

# Geological features and geophysical signatures of continental margins of India

K. S. Krishna

National Institute of Oceanography, Dona Paula, Goa-403 004.

krishna@nio.org

The shape and classification of continental margins are in general dependent on style of continental splitting, rifting, subsidence and their proximity to the tectonic plate boundaries, at times the margins undergo for modifications by sediment deposition and volcanic activity. Worldwide continental margins are broadly categorized into two groups: passive (Atlantic) and active (Pacific) type margins. The main features of passive continental margin are shelf, slope, rise and abyssal plain. Analyses of marine geophysical data across the eastern and western continental margins of India show that both the margins are different in shape although both belong to passive margin group. While continental slope along the western continental margin is wider and provides scope for multiple picks of foot-of-slope, it narrows along the eastern continental margin and is clear for single pick of foot-of-slope. Continental slope and rise on western margin and rise on eastern margin were modified to a major extent by Deccan-Reunion hotspot volcanism and Bengal Fan sedimentation respectively. Volcanism has dominated on the western continental margin of India, thereby the margin had been turned into a volcanic passive continental margin, while eastern continental margin of India remained as non-volcanic passive margin.

## Introduction

The surface of the Earth consists of two dominant morphological features - the continents and the oceans. Since the beginning of the geological record the continents underwent for breakups within it and collisions with other continental masses, while the oceans have took birth and death. The oceans are relatively short-lived features on the Earth. Continental rocks (granites) do not come to an end at the coastline, they in fact extend into the sea to a distance where they meet the oceanic type rocks (basalts). The submerged portion of continents, commonly known as the continental margins does include main geological features of seabed, and subsoil of the shelf, the slope and the rise.

The Indian subcontinent on eastern side has got separated from West Australia and East Antarctica in South Pole during the early Cretaceous age (130-120 million years before present). Elan Bank, a micro-continent presently lies on the west margin of the Kerguelen Plateau in the southern Indian Ocean, got detached from the eastern margin of India at second stage about 120 million years ago (Gaina et al., 2003). Thus the eastern margin of India had experienced two

continental breakups in early stages of eastern Gondwana splitting. At a later stage during the mid-Cretaceous age (about 90 million years ago) Madagascar and at Cretaceous-Tertiary boundary (about 65 million years ago) Seychelles micro-continent have splintered and rifted away from the western side of the Indian subcontinent. Subsequently major geological processes of volcanism and sediment deposition have influenced the morphology of western and eastern continental margins of India, with which some of the main geological features of continental margins have been modified.

This article provides a brief review on theory of plate tectonics for understanding the process of intra-continental breakup and formation of continental margins and associated main geological features. The marine geophysical data of the continental margins of India are analyzed with a view to identify the main geological features as well as geophysical signatures of the margins, thereby the results are discussed for classification of the margins.

## The Theory of Plate Tectonics

The theory of continental drift, which paves the way for discovery of plate tectonics, was put forward by Alfred Lothar Wegener as early as in 1912. He proposed that the continents are not fixed, but rather 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. As years passed, more and more evidences were uncovered to support the idea that the plates were moving constantly over geologic time. Paleomagnetic observations and seafloor spreading records have provided the rock-solid reasoning for establishing the theory of plate tectonics. 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.

In geological terms "*plate*" is a large, rigid slab of solid rock. The word "*tectonics*" comes from the Greek root "to build." Putting these two words together, we get the term "*plate tectonics*", which refers to how the Earth's surface is built of plates. The plate tectonic theory along with seafloor spreading process have become

indispensable in earth sciences to explain the formation of rifted margins during continental breakup and subsequent formation of oceanic basins.

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 segments. These segments are called lithospheric plates (Garrison, 1999; Rothery and Wright, 2001). There are about 12 major plates such as North American, South American, African, Indian, Australian and so on covering the entire earth surface (Fig. 1). The lithospheric plates are bounded by one of the three main types of geological features: (1) mid-oceanic ridges (2) subduction zones (3) transform faults. They are also alternatively termed as divergent plate boundary, convergent plate boundary and transform plate boundary respectively (Fig. 2). The boundaries are narrow deforming zones, which accompanied by earthquake activity, but the plate's interiors are rigid. In recent times these assumptions are extended by few global observations that the plate boundaries in both continents and oceans are diffuse exceeding dimensions of 1000 km, which are also coinciding with the regions of high magnitude intraplate earthquakes. The plates upon which continents and ocean floor lie are in continuous motion at a speed of few centimeters per year. Each plate is in relative motion with respect to the other on the surface of the Earth. The relative motion between the plates produce new crust at mid-oceanic ridges, consume crust at subduction zones and conserve the crust along the transform faults (Fig. 2). 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 propagating episodes from the origin of the Earth to the present.

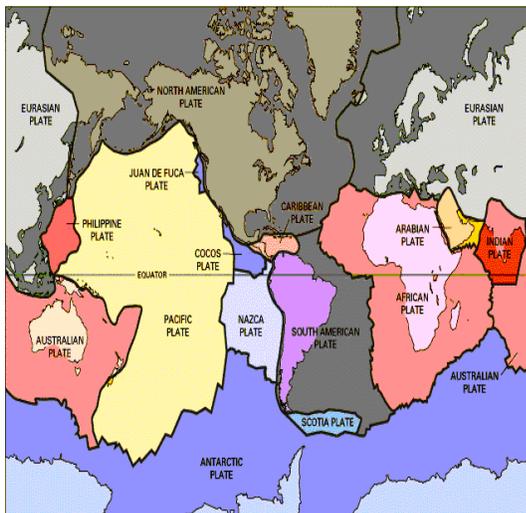


Fig. 1. Major lithospheric plates of the earth.

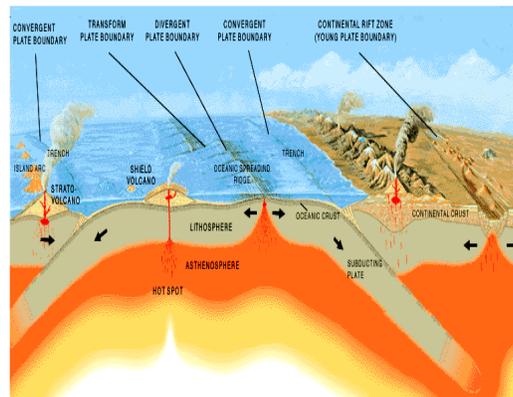


Fig. 2. Types of lithospheric plate boundaries and continental rifting.

### Types of Continental margins

Continental margins do evolve by fragmentation of super-continents or larger continental masses and rift apart by the formation of new ocean basins in between (Fig. 2). The shape of continental margins is in general constrained by style of continental breakup, rifting, stretching and following subsidence, occasionally the margins undergo for modifications by sediments drained from the land and volcanic activity. Initially two basic types of continental margins have been recognized and were termed as Atlantic and Pacific type margins (continental shelf limits, 2001). Today, three main types of continental margins are differentiated based on their relation to plates, plate boundaries and seismic and volcanic activities (Jones, 1999).

- 1) Atlantic type: passive, divergent or aseismic continental margin
- 2) Pacific type: active, convergent or seismic continental margin
- 3) Transform, conservative, translational or sheared margin.

#### *Passive (divergent) continental margin*

Passive continental margins are evolved within a single lithospheric plate, in which continental crust adjoins the oceanic crust (Fig. 3, upper part). As there is no collision or subduction taking place near the continental margin, earthquake activity is minimal but sediment deposition dominates. This leads to build-up of the wide and low-relief (flat) continental shelf (covered by shelf seas), slope and rise. Initially passive margins form at divergent plate boundary following break-up of the continent, then they move away with the accretion of new oceanic crust by seafloor spreading activity. This type of continental margin is found mostly along the coasts bordering the Atlantic and Indian Oceans.

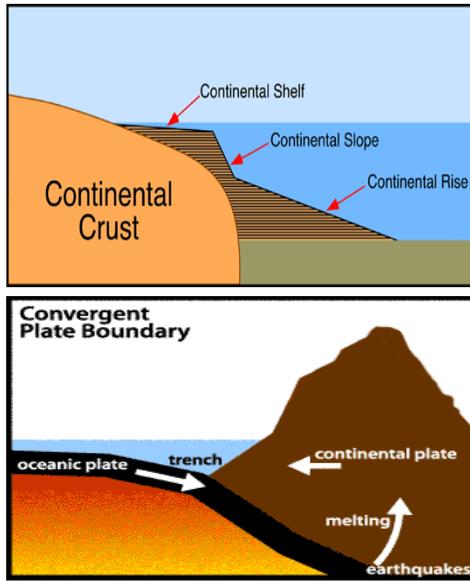


Fig. 3. Crustal configuration of the divergent (passive) and convergent (active) continental margins.

#### Active (convergent) continental margin

Active continental margins typically have a trench at the foot of the continental slope. The margins are found near convergent plate boundaries where the oceanic plate is being pushed down into the Earth's interior beneath continent on another plate (Fig. 3, lower

part). Here the continent and ocean floor belong to different lithospheric plates. Active margins are commonly the sites of tectonic activity such as earthquakes, volcanoes, mountain building and formation of new igneous rocks. Because of the mountainous terrain the continental shelf is narrow to non-existent, dropping off quickly into the depths of the subduction trench. The trench at the foot of the continental slope generally replaces the continental rise found at passive continental margins. This type of continental margin is found mostly along the coasts bordering the Pacific Ocean.

#### Transform continental margin

Rifted margins that were evolved by continental breakup and following seafloor spreading in general have indented shape with rifted and non-rifted segments (Fig. 4). While the rifted margin segments are pushed in more-or-less perpendicular to the direction of plate motion, the non-rifted segments that are sheared and carried away by the rifted margins are approximately parallel to the initial plate motions between the parting continents (Fig. 4). Such margins are called transform or rift-transform margin. Transform margins can occur in both passive and active type continental margin settings. Large segments of transform margins are found mostly around the Atlantic, Indian and Southern Oceans (Jones, 1999).

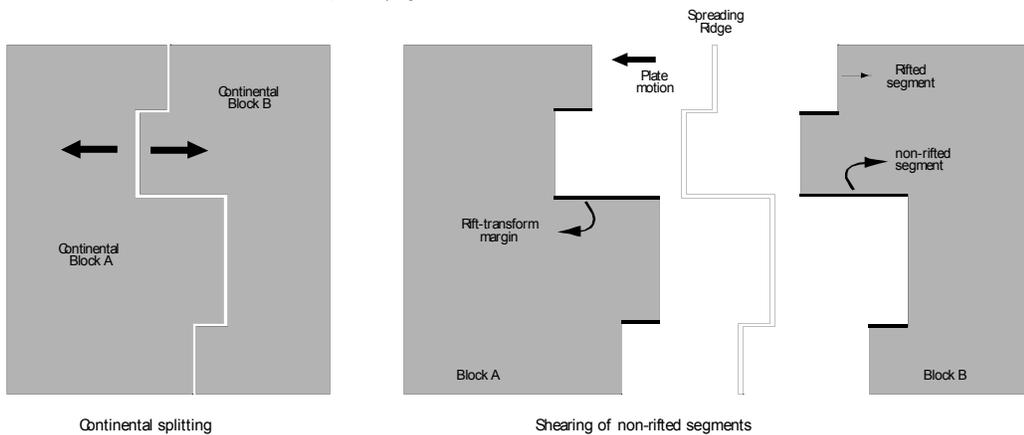


Fig. 4. Development of rift-transform. Margin.

#### Geological features of Passive Continental margins

The Earth's solid surface is dominated by different scale geological features such as mountains on land and trenches in oceans. With respect to sea surface mean elevation of land reaches to 840 m, whereas in the sea mean depth reaches to 3800 m (Jones, 1999; Rothery and Wright, 2001). Continental margins lying between the coastline and abyssal plain are normally divided into

three main components with increasing depth: continental shelf, continental slope and continental rise.

#### Continental Shelf

It is a gentle seaward sloping surface that extends from the shoreline of the coast (Fig. 3, upper part). The continental shelf generally slopes gently up to 1:1000 with an average width of approximately 70 km. The outer edge of the shelf marked by an abrupt increase in slope

is called the shelf break or shelf edge. The water depth to the shelf break varies from 20 to 500 m, but averages around 130 m.

### Continental slope

It is a steep sloping surface that extends from the outer edge of a continental shelf down to the continental rise (Fig. 3, upper part). The relief is substantial reaching greater than 1:40, averaging about 4°, but can be as high as 35-90°. Continental slopes are usually between 20 and 100 km wide, and between 1.5 and 3.5 km deep at their base. At the base of the continental slope seafloor gradient drops and grades into rise, the intersecting point is called the foot-of-slope. Geologically continental shelf and slope have characteristics of continental crust. The continent-ocean transition is generally expected at or around the foot-of-slope.

### Continental rise

It is a gentle low relief seaward gradient surface that lies between the continental slope and the deep ocean basin (Fig. 3, upper part). Continental rises vary in width from 100 to 1000 km, with gradients from 1:100 to 1:700. These are the locations where sediments largely derived from the continent are accumulated immensely.

### Abyssal plain

It has an average gradient of less than 0.05° and a change in height of less than 1 m per km. This is flatter than any other ocean feature and much flatter than most land areas. However, the seafloor flatness is frequently interrupted by abyssal hills and seamounts.

### Marine geophysical signatures of the continental margins of India

Bathymetry, gravity and magnetic data acquired along two profiles (MAN - 01 and 03) across the eastern continental margin (Gopala Rao et al., 1997) and four profiles (C1707 - A, B, C and D) across the western continental margin of India (Naini, 1980) shown in Fig. 5 were investigated for identification of main geological features of the continental margins of India as well as to classify the margins. Stacked plots of bathymetry, free-air gravity anomaly and magnetic anomaly profiles, C1707-D, C1707-A, C1707-C and MAN-03, are presented in Fig. 6 for depicting the seafloor morphology and geophysical signatures associated with simple and complex continental margins. Seafloor topography and geophysical signatures of the western continental margin of India are deviating to some extent from that of eastern margin of India and considerably differing from the results of passive continental margins (Fig. 3, upper part).

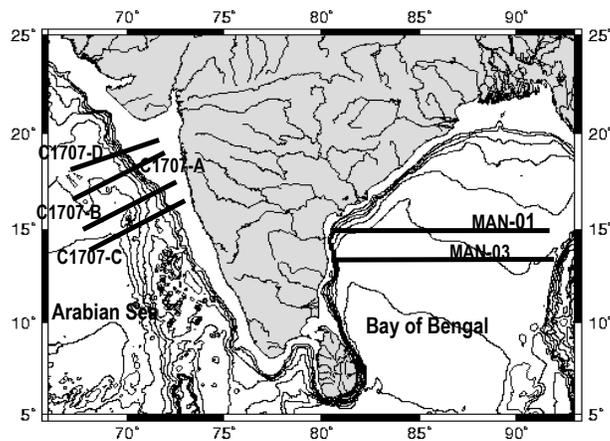


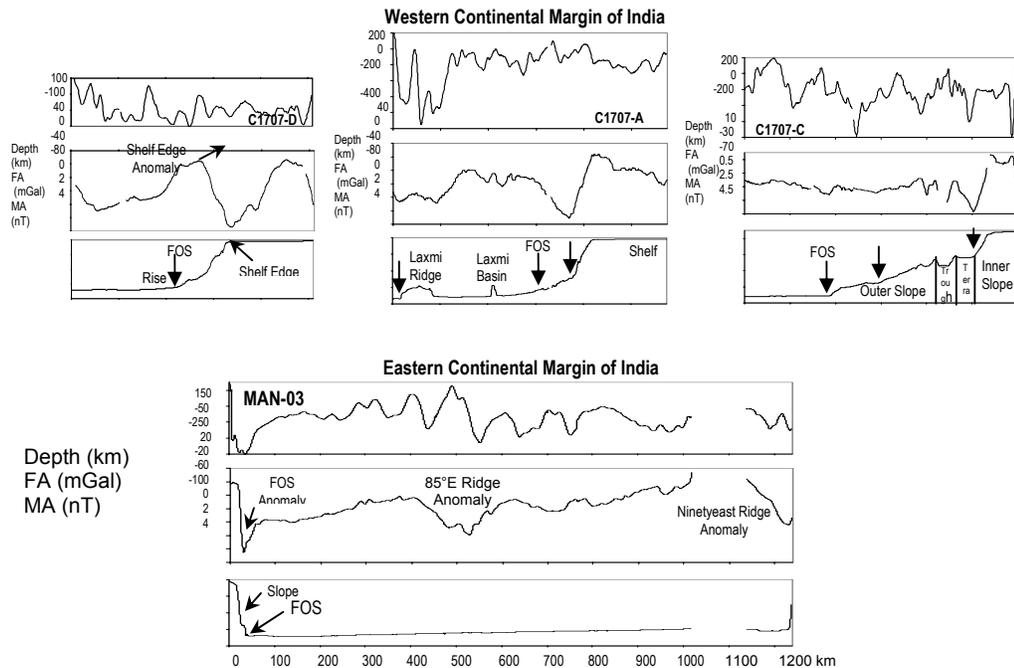
Fig. 5. Geophysical profiles of the eastern and western continental margins of India used for identification of signatures of the geological features of the margins.

Table 1. Physical characteristics of main features of the continental margins of India.

Geological features of the continental margin	Profiles in Arabian Sea										Profiles in Bay of Bengal		
	C1707-D	C1707-A				C1707-B			C1707-C			MAN-01	MAN-03
Width of the continental shelf (km)	>170	>160				>63			>60				
Water depth at shelf break (m)	99	160				111			242				130
Width of the continental slope (km)	115	40	127	360	116	206	485	43	258	357	>70	36	
Water depth at foot-of-slope (m)	3191	2450	3304	3683	2536	3616	3934	1699	3296	4066	2819	3353	
Width of the continental rise (km)	180											185	184

Bathymetric data along profiles MAN-01 and 03 on eastern continental margin of India clearly show shelf break, slope and foot of the slope (Fig. 6). Continental rise is noticeable on MAN-01 with certain confidence, while on profile MAN-03 the rise seems to be absent or non-identifiable. It appears sediment accumulations discharged from the Ganges and other major rivers of east coast have modified the continental rise at some locations on eastern margin of India. Shelf break and continental slope and its foot are clearly expressed in free-air gravity anomaly data, the anomaly trend in the vicinity of the margin just follows the trend of the seafloor topography as that was maintaining significant density

contrast as opposed to water body (profile MAN-03, Fig. 6). Steep low short-wavelength gravity anomaly, a typical signature associated with foot of the continental slope all along the eastern margin of India, swiftly returns back and merges with regional trend of the gravity anomalies (Fig. 6). The merging location indicates the boundary separating lighter material (granite rocks) from denser material (basaltic rocks) on seaward side. A magnetic low signature is seen associating with the foot of the continental slope. On further seaward side gravity and magnetic anomalies are mostly caused by the subsurface structures (85°E Ridge, Ninetyeast Ridge, etc.) of the Bay of Bengal.



**Fig.6.** Bathymetry, free-air gravity anomaly and magnetic anomaly plots are stacked for profiles C1707-D, A and C and MAN-03. Multiple picks of foot-of-slope (FOS) are shown on profiles C1707-A and D.

Bathymetric data along C1707 profiles on western continental margin of India clearly show shelf and shelf break, whereas other features like slope, foot of the slope and rise are indistinct (Fig. 6). Continental slope along the western margin of India is in general wider than the eastern margin. At locations the slope on the western margin is not distinguishable against rise on plain observation, suggesting that the slope-rise provides scope for multiple picks of foot-of-slope. On southern profiles continental slope indeed becomes complex in a way of adding several morphological features. For example on profile C1707-C foot of the slope is not discernible and seems to be extending for about 350 km. Keeping the seafloor morphology and gradients in consideration three possible potential foot-of-slope picks can be recognizable along the profile from inner to outermost locations (Fig. 6). The continental slope along the profile C1707-C includes inner slope, terrace, trough

and outer slope (Fig. 6). Deep seismic reflection data may be useful for identification of actual foot-of-slope although it differs from the one identified by a more conventional geomorphic approach. On the basis of seismic reflection data it may be possible to consider the outer foot-of-slope pick at the edge of the abyssal plain as valid one.

Free-air gravity anomalies of the western continental margin of India mostly do not follow the trend of the seafloor morphology except the ones shelf break and continental slope. The most intrinsic observations are noted on northern part of the margin (profiles C1707-D, A and B). Nearly flat seafloor region adjacent to continental rise (termed as Laxmi Basin) is as a whole characterized by a regional gravity high and a prominent gravity low, ~20 mGal and 100 km wide within it (Fig. 6). The low is clearly seen extending in NNW direction as a

linear anomaly paralleling the shelf. The gravity low is further obliterated by high on profile C1707-A where the structure is elevated from the adjacent nearly flat seafloor. On further seaward the structural rise on profiles C1707-A and B (termed as Laxmi Ridge) is associated with broad low gravity anomaly. No prominent gravity signatures are noticed on seaward side of profile C1707-C and neither follows the trend of the seafloor nor anomaly pattern of the Laxmi Basin.

Continental rocks (granites) along the margins are in general expected to possess a weak magnetic field strength as they are much older in age than that of oceanic basaltic rocks. In contrast to this along the western continental margin of India varied amplitude and wavelength magnetic anomalies are seen associated with the features (Fig. 6). In the event of volcanic activity along the margin igneous structures are expected to emplace in different forms within the continental crust, which produce significant magnetic anomalies. About 65 million years ago a hotspot volcano (called Reunion) had produced Continental Flood Basalts (CFB), what is known as Deccan Trap lavas on western margin of India. Widespread emplacement of volcanic rocks occurred within the continental crust of the western margin of India when the Indian plate was moved over the Reunion hotspot. The process led to alter the margin's initial crustal configuration and caused for presence of significant magnetic anomalies along the western margin. Volcanism has dominated on the western continental margin of India and turned the margin into a volcanic passive continental margin. Volcanic activity and sediment deposition of Indus and other major west coast rivers had modified the seafloor morphology of the western margin of India and become complex for identification of foot-of-slope along western margin.

### **Passive volcanic continental margin**

The Indian continental margins are classified as passive continental margins as the continental crust and

the oceanic crust are together on the same lithospheric plate and in general due to the absence of seismic activity in these regions. But a volcanic origin for the western continental margin is ascribed as the margin bears evidences of large-scale magmatic activity related to the Reunion hotspot. Whereas absence of hotspot related volcanic activity on the eastern continental margin of India brings it under the non-volcanic passive margin category.

### **Suggested Reading**

Continental shelf limits – The scientific and legal interface, 2000, edited by P.J. Cook and C.M. Carleton, Oxford University Press, Inc. New York, pp. 1-363.

Gaina, C., Muller, R.D., Brown, B. and Ishihara, T., 2003, Micro-continent formation around Australia, in *The Evolution and Dynamics of the Australian Plate*, edited by R. Hillis and R.D. Muller, Joint Geol. Soc. of Aust. Am. Spec. Pap., 22, 399-410.

Garrison, T., 1999, *Oceanography*, Wadsworth Publishing Company, USA, pp. 1-552.

Gopala Rao, D., Krishna, K.S. and Sar, D., 1997, Crustal evolution and sedimentation history of the Bay of Bengal since the Cretaceous, *J. Geophys. Res.* 102, 17747-17768.

Jones, E.J.W., 1999, *Marine Geophysics*, John Wiley & Sons Ltd., England, pp. 1-466.

Naini, B.R., 1980, A geological and geophysical study of the continental margin of western India and the adjoining Arabian Sea including the Indus Cone, Ph.D. Thesis, Columbia Univ., New York, pp. 1-173.

Rothery, D.A. and Wright, J., 2001, *The Ocean Basins: Their structure and evolution*, Published by Open University and Butterworth-Heinemann, pp. 1-185.