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TO THE DRIFTERS

The energy contained in one well-rooted organizing principle is something to behold. Not much more than a decade ago, the earth sciences were energized by such a principle — the theories of continental drift, now referred to as plate tectonics. The continents move, said the drifters, on rigid plates that grind past, over and under one another as new rock is formed and old rock destroyed.

Today, what was once the premise of a persevering few has become the basic assumption integrating and invigorating much of what is going on in geology and geophysics. And nowhere is the research more intense than at sea, where investigators measure the creep of the ocean floor from the great ridges to the deep trenches. The articles in this issue reflect some of the most exciting work in submarine tectonics.

How much of what is hypothesized today will hold up over the coming decades? New knowledge obviously will drive out some old ideas, for as Einstein reportedly remarked, "any logical formulation of nature is bound not to fit somewhere." But where the pieces do fit, basic research in the geology and geophysics of the sea floor shows evidence of producing information of considerable use to society — from ways to deal with earthquakes to the location of fossil fuels and other resources now in increasingly short supply.

Readers wishing to pursue plate tectonics further might keep the following books in mind:

1. "Debate About the Earth" edited by H. Takeuchi, S. Uyeda, H. Kanamori; Freeman, Cooper and Co., San Francisco, 1967.
2. "Plate Tectonics and Geomagnetic Reversals" edited by Allan Cox; San Francisco, 1973.
3. "Continents Adrift", Readings from Scientific American; W.H. Freeman and Co., San Francisco, 1972.
4. "The History of the Earth's Crust" edited by Robert A. Phinney; Princeton University Press, 1968.
5. "The Earth is a Planet" edited by G. P. Kuiper; Chicago University Press, 1954.
6. "The Restless Earth" by Nigel Calder; Viking Press, New York, 1972.
7. "The Face of the Deep" by Bruce C. Heezen and Charles D. Hollister; Oxford University Press, 1971.

William H. MacLeish
Editor

Oceanus®

Volume XVII, Winter 1973-74

The Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

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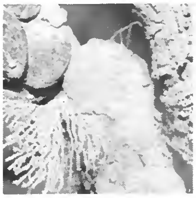

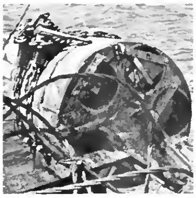

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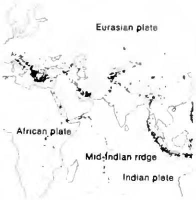

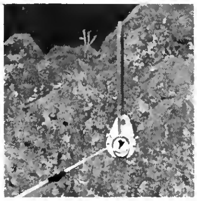

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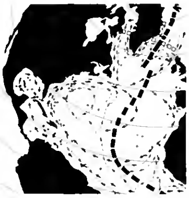

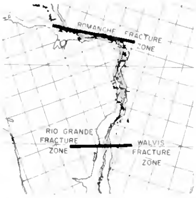

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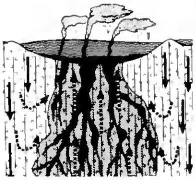

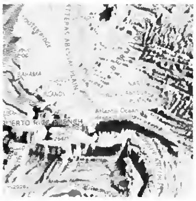

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COVER: Birth of Surtsey, a recent addition to the Mid-Atlantic Ridge.
The island, off the south coast of Iceland, appeared above the surface in November, 1963.
Credit: Sólarfilma, Reykjavík, Iceland.

THE SLOW AND STEADY SURPRISE

J. R. Heirtzler

Continental drift, sea-floor spreading, plate tectonics: these words are the hallmarks of the study of earth sciences today. They are proof that new, simple and comprehensive theories are still possible in science and that the scientific method is not a thing of the past.

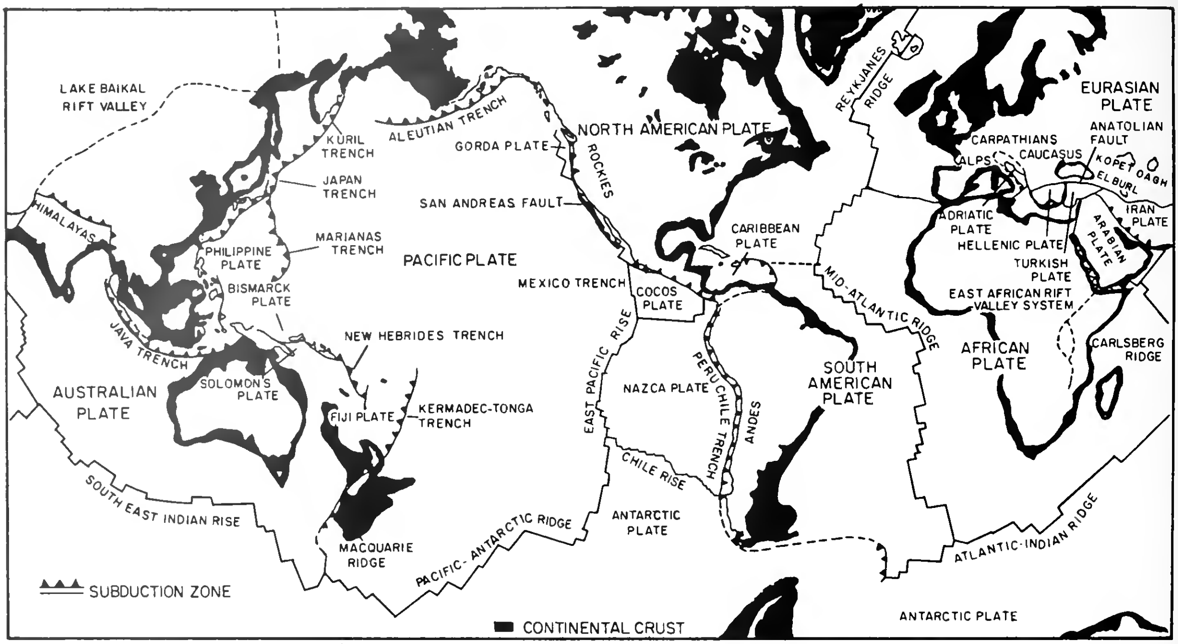
That nature would leave the key to her grand scheme in the sea floor surprised marine scientists as much as anyone. Nevertheless, it is data from the sea floor that has allowed us recently to reconstruct the configuration and evolution of the earth's surface for the last 200 million years (see pages 24 and 28). Since we have deciphered the geologic past, we think that we can predict a bit of the geologic future.

There is more than twice as much land beneath the sea as there is above. Most of this is composed of immense abyssal plains covered with mud up to several miles thick. Beneath the mud is rock that here and there pushes through to form mid-ocean mountain ranges of extraordinary length. The oceans drained dry would present a strange landscape (see page 44) - far stranger than would be immediately apparent. The mountains are not pushed up by great compressive forces as are, say, our Rocky Mountains, but by little known stretching or tensile forces. The rocks are covered by mud that is mainly composed not of decomposed rock, as is the soil underneath our feet, but of the remains of marine life that have settled down through the water. On land wind, rain and temperature changes sculpt the landscape. On the bottom of the ocean, water currents are feeble or nonexistent except in a few locations. Their functions as transporters of sediment are not well known. The temperature environment of the sea floor is one of the most stable on earth and it produces no heaving and thawing. Man and animals have not significantly altered the face of the deep — yet. On the bottom of the sea, nature has time to do things in a slow and steady fashion — on a geologic time scale.

Slow and steady processes are not ones that scientists of today are well suited to study, either temperamentally or technically. Perhaps that is why they were surprised to learn, a few years ago, that they had overlooked the most important of the slow

Photo, opposite: Tubular or "toothpaste" lava photographed at 1050 fathoms in axial valley of the Mid-Atlantic Ridge. The tube, roughly one foot in diameter, is probably less than 10,000 years old. The camera is looking directly down at the tube, which has erupted from the sea floor to a height of 2-3 feet and then broken off from its stump at the lower right. (Atlantis II, Cruise 77)

J. R. Heirtzler has been chairman of the department of geology and geophysics at the Institution since 1969. Previously, he was director of the Hudson Laboratories of Columbia University and with Columbia's Lamont-Doherty Geological Observatory as a senior research associate.



Mosaic of Tectonic Plates.

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and steady processes on the sea floor. The rocks which are exposed at the mid-ocean ridges or are buried beneath the mud nearer the continents are not fixed but have a slow and pervasive creep or spreading away from the axis of the mid-ocean ridges. The rate and direction of this motion seems to be about the same as that predicted for the drift of adjacent continents; it would seem in many cases that the land masses are part of moving areas or plates of the sea floor.

In the early twentieth century, Alfred Wegener, a German atmospheric scientist and explorer of Greenland, strongly advocated continental drift because of geological similarities observed between different continents. Later Keith Runcorn, first at Cambridge and then at Newcastle University, in studying the direction in which rocks of the same age were magnetized on different continents, concluded that the continents must have drifted. Harry Hess of Princeton and Robert Dietz of the National Oceanic and Atmospheric Agency noted the general age of different parts of the sea floor and stated that it was possible for material from deep in the earth to well up at the mid-ocean ridges and move outward across the sea floor.

In 1963, Fred Vine and Drummond Matthews at Cambridge University detected reversals in the magnetization of the ocean-floor rocks in accordance with known reversals of the earth's magnetic field. It was this single observation, more than any other, that convinced earth scientists that the sea floor was spreading and that the earth's magnetic field had really reversed many times in the past. By relating the known reversals of the geomagnetic field, the spreading rates, and the states of magnetization of the ocean rocks, it was possible to date quickly nearly half of the floors of the oceans — an area comprising one-third of the earth's surface. Consecutive age lines (isochrons) of the sea floor provide a record of the consecutive positions of the continents throughout geologic time.

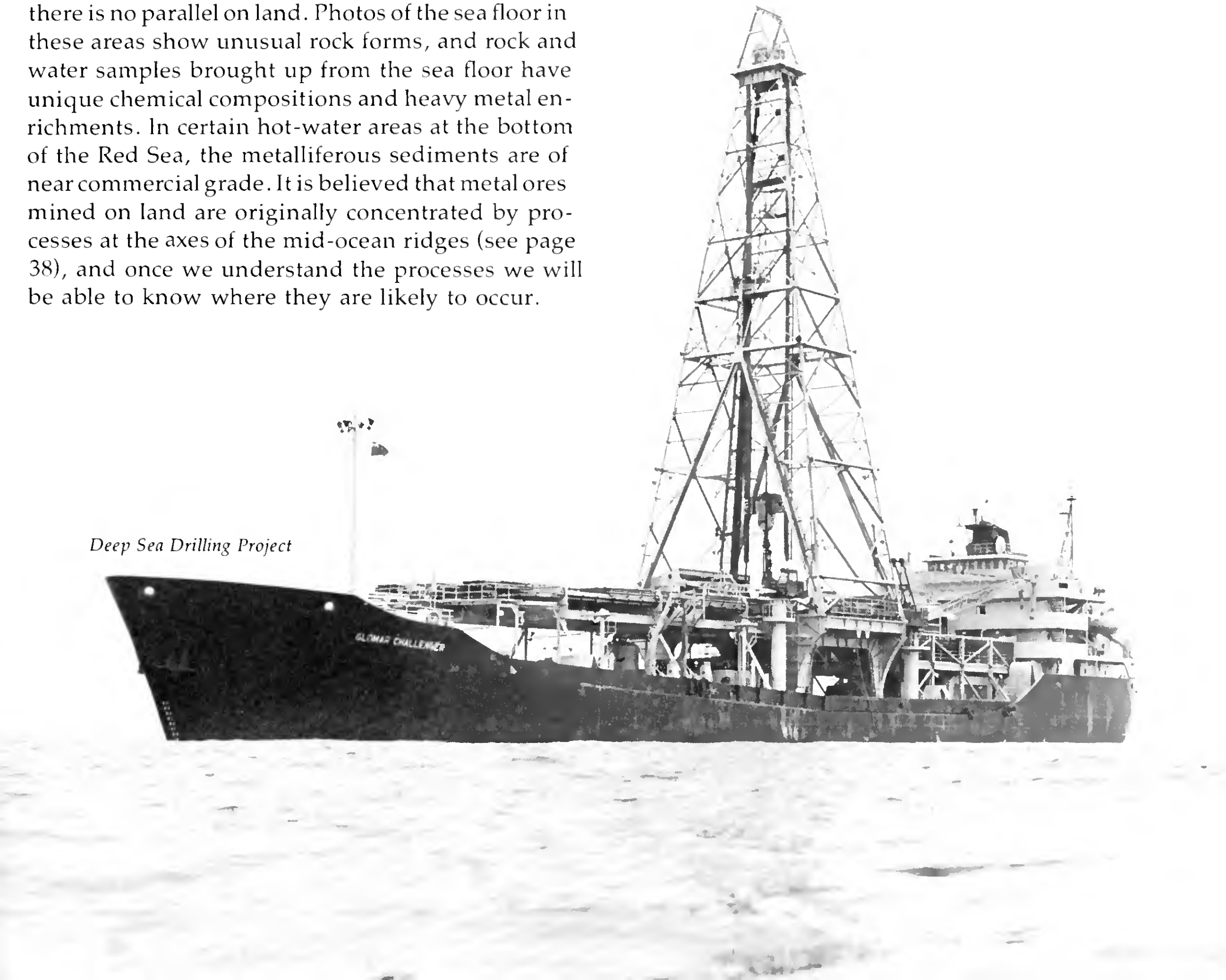
In tracing the moving sea floor from its evolution at the mid-ocean ridge axis, it soon became clear that the plates sink back into the earth's depths at the ocean trenches, such as those around the edge of much of the Pacific Ocean (see page 14). (Continental material is too light to get swallowed up at the trenches; it apparently remains at or near the surface as its plate plunges into the mantle.) The cycle of upwelling, transverse motion, and consumption of oceanic crustal material constitutes the theory of "plate tectonics" and forms the basis of a unified approach to nearly all large-scale earth processes.

To discover that the earth is controlled by relatively simple laws is intellectually satisfying, but does it have any value to mankind in everyday life? Yes. It provides us with guidelines as to where certain earth processes will happen and where certain earth resources can be found. The guidelines are still general, but they permit the broad domain of earth science to be narrowed toward a beneficial end result.

Perhaps the most dramatic area of new global tectonic knowledge is in the field of earthquake research. Earthquakes occur along the axes of the mid-ocean ridges, along fractures that offset these axes, and, most importantly, landward of oceanic trenches when ocean crust is consumed. This means that if you live along the San Andreas Fault in California or near Managua, Nicaragua, or in other very specific regions you can expect to experience a severe earthquake eventually. It also means that we can focus studies on specific regions to work out predictive schemes and even preventive schemes for earthquakes.

At the submerged axes of the mid-ocean ridges, the geologic processes associated with upwelling deep earth materials are not understood, because there is no parallel on land. Photos of the sea floor in these areas show unusual rock forms, and rock and water samples brought up from the sea floor have unique chemical compositions and heavy metal enrichments. In certain hot-water areas at the bottom of the Red Sea, the metalliferous sediments are of near commercial grade. It is believed that metal ores mined on land are originally concentrated by processes at the axes of the mid-ocean ridges (see page 38), and once we understand the processes we will be able to know where they are likely to occur.

Deep Sea Drilling Project drilling vessel, Glomar Challenger. Scripps Institution of Oceanography, of the University of California at San Diego, is managing institution of DSDP under a $68.3 million contract with the National Science Foundation. The drilling vessel is owned and operated by Global Marine Inc., of Los Angeles, which holds a subcontract with Scripps to do actual drilling and coring work. The Glomar Challenger weighs 10,400 tons, is 400 feet long and the million-pound-hook-load capacity drilling derrick stands 194 feet above the waterline. She is the first of a new generation of heavy drilling ships capable of conducting drilling operations in open ocean, using dynamic positioning to maintain position over the bore-hole. A re-entry capability was established on June 14, 1970, which will enable the changing of drill bits and re-entering the same bore-hole in the deep ocean. Forward is the automatic pipe racker, designed by Global Marine Inc., which holds 24,000 feet of 5-inch drill pipe.



Deep Sea Drilling Project

Detail of gullies offset by movement on San Andreas fault in California. *John S. Shelton*

When the oceans were first opened and the original land mass was split in two, petroleum-bearing structures were frequently divided as well. Accordingly, if petroleum reserves are found along one continental margin, there is a good chance they will be found along a matching margin — if the parent continent can be reconstructed with sea-floor-spreading data.

Another source of power that the earth can provide is geothermal energy (see page 8) brought to the surface by the upwelling associated with mid-ocean ridges, fracture zones, and volcanic formations near the places where crust is consumed around the Pacific. In Iceland, New Zealand and other areas, subterranean steam has been successfully harnessed. Elsewhere, it remains untouched.

Where will studies in plate tectonics lead in the future? Are we likely to encounter any more startling scientific discoveries? Future endeavors in this field may well indicate how man can utilize the earth's processes and resources more effectively. At the same time, the great simplicity of our global guiding theory may be an oversimplification. When we drill the first mile-deep hole in the ocean rocks, a project on the agenda of the JOIDES program (Joint Oceanographic Institutions for Deep Earth Sampling), we may find material never suspected by our best guesses. We will map in more detail the interactions of the earth's crustal plates to learn the rules for their motion. We will learn how sea-floor material is scraped off sinking crust at the trenches and why volcanoes periodically erupt there. The special surveys, instruments, and manned submersible operations planned for the French-American Mid-Ocean Undersea Study (Project FAMOUS) should tell us a good deal about the unique geologic processes at work along the axis of the Mid-Atlantic Ridge. And by carefully studying the past, one may discover even more grandiose designs of nature, such as the interrelationships of continental configurations, ocean currents, glacial and climatic changes, alteration of world wide sea level, orogenies or upheavals on land and reversals of the geomagnetic field.

Photo, opposite: The Alps of the Valais, Switzerland, formed by crustal buckling when plates collided.

Swiss National Tourist Office

GEOLOGICAL TIME TABLE

(time spans referred to in the following articles are listed below for readers' convenience)

Approx. time (10^6 years)	Erathem / Era	System / Period		Series / Epoch	
	Cenozoic	Quaternary		Holocene (Recent)	
1				Pleistocene	
		Tertiary	Neogene	Pliocene	
10 25				Miocene	
40			Palaeogene	Oligocene	
60				Eocene	
65				Paleocene	
	Mesozoic	Cretaceous		Upper / Late	Senonian
135				Lower / Early	
		Jurassic		Upper / Late	Malm
				Middle	Dogger
180				Lower / Early	Lias
		Triassic		Upper / Late	
				Middle	
225				Lower / Early	

HEAT BENEATH THE SEA

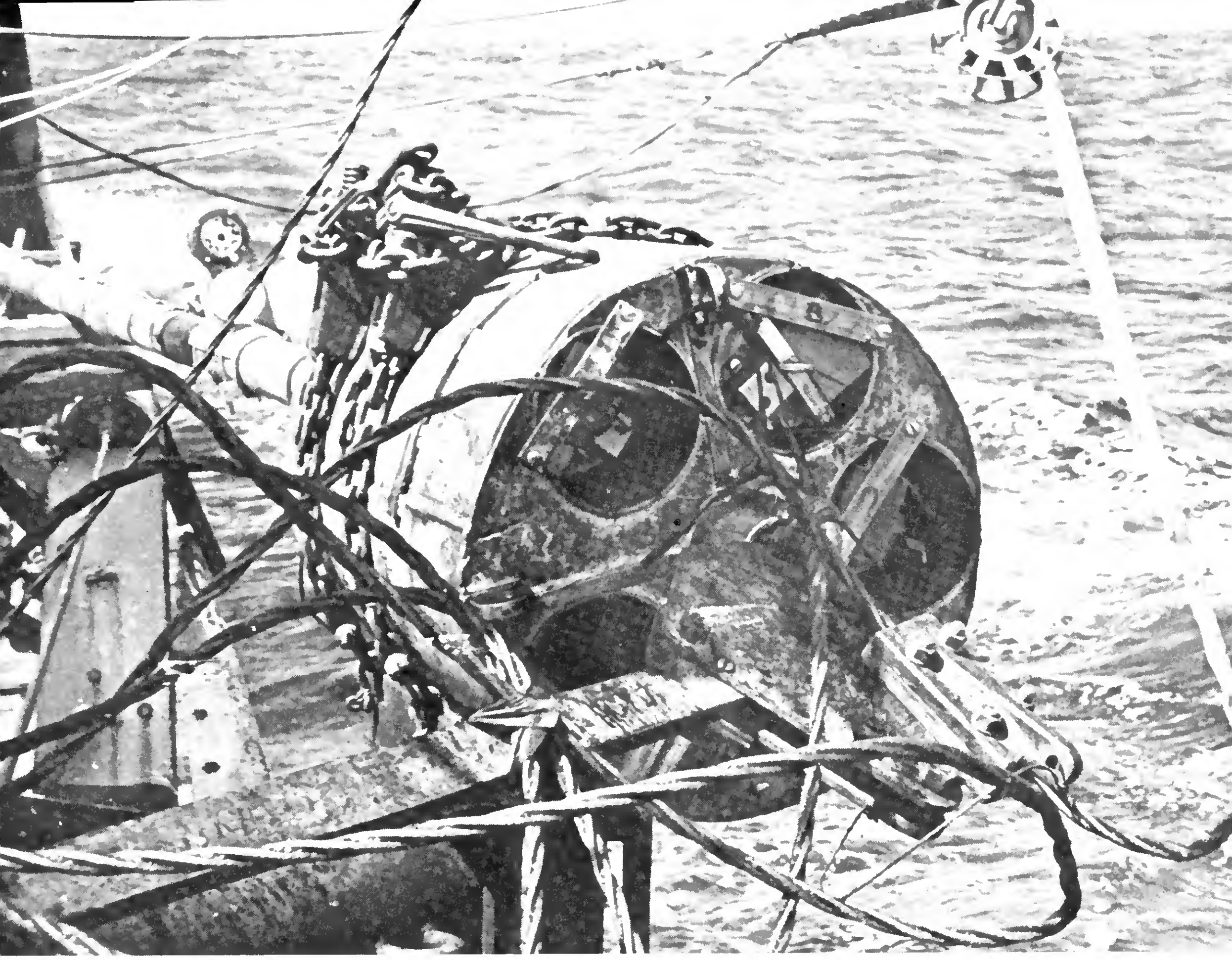
Richard P. von Herzen

Almost all hypotheses developed to explain large-scale tectonic activity on the earth's surface — faulting, mountain building, sea-floor spreading — contain an implicit or explicit assumption that these phenomena have a thermal energy source in the earth's interior. Heat sources may derive from chemical reactions, radioactivity, or perhaps gravitational potential energy springing from formation of the earth itself. The actual mechanism by which most of the heat finally escapes through the surface is by thermal conduction through rocks.

For nearly all measurements at the earth's surface, either on land or under the sea, geothermal heat flow is calculated as the product of the rate of change of temperature with depth (vertical temperature gradient) multiplied by the rate at which heat is conducted through earth materials under a given temperature gradient (thermal conductivity). This seemingly indirect method of deducing a value of one physical quantity (heat flow) by referring to two others comes about because it is much easier to measure temperature than it is to measure a quantity of heat directly.

In some ways, it is easier to measure heat flow on the floor of the deep sea than it is on dry land. The sun's radiation on the land surface is a heat source many orders of magnitude more intense than the heat energy flowing from the earth's interior. Then, too, the temperature at any place on the earth's surface varies with climate. These factors require that measurements of heat flow on continents be carried out at considerable depths beneath the earth's surface — usually more than 100 meters down in mines or bore holes created for other purposes. In contrast, the oceans effectively insulate most of the deep sea floor from almost all external temperature variations. This fact makes it possible for the temperature gradient in the oceans to be measured beneath the sea floor over a relatively short interval with apparatus lowered from a surface vessel. An array of thermal sensors used to measure the vertical temperature gradient is either separately mounted in a

R. P. von Herzen is a senior scientist in the Institution's department of geology and geophysics. He has been at Woods Hole since 1966 when he left the position of deputy director of UNESCO's office of oceanography in Paris.



Channing Hilliard

Figure 1: Piston coring apparatus in horizontal position alongside deck of research vessel. Temperature gradient in the bottom is detected with thermistor sensors strapped to core barrel and measured with instruments inside corehead weight.

probe, which penetrates the soft-sedimented bottom under its own weight or is attached to a core barrel (Figure 1). Thermal conductivity is usually obtained from studies of sediment cores retrieved aboard ship. This relatively simple technique was first developed by Sir Edward Bullard and Arthur Maxwell (now Provost of the Institution) about 1950.

An oceanographic expedition properly equipped and staffed is capable of making one to several station measurements per day. Thanks to many research cruises over the past two decades, marine heat-flow measurements now number several thousand, exceeding continental measurements by about a factor of ten. Measurements have been made in all major ocean basins and seas of the earth, though they are still sparse at high latitudes due to the difficulties of polar research, and in the deeper oceanic trenches. Active tectonic regions, such as mid-ocean ridges, have been the focus of much work, and it is usually in such regions where the highest values and the greatest amount of variability are observed. The East Pacific Rise, the major spreading center in the eastern Pacific, and its environs have been intensively measured (Figure 2).

Beginning with their first measurements in the early 1950's, Sir Edward Bullard and his co-workers noted that the average conducted heat flow per unit area under the oceans appears to be about the same as that from the continental regions — about 1.2 to 1.5 μcal/cm^{2}sec (HFU).* With the greatly increased number and distribution of values, this equality between basically different regions of the earth is still valid but not well understood. The vertical distribution of heat sources in rocks (radioactivity) and

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*1.25 μcal/cm^{2}sec (heat flow units) = 40 cal/cm^2/yr, or a quantity of heat sufficient to melt a layer of ice about ½ cm (0.2 inch) thick in one year.

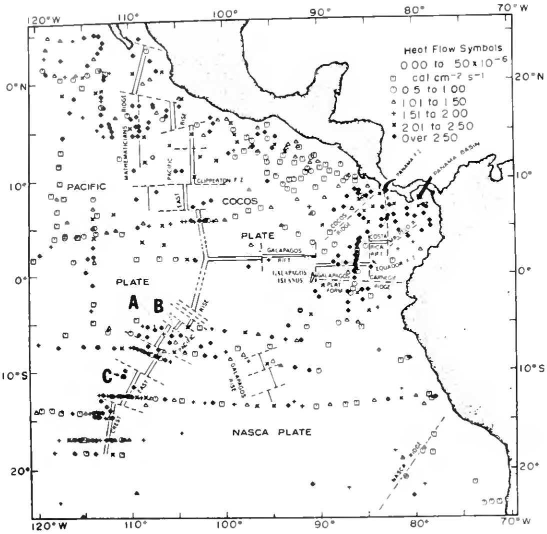


Figure 2: Locations of heat-flow measurements and known tectonic elements in the eastern Pacific, circa 1971. After von Herzen and Anderson (1972).

the nature of tectonic activity, both of which affect the surface heat flow, appear quite different between continental and oceanic areas. However, as we discuss below, the equality may be more apparent than real.

In addition to the differentiation between continents and ocean basins, there are fundamental vertical subdivisions of the earth whose characteristics are inferred largely from studies of earthquake waves. The lithosphere is the relatively cool and brittle upper layer, which may reach a maximum thickness of 100 to 150 kilometers. Below that is the asthenosphere, a relatively "soft" layer several hundred kilometers thick which is largely solid, though it may contain some molten material. Its temperature probably hovers not far below the melting point. The area from roughly 500 to 3,000 kilometers down is known as the mesosphere, a zone whose rigidity is probably greater than that found in the asthenosphere, due to the effects of increasing pressure. At the center and extending outward to the mesosphere is the core, a good part of which is made up of iron and nickel. The inner core is thought to be solid, the outer liquid.

The hypothesis is now widely accepted that the oceanic lithosphere is recreated at a spreading center and thickens with distance (or time) from the center as it cools (Figure 3). The geographic distribution of heat-flow values appears to support this idea, since average values decrease with increasing age of sea-floor rocks (Figure 4). It is obvious, however, that there is a lot of scatter in the data which is not explained by this simple model. From some closely spaced measurements, it appears that some of the heat-flow variability occurs over a lateral scale of a few kilometers or less. These measurements and physical models show that significant modulations in heat flux may be produced by localized topography and by the contrast in thermal properties between irregular layers of rock and overlying sediments. This is consistent with the general increase in scatter with proximity to spreading centers, where bottom topography is rougher and sediment cover is thinner and more irregular.

Another observation not predicted by the simple spreading model is the generally lower heat flow near a spreading center, compared to higher values on somewhat older sea floor (Figure 4). Notwithstanding the data scatter mentioned previously, this phenomenon appears statistically significant for most spreading centers. The maximum in the observed pattern is found in rocks of different ages on different ridges, ranging between one million years (m.y.) for the Galapagos spreading center (East Pacific) and 3 m.y. for the northern Mid-Atlantic Ridge.

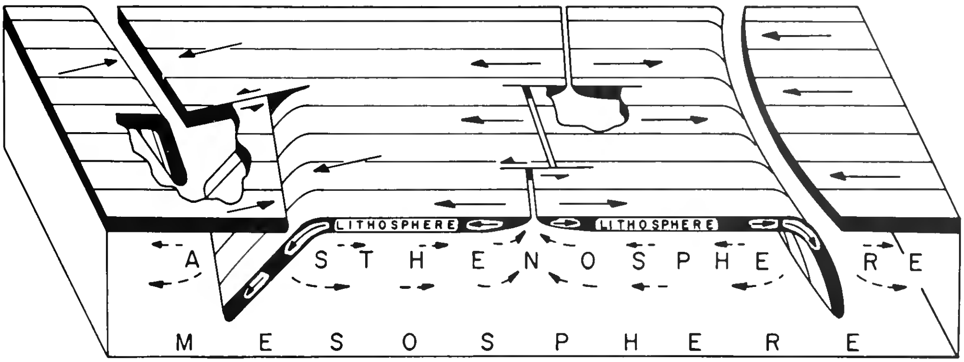
A detailed profile of measurements taken within the zone where heat flow increases with distance from the Galapagos spreading center shows a strong modulation of the heat-flow pattern on a scale of a few kilometers away from the spreading axis. Values are as high as 30 HFU, and as low as 0.1 HFU or less on lithosphere younger than about 1 m.y. Variations over two orders of magnitude cannot be explained by refractive effects of topography and sediment cover variations, which in any case were relatively subdued near this spreading center. Measured values averaged over several kilometers along the profile are everywhere less than the theoretically predicted heat flow for a lithosphere which cools by conduction.

The lower average heat flow near spreading centers and the strong modulation over relatively short distances suggest that hydrothermal circulation plays a significant role in the cooling of young lithosphere. Indeed, the low values — even lower than those on the oldest lithosphere — are difficult to explain by any other mechanism. The rapid cooling of the upper surface of the lithosphere is favorable to creation of cracks or fractures in the rock. Before an impermeable sediment cover can be laid down, such conditions seem conducive to circulation of sea water in and out of the rocks, driven by the thermal energy associated with formation of the lithosphere. Even when the sediment cover becomes thicker (and more impermeable) with increasing age of the lithosphere, closed circulation may persist in the porous rocks below, and the Galapagos spreading center pattern suggests that it may extend to a depth of several kilometers.

If this hypothesis is correct, a substantial amount of cooling of lithosphere near spreading centers occurs by processes other than that of thermal conduction through the sea floor. As such, the heat loss will not be measured by present techniques. David Williams, a graduate student at the Institution, and I have estimated that as much as 25% of the heat flux through the ocean floor may be lost by hydrothermal circulation near spreading centers. If so, it may turn out that the average heat flow through ocean basins is substantially greater than that through continents. The present view is that much of the continental heat flow derives from the decay of radioactive elements dispersed in crustal rocks. In contrast, only a small fraction of the heat flux originates in the thin (5-10 kilometers) oceanic crust, whose basaltic rocks are notably poor in radioactive elements. The heat flux through the sea floor must originate from a deeper distribution of radioactivity or be brought up from the deep earth by tectonic processes. With this difference in earth structure and processes beneath continental and oceanic regions, it is not surprising that there should be a significant difference in average heat flow through the two.

Even a perfect knowledge of heat flow over the earth's surface would not allow us to determine with certainty the distribution of important thermal parameters in the earth's interior, such as temperature, heat sources, modes of heat transfer, or even whether the thermal regime is in "steady state" or perhaps transient or oscillatory. Information from other fields of geophysics, especially seismology, high pressure experiments, etc., can narrow the ranges of parameters, but there are still too many possible variables to establish a unique model. There is not space here to delve meaningfully into these problems, but we might touch on two related and recently proposed tectonic hypotheses which may signal a direction for future research in this field: "hot spots" and "asthenospheric bumps".

Figure 3: Model of the upper few hundred kilometers of the earth. Note that the lithosphere plate increases in thickness as it moves away from the spreading center, finally being overridden by another plate plunging into the asthenosphere at a subduction zone (ocean trench). Relative motion arrows in the asthenosphere are schematic. After Isacks et. al. (1968).



"Hot spots", a concept coined by J. T. Wilson of the University of Toronto, are probably best exemplified by the linear chains of volcanic islands (or ridges) which in some regions extend across thousands of miles in ocean basins (see page 48). They are apparently generated by a localized but continuous source of volcanic material and/or heat generated beneath a moving lithospheric plate. J. Morgan of Princeton has hypothesized that they may be generated by "plumes" moving slowly upward from great depths in the earth. Others have suggested that frictional heating resulting from motion of the lithosphere itself over an irregularity in the asthenosphere might be sufficient to generate such phenomena. A significant number of these hot spots appear to be centered over spreading centers (e.g., Galapagos Islands, Iceland), although some of the major ones appear far from plate boundaries (e.g., Hawaii). There is little anomalous heat flow on the deep sea floor surrounding the Hawaiian chain, which attests to the localization of the source under moving lithosphere. Obviously, the Hawaiian hot spot has been responsible for exuding a substantial amount of molten rock over geologic time. Still, the combined rate of magma production of all hot spots not associated with spreading centers is small compared to the total magma created at the spreading centers.

H. W. Menard of Scripps Institution of Oceanography has recently described regions of the sea floor over 500 kilometers across whose depths are not in keeping with those expected from sea-floor spreading models. Given the assumption that the lithosphere has everywhere undergone the same cooling process, the anomalous depths are presumably due to undulations in the lithosphere-asthenosphere boundary. Menard hypothesizes that relative motion of the lithosphere over these "asthenospheric bumps" may explain the vertical motion of atolls and guyots (flat-topped seamounts) so common in the Pacific Ocean (Figure 5). These bumps might be due to anomalous thermal or flow conditions in the asthenosphere, and other geophysical techniques may help to distinguish these possibilities.

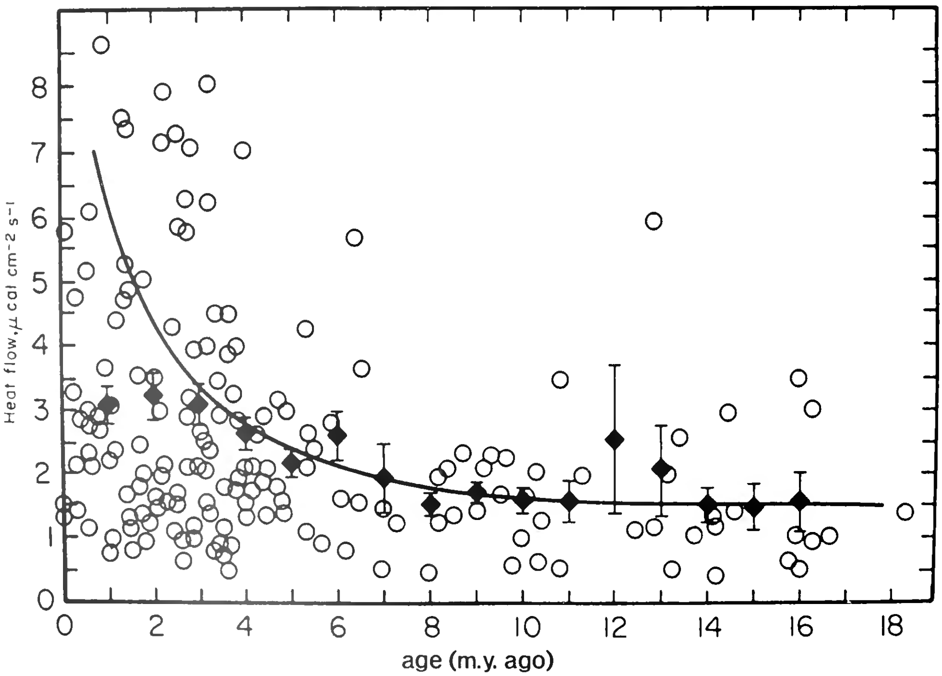


Figure 4: Heat flow versus age of the sea floor for the East Pacific Rise (circa 1971). Solid diamond symbols are running averages of the scattered values. Solid line is theoretical curve for a cooling lithospheric plate. After von Herzen and Anderson (1972).

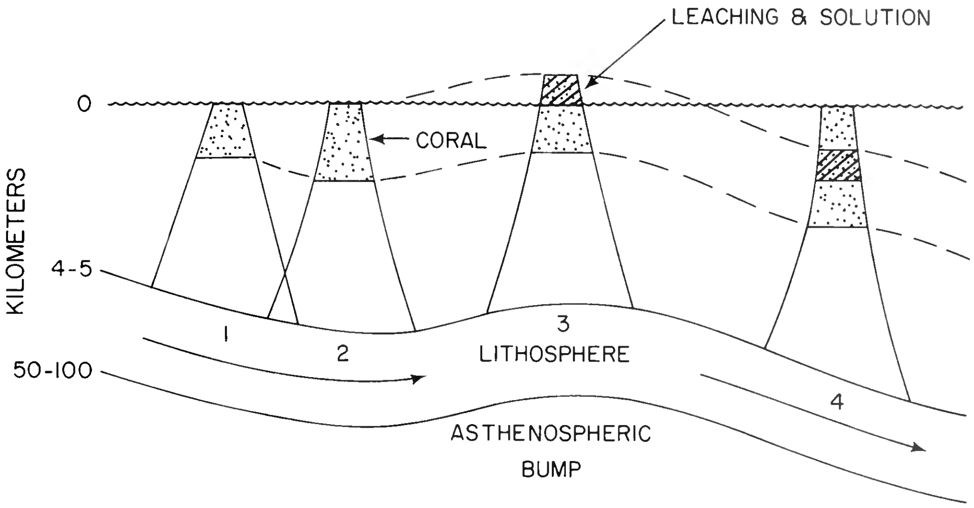
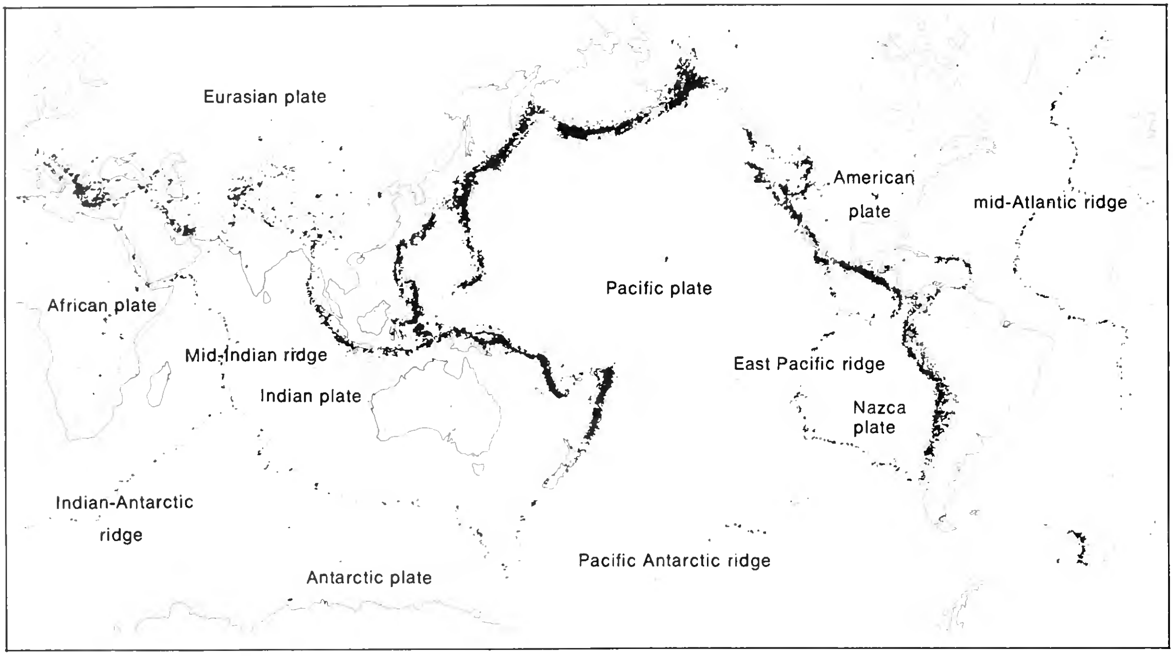


Figure 5: Schematic diagram of elevation changes of an atoll caused by lithospheric motion over an "asthenospheric bump" (after Menard, 1973). Erosion with subsequent rapid subsidence may produce guyots (flat-topped seamounts) most commonly found in the Pacific Ocean.

Thermally convective plumes assumed to cause hot spots may also cause asthenospheric bumps. The heat-flow data do not appear to suggest a correlation with these sea-floor undulations, although it might be difficult to detect a 10% heat-flow anomaly in view of the data scatter. We have already noted the lack of a conductive heat-flow anomaly in association with the Hawaiian hot spot. If viscosity in the earth is an exponentially decreasing function of temperature, as indicated by laboratory experiments on rocks, a convective plume may not necessarily represent a large temperature anomaly.

The plumes provide a mechanism for transferring heat generated in the deep interior of the earth, and such "fluid" motion in the interior may be quite complex. One net effect of the plumes, if they exist, may be to provide an adequate energy source for driving plate tectonic motions. They are not necessarily located under accreting plate boundaries (spreading centers) as was once thought; the new plate material may upwell in rather passive fashion as the plates spread apart. The effect at the surface is the growth and consumption of lithospheric plates as the process by which the earth rids itself of excess heat. However, the tectonics of rigid plates at the earth's surface tends to mask the details of motion in the asthenosphere below. An adequate description of these interior motions may well be a major goal of geoscientists over the next decade or so. The ocean basins are likely to play a major role in that study, in much the same way as they dominated the development of the theory of plate tectonics.



CONSUMPTION OF THE LITHOSPHERE

M. Nafi Toksöz

The sea-floor spreading and plate tectonics hypothesis implies the generation of new lithosphere at the mid-ocean ridges and spreading centers. The newly created lithosphere moves away from the spreading centers as rigid plates. Since the earth is not expanding by any appreciable amount, a major question arises about the fate of the "old" lithosphere. The answer, provided by the plate tectonics hypothesis, is that it is subducted — forced down — into the mantle. The idea of subducting lithosphere can now explain a number of phenomena associated with convergence zones, including the first satisfactory explanation of intermediate and deep-focus earthquakes.

New lithosphere is formed at the ridges. It cools and thickens as it moves away from the ridge axis and, as it encounters other rigid plates, it bends down and descends into the mantle. The thickness of the lithosphere is generally about 80 km. The convergence zones between the plates are characterized by very intense earthquake activity, deep oceanic trenches and associated island arcs. The world seismicity map of earthquake epicenters shown in Figure 1 clearly outlines the global distribution of oceanic ridges and convergence zones.

Earthquakes associated with oceanic ridges are characterized by relatively small magnitudes and shallow focal depths. Because of the relatively high temperatures under the ridges, the earth's materials are "softened" and behave as a viscous medium rather than as rigid materials in which faulting and

Figure 1 (opposite): Distribution of earthquake epicenters (1961-1967) and the outline of the lithospheric plates. The oceanic ridges and spreading centers are defined by a fine line of epicenters. The convergence zones (where the lithosphere is subducted) are characterized by heavy density epicenters.

earthquake activity can take place. Interiors of the plates away from the ridges and trenches are generally aseismic.

The convergence zones, on the other hand, are regions in which relatively cool and rigid plates push against each other. One plate will bend, thrust under the other, and then descend into the mantle. This thrusting is responsible for many earthquakes in the convergence zone.

Formation of the lithosphere and its descent into the mantle is illustrated schematically in Figure 2. As the lithosphere descends into the progressively warmer mantle, it gradually heats up. At the beginning this heating process is slow. However, as the slab penetrates deeper than a few hundred kilometers, heating becomes more efficient. At the boundaries, additional heat is generated because of the shear stresses and viscous dissipation between the moving slab and the surrounding mantle. The progressive heating of a descending lithosphere moving at 8 cm/year is shown in Figure 3 for three time periods: 3.24, 6.48 and 12.96 million years after the initiation of subduction. These figures were calculated numerically using realistic parameters. They demonstrate clearly the fate of the subducted lithosphere.

The interior of the descending slab remains cool relative to the surrounding mantle to a depth of about 700 km. Below this depth, however, the interior of the slab is heated to ambient mantle temperature by the combined effects of more efficient radiative heat transfer, a smaller volume of cooler material, and other factors (Figure 3b). The slab can then no longer be distinguished as an identifiable unit; it is now part of the general mantle circulation.

Not all slabs penetrate to such great depths before they are assimilated. A slower moving slab will reach thermal equilibrium sooner; at 1 cm/year, the slab will assimilate at depths of about 400 km. If subduction ceases altogether the slab will equilibrate with the surrounding mantle at any depth below the lithosphere within 50 million years.

The occurrence of oceanic trenches, island arcs, marginal basins and oceanic rises can be explained by the subduction of the lithosphere. Some of these effects are shown schematically in Figure 4. The flexure associated with the bending of the descending lithosphere produces the topographic rise on the oceanic side of the trench. Underthrusting of the material pulls the crust down, producing deep oceanic trenches. Island arcs, volcanoes and mar-

M. N. Toksöz is professor of geophysics in the department of earth and planetary sciences at Massachusetts Institute of Technology. He received his Ph.D. in 1963 from the California Institute of Technology.

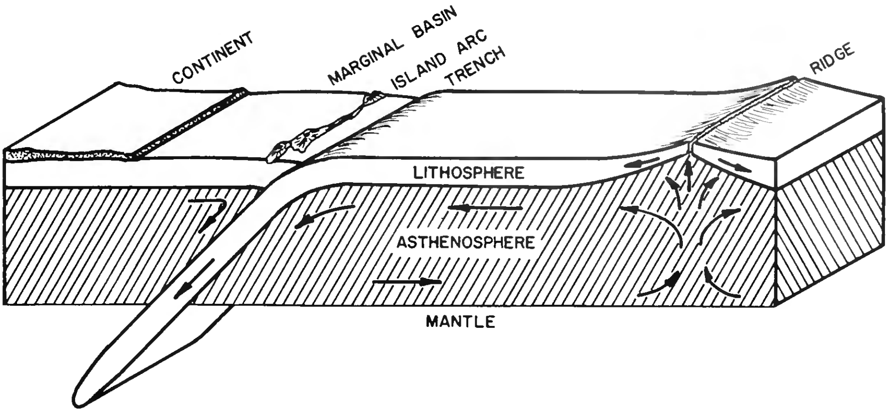
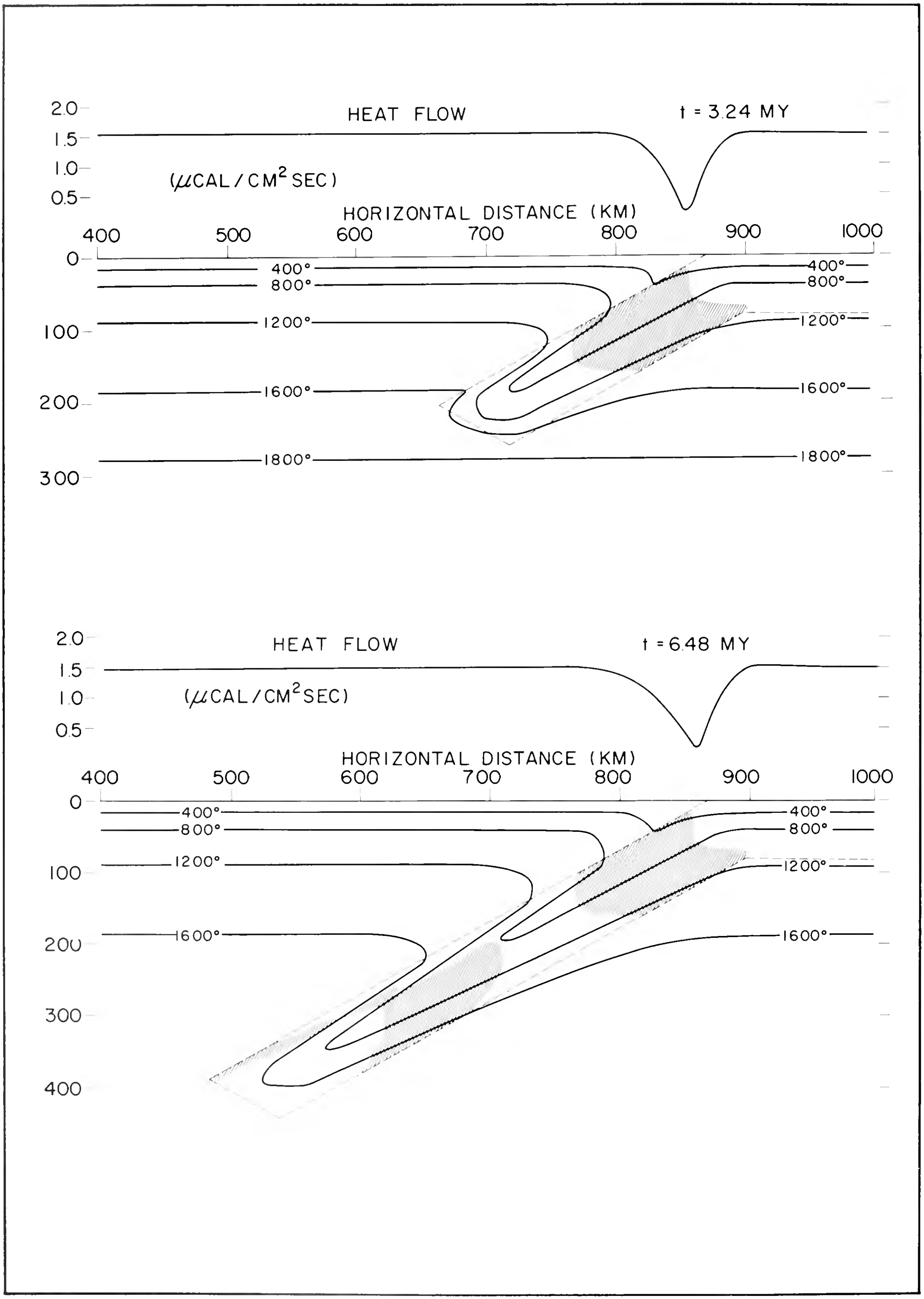


Figure 2: A schematic diagram illustrating the formation, sliding, and subduction of the lithosphere. Arrows indicate the direction of the motion. In the softer asthenosphere, convective motions occur and help drive the lithosphere.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1.5
1.0
0.5
HORIZONTAL DISTANCE (KM)
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500
600
700
800
900
1000
0
100
200
300
400°
800°
1200°
1600°
1800°
HEAT FLOW
t = 6.48 MY
(μCAL / CM² SEC)
2.0
1.5
1.0
0.5
HORIZONTAL DISTANCE (KM)
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700
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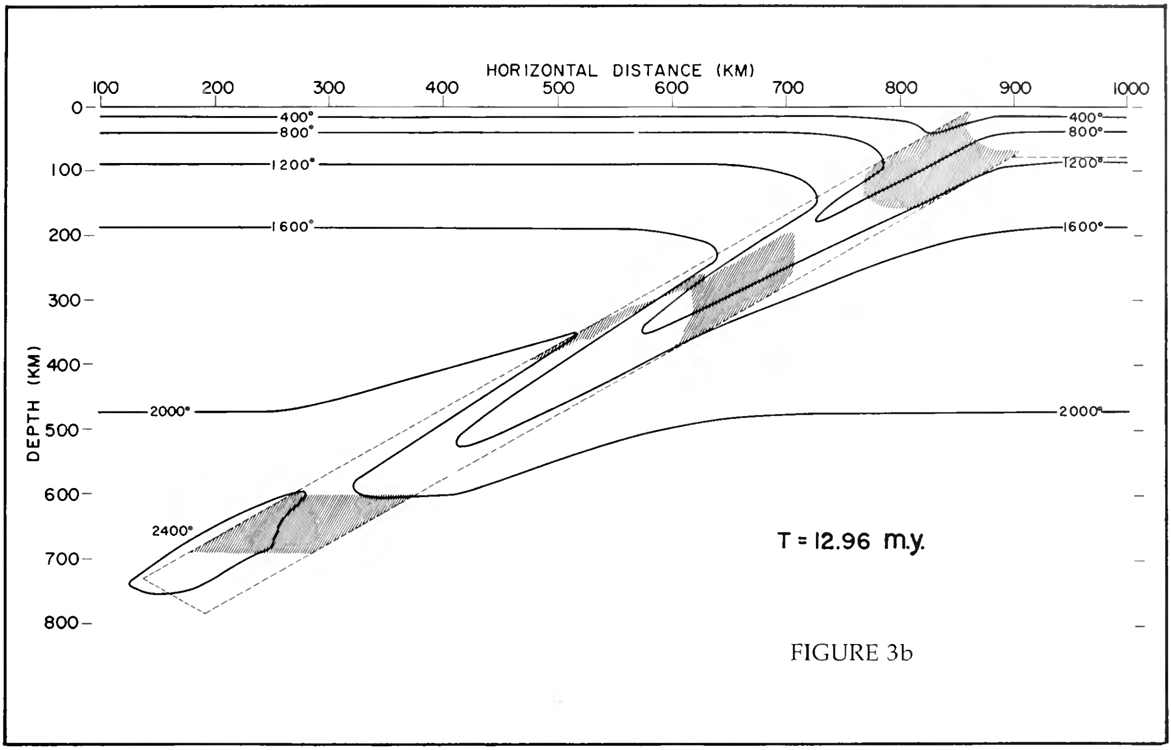


FIGURE 3b

Figures 3a, b: The thermal evolution of a descending lithospheric slab as a function of time. It moves at a velocity of 8 cm/year, corresponding to the rates under Japan and Tonga. The gradual heating at 3.24, 6.48 (opposite page), and 12 million years (above) is visible. At a depth of 700 km the slab reaches thermal equilibrium with the surrounding mantle, and is being consumed. Shaded regions indicate transformation of the material to denser phases. The curves above show the surface heat flux over the subduction zone.

ginal basins are most likely related to viscous coupling between the descending lithosphere and the asthenosphere. The descending lithosphere induces small-scale motions (convection) in the asthenosphere above the slab (Figure 4). Hydrodynamic forces create local tension in the lithosphere under the marginal basin, thus allowing hot material from the asthenosphere to upwell. Upwelling of the material increases melt fraction. Under the island arc, abrasion of the lithosphere takes place and contributes directly to volcanism.

Under the marginal basin, convection and associated stream lines represent a small-scale spreading center. The presence of anomalously thin sediments, young basalts at the basin floors, and high-heat-flow anomalies over these basins strongly support the idea that they may be formed by spreading induced by the descending lithosphere. The best examples of marginal basins are in the Western Pacific. They include the Sea of Okhotsk, the Sea of Japan, the Parace Vela Basin, and the Lau-Havre Basin. Other basins that may fall into the same category are the Andaman Sea behind the Indonesian Arc, Aves Basin behind the Lesser Antilles and the Tyrrhenian Sea behind the Calabrian Arc.

The lower temperatures inside the descending lithosphere relative to the surrounding mantle produce a number of geophysical effects. Because of lower temperatures, material inside the slab manifests higher seismic velocities, higher densities, and lower attenuation, which affect the travel times and other characteristics of seismic waves. Conversely, these observable effects have been used to verify the thermal regime and the subduction of the lithosphere. The density differences produce gravity anomalies which can be explained by the temperature models. In addition, these density differences produce stresses inside the lithosphere which are directly related to deep-focus earthquakes.

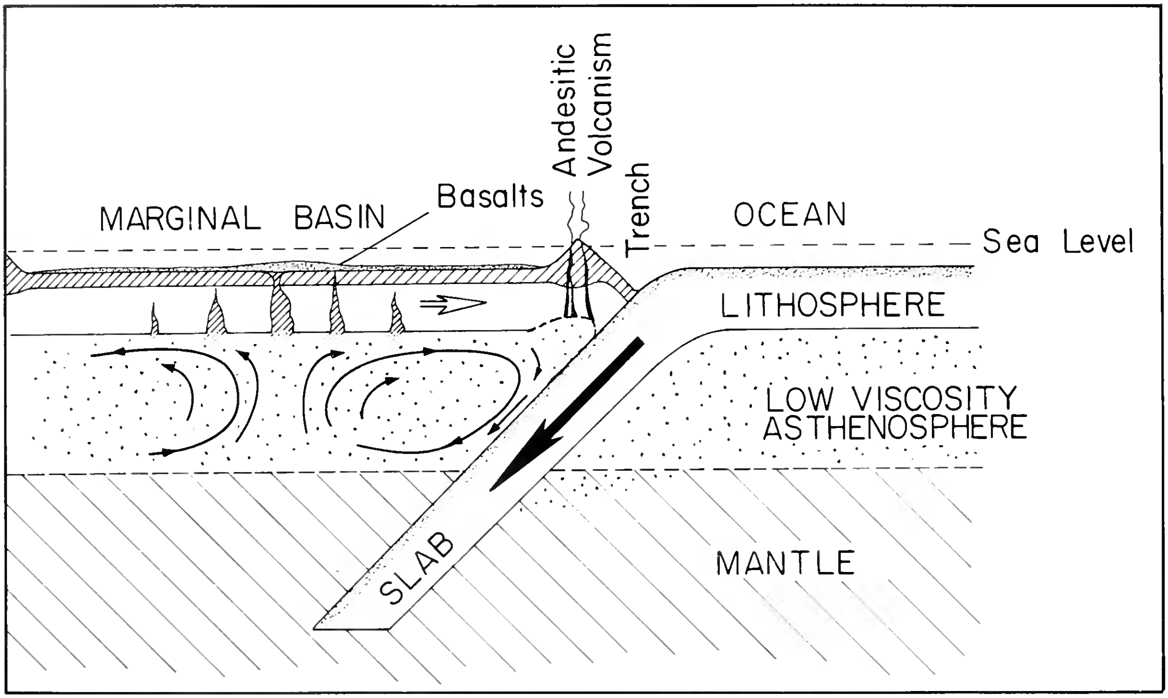


Figure 4: Schematic diagram of the descending lithosphere and the associated phenomena. The magma involved in island-arc volcanism is generated from the asthenosphere, immediately above the slab. In the asthenosphere secondary covection may be induced by the descending lithosphere, causing the marginal basins such as the Sea of Japan.

The intermediate and deep-focus earthquakes under a given island arc define a plane most commonly referred to as the "Benioff zone". At first, this plane was thought to be the shear zone between the upper surface of the descending lithosphere and the adjoining mantle. Focal mechanism studies for earthquakes with hypocenters in these zones showed, however, that the force systems could not be explained by this shearing process. Stress calculations carried out by us have indicated that the earthquake foci should be along the coolest region of the slab's interior.

This point may be clarified by examining the nature of earthquakes in the Central Aleutians and Japan. For both regions, we calculated the temperature field of the lithosphere and the surrounding mantle with proper values for convergence rate, dip angle, and depth of penetration. The results are shown in Figures 5 and 6.

In the Central Aleutians, nuclear explosions Longshot, Milrow and Cannikin provided sources with precisely known locations and origin times for calibrating the velocity models and slab location relative to the trench. Furthermore, the network of seismic stations in the area provided precise locations of the earthquakes. As shown in Figure 5, it is clear that the shallow earthquakes are concentrated primarily along the thrust plane between the stationary and the subducting plates. The mechanisms of these earthquakes, also shown in Figure 5, support the thrusting hypothesis. Shallow earthquakes that occur away from the thrust zone are fewer, and their mechanisms vary. Intermediate-focus earthquakes are located along the coolest region of the slab.

Under Japan, the earthquake locations relative to slab boundaries were determined on the basis of travel times, the attenuation characteristics of the seismic waves, and the focal mechanism solutions.

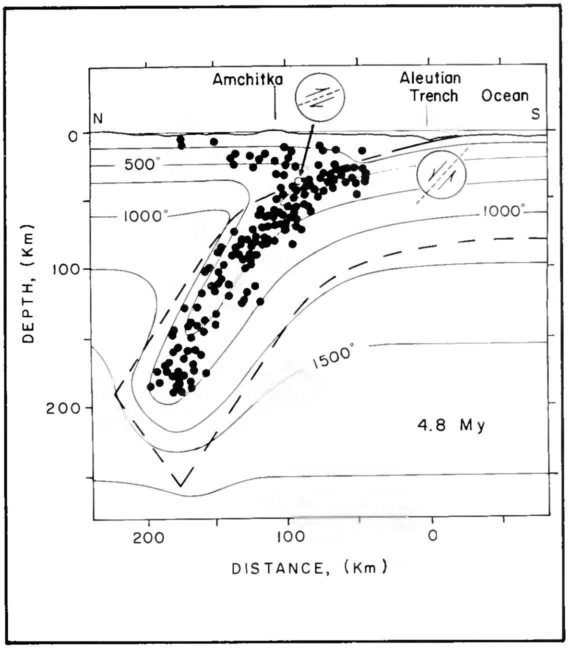


Figure 5: Temperature regime and the distribution of earthquake hypocenters in the Central Aleutians near Amchitka. The focal mechanisms of two representative earthquakes show normal faulting in the oceanside of the trench and thrusting in the convergence zone beneath the arc. Note how intermediate earthquakes are in the coolest region of the slab and not in the shear zone.

These constraints are weaker than the Aleutian case, but again the foci seem to lie along the coolest region of the slab, as indicated by our comparison with the theoretical temperature and stress fields in Figure 6. Similar results are obtained for the Tonga-Kermadec region.

In all cases where the evidence is clear, the intermediate and deep-focus earthquake foci lie along the coolest region of the slab rather than in the shear zone at the slab boundary. The calculated stress regimes within the subducting lithosphere depend not only on the temperature and density anomalies, but also on the rheology — the processes of deformation and flow of matter — of the mantle. With proper values for these parameters, the distribution, orientation and magnitudes of calculated stresses match those observed for intermediate and deep-focus earthquakes.

The absence of earthquakes below a depth of about 700 km may be explained either by the absence of stresses necessary to produce earthquakes or by the absence of material which would undergo brittle failure. These two are related, since temperature plays a strong role in both cases. Below a depth of about 700 km, the interior of the descending slab rapidly reaches thermal equilibrium. The density anomalies causing stresses are greatly reduced below this depth. Furthermore, because of the elevated temperatures, the slab can no longer behave elastically and stresses are effectively relieved by plastic deformation.

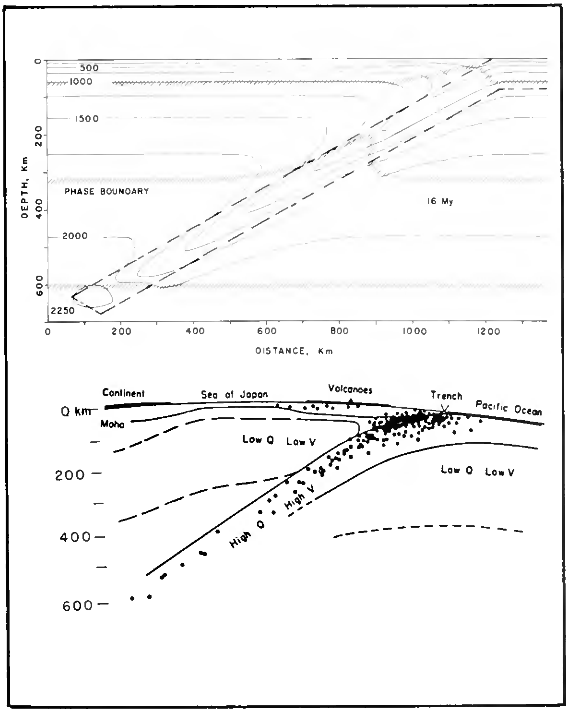
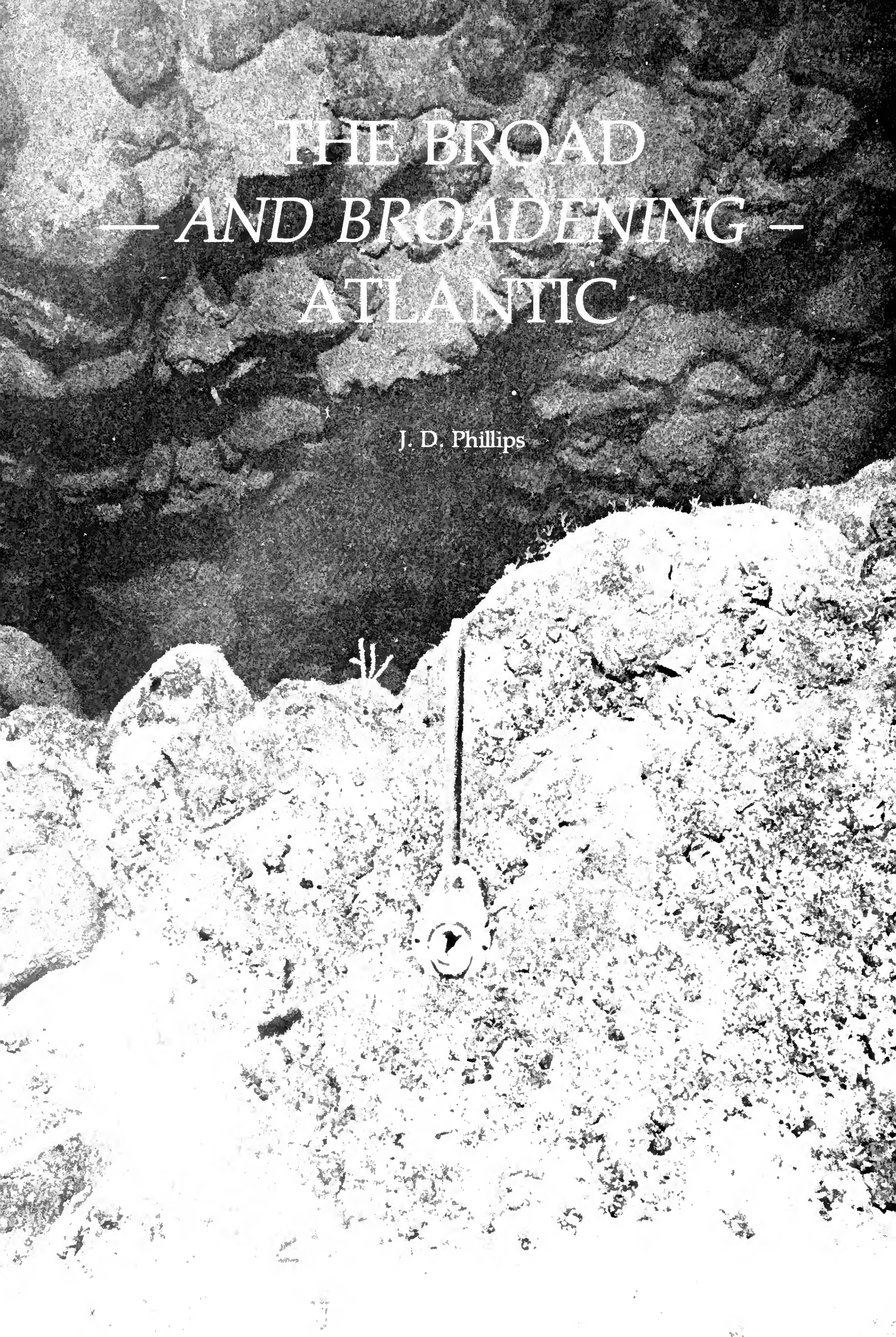


Figure 6: UPPER – The temperature model for the Japanese slab dipping at 30° and 16 m.y. after the start of subduction. The thermal equilibrium is reached at 600 km depth.

LOWER – Cross section showing distribution of earthquake hypocenters under Japan. Intermediate and deep earthquakes are along the coolest region of the slab, and no earthquakes occur below 600 km where the slab has reached thermal equilibrium with the mantle.

THE BROAD — *AND BROADENING* — ATLANTIC

J. D. Phillips



Recent advances in marine geophysics and paleomagnetism have led many scientists to conclude that sea-floor spreading is responsible for the formation of ocean basins. Equally important is the probability that the drift of continents across the earth's surface is directly related to such activity. The theories of spreading, based in the main on magnetic properties of sea-floor rocks and on the study of earthquakes, have provided a concept of global tectonics in which the oceans and continents are regarded as rigid, concave shells or "plates" which move about the globe in response to spreading from the oceanic ridges.

In tracing the history of these movements, it is not possible to reconstruct the exact configurations of ocean basins continuously through geologic time. However, by combining sea-floor spreading, plate tectonics, and paleomagnetic information, a sequence of paleogeographic maps showing the essential tectonic elements can be estimated for certain time periods. A selection of such maps depicting plate motion in and around the Atlantic illustrate this article.

The earliest hypotheses of continental drift date from the early 1900's. These were based primarily on the geometrical fit of the coastlines of South America, Africa, India, and Australia — the lands comprising the primeval supercontinent of Gondwanaland. Geologic support for these geometrical reconstructions came from the remarkable similarity in age, fossil remains, and structure of rocks along the "join lines" where these continents theoretically split away from each other. In more recent years, particularly the last twenty, paleomagnetic investigations have also provided strong geophysical evidence of continental motion. Paleomagneticians generally agree that the apparent shifts in ancient geomagnetic field directions observed in rocks of the Upper Paleozoic (250 million years-or m.y.-ago) and more recent times are best explained by assuming that the continents experienced large-scale translations and rotations with respect to the earth's magnetic poles. These observations were first integrated into the testable hypothesis known as sea-floor spreading by Harry Hess of Princeton in 1960. He proposed that the ocean ridges were sites where upwelling rocks from the earth's interior forced the continents apart as the sea floor spread.

Photo, opposite: Fissure in axial valley, Mid-Atlantic Ridge. The opening, some 5 to 10 feet across, was photographed at 1350 fathoms (Atlantis II, Cruise 73).

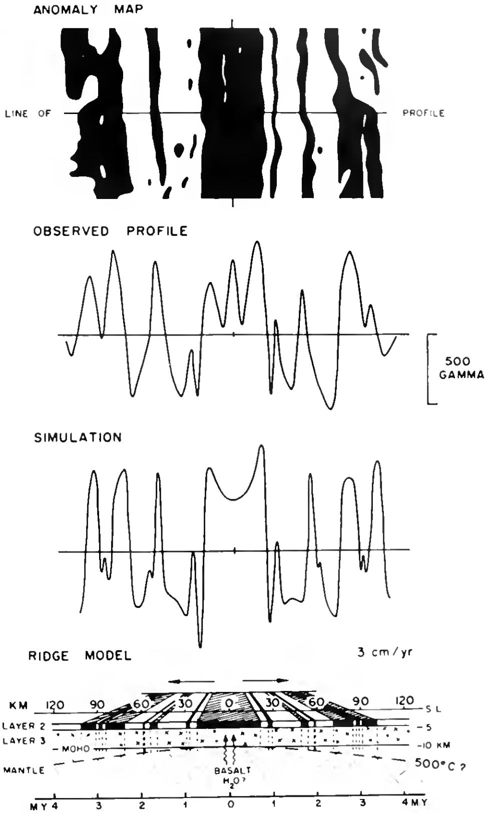


Figure 1: Sea-floor spreading model to account for magnetic anomalies over an ocean ridge. The slab-like body at the bottom of the figure represents the magnetized rock of the sea floor. The alternating black-and-white bands represent rock having either positive or negative magnetization (see text). The simulated profile above the slab results from computer calculation of anomalies one might expect to record aboard a research vessel moving across the area represented by the slab. Note the close similarity between simulated profile and that actually observed along the ship's track. The black and white anomaly map at the top shows in plan view regions of positive and negative anomalies observed in the same area of ocean ridge as that covered by the other representations.

J. D. Phillips is an associate scientist in the Institution's department of geology and geophysics. He received his Ph.D. from Princeton University in 1966.

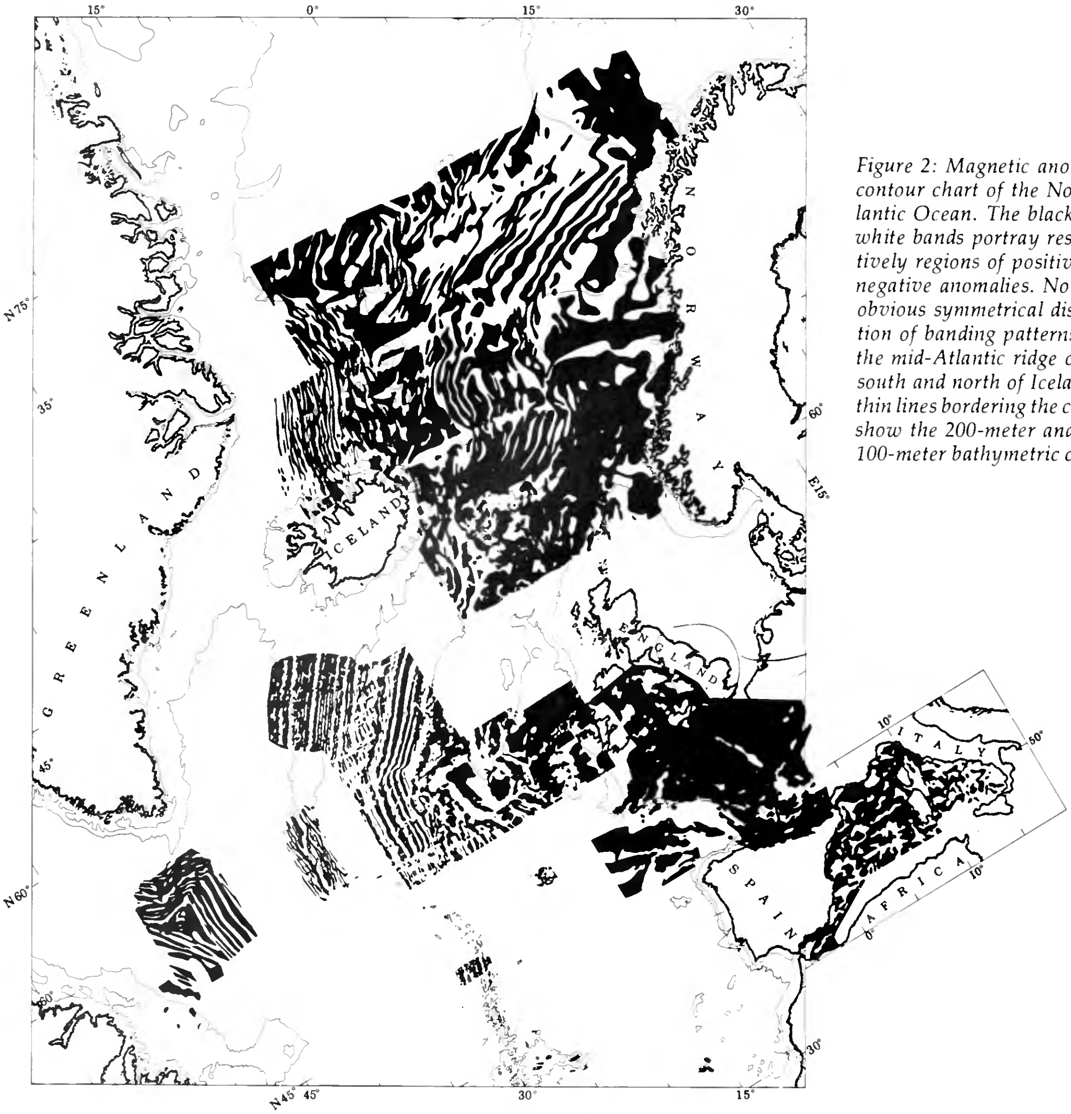


Figure 2: Magnetic anomaly contour chart of the North Atlantic Ocean. The black and white bands portray respectively regions of positive and negative anomalies. Note the obvious symmetrical distribution of banding patterns about the mid-Atlantic ridge crest south and north of Iceland. The thin lines bordering the coastline show the 200-meter and 100-meter bathymetric contour.

United States Naval Oceanographic Office

The rapid development of the sea-floor spreading hypothesis has further served to confirm the drift theory by providing the only model accounting for the motion to be successfully tested by several independent lines of evidence. Studies of geomagnetic field variations across ocean ridges have been particularly helpful in this regard. These variations result from the fact that there is a magnetic field surrounding sea-floor rocks that either increases or decreases the normal (ambient) geomagnetic field intensity at the ocean surface, causing irregularities called anomalies.

The extensive bands of magnetic anomalies over the mid-ocean ridges of the Atlantic, northeast and southwest Pacific, and northwest Indian oceans have long intrigued geophysists. No such banding exists over the continents. To account for this phenomenon, Frederick Vine and Drummond Matthews of Cambridge University suggested a decade ago that the basaltic lavas emplaced beneath the ridges become magnetized in the direction of the ambient geomagnetic field as they cool (Figure 1). They then move laterally away from the ridge by Hess's process of sea-floor spreading. Assuming that the geomagnetic field reverses its polarity from time to time, Vine and Matthews argued that the direction of magnetization of the rocks would be parallel or anti-parallel to the present field direction; the relationship would depend on distance from the ridge axis, spreading rate, and the geomagnetic polarity-reversal time scale as determined from radiometric dating of land lavas whose polarity and age is precisely known. Remarkably, all rocks of the same age have the same polarity.

To explain further, lava rocks formed today are magnetized parallel to the ambient geomagnetic field direction — toward magnetic north. Their external field is added directly to the strength of the ambient field, causing a positive anomaly. Similarly, lavas formed during periods when the geomagnetic field was reversed manifest a field direction which is opposite or anti-parallel to that existing today. This opposition in effect weakens the force of the ambient field, causing a negative anomaly*. If the rocks spread away from the ridge crest at equal rates on both sides, a symmetrical pattern of alternating positive and negative anomaly bands would be anticipated. The separation or opening rate would be twice the spreading rate. This symmetry has indeed been observed over all actively spreading mid-ocean ridges. Thus it appears that the spreading sea floor acts as a digital tape recorder of geomagnetic field history. The machine works well enough to give researchers precise information about spreading rates and detailed time scales of geomagnetic polarity going back more than 150 m.y. ago. Nearly 60 characteristic anomaly patterns are now recognized.

There is probably a direct relationship between the orientation of magnetic anomaly patterns and ridge crests. Both are parallel to each other and appear to trend perpendicular to the direction of continental motion inferred from various pre-drift geometric and geologic reconstructions. In contrast, the trends of the major transverse faults crossing the ocean basins appear to lie parallel to the direction of inferred drift or flow. These faults are presumably the traces of ancient transform faults which were initially formed at offsets in ridge crests and carried out to the flanks as the sea floor spread.

The Atlantic Ocean is an especially appropriate region for studies of crustal evolution in that extensive knowledge of the magnetic anomaly pattern is available. The North Atlantic mid-ocean ridge between the Azores and Norway is particularly well known. In fact, here the very close spacing of ship and aircraft tracks has permitted contour maps to be developed (Figure 2). From these charts, distinct areas of anomaly bands can be treated continuously for thousands of kilometers. Each of these bands represents an isochronous line — one delineating rocks formed at the same interval of geologic time. In the South and Central Atlantic, the data is not so detailed. However, careful analysis of the anomaly profiles has provided correlations of anomalies from profile to profile. In this way, lineation maps have been developed. Anomaly numbers 1-31 are particularly distinctive. These lineations also represent isochrons much like the anomaly contour charts of Figure 2.

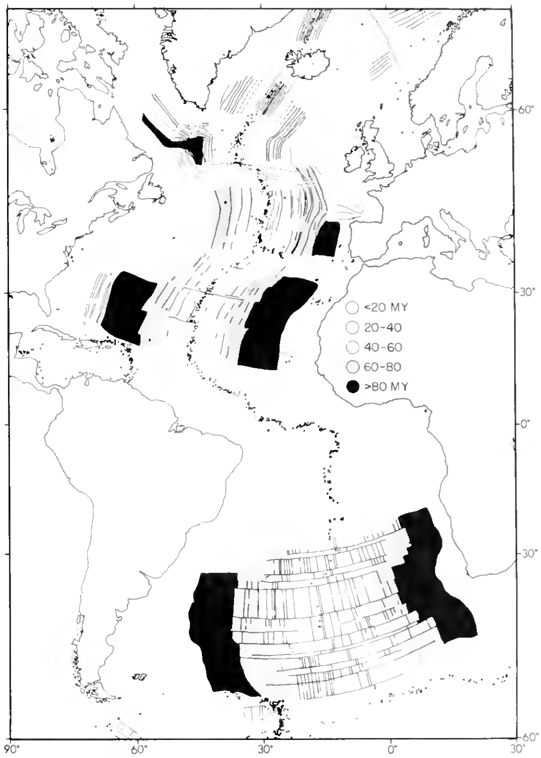


Figure 3: Summary of magnetic anomaly age information in the Atlantic Ocean. The stippled pattern shows regions of anomaly trends of a specific age. The trends themselves are shown by thin lines parallel to the banding. Small dots indicate earthquake locations. Note the concentration of quakes along the ridge crest. Thin lines traversing the bands and anomaly lineations represent trends of transverse faults, which trace motions of continents as they moved apart.

One of the main implications of plate theory is that it should allow us to determine the complete motion or drift of the continents relative to each other. Sir Edward Bullard of Cambridge and his co-workers have shown that reconstruction of pairs of continents can best be described through use of a "center or pole of rotation" concept, the direction of motion being along small circles** or co-latitudes drawn about the respective poles. In fact, the trend of transform faults offsetting the mid-ocean ridge crests do form small circles, and poles of rotation computed from faults across various ridge crests have indeed been used to calculate spreading directions.

The average pole of opening for a continent pair can also be inferred simply by determining the

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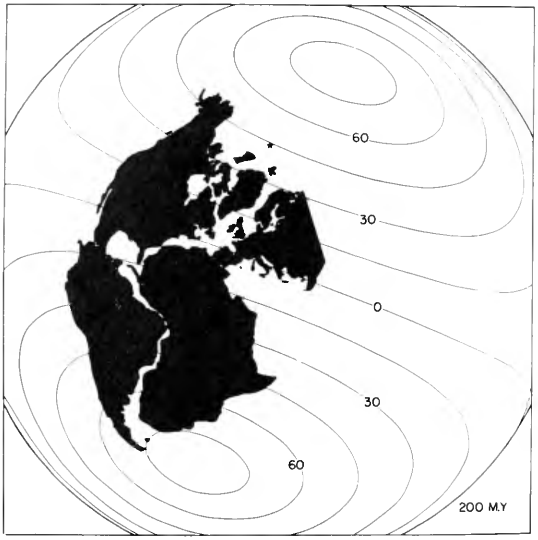
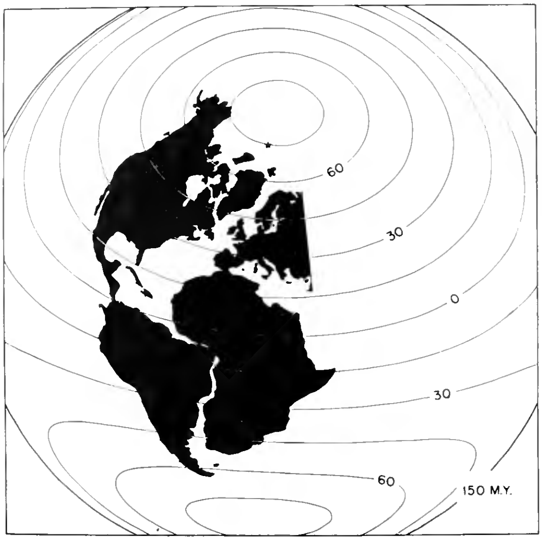
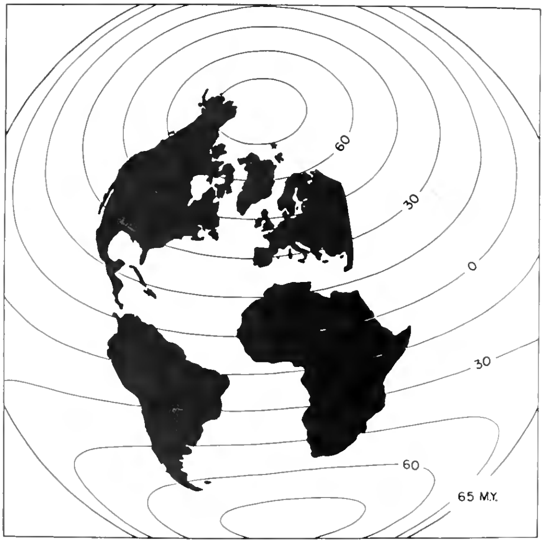
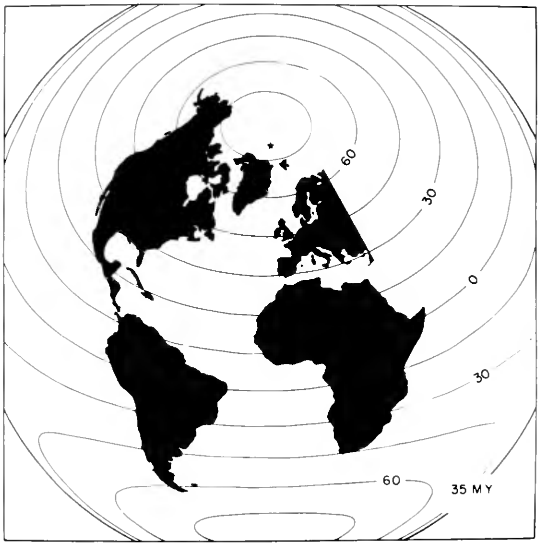
*These effects do not necessarily hold true near the equator.

**The latitude lines on the globe, for example, form small circles about the north and south geographic poles.







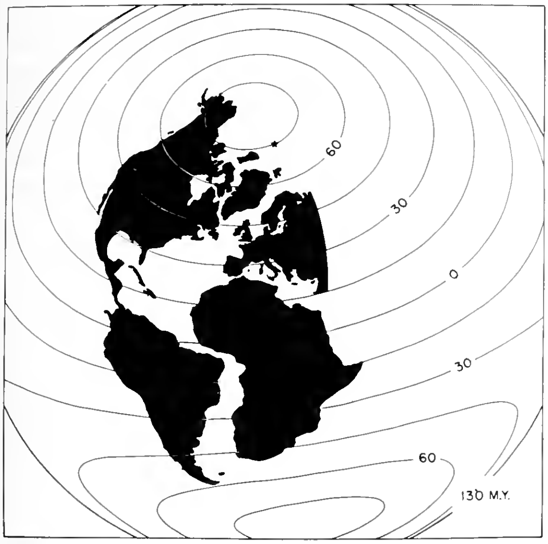


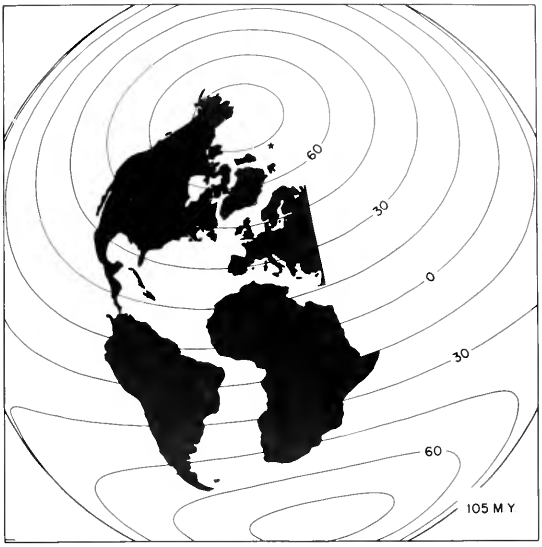
200 m.y. ago: *This is the pre-drift reconstruction of Sir Edward Ballard of Cambridge and co-workers for the continents about the Atlantic (225 m.y. ago). The paleolatitudes are for the Permian period. Note that the continents are located well to the south of their present latitudes. For the reconstructions, North America has been held fixed relative to the present geographic coordinate system. All continents have been rotated relative to North America.*

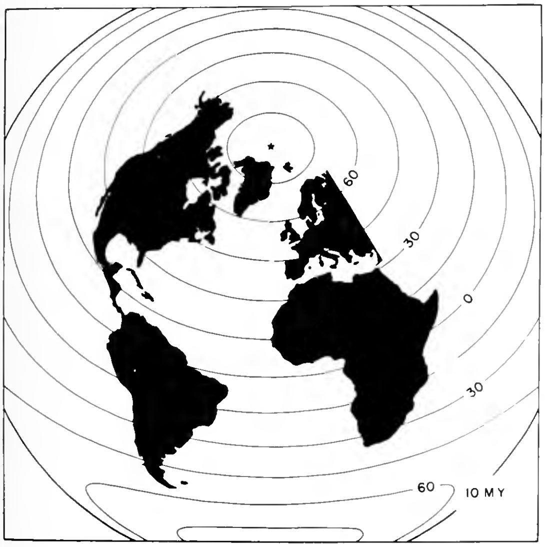
65 m.y. ago: *Separation continues in the central Atlantic at a rate of 3.0 cm/yr and in the north central zone at a rate of about 4.0 cm/yr. Europe begins to rotate eastward relative to Africa considerably faster than in previous times. Some compression is noted as the Tethys region begins to close. Initiation of spreading on the Reykjanes ridge running southwest of Iceland, opens the Atlantic to the newly formed Arctic Seas, marking the first major incursions of cold polar water into the Atlantic basin. The South Atlantic is now open to about 70% of present width.*

150 m.y. ago: *Opening begins first in the central Atlantic between Africa and North America with a separation rate of about 3.0 cm/yr 200 m.y. ago and is about 30% open at this time. The South Atlantic and North Atlantic are still essentially closed.*

35 m.y. ago: *Separation continues at about 2.5 cm/yr in the central Atlantic but has slowed considerably between the Grand Banks and Iberia. This slowing has the effect of rotating Europe clockwise with respect to Iberia. Folding of the Pyrenees and Alps may also have been coincident with this spreading slowdown. Strong horizontal compressive forces associated with the collision of the African and Iberian plates has probably caused relative overthrusting of the intervening sea-floor rocks onto both plate margins in the Straits of Gibraltar region. Deep-water circulation between the Atlantic and the Mediterranean probably ceased after this time. The North Atlantic between Greenland and Rockall Bank northwest of Ireland opens to about 85% of its present width.*







130 m.y. ago: *Opening continues in the central Atlantic, and South America has begun to separate from Africa. The Bay of Biscay probably begins to open as Africa, in its passage by Europe, drags Iberia eastward.*

10 m.y. ago: *The entire mid-Atlantic ridge again begins spreading at rates of 1-2 cm/yr.*

105 m.y. ago: *Separation continues in the central and South Atlantic at 3.0 and 4.0 cm/yr respectively. Formation of the Bay of Biscay is nearly complete.*

Present: *All portions of the ridge are actively spreading. South America is overriding the Pacific Ocean plate along the Peru trench, while the African and Indian Ocean plates are moving northeast and colliding with Asia and Europe. The present intense earthquake activity in the Mediterreanean region results from this collision. Between North and South America, the Caribbean Sea appears to be moving eastward as a separate plate, overriding the floor of the Atlantic Ocean along the Lesser Antilles Islands.*

single rotation which provides the best geometrical fit of opposing continent coast lines. If we assume that continents have always been rigidly coupled to the spreading sea floor in a pattern of plates, it is reasonable to infer that spreading about the rotation pole will reflect the horizontal translation or drift of sea floor and continent alike. Accordingly, precise reconstruction of the ancient configuration of continents and ocean basins should be a relatively simple matter. In effect, one shifts the sea floor with attached continents about rotation poles inferred from the transverse fault trends and geometrical fit considerations so that isochronous magnetic anomalies on either side of oceanic ridges (such as those in Figures 2 and 3) are made to coincide. The sea floor is thus "shrunk" to the dimensions that pertained when a particular pair of isochronous anomalies were created. The reconstructions shown on pages 24-25 were made in this way.

An important aspect of plate rotation theories is the possibility of determining the ancient configuration of the plates relative to the earth's spin axis, the geographic axis about which the earth rotates every 24 hours. This deduction results from the dynamo model for the geomagnetic field, which requires that the spin axis and magnetic axis of the earth be nearly identical. Therefore, by simply restoring the ancient geomagnetic field directions recorded in continental rocks — in a manner consistent with the sea-floor spreading rotation scheme — we can locate the average geomagnetic axis or pole as it existed in the geologic past. Once the axis orientation is known, the paleolatitude on any point in the globe can be determined. This has been done, and the latitudes are shown in the accompanying reconstructions.

Inspection of the reconstructions reveals that the paleoconfiguration of the Atlantic continents and their paleolatitudes have changed markedly since early Mesozoic times 200 m.y. ago. The most apparent result is the sequence of opening in the Atlantic. It is clear that the ocean did not form everywhere at the same time. The central Atlantic between North America and Africa appears to have opened first about 200 m.y. ago. Next came the opening of the south Atlantic about 50 m.y. years later. The latest portion of the ocean to form is the North Atlantic, which opened in two phases. First, there was opening between North America and Greenland to form the Labrador Sea about 85 m.y. years ago, while the northernmost Atlantic between Greenland and Europe did not begin until about 65 m.y. ago.

It is also important that throughout the opening of the Atlantic, North and South America seem to have moved apart to form the Caribbean Sea. The maximum width of the sea appears to have been attained by the end of Mesozoic time (65 m.y. ago). Whether this motion resulted in the formation of the Caribbean by another sea-floor spreading system is problematical. It may be that the Caribbean is a portion of a more ancient Pacific plate, bounded by the Antilles and the northern coast of South America, which gradually moved into the opening caused by the separation of the American plates. In any event, compressional motion across the Caribbean Sea appears to have been active since early Tertiary time as the plates closed to essentially their present separation about 35 m.y. ago. This motion may also have resulted in folding and thrust faulting in the Coast Ranges of Venezuela and compression in the Greater Antilles. During the last 35 m.y., there has been very little relative motion between the Americas.

The Mediterranean Sea appears to occupy a position similar to the Caribbean in that it, too, has formed between plates of the Atlantic spreading system, namely the African and European plates. However, in contrast to the Caribbean, the Mediterranean was the site of compressional and strike slip motions during the earliest phase of Atlantic opening until Cretaceous time (about 130 m.y. ago). In the Cretaceous, extensional motions were active which opened the sea to its maximum width about 65 m.y. ago. Throughout the Tertiary, the relative motion of the African and European plates appears to have been primarily compressional, with some right-lateral as well as minor left-lateral, strike slip. These motions are probably responsible for the Alpine deformation of the Tethys* region and the rotation of the Iberian peninsula as Africa collided with Europe.

It is interesting to speculate what will happen if present plate motions continue into the future. Several workers have suggested that a major change in the circulation pattern of the oceans may occur. For example, fifty million years from now (Figure 4) it is speculated that the Central American Isthmus will have rifted apart; the Caribbean Sea will then completely separate North and South America. The Red Sea will have also breached the Sinai and will serve to connect the Indian Ocean with the Mediterranean Sea and the Atlantic. On land, India will continue its collision with Asia, substantially reducing the area of that subcontinent. Similarly, Arabia will move northward to consume the Persian Gulf, and Australia will have overridden a large portion of the islands and archipelagos to the north.

*Tethys was a vast sea, of which the Mediterranean is a relict, extending from Portugal across southeast Europe and the Himalayan region to Southeast Asia and the Pacific. For further reference, see p. 28.

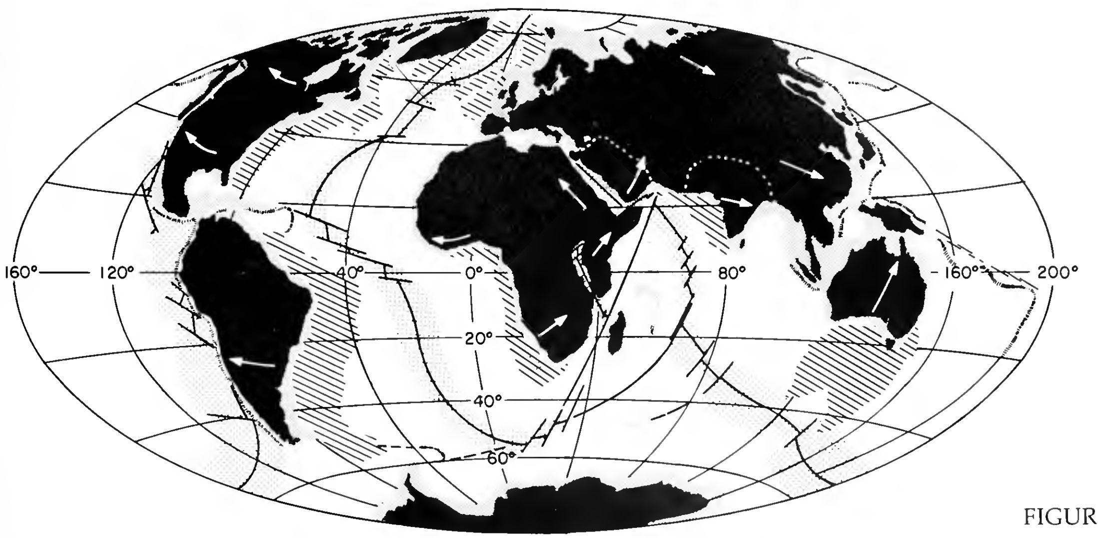


FIGURE 4

50 m.y. in the future: *The Atlantic (particularly the South Atlantic) and the Indian Ocean continue to grow at the expense of the Pacific. Australia drifts northward and begins rubbing against the Eurasian plate. The eastern portion of Africa is split off, while its northward drift closes the Bay of Biscay and virtually collapses the Mediterreanean. New land area is created in the Caribbean by compressional uplift. Baja California and a sliver of California west of the San Andreas fault are severed from North America and begin drifting to the northwest . . . (Diagram and caption courtesy* Scientific American).

The significant changes in the paleoconfiguration of the continents and the shift in their paleolatitudes undoubtedly had profound effects on the environments and climates along the various continental margins. For example, the climate and the ocean circulation in the central Atlantic and Mediterranean was probably very different during Triassic and Jurassic times (200-150 m.y. ago) than it is today. The region was at about 10°S latitude and the basin was very small. The climate was probably much warmer than today's. There was no connection to the polar seas, so that there was little bottom water circulation (see p. 28). The present surface circulation pattern with a strong western boundary current (the Gulf Stream) was clearly not operative. Accordingly, evaporitic conditions might be expected to have prevailed at this time. Recent deep-sea drilling along the eastern margin of the Atlantic basin and the Mediterranean Sea seem to confirm this speculation. Salt deposits were recovered from several of the many diapir-like structures which are common in these areas.

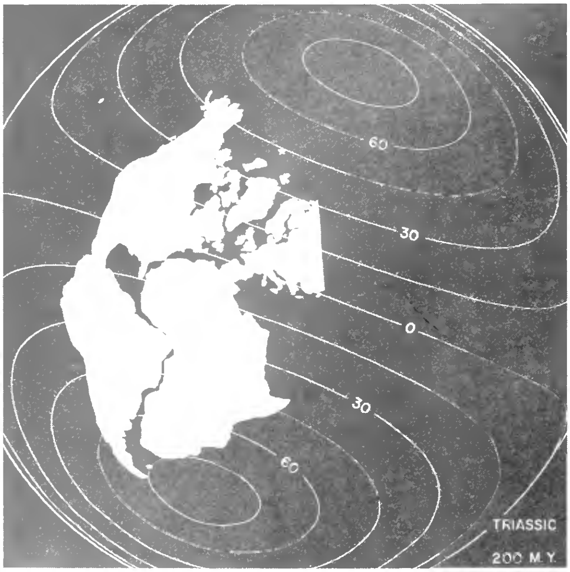
Similar conditions of restricted ocean circulation might also be expected to have prevailed in the proto-Gulf of Guinea region in the South Atlantic as northern Brazil slipped past the bulge of Africa 150-100 m.y. ago. In fact, the extensive non-marine sedimentary deposits found here suggest the region may have been occupied by a band of large brackish water lakes over this time period.

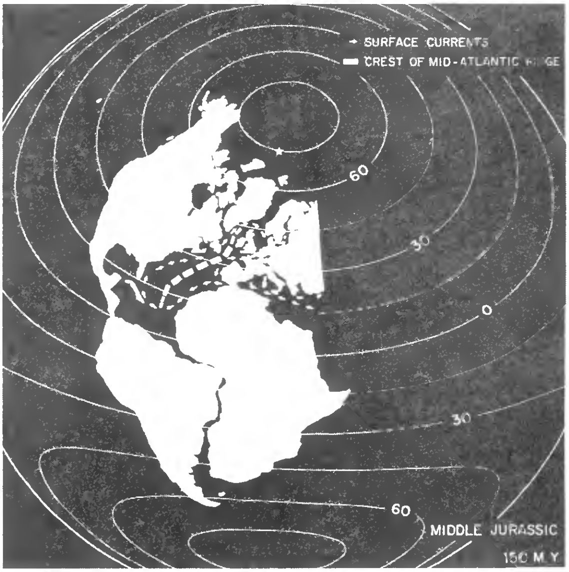
Another observation of global significance is the rapid but smooth migration of the Atlantic plate system northward away from the South Pole as the plates separated. There is also broad agreement of the inferred paleolatitudes with the ancient climatic zones found in the rocks of the continents. That is, rocks found near the paleoequator show evidence of forming under warm conditions while rocks found near the poles appear to be associated with glacial activity. This means that the earth's spin axis must have remained nearly perpendicular to the solar ecliptic plane throughout the opening history; otherwise one would expect a uniform distribution of extreme climatic indicators in the rocks over a wide paleolatitude range. For example, if the spin axis were exactly in the ecliptic plane, all points on the earth's surface would be expected to undergo annually maximum and minimum solar radiation changes approximately equivalent to points which now lie only on the equator and poles respectively. It is unlikely that latitudal zonation of climates found today would prevail.

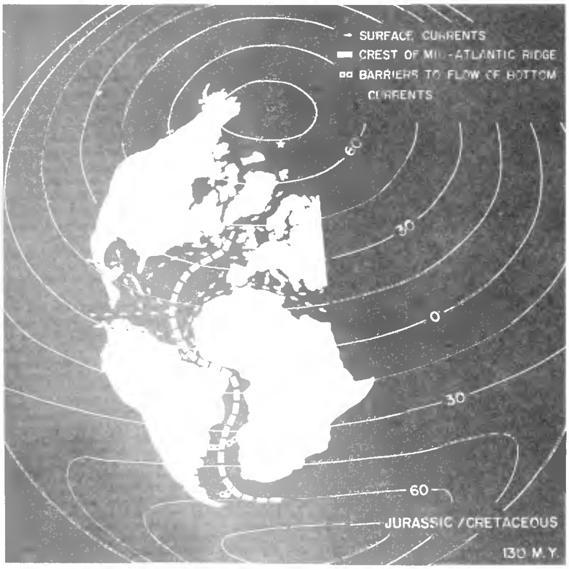
Thus, it appears the crustal plates which make up the outer shell of the earth have moved not only relative to one another but have also shifted as a unit relative to the spin axis, which has remained fixed. It is remarkable that the moving plates do not disturb the spin-axis orientation. There must be a long-term mass transport mechanism operative in the mantle which can balance the surface mass redistribution caused by the moving plates. Otherwise, the earth's angular momentum (spin) axis would have migrated relative to the ecliptic plane through time.

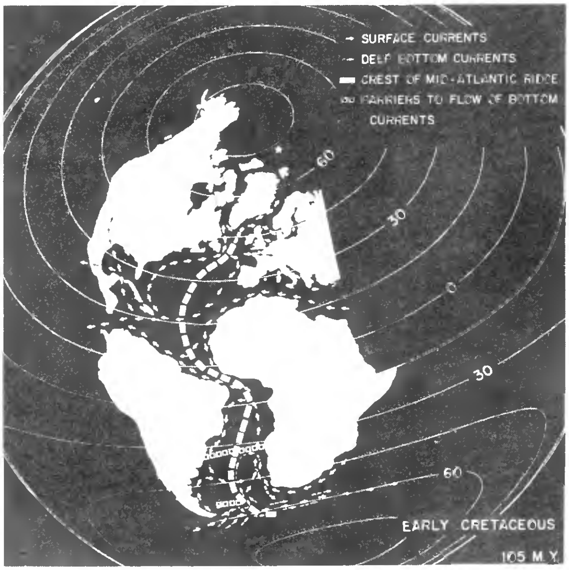
CURRENTS OF TIME

W. A. Berggren
and C. D. Hollister









Patterns of oceanic circulation have changed radically over the eons with the swing of continents and the spread of sea floors. The authors, both scientists at the Institution (Hollister is a marine geologist, Berggren a micropaleontologist) have developed theoretical flows of currents and eddies in the Atlantic area stretching back two million centuries. Their work, which will be published early next year, makes use of the computer-drawn paleogeographic maps produced by Joseph Phillips, author of the previous article, and his colleague Donald Forsyth. The illustrations and captions below illustrate some of their findings.

Late Triassic (200 m.y. ago)

Gondwanaland and Eurasia were essentially contiguous. Marginal and interior evaporite basins developed along the perimeter of the North American Basin and North Africa and possibly the Gulf Coast. Marine Triassic beds were deposited in the Europe - Tethyan region. Circulation was restricted to shallow saline overflows and to the local development of wind gyre patterns in enclosed basins.

Late Triassic - Middle Jurassic (200-150 m.y. ago)

Sea-floor spreading opened a narrow and relatively shallow North Atlantic Basin, and a sluggish, paleo-equatorial surface gyre developed. This North Atlantic gyre (Gulf Stream) flowed northeastward across the northern Atlantic and into the northern or epicontinental (where seawater has encroached on the continent) part of the Tethys Sea and thence eastwards into Himalayan regions. The South Atlantic remained closed. The major circulation in the Tethys Sea was from the east (Indo-Pacific region) to west, similar to the present equatorial currents. The Gulf of Mexico was probably an evaporite basin with no distinct major circulation pattern connected with world ocean systems. Deep thermohaline Atlantic circulation had not yet developed.

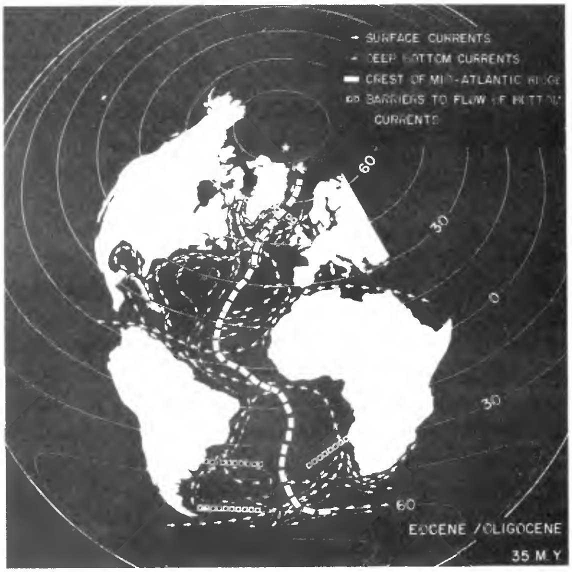
Late Jurassic (150-130 m.y. ago)

A sluggish, widening, elliptical clockwise circulation was initiated in the spreading North Atlantic Basin. Continued flow of a northern branch of this gyre passed through the northern part of Tethys and eastward toward the Himalayan region. A branch of a proto-Gulf Stream flowed along the shallow coastal margin of Newfoundland in response to the increasing fetch of the easterly wind blowing north of the Equator. Northeastward flow of part of this water continued into the narrow, shallow seaway between Greenland and Scandinavia and thence into the Arctic region . . . A more fully-developed equatorial current divergence developed with concomitant development of upwelling along the Equator, i.e. in the central part of the Jurassic Atlantic. The South Atlantic remained essentially closed, although longitudinal rifting in the southern part may have occurred during Late Jurassic - Early Cretaceous. Westward flow in Tethys was dominant. Subsidence of the Gulf of Mexico may have allowed connection with the world ocean system. Part of the westward flowing Tethys - North Equatorial surface current may then have been deflected northeastward across the Gulf of Mexico and into the epicontinental seaway linking the Gulf with the Arctic via Alaska. A marine connection (at least intermittent) existed between the Atlantic and Pacific by means of epicontinental seas in the Mexico - Central American region. Deep and bottom circulation had not yet developed.

Early Cretaceous (130-105 m.y. ago)

A broad North Atlantic gyre developed in conformity with the changing geometry of the North Atlantic Basin and in response to the relative southward migration of the Equator. A branch of the Gulf Stream flowed north around Newfoundland and along the east coast of Labrador. One part of this current flowed northeastward into the shallow seaway between Greenland and Scandinavia and into the Arctic region. Another flowed northeastward across the Atlantic and across the epicontinental Tethyan Seaway of central and northern Eurasia, thence southwestward to the Himalayan region and Indo-Pacific region. Westward flow of the Tethys Sea and its continuation as the North Equatorial Current transported various Tethyan, tropical faunal elements to the Caribbean - Gulf Coast region. Atlantic - Pacific marine connection was maintained across Central America and Mexico, allowing Tethyan faunal elements to colonize marginal areas of Central and South America and California. Part of the

W. A. Berggren is a senior scientist in the Institution's department of geology and geophysics and an associate professor at Brown University. He holds both a Ph.D. and D.Sc. from the University of Stockholm. His colleague, C. D. Hollister, is an associate scientist in the same department at the Institution; he joined the staff in 1967 after receiving his Ph.D. from Columbia University.



westward-flowing North Equatorial Current was deflected northwestward across the Gulf of Mexico and into the epicontinental seaway extending to the Arctic region via Alaska.

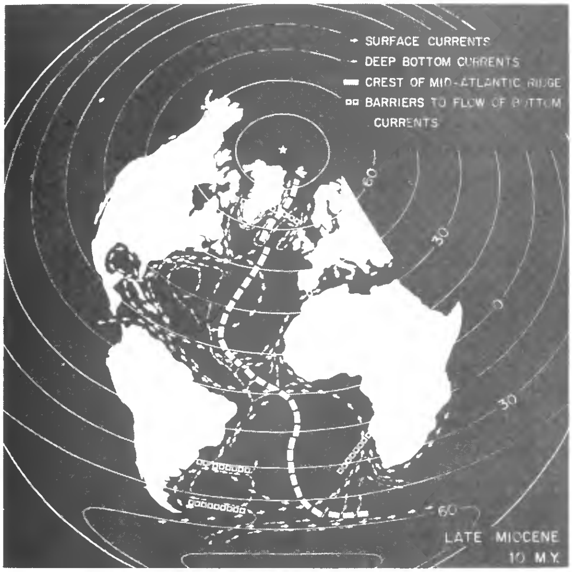
At about this time (*ca.* 90 m.y. ago) marine communication between the North and South Atlantic was formed by the separation of Africa and South America. The major contribution to South Atlantic circulation was probably derived from the easterly-flowing circumpolar current driven by the West-wind Drift. The deep circulation of the North-South Atlantic interchange was still hampered by the topographic barriers of the Walvis Ridge (off Africa) and Rio Grande Rise (off southern Brazil) to the Antarctic bottom water and of the Labrador-Greenland-Spitzbergen land bridge across the North Atlantic to the cold Arctic bottom waters. There is some evidence in recent deep-sea drilling data pointing to periods of stagnation during the early Cretaceous.

Late Cretaceous (130-65 m.y. ago)

Continued spreading of North-South Atlantic seafloor resulted in further development of circulation patterns. The Gulf Stream gyre dominated North Atlantic circulation, and a branch continued to flow eastward across the northern part of epicontinental Tethys Sea to the Himalayan and Indo-Pacific region. A branch flowed northward into the Labrador Sea, around Greenland and northeastward towards the Arctic region. The North Atlantic at this time was essentially a subtropical carbonate province with chalks being deposited in the Labrador Sea, coastal Greenland and Denmark. Northward-flowing currents from Tethys along the coastal margin of Europe probably transported tropical elements as far north as Holland-Belgium during the Senonian. The Atlantic and Pacific Oceans were linked via Central America, allowing continued colonization of Central and South America and California by transoceanic migration of Tethyan faunal elements. With reduction of the epicontinental seaway linking the Arctic and Gulf of Mexico by late Cretaceous regression (shallowing of epicontinental seas), the Gulf of Mexico developed a roughly clockwise circulation (similar to that of the present day) in which the inflowing surface water was derived essentially from the wind-driven Antilles Current and the North Equatorial Current; the outflowing water contributed to the generation of the Gulf Stream and the North Atlantic Drift. Greenland was linked to the Alaskan region via a seaway around the northern margin of the Canadian Shield.

Paleocene - Eocene (65-35 m.y. ago)

Two main paleogeographic events influenced current circulation patterns during the early Cenozoic (Paleogene): the opening of the northeastern Atlantic and Norwegian Sea, and the marked reduction in the areal extent of epicontinental seas, particularly in Eurasia. Active spreading on the Mid-Atlantic Ridge shifted from the Mid-Labrador Ridge to the



Reykjanes Ridge about 60 m.y. ago, separating Greenland and Scandinavia, opening and deepening the Norwegian and Greenland Seas. The final fragmentation of Eurasia was achieved about 50 m.y. ago with the separation of Greenland and Spitsbergen. Abyssal circulation of North Atlantic Deep Water probably began at this time with the development of the Irminger-Labrador-Norwegian-Greenland Seas. Relatively cold Norwegian Overflow Water entered the North Atlantic for the first time, thus significantly modifying the deep circulation of the Atlantic. At the same time, Antarctic Bottom Water started to seep into the North and Equatorial Atlantic via gaps in the Rio Grande Rise. Deep and bottom circulation was probably active in the eastern basins of the North Atlantic due to the eastward leakage of relatively cool Antarctic bottom water through fracture zones north of the Eocene equator. Cooler surface water inflow into the North Atlantic from the Arctic region during the Paleogene resulted in the development of an arctic faunal province.

Widespread geographic distribution of planktonic and benthonic foraminiferal elements occurred between Tethys-Caribbean-Gulf Coast regions and between the Caribbean-Gulf Coast and northern Europe, attesting to the continued efficacy of the North Equatorial Current and Gulf Stream as agents of faunal dispersion. Part of the Gulf of Mexico gyre flowed into the North Atlantic via the Suwanee Channel (northern Florida) during the Paleocene-Middle Eocene, but flow into the North Atlantic was wholly by way of the Straits of Florida by the end of the Eocene. Subtropical climates extended well into northwestern Europe. Atlantic-Pacific marine connection was maintained via Central America.

Early Oligocene - Late Miocene (35-10 m.y. ago)

Three significant events relative to Atlantic-Tethyan circulation patterns occurred during the Miocene.

1) Separation of the eastern and western Tethys by the junction of Africa and Eurasia in the Early Miocene (*ca.* 18 m.y. ago). The eastern Tethys, constricted by the further rotation of Africa and Arabia relative to Southeast Asia, evolved into the Indian Ocean. The western Tethys continued to maintain open connection with the Atlantic, and faunal interchange between the Tethyan and Caribbean region continued. Flow of warm, salty Mediterranean water into the eastern Atlantic began.

2) Junction of Europe and North Africa at Gibraltar and the generation of the Gibraltar Sill about 15 m.y. ago. This is suggested by the almost complete cessation in faunal interchange between western Tethys and Caribbean regions at this time. Surface circulation was significantly modified to an essentially internal one with unstable currents as the western Tethys became further restricted.

Closure of the Tethyan Seaway excluded the Gulf Stream gyre from its former eastward trans-European route towards the Indo-Pacific region. A shallow inland sea (Paratethys) developed in central and southeastern Europe and retained marginal connections with the shrinking Tethys. The Gulf Stream became a self-contained system. A part of the current was deflected northward to form the North Atlantic Drift . . . The incursion of warm waters into the northeastern Atlantic probably enhanced circulation in the North Atlantic with the extrusion of a greater volume of Arctic waters into the western Atlantic (around the coast of Greenland and the Labrador Sea).

3) In the Late Miocene (10-5 m.y. ago) the western Tethys experienced a drastic drop in sea level concomitant with the widespread deposition of evaporite deposits. The western Tethys was cut off intermittently from communication with the Atlantic Ocean for at least part of the Late Miocene (7-5 m.y. ago). Circulation in the Atlantic remained essentially the same as during the early Neogene, except that the Mediterranean Water ceased to flow into the open Atlantic. At this time bottom circulation appears to have favored high rates of sediment redeposition along the continental margins of the western Atlantic. A warm branch of the Gulf Stream continued to flow along the Newfoundland Coast.

Late Miocene - Recent (10-0 m.y. ago)

Three significant events occurred in the Pliocene which affected the circulation of the Atlantic-Mediterranean region. Because of the proximity of these events to each other and the fact that paleogeographic changes were relatively minor during that interval, only a circulation pattern for the period 3-0 m.y. has been constructed. The three events are enumerated below:

1) Early Pliocene (5 m.y. ago) — A eustatic or world-wide rise in sea level led to transgression of the Atlantic Ocean into the Mediterranean region, establishing the Mediterranean Sea as we know it today. Circulation in the Mediterranean was sluggish and irregular, but greater salinity within the basin relative to the Atlantic resulted in relatively less dense surface inflow from the Atlantic.

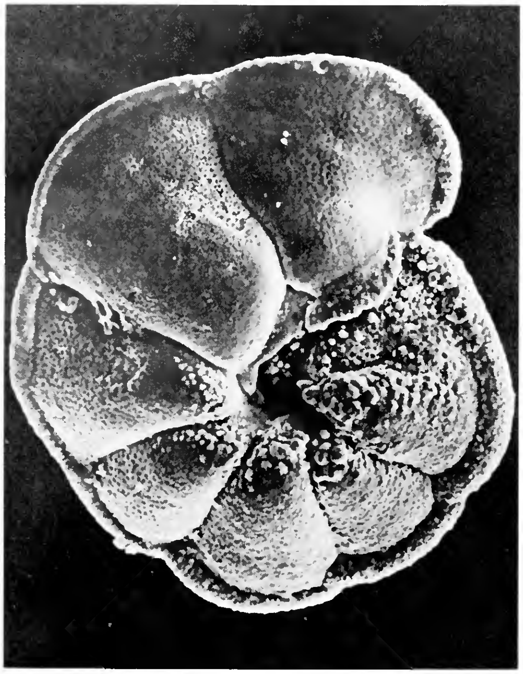
2) Early-Mid-Pliocene — Elevation of the Isthmus of Panama severed the marine connection and faunal interchange between the Atlantic and Pacific oceans. The energy generated in the deflection of the westward-flowing North Equatorial Current probably contributed to a more active Gulf Stream.

3) Mid-Pliocene (3-4 m.y. ago) — Initiation of glaciation in the Northern Hemisphere and formation of the Labrador Current as a significant water mass. The Labrador Current brought subpolar and polar waters southward from Nova Scotia into temperate latitudes (off Newfoundland). The total temperature range of ocean water in the North Atlantic is about 29°C (−1°C to 28°C), but over half that difference may be compressed at any moment into a distance of a few hundred miles, and approximately 0.8°C (30%) into a few thousand meters of the cold wall of the Gulf Stream.

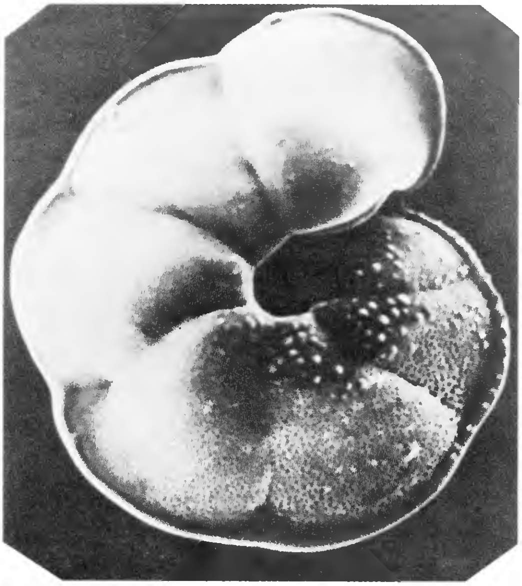
Living planktonic foraminiferal faunas of slope waters are characterized by high standing crops (10,000 - 100,000 specimens per 1,000 m^3) and low diversity. About five species of *Globigerina* (a genus of foraminifera-protozoans having calcarious shells and living close to the surface) and a few other forms are recognizable within this water mass, but northwards the fauna is restricted to a few globigerinids and morphologic differentiation between the forms becomes increasingly difficult.

Although there is evidence of a southward displacement of the temperate faunal province along the coastal margin of the Atlantic Coastal Plain during early-middle Miocene time, the fact that tropical faunas occurred throughout the mid-late Tertiary on the continental shelf and slope off Nova Scotia and were abruptly replaced by subpolar-polar faunas 3 m.y. ago in the Labrador Sea suggests that the Labrador Current was formed at this time. A cool-water current may well have flowed southward around Newfoundland and along the east coast of North America during the Neogene, but the intensification of circulation within the Labrador Sea, caused by the development of glaciation in the Northern Hemisphere, has generated the Labrador Current in its present form.

The Late Pliocene-Pleistocene history of surface circulation in the North Atlantic is essentially one of increasing intensity as a result of climatic deterioration. Although glaciation began in the Northern Hemisphere about 3 m.y. ago, the major cooling — which is probably related to the initiation of intense high-latitude glaciation — occurred between 0.6-0.4 m.y. ago. Over the past 250,000 years the polar front has swept back and forth between lat. 60° and 40°N six times — alternately compressing and expanding the tropical-subtropical belt.



Globorotalia multicamerata



Globorotalia miocenica

The Isthmus of Panama is a recent geological feature. Throughout most of the last 100 million years, the Atlantic and Pacific Oceans have been connected by way of the Panama Straits. The Isthmus rose above sea level during the Pliocene Epoch, about 3.5 million years ago, allowing the long separated mammalian faunas of North and South America to migrate freely. The rather precise estimate of the timing of this event is made possible by the stratigraphic and geographic distribution of the two species of planktonic foraminifera shown here, Globorotalia miocenica *Palmer and* Globorotalia multicamerata *Cushman and Jarvis.* G. multicamerata *evolved about 4.5 to 5.0 million years ago and is found in deep-sea sediments of both the Atlantic and Pacific Ocean.* G. miocenica *evolved in the Atlantic Ocean about 3.5 million years ago; it is not found in deep sea sediments of the Pacific Ocean. Most tropical species of planktonic foraminifera prior to this time enjoyed a circumequatorial distribution because of the connection between the Atlantic and Pacific Oceans. The restriction of* G. miocenica *to the Atlantic Ocean indicates that the Isthmus of Panama became an effective barrier to interoceanic distribution sometime between 4.5 and 3.5 million years ago.*

DEPTH & AGE IN THE SOUTH ATLANTIC

John G. Sclater

and Daniel P. McKenzie

In the theory of plate tectonics, the earth is thought of as a set of rigid plates in constant interaction. These interactions give rise to earthquakes, which in turn define the boundaries of the plates. This theory has had great success in explaining the major features of the ocean floor. The active mid-ocean ridges are places where oceanic crust is formed and plates created by the injection of molten magma. The deep sea trenches on the other hand mark the regions where crust is destroyed as the plate descends into the mantle. Finally, the deep, seismically active gashes in the topography known as transform faults, which offset sections of the ridge axis, are regions along which two plates slide past each other.

The major continuous topographic feature in the deep sea is the world-encircling system of mid-ocean ridges. In the plate theory, these ridges are created by the intrusion of molten magma which cools, solidifies and contracts as it moves away from the zone of intrusion. The mean depth below sea level of oceanic crust of a given age (determined from distinctive magnetic anomalies, see p. 21) agrees remarkably well with the depth predicted by models based on this simple intrusion and cooling process. Figure 1 shows mean depth from all the major deep basins except the North Atlantic plotted against age and distinctive anomaly number. The points group so closely and the theoretical (dashed line) agrees so well with the empirical (heavy line) that if the age of the oceanic crust is known, the depth can be predicted. Similarly, if one knows the complete tectonic history of the basins on either side of the ridge, one can determine the past bathymetry of the ocean.

As an example of how to construct quantitative paleobathymetric charts, we have chosen the South Atlantic. Once the charts are constructed, we will discuss briefly the effect the paleobathymetry has on the past history of both deep-water current systems and sedimentary processes.

The fit of Africa and South America is evidence that no significant internal deformation of either continental margin has taken place. Note, for example, how closely the present-day quakes overlap the continental coastline in Figure 2. Thus, the continents have behaved as rigid plates since their opening and also have spread symmetrically about the spreading centers.

J. G. Sclater is an associate professor of oceanography and marine geophysics at the Massachusetts Institute of Technology. D. P. McKenzie is a senior assistant in research in the department of geodesy and geophysics at Cambridge University. Both received their degrees at Cambridge and for a short time worked together at Scripps Institution of Oceanography.

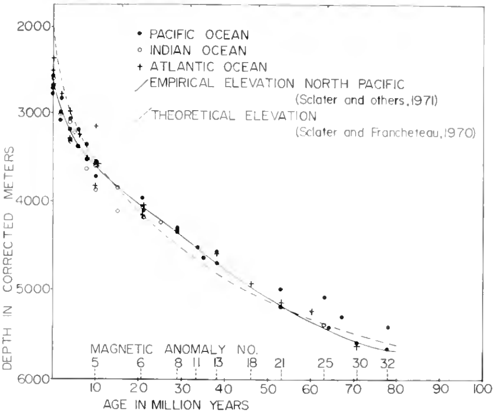
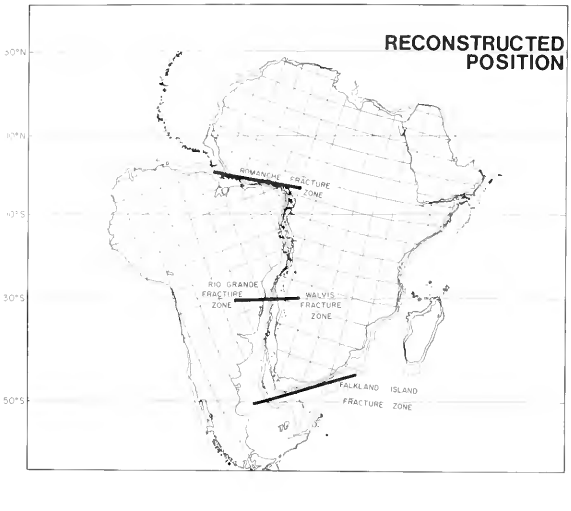


Figure 1: Depth-versus-age plot for the Pacific, Atlantic, and Indian Ocean data (after Sclater and others, 1971).

From Euler's theorem for motions on a sphere, the relative motion of two rigid plates can be represented by a rotation about an axis which passes through the center of the earth and intersects the earth's surface at a point called a pole of rotation. If ω is the angular separation rate of one continent or plate with respect to the other, the position of the first can be found by rotating it through an angle ω T, where T is the time since opening began. Assuming spreading has been symmetrical and has added crust to both plates at the same rate, then the ridge is midway between the broken edges or $\omega T/2$ from both. The positions of magnetic lineations or oceanic crust t years old can also be found since they must be at an angular distance $\omega t/2$ on either side of the present ridge axis. Since the depth of the ocean depends upon t (the time variable) alone, the depth contours must also be at an angular distance ω t/2 each side of the ridge axis. The depth-versus-age curve shows that the ages of the sea floor 3, 4 and 5 km deep are 2, 20 and 50 million years respectively. Therefore, the position of these contours can be found by rotating the ridge axis through the appropriate angles.

In practice there are three difficulties: (1) the position of the ridge axis is often not known with great certainty; (2) the poles of relative rotation do not remain fixed to the plates for long periods of time; and (3) the floors of the ocean do not everywhere slope away from the ridge axis at the predicted shallow angle. All oceans are crossed by at least one basically aseismic volcanic chain (e.g., the Hawaiian chain in the Pacific; the Ninetyeast Ridge in the Indian ocean; and in the South Atlantic, the Walvis and Rio Grande Rises). To resolve the first problem we have assumed that the position of the ridge axis is marked by active seismic epicenters. To cover the second problem we have taken the time of opening as late Jurassic-early Cretaceous (about 130 m.y. ago) and used the pole given by the initial fracture zones, Romanche, Rio Grande and Falkland Islands (Figure 2) back to 80 m.y. ago. From that time until the present, we used the pole from the magnetic lineations and existing transform faults. The third problem is the most difficult to resolve, since both the origin and history of most of the volcanic ridges is still not known for certain. However, in the South Atlantic, from the drilling results on leg 3 of the JOIDES (Joint Oceanographic Institutions for Deep Earth Sampling) program we know the past history of the Rio Grande Rise, and from information brought up by dredging we can speculate upon the past history of the Walvis Rise. The bulk of both ridges was formed during the late Cretaceous close to sea level and has sunk with the oceanic plate to which they are attached. We do not know the origin of these aseismic ridges; but if we know their history, the accuracy of the reconstructions is not affected.

Figure 2: Reconstruction of Africa and South America (after Bullard and others, 1965). Note how well the earthquake epicenters (black dots) overlie the line of the original break between the continents apart from area either side of the Walvis and Rio Grande fracture zones (after McKenzie and Sclater, 1971). The paleolatitude was determined from the Early Cretaceous pole of South America given by McElhinny (1970).



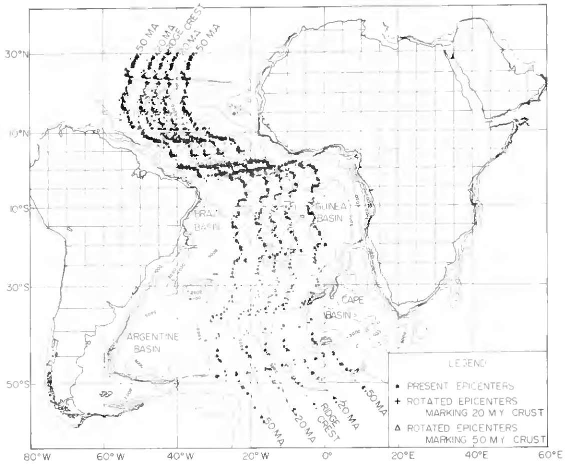


Figure 3: Comparison of earthquake epicenters rotated through various angles about the pole of opening of Le Pichon and Hayes (1971) and the topographic chart of the South Atlantic of Uchupi (1971). The rotated epicenters mark the theoretical 4- and 5-km contours.

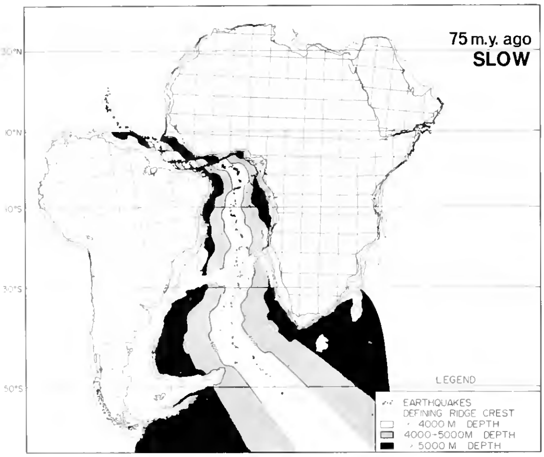


Figure 4: Reconstruction of the physiography of the South Atlantic (75 m.y. ago; slow spreading).

As a test of the model, the present-day theoretical bathymetry for the South Atlantic was computed by rotating the rise crest, as delineated by its earthquakes, about the present pole of opening to give the 4 km and 5 km depth contour. As shown in Figure 3, there is good agreement between the theoretical contours (symbols) and the observed contours (continuous line). This is especially so between 20°N and the Walvis and Rio Grande Rises at 30°S. South of these two rises the predicted 4 and 5 km isobaths are 200 to 300 km further from the ridge axis than the actual contours. This difference is not significant when the present overall accuracy of the reconstructions is considered. It is not known whether it represents inadequate topographic data, excessive sediment deposition or a real difference. However, whatever the reason, the difference can be considered small. In general, apart from the aseismic Walvis and Rio Grande Rises, there is excellent agreement between the computed and observed data.

To consider the reconstructions of the paleobathymetry of the South Atlantic, it is more convenient to start from the initial reconstructed position of the continents and work forward in time. Emphasis will be placed upon the 4000-meter contour, as this is close to the depth of the Antarctic bottom water in the southwest Atlantic. This water mass is thought to dominate present deep-water sedimentary processes in the ocean.

From the time of original opening (Figure 2) until 75 m.y. ago (Figure 4) three very striking features emerge. First, the continental coastlines of Brazil and Africa and the Falkland Island zone separate the South Atlantic from other deep ocean water both to the north and south during the initial stages of opening (Figure 2). Second, as opening continues and the subsidence from the ridge axis becomes noticeable, the active ridge axis plus the aseismic Walvis and Rio Grande Rises separate the South Atlantic into four distinct basins (the Brazil, Guinea, Argentine and Cape) separated from each other at least at the 4000-meter depth level (Figure 4). Finally, the Falkland Island plateau closes the Argentine basin at least until the end of the Cretaceous, probably damming the northward flow of deep water into the Argentine basin before this time.

Between 75 m.y. ago (the late Cretaceous) and 35 m.y. ago (the early Oligocene) major changes occur in the morphology of the South Atlantic (Figure 5). The Brazil and Guinea basins become open to the north at the 4000-m level. At the same level, the Argentine and Brazil basins become connected through the Vema gap. To the south the Falkland scarp no longer acts as a barrier at the 4000-m level. The extreme relief of the Falkland Island fracture zone, which connects the scarp to the active ridge axis, now becomes the barrier, and gaps in this fracture zone control the penetration of deep water to the north. The Walvis Rise probably still remains a major topographic barrier. The Romanche and *Chain* [named for the Institution's R.V. *Chain:* Ed] fracture zones were probably active by this time and provided channels at depths greater than 4000 meters through which water could flow from the Brazil into the Guinea Basin. Thus, by 35 m.y. ago most of the features of the present South Atlantic were formed. Since then there has been little change in the morphology of the ocean basin.

Having demonstrated how paleobathymetric charts can be constructed, it is appropriate to discuss their implications for past and present sedimentary processes. The bathymetry affects these processes in three interlocking ways. First, let us consider the deposition of calcareous sediments, which consist largely of the remains of organisms which concentrate calcium carbonate. These sediments dominate in waters above the Antarctic bottom water. At depths greater than this boundary, the seawater dissolves the carbonate faster than it is precipitated. This depth is called the calcium carbonate compensation level. Thus, as the sea floor is created at a ridge crest close to 2700 meters, calcium carbonate is deposited. As the crust gets older, it moves away from the crest of the ridge and sinks by contraction. At a certain point it passes through the carbonate compensation level, and no more carbonate is deposited.

The second major effect is upon terrigenous sediments deposited by turbidity currents. These sediments have come directly from the continents by slumping down the slopes, producing turbidity currents which spread sand and silt over the abyssal plains. The bathymetry of the ridge affects these processes by acting as a topographic barrier. For example, it is the Mid-Atlantic Ridge which prevents sediments from the Argentine basin from penetrating eastward into the Cape basin.

The third way in which paleobathymetry affects sedimentation is more complex and subtle, as it affects both terrigenous and calcareous sedimentation. We have shown that the bathymetry of the South Atlantic essentially determines the time at which the pronounced topographic gaps (such as the Vema gap) in the western basin drop below 4000 meters. These gaps would have influence over a deep-water western boundary current taking dense saline Antarctic bottom water from the south northward. This water has a different chemistry from the water to the north; thus, it affects the chemical composition of the basins into which it flows and hence their carbonate compensation level. These currents are also strong; they stir up the light clay, silt and sand particles, forming a nepheloid or turbid layer. In the South Atlantic, they pick up sediments from the Argentine basin, take them through the Vema gap and redeposit them in the Brazil basin to the north.

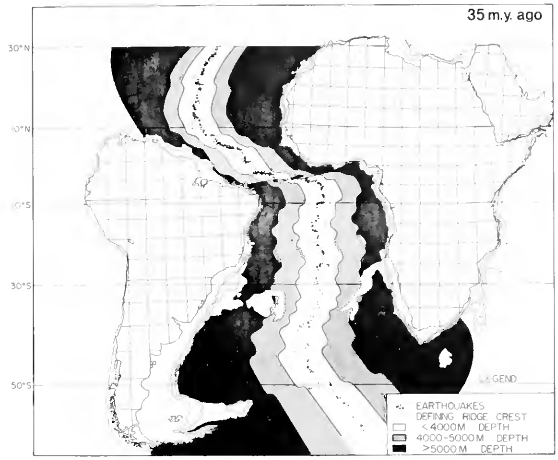


Figure 5: Reconstruction of the physiography of the South Atlantic (35 m.y. ago). The black dots represent the ridge crest.

Though the effects of the paleobathymetry on the sediment processes are major, our interpretation of them is limited by the state of our knowledge of the relationship between depth and age of the oceanic crust and the tectonic history of the basins. A correlation between changes in sedimentary regimes predicted by paleobathymetric charts and those observed in the sediment record would go a long way to increasing our quantitative understanding of sedimentary processes.

THE SEA AS ALCHEMIST

John B. Corliss

The discovery of sea-floor spreading and the subsequent development of plate tectonic theory has brought about a far reaching revolution within the geological sciences. One aspect of this revolution is a reexamination of theories regarding the origin and distribution of metalliferous ore deposits on land. A clarification of the relationship between metallogenesis and plate tectonics is the principal goal of the Nazca Plate Project, a study of ore-forming processes related to the creation of the Nazca lithospheric plate at the East Pacific Rise and its destruction by subduction beneath the South American continent along the Peru-Chile Trench.

An exciting feature of this work from an oceanographer's point of view is the possibility that seawater plays a fundamental role in the formation of a wide variety of economically valuable concentrations of metallic elements. This suggestion has evolved from a series of seemingly unrelated geochemical and geophysical observations of phenomena in the deep sea — such as the patterns of distribution of chemical elements and isotopes in certain rocks dredged from the sea floor; the nature of an unusual metalliferous basal sediment layer repeatedly cored by the Deep Sea Drilling Project (DSDP); patterns of heat flow over spreading centers; anomalous profiles of suspended matter and dissolved gases in vertical profiles in the oceans; and observations of submarine hot springs on a submerged volcano in Indonesia.

The growth of the plate tectonic theory is largely responsible for the recognition that processes which fractionate and concentrate metal in the deep-sea environment have implications for the formation of ore deposits on land. It is increasingly evident that the distribution patterns of important types of ore deposits on land can be related both in space and time to the distribution of convergent and divergent plate boundaries. We shall first examine the evidence that seawater serves as a medium for extracting and transporting metals initially disseminated in rocks and then look at evidence that this process leads to the formation of ore deposits exposed on the continents.

In the last decade or so, the suggestion that hot, salty waters can serve as metal-bearing "hydrothermal" solutions has grown from two important observations. First, exhaustive studies of microscopic amounts of trapped fluids found in crystals deposited by ore-forming solutions showed that these fluids were predominantly chloride brines. Additional research revealed that the only reasonable method by which the required large concentrations of metals could be transported in aqueous solution would involve their being held in solution through formation of soluble, complex ions with chloride. This notion is winning out over the idea that the metals are transported as various complexes with sulfur, a theory of long standing based on the

J. B. Corliss is an assistant professor of oceanography at Oregon State University. He received his Ph.D. from Scripps Institution of Oceanography.

fact that the metals in ore deposits commonly occur as sulfides. A liter of seawater contains over 30 grams of chloride salts as well as nearly one gram of sulfur, present in its oxidized soluble form as sulfate. These qualities make seawater an ideal metal-bearing solution in sulfide ore deposits formed by hydrothermal processes.

As the name implies, such ore deposits also require a source of heat as well as of metals, and this is where the processes of plate tectonics are crucial. One such process important for ore formation is submarine volcanism. This occurs primarily along divergent plate boundaries — the mid-ocean ridges; evidence of it has also been found near convergent plate boundaries — behind island arcs and along trench walls.

A model for the interaction of seawater with newly formed crustal rocks is illustrated in Figure 1. According to this model, the newly erupted basalt contracts as it cools, and submarine ground water, seawater, penetrates into the resulting fractures.

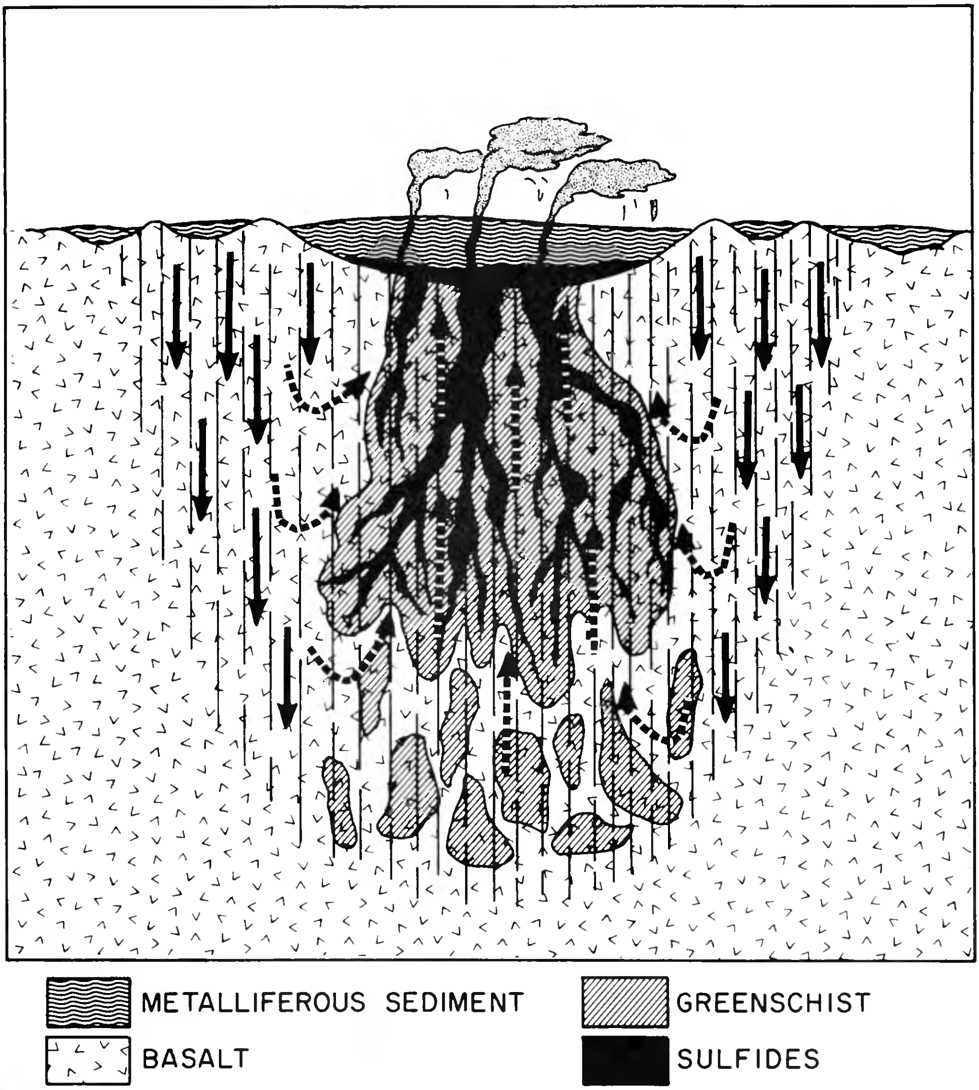


Figure 1: Model of a seawater - basalt hydrothermal system. Seawater permeating hot fractured basaltic crust leaches metals from the rock, altering it to greenschist at depth. The resulting hot solutions are carried toward the surface by corrective flow, precipitating sulfides as they cool. When the fluids enter seawater, the remaining metals are precipitated as finely dispersed oxides.

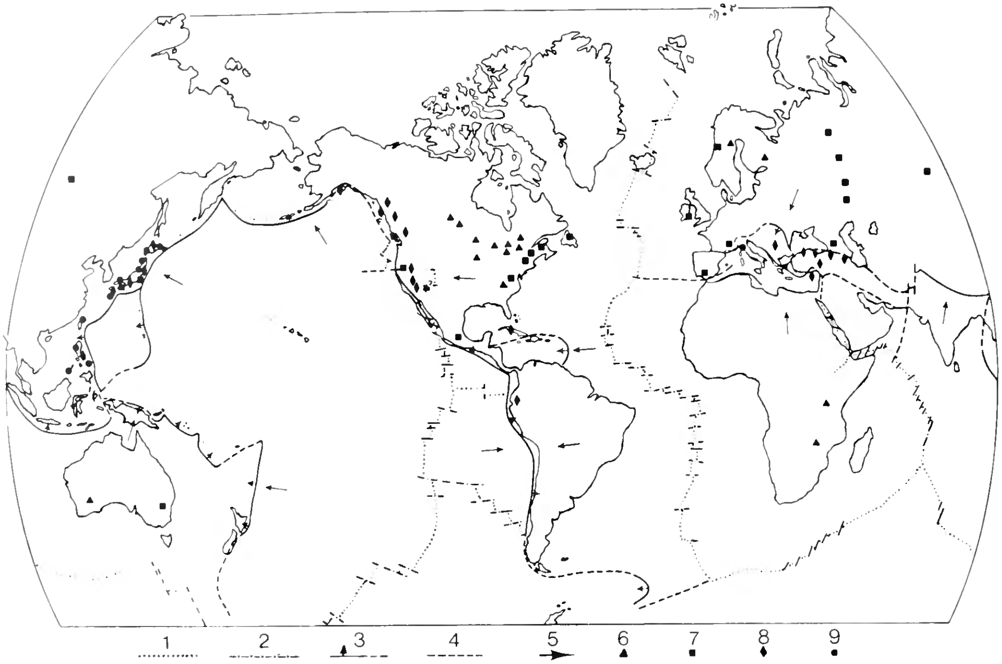


Figure 2: Stratabound massive sulfide deposits with volcanic affinities. 1) Accreting plate margin; 2) transform plate margin; 3) consuming plate margin with dip direction of downgoing plate; 4) margin of uncertain nature and (or) location; 5) relative plate motion; 6) Precambrian deposit; 7) Paleozoic deposit; 8) Mesozoic deposit; 9) Cenozoic deposit.

These fissures extend to some depth, as can be readily observed in volcanic piles on land. The net result is an extensive hydrothermal circulation system driven by density gradients caused by heating of the water at depth.

Most of the metals of economic interest are in the last minerals to crystallize in the slowly cooling lavas. These minerals occupy grain boundaries in the rocks and thus are accessible to leaching by the circulating, heated seawater through the formation of soluble chloride complexes. The model suggests that this interaction of seawater and basalt leads, at shallow depth, to simple leaching of rocks with little apparent alteration of the major mineral phases. At somewhat greater depths and higher temperatures, the interaction leads to alteration of major mineral phases and conversion of the basaltic rocks to greenschists. During such alteration, considerable iron is leached from the rocks along with lesser amounts of manganese, copper, nickel, lead, cobalt, and other metals. The remaining iron is extensively oxidized from its initial reduced state in the magma. This oxidation is coupled with a reduction of the sulfate in seawater which initiates the precipitation of the metals from solution as sulfides. The solutions rise and are vented into seawater as submarine hot springs. A reddish-brown precipitate of iron hydroxide then forms, incorporating other metals in the hydrothermal solutions and scavenging elements from the overlying seawater. Most of the precipitate settles, forming a layer of metalliferous sediment around the vent. Some fraction may be more widely dispersed into the seawater and remain in suspension to be introduced into the blanket of pelagic muds over broad areas, diluted by other components of the sediments.

This model, it must be said, is speculative and somewhat controversial, but the hypothesis serves a useful purpose in suggesting critical observations to test the model. There is, of course, considerable evidence that such seawater hydrothermal systems exist:

(1) Observations of dredged basalts from the Mid-Atlantic Ridge show that rapidly quenched, glassy pillow basalts must represent the composition of the erupted magma. This is suggested by the observation that these basalts still contain the helium and argon generated in the mantle by radioactive decay of uranium, thorium, and potassium and dissolved in the magma. On the other hand, the *slowly* cooled rocks from some depth within the flows have been depleted of rare gases, sulfur, and significant amounts of iron and other metals.

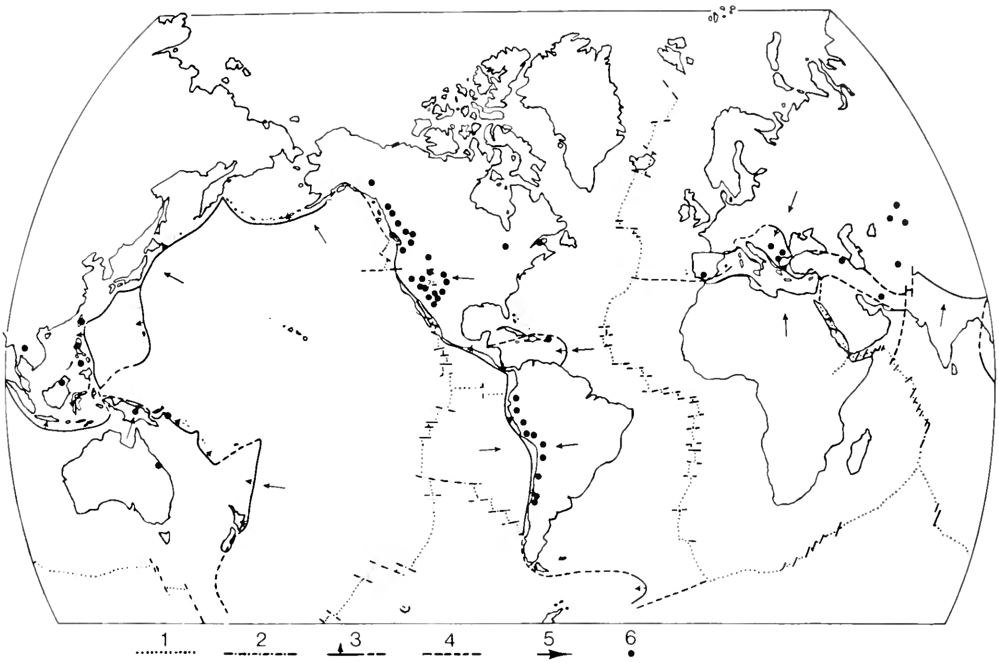


Figure :3: Porphyry deposits. 1) Accreting plate margin; 2) transform plate margin; 3) consuming plate margin with dip direction of downgoing plate; 4) margin of uncertain nature and (or) location; 5) relative plate motion; 6) porphyry deposit.

(2) The water content of glassy pillows is very low, below the amount which would dissolve in a basaltic melt at equilibrium. This suggests that no separate aqueous phase accompanied the melt during its ascent from the mantle. If hydrothermal "emanations" are produced at spreading centers, the water involved must be seawater.

(3) The distribution of oxygen isotopes in greenschist and serpentine from the Mid-Atlantic Ridge have been studied in some detail; the greenschists by Karlis Muehlenbachs and Robert Clayton at Chicago and the serpentines by David Wenner and Hugh Taylor at California Institute of Technology. The data suggest that these rocks form by metamorphism of basalt and more deep-seated rocks in the presence of circulating seawater at temperatures of 200° to 300°C. The data are incompatible with an explanation invoking juvenile magmatic water as a metamorphic fluid.

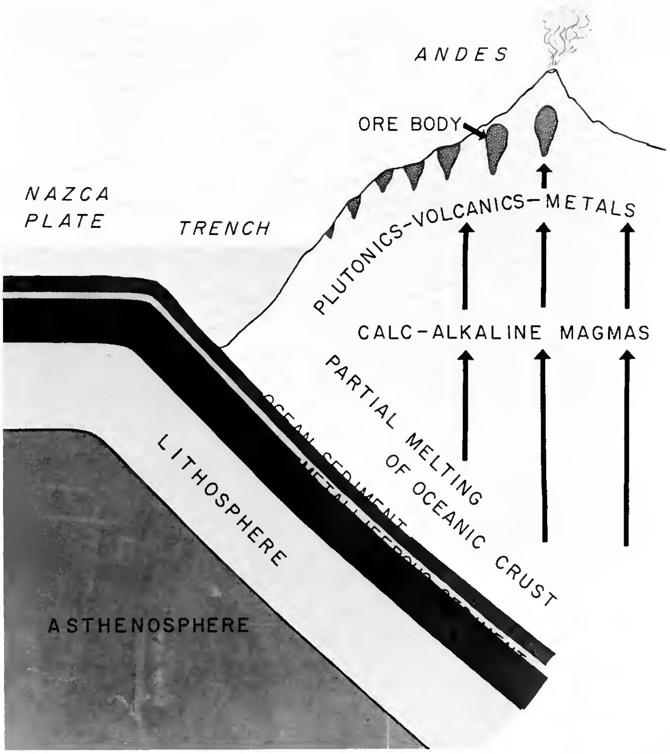
(4) The isotopic composition of the lead in metalliferous sediments from the East Pacific Rise has been shown by Julius Dasch at Oregon State to be identical to that of lead in the underlying basalts and quite distinct from that found in normal deep-sea sediments or material eroded from the continents.

(5) Anomalously low heat-flow values near spreading centers have been found and are attributed to the effect of seawater circulation transporting heat out of the crust (see p. 8). This removal of some heat by convection reduces the amount of heat released by conduction, which is the component determined by heat flow measurements.

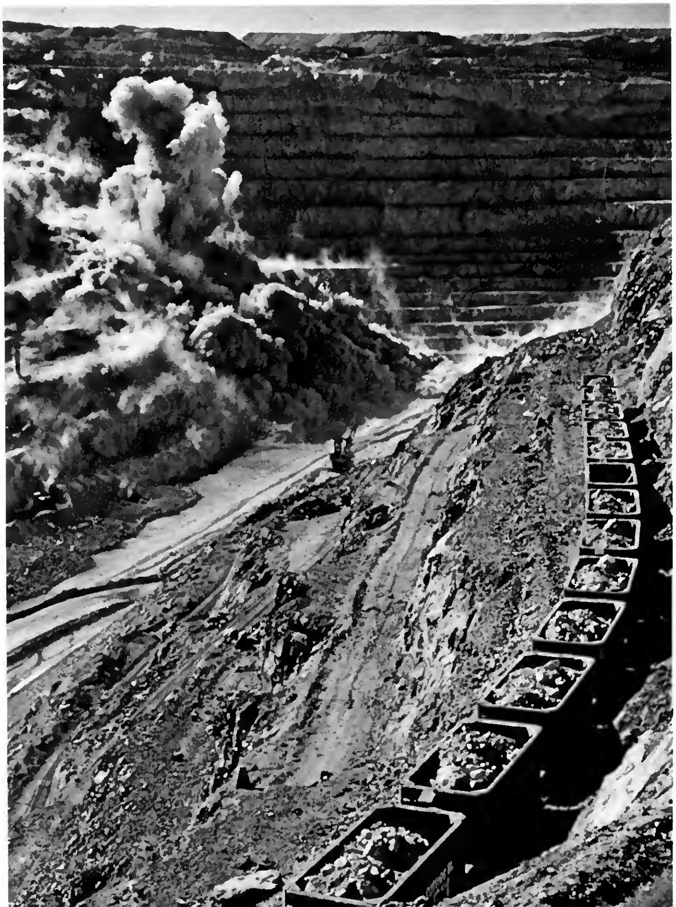
(6) Vertical profiles of particulate iron and manganese and dissolved He^3 (a helium isotope) show maxima of these components in mid-waters. Hydrothermal vents on mid-ocean ridges constitute one possible source of the iron and manganese and the only feasible source of the associated He^3 anomaly.

(7) Actual submarine hot springs producing metalliferous sediment were observed in 1963 by a Russian scientist, K. K. Zelenov, on the submarine volcano Banu Wuhu in Indonesia. Zelenov concentrated his work on the site of a 1919 eruption, a submarine bank of dacite-andesite that ranged in depth from sea level to about 30 meters. Jets of hot water streamed from the bank. Their composition was similar to that of seawater with added iron, manganese, and silicon. "Suspended iron and manganese hydroxides can be seen precipitating right under the water", wrote Zelenov. "The rising jet

Figure 4: Model of ore-forming processes at a subduction zone. Melting occurs within the upper oceanic crustal plate where any subducted sediment and related melting concentrations are readily mobilized and transported by seawater, both in the sediments and the rocks.



Fruits of seafloor alchemy: Chuquicamata copper mine in Chile. ©*Bruno Barbey Magnum.*



starts becoming yellow and turbid about one meter above the bottom." On cooling, these jets precipitated 100 to 140 milligrams per liter of iron and manganese hydroxides. Brown iron-manganese-silica sediment rich in trace metals covered the sea floor around these vents and was also carried away from the area by the current.

One aspect of the seawater hydrothermal systems model not clarified by marine research is the formation and deposition of sulfides. The best evidence for this process is found in sulfide deposits on land, and we are thus led to look at evidence which suggests that submarine metallogenic processes can result in formation of ore deposits that are eventually exposed on the continents. The clues are found in the ore deposits themselves and in their relationship to their geological surroundings. Two economically important classes of ore deposits — massive stratiform sulfide concentrations with volcanic affinities and porphyry ore bodies — can serve as illustrations here.

The origin of massive stratiform sulfide deposits in island-arc environments is attested to by a number of signposts, including the nature of the sediments in which the deposits are found and the chemistry of the associated volcanic rocks. But perhaps most striking is the good correlation between the distribution of younger massive sulfide deposits and present-day convergent plate margins (Figure 2). Paleozoic, Mesozoic, and Cenozoic deposits occur in close association with the oceanic plate margins in island-arc environments of the Pacific. The older deposits can largely be related to contemporary convergent plate margins, with the exception of the Pre-Cambrian deposits of the Canadian shield. Some suggestion of environments similar to the island arc exists for these deposits, but no clear-cut evidence for plate motions has been found.

There is yet another important link between deposits which form typically in a near-shore environment, and our model for seawater hydrothermal systems. The connection is found in the massive stratiform sulfide bodies of the Troodos Massif on Cyprus, a section of uplifted oceanic crustal rocks and sediment. These ore bodies are typical of the class, with one exception: they formed in deep water, probably at a mid-ocean ridge spreading center, and are overlain by normal pelagic sediments. They have been mined for over 2000 years. In cross-section, they look much like the model of a hydrothermal system shown in this paper. The importance of these Cyprus ore bodies is that they present very strong evidence that the circulation of seawater through newly erupted volcanic rocks can indeed give rise to economically valuable massive stratiform sulfide ore bodies.

We can thus hypothesize that submarine volcanism in a variety of environments can lead to the formation of massive sulfide bodies. Those in the island-arc environment related to inter-arc basin volcanism have a reasonable chance of being preserved. Those formed at mid-ocean ridge spreading centers are liable to be subducted and disappear.

This last notion leads us to consider ore bodies closely related to zones of subduction of oceanic crust — deposits of porphyry and particularly of porphyry copper. Porphyry deposits are remarkably uniform. They form in the upper portions of large, slowly-cooling igneous intrusions which accompany the extensive volcanism overlying the subduction zone. The map in Figure 3 shows their close association with subduction zones and their occurrence along simple ocean-ocean joins and ocean-continent joins of varying complexity. Both the association and the uniformity suggests that the deposits have a common origin with the metals, ore-bearing fluids and associated magmas in that all derive from the subduction zones (Figure 4).

The water added to the upper oceanic crust during hydrothermal activity causes this portion of the subducted plate to melt first. Hydrothermal activity presumably has also fractionated metals into this portion of the oceanic crust as metalliferous sediments and perhaps as massive sulfide bodies. In addition, considerable chlorine has been added. When melting occurs, the water, chlorine and metals dissolve in the magma and are transported upward as a single liquid phase. In that portion of the magma which cools slowly beneath the surface, crystallization increases the water content of the residual liquid until an aqueous fluid separates. The chlorine and metals will fractionate into this fluid dissolved as chloride complexes. The fluid is then capable of transporting and depositing the metals to form ore bodies.

As has been pointed out before, the models are speculative, and will be revised as our knowledge progresses. But it appears certain that seawater will play a fundamental role in models which relate the origin of ore deposits to plate tectonics.

Atlantic Ocean Floor map: "©1973 National Geographic Society".

The Atlantic Ocean floor, as well as the other ocean-floor panoramas produced by the National Geographic Society, are based on the detailed studies of Marie Tharp and the author of this article and are painted by H.C. Berann.

MAPPING THE SEA FLOOR

Bruce C. Heezen

In the 1950's and early 1960's, a great revolution occurred in the earth sciences. It was a revolution in the manner of thinking about the earth, one that produced a view of our planet as a constantly changing body — the continents, like icebergs in a sea, moving through circuits of evolution and destruction.

The idea of continental movement, of sea-floor creation and destruction, was clearly stated sixty years ago. For some time thereafter, however, it was held that the concept could not be taken seriously unless the forces and mechanisms involved could be specified. Despite frequent claims to the contrary in the past decade, these basic processes still evade us. But though we do not know the cause, we have hard data to chart the effects.

Geological maps are a presentation and generalization of raw facts used in conjunction with certain basic principles (such as the uniformitarian principle that physical laws do not change with time) to determine the geological history of the earth. Although reasonably accurate geological maps could be drawn of the continents in the late 19th century, it has been only over the past two decades that maps of the deep sea floor could be even dreamed of, let alone seriously attempted.

On land, the geologist must first ascertain the topography of the area to be studied or mapped. This is done for him nowadays by civil engineers employing aerial photography. The topography is a good indication of the nature and distribution of the rocks and structures and the principal indication of the subsequent erosional and depositional history of the area. The first step then is to establish the basic shapes and then to sample them to establish their composition and to determine their origin.

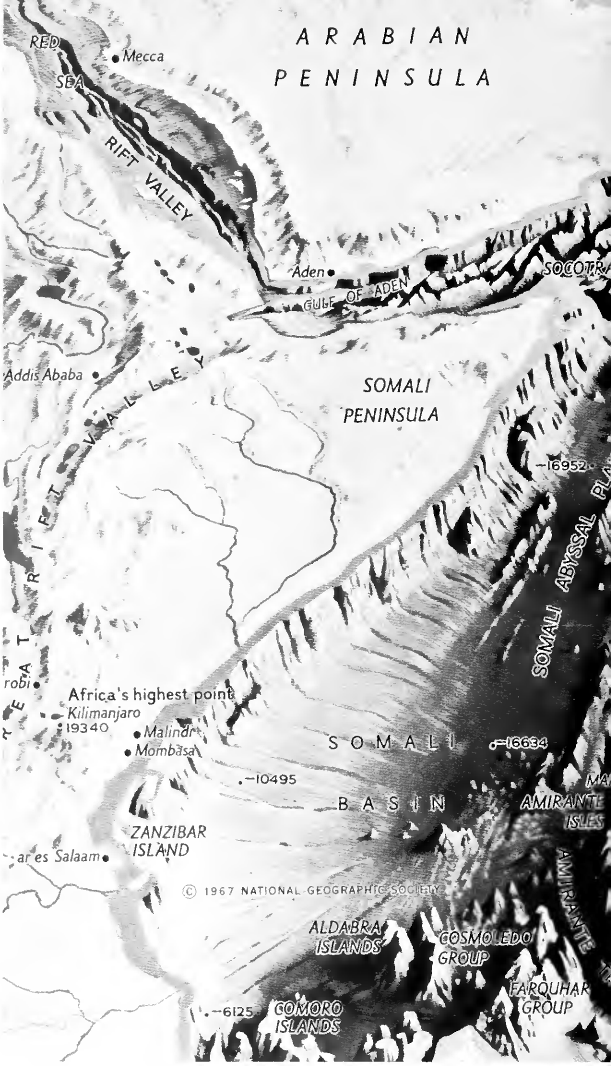
B. C. Heezen is an associate professor of geology at Lamont-Doherty Geological Observatory at Columbia University. Marie Tharp, whom Dr. Heezen cites in his article, is a senior research associate at Columbia University. She and the author have worked for years on the preparation of seafloor maps, including those on these pages, published (originally in color) by the National Geographic Society.

So little was known about the ocean at the turn of the century that the geology of the sea floor provided few clues to the origin and relative mobility of the continents. The presence of some of the largest subsea mountain ranges had been detected by differences in deep-sea water temperatures which suggested barriers, but the form, composition, age or origin of the supposed "ridges" remained a mystery. Since oceanographers could not speculate intelligently on the nature of the topography, they had not even the faintest hint of the geological structure of the sea bed.

This all began to change in a dramatic way once the continuously recording echo sounders installed on many ships during World War II were put to peacetime use in exploring the deep sea floor. By 1952, six continuously recorded echo sounding profiles were assembled for the North Atlantic. It became apparent that the North Atlantic Ocean could be divided into a rough central zone and two smooth zones reaching out from each continental margin. The central barrier to water circulation, known as the Mid-Atlantic Ridge, was found in reality to be a complex mountain range. Extremely smooth abyssal plains were discovered in the basins, and small channels and canyons were found on the continental margins. The small size of the features seen in the smoother portions required the subsequent development of high-resolution, precision echo sounders. These would also be needed to aid in unravelling the complexities of the confusing array of mountains which compose the Mid-Atlantic Ridge, but that would come later.

What was needed in the early 1950's, when Marie Tharp and I set to work on the first of our physiographic diagrams, were useful generalizations drawn from data gained in several years of work aboard the *Atlantis* and other research vessels. We were searching for some theme to guide us in interpreting our results, some focus to help us in planning for subsequent exploration. Since most American scientists at the time held that the oceans were permanent, that drift had not occurred, we were inclined at first to look for other explanations. But the guiding principle eluded us.

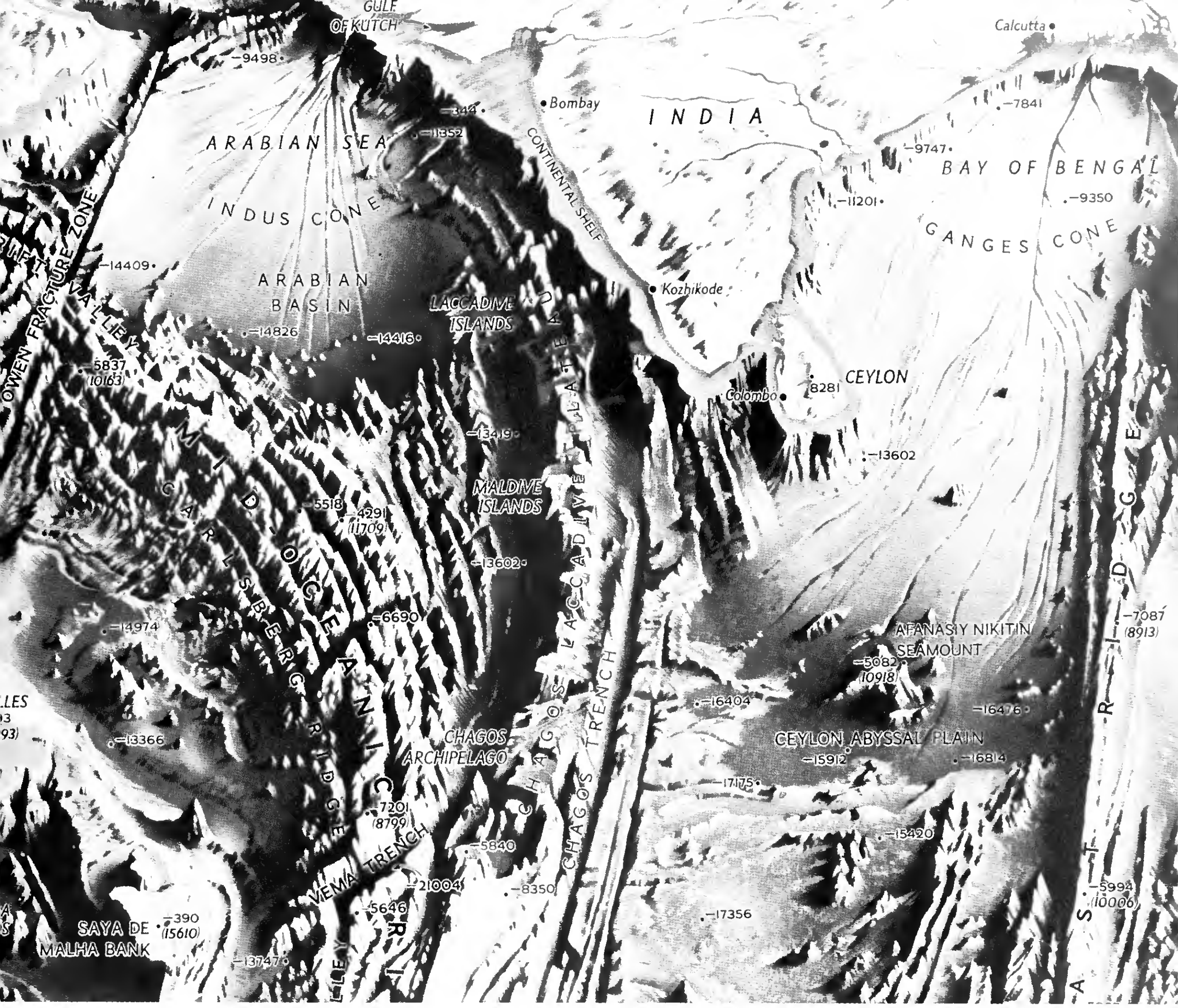
Continental drift was, I suppose, considered an easy way out. It provided a seemingly superficial explanation of not too solid facts. Yet we were struck — as were those who first espoused the drift idea — by the exceptionally good fit of the opposed Atlantic continental margins. The boundary between the abyssal plains and the Mid-Atlantic Ridge was also generally parallel with the margins, as was the axis of the Ridge itself.



Indian Ocean Floor map: "©1967 National Geographic Society".

Miss Tharp and I chose the physiographic style of presentation for two reasons. First, there was not enough information available to permit the construction of meaningful depth contours or isobaths. Second, isobaths derived from echo-sounding profiles received a military security classification in 1952 which remained in effect for a dozen years.

The first step in preparing the diagram was to represent the features already well established, such as the location of the shore lines of continents and islands, the limit of the continental shelf, and the few features such as the New England submarine canyons which had been surveyed in some detail. For most of the study, we turned to an analysis of original echo-sounding profiles, which we used as a basis for our conclusions for the deep sea floor. We identified the abyssal plains and mapped their extent as precisely as permitted by the limited number of sounding profiles.



The panorama of the Indian Ocean floor resulted from the author's study of the early results of the International Indian Ocean Expedition. Original diagram was published by the Geological Society of America in 1964. This revised and simplified panorama, the first of a series, was published in 1967. Bathymetry by B.C. Heezen and Marie Tharp, painted by H.C. Berann. Copyright by National Geographic Society 1967.

At first we were wary of the Mid-Atlantic Ridge. It is so huge and so complex; how were we to define its topographical pattern, structure and origin on the basis of such a small amount of data? Marie Tharp identified a characteristic deep central valley on three of the grand total of six profiles which had been obtained to that date. She hypothesized that a central valley was a characteristic feature of the Ridge and drew it on our manuscript diagram. When we plotted up the earthquake epicenters for the area, we became convinced that the hypothesis was correct and henceforth set about to determine other associated characteristics of the feature in the search for its origin.

The earthquake belt allowed us to trace the feature through unexplored areas, to predict valleys and mountains where no soundings had been taken. It also led us directly to the rift valley of Africa and the conclusion that a tensional rift valley marks the crest of a single Mid-Oceanic Ridge which encircles the globe, extending from the Arctic to the North Pacific via the Atlantic and Indian Oceans.

Our first ocean-floor diagram was of the North Atlantic and was printed in 1956. Our approach brought both praise and scorn. Too little information to substantiate, some said. Pure bunk, said others. Many were dismayed by the new mode of presentation; no snaky isobaths separated by multiple shades of blue.

The principal story told by our representation of the Mid-Atlantic Ridge was that it was both axially

Pacific Ocean Floor map: "©1969 National Geographic Society".

A thick layer of ooze laid down on the Pacific crust as it passed beneath the equator is responsible for the comparative smoothness of the Western Pacific.

symmetrical within the ocean basin and bilaterally symmetrical with respect to an axial, seismically active rift valley. In 1954, we got into hot water with our anti-drift colleagues when we concluded that the rift valley is a steady-state feature of an expanding ocean floor which marks the site of crustal growth. When we prepared the second printing of the North Atlantic diagram in 1957, we had one anguishing concern: we had found that the Mid-Atlantic Ridge is cut by east-west breaks. We had confirmed one at 24° North, but our survey was inadequate to give the exact trend or extent. So, as with geographers of the past, we put the map legend over the perplexing area and turned to the South Atlantic.

Ships sailing from north to south in the equatorial Atlantic had accumulated sufficient numbers of profiles by 1958, so that Marie Tharp was able to map a dozen or more of the east-west breaks in the Ridge which we now know as fracture zones. When our South Atlantic diagram was completed in 1961, we were persuaded by Woods Hole Oceanographic Institution's Brackett Hersey* that we should tackle the Indian Ocean next and help sharpen the objectives of the International Indian Ocean Expedition. This study was perhaps the most exciting of all, for with the principles developed by our previous studies and a flood of recent data, the pattern of the Indian Ocean floor progressed from chaos to modern form in less than three years.

Concurrently, paleomagnetists were finding increasingly convincing evidence that the relative positions of continents had systematically changed with time. Thus in the early 60's, our diagrams were no longer widely ridiculed; our ideas of the continual creation of new crust in the world-encircling Mid-Oceanic Rift Valley were incorporated into modified models of mantle convection. And with our work, so with the work of others: continental drift, after a face lift and a name change to plate tectonics, shifted into the favor of the scientific world.

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*Now Director of the Maury Center for Ocean Science in the Office of Naval Research.

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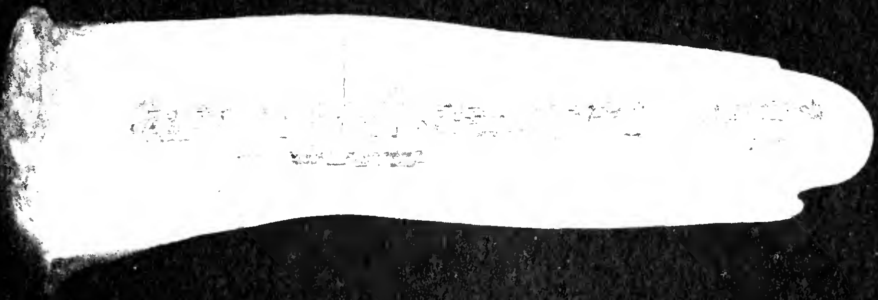
The whaler's art of scrimshaw, as practiced today aboard one of the Institution's research vessels, has produced a handsome engraving of the New Bedford whaling port as it appeared in the mid-19th century. Barrett McLaughlin, chief engineer of the KNORR and nine years a scrimshander, has reproduced part of a handsome Benjamin Russell-Caleb Purrington work. The scene is taken from the initial portion of a gigantic (1,300 by 8½ feet) muslin on which Russell and Purrington painted in watercolors a series of scenes giving a "Panorama of a Whaling Voyage Around the World". A member of a New Bedford whaling family, Russell had sailed on a four-year whaling expedition in 1841, returning with sketches for the panorama. The work is now in the vault of the New Bedford Whaling Museum.



McLaughlin's great grandfather was a scrimshander while serving aboard one of the last whaling vessels out of Edgartown, Martha's Vineyard. He himself got his start in 1964 when invited to dip into a barrel of whales' teeth on a visit to a Russian ship in port in the Azores. With that tooth and instruments he fashioned himself, McLaughlin launched his artistic career. He has engraved a total of about 150 teeth, and this is his second jawbone. Most of his work has been given away. This jawbone will be a prime item in the annual Falmouth, Mass. (McLaughlin's home town), Heart Fund auction in February. Because the sperm whale has been declared an endangered species and any part of its body prohibited from import, scrimshaw is growing more valuable and stocks of good materials for the work are getting slim. The jawbone in question, we hasten to add, is an old one.