands. Accretion of submarine plateaus in this manner is believed to be an important process by which continents originate and grow larger.

HISTORY AND EVOLUTION OF PLATE-TECTONIC THEORY

A small group of scholarly papers has had a dominant influence on the development of the theory of plate tectonics. Some of these papers contain truly novel ideas, whereas hindsight reveals that the individual concepts in other papers were anticipated in previous research, when that research was out of pace with the development of the science.

The following summary focuses on papers that have had the greatest impact on later work. Also cited are earlier studies that led to the ideas in the later papers, and yet later ones that filled out the ideas and linked them to later stages in the plate-tectonic revolution.

The development of the theory of plate tectonics constitutes a splendid example of how major new areas of understanding are integrated into a scientific field of study, or, for that matter, into general human knowledge. The growth of such new knowledge progresses less like the steady forward flow of a great river than like the accelerating movement of a landslide—first comes an incipient creep of ideas outside the usual framework of understanding, then a gathering of momentum, and finally a burst of research and publication. Afterward, the scientific discipline is never again the same.

CONTINENTAL DRIFT (ALFRED WEGENER, 1924)

The theory of plate tectonics has firm roots in Alfred Wegener's theory of continental drift. "The Origin of Continents and Oceans," a 1924 translation of the third edition of his book "Die Entstehung der Kontinente und Ozeane," is the first English-language version of Wegener's work, which went through four successively revised German editions from 1915 to 1929. The third edition was also issued in French, Spanish, Swedish, Japanese, and Russian. Wegener's major contribution consisted of diagrams showing past continental positions. Those diagrams are strikingly similar to modern versions based on totally new data, such as dated magnetic lineations on the seafloor, earthquake slip vectors, and rock-magnetic values (on the continents) which show past latitudes and pole directions.

To develop his theory of continental drift, Wegener utilized the present distribution of plant and animal fossils that occur outside the climatic range of their living relatives, geologic evidence for ancient glaciations in presently tropical areas, and especially, the matching coastlines on opposite shores of oceans—for example, those of Africa and South America that flank the South Atlantic Ocean. Wegener acknowledged that some of his concepts of continental displacement were published previously by other authors, including Taylor (1910), who emphasized the role of continental displacement in creating mountain ranges. The fit of the continents across the Atlantic was commented on by many previous workers, and most clearly by Snider-Pellegrini (1858).

In an earlier paper on the subject, Wegener (1912) mentioned midocean rifting and even the present-day plate-tectonic concept that young seabed areas are shallower than old ones because a young and relatively hot oceanic block has a lower density than does an old and relatively cold one. But in his later books, he viewed the continents as traveling through the ocean basins like rafts through the sea. Therefore—in contrast with modern plate-tectonic theory in which the boundaries of relatively thick plates cut across both continents and ocean basins—in Wegener's continental drift theory, the boundaries between the moving blocks of crustal thickness all were the edges of continents.

The distinction between Wegener's concept of continental drift and the present-day understanding of plate tectonics is illustrated by his discussion of the movement of coastal California and Baja California along the San Andreas Fault to open up the Gulf of California. Wegener (1924) saw California as a thin splinter beginning to lose its moorings to a southward-drifting North America, but still plowing through a stationary subcrust so as to buckle the tip of Baja California and cause compressional bulges along the coast of California. In plate-tectonic theory, two thick plates shear past each other at the San Andreas Fault and in the Gulf of California. Rather than being under compression, Baja California is being stretched out along secondary faults that lie adjacent to the main plate boundary.

An intuitive distrust of the (mechanical) concept that thin crustal slabs could account for all observed geologic phenomena caused most geologists to reject the theory of continental drift, although a few such as Argand (1924), studying strongly compressed mountain ranges, found the concept useful in those areas. Despite the deficiencies of the continental drift theory, during the period leading up to the formulation of the theory of plate tectonics, Wegener's ideas were a great deal closer to the view that is now generally accepted than was the majority opinion, which then held that the present ocean basins were always a permanent part of the world scene.

GREAT FAULTS (MASON HILL AND THOMAS DIBBLEE, 1953)

The suggestion that there have been large horizontal displacements of the Earth's surface first came from detailed geologic investigations along great active faults such as the San Andreas. During the 1906 San Francisco Earthquake, the San Andreas Fault slipped by as much as 6.4 m, and similar events on the fault occurred during the preceding historic period (Lawson and others, 1908). In many places, rocks on opposite sides of the fault are greatly different from each other. Most investigators assumed that the sharp contrasts in rock type were a consequence of uplift and erosion on one side that had exposed rocks which were presumed to occur at depth on the other side. But Hill and Dibblee (1953) showed not only that the distribution of contrasting rock types required a history of horizontal displacement along the fault, but that the total displacement was as great as 560 km.

In their monumental paper "San Andreas, Garlock, and Big Pine Faults, California—A Study of the Character, History, and Tectonic Significance of Their Displacements," Hill and Dibblee (1953) showed that the lowest basement rocks on opposite sides of the San Andreas Fault are greatly different in type, so no amount of uplift alone could result in a matching of rocks across the fault. More important, they showed that distinctive rock types were displaced by distances proportional to their ages. Young rocks were displaced small distances and older ones progressively greater distances. When all the evidence is brought together, the resulting age-versus-displacement graph shows that, over all, the fault has slipped very regularly during recurring earthquakes through a long period of geologic time.

Large displacements were previously reported along inactive faults on the basis of distinctive offset rocks, for example, along the Great Glen Fault in Scotland (Kennedy, 1946). Wellman (1955), working in New Zealand at about the same time as Hill and Dibblee, measured 450 km of displacement along the active Alpine Fault. Subsequent more accurate dating of offset features along the San Andreas Fault, such as boundary lines of various ages between marine and nonmarine strata (Addicott, 1968), further refined the movement history of the fault. Today, the San Andreas Fault is the world's best studied active plate boundary.

At the time, many other scientists accepted Hill and Dibblee's well-documented study, but the full implication of the 560-km displacement along the San Andreas Fault remained unresolved for more than a decade.

DEEP EARTHQUAKE ZONES (HUGO BENIOFF, 1954)

Turner (1922) reported that some earthquake waves traveling to seismographs from a source on the opposite side of the Earth arrived more than 1-minute earlier than expected. He suggested that those waves come from sources hundreds of kilometers below the surface, with that depth causing a short travel distance and travel time through the Earth. At first, Turner's work was discounted because the Earth was believed to be too hot and plastic to sustain faulting at such a depth. But other workers soon substantiated his evidence. It remained for the theory of plate tectonics to provide a full explanation by showing that cold crustal material can move downward quickly enough to emplace brittle rocks at a depth where faulting can cause deep-focus earthquakes.

Seismologists found that the deep earthquakes consistently occurred at certain places in the world, for example, South America, Polynesia, and Japan. Some investigators thought that the earthquakes resulted from abrupt changes in rock volume caused by minerals reacting to pressure. But in Japan, Wadati (1935) demonstrated that movement along faults caused the deep earthquakes, and that the earthquake foci become progressively deeper with distance from the Pacific Ocean.

Benioff (1954) interpreted the deep earthquake zones around the Pacific as great thrust faults; that is, as inclined faults in which an upper crustal block has overridden a lower. He directed attention to the close spatial relationship between the faults and the volcanoes of island arcs. He emphasized that the length of those faults proves that they have major mountain-building importance, and that their great depth argues against the drift of relatively shallow continents as a cause for tectonics. His clear profiles showing the distribution of the depths of earthquake foci had great impact, and today these inclined earthquake zones are often called Benioff zones. Benioff zones have become the principal evidence that the downward movement of plates is a mechanism for plate convergence.

DIRECTIONS TO THE EARTH'S MAGNETIC POLE (KEITH RUNCORN, 1956)

Basaltic lava erupting from volcanoes includes a slurry of tiny crystals, one type composed of magnetite, the iron mineral that forms natural magnets called lodestones. High temperature destroys magnetism, so these tiny magnetite crystals in the lava (initially) are nonmagnetic. As the lava cools, each crystal acquires a magnetization from the Earth's magnetic field. Because all the crystals are magnetized in the same direction, the solid basalt acts as a weak magnet.

In their natural settings, basalt and other rocks with measurable magnetization record the direction of the Earth's magnetic pole at the time they formed. They also record the latitude at which they were formed, because the Earth's magnetic field at any locality has an inclination (steep near poles, flat near Equator) as well as a declination.

Most young rocks contain a remanent magnetization that points toward the present pole, but older ones do not. Initially this information was interpreted to mean that the poles had wandered—that the body of the Earth had shifted with respect to its axis of rotation and the magnetic poles.

Runcorn (1956) assembled data on magnetic-pole directions in rocks of various ages on different continents. He found that whereas the younger rocks on the continents showed poles near the present one, the apparent location of the poles gradually diverged for two continents as the directions given by older and older rocks were determined. Thus, rocks that formed during the Jurassic Period (180 m.y. ago) in North America indicate a magnetic pole displaced about 24° of longitude from the pole of the same age for Europe.

This evidence clearly shows that North America had been displaced from Europe since Jurassic time, but Wegener's version of continental drift remained inadequate to fully explain all the known facts about the active processes in the Earth. At this point in its development, the science of tectonics teetered unsteadily. Diverse ideas came forth; with passing time some proved to be fruitful, others not. Scientific journals began to abandon their former reluctance to publish "outrageous" hypotheses, and the science of geology entered the most healthy period in its history.

But other still more surprising new factors appeared in this chapter of the history of geology before the final paragraph was written.

OCEANIC RIFT SYSTEM (BRUCE HEEZEN, 1960)

The great linear mountain ranges on the ocean floor, such as the Mid-Atlantic Ridge, East Pacific Rise, and Southeast Indian Ridge, rise to about 2,500 m below the ocean surface, whereas the general depth of the deep-ocean basins is more than 5,000 m. Ewing and Heezen (1956) found that a steep-walled linear valley follows along the crests of many of the midocean mountain ranges. It was also known that small earthquakes occur along the ridges (Tams, 1927) and that the material at shallow depth below the seafloor ridges is especially hot (Bullard, Maxwell, and Revelle, 1956).

Heezen (1960) assembled and published the data on the world's midocean ridges. He showed that the rift system is worldwide and is in a dynamic state. He proposed that the ridges are expanding laterally to create the rifts. Because of the fairly regular distribution of the rifts on the surface of the Earth, his first hypothesis was that the entire globe was expanding to create them. However, a few years later he abandoned that idea when it was shown that divergence at the ridges could be balanced by convergence at subduction zones. The great rift system, however, became another factor to be reckoned with in the gradually lengthening tectonic formulation.

MAGNETIC LINEATIONS (RONALD MASON AND ARTHUR RAFF, 1961)

For many years, geophysicists have used surveys of the natural magnetization of rocks in land areas as an aid in interpreting subsurface geology as it might relate to mineral and petroleum occurrences. Following the development of a continuously recording magnetometer and an improved means of radio navigation, the U.S. Coast and Geodetic Survey vessel *Pioneer* conducted a detailed magnetic survey of the ocean off the west coast of the United States. Mason and Raff (1961) reported on this survey.

After Mason and Raff subtracted the average magnetic field of the Earth and the gradient resulting from the rapid change in the field from the Equator to the North Pole, a remarkable magnetic pattern was found to remain. Extremely regular lines of anomalously high and low magnetization extend for hundreds of kilometers along the nearly smooth seafloor, then terminate abruptly against equally straight lines running at right angles to the trend of the anomalies. The lines of termination were immediately recognized as the long lines of disturbed seafloor that Menard (1955) called fracture zones, but the magnetic anomalies were inexplicable.

Mason and Raff's paper was published in the Geological Society of America Bulletin. Their large foldout map caused that issue to fall open to their article. Most American geologists and many others around the world puzzled over the main map, and especially over a smaller scale "zebra-striped" diagram on which seafloor of positive magnetization is shown in black and negative in white.

The short wavelength of the anomalies indicates that the magnetic sources lie only a short distance below the seafloor, but no convincing mechanism could be found that would cause such an extremely regular alternation. Most who saw the maps knew that the explanation must be simple, but despite the application of many minds to the problem, the answer was still several years away.

SEAFLOOR SPREADING (HARRY HESS, 1962)

At about this time, Harry H. Hess, professor of geology at Princeton University and president-elect of the Geological Society of America, published a paper that had been available as a preprint for several years (Hess, 1962). He pointed out that the known thickness of sediment on the seafloor and the known rate of sedimentation gave an age for the ocean basins of only a few hundred million years, in contrast to the 4,600-m.y.-old age of the Earth. He also pointed out that the volume of rock in extinct volcanoes in the ocean basins is far too small for the age of the Earth in the context of the known rate of growth of active oceanic volcanoes.

Rejecting the idea of an expanding Earth, Hess suggested that some oceanic margins are overridden by continents, and that the oceanic sediments at those margins and the volcanic seamounts ride down into a "jawcrusher" and are welded onto the continents. Coats (1962) went a step further, proposing that the active volcanoes near oceanic trenches originate from those oceanic crustal materials as their temperature increases with depth.

PALEOMAGNETIC TIME SCALE (ALLAN COX, RICHARD DOELL, AND BRENT DALRYMPLE, 1963)

Brunhes (1906) discovered that the direction of polarity for certain magnetized volcanic rocks is precisely opposite to that of others nearby. Both the polarity and the inclination match values to be expected if the north and south magnetic poles of the Earth were reversed.

This observation later became well-known to investigators studying apparent past positions of the magnetic poles with respect to rocks of known age. Approximately half the rocks are reversed, and half are normal. This phenomenon is taken to indicate that the polarity of the Earth's magnetic field has itself undergone reversals.

Matuyama (1929) discovered that the most recent reversal, which established the present magnetic field of the Earth, seems to have taken place during the early part of the Pleistocene Epoch (the Great Ice Age). The pursuit of Matuyama's discovery was delayed many years, because there was no known way to accurately determine the age of young volcanic rocks. This problem was solved by John Reynolds (1956) with his invention of a greatly improved mass spectrometer for measuring, in volcanic rocks, argon that had formed by the radioactive decay of potassium. Because fresh lava contains little argon, the ratio of argon to potassium found in volcanic rocks becomes a measure of their age.

Cox, Doell, and Dalrymple (1963), in the laboratories of the U.S. Geological Survey, used Reynolds' new mass spectrometer to date a series of young onshore volcanic rocks of various magnetic polarities. Their paper "Geomagnetic Polarity Epochs and Pleistocene Geochronometry" was the beginning of the geomagnetic time scale. It established not only that the period of the present normal direction of the Earth's magnetic field began about 1 m.y. ago (it is now accepted to have begun 780,000 years ago), but also that the preceding reversed period had a duration of about 1 m.y. and that an earlier normal period began about 3.3 m.y. ago.

The geomagnetic polarity time scale has since become the most precise basis for intercontinental correlation of rocks of young geologic age. And soon after its publication, the time scale also became a key factor in the development of the theory of plate tectonics, because it offered an explanation for Mason and Raff's magnetic anomalies.

MAGNETIC RECORD OF SEAFLOOR SPREADING (FRED VINE AND DRUMMOND MATTHEWS, 1963)

Vine and Matthews (1963) combined the ideas of seafloor spreading and the recurring reversals of the Earth's magnetic field to solve the problem of the puzzling magnetic lineations on the seafloor.

As the seafloor spreads apart and the rift along the midocean ridge widens, subcrustal material wells up in a long linear belt to fill the gap (fig. 2). Initially this material is too hot to hold magnetization. When it cools, it acquires the magnetization of the Earth's magnetic field at the time. The direction of polarity is either present-day normal or reversed, depending on the geomagnetic polarity epoch.

As spreading continues, the new seafloor splits along its middle, and a new belt of lava is interposed between the two halves of the older belt. If, in the meantime, the polarity of the Earth's magnetic field has changed, the young central belt is flanked by two belts of opposite polarity. Ultimately, the entire seafloor becomes covered by the "zebra-striped" pattern of magnetic lineations discovered by Mason and Raff (1961). Because the seafloor moves continuously outward from the spreading axis and carries with it half of each magnetic belt in each direction, the pattern of stripes is symmetric from the axis.

This pattern was sought and found along the world's active spreading axes. The actual patterns differ only in the width and spacing of the component magnetic anomalies, factors dependent on the rate of spreading at a given axis.

The seafloor anomalies constituted a precise record of the reversals of the Earth's magnetic field. A much longer geomagnetic polarity time scale was obtained when the anomalies in older parts of the ocean basins were added to those only a few million years old near the spreading axes (Pitman and Heirtzler, 1966).

Dating the rate of seafloor spreading by means of the magnetic anomalies permits a quantitative analysis of the height of the midocean ridges, which is dependent on their temperature, itself dependent on their youthfulness. Inasmuch as mantle material moves upward from depth to fill the gap created by spreading, rocks down to the base of a plate and below are much hotter near a spreading axis than are rocks at a similar depth in an older part of the basin, where a more nearly normal geothermal gradient has had time to reestablish itself by cooling from the surface. The occurrence of greater thermal expansion at ridges than at the roughly 100-km-thick plate in deep basins explains why the ridges rise about 2.5 km above the deep basins. Because rock is a slow conductor of heat and the plates are thick, as long as 40 m.y. is required for the flanks of the ridges to cool down (and shrink) sufficiently to produce a water depth of 5,000 m (Sclater, Anderson, and Bell, 1971).

TRANSFORM FAULTS (TUZO WILSON, 1965)

When the offset of magnetic lineations along fracture zones was discovered, the anomalies were assumed to have been continuous originally and displaced later by faulting along the fracture zones. In rejecting this notion, and proposing instead that they were offset from the beginning, J. Tuzo Wilson (1965) made a quantum jump in geologic understanding that established the theory of plate tectonics.

All previous tectonic models had assumed that individual tectonic elements, such as mountain ranges, grade smoothly into one another. In Wilson's model, many of them intersect at right angles. And it soon became apparent from newly completed surveys that many major tectonic boundaries on the seafloor are mutually perpendicular, hence the concept of transform faults.

The concept can be understood by studying a spreading axis on the plate-tectonic map such as the Juan de Fuca Ridge. It also can be visualized with a sheet of paper and a pair of scissors. Cut across the sheet, but in the middle make a long steplike cut at right angles to the left, then continue across the sheet in the original direction until the paper is severed. Reassemble the two pieces, then pull them apart, keeping the horizontal step (the transform fault) tightly closed and creating two vertical gaps (the spreading axes). Note that whereas the spreading

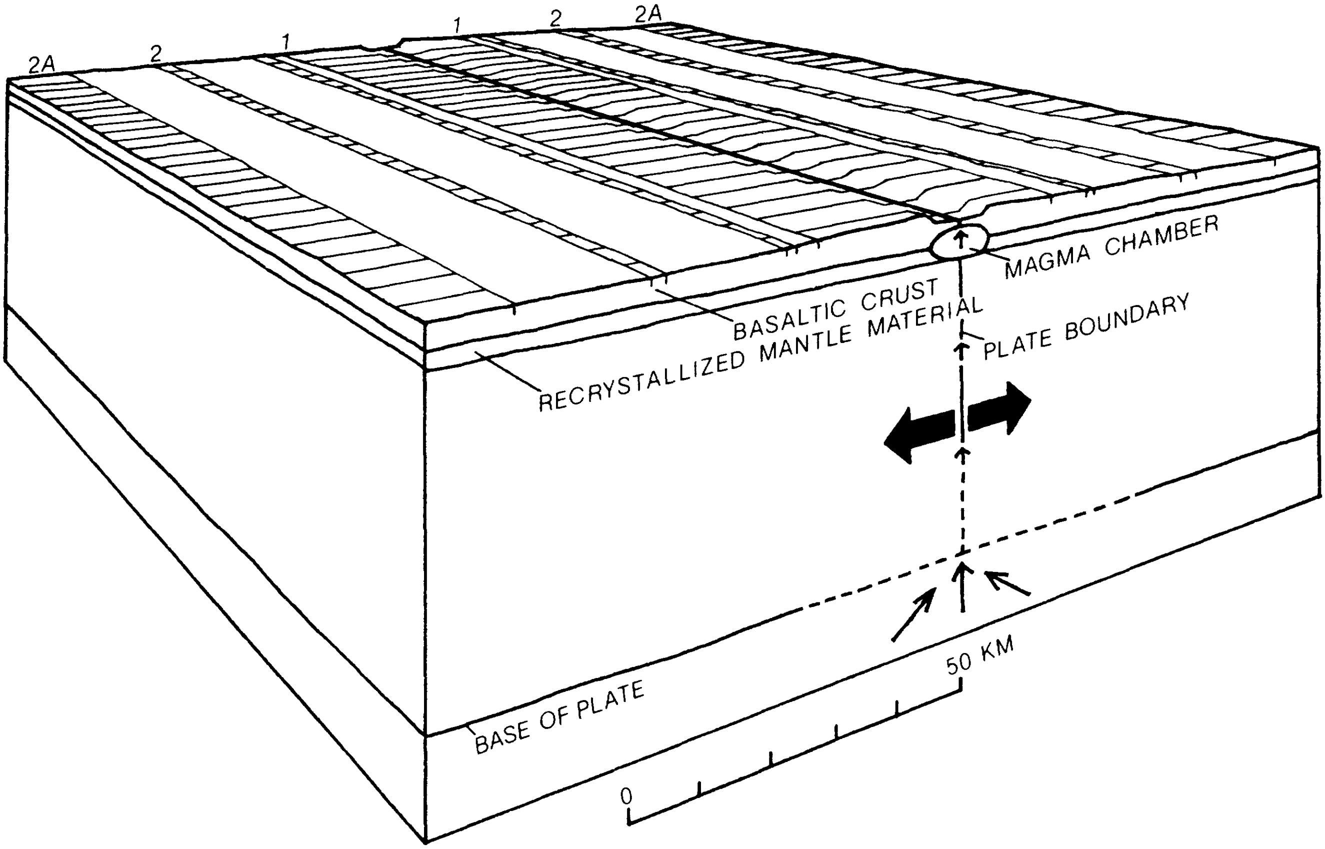

FIGURE 2.—At the rifted crest of a spreading axis, reversals in the Earth's magnetic field produce magnetic lineations between belts of basaltic lava in which the magnetization is normal (line pattern) and reversed (unpatterned). The lineations 1, 2, and 2A, on a plate 3-m.y. old, have formed symmetrically along an active spreading ridge that is opening at a rate of 5 cm/yr.

axes step to the left, the slippage between the sides of the transform fault is in the opposite direction, to the right.

The active part of the transform fault lies between imaginary lines at the center of each gap where the spreading area occurs at right angles to the transform fault. The inactive parts extend along the transform fault from the centers of the gaps to their outer edges.

The relationship between the active and inactive parts of the transform fault can be understood further by imagining the paper is an ice floe on a lake in winter. The surface of the water exposed in the gaps freezes as the gaps open, and the new ice becomes thickest next to the sides. Hence, the new breakage that comes with further spreading will occur in the middle of the gaps.

The turning point for the theory of plate tectonics came at the annual meeting of the Geological Society of America in San Francisco in November 1966. Earthquakes were known to be confined mainly to only short segments at the middle of fracture zones, that is, to the active parts of Wilson's transform faults (see the plate-tectonic map). If it could be shown that those earthquakes resulted from faulting in a direction opposite to the direction indicated by the offset of the ridge axes, Wilson's transform-fault model would be given very strong verification: perhaps it would be proved.

Lynn R. Sykes (1966), of Lamont-Doherty Geological Observatory, made the test. He used the method of earthquake first-motion analysis. In it, seismograms from stations in all directions around an earthquake under study were examined and noted as to whether the first signal received pushed toward the station, or pulled away. For any earthquake, the station signals divide into those from four quadrants on the Earth, two for each side of the fault. One is the quarter of the Earth toward which that side of the fault moves; the other, the quarter from which it moves away. By this method, the slip direction along the active transform faults can be determined. Sykes' research asked the question: Is the slip direction along transform faults invariably opposite to the direction of ridge offset? He found that it is, and Wilson's hypothesis was proved correct.

Sykes presented his paper to an audience of specialists in a technical session. But the organizers of the San Francisco meeting had arranged for a special session of "selected longer papers" on topics of general interest. One of the speakers was Fred Vine (1966). In a presentation in a large auditorium to an overflowing audience, he masterfully laid out the evidence for seafloor spreading and transform faults. He projected a slide of the seafloor magnetic anomalies off the west coast of North America in which the anomalies were colored according to age. The slide clearly illustrated the theory's principles to everyone, and it convinced most.

After that lecture, the halls outside the meeting room buzzed with talk of new concepts. As the attendees at the San Francisco meeting dispersed to their universities and laboratories, many resolved to test the new concepts and incorporate them into their research. The plate-tectonic revolution had come of age.

RELATIVE PLATE MOTIONS

On the first plate-tectonic map of the world, Wilson (1965) showed eight plates within the area covered by the new "Plate-Tectonic Map of the Circum-Pacific Region," later named the Antarctic, America, Australia-India, Caribbean, Cocos-Nazca, Eurasia, and Philippine Plates. On the present plate-tectonic map, the Cocos and Nazca Plates and the Australia and India Plates of the first map are separated, and the America Plate is divided into the North and South America Plates. In addition, nine smaller plates are now distinguished in the Circum-Pacific Region: Bismarck, Burma, Juan de Fuca, Mariana, Okinawa, Sandwich, Scotia, Solomon, and Tonga.

Many investigators tried to establish the rate of movement along various plate boundaries, in order to estimate the recurrence intervals of earthquakes. Three kinds of data are used: magnetic-lineation spacings, transform-fault directions, and earthquake mechanisms.

MAGNETIC-LINEATION SPACINGS

The geomagnetic polarity time scale (Larson, Golovchenko, and Pitman, 1992) is used to establish the age of the various magnetic lineations on the seafloor. The younger parts of the time scale were calibrated first on the basis of the magnetic polarity of onshore volcanic rocks of known age (Cox, Doell, and Dalrymple, 1963). Subsequently the scale has been repeatedly refined by deep-sea drilling, by determining the geologic age of microfossils that occur in sediment directly above the basaltic oceanic crust, and by dating the basalt itself by the potassium-argon radiometric method.

The spacing of the dated lineations next to a spreading axis defines the recent rate of movement of the two adjacent plates. Although the rate of movement between the Pacific and North America Plates had been known generally from several lines of evidence (such as the offset that recurred along the San Andreas Fault during earthquakes, and the offset of distinctive rocks of known age), the first precise value (about 5 cm/yr) came from a study of the spacing of magnetic lineations southeast of the tip of the Baja California Peninsula, where the peninsula has pulled away from mainland Mexico. Note that although on the Circum-Pacific map the full relative movement between the two plates is assigned to the principal fault, the San Andreas, part of the movement is distributed on nearby parallel faults: that distribution is indicated by the wide belt of earthquake epicenters in western North America.

TRANSFORM-FAULT DIRECTIONS

As already noted, midocean-ridge axes are offset at right angles along fracture zones (transform faults). Laboratory experiments show that when a crust of freezing wax is pulled apart it also breaks into faults and spreading axes at right angles, because slip between the two walls of a fault results in less frictional resistance to displacement than does the squeezing up of subcrustal material to fill in the narrow gap that occurs at spreading axes (Oldenburg and Brune, 1972; Lachenbruch and Thompson, 1972). Transform faults develop along alignments that tend to minimize the lengths of spreading axes; this places the transform faults precisely in the direction of relative motion of the adjacent plates.

The transform faults can be mapped by means of the rough topography usually characterizing them (Menard, 1955) and by means of the lines of earthquake epicenters that follow their active segments. Once mapped, the transform faults indicate the direction of relative movement of two adjacent plates, and the rate of movement can be measured from magnetic-lineation spacings associated with nearby spreading axes.

EARTHQUAKE MECHANISMS

The relative motion between plates is more difficult to measure at subduction zones than at spreading axes and transform faults, because a usable magnetic record is lacking and the direction of motion is not systematic with respect to the trench. For example, in the Gulf of Alaska the motion between the Pacific and North America Plates is squarely toward the Aleutian Trench, whereas farther west near Kamchatka, the motion is approximately parallel with the trench.

But relative motion at subduction zones can be determined by earthquake first-motion analysis. Just as we can learn the direction of faulting on a transform fault by an analysis of earthquake waves at an array of seismograph stations, a line separating where the first wave from a subduction-zone earthquake pushes toward the stations and where the first wave pulls away can be determined. This separating line lies at right angles to the direction of slip. Therefore, this line can be used to determine the direction of relative motion of plates at subduction zones.

GLOBAL PLATE-MOTION VECTORS

The plates move on the surface of the Earth in much the same way that a piece of a spherical shell moves on a globe (fig. 3). If the piece is small, its movement closely resembles that of a flat tile moving on a table. But if the piece is as large as a half sphere, its movement on the globe can be seen as a rotation about an axis passing through the center of the globe and intersecting the half sphere at poles of rotation at its two opposite edges.

The rate of movement of a half-spherical plate on a globe approaches zero near the two poles of rotation, and is at a maximum along a centerline midway between the poles.

The motion even of a small shell-like plate on the Earth occurs as if it had two poles of rotation, and for small plates these are commonly located far outside

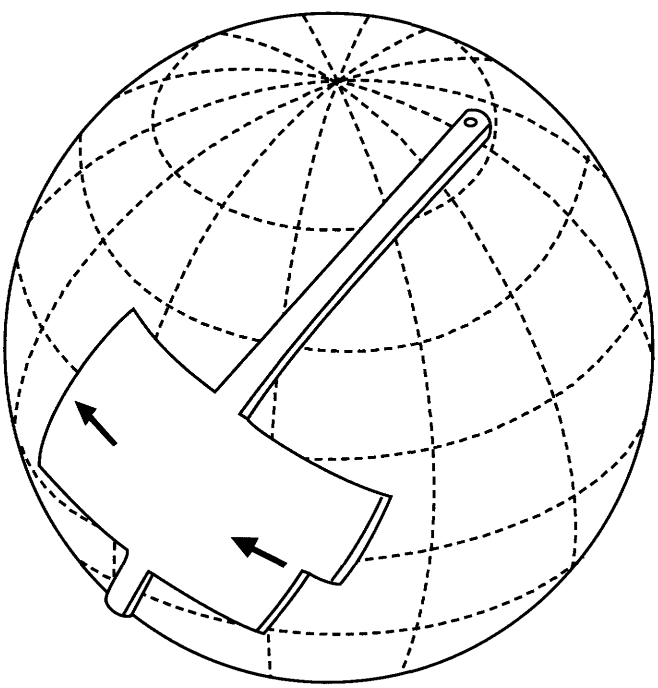

FIGURE 3.—Tectonic plates rotate about poles of rotation with a rate that is greatest halfway between the two poles, and which approaches zero at the poles.

the area of the plate. Such a small plate can be imagined as though it were attached to a half sphere moving on the surface of the Earth and revolving about a pair of poles of rotation.

On the Circum-Pacific map, the rotation of the individual shell-like plates is represented by curved lines of arrows that depict the direction and rate of movement at various places on the plates with respect to the body of the Earth. For example, on the large Pacific Plate, where the maximum rate of movement (along what can be called the equator of rotation) extends from Chile to China, the two poles of rotation are both outside the area of the plate: one in northern Canada, the other near the coast of Antarctica.

The movement of the Pacific Plate is approximately symmetric with respect to its poles of rotation. The maximum rate, along the centerline, is 10.9 cm/yr; closer to the poles of rotation—for example near the edges of the plate in the Gulf of Alaska and near New Zealand—the rate is 6 cm/yr.

Some smaller plates seem to lie close to one of their poles of rotation. A pole for the Philippine Plate is nearby close to Kamchatka, and so the movement of the Philippine Plate resembles a door swinging open. The rate is 10 cm/yr in the southern part of the Philippine Sea, but only 5 cm/yr in the northern part.

The examples of plate motion given thus far describe the motion of individual plates with respect to the Earth. The movements between two different plates are also expressed in terms of rotations about poles, in this case relative poles of rotation between the two plates. Just as single plates move by rotation on the Earth as a whole, each individual plate rotates with respect to any other plate. For example, a pole of relative motion between the Pacific Plate and the North America Plate is in Quebec. The rotation around this pole defines the transform faulting at the San Andreas Fault as about 5 cm/yr, the seafloor spreading south of the Baja California Peninsula as about the same, and the subduction in the middle of the Aleutian Trench as 7 cm/yr. The constant rate of angular rotation around the relative-motion pole causes various rates of motion between the plates at different places, depending on the distance of a given place from the pole.

By means of seafloor-spreading rates, transform-fault directions, and earthquake slip directions, numerous investigators have made measurements of the rate and direction of relative motion between all the major plates. But the rate measurements are commonly taken at different places than the direction measurements. And measurements of rate and direction at several places are necessary to define the curved pattern of motion of the shell-like plates. Also, each measurement has a certain error attached to it: for example, earthquake slip vectors are dependent on the density and spacing of seismograph stations, and transform-fault directions are affected by irregularities in the topography. Consequently, the global synthesis of all the measurements of rate and direction into a single set of internally consistent relative plate motions would be virtually impossible if it had to be done exclusively by hand methods of computation.

Recent sheets of the "Plate-Tectonic Map of the Circum-Pacific Region" use the computer-derived relative plate-motion model of DeMets and others (1990). This model is a best fit of 1,122 worldwide measurements of the rate and direction of motion between the world's major plates. On the Circum-Pacific map the motion of some minor plates with respect to the major plates has been determined from additional local measurements of relative rate and direction.

ABSOLUTE PLATE MOTIONS

The relative-motion model of DeMets and others (1990) is the latest in a series of similar studies undertaken by several laboratories as more and more local data from around the world has become available. The various models clearly converged on a single movement picture. Although much information is still needed on the direction of movement of large slow-moving plates and on both the direction and rate for some small plates, it now seems unlikely that future work will greatly change the model for relative motion between the large fast-moving plates.

Much more uncertainty remains, however, in regard to the absolute motion of an individual plate with respect to the body of the Earth. In analogy with a jigsaw puzzle on a table, if movements between the individual pieces are combined with a slow slippage of the entire puzzle (or plate system) across the supporting surface, then the movement of a single piece with respect to the underlying surface is not easily discerned.

J. Tuzo Wilson (1963), in a paper that preceded his landmark paper on transform faults in 1965, suggested a method by which the absolute motion of plates might be determined. As mentioned on a preceding page, the rocks composing several long lines of islands are known to become progressively younger with movement along the line. Along the Hawaiian Ridge, for example, the present-day volcanism occurs at

Hawaii, the southeasternmost island, and potassium-argon dating shows a regular progression of older ages for rocks of the other islands to the northwest. Wilson suggested that a stationary hotspot now below Hawaii was overridden by the Pacific Plate, so that lava from the hotspot broke through the plate at successively different places to form the line of islands.

Given a relative-motion model for the world's plates, a rate and direction for one plate, inferred from such a hotspot trace, can be used to derive the absolute motion for all the plates. For recent sheets of the "Plate-Tectonic Map of the Circum-Pacific Region," the individual plate motions come from Gripp and Gordon's (1990) absolute-motion model, which is based on a best fit of the hotspot traces depicted on the Circum-Pacific map sheets.

A third independent method was used on the plate-tectonic map to derive the motion vectors for some of the smaller plates. If you can assume that deeply rooted subduction zones extending 700 km into the mantle are geographically fixed with respect to the body of the Earth, then you can also assume that small plates directly above them are also fixed. This hypothesis was used for the map to suggest that the Mariana, Sandwich, and Tonga Plates are fixed with respect to the mantle. That inference then aided in defining the movement of other small plates nearby.

THE SEARCH FOR A MECHANISM

Since the theory of plate tectonics has become widely accepted, a large cadre of earth scientists has studied active geologic processes and the rock record of past events as they might relate to the theory. Nevertheless, a generally accepted explanation for the driving force of the plates has remained elusive. Three main classes of plate-driving mechanisms are currently under consideration: (1) convection, by which a slow overturn of material within the Earth results when lighter material at depth changes places with heavier material near the surface (Morgan, 1971); (2) ridge push, in which a plate moves away from a spreading axis because hot low-density material from below wedges it apart (Orowan, 1964; Moore, 1975) or gravity drives it from an elevated spreading axis (Hales, 1969); and (3) slab pull, by which cool and therefore dense upper-mantle material in a plate descends into a subduction zone and draws in the remainder of the plate (Isacks, Oliver, and Sykes, 1968; Forsyth and Uyeda, 1975).

At present, the convection model is receiving the most attention. At spreading axes, where the plates move apart, material from deeper in the Earth must fill the gap; at subduction zones, where plates move deeply into the mantle, displaced material must move away to make room for that which follows. Thus, regardless of the fundamental driving mechanism, some convection is necessarily associated with plate motion, although not necessarily as its cause.

To maintain the form of the Earth, the amount of newly introduced material at spreading axes must match the amount of material displaced as plates move down into subduction zones, so one can think of flow in the Earth as moving from subduction zones to spreading axes. The pathway for this flow differs, however, for different hypothetical driving mechanisms. For example, if the flow is mainly a consequence of plate movement, then it might occur as a backflow, directly below a plate and in a direction opposite to plate motion. But if a flow of mantle material below the plates is what drives them, then the movement below a plate would generally be in the same direction as the plate's motion, and as fast or faster. Experiments to test these options are nearly within the capability of present research methods.

Convection within the Earth usually is thought of as originating from the heat generated by the decay of radioactive elements occurring naturally in the Earth's core and mantle. Because of the great distances involved, ordinary conduction may be inadequate to dissipate such heat to the Earth's surface, and so certain layers at depth become hotter and thus less dense than those above. These hotter layers may rise upward slowly, then spread outward to become cooled near the surface.

Convection in the Earth is considered to occur in convection cells, closed circuits in which mass movement of hot material takes place on rising limbs and of cold material on sinking limbs. It was first thought that rising limbs of convection cells inferred to drive the plates followed spreading axes faithfully, whereas sinking limbs followed subduction zones. But long offsets of spreading axes, and right-angle intersections between spreading axes and subduction zones, seem to invalidate this concept. It is now thought that convection is coupled only loosely to the plate movements. The hot rising limbs and cool sinking limbs generate bulges and depressions on the surface of the Earth, and the force of gravity may drive coherent plates horizontally from areas that are generally high to areas that are generally low.

Solid masses of light material rising upward through a denser medium usually appear cylindrical in laboratory experiments and in such natural structures as salt domes. This shape minimizes the area of contact and of frictional resistance between the two materials. In the convection hypothesis, hotspots such as the one at Hawaii might be the surface expression of convective plumes that drive the plates. Also, an array of other plumes is generally assumed to reach only to the base of the same plates and to spread radially from there to contribute to the driving force.

Conditions at a newly formed midocean subduction zone might be expected to provide clues to the relative importance of convection, slab pull, and ridge push. The subduction zone between the India and Australia Plates has only recently become active (Eittreim and Ewing, 1972). An intensive international research effort is now underway at the India-Australia boundary. The new join is clearly a consequence of collision between India and Eurasia, which has slowed the India Plate and caused the Australia Plate to underthrust it. But the investigators will be sorely taxed to distinguish between a midocean ridge push from the Southeast Indian Rift and an extension of subduction out into the Indian Ocean by slab pull at Indonesia's Sunda Thrust.

Seismic tomography, a recently developed method for imaging the Earth's interior, reinforces the notion that the local driving force for the plates is within the plates themselves (Anderson, Tanimoto, and Zhang, 1992). This method utilizes the time required for seismic waves to pass from natural earthquakes to seismographs. Multiple earthquakes and multiple seismographs are used, and all paths that pass through a given volume of rock are compared by computer. A best fit with all other similar volumes transected by the paths yields the seismic velocity of each volume. And this seismic velocity is inferred mainly to reflect the temperature of the volume.

Tomographic imaging shows that hotspots are rooted quite shallowly below the plates, that spreading axes are underlain by shallow areas of hot mantle off of which they commonly migrate, and that past and present subducted slabs are the principal cause of cool areas below the plates.

Some continents have drifted over hot mantle material presumably formed during previous cycles of seafloor spreading, but most continental areas are underlain by cool mantle emplaced as continental-margin slabs or as slabs associated with previous cycles of continental accretion. The mantle below the lithosphere of the Pacific Basin, long subject to rapid seafloor spreading, and free from subduction for hundreds of millions of years, is the Earth's hottest.

No matter how we explain their movement, plates do move. The lack of complete knowledge of the forces that cause plates to move has not inhibited the use of the fact of their movement in solving many earth-science problems. Once a full understanding of the dynamics of plate movement is achieved, we are likely to benefit from still another level of potential applications, all helping us to make the most effective use of the Earth and its resources.

APPLICATIONS OF THE PLATE-TECTONIC MAP

The concept of plate tectonics has improved our ability to protect people from hazardous earth processes such as earthquakes and volcanic eruptions, and it has aided the search for new mineral and petroleum resources.

Only moderate earthquakes occur at spreading axes, where upwelling of hot material from the mantle causes the Earth's crust to become plastic rather than brittle. Areas susceptible to earthquakes greater than magnitude 7.7 occur at active subduction zones and transform faults; the areas that are particularly susceptible lie in the gaps (along such plate boundaries) that have been free from major earthquakes longer than the flanking areas. Long-term earthquake warnings can be issued for these seismic gaps.

Earthquakes occur when the walls of a fault, that for a long period of time stuck tightly together without moving, suddenly slip. Many investigators are seeking clues to identify forerunners of the slip that might serve as short-term predictors of earthquakes.

Volcanoes occur mainly in three plate-tectonic settings: subduction zones, spreading axes, and hotspots. Danger from volcanoes is related to the chemical composition of the lava. Relatively siliceous light-colored lava such as andesite, which occurs above subduction zones, is dangerous because it is viscous. Such lava retains gas pressure until it reaches a critical threshold, and then it erupts explosively.

Most of the volcanoes around the Circum-Pacific "ring of fire" are associated with subduction zones (fig. 4). The lava is inferred to have acquired its chemical composition and viscosity through two stages of separation: in the first, water rising from subducting oceanic crust causes basalt to separate from the peridotite of the mantle by partial melting; in the second, the basalt rises to a magma chamber below the volcano where heavy dark minerals settle out leaving a residual liquid with the composition of andesite. Either increased earthquake activity or bulging of such a volcano (or both) can signal an impending eruption.

Spreading-axis volcanoes in the deep sea do not constitute a hazard, but volcanoes formed during rifting on land can (for example, along the African Rift Valley). The indicated danger of explosive eruption ranges from relatively low for dark-colored basaltic lava, to high for the light-colored lava that has differentiated from basalt by crystal settling.

The eruption of properly instrumented oceanic volcanoes, such as those at Hawaii, is often predicted with accuracy. The highly fluid basaltic lava usually does not kill people, but it can overwhelm property. Long-term predictions are made on the basis of increased earthquake frequency and swelling of the volcano; short-term predictions, from listening with seismographs to earthquake signals that are caused by the upward flow of magma from reservoirs below the surface.

Many metalliferous ores form as a result of high temperatures like those associated with spreading axes and with the magmas that rise from subduction zones. Recently, deposits of metal sulfides were found forming along the crests of deep-sea spreading axes. In the Circum-Pacific region, such deposits now are known to occur at the Juan de Fuca Ridge off the coast of Oregon, at the Galapagos Ridge off Equador, along the East Pacific Rise, at spreading between the Pacific and Tonga Plates, and at the Okinawa Rift. These deposits, when fresh, are all associated with vents discharging hot water. Some of the deposits on the seafloor contain abundant black zinc sulfide; copper sulfide occurs inside chimneys made of zinc and iron sulfide. Studies indicate that seawater at the spreading axis circulates to a depth of about 2 km in fresh volcanic rocks that are being cracked and rifted by further spreading. The water moves at high temperature through large quantities of basalt, from which it leaches out the metals normally found there in small quantities. The metals are reprecipitated where cold seawater is encountered, at the seafloor.

Understanding this process aids in finding similar ancient deposits now located on land. In places, extensions of mining districts can be sought on opposite sides of rifted oceans. For example, the diamond mines of Africa and South America, once closely continuous, are now separated by 7,000 km. Another large family of mineral deposits, such as porphyry copper deposits, is associated with the magmas that rise from subduction zones, and this knowledge also aids in the search for new resources.

Plate-tectonic phenomena can help explain anomalous distributions of animal and plant species. Wallace's line, mapped by the great naturalist Alfred Russel Wallace (1859), separates the fauna and flora of Asia from those of Australia. A puzzling aspect of Wallace's line was that very abrupt differences in the biota occur where the line passes between closely spaced islands in Indonesia. We now know that the areas of this archipelago that fall on

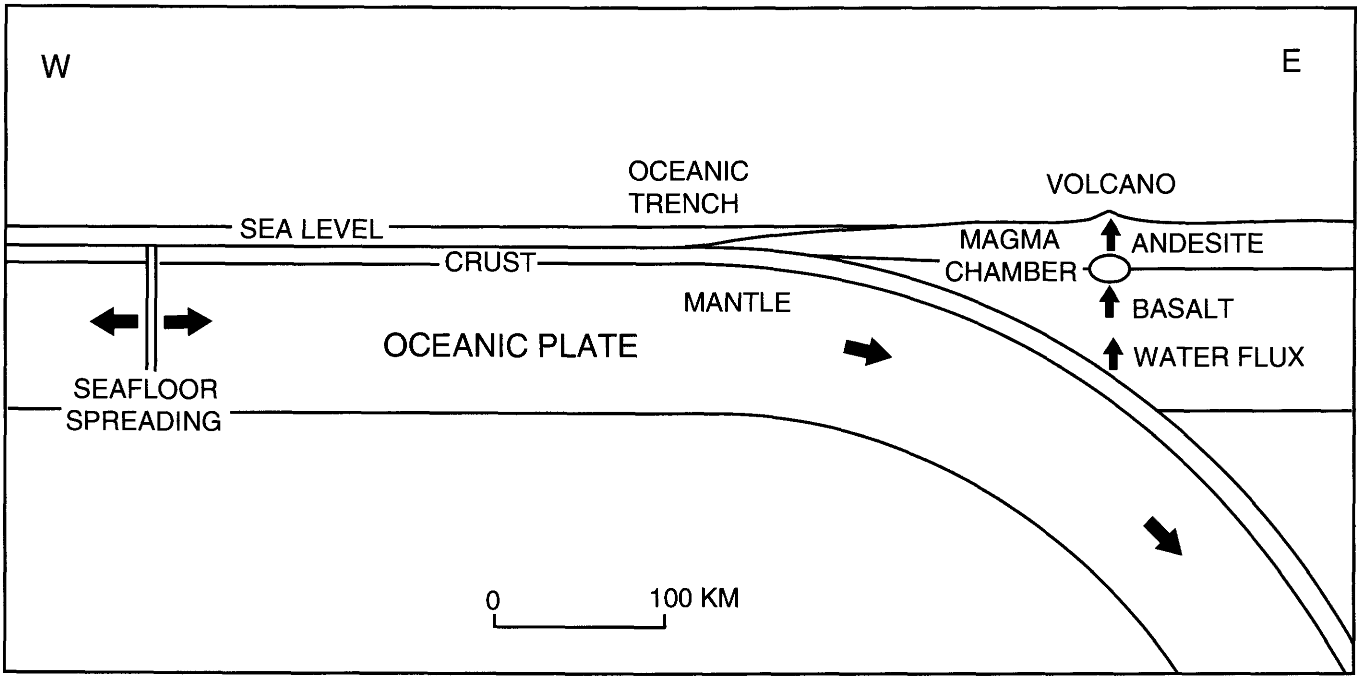

FIGURE 4.—Cross section showing the downward movement of an oceanic plate, the relation of its water-bearing upper surface to basalt generation in the mantle below a volcanic arc, and andesite generation from the basalt by the settling out of heavy dark-colored minerals to change the composition of the remaining liquid.

opposite sides of Wallace's line came together only 15 m.y. ago, and for a long period before that Asia and Australia were widely separated by the ancient Tethys Sea.

Another plate-tectonic concept, useful in prospecting both for mineral deposits and for petroleum, is the concept of accreted terranes (Jones, Silberling, and Hillhouse, 1977). Accreted terranes are oceanic plateaus, old island arcs, and small detached pieces of continents that move with the seafloor across ocean basins and accumulate at subduction zones as a geologic collage of mixed fragments. Much of northeastern Asia and northwestern North America are made up of such terranes accreted during relatively young geologic periods.

Some mineral and petroleum accumulations are carried in on these terranes, some are formed by processes that accompany the accretion, and some are concealed at shallow depth by the thrusting of cover over them during the collisions.

Petroleum is formed by the natural cracking by heat of dispersed organic matter in sedimentary rocks. Sufficient heat to form petroleum is made available near the Earth's surface by plate-tectonic processes. A particularly favorable environment is found along the edges of rifted continental margins, such as those around Australia and in the Gulf of Mexico. At such places, oceanic crust, newly formed and hot, lies close to an abundant source of sediment carried down from the continent. Sediment rapidly buries particulate organic matter, preventing its decay. The thick sediment pile that results receives heat from the warm oceanic crust below, and the organic matter is converted into petroleum.

Some oil-bearing rocks on rifted crust, such as those along the United States Gulf Coast, have remained tectonically passive: others, such as those in the Middle East, have been folded by later subduction events. Plate tectonics is now used as a conceptual tool in prospecting for new petroleum-producing basins. Because the concept of plate tectonics is such a coherent and comprehensive theory, it can unify our understanding of dissimilar areas, while providing a basis for solving diverse geologic problems in local areas. Plate-tectonic theory is truly the Rosetta Stone of the earth sciences.

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