CONTINENTAL DRIFT

In 1912 Alfred Wegener proposed that the continents had originated in the breakup of one supercontinent. His idea has not been widely accepted, but new evidence suggests that the principle is correct

by J. Tuzo Wilson

Geology has reconstructed with great success the events that lie behind the present appearance of much of the earth's landscape. It has explained many of the observed features, such as folded mountains, fractures in the crust and marine deposits high on the surface of continents. Unfortunately, when it comes to fundamental processes—those that formed the continents and ocean basins, that set the major periods of mountain-building in motion, that began and ended the ice ages—geology has been less successful. On these questions there is no agreement, in spite of much speculation. The range of opinion divides most sharply between the position that the earth has been rigid throughout its history, with fixed ocean basins and continents, and the idea that the earth is slightly plastic, with the continents slowly drifting over its surface, fracturing and reuniting and perhaps growing in the process. Whereas the first of these ideas has been more widely accepted, interest in continental drift is currently on the rise. In this article I shall explore the reasons why.

The subject is large and full of pitfalls. The reader should be warned that I am not presenting an accepted or even a complete theory but one man's view of fragments of a subject to which many are contributing and about which ideas are rapidly changing and developing. If it is conceded that much of this is speculation, then it should also be added that many of the accepted ideas have in fact been speculations also.

In the past several different theories of continental drift have been advanced and each has been shown to be wrong in some respects. Until it is indisputably established that such movements in the earth's crust are impossible, however, a multitude of theories of continental drift remain to be considered. Although there is only one pattern for fixed continents and a rigid earth, many patterns of continental migration are conceivable.

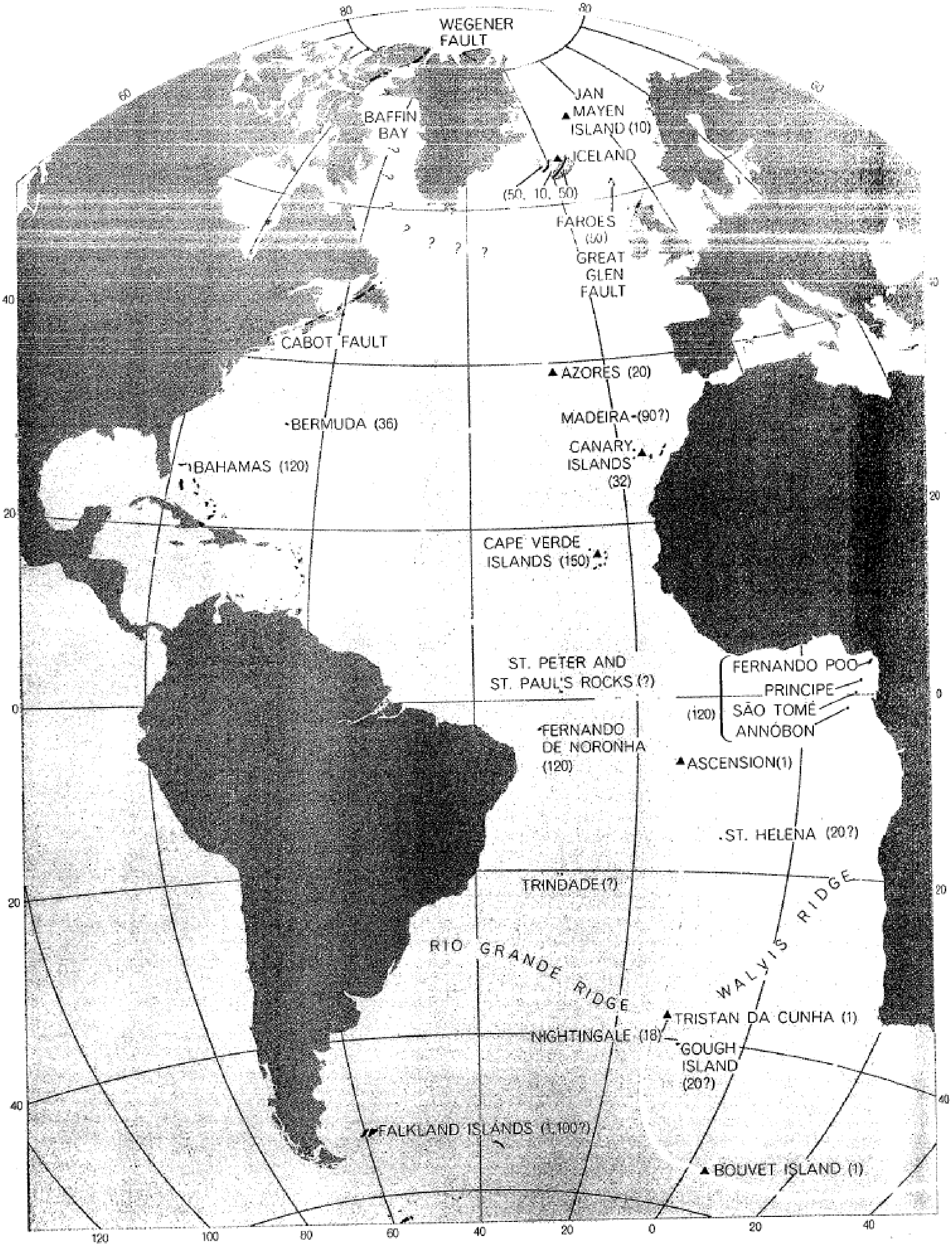
The traditional rigid-earth theory holds that the earth, once hot, is now cooling, that it became rigid at an early date and that the contraction attendant on the cooling process creates compressive forces that, at intervals, squeeze up mountains along the weak margins of continents or in deep basins filled with soft sediments. This view, first suggested by Isaac Newton, was quantitatively established during the 19th century to suit ideas then prevailing. It was found that an initially hot, molten earth would cool to its present temperature in about 100 million years and that, in so doing, its circumference would contract by at least tens and perhaps hundreds of miles. The irregular shape and distribution of continents presented a puzzle but, setting this aside, it was thought that the granitic blocks of the continents had differentiated from the rest of the crustal rock and had frozen in place at the close of the first, fluid chapter of the earth's history. Since then they had been modified *in situ*, without migrating.

This hypothesis, in its essentials, still has many adherents. They include most geologists, with notable exceptions among those who work around the margins of the southern continents. The validity of the underlying physical theory is defended by some physicists. On the other hand, a number of formidable objections have been raised by those who have studied radioactivity, ancient climates, terrestrial magnetism and, most recently, submarine geology. Many biologists have also thought that, although the evolution and migration of later forms of life—particularly since the advent of mammals—could be satisfactorily traced on the existing pattern of continents, the distribution of earlier forms required either land bridges across the oceans—the origin and disappearance of which are difficult to explain—or a different arrangement of the continents.

The discovery of radioactivity altered the original concept of the contraction theory without absolutely invalidating it. In the first place, the age of the earth could be reliably determined from knowledge of the rate at which the unstable isotopes of various elements decay and by measurement of the ratios of daughter to parent isotopes present in the rocks. These studies showed the earth to be much older than had been imagined, perhaps 4.5 billion years old. Dating of the rocks indicated that the continents are zoned and have apparently grown by accretion over the ages. Finally, it was found that the decay of uranium, thorium and one isotope of potassium generates a large but unknown supply of heat that must have slowed, although it did not necessarily stop, the cooling of the earth.

The rigid earth now appeared to be less rigid. It became possible to explain the knowledge, already a century old, that great continental ice sheets had depressed the earth's crust, just as the loads of ice that cover Greenland and Antarctica depress the crust in those regions today. Observation showed that central Scandinavia and northern Canada, which had been covered with glacial ice until it melted 11,000 years ago, were still rising at the rate of about a centimeter a year. Calculations of the viscosity of the interior based on these studies led to the realization that the earth as a whole behaves as though a cool and brittle upper layer, perhaps 100 kilometers thick, rests on a hot and plastic interior. All the large topographical features—continents, ocean basins, mountain ranges and even individual volcanoes—slowly seek a rough hydro-

ROBESON CHANNEL separating northwestern Greenland (*upper right*) from Ellesmere Island (*foreground*) marks the Wegener Fault. The latter was named by the author for the German meteorologist who 50 years ago predicted the existence of such a fault and of a great lateral displacement along the length of the channel. Not yet fully mapped, it probably joins a known fault farther southwest.



AGE OF ATLANTIC ISLANDS, as indicated by the age of the oldest rocks found on them, apparently tends to increase with increasing distance from the Mid-Atlantic Ridge. The numbers associated with the islands give these ages in millions of years. Geologists divide Iceland into three areas of different ages, the central one being the youngest. The Rio Grande and Walvis ridges are lateral ridges that may have formed as a result of the drifting apart of Africa and South America. Other lateral ridges along the Mid-Atlantic Ridge are also represented. Islands that have active volcanoes are represented by black triangles; most of these islands lie on or near the Mid-Atlantic Ridge. The extension of the ridge into Baffin Bay is postulated. Broken colored lines are faults.

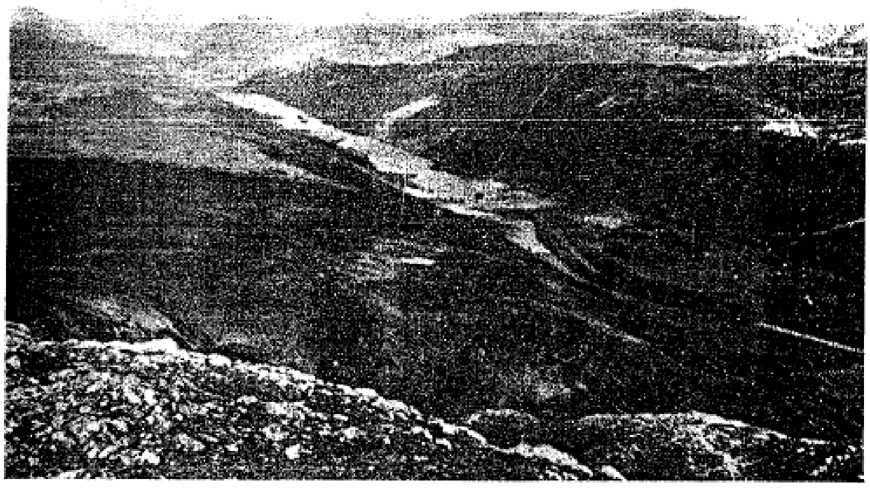
static equilibrium with one another on the exterior. Precise local measurements of gravity showed that the reason some features remain higher than others is that they have deeper, lighter roots than those that are low. The continents were seen to float like great tabular icebergs on a frozen sea.

Everyone could agree that in response to vertical forces the outer crustal layer moved up and down, causing flow in the interior. The crux of the argument between the proponents of fixed and of drifting continents became the question of whether the outer crust must remain rigid under horizontal forces or whether it could respond to such forces by slow lateral movements.

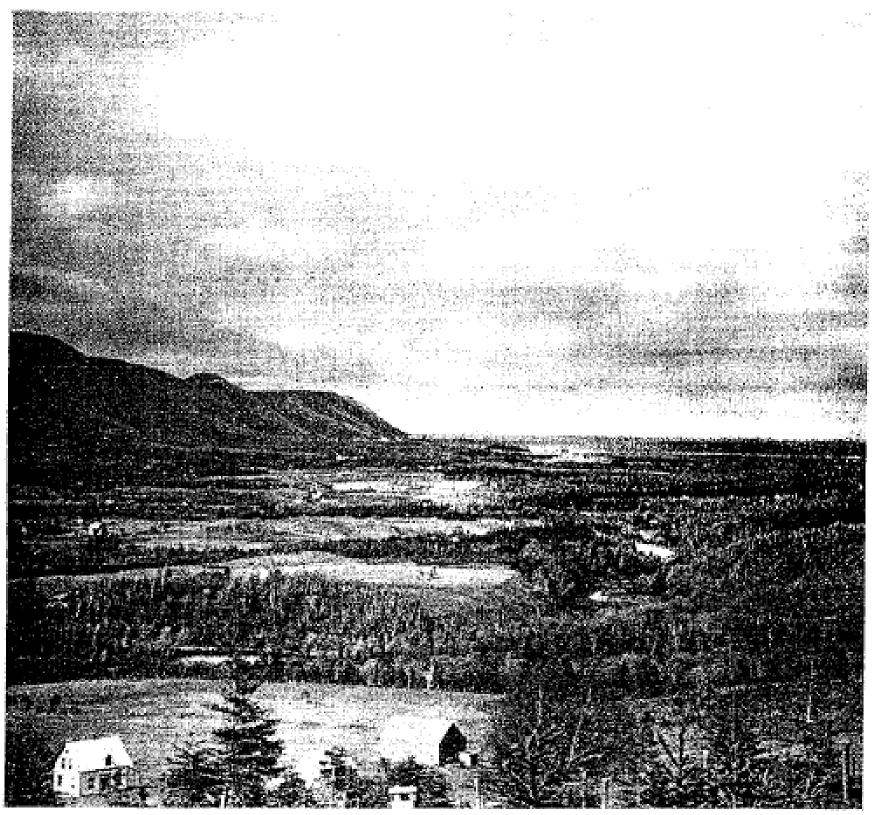
Gondwanaland and "Pangaea"

Suggestions that the continents might have moved had been advanced on various grounds for centuries. The remarkable jigsaw-puzzle fit of the Atlantic coasts of Africa and South America provoked the imagination of explorers almost as soon as the continental outlines appeared opposite each other on the world map. In the late 19th century geologists of the Southern Hemisphere were moved to push the continents of that hemisphere together in one or another combination in order to explain the parallel formations they found, and by the turn of the century the Austrian geologist Eduard Suess had reassembled them all in a single giant land mass that he called Gondwanaland (after Gondwana, a key geological province in east central India).

The first comprehensive theory of continental drift was put forward by the German meteorologist Alfred Wegener in 1912. He argued that if the earth could flow vertically in response to vertical forces, it could also flow laterally. In support of a different primeval arrangement of land masses he was able to point to an astonishing number of close affinities of fossils, rocks and structures on opposite sides of the Atlantic that, he suggested, ran evenly across, like lines of print when the ragged edges of two pieces of a torn newspaper are fitted together again. According to Wegener all the continents had been joined in a single supercontinent about 200 million years ago, with the Western Hemisphere continents moved eastward and butted against the western shores of Europe and Africa and with the Southern Hemisphere continents nestled together on the southern flank of this "Pangaea." Under the action of forces



GREAT GLEN FAULT in Scotland is named for a valley resulting from erosion along the line of the fault. About 350 million years ago the northern part of Scotland was slowly moved some 60 miles to the southwest along this line ***(see illustration on opposite page).***

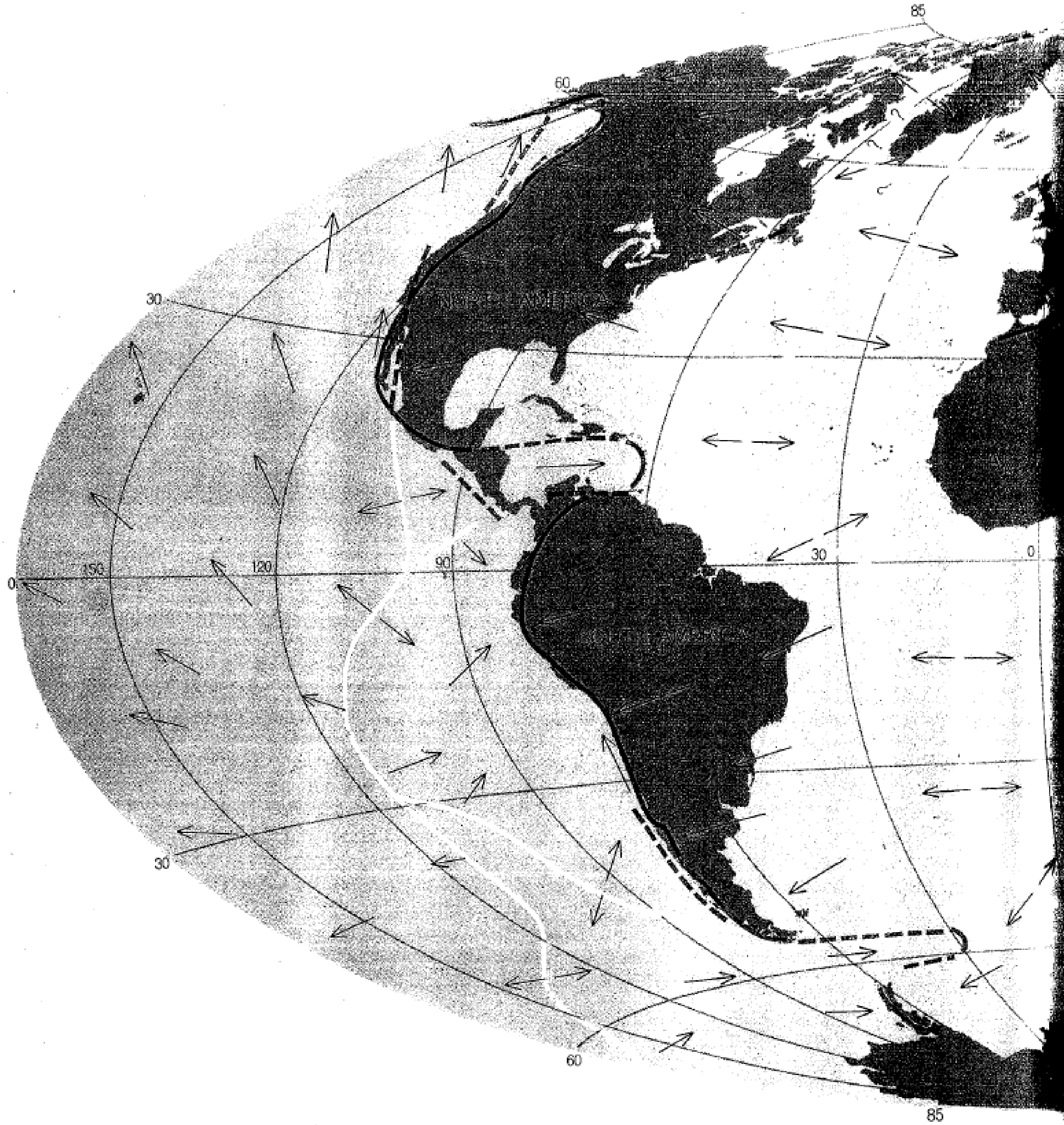


ASPY FAULT in northern Nova Scotia is marked by several cliffs like the one seen here. The fault is part of the Cabot Fault system extending from Boston to Newfoundland ***(see illustration on opposite page)*** **and may represent an extension of the Great Glen Fault.**

associated with the rotation of the earth, the continents had broken apart, opening up the Atlantic and Indian oceans.

Between 1920 and 1930 Wegener's hypothesis excited great controversy. Physicists found the mechanism he had proposed inadequate and expressed doubt that the continents could move laterally in any case. Geologists showed that some of Wegener's suggestions for reassembling the continents into a single continent were certainly wrong and that drift was unnecessary to explain the coincidences of geology in many areas. They could not, however, dispute the validity of most of the transatlantic connections. Indeed, more such connections have been steadily added.

It was the discovery of one of these connections that prompted my own recent inquiries into the subject of continental drift. A huge fault of great age bisects Scotland along the Great Glen in the Caledonian Mountains. On the western side of the Atlantic, I was able to show, a string of well-known faults of the same great age connect up into another huge fault, the "Cabot Fault" extending from Boston to northern Newfoundland. These two great faults are much older than the submarine ridge and rift recently discovered on the floor of the mid-Atlantic and shown to be a



CONVECTION CURRENTS in the earth's mantle may move blocks of crustal material with different effects. Continental mountain chains and island arcs could form where currents sink and blocks meet; mid-ocean ridges, where currents rise and blocks are torn young formation. The two faults would be one if Wegener's reconstruction or something like it were correct. Wegener also thought that Greenland (where he died in 1930) and Ellesmere Island in the Canadian Arctic had been torn apart by a great lateral displacement along the Robeson Channel. The Geological Survey of Canada has since discovered that the Canadian coast is faulted there.

Many geologists of the Southern Hemisphere, led by Alex. L. Du Toit of South Africa, welcomed Wegener's views. They sought to explain the mounting evidence that an ice age of 200 million years ago had spread a glacier over the now scattered continents of the Southern Hemisphere. At the same time, according to the geological record, the great coal deposits of the Northern Hemisphere were being formed in tropical forests as far north as Spitsbergen. To resolve this climatic paradox Du Toit proposed a different reconstruction of the continent. He brought the southern continents together at the South Pole and the northern coal forests toward the Equator. Later, he thought, the southern continent had broken up and its component subcontinents had drifted northward.

The compelling evidence for the existence of a Gondwanaland during the

apart. On this assumption arrows indicate directions of horizontal flow of currents at the present time. Solid colored lines represent mountain chains and island arcs; heavy white lines, the world-wide system of mid-ocean ridges; and broken colored lines, faults.

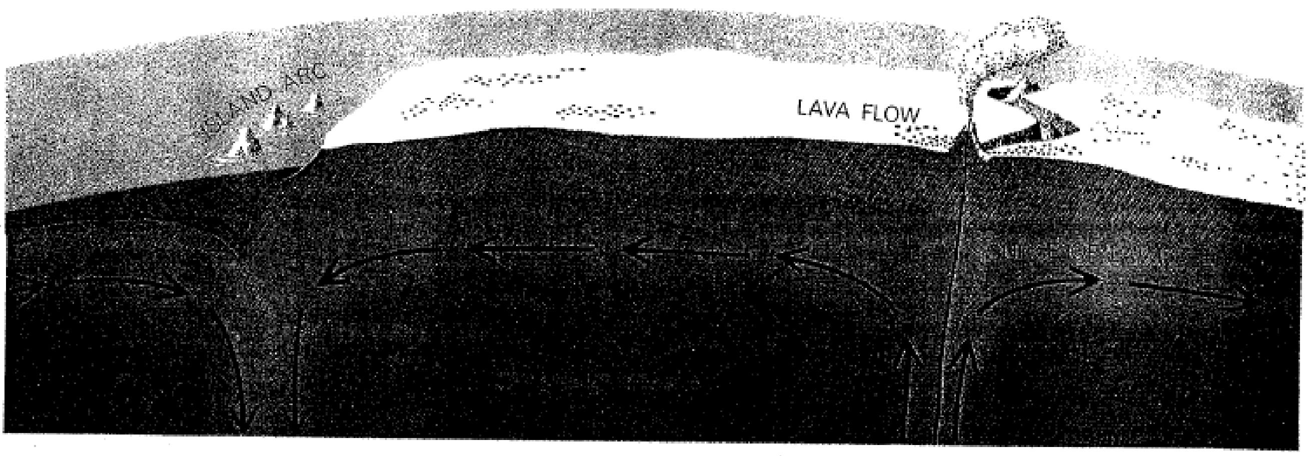
Mesozoic era—the "Age of Reptiles"—has been reinforced by the findings made in Antarctica since the intensive study of that continent began in 1955. The ice-free outcrops on the continent, although few, not only show the record of the earlier ice age that gripped the rest of the land masses in the Southern Hemisphere but also bear deposits of a low-grade coal laid down in a still earlier age of verdure that covered all the same land masses with the peculiar big-leafed *Glossopteris* flora found in their coal beds as well.

Many suggestions have been made as to how to create and destroy the land bridges needed to explain the biological evidence without moving the continents. Some involve isthmuses and some involve whole continents that have subsided below the surface of the ocean. But the chemistry and density of continents and ocean floors are now known to be so different that it seems even more difficult today to raise and lower ocean floors than it is to cause continents to migrate.

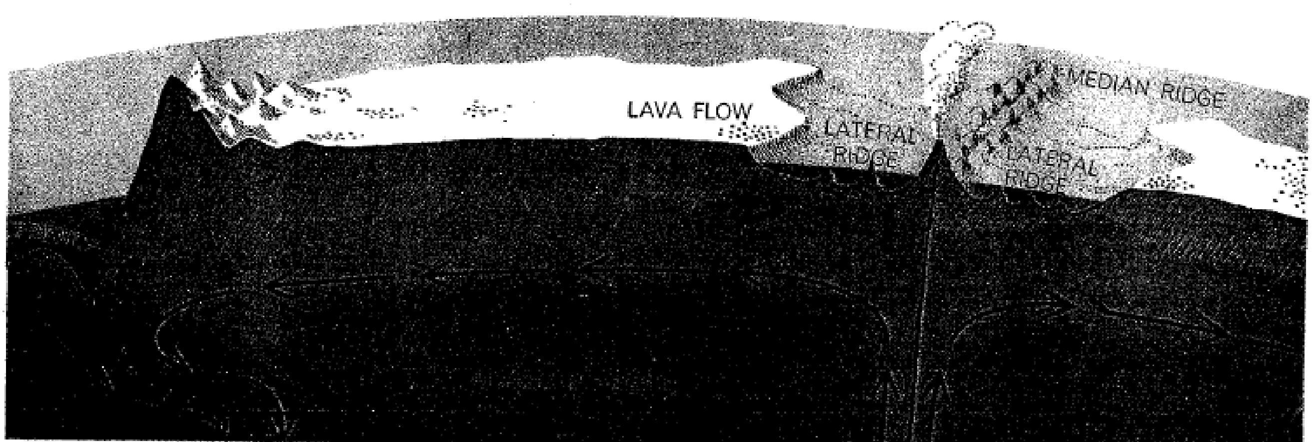
Convection in the Mantle

One of the first leads to a mechanism that would move continents came more than 30 years ago from the extension to the ocean floor of the sensitive techniques of gravimetry that had established the rule of hydrostatic equilibrium, or isostasy, ashore. The Dutch geophysicist Felix A. Vening Meinesz demonstrated that a submerged submarine would provide a sufficiently stable platform to allow the use of a gravimeter at sea. Over the abyssal trenches in the sea floor that are associated with the island arcs of Indonesia and the western side of the Pacific he found some of the largest deficiencies in gravity ever recorded. It was clear that isostasy does not hold in the trenches. Some force at work there pulls the crust into the depths of the trenches more strongly than the pull of gravity does.

Arthur Holmes of the University of Edinburgh and D. T. Griggs, now at the University of California at Los Angeles, were stimulated by these observations to re-examine and restate in modern terms an old idea of geophysics: that the interior of the earth is in a state of extremely sluggish thermal convection, turning over the way water does when it is heated in a pan. They showed that convection currents were necessary to account in full for the transfer of heat flowing from the earth's interior through the poorly conductive material of the mantle: the region that lies between the core and the crust. The trenches, they said, mark the places where currents in



EFFECTS OF CONVECTION CURRENTS, schematized in the two illustrations on this page, provide one possible means of accounting for the formation of median ridges, lateral ridges, mountain ranges and earthquake belts. Rising and separating currents (*arrows at right*) could break the crustal rock and pull it apart; the rift would be filled by altered mantle material (as suggested by H. H. Hess of Princeton University) and lava flows, forming a median ridge. Sinking currents (*left*) could pull the ocean floor down.



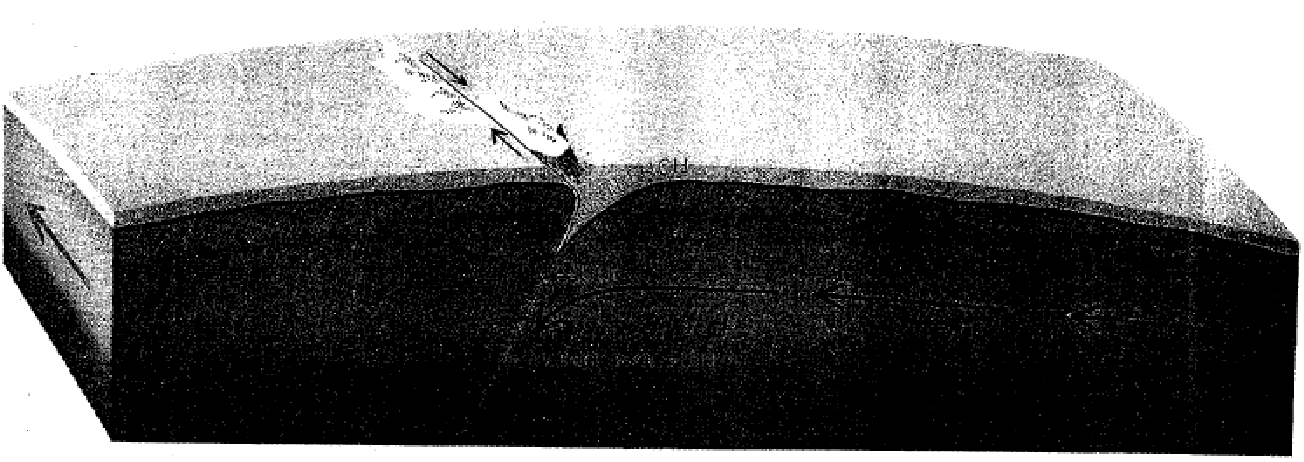
DRIFTING CONTINENT may be "piled up," where it meets sinking currents, to form mountains like those of the Andes (*left*). Since continents are lighter than the mantle material of the ocean floor, they cannot sink but tend to be pushed over sinking currents, which are marked by deep earthquakes. Active volcanoes continue to form over rising currents (*right*), but drift may carry these volcanic piles away to either side of the median ridge. Separated from their source, the inactive cones form one or two lateral ridges.

the mantle descend again into the interior of the earth, pulling down the ocean floor.

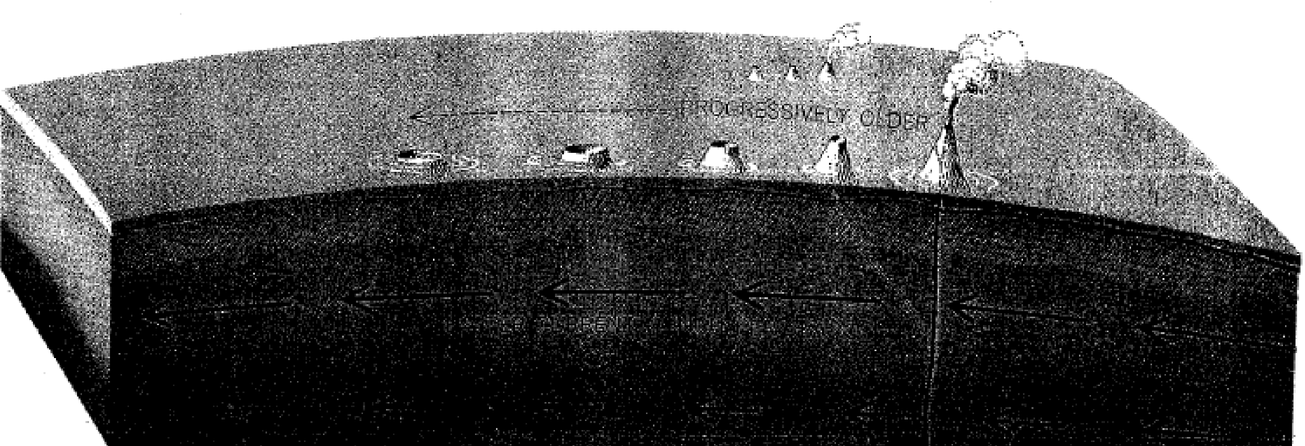
Convection currents in the mantle now play the leading role in every discussion of the large-scale and long-term processes that go on in the earth. It is true that the evidence for their existence is indirect; they flow too deep in the earth and too slowly—a few centimeters a year—for direct observation. Nonetheless their presence is supported by an increasing body of independently established evidence and by a more rigorous statement of the theory of their behavior. Recently, for example, S. K. Runcorn of Durham University has shown that to stop convection the mantle material would have to be 10,000 times more viscous than the rate of postglacial recoil indicates. It is, therefore, highly probable that convection currents are flowing in the earth.

Perhaps the strongest confirmation has come with the discovery of the regions where these currents appear to ascend toward the earth's surface. This is the major discovery of the recent period of extraordinary progress in the exploration of the ocean bottom, and it involves a feature of the earth's topography as grand in scale as the continents themselves. Across the floors of all the oceans, for a distance of 40,000 miles, there runs a continuous system of ridges. Over long stretches, as in the mid-Atlantic, the ridge is faulted and rifted under the tension of forces acting at right angles to the axis of the ridge. Measurements first undertaken by Sir Edward Bullard of the University of Cambridge show that the flow of heat is unusually great along these ridges, exceeding by two to eight times the average flow of a millionth of a calorie per square centimeter per second observed on the continents and elsewhere on the ocean floor. Such measurements also show that the flow of heat in the trenches, as in the Acapulco Trench off the Pacific coast of Central America, falls to as little as a tenth of the average.

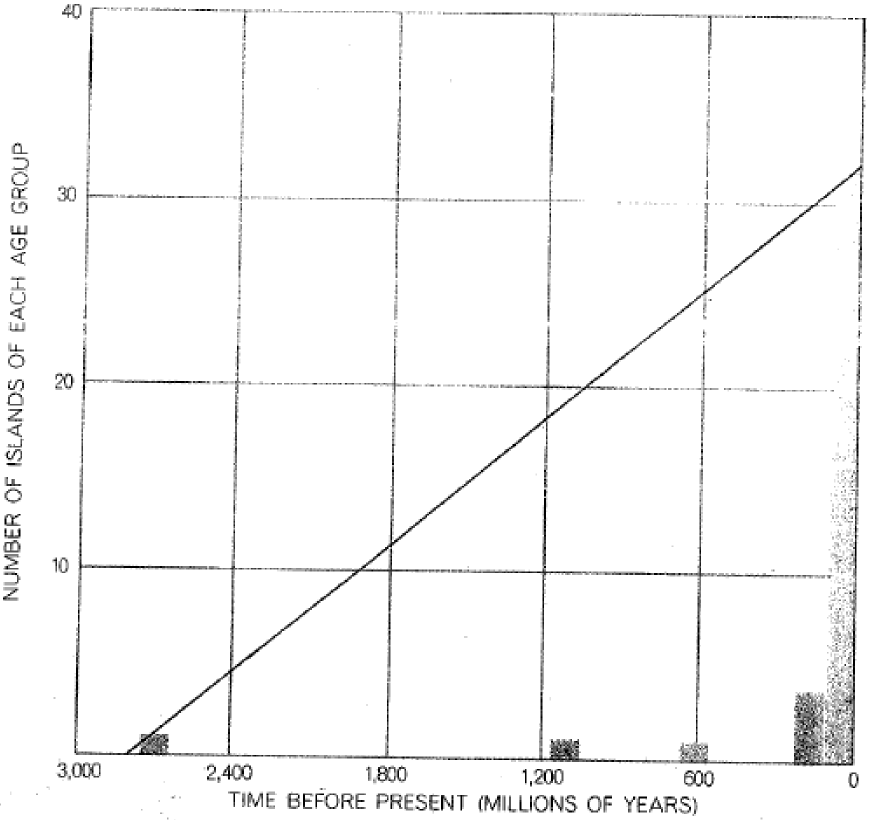
Most oceanographers now agree that the ridges form where convection currents rise in the earth's mantle and that the trenches are pulled down by the descent of these currents into the mantle. The possibility of lateral movement of the currents in between is supported by evidence for a slightly plastic layer—called the asthenosphere—below the brittle shell of the earth. Seismic observations show that the speed of sound in this layer suddenly becomes slower, indicating that the rock is less dense, hotter and more plastic. These observations have also yielded evidence that the asthenosphere is a few hundred kilometers thick, somewhat thicker than



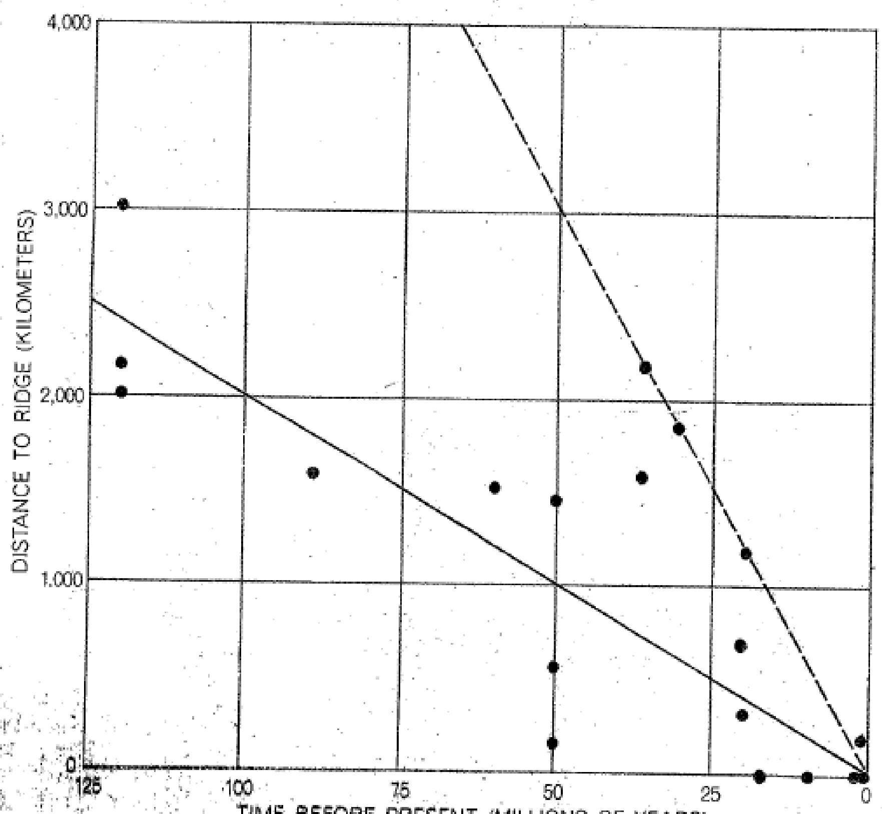
TWO CONVECTION CURRENTS perpendicular to each other suggest a mechanism for producing large horizontal faults such as the one that has offset western New Zealand 300 miles northward. The two convection currents (*arrows indicate direction*) would produce a fault. One current would be forced downward, producing a trench and earthquakes along the sloping surface. Continued flow of the second current would result in a sliding motion, or lateral displacement, along the plane of the fault, shearing the island in two.



/OLCANIC-ISLAND CHAINS like the Hawaiian Islands must ave originated in a process slightly different from that which ormed pairs of lateral ridges. The source of lava flow does not lie n a mid-ocean ridge; it is considered that the source may be deep (100 miles or more) in the slower moving part of convection currents. The differential motion carries old volcanoes away from the source, while new volcanoes form over the source. The length of the island chain depends on how long the source has been active.



FREQUENCY DIAGRAM shows the age distribution of about 40 islands (in main ocean basins) dated older than "recent" (the number of very young islands is vastly greater). The diagonal line shows the corresponding curve for continental rock ages over equivalent areas.



DISTANCE FROM MID-OCEAN RIDGE of some islands in Atlantic and Indian oceans is plotted against age. If all originated over the ridge, their average rate of motion has been two centimeters a year (*solid line*); maximum rate, six centimeters a year (*broken line*).

the crust, and that below it the viscosity increases again.

Here, then, is a mechanism, in harmony with physical theory and much geological and geophysical observation, that provides a means for disrupting and moving continents. It is easy to believe that where the convection currents rise and separate, the surface rocks are broken by tension and pulled apart, the rift being filled by the altered top of the mantle and by the flow of basalt lavas. In contrast to earlier theories of continental drift that required the continents to be driven through the crust like ships through a frozen sea, this mechanism conveys them passively by the lateral movement of the crust from the source of a convection current to its sink. The continents, having been built up by the accumulation of lighter and more siliceous materials brought up from below, are not dragged down at the trenches where the currents descend but pile up there in mountains. The ocean floor, being essentially altered mantle, can be carried downward; such sediments as have accumulated in the trenches descend also and, by complicated processes, may add new mountains to the continents. Since the material near the surface is chilled and brittle, it fractures, causing earthquakes until it is heated by its descent.

From the physical point of view, the convection cells in the mantle that drive these currents can assume a variety of sizes and configurations, starting up and slowing down from time to time, expanding and contracting. The flow of the currents on the world map may therefore follow a single pattern for a time, but the pattern should also change occasionally owing to changes in the output and transfer of heat from within. It is thus possible to explain the periodicity of mountain-building, the random and asymmetrical distribution of the continents and the abrupt breakup of an ancient continent.

Some geophysicists consider that isostatic processes set up by gravitational forces may suffice to cause the outer shell to fracture and to slip laterally over the plastic layer of the asthenosphere. This mechanism would not require the intervention of convection currents. Both mechanisms could explain large horizontal displacements of the crust.

Evidence from Terrestrial Magnetism

Fresh evidence that such great movements have indeed been taking place has been provided by two lines of study in the field of terrestrial magnetism. On the one hand, surveys of the earth's magnetic field off the coast of California show a pattern of local anomalies in the ocean floor running parallel to the axis of a now inactive oceanic ridge that underlies the edge of the continent. The pattern bears a persuasive resemblance to the "photoelastic" strain patterns revealed by polarized light in plastics placed under stress. More important, the pattern shows that the ocean floor is faulted at right angles to the axis of the ridge, with great slabs of the crust displaced laterally to the west by as much as 750 miles. These are apparently ancient and inactive fractures; now the active faults run northwesterly, as is indicated by the earthquakes along California's San Andreas Fault.

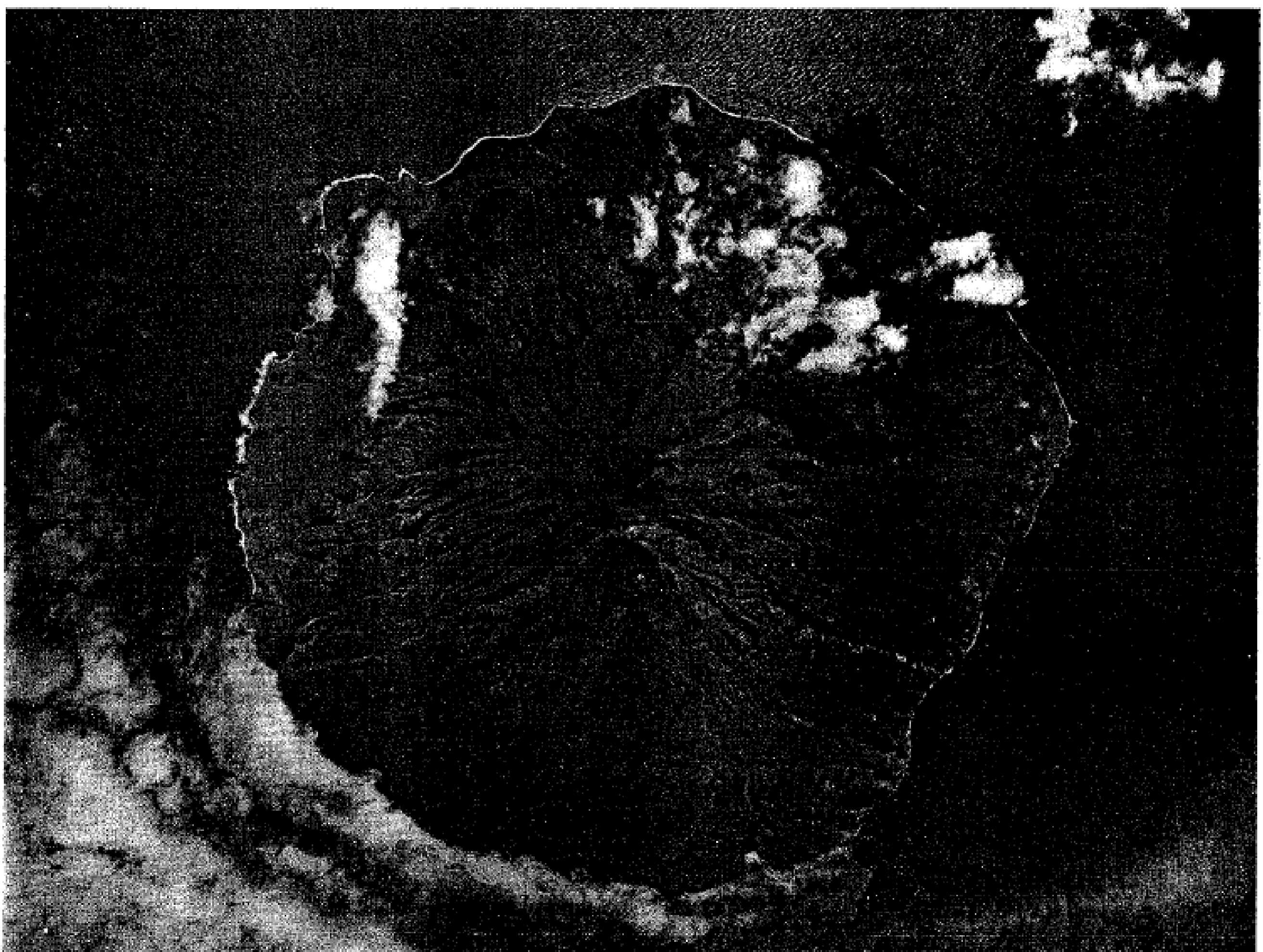
Evidence of a more general nature in favor of continental drift comes from the studies of the "remanent" magnetism of the rocks, to which Runcorn, P. M. S. Blackett of the University of London and Emil Thellier of the University of Paris have made significant contributions. Their investigations have shown that rocks can be weakly magnetized at the time of formation—during cooling in the case of lavas and during deposition in the case of sediments—and that their polarity is aligned with the direction of the earth's magnetic field at the place and time of their formation. The present orientation of the rocks of various ages on the continents indicates that they must have been formed in different latitudes. The rocks of any one continent show consistent trends in change of orientation with age; those from other continents show different shifts. Continental drift offers the only explanation of these findings that has withstood analysis.

Some physicists and biologists are now prepared to accept continental drift, but many geologists still have no use for the hypothesis. This is to be expected. Continents are so large that much geology would be the same whether drift had occurred or not. It is the geology of the ocean floors that promises to settle the question, but the real study of that two-thirds of the earth's surface has just begun.

The Oceanic Islands

One decisive test turns on the age of the ocean floor. If the continents have been fixed, the ocean basins should all be as old as the continents. If drift has occurred, some regions of the ocean floor should be younger than the time of drift.

A survey of the scattered and by no means complete literature on the oceanic islands conducted by our group at the University of Toronto shows that of all the islands in the main ocean basins only about 40 have rocks that have been dated older than the Recent epoch. Only three of these—Madagascar and the Seychelles of the Indian Ocean and the

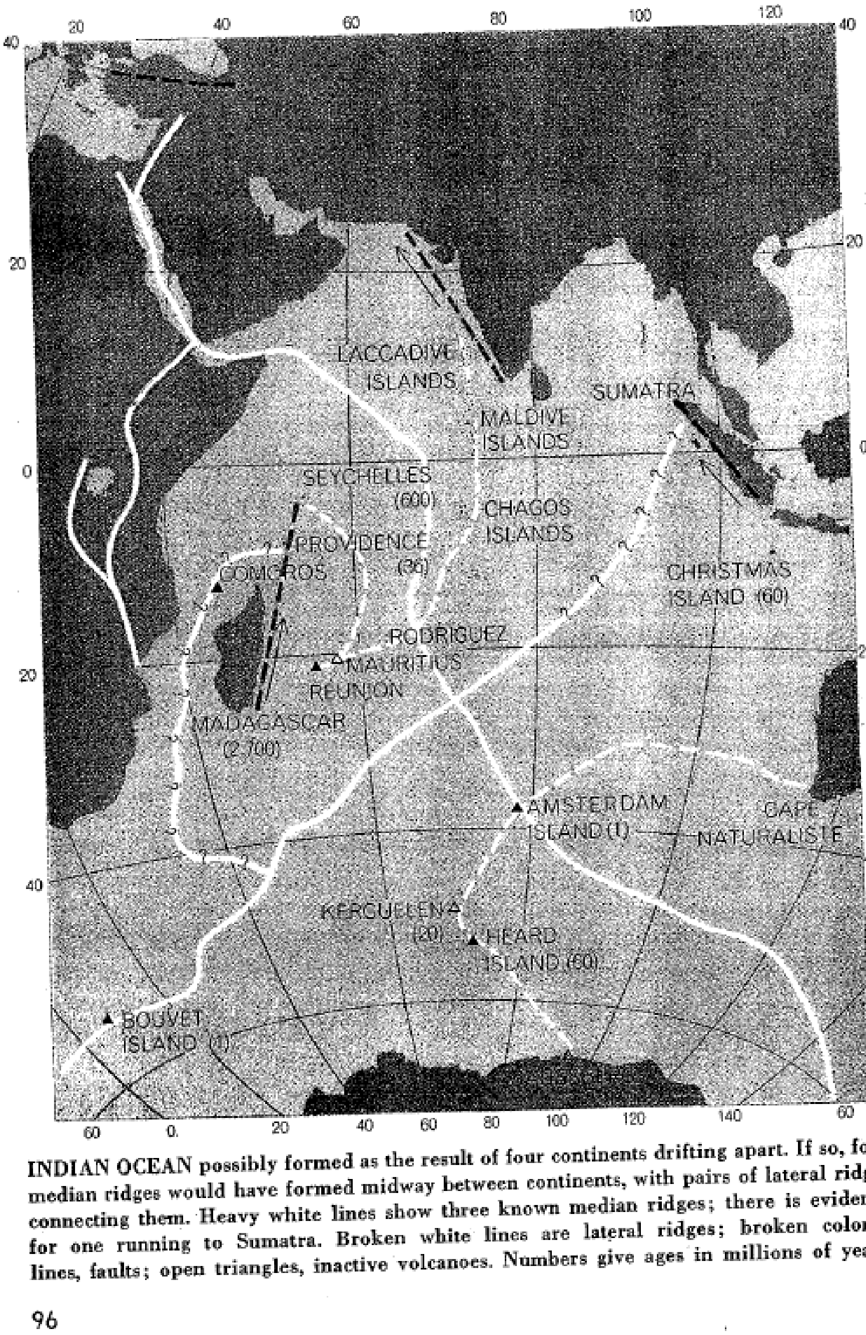


TRISTAN DA CUNHA ISLAND in the South Atlantic lies on the Mid-Atlantic Ridge. At center are the lava beds and partially filled crater of the main cone, which has not erupted for several centuries. Along the perimeter of the island secondary cones are just discernible, as is the settlement on the island's northeastern promontory (*upper left*). Several months after this aerial photograph was made in 1961 a volcanic eruption took place about 300 yards east (*to right*) of the settlement. The island is eight miles at its widest.

Falklands of the South Atlantic—have very old rocks; all the others are less than 150 million years old. If one regards the exceptions as fragments of the nearby continents, the youth of the others suggests that either the ocean basins are young or that islands are not representative samples of the rock of the ocean floor.

Significantly, it turns out that the age of the islands in the Atlantic Ocean tends to increase with their distance from the mid-ocean ridge. In this reckoning one need not count the island arcs of the West Indies or the South Sandwich Islands, which belong to the Cordilleran system—that is, the spine of mountains running the entire length of North and South America—and so have a continental origin. At least six of the islands on the ridge or very close to it have on them active volcanoes that have had recent eruptions; the most recent was the eruption of Tristan da Cunha, which is located squarely on the ridge in the South Atlantic. Only two of the islands far from the ridge have active volcanoes. If the hot convection currents of the mantle rise under the mid-ocean ridge, it is easy to understand why the ridge is the locus of active volcanoes and earthquakes. The increase in age with distance from the ridge suggests that if the more distant islands had a volcanic origin on the ridge, lateral movement of the ocean floor has carried them away from the ridge. Their ages and distances from the ridge indicate movement at the rate of two to six centimeters a year on the average, in keeping with the estimated velocity of the convection currents.

Of great significance in connection with the mechanism postulated here are the two lateral ridges that run east and west from Tristan da Cunha to Africa on the one hand and to South America on the other. It is reasonable to suppose that these ridges had their origin in a succession of volcanoes that erupted and grew into mountains on the site of the present volcano and were carried off east and west to form a row of progressively older, extinct and drowned volcanoes [*see illustration on page 88*]. There are no earthquakes along the lateral ridges and so they are distinctly different in character from the mid-ocean ridge. These ridges meet the continental margins at places that would fit together on the quite independent criterion of the match of their shore lines. One explanation of this coincidence is that the continents were indeed joined together and have moved apart, with the lateral ridges forming trails that record the motion. The two ridges are roughly mirror images of each other, showing that the motion was uniform on each side. Another similar pair of ridges connects Iceland—where the mid-ocean ridge comes to the surface and where the great tension rift is visible in the Icelandic Graben—to Greenland and the shelf of the European continent.

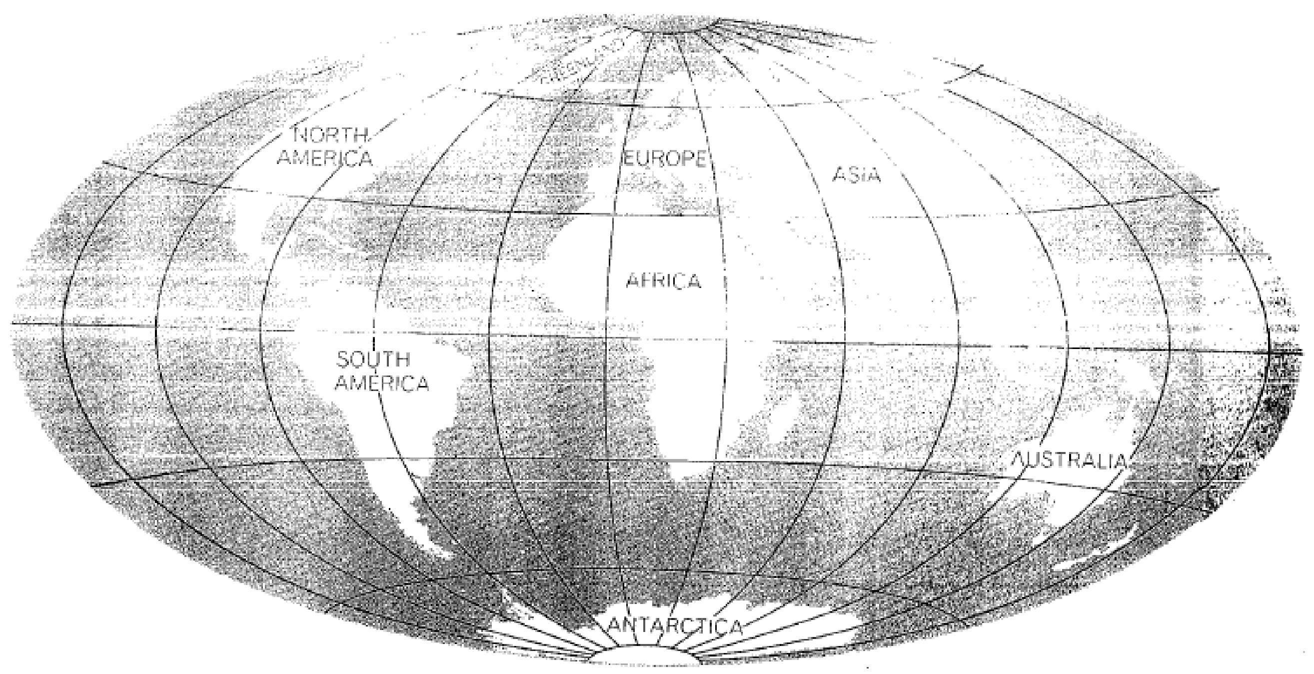


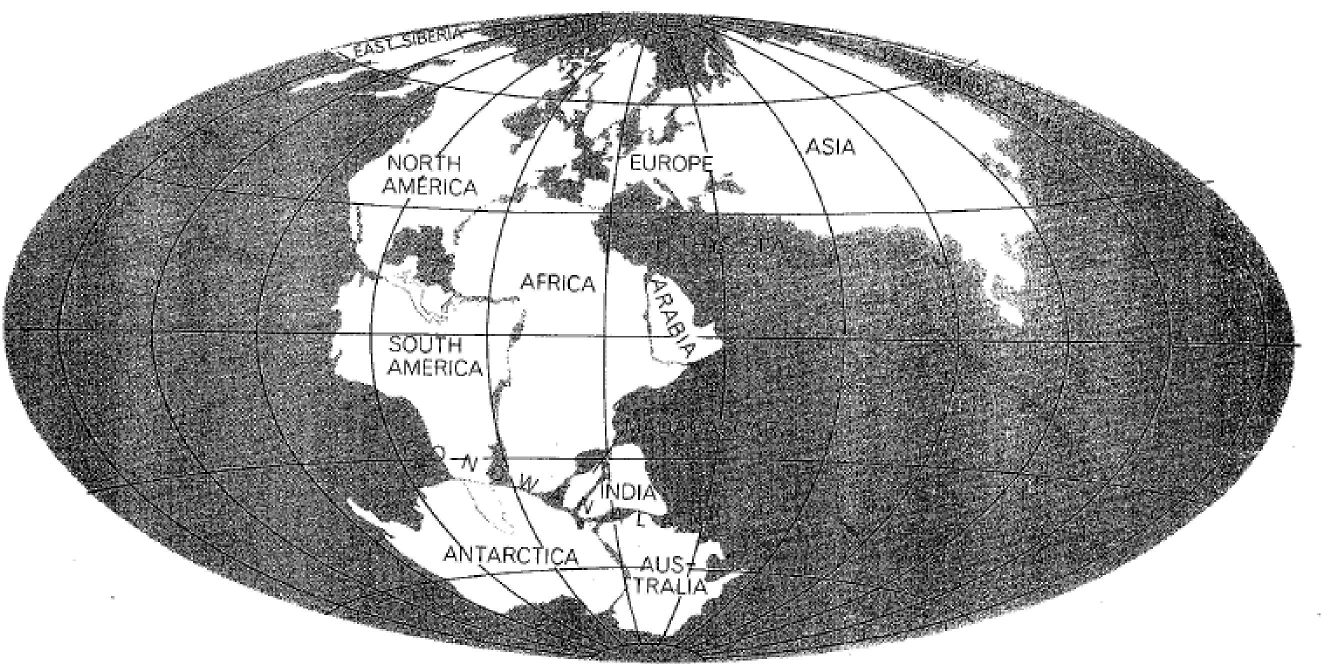
INDIAN OCEAN possibly formed as the result of four continents drifting apart. If so, four median ridges would have formed midway between continents, with pairs of lateral ridges connecting them. Heavy white lines show three known median ridges; there is evidence for one running to Sumatra. Broken white lines are lateral ridges; broken colored lines, faults; open triangles, inactive volcanoes. Numbers give ages in millions of years.

A Double Hypothesis

We have therefore advanced two related hypotheses: first, that where adjacent continents were once joined a median ridge should now lie between them; second, that where such continents are connected by lateral ridges they were once butted together in such a manner that points marked by the shoreward ends of these ridges coincided. If this is correct, it provides a unique method for reassembling continents that have drifted apart. One of the major troubles with theories of drift has been that the possibilities are so numerous no such precise criterion existed for putting the poorly fitting jigsaw puzzle together.

Without doubt the most severe test of this double hypothesis is presented by the Indian Ocean. Here four continents—Africa, India, Australia and Antarctica—may be assumed on geological and paleomagnetic evidence to have drifted apart. The collision of India with the Asian land mass could have thrown up the Himalaya mountains at their



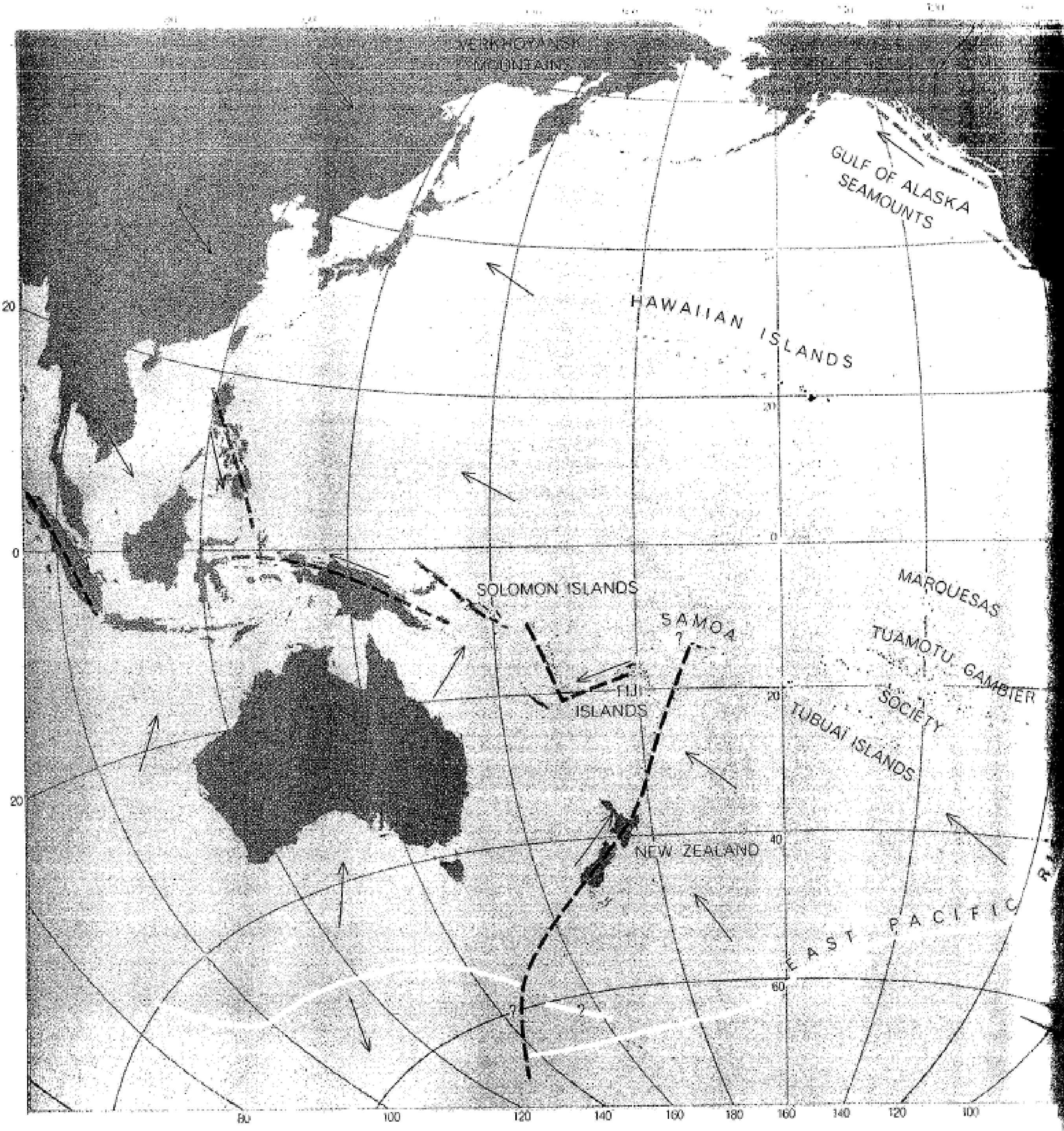


SINGLE SUPERCONTINENT, presumed to have existed some 150 million years ago, would have resembled that depicted in the map at bottom. A present-day map appears at top. In both maps the distortion of the continents is a result of the projection employed.

junction. These continents should accordingly be separated by four mid-ocean ridges. Three such ridges have already been well established by surveys of the Indian Ocean, and there is evidence for the existence of the fourth. In each quadrant marked off by the ridges there is also, it happens, a lateral ridge! These submarine trails may be presumed to be records of the motion of the continents as they receded from one another. From Amsterdam Island one of these lateral ridges runs through Kerguelen Island to Gaussberg Mountain on the coast of Antarctica; a mirror image of this ridge runs from Amsterdam Island to Cape Naturaliste on Australia. The corresponding ridges connecting Africa and India are distorted by lateral faults running along the coasts of Madagascar and India. Thus in each quadrant there exists a lateral ridge to show how points on Madagascar, India, Australia and Antarctica once lay close together. What is remarkable is not that there is some irregularity in the present configuration of these ridges but that the floor of the Indian Ocean should show such a symmetrical pattern.

The mid-ocean ridge separating Australia from Antarctica has been traced by Henry W. Menard of the Scripps Institution of Oceanography across the eastern Pacific to connect with the great East Pacific Rise. From the topography of the Pacific floor it can be deduced that this ridge once extended through the rise marked by Cocos Island off Central America and formed the rifted ridge that moved North and South America apart. Another branch of this ridge, running across the southern latitudes, suggests the cause of the separation of South America from Antarctica. The oceanic islands in this broad region of the Pacific form lines that extend at right angles down the flanks of the East Pacific Rise; geologists long ago established that these islands grow progressively older with distance from the top of the rise. Unlike the rest of the continuous belt of mid-ocean ridges to which it is connected, the East Pacific Rise tends to run along the margins of the Pacific Ocean; it has rifted an older ocean apart rather than a continent. The floor of the western Pacific is believed to be a remnant of that older floor.

There are therefore enough connections to draw all the continents together, reversing the trends of motion indicated by the mid-ocean ridges and using the continental ends of pairs of lateral ridges as the means of matching the coast lines together. The ages of the islands and of the coastal formations suggest that about



AGE OF PACIFIC ISLANDS appears to increase with increasing distance from the mid-ocean ridge. This is compatible with the idea that the eastern half of the Pacific Ocean has been spreading from the East Pacific Rise (as has been suggested by Robert S. Dietz of the U.S. Navy Electronics Laboratory). Broken colored lines represent faults; the associated arrows indicate the direction of horizontal motion, where known, along the fault. Other arrows show the probable directions of convection flow. Island arcs of the kind

150 million years ago, in mid-Mesozoic time, all the continents were joined in one land mass and that there was only one great ocean [*see illustration on page 97*]. The supercontinent that emerges from this reconstruction is not the same as those proposed by Wegener, Du Toit and other geologists, although all have features in common. The widespread desert conditions of the mid-Mesozoic may have been a consequence of the unusual circumstance that produced a single continent and a single ocean at that time. Since its approximate location with respect to latitude is known, along with the location of its major mountain systems, the climate in various regions might be reconstructed and compared with geological evidence.

represented by Japan develop where the forces associated with such flow are directly opposed; great horizontal faults, where these forces meet at right angles.

It is not suggested that this continent was primeval. That it was in fact assembled from still older fragments is suggested by two junction lines: the ancient mountain chain of the Urals and the chain formed by the union of the Appalachian, Caledonian and Scandinavian mountains may have been thrown up in the collisions of older continental blocks. Before that there had presumably been a long history of periodic assembly and disassembly of continents and fracturing and spreading of ocean floors, as convection cells in the mantle proceeded to turn over in different configurations. At present it is impossible even to speculate about the details.

Breakup of the Supercontinent

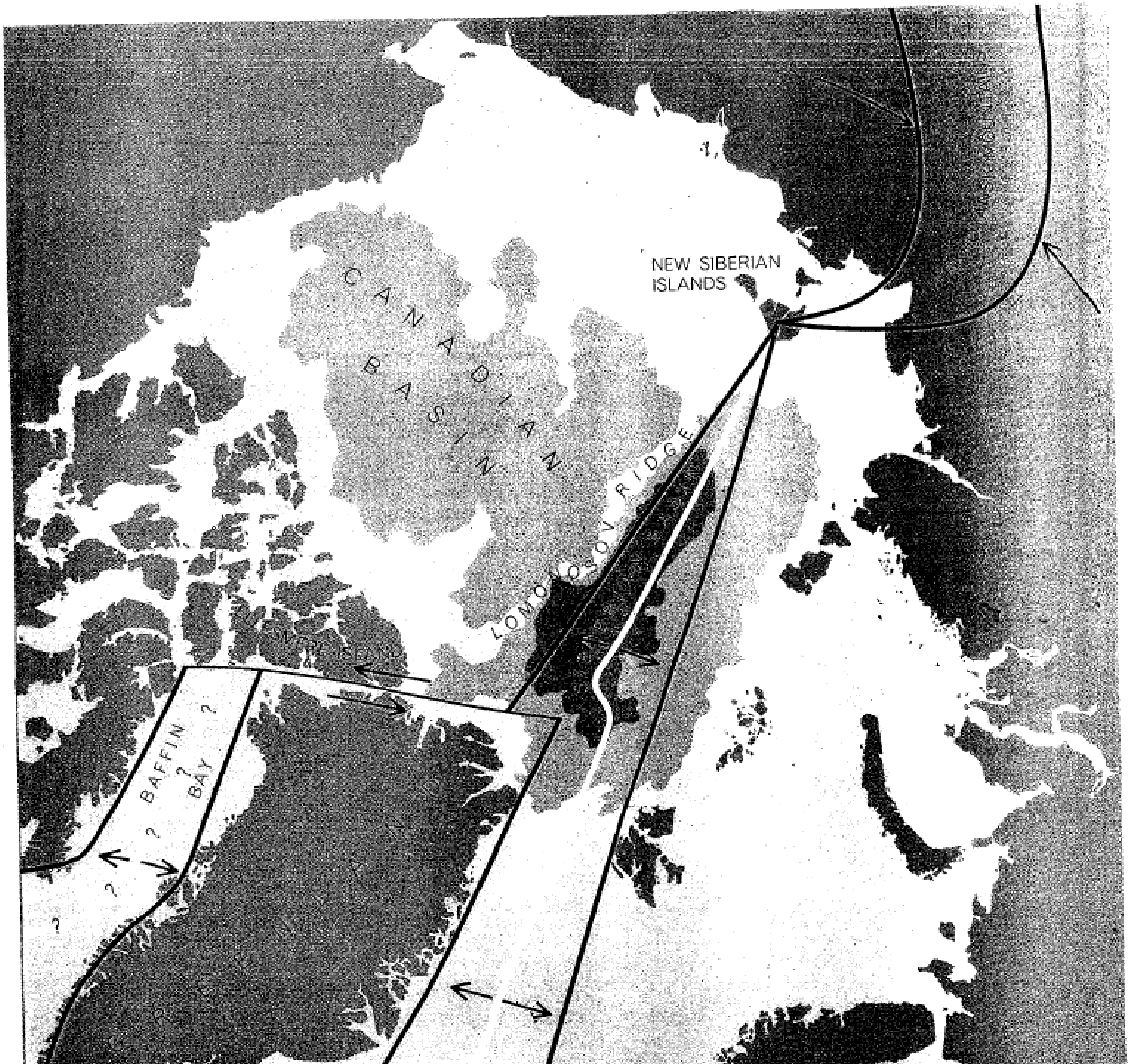
If it can be assumed that the proposed Mesozoic continent did exist and spread apart, geology provides some guide to the history of its fragmentation. The present system of convection currents has apparently been constant in general configuration ever since the Mesozoic, but not all parts of it have been equally active all of that time. Shortly before the start of the Cretaceous period, about 120 million years ago, the continent developed a rift that opened up to form the Atlantic Ocean. The rift spread more widely in the south, with the result that the continents must have rotated slightly about a fulcrum near the New Siberian Islands [*see illustration on next page*]. Soviet geologists have found that the compression and uplift that raised the Verkhoyansk Mountains across eastern Siberia began at about that time. To the south a continuation of the rifting separated Africa from Antarctica and spread diagonally across the Indian Ocean, opening the northeasterly rift. Africa and India were thus moved northward, away from the still intact Australian-Antarctic land mass.

It seems reasonable to suggest, particularly from the geology of the Verkhoyansk Mountains and of Iceland, that at the start of Tertiary time, about 60 million years ago, this convection system became less active and that rifting started up elsewhere. A new rift opened up along the other, northwesterly, diagonal of the Indian Ocean, separating Africa from India and Australia and separating Australia from Antarctica. With the collision of the Indian subcontinent against the southern shelf of the Asiatic land mass, the uplift of the Himalaya mountains began. The proposed succession of activity in the two main ridges of the Indian Ocean would explain why India has moved twice as far north with relation to Antarctica as Australia or Africa has and why the older northeast ridge is now a somewhat indistinct feature of the ocean floor. The younger rift in the Indian Ocean seems to have extended along the East Pacific Rise and Cocos Ridge to cross the Caribbean. A branch also passed south of South America. As these median ridges have continued to widen they have been forced by this growth to migrate northward, forming great shears or faults off the coast of Chile and through California. Indeed, a case can be made out for the idea that every mid-ocean ridge normally ends at a great fault or at a pivot point, as in the New Siberian Islands.

A few million years ago activity in this system decreased, allowing the North and South American continents to be joined by the Isthmus of Panama. The Atlantic rift now became more active again, producing renewed uplift in the Verkhoyansk Mountains and active volcanoes in Iceland and the five other still active volcanic islands down the Atlantic. Again the pattern of rifting in the Indian Ocean was altered. The distribution of recent earthquakes shows that the greatest activity extends along the western half of each diagonal ridge from the South Atlantic to the entrance of the Red Sea and thence by two arms along the rift valley of the Jordan River and through the African rift valleys, where the breakup of a continent has apparently begun.

The presently expanding rifts run mostly north and south or northeasterly so that dominant easterly and westerly compression of the outer crust is absorbed by overthrusting and sinking of the crust along the eastern and western sides of the "ring of fire" around the Pacific. For this reason East Asia, Oceania and the Andes are the most active regions of the world. The westward-driving pressure of the South Atlantic portion of the Mid-Atlantic Ridge has forced the continental block of South America against and over the downward-plunging oceanic trench along its Pacific coast. The northwest-trending currents below the Pacific floor have pulled down trenches under the eight island arcs around the western and northern Pacific from the Philippines north to the Aleutians. Even at the surface of the Pacific, the direction of the subcrustal movement is indicated by the strike of several parallel chains of volcanic islands, such as the Hawaiians, which may be thought to have risen like bubbles in a stream from the slower moving deep interior [*see lower illustration on page 93*]. These chains run parallel with the seismically active shearing faults that border each side of the Pacific, along the coast of North America and from Samoa to the Philippines. The compression exerted by the mid-ocean ridge through the southern seas is absorbed, with less seismic activity, along a line from New Zealand, through Indonesia and the Himalaya highlands to the European Alps. In all cases, the angle at which the loci of deep-focus earthquakes dip into the earth seems to follow the direction of subsurface flow—eastward and downward, for example under the Pacific coast of South America; westward and downward under the island arcs on the opposite side of the Pacific.

The theory I have outlined may be highly speculative, but it is indicative of current trends in thought about the earth's behavior. The older theories of the earth's history and behavior have proved inadequate to meet the new findings, particularly those from studies of terrestrial magnetism and oceanography. In favor of the specific details suggested here is the fact that they fit observations and are precise enough to be tested.



RIFTING OF SUPERCONTINENT to form the Atlantic Ocean could have produced the Verkhoyansk Mountains in eastern Siberia. As shown on this map of the Arctic, the rift spread more widely to the south. The opening of the Atlantic Ocean and Baffin Bay separated Greenland from both North America and Europe. The continents were rotated slightly about a fulcrum near the New Siberian Islands. The resulting compression and uplift would create a mountain range. Opposing arrows mark the Wegener Fault.