

Continental Drift

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Introduction

Continental drift is the motion of the earth's continents over geological time. Since the seventeenth century, cartographers have noticed the jigsaw-puzzle fit of the continental edges; in the nineteenth century, paleontologists discovered that some fossil plants and animals were extraordinarily similar across the globe. Some rock formations in distant continents were also surprisingly similar. To account for these similarities, Austrian geologist Eduard Suess proposed the theory of Gondwanaland—a giant supercontinental that had once covered the entire earth surface before breaking apart to form continents and ocean basins. In the early twentieth century, German meteorologist Alfred Wegener suggested an alternative explanation: continents drift. The paleontological patterns could be explained if the continents migrated, periodically joining together, periodically breaking apart.

Continental drift was not accepted when first proposed, but in the 1960s it became a cornerstone of the theory of global plate tectonics. Continental drift is now explained as a consequence of moving plates. The continents are embedded within the lithospheric plates that comprises the upper 80-100 km of the earth, and are carried along with the plates as they migrate at average rates of 3-10 centimeters per year. As a result, the global configuration of continents and oceans is constantly changing. For several hundred million years during the late Paleozoic and the Mesozoic eras, the continents were united into a supercontinent called Pangea. The break-up of Pangea produced the configuration of the continents we have today.

Continental drift is a fundamental natural cause of global change. The major geological processes—earthquakes, volcanoes, mountain-building—are caused by plate motions and interactions. These processes control the large-scale physiography of the globe, and with it, the distribution of habitat. In addition, many facts of evolution are explained as effects of continental drift. With the break-up of Pangea, previously unified populations began to diverge and speciate in response to their new environmental conditions. Other types, such as South American emus and African ostriches, retained obvious similarities even while physically segregated. Paleo-climate change is also explained by continental drift, as the direct result of continents moving passively through climate zones, and the indirect consequence of the re-configuration of continents and oceans on oceanic circulation and climate patterns.

The development of the theory of continental drift and plate tectonics illustrates the tortuous process by which new scientific knowledge is established. The idea of globally moving continents was adamantly rejected when first widely debated in the 1920s, then established as scientific fact only forty years later. Studying this history illuminates some of the reasons why scientific communities resist new ideas.

I. Historical background: The Origin of Mountains and Contraction Theory

One of the central scientific questions of nineteenth century geology was the origin of mountains. How were they formed? What process squeezed and folded rocks like putty? What made the earth move? Most orogenic theories invoked terrestrial contraction as a causal force. It was widely believed that the Earth had formed as a hot, incandescent body, and had been steadily cooling since the beginning of geological time. Because most materials contract as they cooled, it seemed logical to assume that the Earth had been contracting as it cooled.

In Europe, Austrian geologist Edward Suess (1831-1914) popularized the image of the Earth as a drying apple: as the Earth contracted its surface wrinkled to accommodate the diminished surface area. Suess assumed that the earth's initial crust was continuous, but broke apart as the Earth's interior shrunk; the

collapsed portions formed the ocean basins, the remaining elevated portions formed the continents. With further cooling, the continents became unstable and collapsed to form the next generation of ocean floor; what had formerly been ocean now became dry land. The interchangeability of continents and oceans explained the presence of marine deposits on land (which had long before puzzled Leonardo Da Vinci), and the extensive interleaving of marine and terrestrial materials in the stratigraphic record. Suess's theory also explained the widely known similarities of fossil assemblages in parts of India, Africa, and South America by attributing them to an early geological period when these continents were still contiguous. He called this ancient supercontinent Gondwanaland.

In North America, a different version of contraction theory was developed by James Dwight Dana (1813-1895). Dana suggested that the Earth's continents had formed first, when minerals with relatively low fusion temperatures such as quartz and feldspar had solidified. Then the globe continued to cool and contract, until the high temperature minerals such as olivine and pyroxene finally solidified: on the moon, to form the lunar craters, on Earth, to form the ocean basins. As contraction continued after the Earth was solid, it induced surface deformation. The greatest pressure was experienced at the boundaries between the oceanic and continental blocks, explaining the concentration of mountains along continental margins. Because continents and oceans were viewed as globally permanent features, Dana's account came to be known as permanence theory.

In North America, permanence was linked to the theory of geosynclines, developed by Dana and James Hall (1811-1889), State Paleontologist of New York and the first President of the Geological Society of America (1889). Hall noted that the Appalachian mountains mostly consisted of folded sequences of shallow-water sedimentary rocks, thousands of feet thick. How did thick sequences of shallow-water form? How were they folded and uplifted into mountains? Hall suggested that materials eroded off the continents accumulated in the adjacent marginal basins, causing the basin to subside. Subsidence allowed more sediments to accumulate, causing more subsidence, until finally the weight of the pile caused the sediments to be heated, lithified, and then uplifted into mountains. Dana modified Hall's view by arguing that thick sedimentary piles were not the cause of subsidence but the result of it. Either way the theory provided a concise explanation of how thick sequences of shallow-water rocks could form, but was vague on the question of how they were transformed into mountain belts.

II. Continental Drift as an Alternative to Contraction Theory

In the early twentieth century, contraction theory was refuted by three independent lines of evidence. First, field mapping in the Swiss Alps and the North American Appalachians demonstrated hundreds of miles of shortening of strata. This would require impossibly huge amounts of terrestrial contraction to explain. Second, geodesists studying the problem of surface gravitational effects showed that the surface mass associated with mountains was counterbalanced by subsurface mass deficit. Mountains were held aloft not by their internal strength, but by floating—a concept called isostasy. Contra Suess, continents and oceans were not interchangeable. Third, physicists discovered radiogenic heat, which refuted the basis of contraction theory. With contraction no longer axiomatic, earth scientists were motivated to search for other driving forces of deformation. Many did; Alfred Wegener (1880-1930) is the most significant, for his theory was the most widely discussed.

Primarily known as a meteorologist and author of a pioneering textbook on the thermodynamics of the atmosphere, Wegener realized that paleoclimate change could be explained if continents had migrated across climate zones, and the reconfiguration of continents and oceans altered the Earth's climate patterns. However, continental drift was more than just a theory of paleoclimate change. It was an attempt to unify disparate elements of earth science: on one hand, paleontological evidence that the continents had once been connected; on the other, geodetic evidence that they could not be connected in the way European contractionists had supposed. Wegener's answer was to re-connect the continents by moving them laterally.

Wegener's theory was widely discussed in the 1920s and early 1930s. It was also hotly rejected, particularly by Americans who labeled it bad science. The standard explanation for the rejection of continental drift is the lack of a causal mechanism, but this explanation is false. There was a spirited and

rigorous international debate over the possible mechanisms of continental migration. Much of it centered on the implications of isostasy: if continents floated in a denser substrate, then this substrate had to be plastic or fluid and continents could at least in principle move through it. The Fennoscandian rebound—the progressive uplift of central Scandinavia since the melting of Pleistocene glacial ice—provided empirical evidence that they did, at least in the vertical direction and at least in the Pleistocene period. However, in Scandinavia the cause of motion was known: first the weight of glacial ice, then the pressure release upon its removal. What force would cause horizontal movement? Would the substrate respond comparably to horizontal as to vertical movement? Debate over the mechanisms of drift concentrated on the long-term behavior of the substrate and the forces that could cause continents to move laterally.

In the United States, the question was addressed by Harvard geology Professor Reginald A. Daly (1871-1957), that country's strongest defender of continental drift. Daly argued that the key to tectonic problems was to be found in the earth's layered structure. Advances in seismology demonstrated that the earth contained three major layers: crust, substrate (or mantle) and core. The substrate, he suggested, might be glassy, and therefore could flow in response to long-term stress, just as old plates of glass gradually thicken at their downward edges, and glassy lavas flow downhill. Continents might do the same. Building on the geosyncline concept of Dana and Hall, Daly suggested that sedimentation along the continental margins resulted in subtle elevation differences, which in turn produced isostatic instabilities. Eventually, the continent could rupture, sliding down over the glassy substrate under the force of gravity. The sliding fragment would then override the other half—an early suggestion of subduction—and, over time, the accumulation of small increments of sliding would result in global continental drift.

Daly admonished his American colleagues to take up the question of drift, but few did. Reaction in Europe was more favorable. Irish geologist John Joly (1857-1933) linked the question to discoveries in radioactivity. Trained as a physicist, Joly had demonstrated that pleochroic haloes in mica were caused by radiation damage from tiny inclusions of U and Th-bearing minerals, such as apatite. Radioactive elements were therefore ubiquitous in rocks, suggested that radiogenic heat was also ubiquitous. If it were, then it could be a force for geological change. Joly proposed that, as radiogenic heat built up, the substrate would begin to melt. During these periods of melting, the continents would move under the influence of small forces—such as the Eötvös force—which would otherwise be ineffectual. These were the periods of global orogeny, such as the Appalachian-Caledonian that transcended Europe and North America in the Paleozoic or the Alpine-Dinaric that crossed Europe in the Cenozoic.

Joly's theory responded to a geophysical complaint against a plastic substrate: that the propagation of seismic waves indicated a fully solid and rigid earth. He pointed out that although the Earth was solid now, it might not always have been. More widely credited was the suggestion of British geologist Arthur Holmes (1890-1965) that the substrate was partially molten or glassy. Underscoring arguments made by Wegener, Holmes emphasized that the substrate did not need to be liquid, only plastic, and that it might be rigid under high strain rates (during seismic events) yet still be ductile under the low strain rates that prevailed under most geological conditions. If it were plastic in response to long-term stress, then continents could move within it. Holmes's driving force was convection currents in the mantle. He argued that radiogenic heat would generate convection currents: the mid-ocean ridges were the sites of upwelling convection currents, where continents had split, and the ocean deeps (geosynclines) were the sites of downwelling currents, where continents were deformed as the substrate descended. Between the ridges and the trenches, continents were dragged along in conveyor-like fashion.

III. The Rejection of Continental Drift

Arthur Holmes's papers were widely read and cited; many geologists thought he had found the cause of continental drift. However, opposition was none the less for that, particularly in the United States, where reaction to Wegener's theory was vitriolic. More was at stake than a matter of scientific fact.

Three factors contributed to the American animosity to continental drift. One, Americans were widely committed to the method of multiple working hypotheses, and Wegener's work was interpreted as violating it. For Americans, right scientific method was empirical, inductive, and required weighing observational evidence in light of alternative explanatory possibilities. Good theory was also modest, holding close to the objects of study. Most closely associated with the University of Chicago geologist T.C. Chamberlin

(1843-1928), who named it, the method of multiple working hypotheses reflected American ideals expressed since the eighteenth century linking good science to good government: Good science was anti-authoritarian, like democracy. Good science was pluralistic, like a free society. If good science provided an exemplar for good government, then bad science threatened it. To American eyes Wegener's work was bad science: It put the theory first and then sought evidence for it. It settled too quickly on a single interpretive framework. It was too large, too unifying, too ambitious. In short, it was seen as *autocratic*. Features that were later viewed as virtues of plate tectonics were attacked as flaws of continental drift.

Second, continental drift was incompatible with the version of isostasy to which Americans subscribed. In the late nineteenth century, two accounts of isostatic compensation had been proposed: John Henry Pratt (1809-1871) attributed it to density variations, George Biddell Airy (1801-1892) attributed it to differences in crustal thickness. Until the early twentieth century, there had been no empirical confirmation of the concept beyond the original evidence that had inspired it, nor any means to differentiate the two explanations. Then American geodesists John Hayford (1868-1925) and William Bowie (1872-1940) used the Pratt model to demonstrate that isostatic compensation was a general feature of the crust. By making the assumption of a uniform depth of compensation, they were able to predict the surface effects of isostasy to a high degree of precision throughout the United States. At first, their work was hailed as proof of isostasy in general, but in time, it was viewed as confirmation of the Pratt model in particular. However, if continental drift were true, then the large compressive forces involved would squeeze the crust to generate thickness differences. Continental drift seemed to refute Pratt isostasy, which had worked for Americans so well. Rather than reject Pratt isostasy, they rejected continental drift.

Third, Americans rejected continental drift because of the legacy of uniformitarianism. By the early twentieth century, the methodological principle of using the present to interpret the past was deeply entrenched in the practice of historical geology. Many believed this the only way to interpret the past, that uniformitarianism made geology a science, for without it what proof was there that God hadn't made the Earth in seven days, fossils and all? Historical geologists routinely used faunal assemblages to make inferences about climate zones, but according to drift theory, continents in tropical latitudes did not necessarily have tropical faunas, because the reconfiguration of continents and oceans might change matters altogether. Wegener's theory raised the specter that the present was not the key to the past—that it was just a moment in Earth history, no more or less characteristic than any other. This was not an idea Americans were willing to accept.

In North America, the debate over continental drift was quelled by an alternative account of the faunal evidence. In 1933, geologists Charles Schuchert (1858-1942) and Bailey Willis (1857-1949) proposed that the continents had been intermittently connected by isthmian links, as the isthmus of Panama presently connects North and South America and the Bering Land Bridge recently connected North America to Asia. The isthmuses had been raised up by orogenic forces, then subsided under the influence of isostasy. This explanation was patently ad hoc—there was no evidence of isthmian links other than the paleontological data they were designed to explain (away). Nevertheless, the idea was widely accepted, and a major line of evidence of continental drift undercut. In 1937, South African geologist Alexander du Toit (1878-1948) published *Our Wandering Continents*, a comprehensive synthesis of the geological evidence of continental drift, but it had little impact in North America. The matter rested there for two decades, until the debate was re-opened on the basis of entirely new evidence.

V. From continental drift to plate tectonics

In the 1950s, continental drift was revived by British geophysicists studying on rock magnetism as a means to understand the Earth's magnetic field, one group at Imperial College led by P.M.S. Blackett (1897-1974), and one at Cambridge (later at Newcastle) led by S. K. Runcorn (1922-1995). Both groups found evidence that rocks had moved relative to the Earth's magnetic poles, so either the continents or the poles had moved. Initially geophysicists were more receptive to the idea of polar wandering, but by the late 1950s comparative evidence from India and Australia pointed in the direction of moving continents. Inspired by these results, American geologist Harry Hess (1906-1969) revived the idea earlier proposed by Arthur Holmes: that convection currents drove continental motions.

Hess suggested that mantle convection drives the crust apart at mid-ocean ridges and downward at ocean trenches, forcing the continental migrations in their wake. He interpreted the oceanic crust as a hydration rind on serpentinized mantle; his colleague Robert Dietz (1914-1995) modified this to generate oceanic crust by submarine basalt eruptions, and gave it the name it holds today: sea floor spreading. Dietz's interpretation was later confirmed by direct examination of the sea floor. Meanwhile, geophysicists had demonstrated that the earth's magnetic field has repeatedly and frequently reversed its polarity. Magnetic reversals plus sea-floor spreading added up to a testable hypothesis, proposed independently by Canadian Lawrence Morley and British geophysicists Frederick Vine and Drummond Matthews: If the sea floor spreads while the Earth's magnetic field reverses, then the basalts forming the ocean floor will record these events in the form of a series of parallel 'stripes' of normal and reversely magnetized rocks. Since World War II, the United States Office of Naval Research had been supporting sea-floor studies for military purposes, and large volumes of magnetic data had been collected. American and British scientists examined the data, and by 1966 the Vine and Matthews hypothesis had been confirmed. In 1967-68, the evidence of drifting continents and the spreading sea-floor was unified into a global framework. Working independently, Daniel P. McKenzie and Robert L. Parker at the Scripps Institution of Oceanography, and Jason Morgan at Princeton University, showed that existing data could be used to analyze crustal motions as rigid body rotations on a sphere. The result became known as plate tectonics; by the early 1970s it was the unifying theory of the earth sciences.

Continental drift is now subsumed into global plate tectonics, but the problems it was designed to explain--global physiography, disjunctively distributed fauna, and paleo-climate change--are still explained by same basic idea: Continents drift. So faunal assemblages are divided or united, climate patterns are altered, and the Earth's physiography is transformed.

IV Lessons from continental drift: The tortuous development of scientific knowledge

Most people believe that when the weight of evidence becomes sufficiently great, scientists accept the reality of new phenomena and the truth of new theories. The case of continental drift suggests that reality is more complex. Scientific theories are not judged only in light of evidence, but also in light of methodological standards and epistemic preferences. Because these standards and preferences are forged prior to the onset of any theoretical debate, the legacies of past intellectual debates may weigh heavily in the outcomes of new ones.

The problem with continental drift was not a lack of evidence, nor a lack of causal explanation. The evidence presented by Wegener and du Toit has been largely confirmed by global plate tectonics, and Holmes's causal account—mantle convection—is now generally accepted as the cause of plate tectonics. The problem with continental drift was a conflict with prior intellectual commitments. Between the 1920s and the 1960s, these earlier commitments—to Pratt isostasy, to the method of multiple working hypothesis, to uniformitarianism—were loosened, modified, or abandoned altogether. With this, the debate could be re-opened on the basis of new evidence, and a previously discarded idea resurrected.

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