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Chapter 16

Continental Drift

Alfred Wegener

On January 6, 1912, Alfred Wegener (1880–1930) read a paper at the Geological Association at Frankfurt am Main entitled, "Die Herausbildung der Grossformen der Erdrinde (Kontinente und Ozeane) auf geophysikalischer Grundlage" (Geophysical basis of the evolution of large-scale features of the earth's crust).[1] Wegener's fundamental idea was that continents were joined together at a certain time in the past; thereafter, they drifted like rafts over the ocean floor, finally reaching their present position. This revolutionary idea was published in a book in 1915, *Die Entstehung der Kontinente und Ozeane* (The origin of continents and oceans).[2] Three revised editions followed after World War I, in 1920, 1922, and 1929, each containing new data.

Interested in meteorology, Wegener had joined a Danish expedition to northeastern Greenland in 1906–1908. Between 1908 and 1912, he taught meteorology at the Physical Institute in Marburg, Germany. Together with Captain J. Koch, he led the second expedition to Greenland in 1912–1913, a trip that allowed him to cross the ice cap of Greenland. In 1929 Wegener organized a third expedition to the western coast of Greenland in preparation for an important trip scheduled for the following year. He planned to study an area across the ice cap along the 17° parallel on a route slightly to the south of the 1912 expedition. In 1930–1931 he tried to set up three stations: a station in the west that had been explored in 1929; one in the east; and one in the middle of the ice cap, at 3,000 meters elevation and 400 kilometers from the western station.

The fourth expedition was Wegener's last one. Bad weather delayed the setting up of the three stations. On August 6, 1930, he wrote, "August shall bring the decisive battle, particularly in regard to the middle station on the ice."[3] On September 21 he left the western station to bring supplies to the middle station. But the trip took longer than planned, and he reached the station only on October 30, without any supplies. He left the next day—it was his fiftieth birthday—with a young man from Greenland to return to the coast. His body was found under the snow on May 8 of the following year, wrapped in his sleeping bag and a reindeer hide, halfway between the two stations. His hands showed no frostbite, which seemed to indicate that he had not died while on the road from the cold, but in his tent from cardiac arrest due to excessive physical effort.[4]

Wegener's ideas were debated during his lifetime, and acceptance came only in the 1960s. For thirty years, the theory met with an incredible amount of skepticism both in Europe and in North America.[5]

Continents as Jigsaw Fits

Wegener wrote:

> The first concept of continental drift first came to me as far back as 1910, when considering the map of the world, under the direct impression produced by the congruence of the coastlines on either side of the Atlantic. At first I did not pay attention to the idea because I regarded it as improbable. In the fall of 1911, I came quite accidentally upon a synoptic report in which I learned for the first time of palaeontological evidence for a former land bridge between Brazil and Africa. As a result I undertook a cursory examination of relevant research in the fields of geology and palaeontology, and this provided immediately such weighty corroboration that a conviction of the fundamental soundness of the idea took root in my mind.[6]

The correspondence in shape between the coasts of South America and Africa, which makes the Atlantic Ocean resemble a huge valley with parallel flanks, had impressed earlier authors. In 1858 Antonio Snider-Pellegrini (active 1851–1861, dates unavailable) published an illustration of the world before and after the separation of

Africa and South America in *La Création et ses Mystères dévoilés* (The creation and its mysteries explained).[7] Although some textbooks still claim Francis Bacon as a forerunner of drift, he compared only the similar triangular shapes of South America and Africa, not their corresponding coasts.[8]

Paleontological and geological arguments demonstrated correlations between the two continents. Marcel Bertrand and Eduard Suess had stressed structural analogies between Paleozoic chains on both sides of the Atlantic, that is, between the Appalachians and the Hercynian chain. Suess coined the word **Gondwana** for a continent joining Africa and India across the Indian Ocean and the island of Madagascar. Since the same flora was found in Carboniferous rocks in these countries, including Brazil, the continent of Gondwana was believed to have included all the continents in the Southern Hemisphere. In addition, a fossil plant called *Glossopteris* was found on all these southern continents, so the name *Glossopteris* flora was given to all plants of the end of the Paleozoic found on the former continents of Gondwana. A small Permian reptile called *Mesosaurus* was further proof of a former Gondwana: it was found only in Africa and South America, not in Eurasia nor North America.

Similar correspondences were observed in different regions of different age. In the last edition of his book, Wegener referred to studies on the garden snail, distributed "from Southern Germany via the British Isles, Iceland and Greenland across to the American side."[9] Finally, correlations were established between continents of the Southern and the Northern Hemispheres.

Structural geology also revealed connections across the Atlantic. Besides the examples of the Hercynian chain and the Appalachians mentioned by Bertrand, Wegener showed that the South African chains of the Cape of Good Hope extended to the region of Buenos Aires, Argentina. Similarly, the gneissic plateau of Africa corresponds to that in Brazil.

Land Bridges or Drifting?

There were two different ways to explain these continental jigsaw fits. Suess held that the crust is continuously collapsing. That gave an easy explanation for the fits: the former continents had been larger than today, and their fragments are now resting at the bottom of the ocean. Early twentieth-century authors believed the existence of former land bridges between present-day continents explained fauna

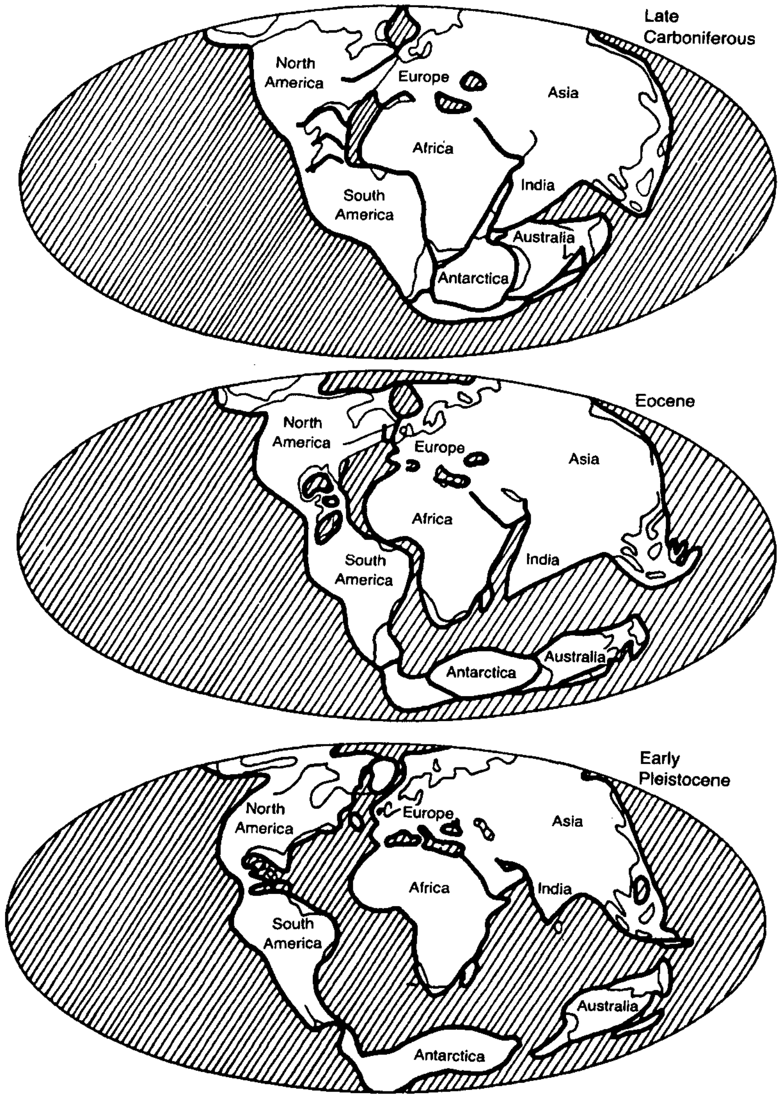

Figure 16.1. Reconstruction of the Globe during Three Geological Periods According to the Theory of Continental Drift (From Wegener, Die Entstehung der Kontinente und Ozeane, *1912). In the Late Carboniferous, continents were welded into a single mass. In the Eocene, the Atlantic and the Indian oceans began to open. In early Pleistocene, only an isthmus between South America and Antarctica remained. Arabia and Africa were joined before the opening of the Red Sea.*

and flora from one continent to another. Numerous imaginary bridges were proposed: Africa and Brazil were connected by the bridge called Archhelenis, and Europe and North America by Archatlantide. Smaller land bridges across the Indian Ocean joined Madagascar to India and India itself to Australia.

To these explanations of land bridges, Wegener opposed the idea of continental drift, or simply drift as it was soon called. Instead of huge land bridges across oceans, he proposed that continents were originally joined together and then gradually separated (fig. 16.1). He wrote: "South America must have lain alongside Africa and formed a unified block which was split in two in the Cretaceous; the two parts must then have become increasingly separated over a period of millions of years like pieces of a cracked ice floe in water."[10]

Wegener did not present his theory as a fantasy of floating and breaking icebergs. On the contrary, each argument was based on the latest data. True, certain correlations of fauna or flora could have been equally well explained by land bridges, but the theory of collapsed land bridges was often faced with simple objections. For instance, in the case of the garden snail, Wegener objected: "Even if we neglect the fact that the theory of sunken continents is untenable on geophysical grounds, this explanation is still given by drift theory, because it must interpolate a very long hypothetical bridge in order to connect the two small areas of distribution. . . . Some bridges even stretched across different climatic zones. It is therefore certain that the bridges could not have been used by all the animals on the continents that they connected."[11]

The Alpine Shortening

Wegener argued that the theory of collapse was conceivable only in Suess's day, when the contraction of the globe was generally accepted. This theory explained mountain building as a kind of wrinkling because naturalists were not aware of the magnitude of tangential movements during mountain building. Believers in the contraction theory reduced the Alps by numerous overthrusts to one fourth, if not one eighth, of their original width. Since the present width of the Alps is about 150 kilometers, the original width must have been 600 to 1,200 kilometers and must have covered five to ten degrees latitude. R. Staub's estimates were even higher: in 1924 he postulated an Alpine compression of 1,500 kilometers.[12] Staub, as quoted by Wegener, said that "Africa must have been displaced relative to Europe by this amount. What is involved here is a true continental drift of the African mass and an extensive one at that."[13]

Wegener claimed that the discovery of radioactivity completed the destruction of the old theory of secular cooling. Radioactive elements within the crust prevent its cooling; hence, "it is no longer possible, as it once was, to consider the thermal state of the earth as a temporary phase in the cooling process of a ball that was formerly at a higher temperature. It should be regarded as a state of equilibrium between radioactive heat production in the core and thermal loss into space."[14]

Isostasy

The theory of isostasy also refuted the concept of collapsed land bridges. Mentioned earlier (chapter 11), the theory says that the earth's crust floats in a hydrostatic equilibrium on a denser, viscous substratum, forming the floor of the oceans. If continents are lighter than their substratum, they cannot sink to the bottom of the ocean unless they have been overloaded. Hence, the theory of collapsing land bridges is incompatible with isostasy.

The concept of isostasy is based on a series of observations made in the middle of the nineteenth century. In India, measurements of the meridional arc across the continent revealed a discrepancy between astronomical and geodetic (triangulation) measurements between two cities. John Henry Pratt (1800–1871), archdeacon of Calcutta, interpreted this difference as the effect exerted by the Himalayas on the direction of the plumb line. The plumb bobs, which under normal conditions point toward the center of gravity of the earth, were deflected because of the vicinity of attracting masses. Pratt made the appropriate calculations and found to his surprise that the Himalayas should have produced an even greater deflection.

Pratt's paper, sent to the Royal Society of London,[15] aroused the interest of George Biddel Airy (1801–1893), the royal astronomer of the United Kingdom. He imagined the crust floating on a fluid of a higher density than the crust and compared it to a raft made of tree trunks floating on water. He pointed out that the trunks that rise highest above the surface should also be immersed deeper in the fluid, following Archimedes' principle whereby the weight of the immersed body is equal to that of the fluid displaced. Airy assumed that "roots" of the lighter crust are present underneath the Himalayas and

Tibet, extending into the underlying fluid and compensating, to a certain extent, for the deflection produced by the mountain masses. In summary, a mountain with light roots is not heavier than a plain lying directly upon the denser fluid.[16]

In 1859 Pratt refuted Airy's hypothesis, saying that the crust is denser than the underlying fluid because, although both consist of the same material, cooling and contraction makes the crust heavier. Since contraction is less strong in mountain regions than in plains (and, of course, at sea), the density would be lower in mountain ranges. Hence, lower density compensates for higher altitude.[17]

In 1889 C. E. Dutton (1841–1912) called this phenomenon the theory of isostasy.[18] Measurements soon verified the compensating effect of reliefs; that is, mountains do not have a greater gravitational attraction than oceans, despite their greater mass. Explanations varied, however, from one author to another. In the twentieth century, seismology confirmed Airy's ideas and showed that the lower boundary of the crust (recognized by the existence of a surface of **discontinuity**) is deeper below mountains—as if roots indeed existed there. It was also established that the crusts of the continents and of the ocean are of different nature and of different density.

Wegener thus wrote: "The correct interpretation may be found in amalgamation of both concepts. In the case of mountain ranges, we have to do basically with thickening of the light continental crust, in Airy's sense; but when we consider the transition from continental block to ocean floor, it is a matter of difference in type of material, in Pratt's sense."[19]

As a result, Wegener understood that if continents do not have the same composition as oceans, then they are not interchangeable by random collapses of the crust, as Suess assumed. More importantly, isostasy implied vertical movements of the crust. It was known that Scandinavia sank under the weight of the ice during the Pleistocene glaciation, and then bounced back during warmer postglacial times (see chapter 11). Similarly, when continental crusts become thinner by erosion, they become lighter and rise.

Drift versus Permanence

If vertical movements are possible, asked Wegener, why should that not be the case for horizontal displacements? He assumed that the material forming the ocean floor extended beneath the continents. He equated this material with Suess's sima and, following the work of seismologists, identified it as basalt. He gave the name *sial* to the material of granitic and gneissic composition that forms continents, slightly changing the term *sal* to avoid any confusion with the word *sal* (salt in Latin) proposed by Suess.

To consider sial as a discontinuous layer, limited to continental masses, was a noticeable change from Suess's interpretation of a continuous layer. This made it possible for continents to move horizontally like rafts. Wegener's theory was therefore in agreement with the knowledge of his own time, which disavowed Suess's synthesis made at the end of the previous century.

Some conservative American geologists, however, believed with Bailey Willis (1857–1949) in the permanence of the features of the earth. Willis said, "The great ocean basins are permanent features of the earth's surface and they have existed where they are now, with moderate changes of outline, since the waters first gathered."[20]

A similar idea had been proposed in 1846 by James Dana.[21] He accepted the contraction theory, which postulated that the earth was cooling, but stated that the continents had contracted before the oceans. During the Silurian, contraction of continents led to subsidence of ocean floors. The waters that had initially covered the entire earth were now assembled in ocean basins. Because ocean floors underwent stronger contractions, they exerted lateral pressure upon the continents, which along their borders produced geosynclines and **geanticlines** that surrounded the continents.[22] Greatly influenced by Dana, American geologists never accepted collapses of continents as proposed by Suess. Modern historians maintain that, around 1900, two schools existed: that of Suess and his followers in Europe, who emphasized repeated collapses; and that of permanists, who stressed permanence while accepting contraction. American geologists from Dana to Willis persisted in that belief.[23]

Paleoclimatic Arguments

Once the difference in composition between oceans and continents was understood, analogies of faunas and floras between distant continents remained to be explained. So did climatic variations through geological time. It was known that during the Late Paleozoic, Europe had a warmer climate, which allowed the development of the Carboniferous flora; whereas land masses of the former continent of Gondwana, in the Southern Hemisphere, display today remains of glaciations and a *Glossopteris* flora of cold climates dating back to the same period. But as long as proofs of glaciations were not common knowledge, it was possible to claim that the globe had gone through warmer periods in the past. Buffon and many other naturalists had assumed that the surface of the earth was gradually cooling. But the *Glossopteris* flora compelled scientists to accept the idea of a distribution of climates different from that known today. More precisely, today's continents must have been in different positions with regard to the poles.

Although the law of permanence was not opposed to the idea of a displacement of the poles, it was imperative to know where the Carboniferous pole was located in order to determine whether today's widely separated land masses—Australia, India, Africa, Brazil, and even Antarctica—could have been covered at the same time by an ice cap. If these continental blocks could be joined into a single one, the problem would be solved.

Wegener could thus claim that his theory was a synthesis of all existing data and explanations. He wrote:

> If drift theory is taken as the basis, we can satisfy all the legitimate requirements of the land-bridge theory and of permanence theory. This now amounts to saying that there were land connections, but formed by contact between blocks now separated, not by intermediate continents which later sank; there is permanence, but of the area of ocean and area of continent as a whole, but not of individual oceans or continents.[24]

Wegener's theory was certainly very appealing. But for his contemporaries, it had one serious flaw: it did not explain the forces or the mechanism that moved the continental rafts. Wegener believed that the drift toward the equator could be explained by a "flight from the poles" (*Polflucht*) or a push toward the equator, and the westward displacement could be attributed to "tidal friction." These forces supposedly not only pushed sialic continents over their sima substratum, but also folded the sediments, which they transported, into mountain chains. Clearly, Wegener's assumed forces were incapable of performing such a task. He recognized modestly that "the Newton of drift theory has not yet appeared."[25]

Wegener's Opponents

Wegener's theory was thoroughly discussed all over the world. In 1923 the Geological Society of France organized a colloquium at the request of its president, Paul Lemoine (1878–1940). Drift was strongly criticized by Léonce Joleaud (1880–1938).[26] Another debate had taken place in England the year before without any better conclusion.[27] In 1926 a symposium on continental drift was organized by the American Association of Petroleum Geologists. Discussions were heated, but in the end opponents of drift won out, in particular because of the insufficient nature of paleontological and geological arguments and the lack of an adequate mechanism for moving continents—this in spite of the efforts of Waterschoot van der Gracht (1873–1943), who had organized the symposium and who was enthusiastically in favor of continental drift.[28]

The most decisive objections were raised by geophysicists. To assume the gliding of sial over sima, Wegener had to admit the fluidity of sima. He claimed that sima melted at a lower temperature than sial, but experiments proved the opposite. Furthermore, seismic waves demonstrated that the substratum of oceanic depths is rigid. The opponents therefore openly stated that the theory of continental drift was unscientific.

The theory also encountered strong opposition in Germany. The main opponent was Hans Stille (1876–1966), a well-known structural geologist. He subdivided the earth's history into a series of tectonic phases that recall the ideas of Élie de Beaumont (chapter 12). Stille was a **fixist** and hence believed in the permanence of oceans.[29]

Wegener's Allies

The American scientist F. B. Taylor (1860–1938) was actually a precursor of Wegener. In 1910 he published a long paper demonstrating that the distribution of Cenozoic mountain ranges, particularly in Asia, suggested a displacement of continents from north to south. But he rejected isostatic adjustments as a mechanism for drifting continents. He interpreted the **Mid-Atlantic Ridge** as the trace left by the separation of Africa from the Americas.[30] The impact of Taylor's theory was such that contemporaries often called drift the Taylor-Wegener theory.

In Europe, Wegener was supported by Émile Argand (1879–1940), a renowned Swiss expert of the Alps and of world tectonics. In his address at the International Geological Congress in Brussels (August 10, 1924), which was published in 1922, he assumed that the entire Alpine system, stretching from the western Alps to the Himalayas, originated from a drift of the Gondwana continent against **Eurasia.**[31] He coined the term *mobilism* for ideas that considered horizontal displacements to be the major factor in the formation of nappes. Rudolf Staub (1890–1961), another Swiss structural geologist, held similar views.

Wegener's major supporter was the South African geologist Alexander L. Du Toit (1878–1948). In 1927 he published a long paper comparing the geology of South Africa and South America. Wegener was very impressed and quoted him in the last edition of his book. In 1937 Du Toit published *Our Wandering Continents,* dedicated "To the memory of Alfred Wegener for his distinguished services in connection with the geological interpretation of our Earth."[32] He presented new arguments in favor of the drift theory, showing in particular that not only the Alpine chains, but also earlier orogenic belts (Hercynian and Caledonian) could now be explained by continental drift. Wegener had joined all continents in Late Paleozoic as a single mass, called Pangea, but Du Toit introduced the idea of two more or less independent supercontinents: **Laurasia** in the north, and Gondwana in the south.

Nevertheless, the major obstacle to the acceptance of the continental drift theory was the question, What mechanism is pushing the continents?

Convection Currents

In an article entitled "Radioactivity and Earth Movements," Arthur Holmes (1890–1965), a well-known Scottish geologist and professor at the University of Edinburgh, proposed in 1928 a motor for the drift.[33] He stated that ordinary volcanic activity was insufficient to discharge the amount of heat generated by radioactivity in the substratum that was believed to rise to the earth's surface. It was therefore necessary to invoke **convection currents** in the substratum.

He wrote that when a liquid is gently heated from underneath, heat diffuses gradually upward until a critical temperature gradient is reached. If the fluid is strongly heated, the gradient is exceeded and at a certain point currents are generated that make the liquid rise and then fall along a pattern of convection circulation. He believed that a similar situation might occur within the fluid substratum underlying the earth's crust.

According to Holmes, granites in continents are particularly rich

Measuring Continental Drift

As a typical uniformitarian, Wegener hoped to prove the present-day drift of continents by geodetic measurements, saying:

> If continental displacement was operative for so long a time, it is probable that the process is still continuing, and it is just a question of whether the rate of movement is enough to be revealed by our astronomical measurements in a reasonable period of time.
>
> P. F. Jensen carried out new longitude determinations in western Greenland during the summer of 1922 [the earlier ones dated back to 1823] with this in mind, using the far more precise method of radio telegraphy time transmissions. . . . [For this purpose he established] an observatory at Kornok, in the favorable climate of the upper section of Godthaab Fjord. . . . The determination of the longitude of Kornok has now been repeated (summer, 1927) by Lieutenant Sabel-Jörgensen, using the modern impersonal micrometer which eliminates the "personal equation." This allows for greater accuracy to be achieved than was possible in Jensen's measurements.
>
> Comparison with Jensen's figures yields an increase in the longitude difference relative to Greenwich, i.e., in the distance of Greenland from Europe, of about 0.9 seconds (time) in five years, or about a rate of 36 m/yr.*

Unfortunately, these values were erroneous. Measurements of longitude were too imprecise at that time to determine continental drift. A much longer duration was required to establish the rate of separation between Europe and North America, known to be a few centimeters per year.

*Alfred Wegener, *The Origin of Continents and Oceans*, trans. John Biram from 4th rev. German edition (New York: Dover, 1966), 23, 27–29.

in radioactive elements, so the temperature beneath them should be higher than under the ocean. Currents would thus rise under continents, spread horizontally toward their peripheral regions, and then move downward when encountering, at the edges of continents, the weaker currents of the oceanic area (see fig. 16.2).

Holmes declared himself in favor of continental drift in his later work, *Principles of Physical Geology* (1964), saying: "What is really important is not to disparage Wegener's great achievement because

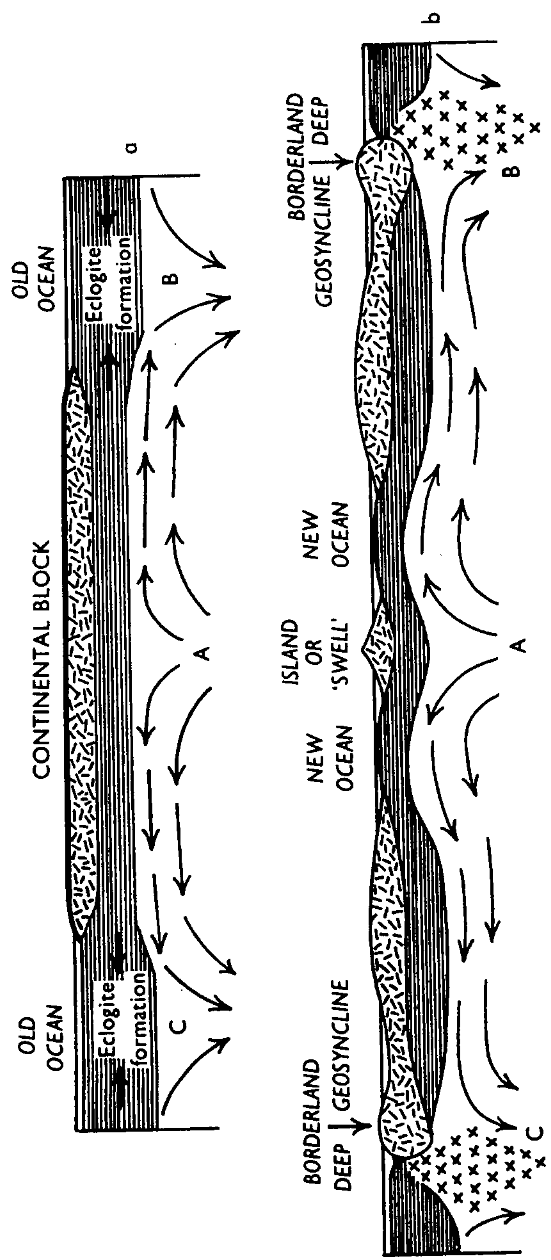

Figure 16.2. Arthur Holmes's Convection Currents Hypothesis (Transactions of the Geological Society of Glasgow 18 [1928–1929]: 579). This hypothesis was used to explain continental drift and the development of new ocean basins when it was thought that the oceanic crust was a thick continuation of the continental basaltic layer (horizontal line shading). (a) A current ascending at A spreads out laterally, extends the continental block, and drags the two main parts aside, provided the obstruction of the old ocean floor can be overcome. This is accomplished by the formation of **eclogite** *at B and C, where subcontinental currents meet suboceanic currents and turn downwards. Being heavy, the eclogite is carried down, thus making room for the continents to advance. (b) The foundering masses of eclogite at B and C share in the main convective circulation and, melting at depth to form basaltic magma, the material rises in ascending currents; e.g., at A, healing the gaps in the disrupted continent and forming new ocean floors (locally with a swell of old sial left behind, as in Iceland). Other, smaller current systems, set in motion by the buoyancy of basaltic magma, descend beneath the continents and feed great floods of plateau basalts, or beneath the "old" (Pacific) ocean floor to feed the outpourings responsible for the volcanic islands and seamounts.*

some of his conjectures can be shown wrong, but from the wealth of relevant evidence now available to assess the extent to which continental drift and other lateral displacements of the crust are genuine geological happenings."[34]

Wegener died without having understood the implications of Holmes's ideas, or of similar ones from R. Schwinner, whom he had met in college at Graz.[35] Wegener's theory was rejected by most of his contemporaries in 1930, but became suddenly famous in the 1960s.