The Changing Crust of the Earth

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CONTINENTS AND OCEAN BASINS

There are two distinct levels over the surface of the Earth (Figure 1). One corresponds with the continents, and the other with the ocean basins. The continents, with their submerged continental shelves, for the most part stand very close to sea level. Narrow continental slopes separate them from the extensive and relatively flat floors of the ocean basins which are at a depth at about 5 kilometres below sea level. This bimodal distribution of elevations at the Earth's surface arises from the fundamental differences in character and thickness between the continental and oceanic parts of the Earth's crust.

The crust of the Earth, some 10 to 60 kilometres thick, is little more than a thin skin when compared with the Earth's radius (6,400 kilometres), and yet only the upper part of it can be observed directly in the exhumed roots of ancient mountain belts. The character and thickness of the remainder of the crust, as well as the mantle beneath it, can only be inferred from indirect observations.

The Mohorovicic discontinuity (Moho) is a sharp contrast in density between the rocks of the crust and those of the mantle. It is marked by an abrupt increase in the velocity of propagation of the sound waves within the Earth which are generated by earthquakes or man-made explosions.

Seismologists who study the transmission of these waves have shown that the crust of the Earth is layered and that it is thicker and less dense beneath the continents than beneath the ocean basins. Variations in the strength of the Earth's gravitational field show that the continents and ocean basins are in a state of isostatic (floating) equilibrium. The continents stand high because they are formed of lighter rocks like granite, and are thicker. The ocean floors are lower because the oceanic crust consists of more dense rocks like basalt, and is thinner. Both are buoyant and float in the dense material of the upper part of the Earth's mantle, each at a level that is appropriate to its thickness and density.

The geologic record of the shallow seas which periodically flooded the continents indicates that this state of buoyant equilibrium has existed for at least 2.5 billion years, and that the continents have maintained a relatively constant freeboard with respect to the surrounding oceans.

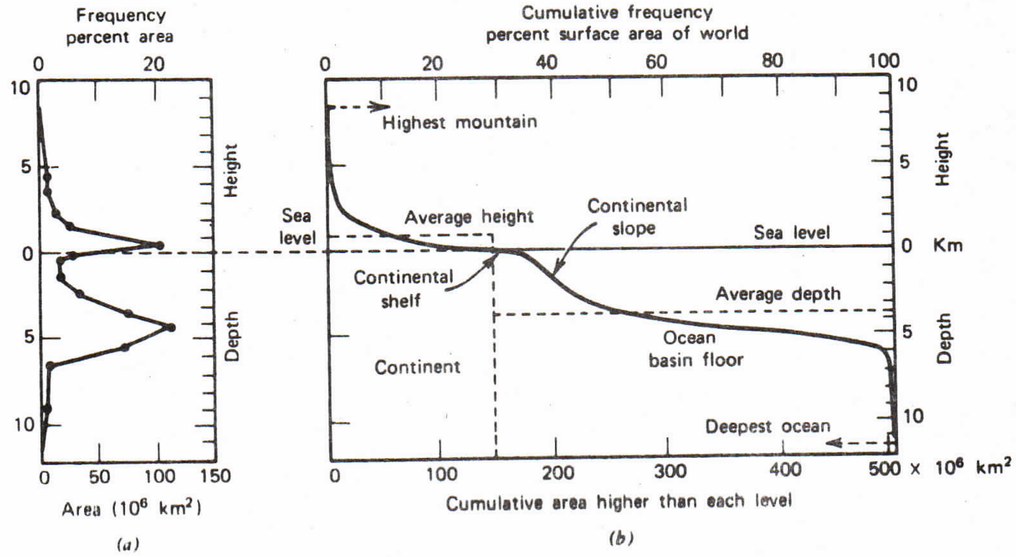

FIGURE 1. DISTRIBUTION OF AREAS OF THE SOLID EARTH BETWEEN SUCCESSIVE LEVELS. (a) FREQUENCY DISTRIBUTION. (b) CUMULATIVE HYPSOGRAPHIC CURVE. (From Wyllie, P.J., *The Dynamic Earth*, John Wiley and Sons, Toronto, 1971, by permission of John Wiley and Sons, Inc.)

CONTINENTAL DRIFT

The similarity in the shape of the margins of the continents on either side of the Atlantic is striking (Figure 2). It gives the impression that South America and North America, on one hand, and Europe and Africa, on the other, have been split apart along some colossal rift which opened to form the Atlantic Ocean basin. A comparison of the rocks and their geological history on opposite sides of the ocean reinforces this impression. It is the basis for the theory of continental drift, which was outlined over half a century ago.

According to this theory, the continents are fragments of a larger mass which broke apart some 200 million years ago. The drifting fragments have become rearranged over the face of the globe, and the mountain building, volcanism, and earthquakes, which have occurred since that time are a result of the continents plowing over the ocean basins or colliding with one another. Although the theory provided a very simple explanation for many global patterns in geological evolution there was no convincing mechanism for the drift, and the idea of a mobile crust ran counter to the time-honoured notion of the permanence and stability of continents and ocean basins. Consequently, by 1930, the whole idea had been dismissed throughout most of the world as unrealistic; and there the matter rested until about ten years ago.

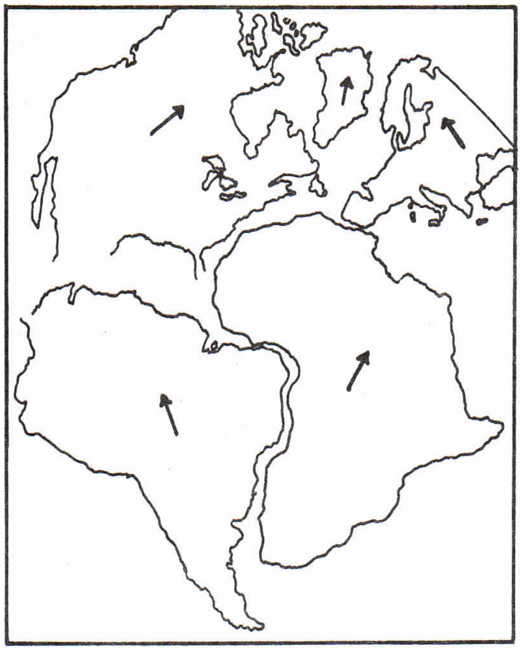

FIGURE 2. GEOMETRICAL FIT OF THE CONTINENTS AROUND THE ATLANTIC OCEAN. ARROWS POINT NORTH, INDICATING ACTUAL GEOGRAPHIC ORIENTATION OF THE CONTINENTS.

Two independent lines of investigation focussed attention back on the idea of continental drift. The study of fossil magnetization, frozen into rocks at the time they were formed, makes it possible to determine the orientation of the Earth's magnetic field in the geological past. By 1960 the changing position of the magnetic poles with respect to each of the continental masses had been outlined in a series of polar wandering curves; and the polar wandering curve which connected the successive locations of the north magnetic pole for each of the various continents diverged from the others in a very systematic and perplexing manner with increasing age of the rocks. The continents appeared to have been drifting apart as the rocks at various places within them were being magnetized.

Since World War II there has been a flood of new information on the ocean floors, a vast unknown area which makes up two-thirds of the Earth's surface. One startling discovery was a globe-encircling system of mountainous submarine ridges. The character and position of these oceanic ridges suggested that they marked a narrow zone along which the floor of the ocean was being split and pulled apart along deep rifts. Concurrent new information on the deep trenches which occur in the floor of the oceans adjacent to volcanic island arcs and young mountain belts strengthened the view that the crust of the Earth was being compressed and thrust down into the mantle.

Ocean-floor spreading, the concept of a mobile, ephemeral ocean floor, which grows by lateral accretion at a zone of upwelling in the mantle beneath the oceanic ridges, and is destroyed where it sinks into the mantle beneath the deep trenches, revitalized the old theory of continental drift and opened exciting new perspectives in the Earth Sciences. According to this theory, the floors of the oceans act like gigantic conveyor belts carrying everything above them, including the continents, away from the rift zones and into the oceanic trenches. Ocean basins form above fresh oceanic crust where a rift has split a continental mass into separate fragments that have drifted apart (Figure 3). Mountain belts form where light rocks have been scraped off the surface of the oceanic crust as it sinks into a trench, or where two continental fragments, such as India and Asia, collide along the zone of crustal sinking at a trench (Figure 4). At last the paucity of sediment and the lack of old rocks on the ocean floors could be reconciled with the geologic evidence for the great antiquity of the ocean basins.

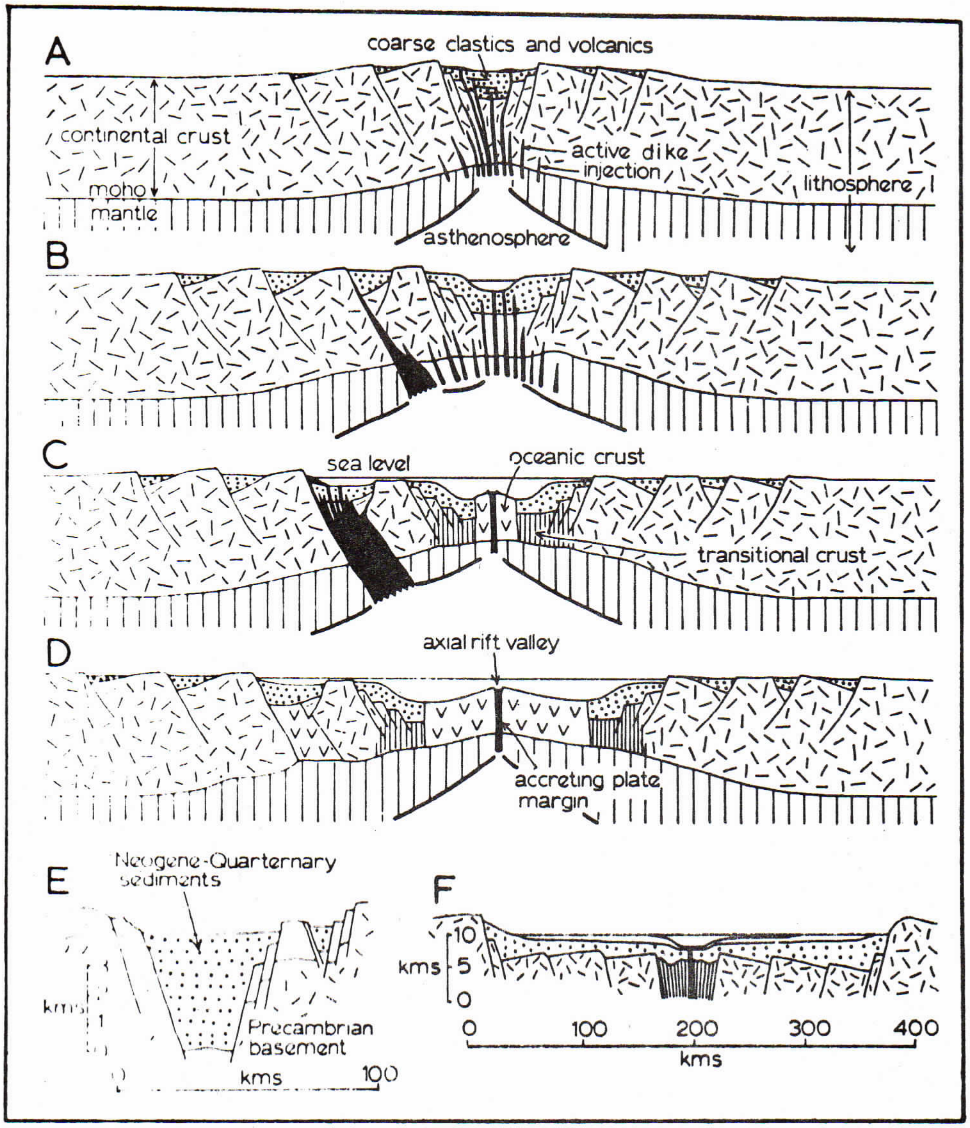

FIGURE 3. SCHEMATIC SECTIONS (A-D) ILLUSTRATE A POSSIBLE SEQUENCE OF EVENTS IN THE RUPTURING OF A CONTINENT AND THE EARLY EXPANSION OF AN OCEAN. (E) REPRESENTS A SECTION ACROSS THE GULF OF SUEZ (after Picard, L., in *The World Rift System, Can. Geol. Surv. Pap. No. 66-14*, pp. 22-32, 1966); (F) SHOWS A SECTION ACROSS THE RED SEA (after Girdler, R.V., in *The World Rift System, Can. Geol. Surv. Pap. No. 66-14*, pp. 65-75, 1966). (From Dewey, J.F. and J.M. Bird, *J. Geophys. Res.*, Vol. 75, Page 2629, 1970. Reprinted by permission of the American Geophysical Union.)

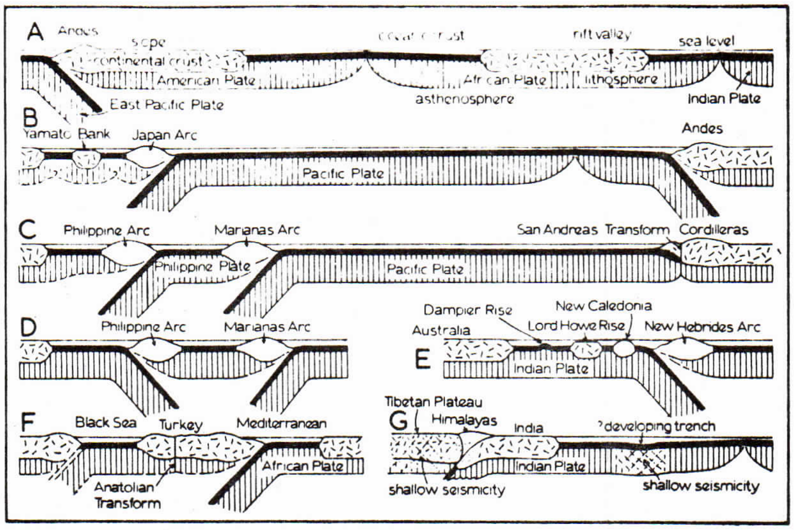

FIGURE 4. SCHEMATIC SECTIONS SHOWING PLATE, OCEAN, CONTINENT, AND ISLAND ARC RELATIONSHIP. THE ?DEVELOPING TRENCH INDICATED IN (G) IS FROM: Sykes, L.R., *Trans. Amer. Geophys. Union*, Vol. 51, P. 356, 1970. (From Dewey, J.F. and J.M. Bird, *J. Geophys. Res.*, Vol. 75, Page 2629, 1970. Reprinted by permission of the American Geophysical Union.)

LITHOSPHERE PLATE TECTONICS

Measurements of fossil magnetization show that the polarity of the Earth's magnetic field has periodically been reversed. Moreover, the reversals can be dated using the decay of radioactive isotopes from the same rocks in which the fossil magnetism was measured. A time scale for the reversals which have occurred during the past 4 million years has been established on this basis. New oceanic crust which forms where hot rock from the mantle wells up and cools beneath the oceanic ridges is magnetized in the direction of the contemporary field. The ocean-floor conveyor belt is also a tape recorder! Parallel strips of rock accreted along the edges of the spreading sides of the ocean floor are alternately magnetized with normal and reversed polarity. Airborne or shipborne measurements of the intensity of the Earth's field can locate these magnetized strips because they distort the Earth's main magnetic field (Figure 5). The history of growth of the spreading ocean floor is recorded in detail, step by step, in

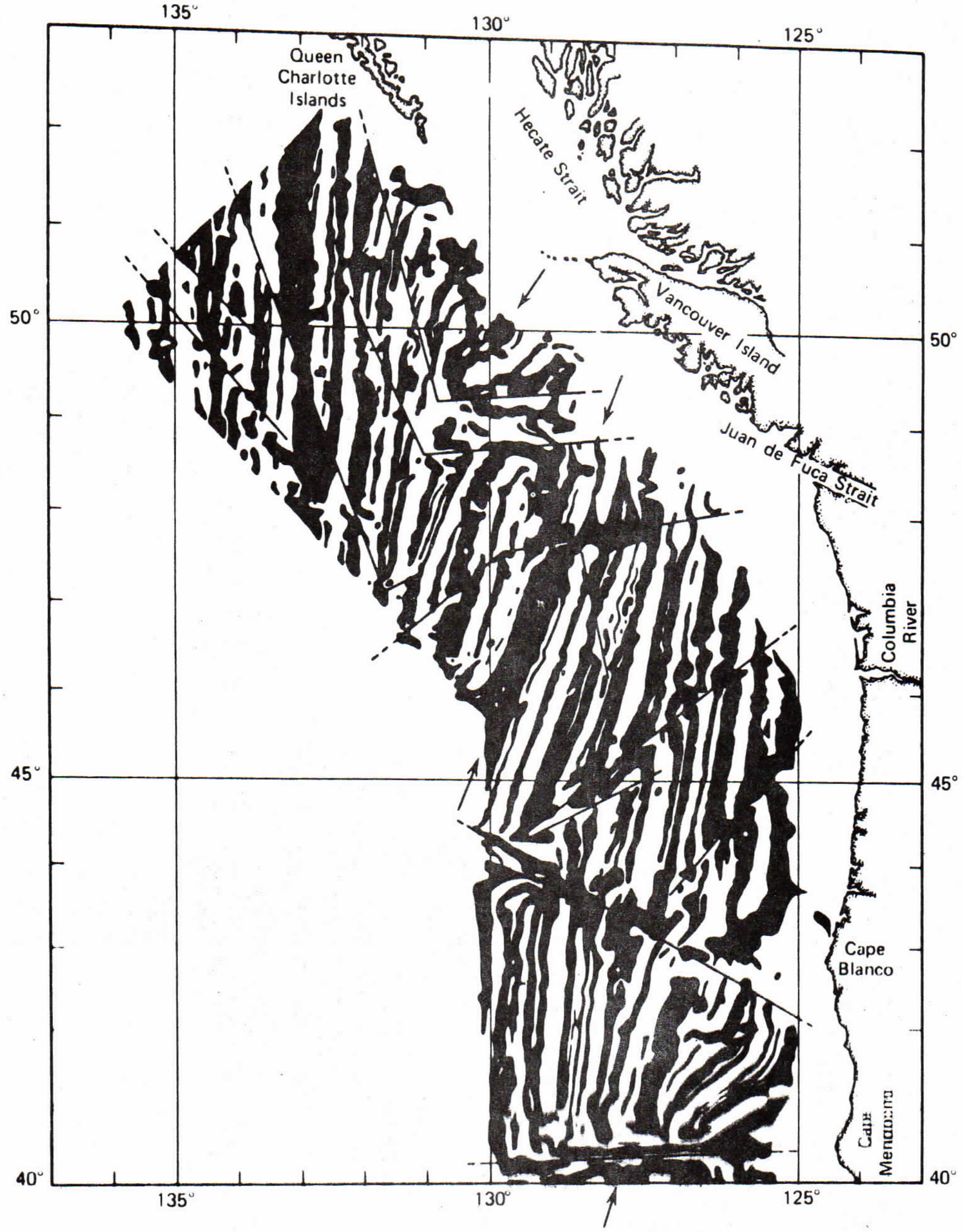

FIGURE 5. SUMMARY DIAGRAM OF TOTAL MAGNETICFIELD ANOMALIES SOUTHWEST OF VANCOUVER ISLAND. AREAS OF POSITIVE ANOMALY ARE SHOWN IN BLACK. STRAIGHT LINES INDICATE FAULTS OFFSETTING THE ANOMALY PATTERN; ARROWS, THE AXES OF THE THREE SHORT RIDGE LENGTHS WITHIN THIS AREA--FROM NORTH TO SOUTH, EXPLORER, JUAN DE FUCA, AND GORDA RIDGES. (After Raff, A.D. and R.G. Mason, *Bull. Geol. Soc. Amer.*, vol. 72, p. 1267, 1961. This version is from Wyllie, 1971. Reprinted by permission of The Geological Society of America and John Wiley and Sons, Inc.)

the magnetic imprint of the rocks of which it is formed. The ocean basins have been growing by lateral accretion. New rock is added to the edge of each plate at the zone of upwelling mantle beneath the oceanic ridges as each moves away from the ridges with velocities of up to 10 centimetres per year (Figure 6). This is continental drift at a rate that is quite adequate to account for the opening of the Atlantic Ocean basin and the dispersion of the southern continents during the past 200 million years. The history of continental drift deduced from a study of the regional geology around the periphery of the Atlantic and Southern Ocean basins had been dismissed as physically unrealistic by geophysics.

New, more precise information on the distribution of earthquakes has been gleaned from an enlarged and more sophisticated world-wide earthquake and nuclear-explosion detection system. This has clarified certain aspects of the pattern of deformation in the relatively cold, brittle, and rigid outer shell of the Earth which has been called the lithosphere. The earthquakes are systematically distributed over the surface of the Earth in narrow zones that follow the main oceanic trenches and ridges, the youthful mountain belts, and the great fracture zones which offset or link various segments of all of these (Figure 7). These narrow zones also include most of the active volcanoes. They are the zones in which the deformation of the lithosphere is localized. They mark the boundaries between a small number of large, rigid, spherical plates of the lithosphere that are about 100 kilometres thick and include both continental and oceanic crust as well as the upper part of the mantle (Figure 8). These plates of lithosphere move one relative to the other over the surface of the Earth in a pattern that changes intermittently from place to place. The displacements, which occur on the spherical surface of the Earth, involve rigid body rotations about axes through the centre of the Earth (Figure 9). This model for the behaviour of the crust of the Earth has come to be known as lithosphere plate tectonics.

There are three distinct types of margins between plates of lithosphere:

1. Rift zones are marked by upwelling of the mantle; shallow earthquakes, basalt volcanoes; and the growth of new oceanic crust which is accreted symmetrically along the edges of two plates that are moving away from each other.
2. Subduction zones are marked by sinking of the lithosphere into the mantle; shallow, intermediate, and sometimes deep (700 - kilometre) earthquakes distributed along a zone which slopes beneath one of the plates in which there is a range of high mountains capped by

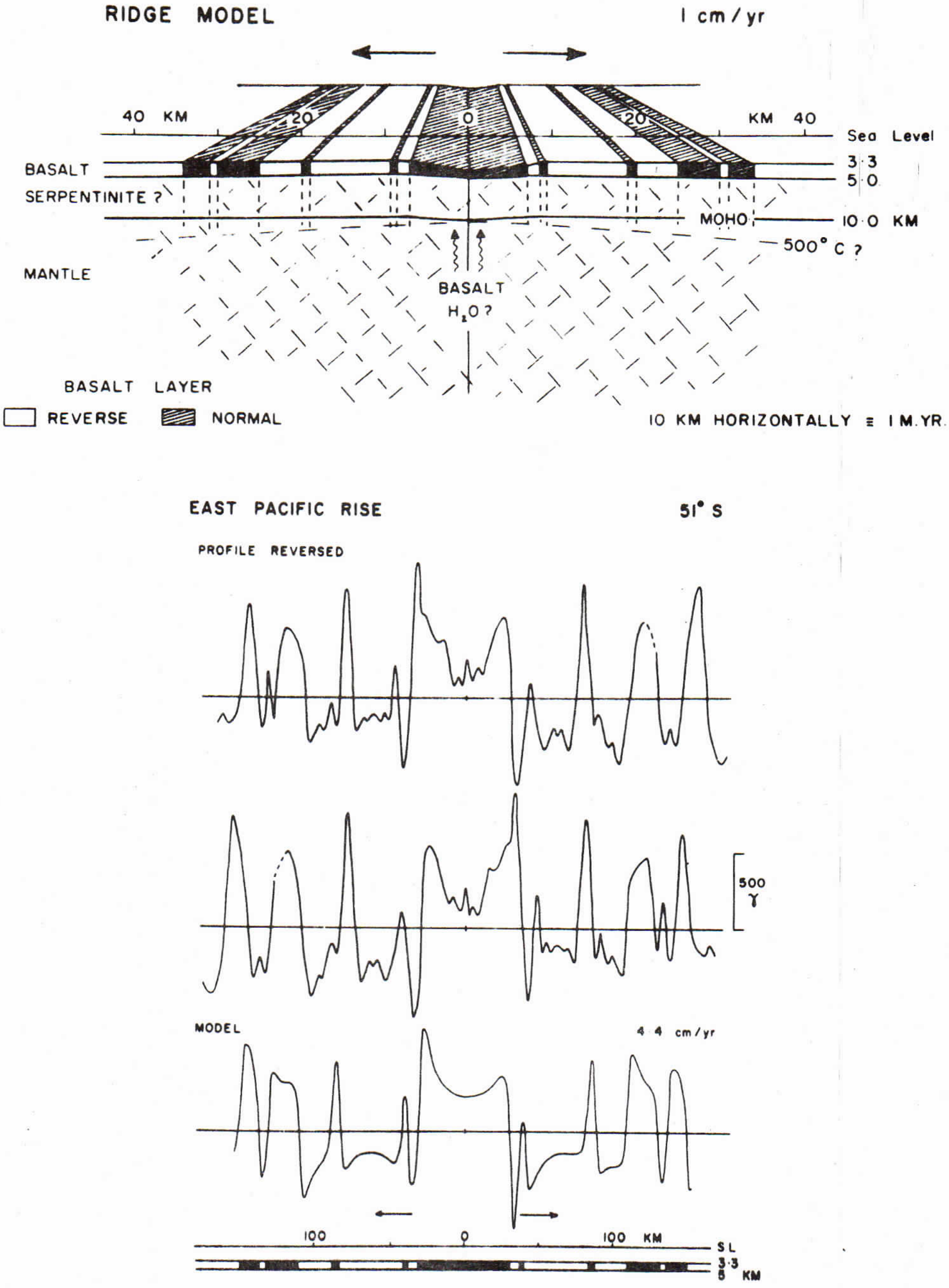

FIGURE 6. TOP: DIAGRAMMATIC REPRESENTATION OF THE OCEANIC CRUST AT A MID-OCEAN RIDGE CREST, ASSUMING ACTIVE SPREADING AT A RATE OF 1 CM. PER YEAR RIDGE FLANK. BOTTOM: AN OBSERVED MAGNETIC ANOMALY PROFILE ACROSS THE EAST PACIFIC RISE (UPPER CURVES) COMPARED WITH A COMPUTED PROFILE FOR THIS AREA. (From Vine, F.J. *J. Geol. Educ.*, vol. XVII, no. 1, p.6, February 1969, with permission from the National Association of Geology Teachers and the author.) (Observed profile taken from Pitman, W.C. and J.R. Heirtzler, *Science*, vol. 154, pp. 1164-1171, 2 December 1966. Copyright 1966 by the American Association for the Advancement of Science.)

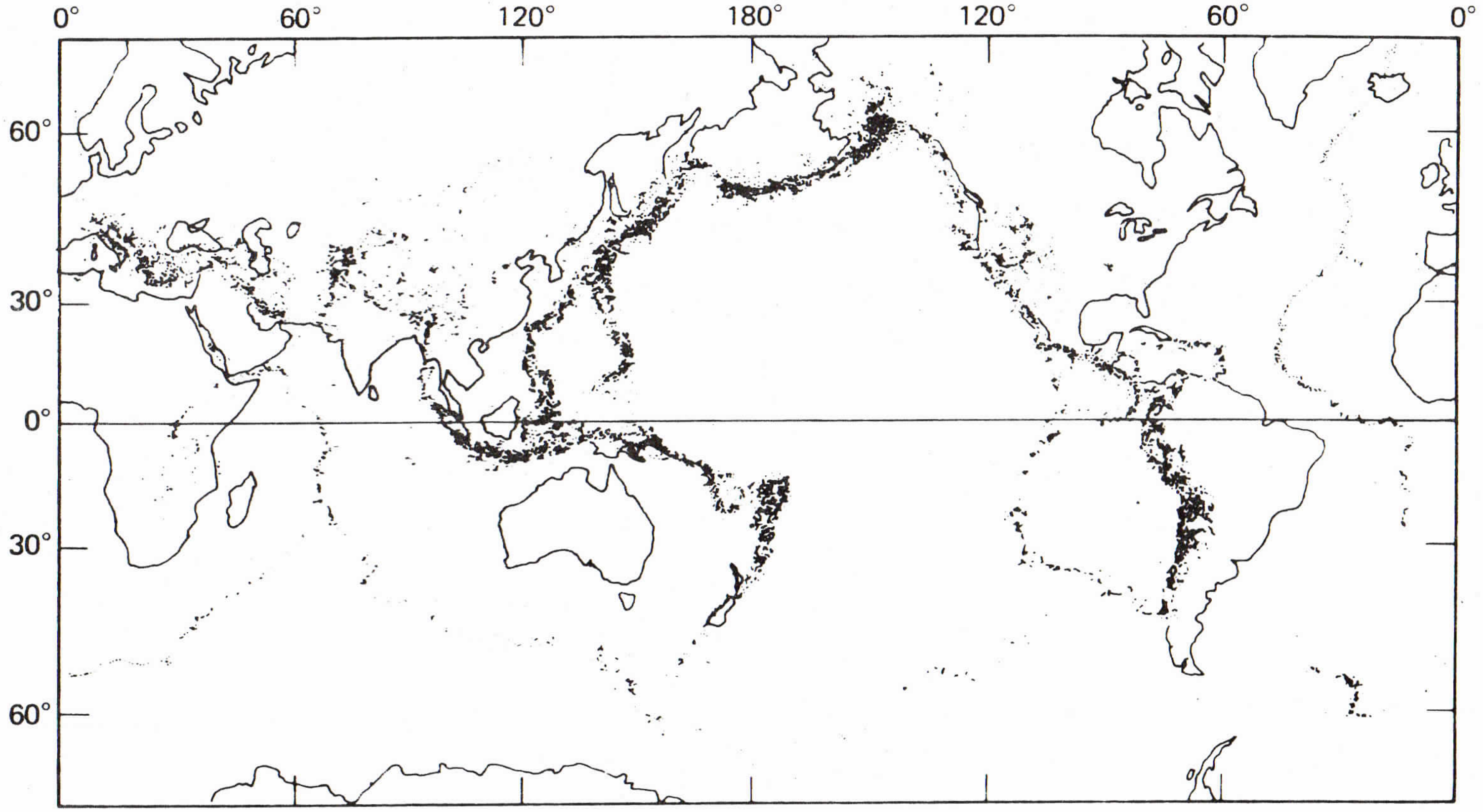

FIGURE 7. SEISMICITY OF THE EARTH, 1961-67, ALL EPICENTERS. (After Barazangi, M. and J. Dorman, *Bull. Seismol. Soc. Amer.*, vol. 59, p. 369, 1969. This version is from Wyllie, 1971. Reproduced by permission of the Seismological Society of America and John Wiley and Sons, Inc.)

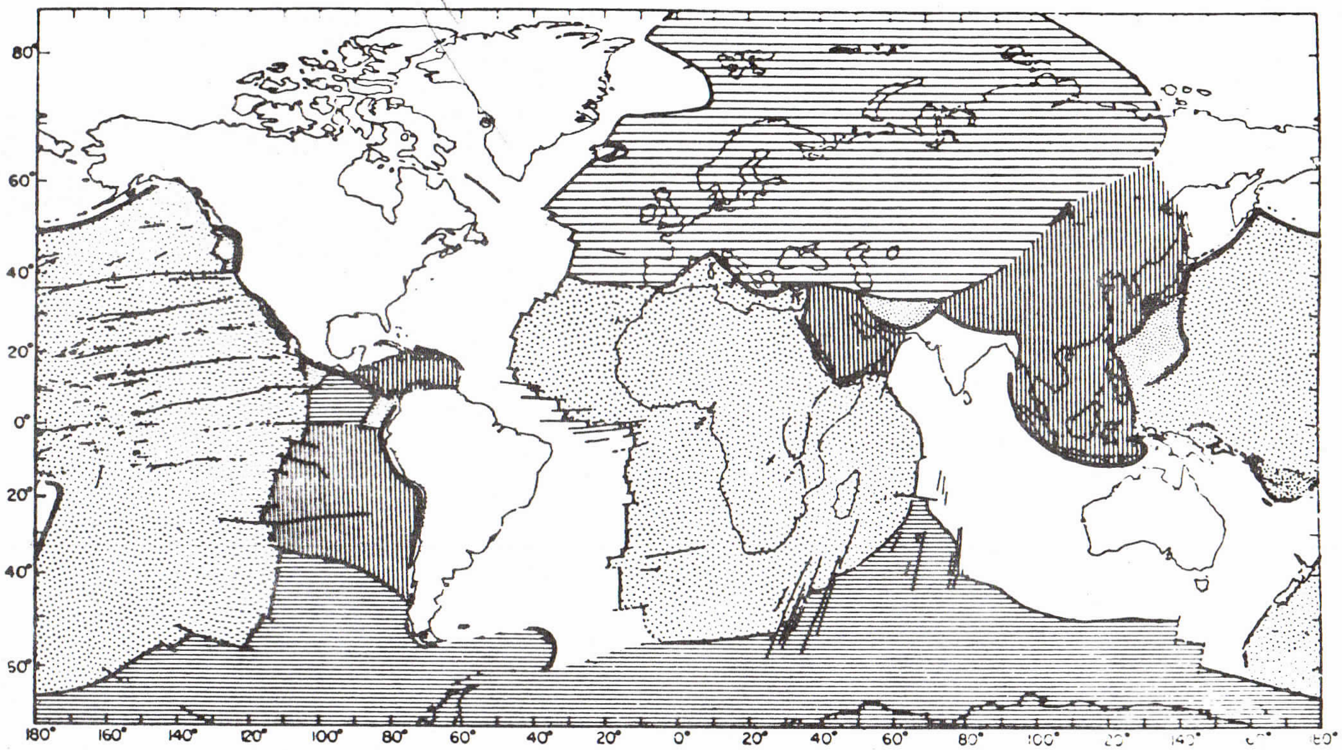

FIGURE 8. GLOBAL PLATE TECTONICS. THE CRUST IS DIVIDED INTO UNITS THAT MOVE AS RIGID BLOCKS. THE BOUNDARIES BETWEEN BLOCKS ARE RISES, TRENCHES (OR YOUNG FOLD MOUNTAINS) AND FAULTS. THE BOUNDARIES DRAWN IN ASIA ARE TENTATIVE, AND ADDITIONAL SUB-BLOCKS MAY BE REQUIRED. (From Morgan, W. Jason, *J. Geophys. Res.*, vol. 73, P. 1960, 15 March 1968, with permission. Figure is based on map of the ridge system in Sykes, L.R., "Seismicity of the mid-ocean ridge system", Upper Mantle Committee monograph, 1968, with additional features from tectonic map in Heezen, B.C. and M. Tharp, *Phil. Trans. Roy. Soc. London, Ser. A*, vol. 258, p. 90, 1965.)

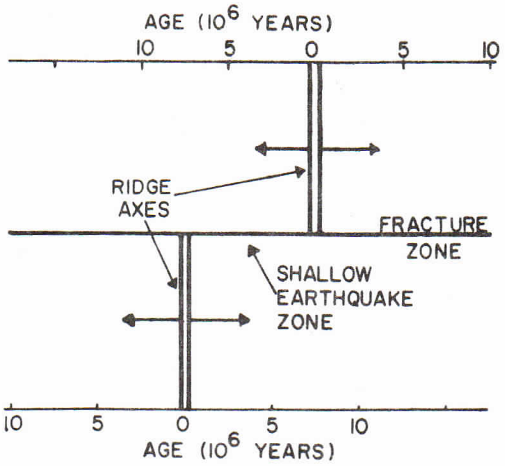

FIGURE 9. MOTION OF THE EARTH'S CRUST ABOUT A RIDGE AXIS. UPWELLING OF MOLTEN ROCK ALONG THE AXIS CAUSES SPREADING OF OLDER ROCK. SHALLOW EARTHQUAKES MAY OCCUR ALONG A FRACTURE ZONE BETWEEN THE OFFSET AXES.

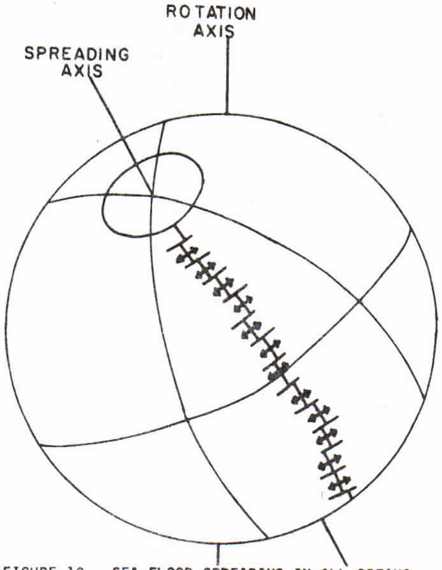

FIGURE 10. SEA-FLOOR SPREADING IN ALL OCEANS IS DEVELOPED AROUND A "SPREADING AXIS" RATHER THAN AROUND THE EARTH'S AXIS OF ROTATION. FRACTURE ZONES ARE PARALLEL TO HYPOTHETICAL LINES OF LATITUDE AND PERPENDICULAR TO RIDGE AXES. THE RATE OF SPREADING DECREASES WITH DISTANCE FROM THE EQUATOR.

andesite volcanoes; destruction of oceanic crust that is resorbed in the mantle; and the over-riding of one converging plate by the other.

3. Transform faults are marked by great fracture zones along which adjacent plates slide past one another to the accompaniment of frequent earthquakes (Figure 10).

MOUNTAIN BUILDING

Most of the world's high mountains occur above the subduction zones along which the lithosphere sinks into the mantle. Island arcs, made up of chains of volcanoes that discharge andesite lavas, occur where the crust on both sides of the subduction zone is oceanic. The veneer of sediment on top of the oceanic crust and some of the rocks within it melt as the lithosphere sinks into the hot mantle, and these molten rocks are extruded in the area behind the deep oceanic trench. Lofty mountains like those along the western margin of the Americas which are capped with andesite volcanoes, occur where the crust on the over-riding plate is continental. The products of partial melting of the oceanic crust as it descends into the mantle rise up through the continental crust, which becomes thickened as it scrapes off the upper layers of the plate that is sliding under it. Fragments of continental crust are passive components which are frozen into plates of lithosphere like logs in an ice floe. Sediments which are eroded from the emergent parts of the continents and accumulate along the inactive margins form thick sedimentary wedges that grow out into the ocean basins. Eventually, these wedges of sediment become compressed and uplifted to form mountain ranges, either when a subduction zone forms along the continental margin, or when the edge of the continent is carried into a subduction zone. The history of the breakup and dispersion of the southern continents provide examples of all these various relationships.

RESOURCES AND ENVIRONMENT

The search for future supplies of fossil fuels and metallic mineral deposits is simplified if exploration targets can be identified more accurately from an understanding of the geologic evolution of the rocks in which they occur. There has been a conceptual revolution in the earth sciences. The constraints inherent in a view of the Earth based on the assumption of a permanent stable configuration of the continents and the ocean basins have been relaxed. The notion of a dynamic, mobile, shifting crust comprising fragments of continents transported around the globe on a conveyor belt of self-regenerating oceanic crust has opened up new perspectives in the search for future sources of petroleum and natural gas, on the possible extension of established mineral belts, and on the hazards of physical catastrophes in the world in which we live. It touches upon a whole host of environmental problems ranging from the controlled release of seismic energy to prevent earthquakes in California, to predictions of volcanic eruptions in the southwest Pacific, and the selection of sites for the disposal of toxic wastes beneath the ocean depths.

READING LIST

Background Reading

Heirtzler, J.R., "Sea-Floor Spreading", *Scientific American*, December 1968, pp. 60-70 (offprints available).

Dietz, R.S., and Holden, J.C., "The Breakup of Pangea", *Scientific American*, October 1970, pp. 30-41.

Anderson, D.L., "The San Andreas Fault", *Scientific American*, November 1971, pp. 53-68.

Dewey, J.F., "Plate tectonics", *Scientific American*, May 1972, pp. 56-68.

Supplementary Reading

Takeuchi, H., Uyeda, S., and Kanamori, H., *Debate about the Earth* (Revised Edition), Freeman, Cooper and Company, San Francisco, 1970 (paperback edition).

Menard, H.W., "The Deep Ocean Floor", *Scientific American*, September 1969, pp. 127-142 (offprints available).

Heezen, B.C., "The Rift in the Ocean Floor", *Scientific American*, October 1960, pp. 99-110.

Raff, A.D., "The Magnetism of the Ocean Floor", *Scientific American*, October 1961.

Wilson, T.J., "Continental Drift", *Scientific American*, April 1963, pp. 86-100 (offprints available).

Cox, A., Dalrymple, G.B., and Doell, R.R., "Reversals of the Earth's Magnetic Field", *Scientific American*, February 1967, pp. 44-54.

Bullard, E., "The Origins of the Oceans", *Scientific American*, September 1969, pp. 66-75 (offprints available).

Emery, K.O., "The Continental Shelves", *Scientific American*, September 1969, pp. 107-122 (offprints available).

Hedberg, H.D., "Continental Margins From The Viewpoint of the Petroleum Geologist", *American Association Petroleum Geologists Bull.*, vol. 54, pp. 3-43, 1970.

Crawford, A.R., "Continental Drift and Uncontinental Thinking", *Economic Geology*, vol. 65, pp. 11-16, 1970.

Advanced Reading

Hart, P.J. (editor), *The Earth's Crust and Upper Mantle*, American Geophysical Union Monograph No. 13, 1969 (available in paperback edition).

Vine, F.J., "Spreading of the Ocean Floor: New Evidence", *Science*, vol. 154, pp. 1405-1415, 1966.

Morgan, W.J., "Rises, Trenches, Great Faults, and Crustal Blocks", *Journal Geophysical Res.*, vol. 73, pp. 1959-1982, 1968.

Le Pichon, X., "Sea-Floor Spreading and Continental Drift", *Journal Geophysical Res.*, vol. 73, pp. 3661-3697, 1968.

Isacks, B., Oliver, J., and Sykes, L.R., "Seismology and the New Global Tectonics", *Journal Geophysical Res.*, vol. 73, pp. 5855-5899, 1968.

Fischer, A.G., and others, "Geological History of the Western North Pacific", *Science*, vol. 168, pp. 1210-1214, 1970.

Dewey, J.F., and Bird, J.M., "Mountain Belts and the New Global Tectonics", *Journal Geophysical Res.*, vol. 75, pp. 2625-2647, 1970.

Dietz, R.S., and Holden, J.C., "Reconstruction of Pangea: Breakup and Dispersion of Continents, Permian to present", *Jour. Geophysical Res.*, Vol. 75, 4939-4956, 1970.

Wyllie, P.J., *The Dynamic Earth*, John Wiley and Sons, Toronto, 1971.