Classic Paper in the History of Geology

Alfred Wegener's "The Origin of Continents", 1912

The year 1912 was a crucial one in the history of modern Earth sciences. It was the year in which Alfred Wegener (1880–1930) (see Figure 1) published his classic paper on the "The Origin of Continents", and also the year when Max von Laue (1879–1960) and his co-workers experimentally demonstrated interference phenomena with X-rays. However, while Laue's method was immediately recognised as a clue to the nature of crystals, Wegener's theory had to wait for more than fifty years to become fully acknowledged. Nevertheless, there was hardly any geological idea in the twentieth century that was subjected to more scientific and public dispute than Wegener's idea of drifting continents. And there was none that became more popular outside the disciplinary boundaries of the Earth sciences.

***Figure 1** Alfred Wegener in 1910, the year when he first thought of a former direct connection of Africa and South America (by kind permission of Deutsches Museum, Munich).*

A new culture of Earth science

Wegener's new picture of a dynamic Earth had two essential features. The first was the postulate of large-scale—and ongoing—horizontal movements of the continents, contrary to the then prevailing theory of the permanence of continents and oceans. The second was a geophysical point of view, which was due to Wegener's specific background. He had studied astronomy at Heidelberg and Berlin, turning more and more to geophysics and to meteorology. As an assistant at the Aeronautical Observatory at Lindenberg near Berlin, he became acquainted with modern methods for the study of the upper atmosphere—and, together with his older brother Kurt Wegener (1878–1964), he set a world record for balloon riding (fifty-two hours) in 1906.

The same year Wegener set off for his first expedition to Greenland, carrying out some of the earliest kite and attached balloon ascents in the Arctic. A year after his return, in 1909, Wegener moved to the University of Graz as a lecturer in astronomy and meteorology, where he published his first comprehensive meteorological book entitled *The Thermodynamics of the Atmosphere* (1911). During the preparation of the Arctic expedition, Wegener had met Wladimir Köppen (1846-1940), one of Europe's leading meteorologists, who was to become his mentor and collaborator, and also his father-in-law; for in 1913 Wegener married Köppen's daughter, Else (1892–1992).

Thus, Wegener's theory was essentially a geophysical critique of some common assumptions of Earth sciences around 1900. In particular, he rejected the hypothesis of former, now sunken, land bridges between continents—postulated in order to account for the striking geological and palaeontological similarities of the continents (particularly those of the Southern Hemisphere)—as being inconsistent with the geophysical doctrine of isostasy.

First ideas on drifting continents

The elaboration of the theory of continental drift was a work of just a few months. Although Wegener may have noticed the striking congruence of the coastlines on the opposite sides of the Atlantic Ocean as early as 1904, he did not think of a former direct connection before late 1910. His actual starting point, however, was a paper summarising the observations on the close relationship of the older fauna of South America and West Africa. He became aware of this in the autumn of 1911, and, only a few weeks later, he gave a preliminary account of his ideas to his mentor Wladimir Köppen:

> *Dear Father*, [...] *I think you take my primeval continent to be more fanciful than it is, and you still don't see that it is simply a matter of the interpretation of observational material.* [...] [W]*e are obliged to assume a land connection, for instance, between South America and Africa, which broke off at a certain time. This event could be explained in two different ways: (1) by the sinking of a connecting continent "Archhelenis"; or (2) by the drawing asunder of each landmass at a great fault. Hitherto, starting from the unproven idea of the fixed position of each landmass, one has always just considered (1) and ignored (2). However, (1) contradicts the modern doctrine of isostasy, and our physical notions. A continent cannot sink, for it is lighter than that upon which it is floating. Therefore, let us, just for once, take (2) into consideration! If such a series of astonishing simplifications follows, if it is shown that rhyme and reason will now come to Earth history, why should we hesitate to cast the old view overboard? Why should one withhold this idea for 10 or even 30 years?* [...] *Is it, perhaps, revolutionary?* [...] (Wegener to Küppen, 6 December, 1911, Deutsches Museum München, Manuscript Department, 1968-596/17, N 1/36).

A month later, on 6 January, 1912, Wegener presented his theory for the first time at the meeting of the *Geologische Vereinigung* [Geological Association] in Frankfurt [am Main], and immediately published it. The new theory was, however, almost completely rejected, for quite diverse reasons: for instance, Wegener's inability to give a satisfactory explanation of the forces that keep the continents moving; his futile hope for direct confirmation by astronomical or geodetic measurements; or his particular geophysical point of view, which did not mesh well with the practices of Earth sciences in the early twentieth century. In addition, a slight "anti-Germanism" among the international scientific community, arising from World War I, may also have played a part. In any case, one should be cautious about interpreting the early history of the reception of Wegener's theory simply as a story of an ingenious young man battling "hide-bound" and "stubborn" colleagues. It should be realised that by 1912 Wegener was already an acknowledged meteorologist. Later, his reputation as a hero of polar exploration may have helped keep his theory alive. Nevertheless, the idea of "wandering continents", and its modification to modern plate tectonics, will always remain one of the most fascinating episodes of twentieth-century geoscience.

Extracts

The following extracts from Wegener's paper (in italics) focus on his specific ideas and arguments for continental drift, omitting particularly his extended exemplifications of the doctrine of isostasy, etc. A few comments are provided to assist understanding of Wegener's train of thoughts. The translation follows the text carefully, though with smoothing of Wegener's "German style" (i.e. some of his long sentences have been divided and some of his superfluous words omitted). The original page numbering is given in parentheses.

[185] Extracts from: Alfred Wegener, *"Die Entstehung der Kontinente"*, Dr. A. Petermanns Mitteilungen aus Justus Perthes' Geographischer Anstalt, 1912, Volume 58, 185-195, 253-256, 305–309.

In what follows a first [and] *approximate attempt will be made to give a genetic explanation of the large-scale features of our Earth's surface, i.e. of the continental blocks and ocean basins, by a single comprehensive principle, namely the principle of horizontal mobility of continental blocks. Wherever we have previously had former land connections sinking down to the ocean depths, we now assume a splitting off and drifting apart of continental blocks. The picture of the Earth's crust that we shall get in this way is a new one, and, in some respects, a paradoxical one. However, as will be shown, it does not lack a physical cause. Moreover, on the other hand, already from the preliminary examination attempted here, based on the principal results of geology, and geophysics, such a large number of surprising simplifications and interrelations is revealed that, for these reasons alone, it appears to me to be justified, and, indeed, necessary, to substitute the new, more effective working hypothesis for the old one of sunken continents, the inadequacy of which is already clearly demonstrated by the doctrine of the permanence of the oceans. Notwithstanding this broad foundation, I call the new principle a working hypothesis, and I should like to have it treated like this, at least until it is possible to prove the continuance of horizontal movements in recent times by means of astronomical position-finding with an accuracy that excludes all doubt.* [...]

I. Arguments from geophysics

[186] *1. THE RROBLEM OF CONTINENTAL BLOCKS.*
[...]

[Wegener begins by stating that, according to the statistical distribution, taken over the Earth's crust, there are two modal values of the level of the land above and below sea level, while intermediate values are rare.]

[186–187] *The present opinions on the origin of those peculiar, tabular elevations of the Earth's crust* [see Figure 2], *provide a rare example in science of contradictory confusion. Although, polemics are to be avoided in this paper, we must take a short critical look at previous ideas, to see what we shall lose if we replace them by our hypothesis. European geologists, for the most part, I suppose, still assume the formerly perhaps useful notion, powerfully illustrated by a drying apple, that the Earth is contracting due to progressive cooling, and that* [the contraction] *occurs more on the inside than the outside. Consequently, within the outer crust, which is continuously becoming too large* [literally "wide"], *there should be an overall and continuous "arching pressure"* [Gewölbedruck], *which produces its wrinkling (fold mountains). Moreover, it is supposed that the sinking of the Earth's crust during its shrinkage occurs irregularly, so that at one place a "horst" may continue standing while the adjacent block has already sunk. The continents are supposed to be such horsts. During the further course of contraction, the horsts may perhaps sink alongside the oceanic blocks so that any change*[s] *of continents and oceans may occur. The chief advocate of this theory, Eduard Suess* [1831–1914], *summed it up in one sentence: "What we are witnessing is the collapse of the terrestrial globe". However, the uncompromising consistency with which Suess elaborated this idea, may already have opened the eyes of many to its weak points, and, thus, indirectly prepared the way for a more satisfactory conception. Since* [Albert] *Heim* [1849–1937] *spoke up for the contraction hypothesis, geophysics has accumulated difficulties upon difficulties. Not even the basic principle that "the Earth is cooling" appears to be beyond doubt and remains untouched, for radium research, on the contrary, has raised the question of whether the temperature within the Earth will increase. Since one can say with high probability that the Earth's interior does not consist of readily compressible gases, but of already highly compressed, and therefore almost incompressible, nickel–iron, the alleged cause appears to be no longer sufficient to account for the large folds of the Earth's crust, particularly since their size in nappe–fault structures has been properly understood. The intense arching pressure, which should be capable of transferring the* [...] *contraction of a whole great-circle to a single point on it has been shown to be physically impossible, since the molecular forces (compressive strength) are not sufficient to preserve the cohesion of even a block 100 kilometres wide, being thrust over another one* [i.e., prevent it from breaking] [...]. *Moreover, it is scarcely intelligible how the same process of Earth contraction could, on the one hand, lead to wrinkling or folding, and on the other hand to the subsidence of enormous blocks and the formation of horsts. The idea of the changing up and down of the continental horsts and the oceanic depressions is also inconsistent with the fact,* [now] *becoming ever more clearly realised, that almost all the sediments found on the continental blocks come from coastal waters, so that they have never formed the floor of the deep sea, but have only been inundated from time to time by shallow transgressions.* [...]

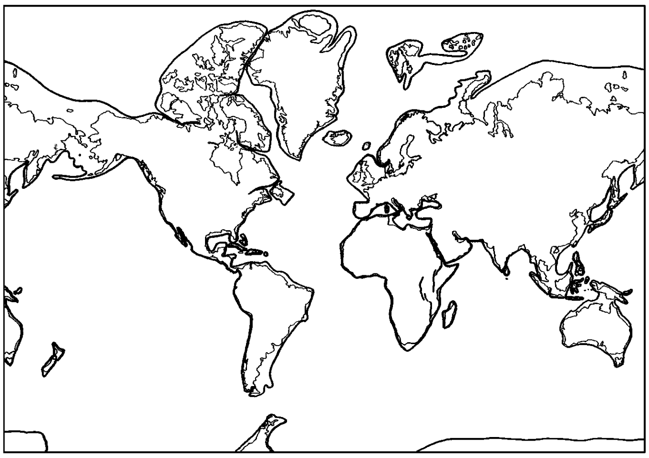

Figure 2 **[Wegener's Plate, figure 1]** ***Map of the continental blocks (i.e., landmasses with continental shelves).***

[187] *However, even without all these arguments against the collapse of the terrestrial globe, we would still have to reject the idea, for it contradicts the results of gravity measurements. If*

the ocean floors were nothing but sunken continents, they would consist of the same material as those. Gravity measurements, however, show with irrefutable logic that the rocks underlying the oceans are heavier [denser] *than those beneath the continents. they are not simply heavier ones but precisely such heavier ones that the altitudinal difference is compensated,* [and an] *equilibrium of pressure prevails. In the following sections we shall discuss the gravity measurements in more detail and the associated hypothesis of isostasy. Anybody who does not close his eyes to the precise results of the former, and is not biased against the achievements of the latter, can hardly insist on the collapse hypothesis. This has often been emphasised by American scientists. However, because horizontal displacements of the continents were not taken into account, and from the* [correct] *neglect of the collapse and the* [false assumption of] *permanence of the continental blocks the erroneous doctrine of the "permanence of the oceans" followed,* [...].

[188] *3. ISOSTASY. The fact that the oceanic gravity is not only greater than expected, considering the existing mass deficit, but, that it shows—though with some deviations—approximately the same value as on the continental blocks, is hardly to be explained other than by the assumption of the equilibration of pressures or "isostasy". Accordingly, the lighter continental blocks are, so to speak, floating in the heavier mass, and are thereby adjusted in such a manner that an equilibrium of static pressure prevails, like an iceberg floating in water.* [See Figure 3.]
[...]

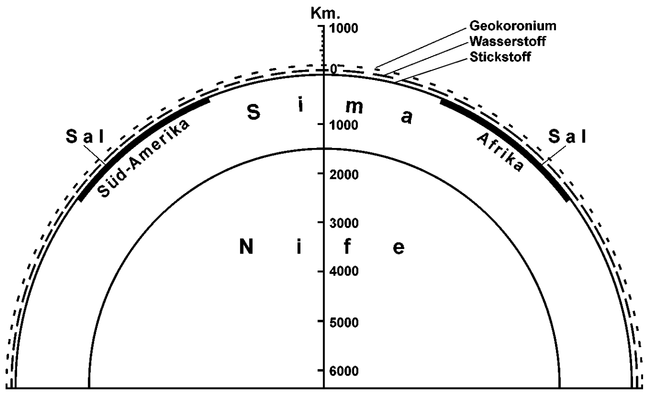

Figure 3 **[Wegener's Plate, figure 2]** ***Cross section in a great-circle through South America and Africa, showing the floating continents within the sima; also represented are the atmospheric layers of Nitrogen, Hydrogen and Geokoronium.***

[Some further discussions of the application of the principle of isostasy (to inland icecaps, etc.) follow, as well as of the thickness of the continental blocks (Wegener assumed a mean value of the lower boundary of the lithosphere of about 114–120 kilometres), and the material of the lithosphere. Referring to Eduard Suess's distinction between "sial" and "sima" layers, Wegener emphasised the different densities of the sial, i.e. the continental blocks (2.5 to 2.7), and the sima, i.e. the ocean floors (about 3.0). [In the present paper, Wegener still used Eduard Suess's original term "sal", whereas in all his subsequent papers, he changed to the modern one "sial". the latter is used here throughout].

[191] *6. PLASTICITY. According to our opinion, sialic blocks should have the ability to move horizontally within the sima. For this, it is important that the melting point of the sial is about 200 to 300˚* [Centigrade], *greater than that of the sima, so that the latter will still be fluid at a temperature at which the former has already solidified. The difference, indeed, is not sufficient to allow one to assume that solid sialic blocks float within a fluid sima, for—because of the large temperature increase towards the Earth's interior—this could only be the case within a layer of about 6 kilometres thickness, while the continental blocks must be presumed to be about 100 kilometres thick. Rather, as we shall now show, we should think of both parts as being viscous or plastic. However, on these conditions—ceteris paribus [other things being equal]—the sima must be more plastic, because, related to the melting point, its temperature will always be 200 to 300˚* [Centigrade] *greater than that of the sial.* [...]

[192] *Moreover, however, from this [*i.e., from the assumption that at a certain depth there is no further increase of temperature, i.e. there is a more or less constant temperature of about 3000˚ [Centigrade], *I suppose it follows that the melting point of silicates, even at greater depth, will not be exceeded, so that—with regard to the viscosity of the molten rocks, mentioned above—we must consider the entire 1500 kilometres thick sima layer of the Earth as being viscous. If, on the other hand, we take into account [the fact] that solid bodies under high pressure generally exhibit plasticity to some degree (pseudo-plasticity), so, either way, we shall reach the conclusion that both the sial and the sima should be considered as being plastic, the latter to a higher degree than the former.*

The characteristics of such viscous fluids are paradoxical in that the duration of the acting forces plays such a significant part. Black pitch provides an extreme example: if one keeps a specimen lying for a long time, it will begin to melt as a result of its own weight, and small balls of lead will sink into it in the course of time; however, it cracks like glass by a blow with a hammer. [...]

[193] *All these observations thus indicate that the sima represents a plastic, but by no means fully mobile, material, and that the Earth's sialic crust has a considerably greater solidity, without, however, lacking plasticity altogether. Thus we have no reason to deny the possibility of extremely slow, but large, horizontal displacements of the continents, insofar as there may be forces acting continuously in the same sense through geological time.*

[193] *7. MOUNTAIN FORMATION AND THE ORIGIN OF CONTINENTAL BLOCKS. In applying the ideas on mountain formation, arrived at in the foregoing, it should be noted that the plasticity of the sediments is, I assume, still considerably less than that of the primeval sialic rocks. Without mentioning* [the fact] *that the sediment cover, being the uppermost crust, always has a lower temperature than that of the underlying primaeval rocks, concerning their plasticity, I also presume that a fundamental structural difference between the two has to be assumed. For sediments we only see, for the most part, large folds whose dimensions are often similar to those of mountains themselves. By contrast, the primaeval rocks mostly show, even in a specimen, the most complex foliation. This difference likewise appears in the peculiar nappe–fault structures of the mountains,* [...]. *According to this, the sediment cover is thrust, one* [layer] *upon another, like numerous scales. Thus the primaeval rocks of the substratum evidently behave quite differently in this* [process], *being more ductile. Comparatively rarely, the substratum participates in the overthrusts; the result is mainly a thickening of the whole block, especially towards the bottom, and instead of large uniform folds a tangle of narrow foliation*[s] *is produced, which is so characteristic of primaeval rocks.*

These studies have also corrected the previous underestimate of the areas thrust up in the mountains. For example, while Heim, still in accordance with the earlier doctrine, calculated a contraction to four-fifths for the Jura mountains of Switzerland, and to a half for the Alps, by taking into account the nappe–fault structure he reached the conclusion that the *compressed mass was, in this case, up to four or five times the present width of the mountains; and because the latter is 150 kilometres, some 600–1200 kilometres of crust were compressed in this case. The implication—that, prior to the compression, the continental block must have had a quite different outline—has, in my opinion, not yet been taken into account sufficiently. If, for instance, the Himalayan chains, are also made up of compressed land masses of a corresponding width, where would the southern point of Lower India [*the Indian peninsula*] be located prior to the compression? Would there have been room for a sunken "Lemuria"?* [...]

[194] *Thus, taking the foregoing into account, the principle follows that mountain formation—acting from ancient times, but frequently changing its place—has brought about, and is still bringing about, a thickening of the continental blocks at the expense of their horizontal extension. In this case, it is a question of a unilateral, irreversible process: each pressure brings about an increase of thickness and a decrease of the surface; tension, however, is never able to bring about the reverse, but merely leads to the disruption of the block.*

Thus, we arrive at a large-scale picture of the origin of the continental blocks. The primeval sialic rocks are nowhere lying horizontally over great distances. Rather, almost everywhere they are set vertically, closely folded, compressed, torn, and dislocated. Hence, I suppose, the assumption is justified that at one time the sialic crust covered the whole Earth to a thickness of about 30 kilometres, and that this crust, by the continuous processes of splitting and compression—the individual stages of which we perceive as mountain formation—gradually lost surface [area] *and connection, and, instead, increased in thickness.* [...] *While a 3 kilometres deep ocean, "Panthalassa", initially covered the Earth's surface, this, associated with the growth of the continental blocks, began to divide itself into a shallow and a deep sea, till the continents emerged, which* [process] *is not yet completed. Only after an uplift of an additional half kilometre, did the coast-line coincide everywhere with the margins of the continental blocks.* [...]

[194] *8. VOLCANISM. So far, an obvious objection has been entirely omitted. With each displacement of the continental blocks the sima of high temperature, lying beneath it, becomes exposed, and, that is, under the ocean. must not this cause catastrophic events? In this respect, it should be recalled that submarine lava ejections are usually unrelated to great catastrophes.* [...] *Furthermore, one should take into account the fact that the sima within a fissure, will, according to the law of the communicating vessels, rise of its own accord insofar as isostasy is prevailing. To carry it onto the surface of the continents, local pressure is always required (provided that a magma of unusually low density is not involved). Such local forces can indeed occur in most parts of the Earth, because the sima is* [...] *not a perfect fluid. However, it should be noted that areas of tension—such as, according to our opinion, the Atlantic Ocean—must be relatively deficient in volcanoes, as compared with areas like the Pacific Ocean, where pressure predominates.* [..] *In general,* [...] *we may say that the front of moving blocks provides conditions more favourable to volcanism than does their rear.*

[Although Wegener concluded that the places where incipient separations of continents are occurring have relatively few volcanoes, he noted that some periods of Earth history indicated increased volcanic activity. This might be due to particularly large displacements. Indeed, the Tertiary period—regarded as an epoch of increased volcanic activity—was also a period of particularly large displacements.]

[194–195] *9. REMARKS ON THE CAUSE OF THE DISPLACEMENTS. The question of the forces causing the claimed horizontal displacements of the continents [*naturally*] suggests itself, so that I cannot omit it entirely, though I think [*its consideration*] is premature. First, it is undoubtedly necessary to determine the reality and manner of the displacements accurately before one can hope to find their cause. Thus, the objective is chiefly to eliminate false ideas rather than offering ones that can already be claimed to be correct. The use of polar oscillations may be suggested as a cause; for each such oscillation releases an army of new centrifugal forces, and thus could bring about displacements of the masses. However, in the last part it will be shown that, on the contrary, the polar wanderings should be understood as a result of displacements of mass* [not their cause].

I should like to suggest that it is more likely that the tides within the terrestrial body, caused by the Moon, may be considered as the essential cause. To me, it seems that the preference for the formation of meridional fissures speaks in favour of [this hypothesis]. *The latter also seems to be the cause of an often highlighted characteristic of the shapes of the continents, namely their terminating in a point towards the poles. At present, this is most distinctly seen in the regions of the former South Pole where, since the great detachments, the contours have not been disturbed subsequently by pressure. At the position where, as will be shown below, we must assume the North Pole* [to have been] *in former times-that is, at the Bering Strait—the continental blocks also end approximately in a point. However, it seems that there, due to the compression, the shapes have not been preserved properly. Presumably, for the present, it is best to consider the displacements of the continents as the result of random tidal motions within the terrestrial body. Perhaps it will, in the future, be possible to separate that which is merely accidental in* [all] *this—i.e. what is due to external causes—from the tendency towards a state of equilibrium due to the* [Earth's] *rotation.* [...]

II. Geological Arguments

[...]

[253] *1. TRENCH FAULTS* [or rift valleys]. *Hitherto, in picturing the tectonics of trench faults to ourselves, gravity measurements have rarely been taken into account. Mostly, one is content with the notion that here the uppermost layers of the Earth have "sunk" along a line* [...]. *From gravity measurements, however, it follows that, beneath a graben, material of greater density lies adjacent to that which is beside it. And this, I suppose, may be explained in that in this case we have a fissure within the continental block into which the heavier sima has risen, insofar as isostasy prevails. According to the foregoing, this will already be the case if the sima is still lying about 3.5 kilometres below the surface of the continents; and such a deep fault, of course, will be filled by lateral sliding [*movements*] of the fault's edges (echelon faults, etc.), so that the occurrence of surface-layers at the bottom of the trench is not surprising. In my opinion, all trench faults must be explained like this, or similarly, as fissures of the continental blocks. That is, they are incipient separations, which might either be actual recent fractures, or previous attempts at separation, which, however, owing to the cessation of the driving forces, have come to rest again. Concerning the Upper Rhine Lowlands, the latter might be the case, for this fault was already active during the Oligocene, contemporaneously with the separation of North America and Europe* [...].

The most interesting example, however, is provided by the East African trenches and their continuation through the Red Sea up to the Jordan valley. [...] *Even if the legend, popular among Somalis, that the Red Sea did not exist prior to Noah's Flood, is doubtless inconclusive, nevertheless the Sea seems to* *be [the product of] a younger disruption of a continental block.* [...] *At most trenches, the measurable mass deficit is not compensated by the greater density of the matter beneath the graben, but, on the contrary, the deficit is additionally accompanied by an underlying relaxation. Thus, we have the picture of fissures penetrating into the continental blocks from above, but not getting right through, so that the dense sima has not yet risen within them.* [...]

[254] *2. Atlantic Ocean and Andes. The large-scale parallelism of the coasts of the Atlantic Ocean is an argument not to be underrated, and favours the assumption that they represent the edges of an immense expanded fissure. A glance at the map is sufficient to enable one to recognise that where there are mountains in the East, such are also to be found in the West; and where such are missing here, they are also missing there. In the North, the Greenland mountain massif corresponds to that of Scandinavia. Furthermore, corresponding to the less mountainous North America there is similarly the less mountainous Europe. For the Central American fault zone there is the* [analogous] *European Mediterranean. And there is the African block corresponding to the great South American block.* [...]

[...] *For those parts we know best, namely Europe and North America, there is an almost complete conformity in the details.* [...] *The most northerly zone consists of gneiss on both sides: in Europe this is the gneiss zone of the Lofoten Islands and the Hebrides, while in the west lies the Greenland massif, consisting almost entirely of gneiss. Also, the western coast of Davis Strait and Baffin Bay consists of gneiss mountains, which extend southwards through Cumberland and Labrador towards the Strait of Belle Isle.*

*Most striking, however, are the relations, first unveiled by Marcel Bertrand in 1887, which follow for the [*more*] southerly adjacent chain of folds of a Carboniferous mountain range, which Suess called the Armorican mountains, and which make the coalfields of North America appear to be the direct continuation of those of Europe.* [...]

Likewise, the breaking off of these "transatlantic Altaides", as Suess calls them, at places lying exactly opposite [one another], *is the most striking proof in favour of the* [former] *connection of the coasts. Concerning the previous assumption—that the connecting mountain chain has sunk into the Atlantic Ocean—the circumstance would constitute a difficulty, as* [Albrecht] *Penck* [1858–1945] *has pointed out, in that the missing section of the assumed mountain range would have to be longer than its known extent.* [...]

[Concerning the questions of whether, on the basis of palaeontological findings, a former connection between America and Europe-Africa may be assumed, and when the separation occurred, Wegener states that both questions have already been answered. Both are quite independent of whether one assumes horizontal displacements or a sinking of land bridges. However, there is a difficulty for both hypotheses, namely transgressions. By shallow transgression, parts of one and the same continental block may have been be separated with respect to the fauna and flora, and it will often be difficult to decide whether there has been a 'splitting' or separation by marine transgression. Wegener then recapitulates some of the chief results hitherto obtained: (1) the connection of South America and Africa during the Mesozoic period by a Brazilian–African continent, called "Archhelensis", which broke off at the end of the Eocene or the beginning of the Oligocene; and (2) a connection between Europe and North America, still present during the older Tertiary, which allowed the exchange of forms, but which was severed during the Miocene. (However, connection might have been retained in the far north, over Scandinavia and Greenland, through to the Ice Age.)]

[255] *With these ideas the occurrence of a steppe climate during the interglacial period in Central Europe, deducible from the numerous remains of steppe animals, corresponds too.* [...] *From the present-day neighbourhood of the deep sea in the west this would be inexplicable.* [...] *Our hypothesis helps overcome this dilemma; for if, during that time, Greenland were still connected to Europe and America, then the North Atlantic Ocean would have formed just a small arm of the sea, as yet incapable of influencing the continental climate of Europe fundamentally.* [...]

Because the folding of the Andes was essentially contemporaneous with the opening of the Atlantic Ocean, the idea of a causal relation is immediately suggested. Accordingly, the American blocks, during their westward drift, would have encountered resistance at the presumably very old and still only slightly plastic floor of the Pacific Ocean, by which the extended shelf with its mighty sediments, which once formed the Western border of the continental block, were compressed to form a range of fold mountains. Additionally, in this case, we have an example of the fact that the sialic blocks may behave in a relatively plastic fashion; the sima relatively rigidly. However, I suppose we may regard it as probable that the sima also yielded, so that the folding of the Andes need not be equivalent to the whole width of the Atlantic Ocean (about 4000 kilometres). Moreover, do we take into account the nappe–fault structures, discussed above—according to which, I presume, as with the Alps, an area of four-to-eight times greater width than that of the [present] *mountain range should be assumed—I do not see any further reason to hesitate about the suggestion of a causal relation between the folding of the Andes and the origin of the Atlantic Ocean.*

[255–256] *3. GONDWANALAND. In applying the foregoing views on the connection of folding with horizontal displacement to the Tertiary folds of the Himalayas, we arrive at a series of unexpected relations. Had that block, by which the compression of the Earth's highest mountain range originated, been of a similar size as—according to the theory of overthrusting—was the Alps, and as we have just supposed it to have been for the Andes, then Lower India would have to have formed an extended peninsula before the folding, the southern end of which lay adjacent to that of South Africa. By this compression of an extended peninsula, the special* [tectonic] *position that Lower India, "all around a fragment" (Suess), occupies in relation to its present-day environment, is explained.*

Indeed, such a former elongated Indian–Madagascan peninsula, "Lemuria", has long been presumed from palaeontological considerations, such that, prior to its supposed sinking, it was long separated from the African block by the wide Mozambique Channel and its northerly extension, which is—according to our opinion—a wide meridional fault. [...]

[256] *The palaeontological results leave no doubt that Australia has had a direct land connection with Lower India as well as with South Africa and South America. This continent has been called "Gondwanaland", to which—assuming an unchanged position of its present remnants—a very wide area had to be ascribed. Thus, we must assume that the Australian block was also formerly connected directly to the primeval continent. The separation of Africa and Lower India seems to fall within the same period as the separation of those parts* [of Gondwanaland] *from each other; for in the Permian (immediately preceding the Triassic) there was still a connection, whereas in the Jurassic, which follows the Triassic, there was no more connection. On the other hand,* [...] *a connection with South America, which first broke off during the Quaternary, seems to have been preserved. This connection, I suppose, ran across the Antarctic continent, which, unfortunately, is still almost completely unknown.* [...] *For the present, it appears as if the west coast of Australia was directly connected to the east coast of Lower India. However, as mentioned above, it got split off during the Triassic period, while the whole of the south coast*

was still firmly connected to Antartica. Subsequently, the Antarctic block, like the South American one during the Tertiary period, appears to have moved over from South Africa towards the side of the Pacific Ocean [...]. *During the Quaternary, then, the Australian block* [became] *detached, still bearing at its eastern edge the continuation of the Antarctic Andes, of which New Zealand represents a separated fragment.* [...]

[256] *4. PERMIAN ICE AGE. These ideas seem to find a very striking confirmation in the phenomenon of a Permian ice age (which, according to some researchers, extended into the Carboniferous), the traces of which may be found at different places in the southern hemisphere, whereas in the northern hemisphere they are as yet missing. Hitherto, this Permian ice age constituted an insolvable riddle for palaeogeography. For these undoubted ground moraines, from an extensive inland icecap, lying on a characteristically scratched bed rock, are found in Australia, South Africa, South America, and also, notably, in eastern India.* [...] [S]*uch a vast extension of the Arctic icecap is quite impossible according to the present arrangement of the lands.* [...] [H]*ardly any part of the Earth's surface could be free from glacial phenomena. And the North Pole would accordingly have fallen in Mexico, where, however, no trace of a Permian glaciation is to be found. The South American findings, however, would be located exactly at the equator.* [...]

If, according to these ideas [i.e. of horizontal displacements of the continents], *we reconstruct the conditions during the Permian, so that all regions subjected to glaciation cluster concentrically round the southern end of Africa, we have merely to place the South Pole in the greatly reduced glaciated area to remove all the inexplicable things from the phenomenon. Accordingly, the North Pole would, I suppose, be lying beyond the widely opened Bering Strait, in the Pacific Ocean.*

[305] *5. ATLANTIC AND PACIFIC HEMISPHERE[S].*
[...]

[Referring to Suess, Friedrich Becke (1855–1931), and Otto Krümmel (1854–1912), Wegener points to some remarkable differences between the Atlantic and the Pacific hemispheres, namely: (1) the well-known distinction between "Pacific" and "Atlantic" types of coast (the presence of marginal chains and ocean trenches in front of the Pacific coasts, as against the Atlantic ones, representing faults in a plateau, with rugged, irregular "ria" coastlines, etc.); (2) the difference in the volcanic lavas of the two hemispheres (the Atlantic ones contain a greater amount of sodium (Na), whereas calcium (Ca) and magnesium (Mg) are dominant in the Pacific lavas); and (3) the difference in the mean depths of the two oceans (4,097 metres for the Pacific as against the Atlantic with 3,858 metres). Taking into account the principle of isostasy, this difference indicates a greater density of the Pacific Ocean's floor due to the lower temperature of its older sima, compared to the newly exposed sima of the Atlantic.]

[305] *Striking though these differences are, little has been done to explain them hitherto.* [...] *By our hypothesis, however, we are guided quite naturally to expect an essential difference of that kind. The opening of the Atlantic Ocean corresponds to an almost universal pressing of the continents against the* [region of the] *Pacific Ocean; at the coasts of the latter, pressure and compression prevail everywhere, whereas at those of the former there is tension and rupture. The first detachment occurred, according to our ideas, near South Africa during the Triassic. This harmonises with the fact that no further folding has occurred in the Cape mountains since the preceding Permian, and thus no further horizontal pressure has played an active role. In the Sahara, Africa has been free from folding even since the Upper Silurian; and on the "Armorican line" since the Middle Carboniferous. One may also assume that that fault, whose wide opening once formed the Pacific and, from either shore, brought pressure and compression to the primeval continent, originated during the earliest geological times, and that the movement died out long ago, when the forces occurred that created the Atlantic. It is not unimportant that the view, thus obtained, of a very great age for the Pacific Ocean, corresponds to all our other information on the question.* [...]

[305–306] *These* [different mean depths, indicated by Krümmel] *also seem to suggest the idea of the mid-Atlantic ridge being that zone in which, during the still continuing expansion of the Atlantic Ocean, its floor was continuously rupturing, thus making room for fresh, relatively liquid and high-temperatured sima from the depth*[s].

[306] *6. POLAR SHIFTS. Notwithstanding the great and justified caution with which all assumptions about polar shifts are treated in geology, nevertheless, a lot of material has been brought forth from this side particularly in recent times, such that [*at least*] one great shift has to be considered proven. During the Tertiary, the North Pole was wandering from the region of the Bering Strait over to Greenland, and the South Pole from South Africa towards the Pacific.*

During the two oldest epochs of the Tertiary, i.e. the Paleocene and the following Eocene, the climate of Western Europe was still decidedly tropical, and during the Oligocene palm-trees and other evergreen plants were distributed as far up as the present-day shore of the Baltic Sea; [...] [L]*ater, however, they disappeared, and the climate became cooler and cooler, so that in the last epoch of the Tertiary, the Pliocene, the temperature conditions of Central Europe were already no different from the present ones; and after that the Ice Age followed. By these changes, the approach of the North Pole is clearly demonstrated. The same picture of polar shifts is shown by non-European observations. At the beginning of the Tertiary,* [...] *when the Pole still had its old position, beeches, poplars, elms, oaks, and even taxodiaceae, plane trees and magnoliaceae, were growing in Greenland, Grinnell Land, Iceland, Bear Island, and Spitsbergen—regions that are presently located about 10–22 degrees north of the timber line* [...]

It seems quite impossible that the North Pole, during its Tertiary wandering, moved directly to its recent position, and also that it could already have been lying there during the Ice Age. For it would then have still been lying about 10 degrees from the edge of the large inland ice-cap, which, at that time, would have covered North America and Europe to an extent similar to the [area of] *the recent antarctic ice-cap. I think it would be more natural to assume that the Pole first wandered at least 10 degrees farther into Greenland, and returned to its recent position since the Ice Age.*

It is [a matter] *of great importance to reconstruct the corresponding position of the South Pole. If the North Pole, lying at the Bering Strait, were shifted by 30 degrees, as compared with the present time, the South Pole would have to be located about 25 degrees south of the Cape of Good Hope, i.e. on the Antarctic continent, which was then apparently still reaching up to these latitudes. In the known regions of the Southern hemisphere, we might thus expect only a few relics of glaciation of that time, or none. On the other hand, the Permian ice age, discussed above, demonstrates that in earlier periods the displacement, was, at times, greater (perhaps 50 degrees). At that time, the North Pole would still have to have been located far beyond the Bering Strait in the Pacific Ocean,* [...].

[307] *Additional special attention needs to be paid to only one further matter* [...] [namely] *the great fault zone of the Mediterranean, which surrounds the Earth in the form of a great-circle* [...]. *Indeed, it represents the equator for that former position of the pole, occupied, perhaps, during the whole of the*

Mesozoic, during which time the North Pole was lying in the area of the Bering Strait, with the South Pole south of Africa.
[...]

Of the greatest importance for the understanding of the whole phenomena, however, is the fact that the great shiftings of the poles obviously took place at the same time as the great displacements of the continental blocks. In particular, the temporal coincidence of the best confirmed pole-shift, during the Tertiary, with the opening of the Atlantic Ocean is evident. Also one might perhaps connect the (relatively small) wandering back of the poles since the Ice Age with the separation[s] *of Greenland and Australia. Accordingly, it seems as if the great continental displacements are the cause of the polar wanderings. In any case, the* [Earth's] *axis of rotation will have to follow its axis of inertia. If the latter is changed by a shifting of the continents, the rotational axis has to wander correspondingly.*
[...]

III. Recent displacements and polar oscillations

[In the last part of his paper, Wegener endeavoured to calculate the recent rate of the continents' displacement. Comparing the longitude determinations of his expedition to Greenland in 1906–1908 with those of a previous German Arctic Expedition in 1869–1870, he deduced an increase of the distance between Greenland and Europe of 11 metres per year. And, referring to determinations by transatlantic cables, he presumed that North America drifts away from Europe at about 4 metres per year. However, he was well aware that these values were uncertain.]

[308] *If, however, a new longitude measurement—twenty years have already passed since the last one—should yield a further change in a like sense, then the reality of the displacement might no longer be doubtful. It is not impossible that, in addition, there are other locations on the Earth's surface where we may hope to determine the horizontal displacement in a relatively short time. Here, especially, Lower India and Australia might be considered, where one could use the much easier and more precise determinations of latitude for this proof.* [...]

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I am grateful to David Oldroyd for his assistance in the preparation of this paper; and to the Deutsches Museum, Munich, for permission to reproduce [in translation] part of a letter from Wegener to his father-in-law, and the picture of Wegener in Figure 1.

When the present paper was almost completed, it came to my knowledge that another English translation of Wegener's paper had recently been published by Wolf Jacoby in the *Journal of Geodynamics* (see the reference list at the end of this paper). Although, at first, I hesitated to seek to publish my version, I thought that Wegener's paper is such an important one that it should have a place in the Classic Paper series in any case, and I hope it may contribute to giving his original thoughts a wider audience.

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