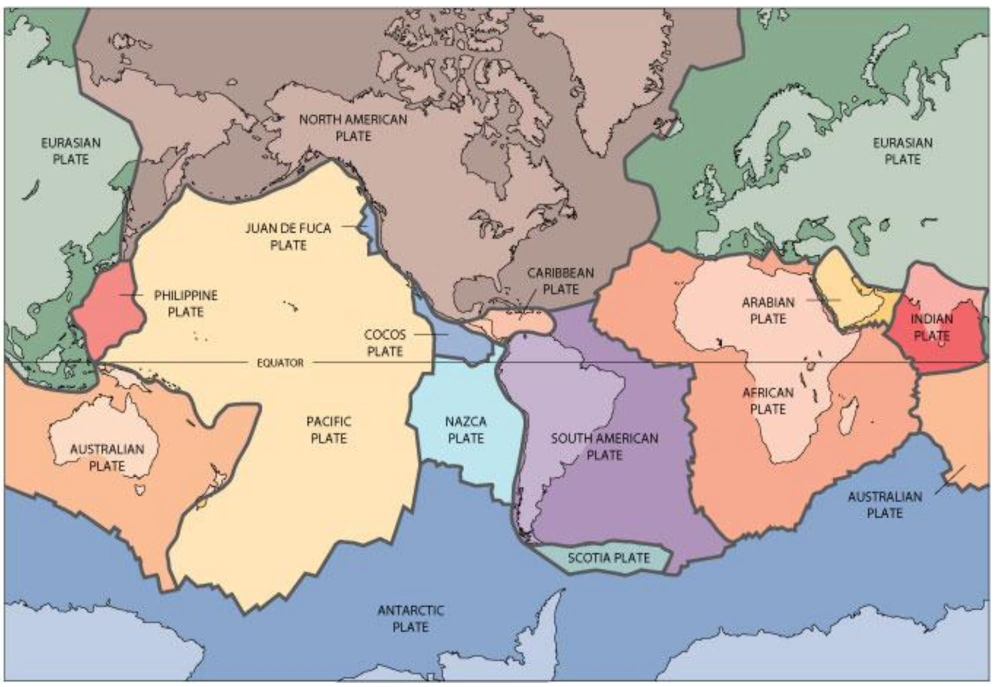
# Not Continental Drift but Plate Tectonics

By Adam T. Mansur

## Introduction

In 1968, Bryan Isacks, Jack Oliver, and Lynn R. Sykes coined the term *global tectonics* to describe the new theory that was remaking the science of geology.[1] The previous two decades had been a fruitful time for geologists. American scientists and the United States Navy had collaborated to study the ocean floor in detail for the first time, allowing geologists to apply the techniques, instruments, and theories they had developed on land to the unexplored reaches of the seafloor. Based on the data collected on these expeditions, geologists made a surprising finding: The continents, big as they were, were moving. What's more, geologists believed they could explain how.




The layer of the Earth we live on is broken into a dozen or so rigid slabs (called tectonic plates by geologists) that are moving relative to one another.
http://pubs.usgs.gov/gip/dynamic/slabs.html

The slow displacement of continents across the surface of the Earth is one of the core principles of plate tectonics, the elegant theory that shapes how geologists understand the Earth's surface. Plate tectonic theory posits that the Earth's crust is composed of a few dozen rigid, laterally extensive plates floating on a partially molten layer at the top of the mantle. A given plate may consist of continental crust, oceanic crust, or both. Continental crust is thick (20-100 km), granitic, and buoyant; oceanic crust is thin (5-10 km), basaltic, dense, and low-lying. Plates move relative to one another in response to convection currents in the underlying mantle. Where con-

[1] Bryan Isacks, Jack Oliver, and Lynn R. Sykes, "Seismology and the New Global Tectonics," *Journal of Geophysical Research* 73:18 (1968): 5855-5899.

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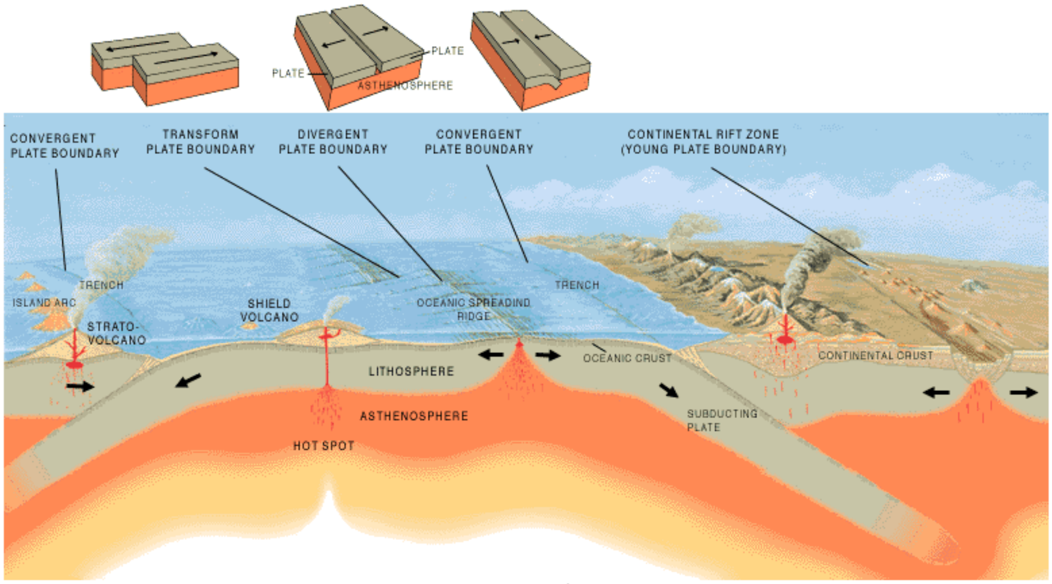
vection currents bring hot material to the surface, plates are driven apart and eruptions of basalt form new ocean floor. Where the mantle cools and sinks, old ocean crust sinks with it, producing ocean trenches, earthquakes, and volcanic arcs. Where two continents come together, the crust compresses and thickens, forming mountain belts. Each plate moves at a rate of only a few centimeters per year.




The main types of plate boundaries. (Cross section by José F. Vigil from This Dynamic Planet, a wall map produced jointly by the U.S. Geological Survey, the Smithsonian Institution, and the U.S. Naval Research Laboratory.)
http://pubs.usgs.gov/gip/dynamic/Vigil.html

The development of plate tectonics during the 1960s is the signature achievement of the science of geology, remarkable for both the small period of time over which the much of the supporting evidence was accumulated and for the explanatory power of the resulting theory. Yet there is a curious prelude: The idea of mobile continents was first proposed as part of a wide-reaching theory of the surface geology of the Earth more than forty years prior to the plate tectonics revolution. In 1912, the German meteorologist Alfred Wegener introduced the theory of continental drift, which imagined the continents splitting, colliding, and plowing through a plastic substrate. While less effective than plate tectonics in explaining the full range of geological phenomena, continental drift was nevertheless far more powerful than contemporary theories of the Earth. Yet the majority of Wegener's peers never accepted that the continents moved, and his theory was never widely adopted. Why was this? How was it that plate tectonics succeeded so quickly where continental drift had failed for so long? How can the disparate fates of the two theories be reconciled?

## An Accumulation of Anomalies

In the nineteenth century, Lord Kelvin and other physicists concluded that the Earth was cooling.[2] The heat generated during the formation of the Earth was slowly leaking into space, and the physicists knew of no source of heat to replace that being lost. They inferred that the Earth was relatively young and would eventually conduct the balance of its heat away, leaving it a frozen lump of rock floating through the solar system.

Grim though this idea was, it held some appeal to geologists grappling with the origin of features of the Earth's surface. Historically, geology has been a science of careful observation: Practitioners look at rocks, as many as they can, and they record what they see in close, sometimes exhaustive detail. These details can then be used to assess the age and origin of rocks, and to recognize ancient ocean floors or the cores of eroded mountain ranges. Whether the perception of geology as a mostly descriptive science is flattering or pejorative is largely in the eye of the beholder; in the 1900s the description at least had the virtue of being accurate. Even then geologists were not exactly theory-deprived; James Hutton's and Charles Lyell's theory of uniformitarianism, which argued that processes operating in the present could, over long time-scales, account for the formation of geological features, was successful in explaining the origin of streambeds, canyons, sedimentary rocks, and many other features. But explanations for other fundamental, large-scale geological phenomena were absent or flawed. Why were continents continents and oceans oceans? How did mountain belts form? No one knew.

If theories were somewhat lacking, it was not for a scarcity of observations. If anything, widespread mapping in the nineteenth century provided too many: Geologists were drowning in observations from the Alps, the American West, and dozens of other localities being mapped in detail for the first time. Reports from the field revealed new problems and contradictions far more quickly than theories could be modified to account for them. Two examples important to the continental drift debate concerned the distribution of fossils and ancient glacial deposits across the continents. Geologists found that similar fossil assemblages sometimes occurred in locations as widely separated as South America and South Africa.[3] These homologies were deeply problematic. According to Darwin's theory of evolution, the development of identical species and similar assemblages in such distant areas was impossible, suggesting that the areas must once have been connected. How this could be when they were now separated by thousands of kilometers of ocean was an open question. Likewise, glacial deposits dating from the Permian had been found scattered across the globe.[4] How glaciers could have formed at the same time over such a wide range of latitude was not at all obvious.

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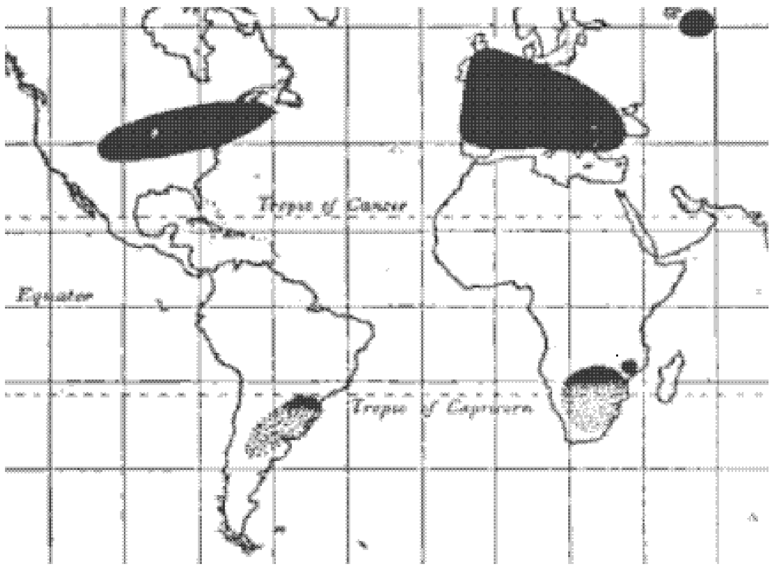
[2] Alfred Wegner, *The Origin of Continents and Oceans* (Methuen and Co. Ltd., 1924) 13.

[3] Naomi Oreskes, *The Rejection of Continental Drift: Theory and Method in American Earth Science* (Oxford University Press, 1999) 11. Wegener devotes chapter 4 of his book to fossil homologies.

[4] Wegener 100-101.




Distribution of the *Glossopteris* flora, an important example of a fossil homology.
A.C. Seward, The British Association. *Nature,* 1771:68 (1903): 556-568

Geologists working during the mid-to-late nineteenth century thus faced a bewildering array of questions, prominent among them these four: What are the differences between continental and oceanic crust? How do mountain belts form, both within and at the edges of continents? How can similar fossil assemblages form at sites separated by the width of an ocean? How did the scattered Permian glacial deposits come to exist? A successful theory of the surface of the Earth must address (or at minimum not contravene) the lines of evidence underpinning each of these questions. Formulating such a theory proved difficult.

To return, then, to the physicists, the appeal of the theory of the cooling Earth was that it provided a way to address these questions and their attendant observations. A cooling Earth was also a contracting Earth, and thermal contraction, geologists argued, could produce many of the features existing at the surface of the Earth.[5] As the Earth shrunk, its surface compressed to form the areas of high topography represented in the modern continents. Low-lying areas would contract more quickly, forming ever-deepening ocean basins. At the edges of continents, the difference in contraction allowed the accumulation and uplift of sediments to form coastal mountain ranges. Geological theories based on contraction, as formulated by Eduard Suess and James Dwight Dana, were widely praised for their explanatory power and popular within the geological community well into the twentieth century.[6]

They were nevertheless flawed theories. To begin with, the two leading versions of contraction disagreed on points as fundamental as the permanence of the continents and ocean basins.[7] Dana thought that continents formed early in the history of the Earth and had remained much the same ever since. Suess argued that continents and ocean basins were transient and subject to periodic upheavals, with continents sinking and the ocean floor rising to take their place. Each formulation ignored a key piece of evidence: Dana's theory offered no explanation for fossil homologies, whereas Suess's contradicted developing ideas about the long-term stability of continental crust.

[5] Oreskes 12-14 and 16-17.
[6] Oreskes 19-20.
[7] Oreskes 12-14 and 16-17 .

(This second point will be discussed in more detail in the next section.) Dana's theory ultimately proved the more successful, with its most pressing difficulty addressed by the addition of *land bridges* to explain fossil homologies.[8] Land bridges were narrow tracts of continental crust linking sites containing identical fossil species. Land bridges would appear, permitting species to migrate between distant sites for a time, then eventually collapse.

Beyond these discrepancies, the contraction theories shared a more fundamental problem: Field observations and mathematical analyses made in the latter half of the nineteenth century suggested that thermal contraction could produce neither the pattern nor extent of deformation seen in existing mountain belts.[9] Detailed mapping of mountain ranges showed that high elevations resulted not from the vertical motions Dana promoted but rather from shortening of huge tracts of continental crust.[10] In the Alps, Albert Heim and Marcel Bertrand mapped stacks of thrust sheets that implied shortening of the original crust by a factor of four or more. Thermal contraction was unable to account for such large amounts of compression.

Shortly before the beginning of the twentieth century, a pair of discoveries further complicated the case for contraction theory. The combined impact of radioactivity and the theory of isostasy would force geologists to reconsider their conception of the surface of the Earth.

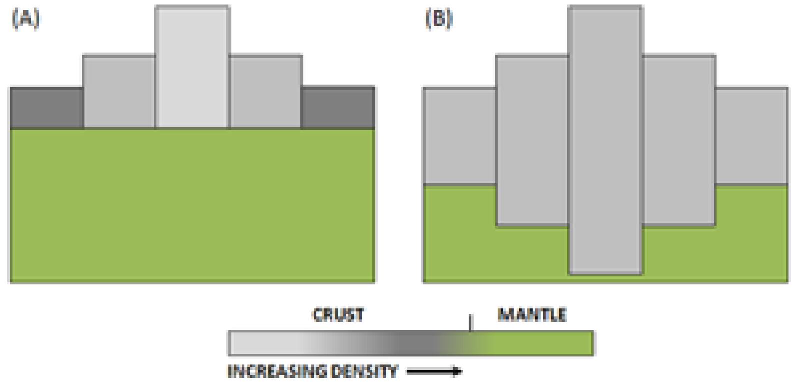
## Radioactivity and Isostasy

Radioactive decay describes the spontaneous breakdown of unstable (or radiogenic) atomic nuclei. When an atom decays, it ejects part of its nucleus and a burst of energy. The discovery of radioactivy in 1895 forced a reinvestigation of the thermal history of the Earth. Geologists like John Joly and Arthur Holmes recognized that decay of radiogenic isotopes of potassium, thorium, and uranium would serve as an important source of heat in the Earth's interior.[11] Radioactivity undermined geological theories of contraction, because the calculations of the cooling Earth at the root of these theories assumed no active heat source within the Earth. With radioactivity, this assumption was no longer valid. The Earth would be cooling more slowly than was previously believed and might even be heating up. Either possibility posed a problem for contraction theory, which already strained to account for the amount of shortening seen in the Alps. The existence of radioactivity required that the Earth was both older and more dynamic than previously thought. It would prove key to the oncoming debates about continental drift.

Equally problematic for existing theories was the development of the principle of isostasy. Isostasy describes the gravitational stability of a section of the Earth's crust. The crust behaves much like an ice cube in a glass of water: Its elevation is supported by the thickness and density of the material comprising it. Thick (or less dense) blocks attain higher elevations than thinner (or denser) blocks.

[8] Oreskes 207-213 and Wegener 17-22.
[9] Wegener 12-15.
[10] Oreskes 21-23.
[11] Oreskes 48-51.

The first explicit observation of isostasy dates to British India in the 1840s.[12] The British Surveyor-General there noted discrepancies in maps of the Himalayas prepared by triangulation and astronomical measurement. Believing that the extra mass of the mountain range may have been deflecting his surveyors' plumb-bobs and skewing their results, he commissioned John Pratt to assess the effect of the mountains on the deflection of a plumb-bob. Pratt's results were surprising. He found that the measured deflection of the plumb-bob was *smaller* than that predicted based on the size and density of the Himalayas.[13] This finding implied that the material comprising the crust below the Himalayas was *thicker* or *less dense* than that underlying the surrounding countryside. In either case, the high elevation of the mountain range was compensated by the reduced mass in the crustal column beneath the mountain. In the first decade of the twentieth century, John Hayford and William Bowie of the United States Coast and Geodetic Survey organized the first large-scale study of isostasy in the Earth's crust, work widely regarded as confirming the geological principle of isostasy.[14]



Isostasy in the Earth's crust. Identical elevation profiles can be explained by differences in (A) the density of the crust, where high elevations occur where rocks are relatively buoyant, or (b) the thickness of the crust, where high elevations are supported by thick roots (like an ice cube).
Graphic by Adam Masur.

Isostasy had crucial implications for geological theory. It implied a fundamental difference between continental and oceanic crust: The continents sat at higher elevations because they were comprised of material distinct from that comprising the oceanic crust. It was unclear at the time whether the continents and mountain ranges were less dense or thicker or both; the exact reason was to an extent immaterial. Rather, the key point was that this difference existed. Continental and oceanic crust could no longer be considered interchangeable. Moreover, the continents were stable: Suess's sinking continents were *verboten*, as were the continental land bridges invoked to account for fossil homologies on Dana's permanent continents.[15]

Both radioactivity and isostasy undermined contraction theory and the *ad hoc* mechanisms that geologists had used to explain fossil homologies. Suess's contraction theory was essentially finished; Dana's theory of permanent continents persisted, but absent thermal contraction and land bridges, was hard-pressed to account for the origin of either mountain belts or fossil homologies. The need for new explanations was evident and growing.

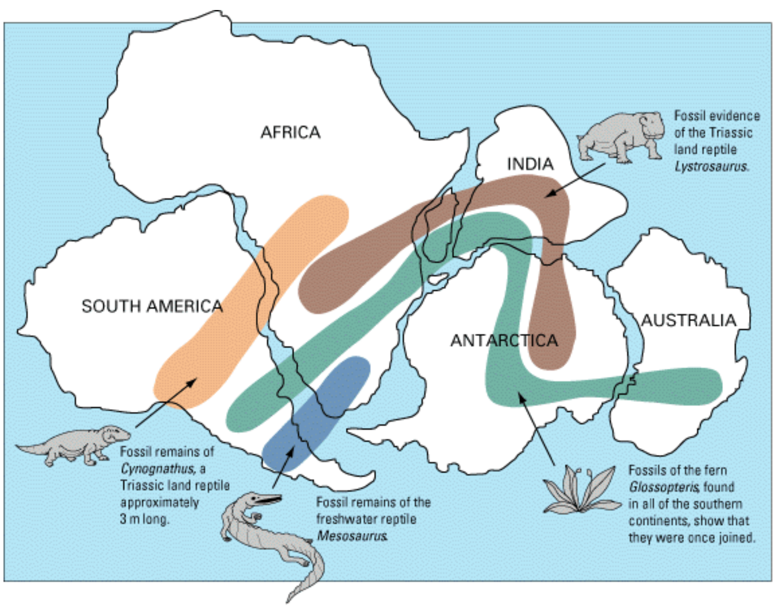
[12] Oreskes 23.
[13] Oreskes 23-25.
[14] Oreskes 37-47.
[15] Wegener 23-26.

This was the environment in which Alfred Wegener first published his theory of continental drift. He completed the first edition of his book *The Origin of Continents and Oceans* in 1915, twenty years after the discovery of radioactivity and on the heels of Hayford's and Bowie's landmark work on isostasy.

**Continental Drift**


Alfred Wegener in Greenland, 1930 expedition. http://en.wikipedia.org/wiki/File:Wegener_Expedition-1930_008.jpg

Wegener believed that his theory of continental drift resolved many of the discrepancies in the geological theories of his day: the fossil homologies, the distribution of glacial deposits, and the origin of mountain belts. In *The Origin of Continents and Oceans*, however, he gives as the starting point for his theory the apparently unrelated observation of the jigsaw fit of the continents.[16] He was not the first to make this observation, but he was among the first to infer from it the previous existence of a supercontinent. Wegener imagined Africa slotting into the curve in the eastern margin of South America, South America sliding into the margin of North America, and so on, until he had combined the modern continents into a single landmass, the supercontinent Pangaea. The explanatory power of this construction became apparent to Wegener when some years later he stumbled upon a discussion of homologies in the geological record.[17] In Pangaea, he realized, homologous fossil assemblages from South Africa and South America sat side-by-side and scattered Permian glacial deposits converged near the South Pole. Other fossil, structural, and paleoclimatic homologies could likewise be reconciled. In Pangaea, these anomalies were no longer anomalous. They made perfect sense.



The locations of certain fossil plants and animals on widely separated continents would form definite patterns if the continents were rejoined. pubs.usgs.gov/gip/dynamic/continents.html

This evidence convinced

[16] Wegener 5.
[17] Wegener 5.

Wegener of the past existence of a supercontinent. However, to argue that the continents were once part of a single landmass required that Wegener abandon the assumption that relative positions of the continents were fixed. This did not trouble him. He argued that the continents were like great ships moving through plastic material of the ocean crust.[18] If the continents could move, he reasoned, their present positions did not conflict with the previous existence of Pangaea. Intriguingly, moving continents also provided a way to address the origin of mountain belts. Large mountain ranges in the interiors of the continents, typified today by the Alps and the Himalayas, could form where tracts of continental crust collided.[19] Because continents were too buoyant to sink, the crust in the zone of compression would thicken, elevating the surface to produce a mountain range. Coastal ranges, on the other hand, formed as a result of the resistance of the ocean floor to the drifting continents.[20]

Wegener thus argued in lectures and four editions of his book that the modern continents had once been part of the supercontinent Pangaea. At some point in the distant past this supercontinent had broken apart, leaving the individual continents to move through the viscous material of the ocean floor. Unlike speculation about land bridges and sunken continents, the theory of continental drift did not violate the principle of isostasy or ignore homologies in the rock record. Its main flaw in Wegener's mind was that it lacked a mechanism, a deficiency for which he tried to compensate by speculating that a tidal or Coriolis force could perhaps drive the motion of the continents.[21] But he was wedded to neither mechanism; future research could address that question. Finally, and not unimportantly, Wegener provided within his theory a testable hypothesis. Continents that had moved in the past were likely to be moving in the present, and if such movements were on the order of a few meters per year, astronomical observations might be precise enough to discern them.[22]

If geologists could accept the idea of moving continents, continental drift was a theory of unique explanatory power. When coupled with isostasy, drift theory provided explanations for the four phenomena described above. Unfortunately, the hurdle posed by mobile continents proved difficult to surmount.

[18] Wegener 1-4.
[19] Wegener 160-161.
[20] Wegener 164-165. Critics of continental drift cited a paradox in Wegener's conception of the ocean floor: How can the ocean floor be weak enough to allow the continents to pass through it yet strong enough to deform the leading edges of the continents? In plate tectonics, plates float on (not through) the mantle substrate.
[21] Wegener 190-205.
[22] Wegener 118.

**A Revolution Deferred**

Despite Wegener's confidence in his theory, he failed to convince many of his peers. Philip Lake wrote that Wegener's theory was "vulnerable in every statement" and that his commitment to it blinded him "to every fact and argument that tells against it."[23] The British seismologist Sir Harold Jeffreys argued that continental drift was mechanically impossible; Chester Longwell accused Wegener of iconoclasm.[24] These reactions and others like them were both typical and durable: Fifty years would pass between the initial publication of *The Origins of the Oceans and Continents* and widespread acceptance of mobile continents. Though the flaws of the current geological theories were well-known, many geologists preferred to tinker with familiar frameworks rather than commit to Wegener's strange new theory. Rejection was quick and final in the United States; elsewhere, the theory was entertained if not immediately adopted.[25]

Station NIU, Oahu Hawaii, during reobservation of World Longitude stations. Looking for evidence of continental drift, but instruments were too crude to measure small earth movements. Photo: 1934 C&GS Season's Report Lushene 1934; 2001 National Oceanic & Atmospheric Administration (NOAA). Taken from Proquest's eLibrary.

All aspects of Wegener's theory and many qualities of Wegener himself were subject to attack. Because Wegener was trained as a meteorologist, critics questioned the relevance of his experience. Because he relied on published studies instead of conducting his own fieldwork, he was criticized for co-opting, misinterpreting, or cherry-picking other scientists' work. Even the jigsaw fit of the continents that initially inspired continental drift was denied, with Jeffreys, Rollin Chamberlain, and others arguing that the margins of the continents matched only if they were dramatically deformed.[26] (This argument is telling of the lack of care of some critics of Wegener, who failed to notice that Wegener's fit was based on the continental *shelves*, not the outlines of the continents as they appeared above sea level.[27])

Above all geologists rejected the notion of the horizontal displacement of the continents. For many critics, the argument against continental drift boiled down to a single point: Continents could not move. Jeffreys, a pioneering seismologist, was particularly adamant that the Earth's

[23] Anthony Hallam, *Great Geological Controversies*, 2nd ed. (Oxford University Press, 1989) 147-148.
[24] Hallam 150.
[25] Oreskes 292-293.
[26] Hallam 150 and Oreskes 304-305.
[27] Wegener 42.

rigidity precluded displacement.[28] Bowie made a similar argument based on isostasy.[29] Most geologists were not so final in their rejection, but nevertheless considered the mechanisms suggested by Wegener and his allies to be inadequate to displace a continent. Nor did they concede that displacement was necessary to explain mountain building or homologies. Other reasonable explanations existed. When attempts to measure continental displacement using astronomical observation and telegraph signals provided ambiguous results, most geologists were content to dismiss continental drift.[30]

The alternative theories developed during and after the debate on drift theory still struggled with the conflicting requirements of isostasy and the fossil and structural homologies. Many theories simply ignored one or the other of these lines of evidence. For example, the fissiparturition hypothesis argued that the present distribution of the continents occurred when the Moon was ripped from the Earth, splitting the then-continuous granitic crust and filling the cracks with basalt. But this theory offered no explanation for fossil homologies.[31] Others tried to reconcile the problematic observations by appealing to processes operating in the deep crust. Joseph Barrell argued that loading the lower crust of land bridges with intrusions of basalt would make them dense enough to sink, a model rejected on isostatic grounds.[32] Perhaps the most successful theory in this period was a different reimagining of the land bridge hypothesis, this one proposed by Charles Schuchert and Bailey Willis. They argued that land bridges were not granitic but rather thick accumulations of basalt, similar to modern ocean islands that rise above the surface of the ocean but eventually subside.[33] Though this model had its flaws -- chief among them that Schuchert believed that the trans-Atlantic land bridge must have been large and granitic, thus burdening it with the same problems that doomed earlier land bridge theories -- it was widely regarded as a good solution to the problem of fossil homologies.

Not all geologists were content with this direction. Outside of the United States, many scientists supported continental drift. The South African field geologist Alexander du Toit, a passionate (and often frustrated) defender of drift, made detailed studies of fossil assemblages and geological structures in rocks from South Africa and South America that were adjacent in Pangaea, addressing concerns about the quality of the homologies cited by Wegener.[34] But perhaps the most important adherent to the theory of continental drift was the British geologist Arthur Holmes, whose research provided the mechanism for driving plate motion lacking from Wegener's theory. Holmes argued that convection of the mantle was necessary to transfer excess radiogenic heat from the base of the mantle to the surface. Convection cells would transfer hot material from near the core to just below the crust, then travel laterally along the base of the crust until the material had cooled sufficiently to sink back into the mantle. The lateral, near-surface currents

[28] Hallam 149-150.
[29] Oreskes 167-177.
[30] Oreskes 227-236.
[31] Oreskes 168-170.
[32] Oreskes 128-193.
[33] Oreskes 208-219.
[34] Alexander du Toit, *A Geological Comparison of South America with South Africa* (Carnegie Institute of Washington, 1927)

would drag the overlying continents along as they moved.[35] As the historian Naomi Oreskes notes, Holmes's theory is similar and in key aspects superior to the theory of mantle convection by Harry H. Hess that is credited with sparking the plate tectonic revolution of the 1960s.[36] In America, where continental drift was a theory *non grata*, a small number of geologists contributed work that supported the theory and foreshadowed key aspects of modern plate tectonic theory. Prominent among these were Reginald Daly and G. A. F. Molengraaf.[37] Despite their efforts, however, and those of international colleagues like du Toit and Holmes, they failed to convince other American geologists of the merits of drift theory.

Wegener died during an expedition to Greenland in 1930. By the mid-1930s, the debate about mobile continents in America had petered out, and adherents would remain in the minority until the 1960s. The revival of the idea came only in response to new data from studies of the Earth's magnetic field and seafloor conducted in the 1950s and 1960s. Some forty odd years after Wegener's initial proposal, mapping of the seafloor revealed faulting and high heat flow along mid-ocean ridges that traced the midline of all the ocean basins, leading Hess to propose that the seafloor was spreading apart at these ridges as a result of deep currents in the mantle.[38]

Evidence consistent with mantle convection came from the new field of paleomagnetism, which looked at changes in the Earth's magnetic field over time as recorded in rocks. Certain iron-rich minerals align with the orientation of the magnetic field operating at the time of their crystallization. Sensitive magnetometers allowed geologists to measure this remanent magnetism in both continental and seafloor samples. Studies of paleomagnetism revealed three additional pieces of evidence key to the formulation of plate tectonic theory:

1) *Magnetic reversals:* The polarity of the Earth's magnetic field was found to have reversed at irregular intervals throughout Earth history. Remanent magnetism in rocks could be either normal (aligned with the current magnetic field) or reversed (aligned opposite to the current field). An absolute paleomagnetic timescale was calibrated based on the history of magnetic reversals in the rock record.[39]
2) *Apparent polar wander:* Paleomagnetic data from rocks of the same age from different continents indicated different locations for the poles, whereas rocks of different age from the same locations showed an apparent change in the poles' location over time. Both observations could be reconciled if the continents had moved relative to one another.[40]
3) *Seafloor striping:* Basalts near the mid-ocean ridges showed a distinctive pattern of alternating bands of normal and reversed remanent magnetism. These bands were parallel to and symmetric across the ridge axis. This seafloor striping was interpreted to reflect con-

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[35] Arthur Holmes, "Radioactivity and Earth Movements," *Transactions of the Geological Society of Glasgow* 18 (1931): 559-606.

[36] Oreskes 268. Hess mentions Holmes's work in his 1961 paper, though he does not cite a specific paper.

[37] Oreskes 93-99 and 276.

[38] Harry H. Hess, "A History of Ocean Basins," *Petrologic Studies: A Volume in Honor of A. F. Buddington* (Geological Society of America, 1961): 599-620.

[39] L. W. Morley and A. Larochelle, "Paleomagnetism as a Means of Dating Geological Event," *Geochronology in Canada* (Royal Society of Canada, 1964) 8: 39-51.

[40] Hallam 165-166 and Oreskes 265-267.

tinuous extrusion of basalts at the mid-ocean ridge in alternating periods of normal and reversed polarity of the geomagnetic field. By measuring the age and thickness of each pair of bands, geologists were able to calculate a rate for seafloor spreading of a few centimeters per year.[41]

Coast and Geodetic Survey Ship PIONEER, in service 1946 – 1966, discovered magnetic striping, the key to plate tectonics.
1952? NOAA Photo Library, Taken from ProQuest's eLibrary.

Unlike Wegener's theory, which failed to gain the support of the geological community, these interpretations of the new geophysical evidence were quickly assimilated into the scientific canon. The result of the 1960s research was a new theory of continental displacement, plate tectonics, which posits that the Earth's surface is divided into mobile plates driven along by deep mantle currents. Plate tectonics differs in key respects from Wegener's continental drift but shares the core, long-controversial premise of mobile continents. Today, plate tectonics enjoys nearly universally acceptance, and Wegener's continental drift is recognized as a perceptive but fatally flawed forerunner of the modern theory.

## Root Causes of Rejection

The most common explanation given in textbooks and college classrooms for the failure of continental drift is that it lacked a mechanism. It offered no compelling way to move a continent. Though many geologists, both during the debate about continental drift and afterward, have echoed this claim, it seems an inadequate explanation. Other novel (and sometimes equally strange) observations have achieved widespread acceptance without a clear cause: Gravity, ice ages, quantum mechanics. Even the Alpine thrust sheets that proved the first chink in the armor of contraction theory were widely accepted even though no one could explain how they formed.[42] Furthermore, even after Arthur Holmes, a geologist considered to be among the brightest of his generation, developed a model of mantle convection similar to the version now central to the theory of plate tectonics, most geologists did not go back and re-examine the merits of continental drift.[43] This suggests that additional factors contributed to its rejection.

In her book *The Rejection of Continental Drift,* Naomi Oreskes offers a pair of explanations to reconcile American geologists' longstanding opposition to continental drift with their rapid ac-

[41] F. J. Vine and D. H. Matthews, "Magnetic Anomalies Over Oceanic Ridges," *Nature* 201 (1964): 591-592.
[42] Oreskes 21-23.
[43] Oreskes 119-120.

ceptance of plate tectonics in the 1960s. Dismissing arguments that blame the lack of a mechanism or Americans' indifference to theory in the first half of the 1900s, she suggests instead that the underlying cause is epistemic. Wegener's initial presentation of his theory violated certain norms operating in the American geological community. Geologists at this time prized detailed evidence and a careful weighing of alternative hypotheses. Wegener, by contrast, was totally committed to his theory. His zeal may have alienated his American colleagues.[44]

But Wegener's theory was also caught in a larger tide: the transition of American science from broadly subjective to objective methodologies.[45] Spurred by the success of physics in the first years of the twentieth century, previously observation-based fields like geology and biology began to redirect their research into the laboratory. This trend was in full swing in the first half of the 1900s, resulting in a devaluation of old forms of evidence and a corresponding elevation of quantification and measurement. In geology, the change in methods was marked by the waning of field geology and waxing of laboratory studies that used chemical and physical data to place hard constraints on the ages and origins of rocks. Most evidence marshaled by Wegener belonged to the field tradition, allowing his critics to dismiss it as equivocal, incomplete, vague, or, most damning of all, subjective. This perception undermined efforts by geologists like du Toit to use new field evidence to reinforce Wegener's arguments. No matter the extent or quality of the new field evidence, its base nature allowed it to be dismissed outright. By contrast, the geophysical evidence underpinning the plate tectonic revolution of the 1960s was considered novel, numerical, and concrete. Despite the formidable complexity of these data, their perceived certainty shielded them against dismissal and provided a firm foundation upon which to build plate tectonics. The theory of continental drift was perceptive and largely accurate, but could not overcome the diminishing standing of the field tradition from which Wegener made his argument.

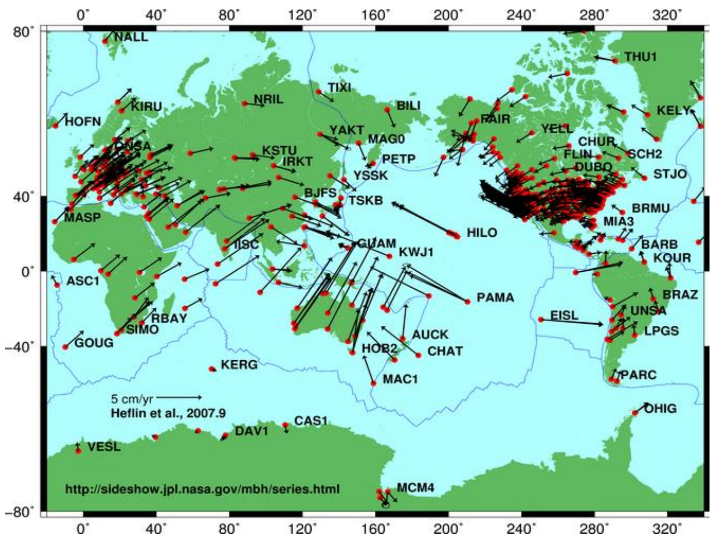


Plate motion based on Global Positioning System (GPS) satellite data from NASA JPL. Vectors show direction and magnitude of motion.
http://sideshow.jpl.nasa.gov/mbh/all/images/global.jpg

Nevertheless, Wegener’s theory was pivotal in the development of plate tectonics. Without it, the tectonic revolution could not have succeeded so easily. By the time the key geophysical evidence and arguments for plate tectonics were being published, geologists had had over forty years to consider the practical problems posed by mobile continents and adjust to the oddness of their

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44 Oreskes, chapter 5.
45 Oreskes, chapter 10.

existence. Many of the issues that troubled Wegener, notably the absence of a mechanism, had already been addressed by geologists studying aspects of continental drift. Finally, the passage of time may have softened scientists' resistance to the unintuitive idea of moving continents. In 1912, Wegener's continents were unforgivably strange; forty years on they could only be less so.