

Seaward dipping reflectors along the SW continental margin of India: Evidence for volcanic passive margin

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Multi-channel seismic reflection profiles across the southwest continental margin of India (SWCMI) show presence of westerly dipping seismic reflectors beneath sedimentary strata along the western flank of the Laccadive Ridge – northernmost part of the Chagos–Laccadive Ridge system. Velocity structure, seismic character, 2D gravity model and geographic locations of the dipping reflectors suggest that these reflectors are volcanic in origin, which are interpreted as Seaward Dipping Reflectors (SDRs).

The SDRs; 15 to 27 km wide overlain by ~1 km thick sediment; are observed at three locations and characterized by stack of laterally continuous, divergent and off-lapping reflectors. Occurrence of SDRs along western flank of the Laccadive Ridge adjacent to oceanic crust of the Arabian Basin and 2D crustal model deduced from free-air gravity anomaly suggest that they are genetically related to incipient volcanism during separation of Madagascar from India.

We suggest that (i) SWCMI is a volcanic passive margin developed during India–Madagascar breakup in the Late Cretaceous, and (ii) continent–ocean transition lies at western margin of the Laccadive Ridge, west of feather edge of the SDRs. Occurrence of SDRs on western flank of the Laccadive Ridge and inferred zone of transition from continent to ocean further suggest continental nature of crust of the Laccadive Ridge.

1. Introduction

The Western Continental Margin of India (WCMI) experienced multiple phases of extensional tectonics in the geological past. The margin has mainly evolved due to:

- rifting between Madagascar and India during the Late Cretaceous,
- short span of rifting between Seychelles–Laxmi Ridge and India around K–T boundary, and
- rifting between Seychelles and Laxmi Ridge during the Early Tertiary (Norton and Sclater 1979; Courtillot *et al* 1988; White and McKenzie 1989; Bhattacharya *et al* 1994; Storey 1995;

Storey *et al* 1995; Collier *et al* 2008; Minshul *et al* 2008).

Massive Deccan flood basalt erupted by the Réunion hotspot (68.5–62 Ma) was approximately time coincident with the last two phases of the rifting and had profound impact on the WCMI.

Rifting between southwestern India and the eastern Madagascar occurred during the Late Cretaceous and this event was associated with the Marion hotspot volcanism (White and McKenzie 1989; Storey *et al* 1995; Torsvik *et al* 1998; Raval and Veeraswamy 2003). The volcanic extrusion of this event was also recorded in the Cretaceous dolerite (91.6 ± 0.3 Ma) of Madagascar

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and volcanics of St. Mary Islands (85.6 ± 0.9 Ma) off southwest India. Numerous basaltic flows and intrusives related to Marion hotspot volcanism are also reported from the southwest India (Radhakrishna *et al* 1994; Kumar *et al* 2001; Pande *et al* 2001).

The second major tectonic event contributed in shaping the western continental margin of India was the short span of rifting between Seychelles–Laxmi Ridge and India. The Laxmi Basin evolved during this phase of rifting. It is not yet conclusively established whether this rift event had led to establishment of seafloor spreading in the Laxmi Basin. Therefore, nature of crust underneath the Laxmi Basin and the adjacent offshore Indus Basin is still being debated to be either oceanic or stretched continental crust (Naini and Talwani 1983; Miles *et al* 1998; Bhattacharya *et al* 1994; Talwani and Reif 1998; Todal and Eldholm 1998; Krishna *et al* 2006; Collier *et al* 2009; Yatheesh *et al* 2009).

Third major tectonic event which shaped the WCMI was separation of Seychelles from Laxmi Ridge–India during the Early Tertiary while the Réunion hotspot activity was in its peak phase. The Réunion hotspot related volcanism occurred initially on continental crust and later on oceanic crust as the Indian plate moved northwards over the hotspot. It created the Deccan Continental Flood Basalt province on the western and central India (Mahadevan 1994) as well as continental flood basalt on the Praslin Island on the Seychelles microcontinent (Devey and Stephens 1991). Further, it emplaced numerous magmatic intrusions/extrusions within the crust of western continental margin of India as the plate moved over it. Considerable stretching during rifting, and Réunion related massive volcanism, obliterated the pre-existing geology and initial margin configuration of southwest continental margin of India (SWCMI).

Though the WCMI is considered as a typical passive rifted margin (Biswas 1982; Chandrasekharam 1985), it is generally understood that southern margin of India is a non-volcanic passive margin evolved during breakup between southern India and eastern Madagascar. Whereas, northern continental margin of India is a volcanic passive margin developed during the breakup of India–Laxmi Ridge–Seychelles. This event of breakup was contemporaneous with predominant Deccan volcanic activity which produced widespread volcanism.

Despite the fact that the India–Madagascar breakup produced an extensive volcanic province along eastern Madagascar and numerous basaltic flows and intrusives on the southwest Indian shield, Seaward Dipping Reflectors (SDRs) – one of the most distinctive characteristic features of

volcanic passive margins – are not yet reported from the SWCMI. The studies carried out so far on passive continental margins worldwide suggest that SDRs represent flood basalts rapidly extruded during either rifting or sub-aerial seafloor spreading. The seismic characters; continuity, dip, amplitude, reflection pattern and thickness of wedges of SDRs are controlled by:

- volume and rate of magma production,
- volcanic constructional environment (vent geometry, relation to sea level),
- syn- and post-volcanic deformation, and
- subsidence (Eldholm *et al* 1995).

SDRs are in general detectable in multi-channel seismic section as thick packets of high-amplitude reflections which are convex upward, offlapping seawards, divergent and laterally continuous. It may be mentioned here that wedges of SDRs are different from the normal faults developed during initial stage of continental rifting. These faults subsequently turn to half-graben structures, whose seismic signature differs from SDRs.

In this study we report, for the first time, occurrence of SDRs along the western flank of the Laccadive Ridge based on multi-channel seismic reflection data, and discuss its implications on the development of the margin.

2. Physiographic and tectonic settings

Physiographically, the SWCMI consists of narrow continental shelf, broad continental slope, Laccadive Basin, Laccadive Ridge and adjacent part of the Arabian Basin (figure 1). The continental crust of Dharwar craton extends in the western offshore up to Laccadive Ridge (Avasthi 2003). The Laccadive Basin, a narrow triangular shaped basin, is located between the Laccadive Ridge in the west and the southwestern continental slope of India in the east. The basin is divided into three sub-basins, at places, by the extruded structure of the Prathap Ridge and bathymetric high (shelf-margin high). The origin of the Prathap Ridge has been suggested as:

- a volcanic construct formed by the Réunion hotspot during northward movement of the Indian plate over the hotspot (Krishna *et al* 1992), and
- as a continental sliver, intermingled with dykes and volcanics, formed during rifting between India and Madagascar (Subrahmanyam *et al* 1995).

The NNW-trending Laccadive Ridge is the northernmost part of the Chagos–Laccadive

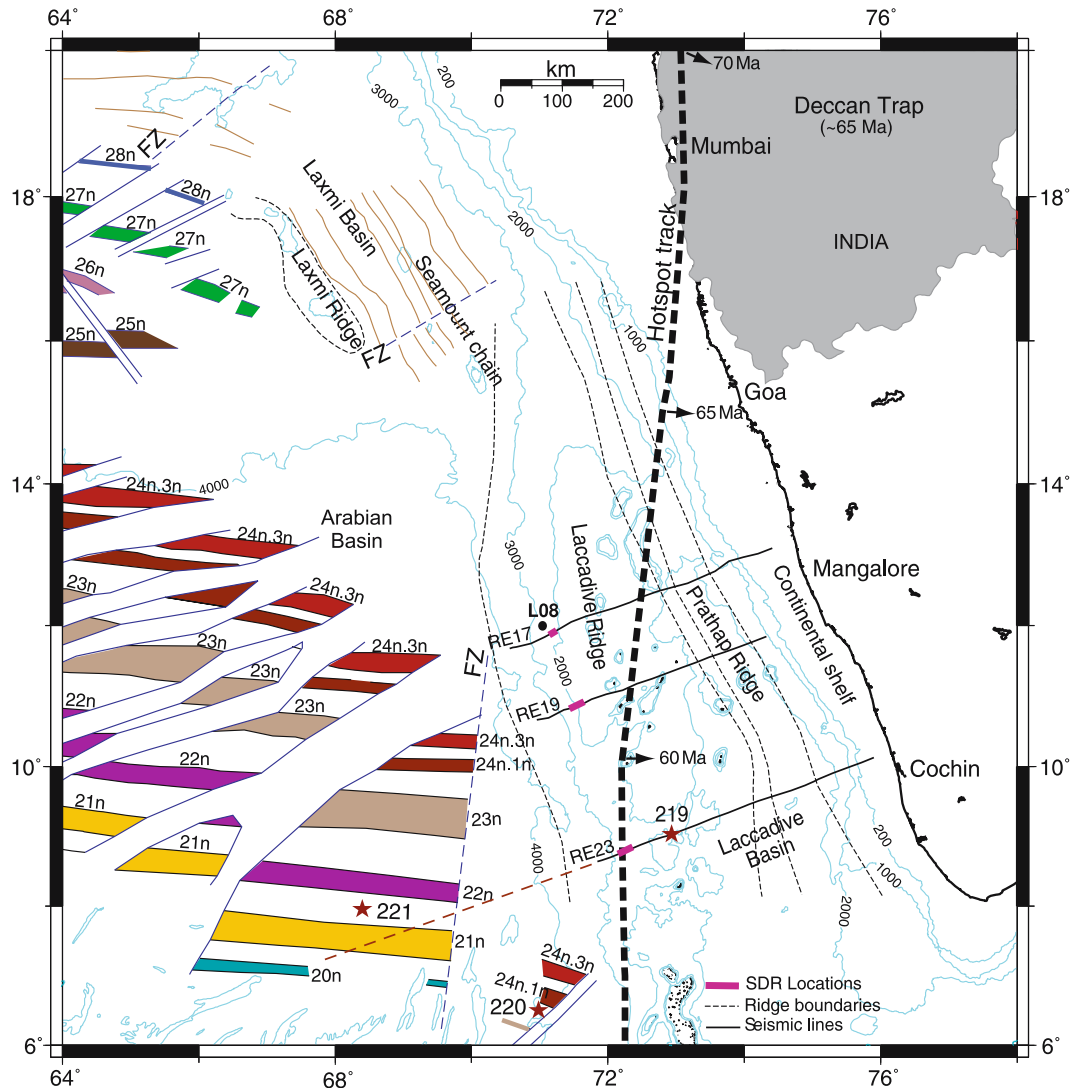


Figure 1. Generalized tectonic map of the western continental margin of India, showing annotated magnetic lineations, pseudofaults (thin blue lines), fracture zones (dashed blue lines annotated as FZ) (Chaubey *et al* 2002a) and boundaries of the Laccadive and Prathap ridges (thin dashed lines) (Naini and Talwani 1983). The locations of identified SDRs are marked on the seismic lines (thick red bar on RE lines); DSDP drill sites are shown with solid stars (Whitmarsh *et al* 1974); solid thick dashed line represents the computer-modeled Réunion hotspot track; numbers along the hotspot track are predicted ages in Ma (Shipboard Scientific Party 1988); magnetic lineations in the Laxmi Basin (thin brown lines) (Bhattacharya *et al* 1994; Malod *et al* 1997). 2D crustal model, shown in figure 5, was derived along line RE23. Extended (dashed line) portion of the line RE23 into the deep Arabian basin lacks multi-channel seismic reflection data.

Ridge (CLR) with an average width of 270 km. The ridge is an elongated feature, lying roughly parallel to the west coast of India between latitudes 8°N and 16°N (Bhattacharya and Chaubey 2001; Chaubey *et al* 2008). The eastern and western limits of the ridge are bounded by fault scarps, which apparently separate the ridge from the Laccadive and Arabian basins, respectively (Avraham and Bunce 1977; Chaubey *et al* 2002b). The ridge is associated with relatively positive free-air gravity anomalies compared to the surrounding region and is characterized by thickened crust of high density (3.0 g/cm^3) material (Radha

Krishna *et al* 2002). Magnetic anomalies over the ridge do not show any definite pattern. The eastern part of the ridge is associated with subdued magnetic anomalies, whereas its western part is characterized by several prominent high magnetic anomalies (Naini and Talwani 1983; Gopala Rao *et al* 1987). The latter was interpreted as due to densely spaced igneous intrusives and flows (Chaubey *et al* 2002b). Even though, the nature of crust of the ridge is equivocal (Bhattacharya and Chaubey 2001 and references therein; Verzhbitsky 2003), the recent studies suggest that the ridge is comprised of thinned continental crust, which

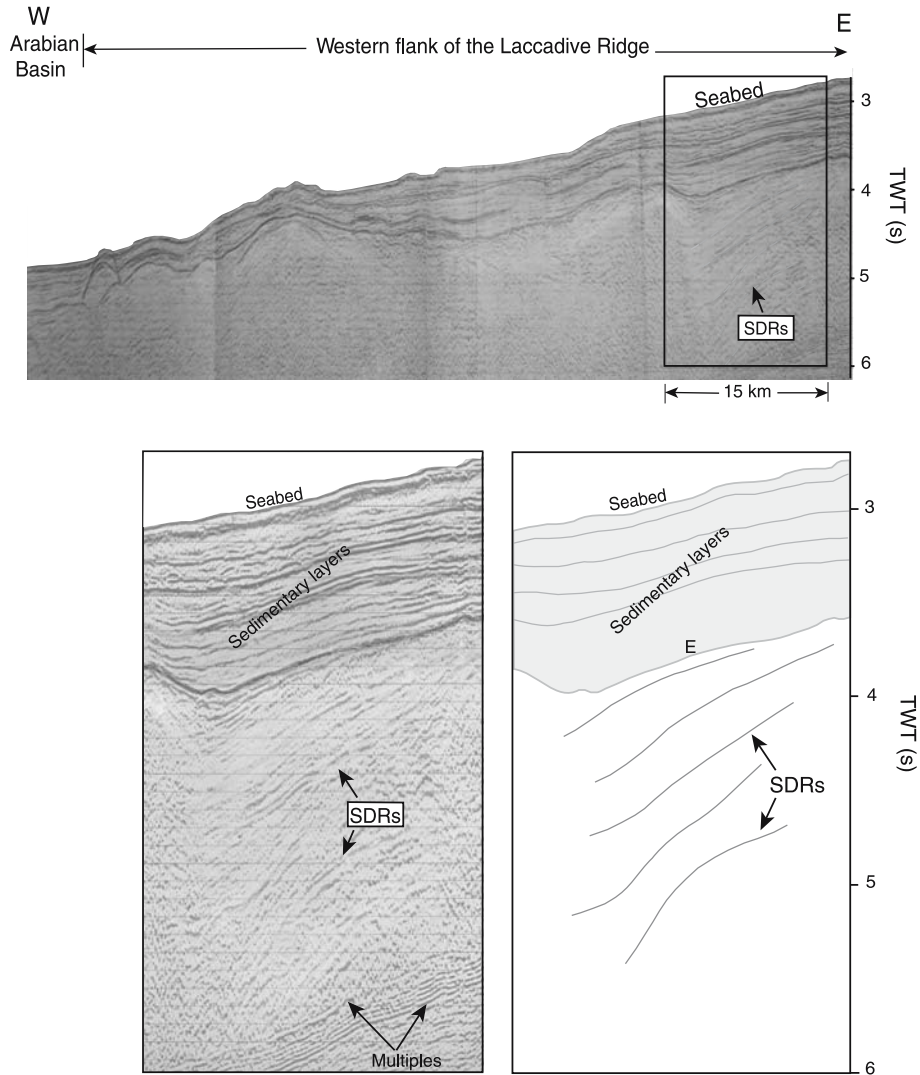


Figure 2. Multi-channel seismic section and interpreted line diagram along part of the line RE17 located on western flank of the Laccadive Ridge. SDRs are interpreted below sedimentary sequence.

was intruded–extruded by magmatic events during Madagascar–India continental rifting and passage of the Indian Plate over the Réunion hotspot (Murty *et al* 1999; Kothari *et al* 2001; Chaubey *et al* 2002a, 2008).

The Arabian Basin, conjugate to the eastern Somali Basin, is located west of the Laccadive Ridge. The basin is demarcated by the Owen fracture zone towards west and Carlsberg Ridge towards south. The northern and eastern limits of the basin is bounded by the aseismic Laxmi and Laccadive Ridges. The topography of the basin is determined by Indus fan sediments. The water depth varies from 3400 m in the north to about 4400 m in the south. The well developed Tertiary magnetic lineations established by various researchers indicate oceanic nature for the crust beneath the basin (Chaubey *et al* 1998, 2002b; Miles *et al* 1998; Dymont 1998; Royer *et al* 2002).

3. Data

We analyzed 2-D multi-channel seismic reflection profiles (figure 1) across SWCMI, under a collaborative project between National Institute of Oceanography (NIO) and Oil and Natural Gas Corporation (ONGC). The data were acquired in 100 to 4000 m water depth onboard *M/V Anweshak* during December 1979 with 48-channel seismic streamer and Bolt type air gun array with a total capacity of 101 as a seismic source. A recording duration of 8 s, a sampling interval of 4 ms and a shot interval of 50 m were chosen with a ship speed of 4–5 knots to achieve a 12-fold coverage. The data were processed at the Computer Service Division of ONGC, Dehradun. We present part of the MCS section; located across the western flank of the Laccadive Ridge; of line RE17 (figure 2), RE19 (figure 3) and RE23 (figure 4) along with interpreted line drawings for analysis

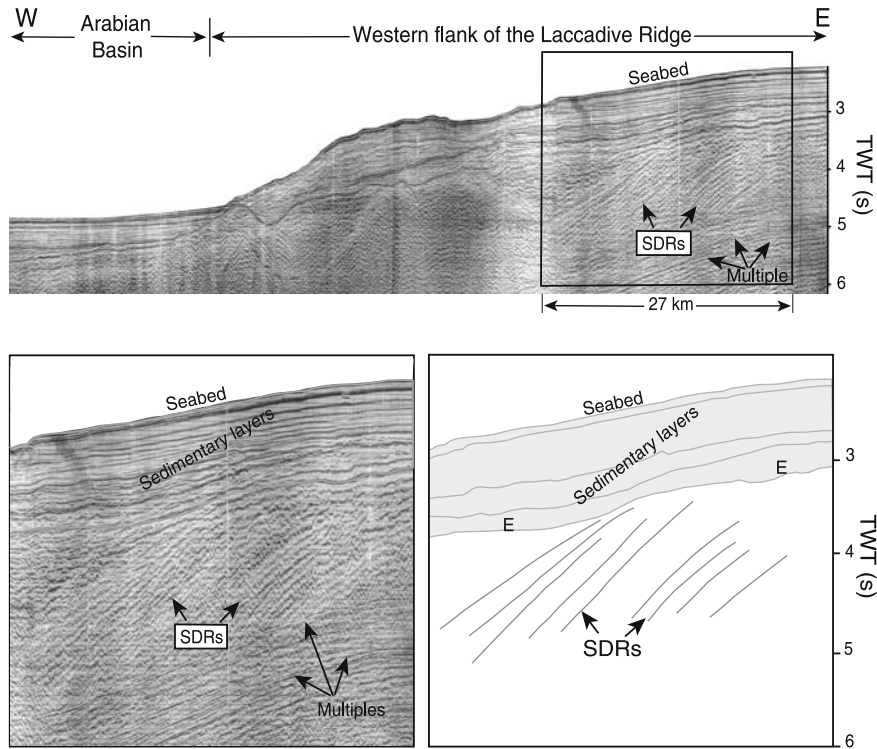


Figure 3. Multi-channel seismic section and interpreted line diagram along part of the line RE19 located on western flank of the Laccadive Ridge. SDRs are interpreted below sedimentary sequence.

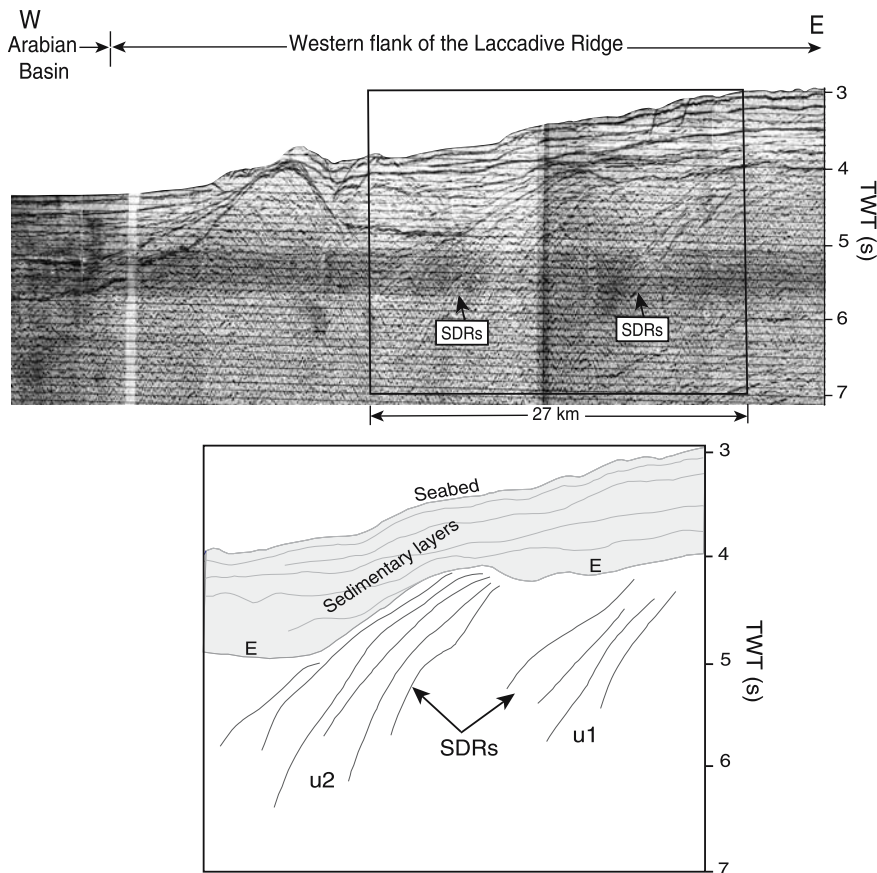


Figure 4. Multi-channel seismic section and interpreted line diagram along part of the line RE23 located on western flank of the Laccadive Ridge. SDRs are interpreted below sedimentary sequence. U1, U2 and reflector E are explained in the text.

Table 1. *Seismic velocity of crustal layers at refraction station L08 (11.9067° N, 71.1750° E) located on western flank of the Laccadive Ridge.*

Layer velocity (km/s)	1.50	1.65	2.12	4.40	5.60	6.30	7.20
Layer thickness (km)	2.12	0.41	0.42	0.66	1.49	4.69	8.40
Layer thickness {(TWT (s))}	2.83	0.50	0.40	0.30	0.53	1.49	2.33
Cumulative layer thickness {(TWT (s))}	2.83	3.33	3.73	4.03	4.56	6.05	8.38

and interpretation. To support our interpretation, we utilize published results of seismic refraction (Naini and Talwani 1983) and DSDP Site 219 (Whitmarsh *et al* 1974). In addition, 2D gravity model studies were carried out along the profile RE23 under seismic constraints for determining crustal architecture across the SWCMI. Free-air gravity anomaly data along seismic line RE23 were retrieved from satellite altimetry derived grided gravity database of Sandwell and Smith (1997) as shipborne gravity data were not available along RE23.

4. Analysis and interpretation

The multi-channel seismic sections across the SWCMI have been compiled and analyzed in order to study igneous structures formed during initial stage of continental breakup. We found interesting dipping seismic reflectors beneath sedimentary strata along western flank of the Laccadive Ridge. These reflectors are interpreted as SDRs which provide sufficient condition for classifying SWCMI as a volcanic passive margin.

4.1 Characteristics of SDRs

The dipping seismic reflectors observed below sedimentary strata along the western flank of the Laccadive Ridge are discontinuous to continuous, high amplitude, divergent and westerly dipping (figures 2, 3 and 4). Along line RE17 (figure 2), the westerly dipping reflectors are overlain by ~ 0.95 s TWT thick sediments. Individual reflectors can be traced for up to ~ 15 km down dip and the depth to the highest distinguishable point of top layer of the reflectors is ~ 3.8 s TWT. Along line RE19, well developed dipping reflectors are overlain by ~ 1.2 s TWT thick sediments and extend seaward for ~ 27 km (figure 3). The top of the dipping reflectors lies at a depth of ~ 3.6 s TWT. Figure 4 depicts two sets of westerly dipping reflector sequences (u1 and u2) along line RE23. The reflector sequences, separated by ~ 5 km apart, are overlain by ~ 0.9 s TWT thick sediments and extend seaward for ~ 27 km. The depth to the top of the dipping reflectors is ~ 4.2 s TWT. It may be noted that the dipping reflectors are

convex upward, offlapping seawards, divergent and laterally continuous.

In order to investigate the nature of the dipping seismic reflectors, we used published results of DSDP Site 219 (Whitmarsh *et al* 1974) and refraction study at site L08 (Naini and Talwani 1983) located on the crest and western flank of the Laccadive Ridge, respectively. The velocity structure at site L08 (table 1) which is close to the dipping seismic reflectors observed at line RE17 consists of crustal layers of P-wave velocities 1.65–2.12, 4.4, 5.6, 6.3 and 7.2 km/s. The presence of chert layer of P-wave velocity 4.0 km/s of Early and Middle Eocene age overlain by ~ 1 km thick sediment over the Laccadive Ridge was inferred at DSDP Site 219. The chert layer appears as a strong diffuse reflector with irregular surface often with sawtooth appearance (Whitmarsh *et al* 1974). Chaubey *et al* (2002b) observed that reflection character of chert layer is of high-amplitude, and discontinuously associated with numerous diffraction hyperbolae. Such reflection character at bottom of the sedimentary strata (figures 2–4) is not observed in the study area. Instead, it displays high amplitude and continuous reflector named as ‘E’. Below the reflector ‘E’, we observed discontinuous to continuous, high amplitude, divergent and westerly dipping offlapping reflectors (figures 2–4).

The velocities in the range 5.8–6.4 km/s are generally considered as characteristic of granitic layer in continental crust (Tucholke *et al* 1981). From a compilation of global crustal model, Mooney *et al* (1998) suggested 6.1–6.3 km/s velocity to upper–middle crustal layer of extended continental crust. We, therefore, assign seismic velocity of the dipping reflectors as ≥ 4.4 km/s (table 1). Deep seismic sounding investigations of the western Indian shield suggested that seismic velocity of Deccan flow basalt, lie below thick sediment column, vary between 4.7 and 5.1 km/s (Kaila *et al* 1981a, 1981b; Reddy 2005). From the study of dipping reflector sequence on Hatton Bank, White *et al* (1987) suggested that the seismic velocities increase through the SDRs from typically 3.5 km/s at the top to about 6 km/s at the base. We therefore suggest that the seismic reflectors are dipping volcanic reflectors with seismic velocity ≥ 4.4 km/s. Considering the geographic location and seismic characters of dipping

volcanic reflectors, we interpret them as SDRs and not as dipping normal faults because the latter do not show associated half-graben structures which are formed during initial stage of continental rifting. Further, in the locations where the SDRs are interpreted; the sub-surface is clearly devoid of normal fault characteristics. In view of the above, we believe that the dipping volcanic reflectors identified on the western flank of the Laccadive Ridge are well developed SDRs. We consider that the dips of the SDRs arose from basaltic lava flows emplaced during initial continental split-up and subsequent subsidence. According to Hinz (1981) and Mutter *et al* (1982) the regions of SDRs generally mark areas of rifted continent and their dips arose from the subsidence of enormous volumes of basaltic lava flows. Feather edge of the SDRs have been used to demarcate seaward extent of the continental crust of the Voring Plateau of Norwegian margin, Argentina margin and east coast of US (Baltimore Canyon Trough and Carolina Trough) (White *et al* 1987). We interpret the identified SDRs on western flank of the Laccadive Ridge are indicative of rifted continents and volcanism prior to onset of seafloor spreading. The presence of SDRs and their feather edge along the western flank of the Laccadive Ridge lead us to identify the edge of the rifted continent, and thereby to demarcate the region of continent–ocean transition along the western margin of the ridge.

4.2 Crustal architecture from 2D gravity model

Satellite altimetry derived free-air gravity anomaly data are used to derive crustal model along seismic line RE23 which traverses across the southwest continental margin of India. We extended line RE23 into the deep Arabian Basin, although not covered by the MCS data, for the purpose of crustal modelling from known oceanic crust of the basin to continental shelf. 2D gravity modelling was carried out using the GM-SYS software. As a first step, main crustal layers are identified and thickness of each crustal layers are computed based on the MCS time section, MCS derived average seismic velocity in the sedimentary strata and published refraction results (Naini and Talwani 1983) of the study area. The depth-converted horizons were incorporated into the simplified crustal model in order to obtain initial crustal configuration for forward gravity modelling. Bathymetry, sediment thickness and igneous crustal layers were extracted from the public domain data (NGDC, National Geophysical Data Center, USA) and the published refraction results. Deep seismic sounding results from western Indian shield (Kaila *et al* 1981a; Reddy 2005) are used to estimate the Moho

depth on the continental shelf region. Densities for various crustal layers are obtained from velocity–density conversion table of Barton (1986), which provides a range of densities for a seismic velocity of a rock formation. Since density–velocity relation is non-linear, it possesses limitations on the direct use of density obtained from an assumed linear density–velocity relationship. Therefore, we selected mean density within the given range of densities for a particular seismic velocity (Barton 1986). Modelling was performed by continuously applying small adjustments to the geometries of crustal layers in order to obtain a crustal model which satisfies both the geometrical constraints and an acceptable fit between observed and calculated gravity anomalies.

The investigations along Kavali-Udipi profile in the south, and Koyna-I and Koyna-II profiles in the north revealed that the P-wave velocities vary between (i) 4.7 and 5.0 km/s in Deccan Traps; (ii) 5.5 and 5.8 km/s in Cuddapah sediments and Dharwar schists, and (iii) 5.8 and 6.2 km/s in granites and granitic gneisses (Kaila *et al* 1979, 1981a, 1981b). The refraction velocities data; compiled from the SWCMI; comprise of 1.7–2.1 km/s, 4.2–4.4, 5.4–5.7, 6.1–6.4 and 7.2–7.3 km/s. The seismic velocities 1.7–2.1 km/s represent sedimentary column, whereas 4.2–4.4 km/s represent basaltic flows. The rocks with velocities of 5.4–5.7 km/s and 6.1–6.4 km/s below sedimentary strata are similar to the velocities observed in Dharwar schists/Cuddapah sediments and granitic gneisses, respectively. The velocities 7.2–7.3 km/s may represent lower continental crust. It may be noted that the inferred granitic crustal velocities 6.1 to 6.4 km/s are slightly higher compared to that of DSS results. The high velocity may indicate altered granitic layer due to intrusive volcanism during rift related extensional tectonics and/or hotspot magmatism. The seismic velocities of the crustal layers have been converted into densities as described above.

The best-fit crustal model (figure 5) revealed 22, 19 and 6 km thick crusts of the outer shelf, Laccadive Ridge and Arabian Basin, respectively. The crustal densities of the Arabian Basin consist of three layers of 2.1, 2.7 and 2.95 g/cm³ representing sediments, layers 2 and 3 of the oceanic crust respectively, whereas the crustal densities of the continental shelf, Laccadive Basin and the Laccadive Ridge consist of 2.1, 2.8, 2.9 and 3.0 g/cm³, representing sediments, upper and lower stretched continental crust, and lower crustal body, respectively. A thick layer of meta sediment of density 2.65 g/cm³ is inferred below basaltic flows. Densities ranging from 2.4–2.65 g/cm³ are of igneous intrusive bodies, SDRs and chert layer. A lower crustal body, characterized by high density

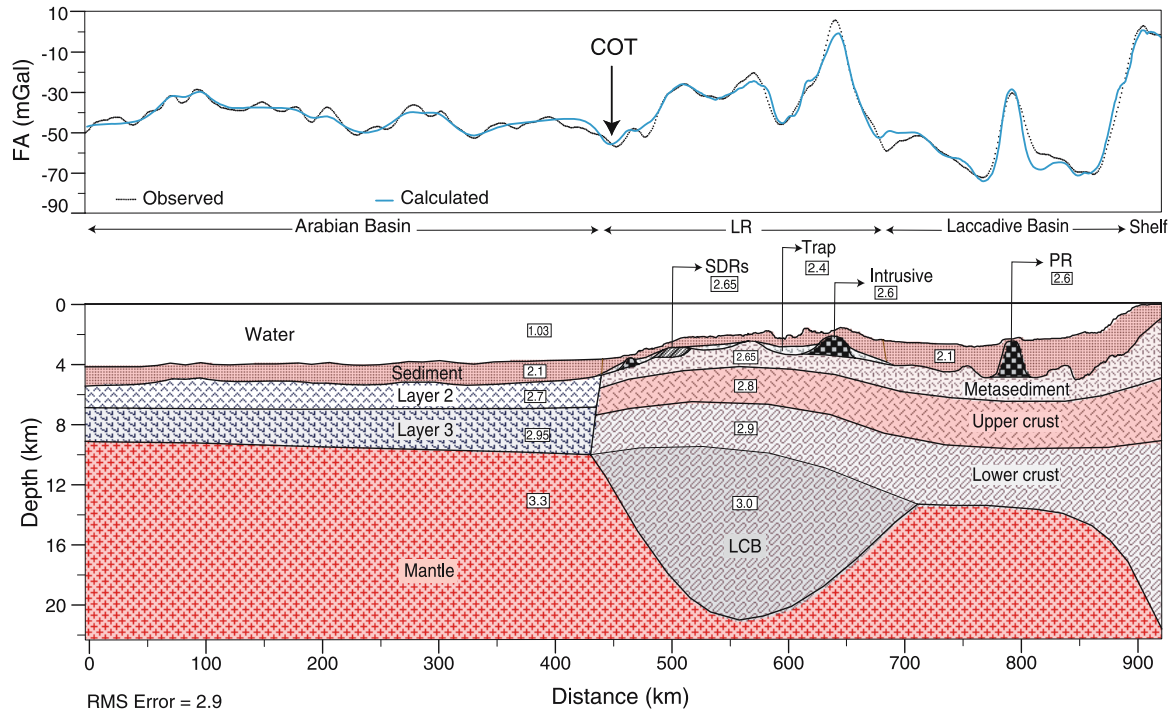


Figure 5. 2D crustal model based on gravity anomaly across the southwest continental margin of India along line RE23. Structure of volcanic intrusives and the Prathap Ridge (PR) are shown only in sedimentary and water columns as there are no appreciable lateral density contrast between adjoining horizons and the structure underlying the sedimentary strata. High density (3.0 g/cm^3) Lower Crustal Body (LCB) of the Laccadive Ridge may represent stretched crust associated with injection of dykes and sills. Inferred continent–ocean transition (COT) at feather end of the SDRs is indicated. Annotated values in rectangular boxes refer to inferred densities in g/cm^3 .

(3.0 g/cm^3) material, is inferred below Laccadive Ridge. It may be noted that structure of volcanic intrusives and the Prathap Ridge (PR) are shown only in sediment and water columns as there are no appreciable lateral density contrast between adjoining horizons and the structure, underlying the sedimentary strata.

5. Tectonic implication

One of the most important results of the present study is seismically imaged strong SDR sequences along the western flank of the Laccadive Ridge (figure 1). They have been identified below sedimentary strata at three locations (figures 1–4). Seaward of their occurrences, the Laccadive Ridge gradually thins towards offshore and juxtaposed with Early Tertiary normal oceanic crust ($\sim 6 \text{ km}$ thick) of the Arabian Basin. We infer that these wedges have been emplaced under subaquatic conditions due to progressive subsidence of the volcanic–magmatic crust. It may be noted that DSDP Site 219, drilled at the crest of the Laccadive Ridge (9.02917°N , 72.87783°E), bottomed in Upper Paleocene sediments having an approximate age of $\sim 58 \text{ m.y.}$ The oldest sediment (limestone, sandstone and silt) strongly reflect typical

shelf type nearshore shallow water sedimentation. These results led Weser (1974) to suggest that Site 219 was much closer to shoreline of India than it is today. Though, the identified SDRs are away from Site 219, it may be interpreted that (i) the SDRs are older than 58 m.y. as they are found below the sedimentary column, and (ii) the SDRs are emplaced under sub-aerial condition.

In paleo-geographic reconstructions, it is presumed that the southwest India rifted from the eastern margin of Madagascar during the Late Cretaceous (White and McKenzie 1989; Storey *et al* 1995, 1997; Torsvik *et al* 1998; Raval and Veeraswamy 2003). The rifting process was associated with the Marion hotspot volcanism which occurred at Volcan de l'Androy, southeast Madagascar and caused the eruption of widespread basalts and rhyolites in Madagascar and Fe-Ti-enriched tholeiites in southwest India. In light of the results of the present study we believe that eastern Madagascar rifted from the Laccadive Ridge which was part of Indian mainland. Based on admittance analysis of gravity and bathymetry data, Chaubey *et al* (2008) suggested that the Laccadive Ridge comprises thinned continental crust that is locally compensated by the Airy model of isostasy. Their inferences were further supported by comparable velocity and inferred crustal

structure of the Laccadive Ridge with that of the Laxmi Ridge, which has been widely accepted as a continental sliver (Miles and Roest 1993; Bhattacharya *et al* 1994; Miles *et al* 1998; Talwani and Reif 1998; Todal and Eldholm 1998; Radha Krishna *et al* 2002).

It is quite likely that the Marion hotspot might have played a limited role at the SWCMI unlike the widespread volcanism by Réunion hotspot in the north (Dev *et al* 2007). The crustal structure derived from modelling of free-air gravity anomalies in the present study reveals high density lower crustal body below the Laccadive Ridge, which is consistent with the crustal model suggested by Radha Krishna *et al* (2002). The geophysical expression of the high-density lower crust is complex. Such lower crustal bodies may be interpreted as either a magmatic structure or a stretched crust associated with injection of dykes and sills. The presence of thick high-density lower crustal body below the Laccadive Ridge can be interpreted due to massive intrusions by the Marion hotspot during initial stage of rifting between Madagascar and Laccadive–India, and later by the Réunion hotspot when the Indian Plate moved over it during northward motion.

The results of present study warrant a fresh look of multi-channel seismic reflection, Ocean Bottom Seismometer (OBS) derived refraction, gravity and magnetic data in order to address Late Cretaceous continental breakup between Madagascar and Laccadive–India. It may be noted that volcanic rifted margin segment may be predominantly volcanic without SDRs being imaged in seismic records. Therefore, SDRs are a sufficient, but not necessary condition for volcanic margin classification (Eldholm *et al* 1995). SDRs of the present study, indeed, suggest that SWCMI is a volcanic passive margin developed during breakup between Madagascar and Laccadive–India in the Late Cretaceous.

6. Conclusions

Study of multi-channel seismic reflection and free-air gravity anomaly profiles provided important constraints on early tectonic development of the SWCMI. We identified and interpreted, for the first time, the SDRs on the SWCMI. The crustal architecture derived from gravity model across the margin highlights large variation in crustal configuration and presence of lower crustal body of density 3.0 g/cm^3 below the Laccadive Ridge. We infer that SWCMI is a volcanic passive margin developed during breakup between India and Madagascar in the Late Cretaceous based on occurrences

of extrusive volcanism (SDRs), intrusive magmatism and lower crustal body associated with injection of dykes and sills. We also infer that the Laccadive Ridge is a thinned continental crust and the continental–ocean boundary lie on western margin of the ridge, west of the inferred SDRs.

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