

## Continental margins offshore west and east coasts of India based on satellite gravity and seismic sections – seaward dipping reflectors

Continental margins which are involved with plate tectonic processes such as subduction along the west coast of Andaman–Sumatra islands are known as active margins. Contrary to this, the margins which are devoid of plate tectonic processes are known as passive margins. Passive margins can form in two ways due to plume-related break-up forming a large volcanic province along the continental margins. Such margins are called volcanic passive (rifted) margins, whereas break-up due to localized igneous activity from the upper mantle caused by decompression or local thermal sources results in non-volcanic passive (rifted) margins.

Break-up of continents causes reduction in the crustal thickness and produces several specific structures between continent and the deep ocean formed due to the break-up<sup>1</sup>. Figure 1 is a schematic diagram of a typical continental margin showing its various details. The entire section between the coastline and the ocean is known as continental margin, which is further divided into continental shelf, shelf break, etc. Due to igneous activity, the continental shelf is characterized by mafic rocks and shows extensional tectonics in the form of normal faults developing into graben-like basins and they represent the stretched lithosphere. There are normally two stages of intrusion that are referred to as intrusive (1) and intrusive (2) as shown in Figure 1. The first stage of intrusion in the form of dykes, etc. is found close to the coastline, whereas the second stage forms the main phase of igneous activity along the shelf break and is primarily responsible for the break-up. These intrusions originating from the plumes or upper mantle primarily consist of mafic rocks that cause gravity highs. However, subsequently due to subsidence basins are formed that give rise to gravity lows between the inner and outer seaward dipping reflectors (SDRs).

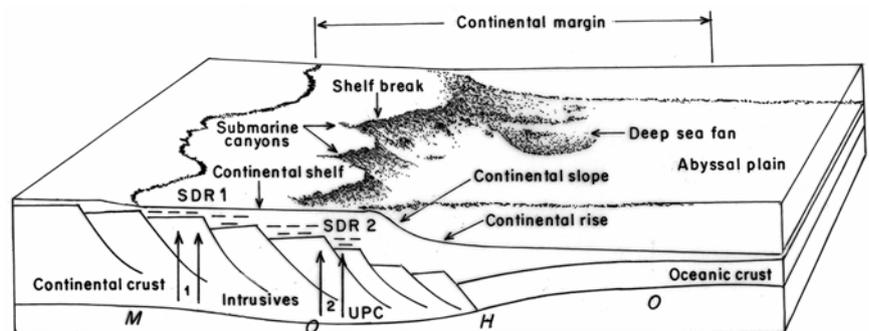
The igneous intrusions discussed above show SDRs in the seismic section as inner SDR and outer SDR (SDR1 and SDR2 respectively, Figure 1). However, the outer SDR is more common. Menzies *et al.*<sup>2</sup> have shown both these SDRs in the case of offshore Norway, that repre-

sent a volcanic rifted margin due to a plume. They are formed due to volcanic flows under submarine conditions, which get solidified layer-wise in the presence of cold water due to quenching and produce reflectors dipping towards the ocean due to rifting<sup>1</sup>. It may be noted that the same volcanic flows at the surface such as the Deccan Volcanic Province do not produce reflections due to their massive nature. Sedimentary deposits on the continental shelf and slope may show sectoral characteristics along the strike direction due to deposits formed from the rivers bringing material from different sources such as sandstones, shales, phyllites, etc., occurring in sections strike-wise. In addition, the slope and deep-sea fan deposits show sorted nature of sediments due to turbidities, which causes heavier and larger grains to settle first.

Satellite data have the advantage that they present the total picture of the continental margin along its entire section, whereas marine magnetic data are usually recorded along profiles and therefore, provide information only along specific sections. Figure 2 is a high-resolution Bouguer anomaly map off the west coast of India based on satellite data and processed especially for oil exploration along the continental margin (Directorate General of Hydrocarbons, DGH, 2010, pers. commun.). We shall try to examine it for geodynamics and understand the nature of the continental mar-

gin in this region. It shows three sets of prominent linear gravity highs along the continental shelf offshore the west coast of India, marked as H1, H2 and H3. In comparison to Figure 1, the first set of these gravity highs, H1 that are close to the coastline and almost parallel to it correspond to SDR1, known as the inner SDR that represents the first phase of intrusion as long dykes initiating the break-up. These features have formed a ridge known as the Prathap Ridge. Occurrences of long dykes along the offshore west coast of India have also been reported based on airborne<sup>3</sup> and marine<sup>4,5</sup> magnetic surveys. The linear gravity highs, H2, coincide with the Chagos–Laccadive ridge and extend northwards as indicated by these gravity highs. The Chagos–Laccadive ridge is made up of basaltic rocks and their ages correspond to the Deccan trap eruption from Re Union plume at the time of the break-up of Seychelles and India during the late Cretaceous (~65 Ma)<sup>6</sup>. Therefore, in comparison to Figure 1, the gravity highs H2 would correspond to the outer SDR (SDR2). The set of gravity highs, H3, coincides with the continental slope and is primarily caused by oceanic crust and thinning of the crust<sup>7</sup>. The gravity lows between the gravity highs H1, H2 and H3 are basins formed due to subsidence and are important for oil exploration.

In order to check the existence of SDR in this region, we examined a seismic section across the region. Figure 3 is a



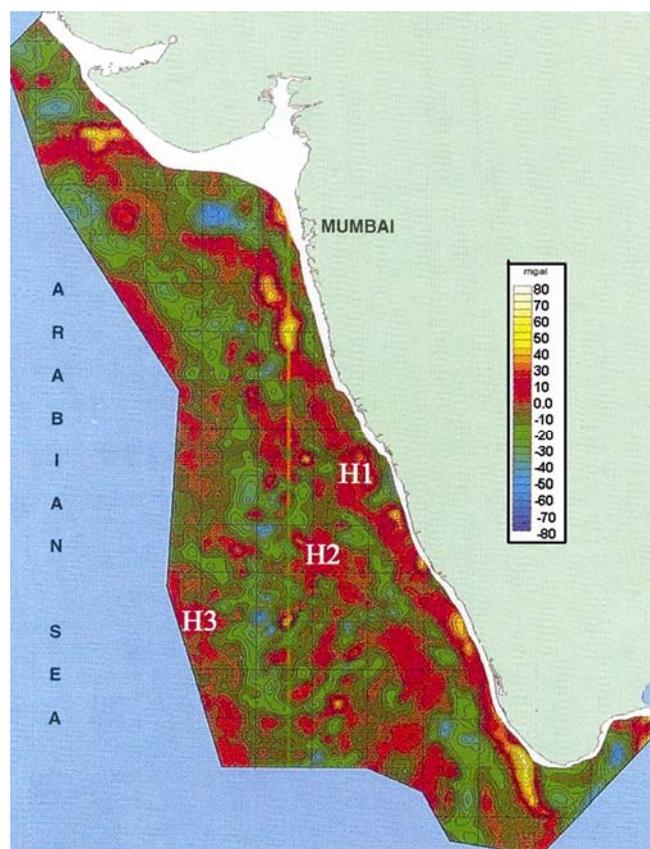
**Figure 1.** Schematic diagram of passive continental margin with continental shelf, shelf break and associated canyons. The figure also shows the intrusive related to break-up which is usually found in two groups near the coast and the shelf break giving rise to two sets of seaward dipping reflectors (SDRs) over the basement and under plated crust (UPC). SDR1 is known as the inner SDR which is usually in the form of long dykes initiating the break-up whereas SDR2 is known as the outer SDR that completes the break-up.

seismic reflection profile across the Kerala–Konkan coast that shows the Laccadive basin between the west coast of India towards the east and the Laccadive ridge towards the west (DGH, 2010, pers. commun.). It shows several reflectors over the basement due to sediments that dip westward on the eastern flank of the basin and eastward on its western flank. However, there are reflectors on top of the basement (SDR, red colour) that dip uniformly towards the sea and represent SDRs, suggesting a volcanic basement related to the Deccan trap eruption that forms the Laccadive ridge towards the west and is exposed in large parts of western India. Hinz<sup>8</sup> reported SDRs in the northern part offshore Saurashtra and Kutch coinciding with the linear gravity highs, H2 and H3, that suggests their presence throughout the offshore west coast of India as volcanic rifted margin. Figure 3 also shows some structural traps like pinch outs that are suitable for oil accumulation, another characteristics of volcanic rifted continental margins.

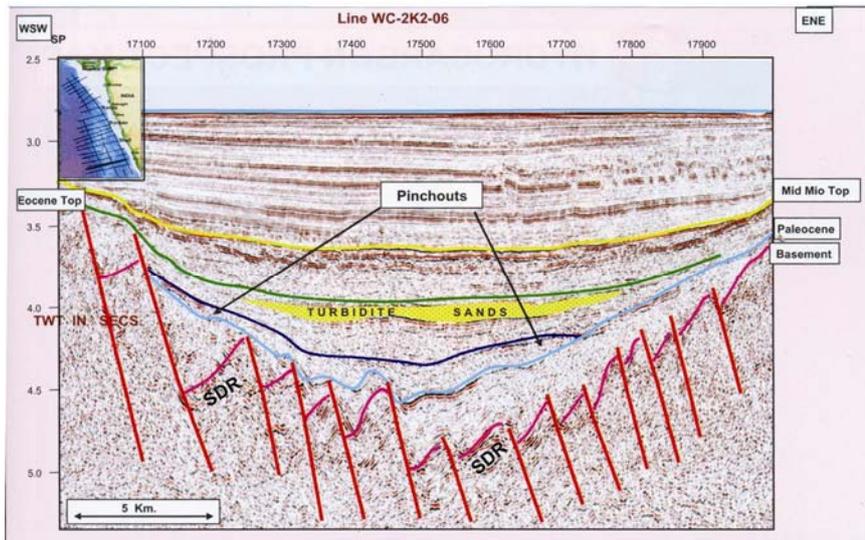
Figure 4 is a similar Bouguer anomaly map offshore the east coast of India obtained from the satellite data and especially processed for oil exploration (DGH, 2010, pers. commun.). We shall try to use it for understanding the geodynamics of this region. The map also shows three sets of linear gravity highs, H1, H2 and H3, but they are not as continuous as in case of the offshore west coast of India (Figure 2). In this case the gravity highs, H1, are just along the coast and a part of it may in fact represent the gravity highs due to the extension of the Eastern Ghats Mobile Belt offshore that forms the east coast of India. The gravity highs, H2, are located over the continental margin that may represent the igneous intrusion related to the break-up between India and Antarctica along this coast. However, the break-up history along this coast is complex as the trace of the Kerguelen hotspot along the 90 East Ridge that is considered responsible for this break-up is sufficiently far off from the coastline. However, the gravity highs, H2, along the continental margin off the east coast

of India extend up to the continental margin offshore West Bengal and Bangladesh, where they join the gravity anomalies due to the 90 East Ridge<sup>7</sup>. The gravity highs due to the 90 East Ridge presumably originated due to igneous intrusions from the Kerguelen hotspot during the break-up between India and Antarctica<sup>7,9</sup>. Therefore, the gravity highs, H2, may also represent the igneous intrusion from the same hotspot during the break-up between India and Antarctica. The gravity highs, H3, are connected to the gravity highs due to the 90 East Ridge towards the west of the gravity low, L1, that is related to crustal thickening under the 85 East Ridge due to isostasy<sup>7</sup>. The gravity highs, H2 close to the coast and H3 away from it may therefore represent the classical pairs of the gravity highs that represent volcanic margins as described above in case of the offshore west coast of India. In the northern part of offshore Orissa, based on airborne magnetic data, Mishra *et al.*<sup>10</sup> suggested mafic dykes on the continental shelf that coincide with the gravity highs, H1, in this section. It is therefore likely that these dykes represented the first phase of volcanic eruption that was responsible to initiate the break-up of India along its east coast. A part of the gravity highs H1 and H2 may represent the initial phase of magmatic intrusion initiating the break-up, whereas the gravity highs H3 (Figure 4) that are connected to the gravity highs due to the 90 East Ridge as described above and extend all along the offshore east coast of India, represent the final phase that was responsible for the break-up. Therefore, continental shelf offshore the east coast of India also appears to represent a volcanic margin. The gravity lows between these gravity highs represent the sediments of the basins formed due to subsidence.

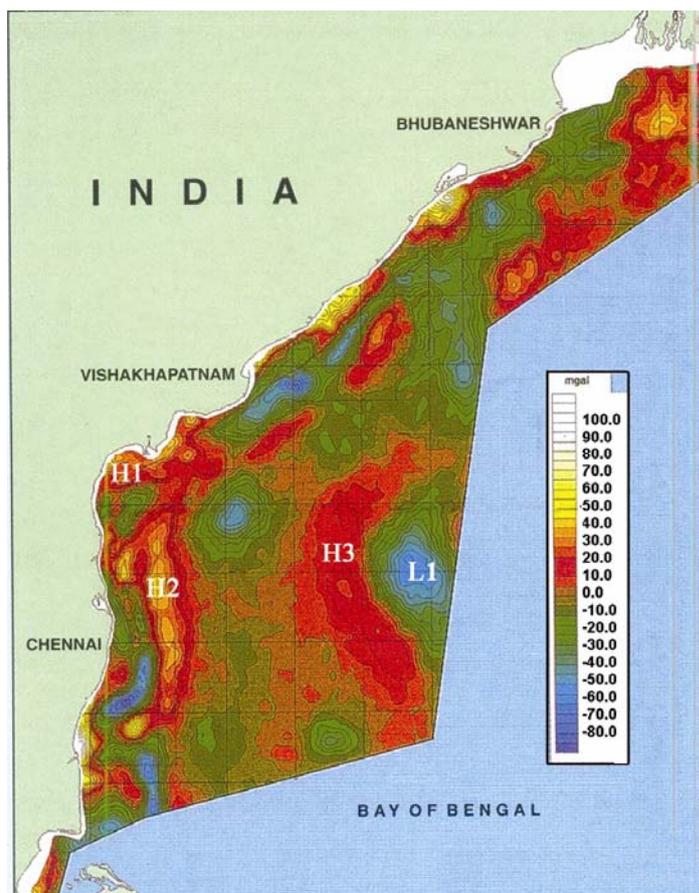
Seismic profiles across the continental shelf offshore the east coast of India could not delineate SDRs due to large thickness of sediments in this region which can be imaged only along the volcanic basement below the sediments as shown in the offshore west coast of India (Figure 3) (DGH, 2010, pers. commun.). However, gravity data do indicate volcanic rifted margin as described above and several structures for hydrocarbon exploration have been delineated offshore the east coast of India that are typical of such margins (DGH, 2010,



**Figure 2.** Satellite-derived Bouguer anomaly map offshore the west coast of India showing linear gravity highs, H1, H2 and H3 related to magmatic intrusion (Deccan trap) associated with the formation of the rifted margin (Directorate General of Hydrocarbons, (DGH), 2010, pers. commun.).



**Figure 3.** A shallow seismic section in deep water off the Kerala-Konkan coast showing SDRs at the top of the volcanic basement that are different from those of the sedimentary section above it on the western side and typically represent volcanic rifted margins world over (modified from DGH, 2010, pers. commun. with regard to identification of the SDR).



**Figure 4.** Satellite-derived Bouguer anomaly map offshore the east coast of India showing linear gravity highs, H1, H2 and H3, almost sub-parallel to the east coast of India that may be related to magmatic intrusion during the break-up of India from Antarctica (DGH, 2010, pers. commun.).

pers. commun.). Further, a shallow sedimentary section derived from several seismic profiles on and offshore the Cauvery basin shows volcanic rocks of the Mid-Cretaceous period overlying the Precambrian basement<sup>11</sup> that may represent volcanic rocks related to the break-up between India and Antarctica as described above with regard to the gravity highs H1 and H2 (Figure 4). The continental shelf offshore the east coast of India is also considerably limited in extent and sharply dipping those indirectly suggesting that it is formed due to a plume or hotspot, namely the Kerguelen hotspot, which was located under the Mahanadi basin in India and Lambert rift in Antarctica during its break-up, forming conjugate structures<sup>10</sup>.

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