

Wegener and his Theory of Continental Drift

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Alfred Wegener, an astronomer by training and meteorologist by profession, visualised that there was once a single very large landmass on the surface of the earth. Gradually it broke up into smaller fragments which drifted away to form the present continents. In a few cases, the drifting fragments subsequently collided, coalesced and formed larger landmasses again. Wegener could thus explain in a simple way (i) similarities in shapes of continental coast lines separated by wide oceans, (ii) similarities in the rocks and fossils occurring on such coasts and in the fauna and flora inhabiting them, (iii) the formation of several major mountain ranges of the world, and (iv) the evidence in rocks on past climates of the earth.

Introduction

Astronomers take immense delight in enumerating the various motions that we partake even as we are apparently stationary on the surface of the earth. Geophysicists, the people who apply the principles of physics to investigate the earth, gleefully add that the surface of the *terra firma* itself is not steady but responds pliantly to many causes in the earth's interior and on its surface as well as to a few causes in the solar system.

Occasionally, we can feel the motion of the earth's surface directly for brief periods, as during a major earthquake or when a heavy object moves near us. But ordinarily, we become aware of the restlessness of the earth's surface with the help of suitably sensitive seismometers and gravity meters or through repeat geodetic measurements which provide estimates of changes in the coordinates of points marked for the purpose. Recent geodetic data, notably the satellite-based GPS (Global Positioning System) observations, confirm that, even as you read these lines,

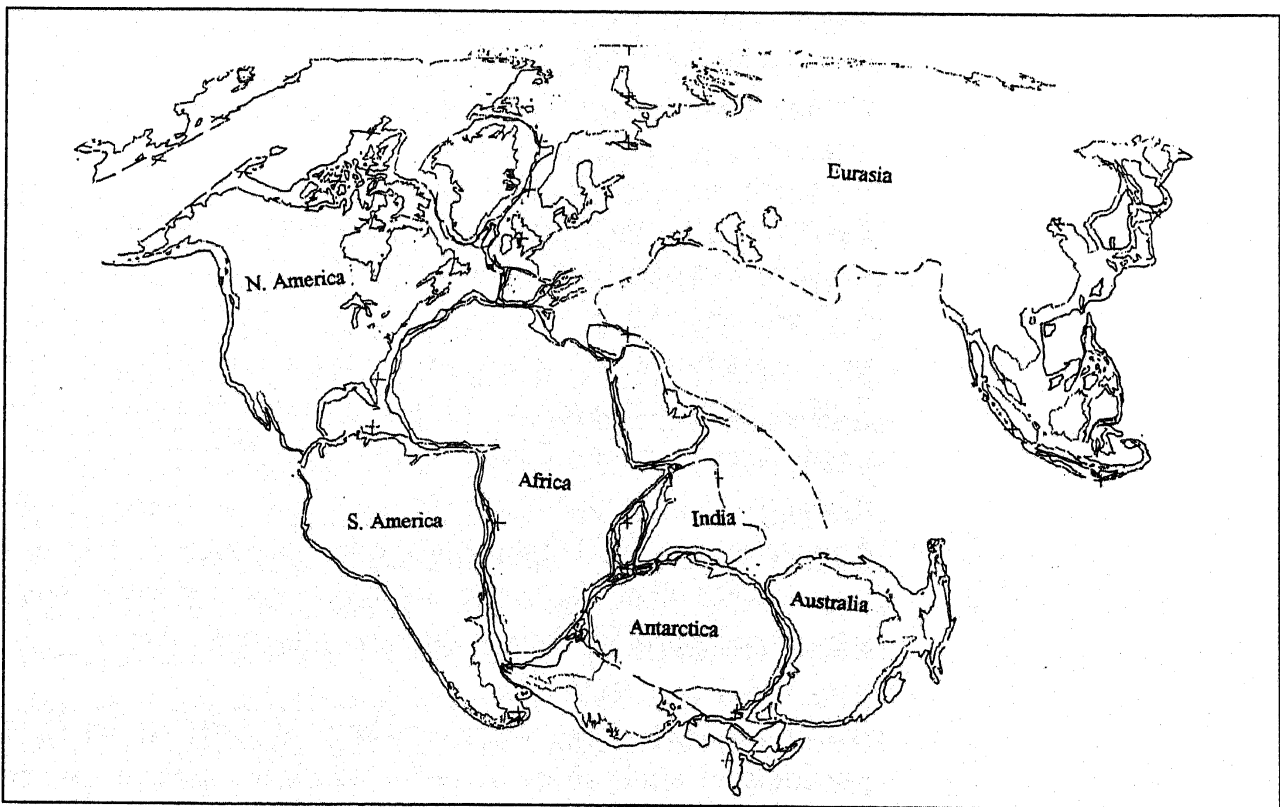
the continents are moving at the rate of a few centimetres per year relative to a coordinate system rotating with the earth as well as relative to each other. The limited GPS data for the Indian subcontinent indicate that it is moving approximately northward at 5-6 cm per year currently relative to the earth-fixed coordinate system.

Several types of evidence in rocks on land and on the seafloor and in the animal and plant kingdoms may be explained simply if we assume that the continents, which are now widely separated, may have been together in the past. Thus, it is surmised that all the present continents of the world may have been joined in a single super continent called Pangea (*Figure 1*) circa 200 Ma, where Ma stands for mega annum or million years. Starting from a position in the Southern Hemisphere, the Indian subcontinent may have drifted over a distance of about 5000 km to reach its present position north of the equator.

The possibility of continental drift has been suggested off and on ever since reasonably accurate maps of continental coasts

All the present continents of the world may have been joined in a single super continent called Pangea

Figure 1. A recent reconstruction of the super continent of Pangea at about 200 Ma. (after Owen, 1983)



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have been available. But the credit for the theory is given to Alfred Wegener (see inside of back cover) because he first provided a detailed and reasoned exposition of the theory of continental drift. He defended his theory against a chorus of criticism for about two decades and constantly sought evidence to strengthen it. I recall here some ideas and events related to Wegener's theory and its subsequent metamorphoses.

The Scene in Earth Sciences ca 1910

In 1910 when Le Grand argued that there was no single ruling paradigm in earth sciences, Wegener first thought about the concept of continental drift. At best, there were two main schools among earth scientists. One school professed broad allegiance to ideas of Hutton and Lyell, and the other to those of Werner, Cuvier and Suess. Neither school could provide satisfactory explanations for all the following problems and dilemmas.

Firstly, there was no agreed theory about the origin of the Alps and other mountain ranges of the world. The Alps are mentioned specifically because at the time they were the most extensively studied mountains and, for obvious reasons, of the greatest interest to European geologists.

Secondly, there was the enigma of the remarkable similarities in the shapes of coastlines on opposite sides of many oceans. For example, the mainly convex coastline of Brazil matches the pronouncedly concave trend in the African coast bordering the Gulf of Guinea (*Figure 2*). This congruence stretches on the South American side from Para to Bahia Blanca and on the African side from Liberia to the Cape of Good Hope. It was demonstrated ca 1964 that the match is even better if, instead of the present coastlines, we consider the corresponding, submerged, seaward edges of the two continental shelves.

A third major problem was to explain the many instances of phenomenal similarities in rocks which are located on the



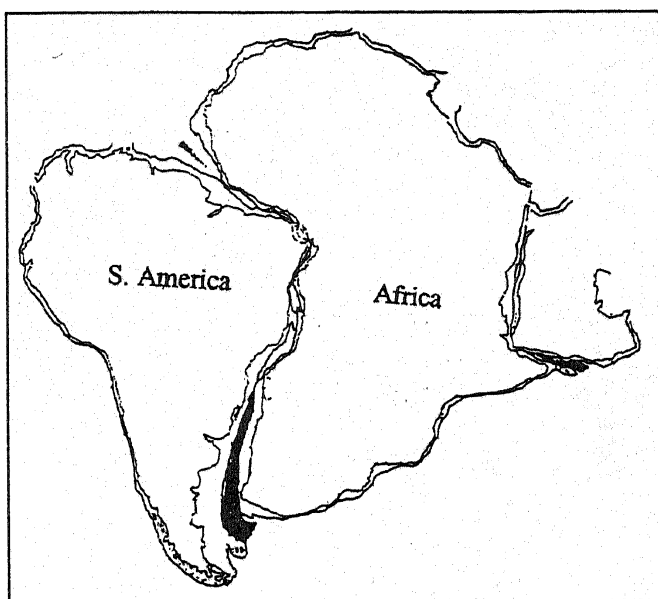
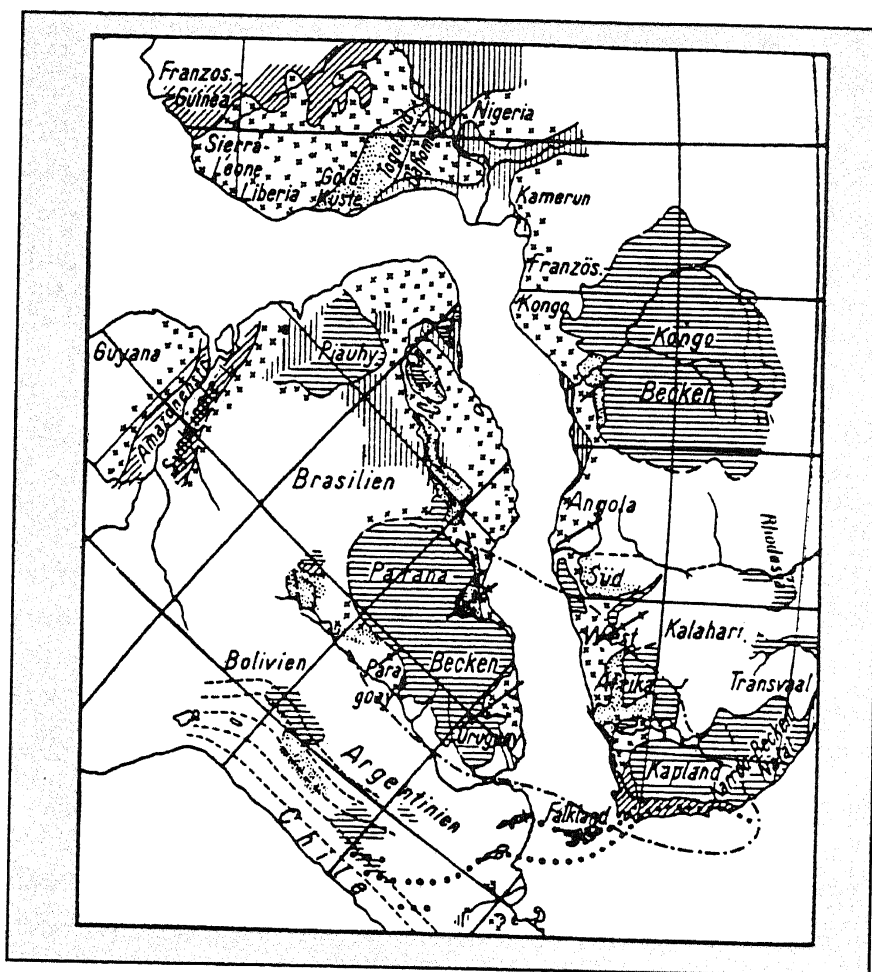


Figure 2. A recent reconstruction showing in detail the pre-drift alignment of South America and Africa. (after Owen, 1983)

opposite shores of oceans and which contain evidence of events over extended intervals of geologic time. For example, studies of rocks from many localities on the eastern coast of South America and western coast of Africa (*Figure 3*) suggest that these regions had remarkably similar histories for the period between 400 and 200 Ma. During this time, in both regions, an extended period of glaciations and deglaciations was followed by a period in which there were massive eruptions of lava.

Fourthly, there was no satisfactory explanation for many similarities evident in fossils and living species of plants and animals on different continents. For example, fossils of *Mesosaurus*, a small reptile living in fresh-to-brackish waters about 280 Ma, are found in Brazil as well as South Africa. Similarly, fossils of *Glossopteris*, an extinct genus of gymnosperms that flourished between 300 and 250 Ma, are found in coal beds of South America, South Africa, Antarctica, Australia and India. Also, the garden snails and earthworms of North America and Europe of today are related. Did these and numerous other such similarities arise because those life forms evolved on parallel lines in widely separated continents or there were connections between landmasses that facilitated migration of fauna and flora?

Figure 3. A figure showing South America and Africa in proximity. Information about the geology of the eastern and western coasts respectively of the two continents is added. Wegener took this figure from Du Toit and included it in the fourth edition of his book.



Finally, a challenging problem requiring explanation was the evidence in rocks from all parts of the globe suggesting that the climates prevailing at the times of their formation were different from the present climates at the respective sites. For example, there are vast coal deposits in Antarctica that could have originated only if that part of the continent was covered with lush tropical forests around 300 Ma.

Wegener's Theory of Continental Drift

Wegener started toying with the concept of continental drift in 1910 when, looking at a new atlas, he was impressed afresh with the remarkable similarity in the coastlines across the South Atlantic Ocean. He thought that the similarity might arise because South America and Africa were parts of the same landmass in the past and had drifted apart subsequently. In late

1911, Wegener read about similarities in many fossils from Brazil and West Africa. He saw that these too would be explained if the two continents had been joined together in the past. Wegener collected from the published literature other lines of geological evidence, such as close similarities in rock formations, which tended to confirm contiguity of continents in earlier times. He also noted that the apparent differences between the present and inferred past climates of different lands could be explained by postulating that the continents had shifted north-south by suitably large distances.

Wegener assumed that the earth consisted of concentric layers in which density increased with depth. Continents, forming the outermost incomplete shell, floated in the material of the second layer in accord with the concept of isostasy. Under the oceans, this layer occurred beneath the sediments. Sometimes the continents drifted apart, as in the case of South America and Africa, and sometimes they collided as in the case of India and Asia. The Rocky Mountains and the Andes were pushed up as the North and South American continents ploughed through the material of the second layer and the Himalaya were pushed up due to the collision of the subcontinent with the main mass of Asia.

Wegener suggested that continents drift in response to two forces. He called the first force the *Pollflucht* or *pole-flight force*, ascribed its origin to rotation of the earth and suggested that it pushed continents from the poles towards the equator. He thought that the continents drifted east or west in response to the tidal forces of the sun and the moon. Wegener admitted that both were weak forces.

Wegener first presented his theory of continental drift publicly in a lecture on January 6, 1912. He wrote *The Origin of Continents and Oceans* dealing with the theory in 1915. The book was revised in 1920, 1922 and 1929 in response to criticisms of the theory and advances in earth sciences.

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Wegener's Reconstruction of Paleocontinents

Towards the end of the nineteenth century, many geologists inferred from fossil evidence that a major continent called *Gondwanaland* existed for several hundred million years. It was made up of parts of the present India, Australia, Antarctica, Africa, South America and the intervening oceans. It was suggested that these landmasses became separated when the intervening continental areas sank to form the present Indian and South Atlantic oceans ca 120 Ma.

Wegener used his concept of continental drift to reconstruct Gondwanaland by omitting the oceans and placing the landmasses right next to each other in the Southern Hemisphere. He reconstructed similarly a northern paleocontinent called *Laurasia* and suggested that Gondwanaland and Laurasia too were joined once in a single super continent called *Pangea*.

Wegener sought to bring precision in his reconstruction of paleocontinents. He not only matched the similar coastlines of continents but also tried to ensure that localities with exposures of similar rocks as well as similar fossil occurrences on the two continents were contiguous to each other after reconstruction (*Figure 3*). The importance of these exertions may be gauged from the following analogy. Take two identical sheets of paper, one blank and the other with intelligible printed text. Let the sheets be torn to pieces. We may be able to reconstruct the two sheets by putting the respective pieces together carefully. However, our faith in the reconstruction of the printed sheet will be greater if the reassembled text makes sense again. The reconstruction of a paleocontinent carries conviction if the geology and geophysics of the reunited lands make sense. See *Box 1* on Wegener's views about the position of India in such reconstructions.

The Response from Earth Scientists

The immediate response of earth scientists to Wegener's theory was not favourable. One possible explanation could be that it

Box 1. The Drift of the Indian Subcontinent

Wegener's Reconstruction: Wegener, in his reconstruction of the Gondwanaland, placed the Indian subcontinent between Madagascar and Australia on the following basis. All three have regions of high, undulating, plateau country composed of gneissic rocks. The east coast of Madagascar and the west coast of Indian peninsula are remarkably straight, and basaltic lava flows occur near the north ends of the linear coastal segments. Similarly, the eastern coast of the Indian peninsula and the western coast of Australia have matching shapes. Narrow, low-lying belts of comparable sedimentary rocks occur along these two coasts. There are similar coal deposits in the Godavari and Irwin river valleys. Also, there are similarities among fauna of India, Australia and Madagascar. Finally, all the southern continents and the Indian peninsula experienced cold climate and were glaciated during 250-300 Ma. However, apart from India, none of the northern continents was glaciated in this period.

Recent computer based reconstructions of Gondwanaland place Antarctica instead of Australia along India's eastern margin (*Figure 1*)

Evidence from the Magnetic Field in the Indian Ocean: Ship borne magnetometers have been used to obtain a detailed picture of the earth's magnetic field in ocean covered areas. The data, when interpreted in light of the seafloor spreading hypothesis and the phenomenon of thermo remnant magnetisation (TRM), can help in reconstructing a detailed chronology of events for the break up of a paleocontinent into two fragments, the gradual drift of the fragments away from each other and concomitant opening of an intervening ocean basin as well as any subsequent changes in the speed of their drift.

Thus, such observations of the Indian ocean reveal that the eastern part of Gondwanaland, comprising Madagascar, India, Antarctica and Australia, separated from the western part consisting of Africa and South America at about 200 Ma. India separated from Antarctica and Australia ca 127 Ma. Australia also started moving north at 45-50 Ma. India collided with Eurasia at about 35 Ma. Subsequent interactions of Eurasia and India led to the rise of the Himalaya.

GPS Results: Today, satellite-based GPS observations indicate that India is moving northward at 55-60 mm per year relative to an earth fixed coordinate system but only at 35-40 mm per year relative to a point, e.g., Kathmandu, in the Himalaya. Many earth scientists suggest that the difference in the two rates arises because India is slipping under the Himalaya at about 20 mm per year. This is consistent with seismological data from the Himalaya, gravity data from the Himalaya and Tibet, as well as the results of PROJECT INDEPTH; a controlled-source seismic study of the deep crust carried out ca 1992 in Tibet and the Nepal Himalaya. It is also consistent with available results on balanced geological cross-sections of the Himalaya.

However, the GPS evidence notwithstanding, the idea of the drift of the Indian subcontinent is still not acceptable to all earth scientists.

Wegener's theory was not favourable. One possible explanation could be that it challenged the then prevalent notion of fixed continents.

challenged the then prevalent notion of fixed continents. It is appealing to compare these events in the history of earth sciences to the events that unfolded following the publication of the Copernican theory of the solar system. One geologist wrote in 1928 that, "if we are to believe in Wegener's hypothesis we must forget everything which has been learnt (in geology) in the past 70 years and start all over again". Opponents of Wegener's theory stressed that the forces suggested for continental drift were inadequate. They also sought scars that ought to exist if the drifting continents plough through the ocean floor. There were numerous other objections on details. Researchers from different subdisciplines of geology noted limitations and contradictions in specific data cited by Wegener in support of his theory. For example, the discovery of *Glossopteris* fossils in many parts of Asia outside India means that they may not be exclusive to the postulated southern continent of Gondwanaland as suggested by supporters of continental drift. It was pointed out that while Wegener's reconstructions of paleocontinents can explain many similarities in rocks and fossil occurrences on now dispersed continents, they lead in other cases to incongruous juxtapositions of geological features. A few rejected the theory merely because they held that Wegener, not being a geologist by training, was unaware of the nuances of geological fieldwork and was meddling in topics outside his areas of competence.

Wegener's Response

Convinced of its strength and tolerant about the limitations of his theory, Wegener sought to silence his critics by securing evidence that continental drift is occurring even today as it had occurred in the past. He focused on determining whether Greenland is presently stationary or has a westward motion away from Europe. One way to check this is by examining successive longitude observations in Greenland and nearby islands. Wegener found that longitude measurements on Sabine Island near Greenland between 1823 and 1907 indicated apparent cumulative westward shift of 950 m at an average rate of about

11 m per year. He admitted that the measurements were inexact and may not have been made at exactly the same spot.

Wegener recalled in the 1929 edition of his book that longitude measurements using radio transmissions of precise time yielded in 1922 a value of 3 h 24 m 22.5 ± 0.1 s west of Greenwich for Kornok, Greenland. This value may be converted to the more familiar degrees of longitude using the well-known factor of 4 minutes of time difference per arc degree of longitude difference. The observations were repeated in 1927 at the same spot using an even better technique and yielded a value of 3 h 24 m 23.405 ± 0.008 s west of Greenwich. The cumulative increase of 0.9 s in west longitude was nine times the mean error of observation. It implied westward drift of Greenland at 36 m per year. Wegener saw in this a vindication of his theory. He wrote, "... *Interest is now transferred from the question of the basic soundness of the theory to that of the correctness or elaboration of its individual assertions.*"

The rates of the order of ten metres per year and more estimated by Wegener are two orders higher than the current estimates.

Continental Drift Idea Through the 1930s and 1940s

Earth science community at large was not moved by Wegener's longitude data. During the 1930s and 1940s only a handful of enthusiasts kept faith in the idea of continental drift, and most of them had worked in the Southern Hemisphere. Alex du Toit was the foremost geologist among this group. Keeping in mind the criticism of Wegener's geological evidence for drift, he identified 17 tests on exposed rocks to establish pre-drift contiguity among the now separated landmasses. Arthur Holmes was among the few geologists from the northern hemisphere to champion this idea in that period. One of his major contributions was to suggest that continental drift could be driven by convection in the earth's mantle.

Paleomagnetic Studies

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exhibited by most rocks developed from an interesting scientific diversion into a rigorous subdiscipline of geophysics with far reaching geological implications. Paleomagnetic studies or the studies of earth's magnetic field in the past based on magnetic measurements on rocks and ocean sediments, are an important component of this subdiscipline.

Briefly, the vast majority of the minerals making up the rocks of the earth's crust show paramagnetic or diamagnetic behaviour and can be magnetised only weakly. The most important exception is magnetite (Fe_3O_4) which shows ferrimagnetic, a variant of ferromagnetic, behaviour and can be magnetised strongly. It retains the magnetisation even when the external inducing magnetic field has disappeared. The ferrimagnetic behaviour of magnetite grains changes to paramagnetic behaviour when they are heated to a characteristic temperature of 580°C called the Curie point of magnetite. Most rocks are weak magnets because they contain magnetite grains in small percentages and the grains are well dispersed.

Igneous rocks acquire thermo-remnant magnetisation (TRM) in the prevailing direction of the earth's magnetic field when, during their cooling from the molten state, the temperature falls below 580°C . Sedimentary rocks acquire depositional remnant magnetisation (DRM) because the magnetite grains in sediments align in the direction of the earth's magnetic field prevailing at the time of their deposition under water. Finally metamorphic rocks too acquire TRM consistent with the earth's magnetic field at the time when they last cooled below 580°C .

Through suitable measurements on rock samples, we can infer the directions of the earth's magnetic field at the sampling sites at the times the rocks acquired their respective remnant magnetisations. As a result of the experimental procedures in use, such estimates of directions are 10000 year averages. It has been surmised from Gilbert's time in the 17th century that the magnetic field of the earth is essentially dipolar and at present the axis of the geomagnetic dipole is inclined at about 11° with



the axis of earth's rotation. Also this field is subject to secular variation with time. It has been inferred from measurements and is now a basic tenet of paleomagnetic studies that, averaged on the time scale of 10000 years, the axis of the geomagnetic dipole coincides with the axis of rotation. This is the so-called *axial dipole hypothesis*. It helps us to estimate the latitude (f) of the sampling site at the time the rocks in question acquired their remnant magnetisation. The formula is

$$\tan f = (\tan D)/2,$$

where D is the measured paleomagnetic angle of dip at the site. The importance of paleomagnetic measurements on rock samples increases many fold when absolute ages of the samples are also determined using techniques based on radioactivity. If rocks of different geologic ages collected from a single geographic location on a continent yield different estimates of ancient latitude then we may conclude that the position of the continent relative to the earth's axis of rotation has changed with time. Concerted efforts have been made to interpret such measurements on rocks from different sites of different continents. It turns out that the theory of continental drift provides a simple and consistent explanation for these paleomagnetic results also.

Thus by the early 1960s, thanks to paleomagnetic studies, the outlook for the idea of continental drift was better than it had ever been.

The Moving Seafloor

The discussion so far has revolved around the evidence obtained from continental areas. Exploration of the seafloor had been in progress at a slow but gradually accelerating pace during the nineteenth century and the first four decades of this century. There was a rapid increase in geological and geophysical exploration of the seafloor after the Second World War. Hess suggested in 1958 that seafloor too may be in motion and, in fact, it may be carrying the continents with it. He gave his idea the sobriquet of *geopoetry* partly to muffle criticism from the hordes

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opposing the theory of continental drift. Hess's idea explained neatly why the drifting continents did not leave any scars on the seafloor. It also shifted the spotlight from the mechanism of continental drift that had bothered Wegener greatly. In time, Hess's geopoetry became known as the seafloor spreading hypothesis.

Plate Tectonics Version of Continental Drift

The concept of continental drift and the seafloor spreading hypothesis were incorporated in the theory of plate tectonics proposed in 1968. It is assumed in this theory on rheological considerations that, down to a depth of about 700 km, the earth may be divided into a lithosphere and an asthenosphere. The lithosphere comprising the earth's crust and upper mantle has variable thickness of up to about 200 km. The material of the lithosphere can support and transmit non-hydrostatic stresses of a few hundred MPa, or a few thousand atmospheres, for long periods of time. On the other hand, the material of the asthenosphere exhibits creep and viscous flow when subjected to non-hydrostatic stresses on the time scale of 1000 to 10000 years and longer. Thus convection currents can occur in the asthenosphere on such time scales.

The lithosphere is divided into a number of large and small plates. Their boundaries have been demarcated by considering the geographic distribution of earthquake epicentres and hypocentres. Most lithospheric plates span continental areas as well as portions of the seafloor. The plates are in relative motion constantly due to convection currents in the asthenosphere. Plates diverge from each other above the rising limbs of adjacent convection cells and converge towards each other over their descending limbs. They slide past each other horizontally along transform faults.

According to the theory of plate tectonics, the continents drift because the lithospheric plates of which they are parts are moving. The inferred speeds of different lithospheric plates,

and thus also of the continents 'drifting' with them, are in the range of 2 to 15 cm per year. See *Box 1* for plate tectonics based chronology for the drift of the Indian subcontinent.

Antiquity of Continental Drift

Wegener visualised that there was only one phase of continental drift. It began with the break up of Pangea and is still continuing. Tell tale signs in rocks have been deciphered, within the plate tectonics framework, to conclude that continents have been coming together and then fragmenting and drifting apart for billions of years. Only, as we move back in time, it gets more and more difficult to be specific about these continental motions.

Philosophical Implications

In an erudite but extremely readable monograph entitled *Drifting continents and shifting theories*, Le Grand suggests that a thorough historical analysis of the idea of continental drift can provide valuable insights into the practice of science generally. He finds that the events leading up to the plate tectonics revolution of 1968, including the above developments related to continental drift, do not conform to Kuhn's definition of a 'scientific revolution' as a convulsive replacement of one world-view with another. This is because, in his opinion, until that time, there never was a single overriding world-view in geology. Le Grand feels rather that these events and developments conform more closely to Laudan's view that a 'scientific revolution' occurs when a new research programme is formed which has a high initial rate of progress such that scientists subscribing to competing research programmes can no longer ignore it.

The Plate Tectonics Bandwagon

Some support for Laudan's view comes from the fact that the number of earth scientists subscribing to the theories of plate tectonics and continental drift indeed increased dramatically after 1968. The converts were vociferous about the virtues of their new faith. This prompted Scharnberger and Kern to write

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"...And I believe in Continental Drift...; which proceedth from Plate Tectonics and Sea-Floor Spreading; which with Plate Tectonics and Sea-Floor Spreading together is worshipped and glorified; which was spake of by Wegener...(sic)".
The Geotectonics Creed

'The Geotectonics Creed' in 1972. The first tenet of this creed begins with "*I believe in Plate Tectonics Almighty, Unifier of the Earth Sciences, and explanation of all things geological and geophysical ;...*". The tenet relevant to continental drift reads in parts as follows. "*... And I believe in Continental Drift...; which proceedth from Plate Tectonics and Sea-Floor Spreading; which with Plate Tectonics and Sea-Floor Spreading together is worshipped and glorified; which was spake of by Wegener...(sic)*".

The Holdouts' Case Against Plate Tectonics and Continental Drift

But in the early 1970s, there were some prominent earth scientists, such as Belousov in Russia, and their spokesmen, such as the two Meyerhoffs in USA, who rejected the very possibility of plate tectonics and continental drift. Storetvedt's 1997 book, reviewed in *Current Science* recently, is in the same vein.

Briefly, the holdouts not only retain the earlier criticism of Wegener's theory but, with time, have acquired new ammunition also. Thus, some quantitative analyses since the 1940s suggest that the similarities in fossil and living species on the drifted continents are not statistically significant. The dissenters have identified geological features on continents and the seafloor, which suggest to them that continents could not possibly have moved. Recent detailed geological maps of individual countries and whole continents, detailed physiographic maps of the seafloor and images of the earth taken from satellites provide fertile ground for collecting such details.

Paleomagnetic measurements rejuvenated the concept of continental drift. But some earth scientists have persistently expressed reservations about magnetic measurements on rocks. For example, Jeffreys was instructed in the physics laboratory ca 1909 to handle a bar magnet with care lest it lost its magnetisation. Thus how could he accept results from magnetic measurements on samples that had to be hammered and battered before they could be plucked from their sites in rock exposures and taken to the laboratory?

Ship-borne measurements of the geomagnetic field in oceanic areas, when interpreted in light of the seafloor spreading hypothesis, help us to reconstruct virtually a running log of how two continents may have drifted apart (see *Box 1*). The critics, notably the Meyerhoffs, have reservations on these results also.

Do Continents Drift or Don't They?

Confounded by his critics on the evidence for drift in the geological past, Wegener turned to geodetic data in the form of longitude measurements around Greenland to establish that continents may be drifting today. Since then, phenomenal advances have occurred in geodetic measuring techniques. Many geodetic methods today utilise the technologies of space. They include very long base line interferometry with radio waves from distant quasars, laser ranging and the GPS. All yield highly precise and repeatable measurements. GPS measurements are with reference to a global coordinate system rotating with the earth. They leave little room to doubt that continents and the seafloor are astir in response to plate tectonic forces. Not only are the continents moving horizontally relative to the earth's rotational axis but also relative to each other. The continents are also deforming with themselves. This helps to explain intracontinental earthquakes, such as at Latur and Jabalpur, in plate tectonic terms. The evidence should get better in the next few years as the geodetic technologies improve and the errors of observation dwindle in comparison with the signals represented by annual rates of continental displacements relative to the earth's fixed coordinate system.

These present day geodetic observations by themselves are no proof that continental drift and seafloor spreading occurred in the past. The best course is to interpret the evidence in rocks objectively. But both, those who suggest continental drift and those who reject it, accuse each other of being selective in citing evidence, which suits their respective purposes.

It is not outside the realm of possibility, but still it would be surprising, if continental drift did not occur in the past and has

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started in our own times. In fact, we may use the inductive principle of uniformitarianism to assert that continents drifted in the past just as they do today. Those who abhor that principle may still permit that continental drift may have proceeded at different rates in the past but proceed it did.

Finally, the relativistic paradigm of physics precludes absolute rest anywhere in the Universe. Thus, may we insist on an absolute fixity of continents on the earth?

According to Le Grand, the theory of continental drift was the first attempt at a truly global theory in earth sciences. The theory of plate tectonics, based on a vastly enlarged data set, represents the actual culmination of that initial effort. We may hope that future advances based on an even broader database will meet the objections of those who still oppose the concept of continental drift. See *Box 2* also.

Conclusion

In retrospect, it was an important day in 1912 when Wegener proposed his theory. Le Grand views the subsequent developments related to the idea of continental drift as the stuff of myth and legend. In one inspired paragraph, he equates continental drift with Cinderella, and its critics with her vain stepsisters. He compares the geophysicists of the 1950s and early 1960s with Cinderella's Fairy Godmother who waved the Magnetic Wand (sic). Cinderella went to the Ball and married the Prince represented by the seafloor spreading hypothesis and the plate tectonics theory.

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The history of science is replete with instances where ideas popular in one period were discarded subsequently. Thus I cannot end in the normal style of fairy tales by saying, "The idea of continental drift lived happily ever after". Changes may be anticipated. How and when, I can't say. But, as of now, GPS results provide a reasonable basis to infer that continents drift and all other earth sciences observations may be reconciled in light of this fact.

Box 2. The Non-Uniqueness in the Interpretation of Scientific Data

Lay readers of this article may wonder how, based on the same data, earth scientists can hold diametrically opposite views on continental drift. Currency of multiple hypotheses based on limited observations of a phenomenon is a common occurrence in science, and in fact, life in general.

To gain some insight, we have to distinguish between direct and inverse problems. A direct problem is one where we predict the effects of a known cause or a set of known causes. An inverse problem is one where we guess the causes from limited observations of their effects. Direct problems have unique answers while inverse problems invariably have multiple possible answers. An elaborate theoretical apparatus has been constructed to analyse this aspect of inverse problems. Backus and Gilbert wrote in 1968 a landmark paper on the theme while interpreting spectra of free oscillations of the earth excited due to earthquakes.

Let us illustrate by reference to electrostatics. We solve a direct problem when we use Coulomb's law to predict the electric field due to a given distribution of electrostatic charges. We have just one correct answer. We solve an inverse problem when we use observations of electric field on a closed surface to predict the electrostatic charges enclosed within it. There cannot be a unique answer because there is an infinity of possible charge distributions, which can give rise to the same field on and outside that surface. An indication of this emerges from Gauss's law of electrostatics but it is proved rigorously in potential theory using Green's theorems.

As an example from daily life, let a set of listeners be screened off from some musicians. One possible inverse problem for the listeners would be to identify the musical instruments by hearing the sounds. Unless exceptionally trained, the listeners would be hard put to decide if they are hearing notes from an actual violin or an electronic synthesizer. In the same vein, but at a deeper level, there is a classic paper written by Kac in 1966 with the title 'Can we hear the shape of a drum?' (See, S Kesavan, *Resonance*, Vol.3, No.9, pg.26; No.10, pg.49).

To speculate about continental drift from limited observations of and about rocks is equivalent to solving an inverse problem. No matter how many observations we collect, we will never be able to prove with mathematical certainty that continental drift did or did not take place in the past.

Suggested Reading

- [1] A Wegener, *The Origin of Continents and Oceans*, 4th edition, translated by John Biram, Dover Publications Inc., New York, 1966.
- [2] H E Le Grand, *Drifting Continents and Shifting Theories*, Cambridge University Press, Cambridge, 1988.

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