

Plate Tectonics

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Introduction

The theory of continental drift, which paved the way for discovery of plate tectonics, was put forward by Alfred Lothar Wegener - a meteorologist from Germany - in 1912. The theory states that continents are not fixed, but have been slowly wandering during the course of Earth's geological history. Although Wegener's continental drift theory was later disproved, it was one of the first times that the idea of crustal movement had been introduced to the scientific community; and it has laid the groundwork for the development of modern plate tectonics.

In the early 1960s, the emergence of the theory of plate tectonics started a revolution in the earth sciences after more and more evidences were found to support the idea that the plates were moving continuously over geologic time. Paleomagnetic observations and seafloor spreading records have provided the rock-solid evidences for establishing the theory of plate tectonics. Scientists have continuously verified and refined this theory, and now have a much better understanding of how our planet has been shaped by plate-tectonic processes. We now know that, directly or indirectly, plate tectonics influences nearly all geologic processes, past and present. Indeed, plate tectonics theory has proven to be as important to the earth sciences as the discovery of the structure of the atom was to physical sciences and the theory of evolution was to the life sciences.

Tectonics is the study of the forces within the Earth that give rise to continents, ocean basins, mountain ranges, earthquake belts and other large-scale features of the earth's surface. The theory of plate tectonics states that the outer rigid layer (about 70-100 km thick) of the earth called *lithosphere*, is divided into number of zones. These zones are called lithospheric plates upon which continents and ocean floor lie. The plates are in continuous motion at a speed of few centimeters per year over the asthenosphere, which is highly viscous, easily deformable layer between upper and lower mantle. The relative motion between the plates produces new crust at mid-oceanic ridges, consume crust at subduction zones and conserve the crust along the transform faults. Apart from normal process of construction and destruction at plate boundaries, plates do undergo break-ups and unifications. The lithospheric plates were reconfigured several times by continental rifting, ridge jumps and ridge propagation from the origin of the Earth to the present. All of the big geologic phenomena, earthquakes, volcanoes, mountain building, occur at plate boundaries.

Plate Boundaries

The place where two plates meet is called plate boundary. Most volcanic and earthquake activities occur at or near plate boundaries as they interact. The plate interiors are relatively quiet. There are four types of plate boundaries:

(i) Divergent plate boundaries

Divergent plate boundaries occur along spreading centers where plates are moving apart and new crust is created by magma pushing up from the mantle. The global mid-ocean ridge system that encircles the Earth is the examples of such boundaries. Shallow earthquakes are normally observed at these boundaries.

(ii) Convergent plate boundaries

These boundaries are formed when two plates moves towards each other. Volcanic activities are common at these boundaries. Some crust is destroyed in the impact and the plate becomes smaller. However, the results differ depending upon what types of plates are involved. Deep, medium and shallow earthquakes occur at these boundaries.

(iii) Transform plate boundaries

At these boundaries, crust is neither produced nor destroyed as the plates slide horizontally past each other. These boundaries generally occur on ocean floor and commonly offset active spreading ridges producing zigzag plate boundary. Small scale or no volcanic activities are observed along these boundaries. Normally shallow earthquakes are focused along these boundaries.

(iv) Plate boundary zones

These are broad belts in which boundaries are not well defined and the effects of plate interaction are unclear. Indo-Australian diffuse plate boundary is the best example of such plate boundary zones.

Vine-Matthews hypothesis of seafloor spreading

At the mid-ocean ridges, the oceanic lithosphere splits and magma is outpoured continuously. To accommodate the newly generated magma, the solidified part of the older magma moves away from the ridge axes. This process is known as seafloor spreading. At subduction zones the old oceanic lithosphere is consumed in the asthenosphere to accommodate the newly created lithosphere such that the surface area of the earth remains constant. The most definitive evidence

for seafloor spreading process comes from study of the linear magnetic anomalies that characterizes the ocean floor. The solidified part of the lithosphere acquires the then magnetization while cooling through Curie isotherm of about 520°C in oceanic areas. The observed pattern of the magnetic anomalies in the north Atlantic and the Indian Ocean have shown pronounced central anomaly associated with the median valley of the mid-ocean ridges and short period anomalies along the flanks of the ridges. The investigations of early sixties in the northeast Pacific Ocean revealed ridge parallel anomalies in the form of high and low magnetic strength. These are known as 'magnetic stripes'. The regular and continuous stripes were also found over most of the ocean floors. However, their origin remained a complete mystery for quite some time. The first successful attempt to account for the 'stripes' was made by F.J. Vine (then a graduate student at Cambridge University) and D.H. Matthews (his supervisor), in 1963 and independently by Morley and Laroche in 1964.

They have explained them in light of the theory of seafloor spreading (Hess, 1960, 1962; Dietz, 1961) with reversals of the earth's magnetic field (Cox et al., 1963). This is known as the Vine-Matthews hypothesis of seafloor spreading. As the earth's magnetic field reverses periodically and seafloor spreading occurs, the generated oceanic crust paralleling the crest of the ridge get magnetized normally or reversely. The crust with normal and reverse polarities caused the successive stripes of increase or decrease in the total intensity depending on the ambient magnetic field.

The hypothesis was at first received with some skepticism. Later, it was received wide acceptance during 1965-1967 due to increased evidence for the stripes of magnetic anomalies from large investigations which led to the development of the plate tectonic theory. The theory accounts the crust formed at mid-ocean ridges and moves away from them is controlled by the convective currents of the mantle material.

It may be mentioned that the discovery of reversal of the earth's magnetic field was one of the most profound discoveries in terms of its impact on the earth-sciences. The most important application of the chronology of reversals is to provide the calibration needed for the interpretation of marine magnetic anomalies.

Geomagnetic polarity time scale

The geomagnetic field has two stable dipole states. A normal state in which the magnetic field over the earth's surface undergoes minor variations about a northerly direction as it is doing at present. A reversed state in which the direction is generally southerly. The field switches back and forth between the two stable states at varied intervals. When asthenospheric mantle

material rises in a narrow zone along the ridge axis and cools through the Curie point of the major magnetic minerals, it acquires magnetization in the polarity of the earth's magnetic field that prevails at the time. As a result they contain information of the magnetization which can be used to determine the time of origin of the rocks and thus provides a basic data in time and space which are required for understanding the tectonic processes.

Brunhes has first discovered reversals of the earth's magnetic field as early as 1906. Mercanton (1926) and Matuyama (1929) have provided the timing of magnetic reversals. Matuyama's study, based on available age information of the rock samples, has revealed that during early part of the Quaternary period the earth's magnetic field was reversely magnetized and that has gradually changed over to normal state. Subsequent investigations have confirmed the reversals and soon made to realize the need for the geomagnetic polarity reversal time scale.

Because the geomagnetic field is a global phenomenon, the field-reversal theory requires that transitions from one magnetic polarity to another must occur at exactly the same time over the entire earth. This necessitated determining ages of the rocks as they are the most important information needed to propose calibrated time scale for the magnetic reversals. The development of different dating techniques (particularly Potassium-Argon method) in the late 1950's have made it possible to determine ages for the volcanic rocks where magnetic polarities have been determined. Cox et al. (1963), for the first time, have proposed time scale for geomagnetic reversals making use of the Potassium-Argon (K-Ar) dates. Further, discovery of short polarity event of duration as small as 10^5 years within the major polarity intervals have led to modify the time scale. Such polarity intervals were termed polarity epochs which are defined as time intervals during which the field is entirely or predominantly of one polarity (Cox et al., 1964). They were named after the early workers in the field of geomagnetism e.g. Brunhes, Matuyama, Gauss, Gilbert, while the short duration polarity events (short intra-epoch fluctuations) were named after the sites of their discovery (Cox et al., 1964). A polarity epoch may contain several polarity events and can be dominantly reversed (e.g. the Brunhes), dominantly normal (e.g. the Matuyama), or mixed. With the discovery of evidence for more and more reversals, it was realized that the length of time between reversals varies continuously over a wide range from very short events to long polarity epochs. By the late 1960's the time scale of reversals were extended back to about 4.5 million years from the combined magnetic data, and dating of volcanic rocks and deep-sea sediments (Cox et al., 1968; Cox, 1969).

While Heirtzler et al. (1968) proposed a magnetic polarity reversal time scale for the Late Cretaceous to

Recent, about 75 Ma (anomaly 32), based on the distribution of oceanic magnetic anomalies on a few long magnetic profiles. This time scale was derived by assuming that all the linear magnetic anomalies are parallel to the ridge axes, and due to geomagnetic field reversals as hypothesized by Vine and Matthews (1963). It was deduced by considering a constant spread rate of 1.9 cm/yr (Dickson et al., 1968) and distance of the model magnetized bodies from the axial zone of spreading i.e. ridge axis in the South Atlantic. The available date of 3.35 m.y. of the Gauss-Gilbert magnetic polarity boundary is taken as basis for extrapolating the ages of the magnetic reversals backward in time. The geomagnetic polarity time scale of Heirtzler et al. (1968) was confirmed by the deep sea drilling results from Joint Oceanographic Institutes for Deep Earth Sampling (JOIDES) investigations in the South Atlantic (Maxwell et al., 1970). This time scale has been widely accepted for interpreting the magnetic anomalies of the world oceans. It has been further improved for still short duration intervals of magnetic reversals and precise dating of the earlier identified anomaly numbers.

Age calibration has been the focus for changes to the geomagnetic polarity time scale of LaBrecque et al. (1977). Subsequent calibration efforts added more control points based on developing magneto-biostratigraphic ties, and relaxed the implicit assumption of constant spreading in the South Atlantic to smaller time scales (Ness et al., 1980; Lowrie and Alvarez, 1981; Harland et al., 1982; Berggren et al., 1985; Haq et al., 1988).

Cande and Kent (1992) proposed a geomagnetic polarity time scale for the Late Cretaceous and Cenozoic based on an analysis of marine magnetic data from the world's major oceanic ridge systems. This scale is based on nine age calibration tie points evenly distributed at approximately 10 m.y. intervals which was fitted with a cubic spline approximation to interpolate the age of polarity intervals. At these tie points the magnetic anomalies are correlated with the ages determined from biostratigraphic studies of oceanic basement and basal sediments. Linear interpolated ages were assigned for the in between anomaly numbers from magnetic profiles. Additional small-scale anomalies (tiny wiggles) that represent very short polarity intervals or intensity fluctuations of the dipole field have been incorporated.

Cande and Kent (1995) again refined their 1992 geomagnetic polarity time scale with more precise age data and proposed a new time scale. It uses an age of 65 Ma (instead of 66 Ma as used by them in 1992) for the Cretaceous-Tertiary boundary as recorded in marine (Swisher et al., 1992; Dalrymple et al., 1993) and non-marine (Swisher et al., 1993) sediments. Secondly, it uses an astronomical age of 5.23 Ma (Hilgen, 1991; Langereis et al., 1994) for the older boundary of

subchron 3n.4n rather than 2.6 Ma for the younger boundary of chron 2A (Matuyama/Gauss boundary).

Polarity chron nomenclature

Normally longest intervals of predominantly one polarity is referred by the corresponding anomaly number followed by the suffix 'n' for normal polarity or 'r' for the preceding reversed polarity interval. If these chrons are subdivided into shorter polarity intervals, they are referred as subchrons and are identified by appending, from youngest to oldest, to the primary chron name and adding an n for a normal polarity interval, or r for a reverse interval. As an example, the three normal polarity intervals of anomaly 6C (chron 6Cn) are denoted as 6Cn.1n, 6Cn.2n and 6Cn.3n subchrons. Similarly, the reversed interval proceeding (older than) subchron 6Cn.1n is referred as subchron 6Cn.1r. In the figures, the normal polarity is denoted as 'N' instead of 'n' for clarity.

What is new after Vine-Matthew's hypothesis?

The most convincing evidences for seafloor spreading, continental drift and plate tectonics come from the configuration of linear magnetic anomalies of the oceans. Vine and Matthews (1963) have proposed a model to explain the origin of these stripes. According to the model, the alternate stripes of positive and negative magnetic anomalies are caused by seafloor spreading and reversals of the Earth's magnetic field. This was one of the most important early attempt towards development of the rigid-plate hypothesis. Later, several researchers have shown that i) these anomalies are symmetrical and could be correlated with similar anomalies throughout the world ocean as well as with the geomagnetic reversal time scale, and ii) the anomalies are offset along transform faults and their fossil traces known as fracture zones. This pattern was constructed assuming that the transform offset was inherited from the original configuration of the spreading ridge boundary, and the ridge consists of impenetrable end points for the two ridge segments which abut against the offset. The simple pattern of geometry of ridge segments and transform offset has led to the development of the concept of seafloor spreading and plate tectonics, and has provided a useful model to explain the gross configurations of seafloor features and plate motions.

In the late seventies and early eighties, deviations to this model have increasingly been proposed where adequate data were available for reinterpretation. The existence of several major seafloor lineation that are oblique to both relative and absolute plate motions have been observed. These observations enabled the study of new aspects of seafloor spreading processes beyond the simplified model of ridge segments and transform faults. These oblique anomaly offsets were previously been interpreted as a result of faulting either due to plate non-rigidity or due to relative motions of several microplates. However, they could not satisfactorily explain the

observations within the framework of plate tectonic theory, which became much more evident with the addition of magnetic profiles world wide. This necessitated development of new models to explain the oblique offsets and other complexities associated with magnetic lineations that seemed incompatible with plate tectonic theory. Finally, Shih and Molnar (1975) and Hey (1977) have proposed the propagating rift hypothesis to explain the oblique offsets in magnetic anomaly pattern and other lineaments that are oblique to both relative and absolute plate motions.

Propagating rift hypothesis

Shih and Molnar (1975) and Hey (1977) independently proposed the propagating rift hypothesis as a mechanism of producing oblique termination of magnetic lineations. According to the hypothesis, propagation progressively occur when a lithospheric plate breaks and a new spreading center forms. The term propagating rift means non-instantaneous rifting and is considered synonymous with progressive or asynchronous rifting. Propagating rifts are extensional plate boundaries that progressively break through rigid lithosphere. If the rifting advances to the seafloor spreading stage, propagating seafloor spreading centers follow behind, gradually extending through the rifted lithosphere. A propagating rift occurs when one segment of a spreading center at a ridge-transform-ridge plate boundary grows at the expense of the other and the transform fault migrates along the ridge axis.

Although the conceptual mechanism appears to be simple, this hypothesis has significant implications for both large and fine scale plate tectonic evolution. It explains i) the existence of many seafloor and continental margin lineaments that are oblique to both relative and absolute plate motion which previously seemed incompatible with plate tectonic theory, ii) why some continental margins are not parallel to seafloor isochrons and, iii) the large scale reorganization of some seafloor spreading system as well as formation of some transient microplates. It is worthwhile to mention that the terms ridge propagation / propagating ridge / propagator may be used to infer propagating seafloor spreading center to distinguish from the propagating tectonic rifting.

The propagating rift hypothesis is only a minor modification towards understanding of seafloor spreading. It explains satisfactorily in a simple way many diverse imperfections associated with magnetic anomaly patterns. It also provides a better insight into the processes by which spreading ridge forms and adjusts to changing conditions.

In several parts of the Indian Ocean in general and the Arabian Basin in particular, the magnetic lineations exhibit offsets at many places. In all earlier studies, such offsets have been interpreted in terms of fracture zones

orthogonal to the magnetic lineations. The existence, trend and extent of the fracture zones proposed earlier are somewhat speculative and poorly constrained. The magnetic lineations mapped with closely spaced and properly oriented magnetic profiles, interestingly, do not support the existence of such orthogonal fracture zones at most places. Instead, it depicts oblique offsets. Several magnetic anomaly profiles commonly show closely or far apart spacing of magnetic lineations compared to predicted symmetrical pattern indicating missing or extra crust. Further, it is strongly suspected that the then nearby Reunion hotspot had a thermal influence on the accretion process of the Early Tertiary oceanic crust of the Arabian Basin. As a result, the magnetic anomaly pattern in this region is much more complex than believed so far. In this lecture, we discuss more insights of spreading ridge propagation from the examples of the Arabian Sea region (Chaubey et al., 1998; Dyment, 1998; Chaubey et al., 2002; Royer et al., 2002).

Suggested Readings

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