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ORIGINAL PAPER

A seismotectonic study of the 21 May 2014 Bay of Bengal intraplate earthquake: evidence of onshore-offshore tectonic linkage and fracture zone reactivation in the northern Bay of Bengal

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Abstract The earthquake of 21 May 2014 (Mw 6.0) in the northern Bay of Bengal (BOB) highlights the importance of studies on intraplate earthquakes in the oceanic regime for understanding the stress state of the oceanic lithosphere. The epicenter of the earthquake is located at a water depth of 2.5 km where the sediment thickness is nearly 12 km, and it occurs at a depth of $\sim$50 km within the upper mantle. Its location on the seismotectonic map of the region shows that the epicenter is far from the seismically active zone of the Burmese Arc in the east and low-to-moderately active seismic region of the east coast of India in the west. The fault plane solution of this earthquake indicates that it was a strike-slip event with a right-lateral sense of motion on a NW-oriented nodal plane, and it occurred on one of the NW-SE-trending fracture zones previously mapped in the BOB. Based on a compilation of long-term (1900–2011) intraplate earthquakes along with available focal mechanisms in the BOB and the adjoining east coast of India, we conclude the following: (1) the Precambrian structural trends, basin-scale faults and minor lineaments on the east coast of India are favorably reactivated in their offshore extensions up to the shelf-slope areas of the margin; (2) earthquake occurrences in the BOB region can be correlated with the fracture zone trends in the central BOB and along the Ninetyeast ridge or at the intersections of fracture zones with the subsurface trace of the 85°E ridge. The 21 May 2014 earthquake is the result of reactivation of such a NW-SE-trending fracture zone lying in the lithosphere of >100 Ma in age. Further evaluation of this event in light of the global occurrence of oceanic intraplate earthquakes in the older lithosphere (>80 Ma) suggests that such reactivation is possible in the high ambient stress state.

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1 Introduction

An earthquake of magnitude Mw 6.0 occurred on 21 May 2014 at 16:21:54 UTC in the northern Bay of Bengal (BOB) at a depth of around 50 km (USGS 2014; Rao et al. 2015; Martin and Hough 2015). The earthquake was located at 18.02 N latitude and 88.09 E longitude (see Fig. 1) about 274 km SE of Konark, Orissa, on the east coast of India (USGS 2014). It occurred at a water depth of around 2500 m in the deepwater area offshore of Mahanadi and Bangladesh where the sediment thickness is around 12 km (Fig. 2). Although there were no reported casualties, the event was felt in many cities located in the eastern and southern parts of India (Martin and Hough 2015). The earthquake occurred in the northern BOB far interior from the adjoining seismically active belt of the Burma-Andaman subduction zone (Fig. 1). Therefore, it can be classified as an intraplate event. Due to its fairly large size (Mw ~6.0) at an unusual location, we became interested to analyze this earthquake along with other major events in this region from the point of view of seismotectonics and discussing probable causative factors behind this earthquake.

The Indian plate comprising the Indian subcontinent and adjoining northern Indian Ocean is characterized by the complex and seismically active plate boundaries (see inset in Fig. 1) such as the Himalayan collision zone in the north, the Burma-Indonesian subduction system in the east, the Carlsberg and Central Indian spreading ridge system in the southwest and the diffuse plate boundary of the Central Indian Ocean Basin in the south (DeMets et al. 1990). However, detailed geophysical studies in the Indian Ocean have revealed that apart from the ongoing deformation along the above plate boundaries, a significant amount of deformation also takes place in the plate interior and indicate large to moderate seismicity in Peninsular India (Chandra 1977; Rastogi 1992), in the BOB region (Biswas and Majumdar 1997) and within the younger oceanic lithosphere (<35 Ma) of the Indian Ocean (Radhakrishna et al. 1998). It is very well known now that Peninsular India and the adjoining oceanic areas are dominantly under a compressive regime (Cloetingh and Wortel 1985) because of the complex interaction of plate boundary forces such as the back thrust from the Himalayas in the north, the ridge push forces due to the spreading Carlsberg ridge in the south and the slab pull forces in the east. As for the present study, we confine ourselves to the area of the BOB and the east of India to analyze more than a century of intraplate seismicity (1900–2011) in the region. We also describe in detail the regional tectonics operative in this region for a better understanding of the seismogenesis.

2 Regional geotectonic history of the BOB

The BOB is one of the thickest sedimentary regions in the world wherein huge amounts of sediments eroded from the Himalayas are transported by the Ganga and Brahmaputra River systems. It is bordered by the east coast of India in the west, Bangladesh in the north and the Andaman-Sumatra arc in the east. It is covered by the sediments of the Bengal Fan, which is one of the largest submarine fans in the world, extending from 20°N to 7°S over a length of 3000 km (Curray et al. 2003). The thickness of sediments in the BOB (Fig. 2)

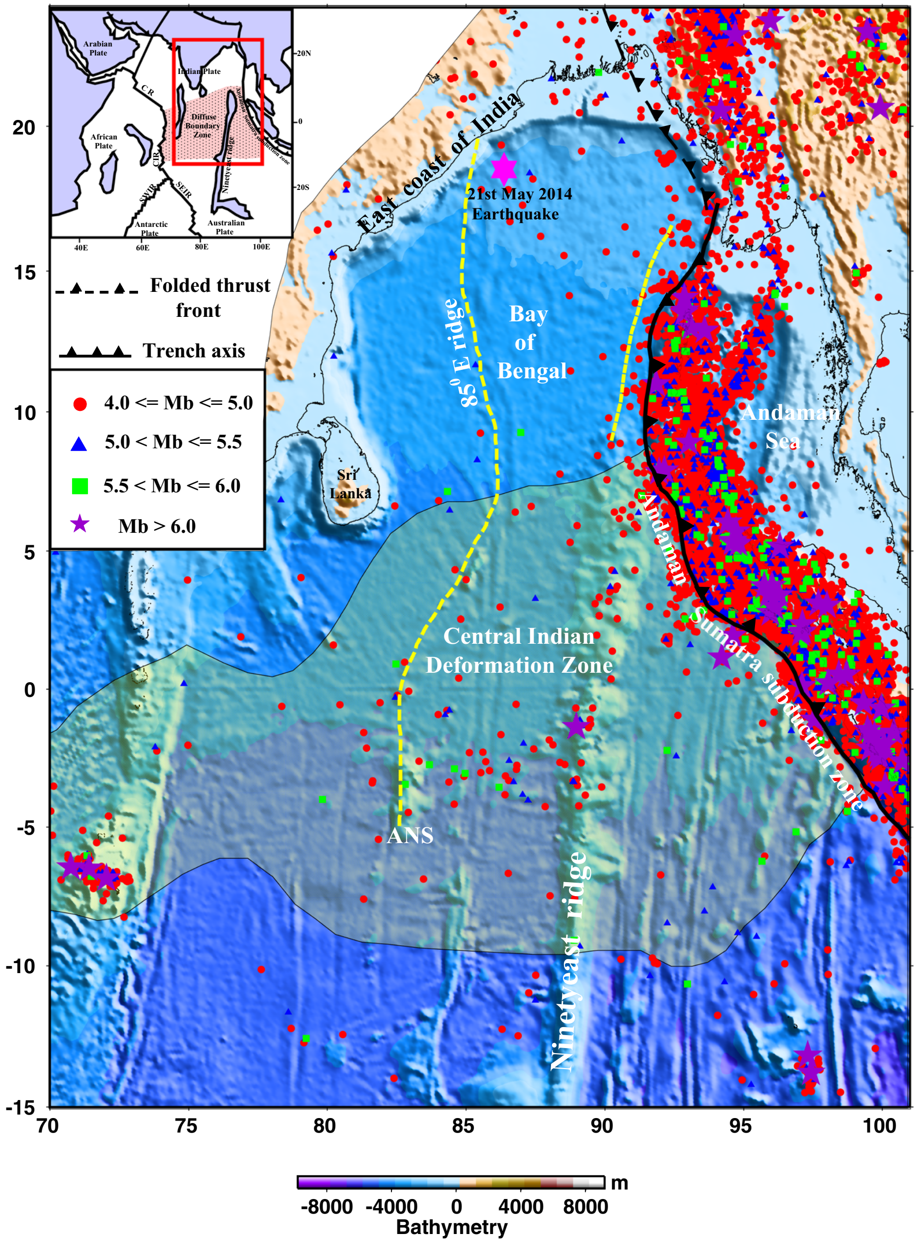
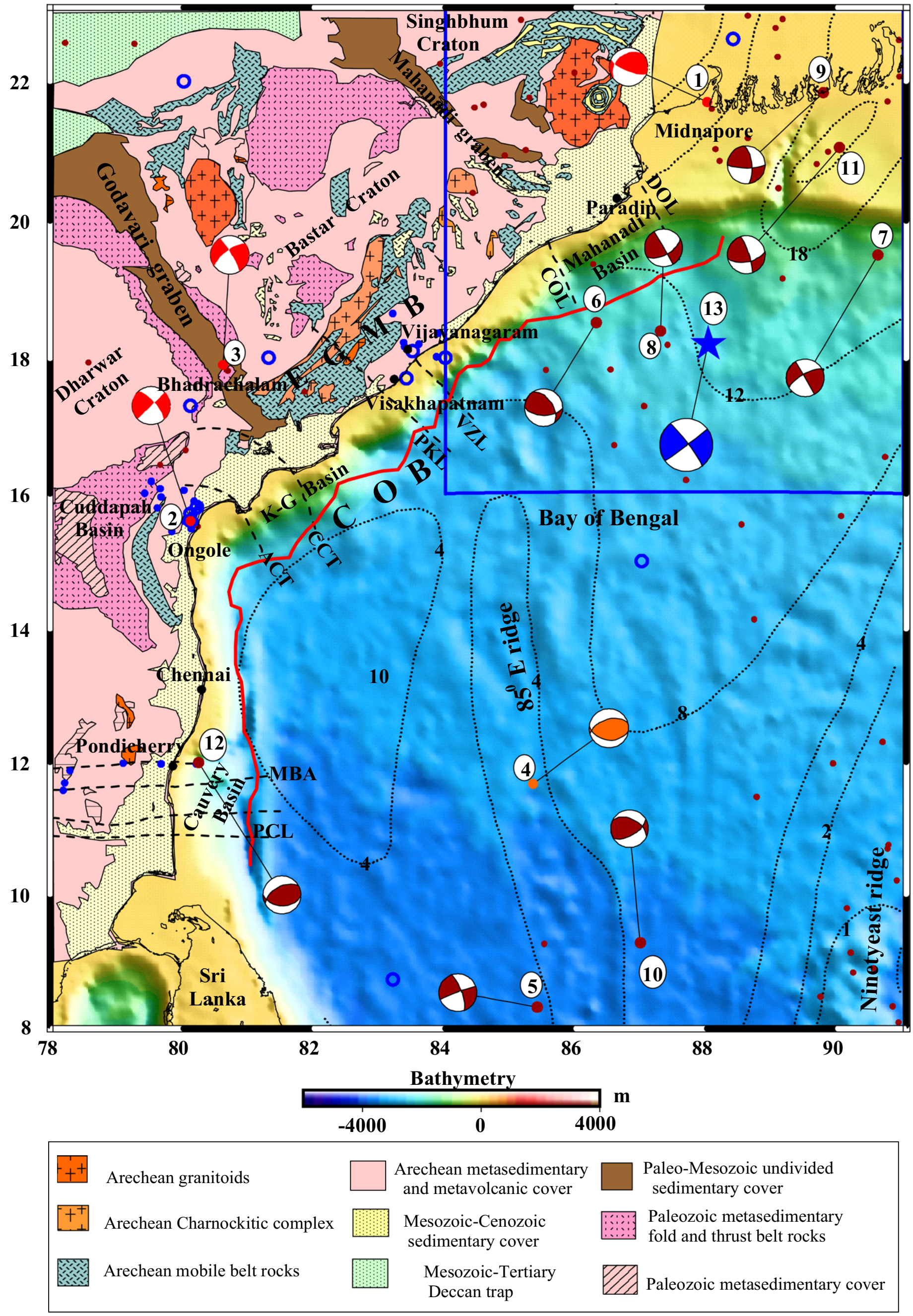


Fig. 1 Shaded relief map of the northeast Indian Ocean showing locations of earthquakes occurring during the 1960–2011 period according to the ISC earthquake catalog. Present-day plate geometry and the diffuse boundary zone in the central Indian Ocean are shown in the *inset* (after DeMets et al. 1990). The folded thrust front at the Burmese arc is from Steckler et al. (2008)

progressively decreases from 22 km below the Bangladesh shelf in the north to as much as 1 km toward the south (Curray 1994). Two long and linear (almost N-S oriented) aseismic ridges, such as the 85°E and Ninetyeast ridges, divide the BOB into three major sub-basins



(Gopala Rao et al. 1997). The sediment thickness over these ridges is <1 km in the south; toward the north, both ridges are progressively buried below the thicker BOB sediments. Steckler et al. (2008) observed that an enormous amount of sediment eroded from the

◀**Fig. 2** Seismotectonic map of the Bay of Bengal and the adjoining east coast of India. The geology of the Indian shield region and coastal areas is from Ray (1963) and Nemcock et al. (2013). The earthquake data used in this study are from the ISC earthquake catalog (Mb >4.0) for the 1960–2011 period and from Chandra (1977) for 1900–1960. Numbers 1–13 are locations of large/moderate events for which focal mechanism solutions are shown. Details of the focal mechanisms are given in Table 1. *Blue dots* represent the location of micro-tremors in the coastal areas (Murthy et al. 2010). *Dashed lines* across the east coast of India indicate the lineaments extending from onshore to offshore (after Murthy et al. 2010). *Dotted contours* are sediment thickness values adopted from Curray et al. (2003). The *star* indicates the location of the 21 May 2014 BOB earthquake. The study area for detailed geophysical data analysis is marked as a square in *blue*. *PCL* Palghat Cauvery lineament, *MBA* Moyar Bhavani Attur lineament, *ACT* Avanigadda cross trend, *CCT* Chintalapudi cross-trend, *PKL* Pudimadaka lineament, *VZL* Vijayanagaram lineament, *COL* Chilika offshore lineament, *DOL* Dhamra offshore lineament, *EGMB* Eastern Ghat mobile belt, *COB* continent-ocean boundary (after Bastia et al. 2010; Nemcock et al. 2013)

Himalayas built the Ganges-Brahmaputra Delta in the onshore Bengal Basin, and the collision of these sediments with the Burma arc gives rise to an active accretionary prism in the northernmost part of the BOB (Fig. 1).

The oceanic lithosphere in the BOB region evolved during the breakup of India and Antarctica in the Early Cretaceous period (Powell et al. 1988) followed by three major phases of seafloor spreading: the initial NW-SE spreading up to the Mid-Cretaceous period, the N-S spreading until the early Tertiary and the present NE-SW spreading (Curray et al. 1982; Krishna et al. 2009). Royer and Sandwell (1989) observed that most of the BOB oceanic crust was formed during the above first two phases. However, the timing of the breakup between India and Antarctica is not clear, and based on magnetic anomaly identifications it ranges between 132 Ma (Ramana et al. 1994) and ~120 Ma (Gopala Rao et al. 1997). Furthermore, due to the requirement of accommodating the Elan Bank micro-continent in the breakup scenario, Gaina et al. (2003) proposed a two-stage breakup history for the Eastern Continental Margin of India (ECMI): first, the India-Antarctica separation during M9o-M2o; second, the separation of Elan Bank from the present-day ECMI at M2. Recent geophysical studies along the ECMI are in agreement with the above double-breakup scenario (Krishna et al. 2009; Radhakrishna et al. 2012). Based on the basement trends in the multichannel seismic reflection data, Radhakrishna et al. (2012) identified several NW-SE-oriented fracture zones in the BOB, and these are in accordance with the earliest seafloor spreading direction. Based on the trends of these fracture zones at the east coast of India along with the reconstruction models (Gaina et al. 2007), Radhakrishna et al. (2012) proposed the possibility of an oceanic crust younger than M4 in the southern part of ECMI and M2 in the northern part of the ECMI.

The East Coast of India is characterized by the presence of major sedimentary basins such as the Cauvery, Palar, Krishna-Godavari, Mahanadi and Bengal basins, which evolved in response to the process of continental rifting and the breakup of India from East Antarctica. The Precambrian structural trends, such as the Godavari and Mahanadi grabens (Fig. 2), the Eastern Ghat Mobile Belt (EGMB), major shear zones and the rocks belonging to the Southern Granulite Terrain (SGT) at the Indian shield margin, have close linkages with a similar geology along East Antarctica (Yoshida et al. 1999). Geophysical studies (Venkatarengan and Ray 1993; Subrahmanyam et al. 1995, 2008; Bastia et al. 2010; Murthy et al. 2010) at the coast revealed the extension of major Precambrian structural trends, basin scale faults/fractures into the offshore areas (Fig. 2). In the fault-controlled Cauvery Offshore basin (Subrahmanyam et al. 1995), the major Precambrian lineaments, namely the Moyar-Bhavani Attur (MBA) and the Palghat-Cauvery Lineament (PCL), are seen to be extending into the offshore area. Major NW-SE-trending cross trends are namely the Avanigadda (ACT) and Chintalapudi (CCT) segment of the offshore Krishna-Godavari basin in different subbasins (Venkatarengan and Ray 1993). In the non-basinal area of the margin, near Visakhapatnam, two NW-SE-trending lineaments such as the Pudimadaka (PKL) and the Vijayanagaram (VZL) continue toward offshore. Further north, the Chilka (COL) and Dharma (DOL) offshore lineaments running across the coast separate the Mahanadi offshore basin from the surrounding Bengal basin in the northeast and the 85°E ridge in the southwest (Subrahmanyam et al. 2008).

3 Seismotectonic evaluation of the BOB region

Globally, the northeastern Indian Ocean is known for the occurrence of significant off-ridge seismic activity (Bergman and Solomon 1984; Stein and Weissel 1990; Radhakrishna et al. 1998) in both the younger (<35 Ma) and older (>35 Ma) oceanic lithosphere. Of this, a wider E-W-oriented corridor between the Chagos-Laccadive and Ninetyeast ridges in the equatorial central Indian Ocean basin has been identified as the diffuse plate boundary zone (DeMets et al. 1990) separating the Indian and Australian plates (Fig. 1), which is characterized by intense intraplate earthquakes, internal deformation and high heat flow (Weissel et al. 1980; Geller et al. 1983; Wiens 1985). Several large earthquakes have occurred in this region during the instrumental era (Wiens 1985) and were attributed to plate-wide stress distribution and significant internal deformation (Bergman and Solomon 1984; Wiens 1985) as a result of back-thrust from the Himalayas. Furthermore, subduction of the Indian plate below the Eurasian plate (locally Burma plate) along the eastern margin of the BOB forms an active seismic belt (Fig. 1) that is characterized by an east-dipping Benioff zone up to a depth of 200 km (Dasgupta and Mukhopadhyay 1993; Radhakrishna et al. 2008) in the Andaman arc region. On the other hand, the east coast of India along the western margin of the BOB is also characterized by low-to-moderate seismic activity that has experienced several moderate (>5.0) seismic events in recent times (Murthy et al. 2010). Furthermore, the close proximity of the Burmese arc has implications for the seismic hazard of the Bengal basin region (Steckler et al. 2008).

We compiled here all earthquakes that occurred in the BOB and the adjoining east coast of India for the 1900–2011 period. For the 1963–2011 period, the events >Mb 4.0 are considered from the International Seismological Center (ISC) bulletin; events prior to 1963 have been compiled from the listings presented in earlier publications (Chandra 1977; Gowd et al. 1996). We observed that except for a few, all pre-1963 events only reported intensities; in some cases, their locations are doubtful. However, the locations for the post-1963 events (Mb > 4.0) reported in the ISC bulletin are accurate and could be used in regional tectonic correlative studies. Finally, the seismic occurrence in the region suggests significant intraplate activity characterized by low-to-moderate seismic events with frequent occurrences of minor tremors in three locations, Pondicherry, Ongole and Vijayanagaram (Fig. 2), along the east coast of India. These three areas are identified as zones of weakness where seismic activity has been linked to the Land-Ocean Tectonics (Murthy et al. 2010 and the references therein). Earthquake activity in the coastal areas of Vijayanagaram and Ongole is characterized by events with a magnitude of tremors on the order of 3–4.5. In the Vijayanagaram area, minor river channels follow the NW-SE structural trend and extend toward offshore (Subrahmanyam et al. 2007) and they correlated the minor tremor of 1995 (M3.3) reported off the Vijayanagaram shelf to the reactivation of the lineaments that extend from the coast to offshore. In the case of the Ongole block, the seismicity is aligned mainly along the NW-SE-trending Gundlakamma River fault, which runs for nearly 100 km from inland to Ongole at the coast (Reddy and Chandrakala 2004). Sarma et al. (2009) delineated the extension of the Gundlakamma fault into the offshore from marine magnetic data. Further south, the Pondicherry region falls within the Cauvery rift basin. The Pondicherry offshore area has a record of an earthquake of 5.5 magnitude in 2001 (Rastogi 2001), which was a fairly larger event in the southern Indian shield in recent times.

In order to understand the nature of faulting and stresses operative in the region, we compiled all available focal mechanism solutions (Table 1) for several moderate events occurring along the east coast of India and the BOB region (Fig. 2) from Chandra (1977), Bergman and Solomon (1985) and Biswas and Majumdar (1997) along with those listed in the Harvard Centroid Moment Tensor (HCMT) database (Dziewonski et al. 1981; Ekström et al. 2012). Along the east coast of India, the focal mechanisms of three prominent earthquakes (after Chandra 1977) suggest that the 1964 Midnapore (event 1) earthquake was dominantly thrust faulting, whereas the 1967 Ongole (event 2) and 1969 Bhadrachalam (event 3) earthquakes showed strike-slip faulting with the left lateral sense of motion. The 2001 Pondicherry earthquake (event 12) occurring in the SE offshore of India shows thrust faulting with a minor strike-slip component having left lateral motion along a northeast striking nodal plane (Rastogi 2001). On the other hand, source mechanisms of earthquakes in the BOB region (Fig. 2) revealed several strike-slip events in the northern part (events 7, 8, 9, 11) and predominantly thrust faulting with a component of strike-slip motion in the vicinity of the 85°E ridge region (events 4, 5, 6, 10).

3.1 Source mechanism of the 21 May 2014 Bay of Bengal earthquake

The source mechanism of the 21 May 2014 Bay of Bengal earthquake was reported early by the USGS (2014) and presented subsequently in the Harvard CMT solutions listing (Harvard 2014), confirming that it was a strike-slip event with steeply dipping nodal planes. The moment magnitude (Mw) estimates of the earthquake vary between 5.9 and 6.1, and the focal depth is estimated to be more than 50 km, which is fairly deep considering the oceanic realm of this event. According to detailed analysis of seismological records obtained from several regional seismic stations located along the rim of the BOB, Rao et al. (2015) suggested that it was an event with a high stress drop, which was further confirmed by Martin and Hough (2015) based on the seismic intensity data.

4 Analysis of geophysical data in the vicinity of 21 May 2014 earthquake

4.1 Data sets

We carried out a detailed interpretation of various geophysical data sets in the region surrounding the earthquake in order to delineate major structural and tectonic features in the region as well as to evaluate probable causes for the occurrence of this intraplate event. The study region encompasses both onshore and offshore areas covering the northeast coast of India and the adjoining Mahanadi offshore in the BOB. The various regional geophysical data sets compiled here include (1) the high-resolution topography data from the Shuttle Radar Topography Mission (SRTM) database in the onshore area (Jarvis et al. 2008). (2) The free-air gravity data are extracted from the Earth Geo-potential model

Table 1 Source mechanisms of large/moderate earthquakes compiled from various sources in the region of the BOB and the adjoining east coast of India

S. no.	Date (mm/dd/year)	Longitude (°)	Latitude (°)	Depth (km)	Mb	Nodal plane 1			Nodal plane 2			Source
						Strike	Dip	Rake	Strike	Dip	Rake	
1	Apr 15, 1964	88.0	21.7	36	5.5	201	72	–	322	32	–	Chandra (1977)
2	Mar 27, 1967	80.1	15.6	17	5.4	317	90	–	47	71	–	Chandra (1977)
3	Apr 13, 1969	80.6	17.9	33	5.3	327	70	–	60	82	–	Chandra (1977)
4	Nov 24, 1972	85.34	11.67	27	5.2	254	52	76	–	–	–	Bergman and Solomon (1985)
5	Apr 12, 1981	85.40	8.27	33	5.2	340	73	−177	249	87	−17	HCMT
6	Apr 8, 1982	86.30	18.51	31.7	5.4	325	51	131	91	54	51	HCMT
7	July 4, 1982	90.61	19.49	33	5.1	240	73	0	330	90	−163	HCMT
8	Jul 1, 1985	87.28	18.39	10	5.3	60	58	1	330	89	148	HCMT
9	Jun 12, 1989	89.77	21.83	15	5.7	354	67	164	90	75	24	HCMT
10	Jan 11, 1992	86.97	9.25	17.1	5.6	296	48	136	59	59	51	HCMT
11	Jul 9, 1992	90.02	21.04	30	5.2	79	59	13	342	79	148	HCMT
12	Sep 25, 2001	80.22	11.98	10	5.5	92	41	113	243	53	71	HCMT
13	May 21, 2014	88.01	18.20	44.3	5.9	322	83	178	52	88	7	HCMT

EGM2008 (Pavlis et al. 2012) in the onshore area and from the DNSC08 global gravity database (Andersen and Knudsen 2008) for the offshore area. (3) The published aeromagnetic anomaly map (Rajaram et al. 2006) of the onshore area and ship-borne magnetic data available from the marine trackline database of the National Institute of Oceanography in the offshore area are used. Additionally, the magnetic anomaly data were retrieved from the global 2′ × 2′ resolution Earth Magnetic Anomaly Grid (EMAG2), which is a compilation of the CHAMP satellite magnetic anomaly model MF6 (for wavelengths >330 km) as well as the aeromagnetic and marine magnetic data (Maus et al. 2009). (4) The multi-channel seismic reflection profiles and oceanic basement trends in the offshore area are compiled from previous investigations (Maurin and Rangin 2009; Bastia et al. 2010; Radhakrishna et al. 2012).

The above data sets are used to prepare the shaded relief images/contour maps for further analysis. The high-resolution topography image map (Fig. 3a) of the onshore region is prepared from the SRTM data, which have 90-m spatial resolution. Furthermore, both global free-air gravity data sets, the EGM2008 and DNSC08, have proven to be very useful

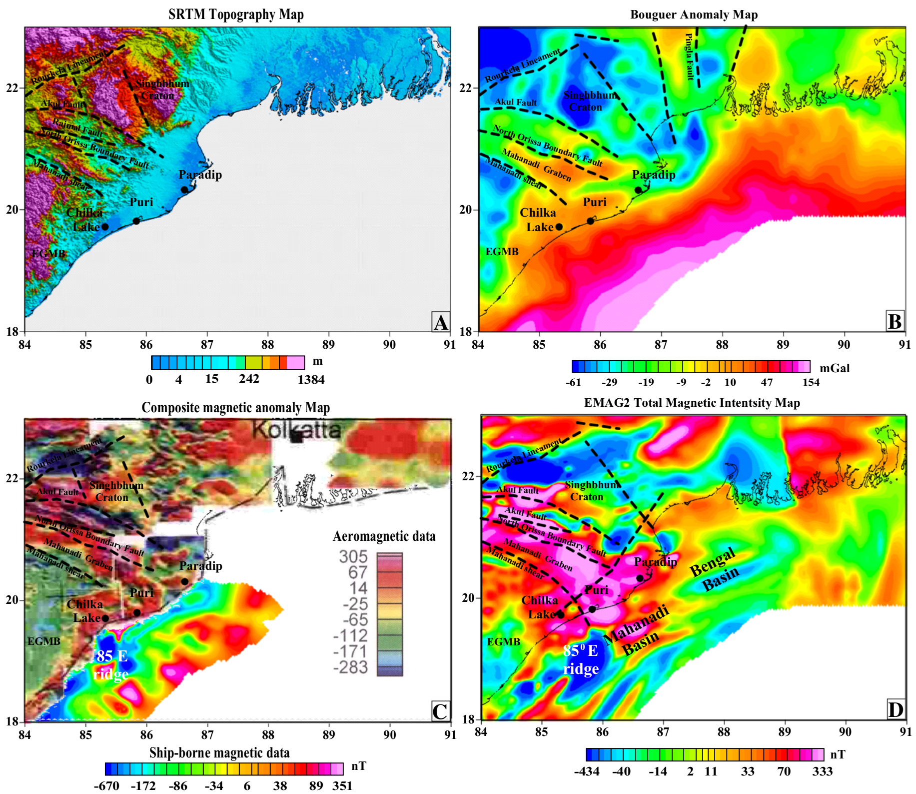


Fig. 3 **a** Shaded relief map of SRTM topography; **b** Bouguer anomaly map; **c** composite magnetic anomaly map prepared using an aeromagnetic map (after Rajaram et al. 2006) onshore and ship-borne magnetic data in the ocean region; **d** magnetic anomaly map prepared from the EMAG2 database (Maus et al. 2009). *Dashed lines* represent major tectonic elements compiled from various sources (Ray 1963; GSI 1993, 2000, 2014; Fuloria et al. 1992; Lisker and Fachmann 2001; Lal et al. 2009; Murthy et al. 2010). Only the tectonic elements that are identifiable/correlatable on these maps are indicated here

in regional tectonic studies as they contain short-wavelength information. First, the free-air gravity data are corrected for topographic undulations by applying the Bouguer correction. For Bouguer reduction, we assumed 2.67 gm/cc for the average density of crustal rocks, and the resulting Bouguer anomaly values are used to prepare the Bouguer anomaly map for the onshore area (Fig. 3b). Utilizing the aeromagnetic map for onshore (Rajaram et al. 2006) and available ship-borne magnetic data for offshore, we prepared a composite magnetic anomaly map (Fig. 3c) of the study area. A comparison of this map with the magnetic anomaly map prepared from the global $2' \times 2'$ resolution EMAG2 data set (Fig. 3d) reveals a similar pattern of magnetic anomaly highs and lows. It should be noted that the EMAG2 data provide leveled data at an altitude of 4 km above the sea floor; therefore, minor differences in the amplitude and wavelength of the anomalies exist. However, due to its uniform coverage, the data set is known to be very useful for regional tectonic investigations (Maus et al. 2009). Here we utilize the magnetic anomaly map generated from the EMAG2 data for further analysis.

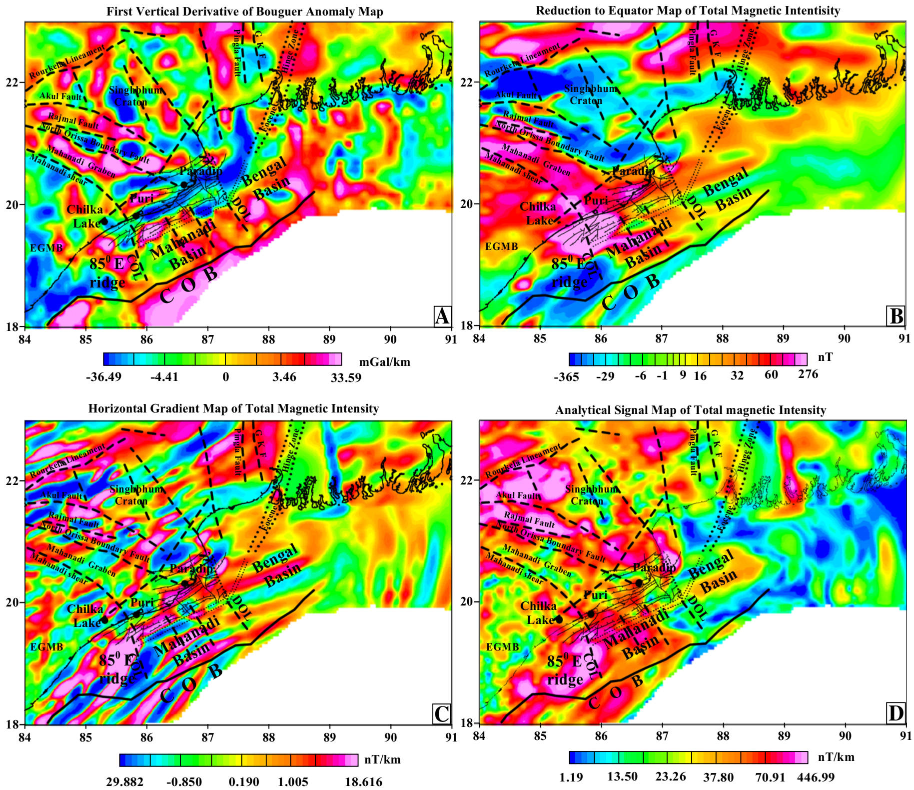


Fig. 4 Different image-enhanced maps prepared in the present study for the purpose of identifying correlatable structural/tectonic elements and their extensions. **a** First vertical derivative (*FVD*) map of the Bouguer anomaly map in Fig. 3b. **b** Reduction to the equator (*RTE*) map of total magnetic intensity (*TMI*) in Fig. 3d. **c** Horizontal gradient map of the TMI map. **d** Analytical signal map of the TMI map. *GKF* Garhmayna-Khandaghosh Fault; *COB* continent-ocean boundary; *COL* Chilka offshore lineament; *DOL* Dharma offshore lineament. Sources for the identifiable tectonic elements on these maps are given in Fig. 3

4.2 Delineation of structural/tectonic trends

4.2.1 Onshore and shallow offshore areas

Integration of the SRTM image with the structural geological details of the northeast coast (Fig. 3a) has elegantly revealed several NW-SE- and NE-SW-trending lineaments that appear on the shaded relief map as linear elongated zones of topographic highs or lows. Continuation of these known structural trends toward the coast has been obscured by the presence of thick sediments of the Mahanadi and Bengal basins. The gravity and magnetic anomaly maps (Fig. 3c, d) have further revealed these trends, and a correlation of these maps with the onshore geology (Fig. 2) showed the following: The Archean mobile belt rocks of the Eastern Ghat Mobile Belt (EGMB) are associated with the NE-SW-trending low in the gravity and magnetic maps, while the Singhbhum craton is characterized by an E-W-trending low magnetic and gravity field. These two trends are further separated by a NW-SE trend associated with the Mahanadi graben. In addition, both maps reveal three sets of lineaments, one in the NW-SE, the second in the NE-SW and the third in the NNE-SSW direction. In order to bring further clarity and for better correlation of the trends, we analyzed these maps by applying various image enhancement techniques.

The first vertical derivative (FVD) method (Blakely 1995) is known to enhance the shallow sources, and application of this filter on the Bouguer anomaly map (Fig. 3a) has revealed several ridge-depression structural features in the Mahanadi basin (Fig. 4a) that were not previously visible on the Bouguer anomaly map. Furthermore, a clear correlation of different gravity high/low trends is noticed very well on the FVD map. On the other hand, interpreting structural/tectonic trends from the total field magnetic anomaly map (Fig. 3d) is more complicated because many times the anomaly may not directly overlie

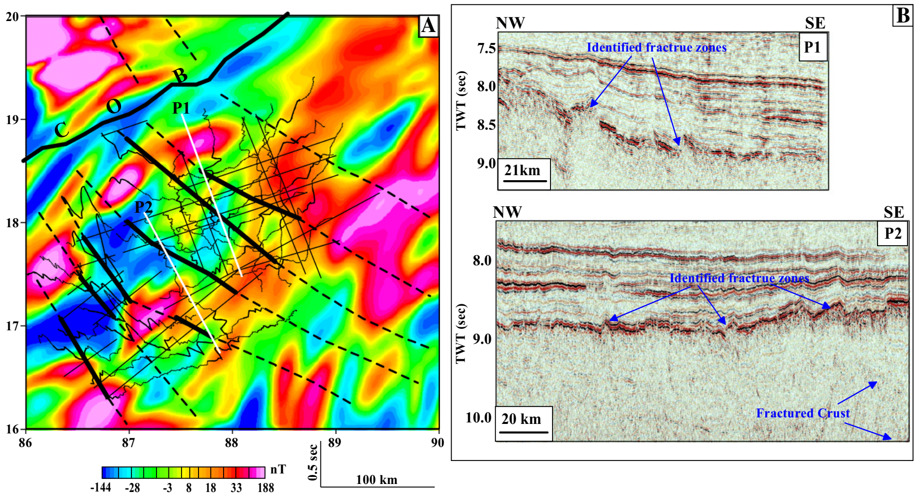


Fig. 5 **a** Total magnetic intensity map prepared for the deep offshore region of the study area using the EMAG2 data showing basement trends identified from multichannel seismic data (adapted from Radhakrishna et al. 2012) as *thick solid black lines*. *Thick dashed lines* are their inferred extensions. *Thin lines* are the along track basement plots. P1 and P2 (*white lines*) represent the location of *seismic lines*. **b** Snapshots of two seismic reflection sections (P1 and P2) across the fracture zones in the close vicinity of the 21 May 2014 earthquake (adapted from Radhakrishna et al. 2012). *COB* continent-ocean boundary

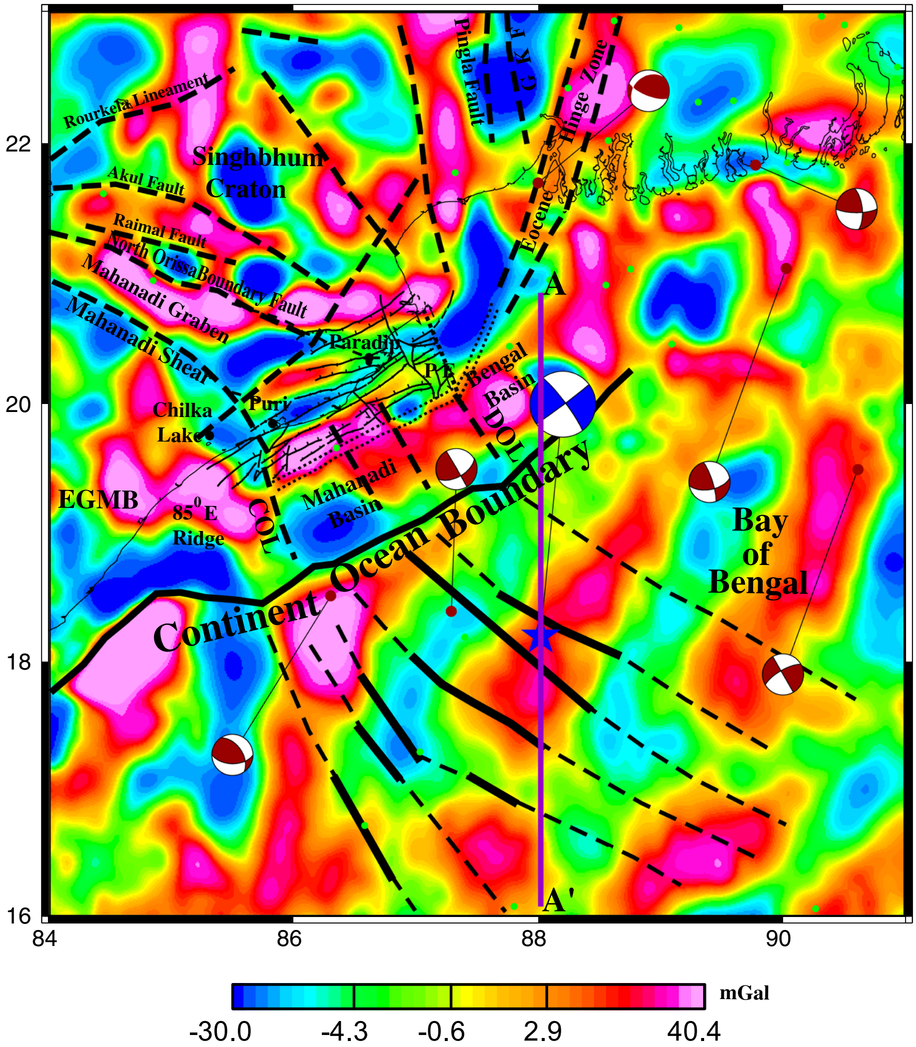


Fig. 6 Composite map showing the onshore-offshore tectonic linkage across the Mahanadi coast at the northeastern continental margin of India. Tectonic elements inferred from the present study as well as those compiled from the literature (sources are the same as in Figs. 3, 4) were overlain on the band-pass-filtered (20–200 km wavelength) Bouguer anomaly map. AA′ represents the location of the transect utilized in the present study for the purpose of combined gravity-magnetic modeling. Star indicates the location of the 21 May 2014 earthquake, and dots represent the earlier events for which focal mechanism solutions are available. Details are discussed in the text

the source or fault zone. It may shift laterally, and the shape could also be distorted (Blakely 1995). Therefore, in the case of magnetic data, the image enhancement methods such as the reduction to the equator (RTE), horizontal gradient (HG) and analytical signal (AS) are helpful in the identification of trends or anomaly features. The RTE method is useful in the case of low latitude regions ($\sim 15°$) as it shifts the magnetic anomalies spatially over the source bodies (Blakely 1995), whereas the HG method places the maximum magnitude directly over the top edge of the boundaries (Cordell and Grauch 1985). Another useful tool for delineating the magnetic source location is AS, especially in the presence of vertical contacts; it is less influenced by the direction of magnetization (Roest et al. 1992). These methods have been applied on the total field magnetic anomaly map (Fig. 3d), and the resultant maps are presented in Fig. 4b–d. A combined analysis of all these maps has provided useful insights for the identification of different structural trends in the region. We have compiled all major structural/tectonic elements in the onshore as well as offshore areas reported in earlier publications (Ray 1963; GSI 1993, 2000, 2014; Fuloria et al. 1992; Mahalik 1996; Lisker and Fachmann 2001; Lal et al. 2009; Murthy et al. 2010) and correlated them with the geophysical expressions on these maps. In the Mahanadi and Bengal basin areas, the sub-surface structural details are mainly from the industry seismic data (Talukdar 1982; Fuloria et al. 1992), which are clearly revealed on the enhanced gravity and magnetic anomaly images. The excellent correlation of the

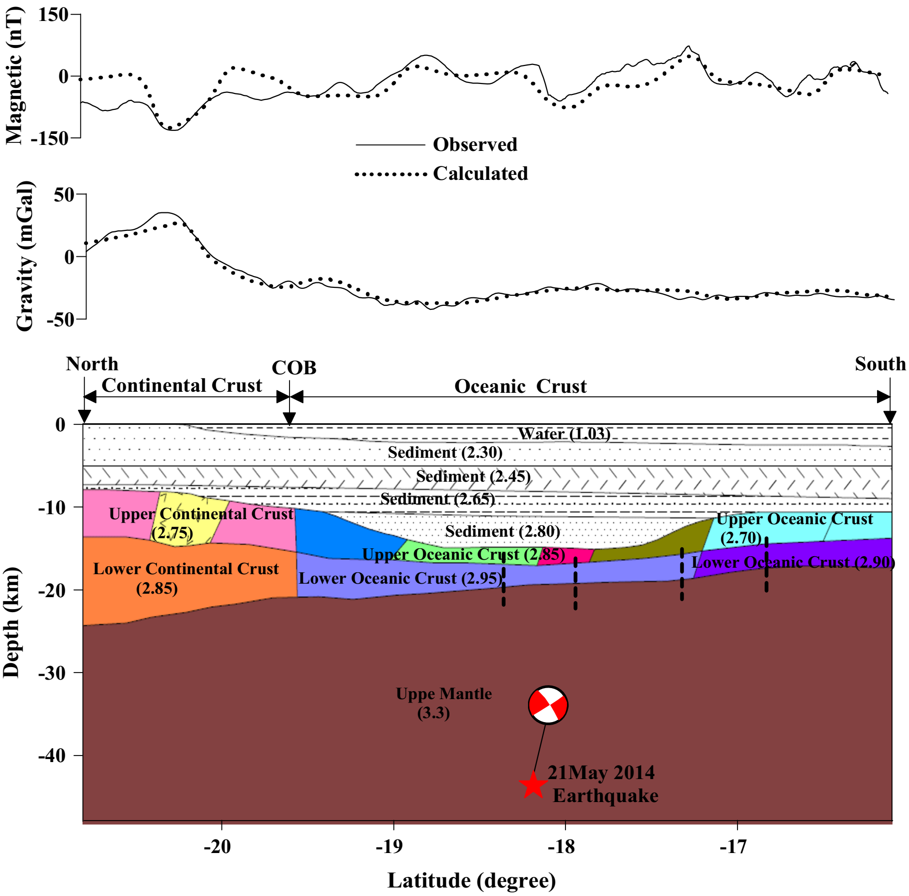


Fig. 7 Crustal structure derived from the combined gravity-magnetic modeling along the N-S transect (AA′) passing through the earthquake. The location of the transect is shown in Fig. 6. The density and susceptibility values utilized for the purpose of modeling are presented in Table 2. Vertical dashed lines on the model are intersections of fracture zones along the transect (see Fig. 6)

seismically mapped structural trends with the anomaly signatures/trends gave us confidence to either further extend these trends or identify new trends in the region.

4.2.2 *Deep offshore areas*

The deep offshore (>1000 m water depth) part of the present study area mostly lies oceanward of the continent-ocean boundary (COB) and encompasses the oceanic crust that evolved during the early breakup evolution of the BOB (Fig. 2) by the NW-SE-trending seafloor spreading regime. However, neither the BOB ocean floor nor the gravity images reveal any signatures of fracture zone trends related to this spreading regime because of the presence of thick sediments. Utilizing the vast compilation of oceanic basement trends from the multi-channel seismic data in the BOB region, Radhakrishna et al. (2012) mapped a number of major fracture zones and inferred a double breakup history between India and the East Antarctica conjugate margins. For the present purpose, we utilized these multichannel seismic profiles of the study area and presented five NW-SE-trending fracture zones based on the correlation of the basement morphology along the profiles (Fig. 5). The trends of these fracture zones are seen to correlate well with the EMAG2 anomaly signatures, and the trends identified in seismic sections have been extended based on these anomaly signatures. Two seismic sections (P1 and P2) presented across these fracture zones reveal their morphological expression (Radhakrishna et al. 2012), and in section P1, the fracture is even observed within the oceanic crust.

A composite map of all identified structural trends in the study area (both onshore and offshore) is presented in Fig. 6 to understand their general correlation with the seismicity of the region and particularly with the location of the 21 May 2014 earthquake.

4.3 Two-dimensional crustal model

In order to further understand the crustal structure in the vicinity of the earthquake, we considered a N-S transect in the offshore passing through the 21 May 2014 BOB earthquake (AA′ in Fig. 6). The bathymetry and free-air gravity data extracted from the DNSC08 database (Andersen and Knudsen 2008) and the regional sediment thickness grid (Radhakrishna et al. 2010) are considered here for the purpose of modeling. The magnetic

Table 2 Density and magnetic susceptibility values utilized for the combined gravity-magnetic modeling along the transect

Rock type	Layer	Density (gm/cm^3)	Susceptibility (C.G.S. units)	Remanent magnetisation (emu/cc)
Sediments	Layer 1	2.30	–	–
	Layer 1	2.45	–	–
	Layer 3 (metasediments)	2.65	–	–
Intrusive or dyke		2.75	0.004–0.006	0.004–0.008
Oceanic crust	Upper crust	2.70–2.80	0.002–0.006	0.004–0.008
	Lower crust	2.90–2.95	–	–
Continental crust	Upper crust	2.75	0.0001–0.0003	
	Lower crust	2.85	–	–
Upper mantle		3.30	–	–

Details are discussed in the text

data along this transect are obtained by projecting the ship-borne magnetic profile retrieved from the NGDC marine geophysical database. The gravity and magnetic modeling is carried out using GM-SYS software, which is primarily based on the algorithms of Talwani et al. (1959) and Talwani and Heirtzler (1964). The sediment thickness along this transect ranges from 8 to 12 km with a maximum thickness of sediment lying in the central part of the BOB. For the purpose of modeling, we divided the entire sediment column into four layers, and their densities were derived from the density-depth empirical relations provided by Radhakrishna et al. (2010) for the northern BOB region. The crustal structure obtained from the modeling is presented in Fig. 7. As can be seen, Moho along this section varies between 24 km in the offshore northeast coast of India to 18 km in the central BOB region. At the epicentral region of the earthquake, Moho is located at a depth of $\sim$20 km, which closely matches the Moho depth value obtained from the waveform modeling (Rao et al. 2015). The density and magnetization parameters utilized for modeling are presented in Table 2.

5 Discussion

The present study area of the BOB belongs to the early oceanic lithosphere that evolved $\sim$130 Ma (Subrahmanyam et al. 1999) and is the site of huge sediment thickness (>16 km). An analysis of more than a century (1900–2011) of earthquake occurrence and the compiled focal mechanism solutions in the BOB and the adjoining east coast of India revealed the importance of regional stresses for the reactivation of older structural features or weak zones. Along the east coast of India, several structural/tectonic features related to the basin formation continue into the offshore areas and could play an important role in transferring/triggering seismic activity in the coastal as well as shelf-slope areas (Murthy et al. 2010). The present study has established the onshore-offshore tectonic linkage in the Mahanadi and Bengal basin area of the east coast of India (Fig. 6) and its relevance to the earthquake occurrence in the coastal/offshore areas. Furthermore, the disposition of structural trends within the continental crust in the shelf region and the orientation of fracture zones (Fig. 6) in the BOB confirmed that the preexisting continental crustal architecture would influence the development of fracture zone trends across the COB at the time of breakup, as pointed out previously by Radhakrishna et al. (2012). The earthquake occurrence in the northern BOB has some spatial correlation with the NW-SE-trending fracture zones (Fig. 6) as evidenced by their dominant strike-slip faulting. The thrust faulting events over the 85°E ridge also occurred in the areas where N-S-oriented fracture zones from the south intersect with the NW-SE-trending fracture zones at the ridge. In the epicentral area of the 21 May 2014 earthquake, Satyanarayan et al. (2014) reported the presence of a magnetic anomaly zone at the intersection of the NW-SE- and NE-SW-trending faults.

However, the seismic activity in the BOB region is in general attributed to the accentuation of compressional forces due to back-thrust from the Himalayas (Biswas and Majumdar 1997); the vertical forces generated by the huge sediment loading and of volcanic aseismic ridges such as the 85°E and Ninetyeast ridges (Fig. 2) could also influence the BOB lithosphere, as suggested by Subrahmanyam and Singh (1992). They opined that causes other than the compressive stress regime could be possible since the lithosphere below the BOB is colder (Brune et al. 1992) with high flexural rigidity (Radhakrishna et al. 2000). Studies also revealed that the oceanic fracture zones can generally retain their morphological expression over longer geological periods and thus are not the inherent zones of weakness (Sandwell and Schubert 1982; Sandwell 1984). However, in the areas of higher ambient stresses, the fracture zones do become reactivated at deeper levels, thereby leaving no surface expression (Bull 1990). Such a reactivation has been observed along N-S-oriented fracture zones within the oceanic lithosphere of >60 Ma in the central Indian Ocean as well as over the Ninetyeast ridge (Bergman and Solomon 1985). Although large intraplate earthquakes occur along the fracture zones lying in the lithosphere of all ages, in the older lithosphere (>80 Ma), large events are rare except in the areas of high stress state conditions (Bergman 1986). The study of Bergman and Solomon (1985) further revealed that most of the large intraplate earthquakes in the northern Indian Ocean occurred at deeper depths within the upper mantle. The strike-slip faulting, deeper focal depth and high stress drop along with the absence of aftershock activity are characteristic features of the present 21 May 2014 earthquake (Rao et al. 2015). The modeled N-S crustal structure passing through the earthquake (Fig. 7) confirmed that it occurred within the upper mantle, having spatial correlation with the fracture zones in the region. It is therefore concluded that the 21 May 2014 earthquake could have been caused by reactivation of a NW-SE-trending fracture zone within the BOB lithosphere, indicating the presence of an abnormally high stress regime in the eastern Indian Ocean.

6 Conclusions

Analysis of ship-borne and satellite-derived potential field data along with multichannel seismic profiles in the vicinity of the 21 May 2014 Bay of Bengal earthquake reveals several NW-SE-trending oceanic fracture zones as well as onshore tectonic/structural trends oriented in different directions (NW-SE, NE-SW, NNE-SSW). Furthermore, the study shows the extension of Precambrian lineaments of the eastern Indian shield toward offshore. The published focal mechanism solution of the 21 May 2014 earthquake indicates that it is a strike-slip with steeply dipping nodal planes and occurred at a depth of $\sim$50 km. We infer a right-lateral sense of motion on the NW-oriented nodal plane and believe that the probable cause of the present earthquake could be the reactivation of the oceanic fracture zones that were mapped in the present study. The modeled crustal structure along the N-S transect passing through the earthquake confirmed that the source lies in the upper mantle. Although the present study could very well show a link between the onland and offshore tectonic lineaments and addresses the probable cause and origin of the 21 May 2014 earthquake in the BOB, further investigation of high-resolution geophysical data sets is needed to understand the factors that govern the reactivation of oceanic fracture zones.

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