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Crustal architecture and rift tectonics across the Visakhapatnam Bay basin, central-east Indian margin: Insights from multichannel seismic and potential field data

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The Visakhapatnam Bay (VB) basin is a passive margin rift basin located at the non-basinal segment of the Eastern Continental Margin of India (ECMI) and formed during the rift–drift events associated with the breakup of eastern Gondwanaland. In the present study, integrated analysis of potential field and multi-channel seismic reflection (MCS) data were carried out to understand the rift tectonics, crustal configuration and onshore–offshore structural continuity across this basin. The study revealed the following: (i) crustal models derived through joint gravity-magnetic modelling show limited stretching with 36–40 thick crust below the Eastern Ghat Mobile Belt (EGMB) thinning down to 16–20 km at the Ocean Continent Transition (OCT), (ii) extension of Charnockitic basement associated with the Eastern Ghat Mobile Belt (EGMB) into the offshore region. Comparison of the crustal configuration across the VB basin with that across the adjacent thick sedimentary area of the Krishna–Godavari shows that upper crustal configuration is significantly different in the VB area. The observed limited rift related structuration (horst-graben morphology), the mapped high angle break-away fault with large offset in the seismic data and narrow width (70–90 km) of extended crustal domain in VB basin suggests that this segment acts as transfer zone between Krishna–Godavari and Mahanadi rift zones. Further, long curvelinear trend of magnetic anomalies associated with Pudimadaka Lineament (PKL) demarcate the VB basin from the adjacent Krishna–Godavari rift zone.

Keywords. Crustal structure; rift tectonics; Visakhapatnam Bay basin; Eastern Continental Margin of India.

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1. Introduction

Previous studies have very well established that the development of passive eastern Indian margin is related to the rifting and breakup of India and East Antarctica during Early Cretaceous (Powell *et al.* 1988). The pre-existing geology of the East Coast of India (figure 1A), predominantly characterized by the eastern Indian shield crust having high-grade granulite rocks in the south, the

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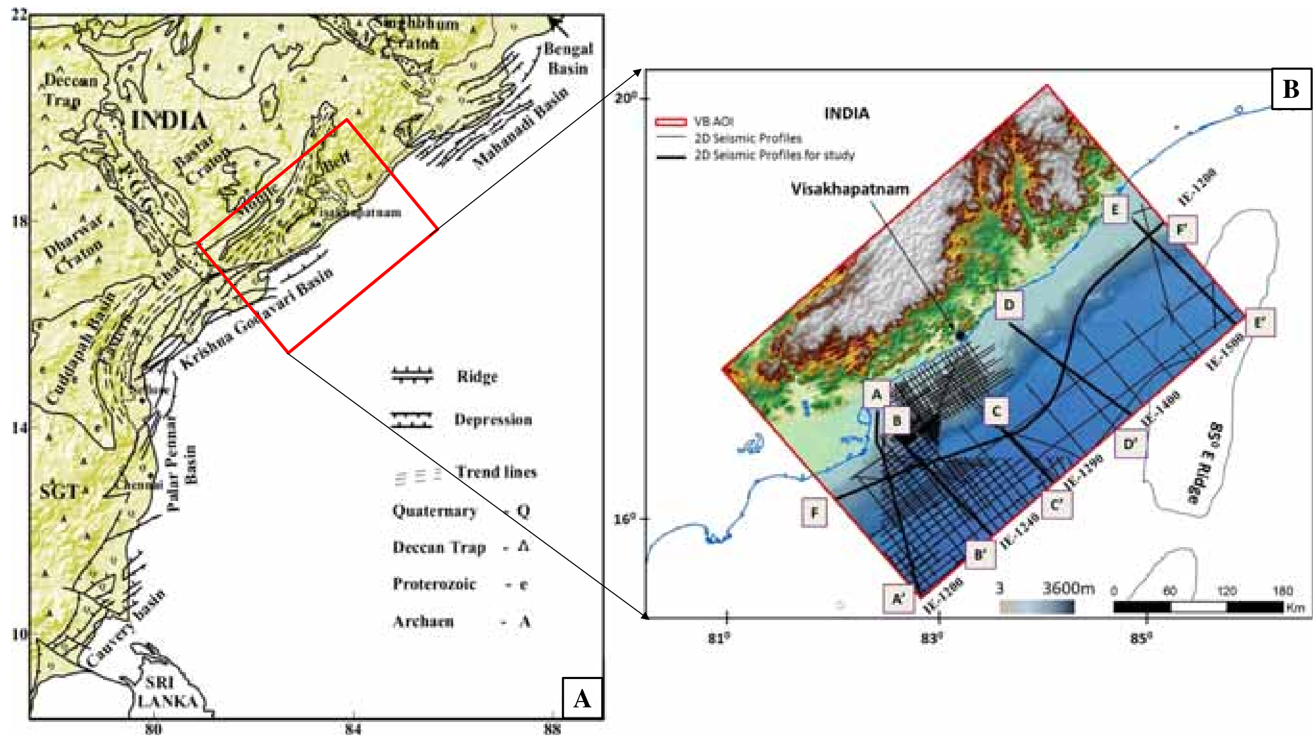


Figure 1. **(A)** Tectonic map of the East Coast margin of India (after Lal *et al.* 2009), **(B)** Topography map of central part of the ECMI (present study area) showing the location of six regional multi-channel seismic reflection (MCS) profiles AA' to FF (thick black lines) and vintage MCS reflection profiles (thin black lines) in the offshore VB basin considered for the present study.

Eastern Ghat Mobile Belt (EGMB) rocks in the central, and the Singhbhum craton in north along with their offshore counterparts has associated with the above rifting process (Lal *et al.* 2009; Radhakrishna *et al.* 2012a). This geological distinctness of different sub-crustal blocks has caused the tectonic and geomorphic segmentation of the ECMI during rifting (Radhakrishna 1989; Lal *et al.* 2009) and resulted in the development of major peri-cratonic passive margin rift basins such as the Cauvery, Palar–Pennar, Krishna–Godavari, Mahanadi and Bengal basins (figure 1A) (Sastri *et al.* 1973; Biswas 1993). The rift related NE–SW trending horst-graben structuration was clearly delineated in all these basins through detailed geophysical investigations (Sastri *et al.* 1973, 1981; Fuloria *et al.* 1992; Rangaraju *et al.* 1993; Prabhakar and Zutshi 1993; Rao 2001). Also, the Krishna–Godavari (K–G) and Mahanadi onshore basins have associated pre-existing NW–SE structural trends, the Godavari and Mahanadi grabens, whose continuity into the East Antarctica was clearly established (Veevers 2009; Lal *et al.* 2009). However, the Cauvery–Palar sector of the coast had no such associated structural feature. Detailed offshore geophysical studies, mainly the multi-channel seismic reflection data along this margin further revealed extension of all these onshore basins into the deep offshore areas of the margin (e.g., Bastia *et al.* 2010) and provided valuable information on the sedimentation all along the margin. Based on the offshore sedimentation and tectonic history, Bastia (2006) made further subdivisions of the east coast basins and proposed a non-basinal segment of the margin qualifying to be an offshore basin, called the Visakhapatnam Bay (VB) basin (figure 1B).

Most of the previous geophysical investigations along the ECMI were mainly confined to the basinal areas with an attempt to understand the rift tectonics, sedimentation and tectonic history of the basins in the overall framework of India–East Antarctica rifting and subsequent breakup. In these studies, the present study area of VB basin used to be considered partly with the southern K–G basin and partly with the northern Mahanadi basin. Therefore, no systematic study or single effort exists in the literature that solely considered the VB basin area to have a holistic view or analysis of this non-basinal segment. In view of this, we undertook a detailed geophysical data analysis of VB basin (figure 1B) to understand or delineate the crustal structure in comparison to the K–G offshore basin through an integrated interpretation of multi-channel seismic (MCS) reflection, gravity and magnetic data.

2. Regional tectonic setting of the VB Basin

The ECMI is a divergent type of margin that evolved as a consequence of these breakup events and subsequent seafloor spreading since Early Cretaceous (Powell *et al.* 1988). Recent geophysical studies and plate reconstruction models for the eastern Gondwanaland support double breakup evolution for the ECMI. While, the first breakup event is between India and the east Antarctica, the second breakup is associated with the separation of Elan Bank from India (Krishna *et al.* 2009; Radhakrishna *et al.* 2012a, b; Gibbons *et al.* 2013). Different geophysical characteristics along the margin further revealed the rift-shear tectonic affinity. As a result, the northern part of ECMI is considered to have evolved under normal rifting and the southern part under shearing or transform (Subrahmanyam *et al.* 1999; Chand *et al.* 2001; Radhakrishna *et al.* 2012b). Associated with the rifting, five major onshore sedimentary basins such as the Cauvery, Palar, Krishna–Godavari, Mahanadi and the Bengal basins (figure 1A) (Sastri *et al.* 1973) have developed along the ECMI. Geophysical data in these basins revealed (i) NE–SW trending horst-graben basement structural configuration (Sastri *et al.* 1973; Fuloria *et al.* 1992; Biswas 1993; Prabhakar and Zutshi 1993), (ii) their continuation into the deep offshore areas of the margin (Bastia *et al.* 2010), and (iii) the basins are separated by major tectonic elements and faults (Lal *et al.* 2009). These basins were classified as peri-cratonic rift basins (Biswas 1993) and have been studied in detail due to their large hydrocarbon potential. Based on the offshore geophysical data, Bastia (2006) proposed another important non-basinal segment of the margin that lies between K–G and Mahanadi offshore, and called it as the Visakhapatnam Bay (VB) basin (figure 1A and B). In the northeast, the VB basin is demarcated by the Chilka Lake and 85°E Ridge in the shelf and deepwater respectively; and towards southwest, the Kakinada terrace along with the Pithapuram cross-trend delimits the basin (figure 1A and B). The EGMB rocks comprising of high-grade metamorphic gneisses such as khondalites, charnockites and porphyritic gneisses (Ramakrishnan *et al.* 1998) along with Terrain Boundary and Nagavalli–Vamsadhara shear zones limits the basin in the onshore.

3. Datasets used

For the present study, the potential field data has been integrated with the MCS reflection data for better structural interpretation. High-resolution topography data from the Shuttle Radar Topography Mission (SRTM) database in the onshore area (Jarvis *et al.* 2008) and bathymetry data obtained from ETOPO1 global topography grid (Amante and Eakins 2008) were utilized for the preparation of topography map (figure 1B).

In the onshore areas, the free-air data is extracted from EGM2008 global earth potential field model complete up to spherical harmonic order and degree 2159 with additional coefficients up to degree 2190 (Pavils *et al.* 2012). This model includes terrestrial, satellite altimetry and satellite gravimetry (GRACE mission) datasets and provides gravity data at $2.5' \times 2.5'$ minutes grid resolution. Further, the free-air gravity data was reduced by applying Bouger slab and terrain corrections to obtain Complete Bouguer anomalies. In offshore regions, the free-air gravity anomaly data is extracted from the satellite altimetry derived $1' \times 1'$ min a global marine gravity grid (Sandwell *et al.* 2014). For the purpose of present study, a composite gravity anomaly map (figure 2A) was prepared utilizing the Bouguer anomaly data in the onshore and free-air gravity anomaly data in the offshore region.

The composite magnetic anomaly map (figure 2B) of VB basin was prepared utilizing the both aeromagnetic data in the onshore and along track ship-borne magnetic profiles in the offshore region. For this purpose, 33 ship-borne magnetic profiles covering about ∼3500 line km in the study area were considered (see figure 2B for location of ship tracks). These data mostly confined to continental shelf-slope areas (30–3500 m water depth) of the east coast of India and were acquired during the 192 cruise of the research vessel *RV Gaveshani* by the Regional Centre of National Institute of Oceanography (NIO), Visakhapatnam (Murthy *et al.* 1993). While, the onshore total field magnetic anomaly map is presented from the available aeromagnetic anomaly map of south India (after Rajaram *et al.* 2006).

The multi-channel seismic (MCS) reflection dataset obtained from the Reliance Industries

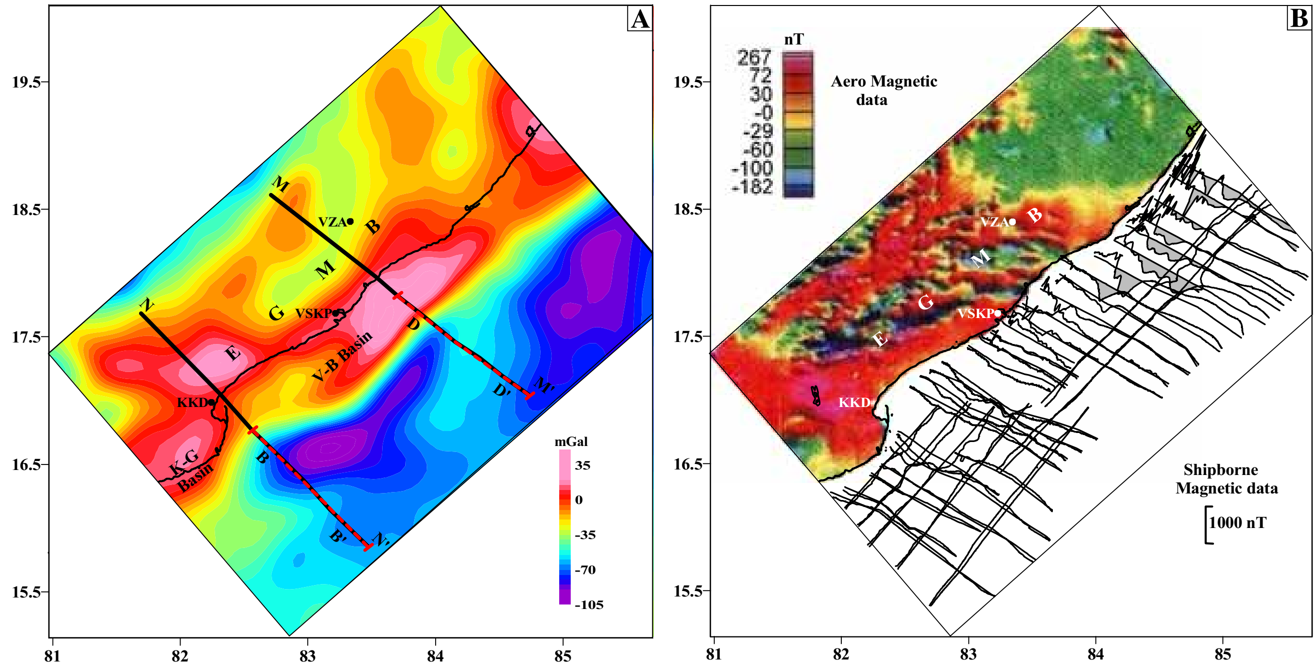


Figure 2. **(A)** Composite gravity anomaly map of VB Basin with Bouguer gravity anomalies in the onshore and free-air gravity anomalies in the offshore region. MM′ and NN′ are regional crustal transects across the margin considered for joint gravity-magnetic modelling. BB′ and DD′ are the MCS reflection profiles constrained for the interpretation. **(B)** The composite total field magnetic anomaly map of VB basin prepared utilizing aeromagnetic map of Rajaram *et al.* (2006) in the onshore and along track ship-borne magnetic profiles in the offshore region (in the present study). Locations of ship-tracks are marked with thin black lines. The darkened portions along the profiles represent the zone of negative anomalies of −800 to −1000 nT. EGMB: Eastern Ghat Mobile Belt; KKD: Kakinada; VSKP: Visakhapatnam; VZA: Vizianagaram.

Limited (RIL), India is also utilized in the present study to understand the basement structure and sediment geometry of the margin. The seismic data includes six (AA′–FF′) regional MCS profiles (see figure 1B for location) covering a total length about 1300 line km pertaining to the central ECMI, in which five MCS profiles (Line AA′–EE′) in dip direction and one seismic profile (Line FF′) in strike direction (figure 3A–C). In addition to this, good coverage of vintage MCS reflection data (see figure 1B for location) available in the southwest corner of the study area is also utilized to get the seismic ties and re-gridding for preparing the isopach maps.

4. Interpreted seismic sections and isopach maps

The morphology of shelf-slope and the abyssal plain features marked on the seismic lines (figure 3) reveal typical passive margin characteristics of this segment of ECMI. The basement topography and associated features help to identify the crustal boundary associated with the Continent Ocean Transition (COT), namely the Continental crust (CC) and the Proto Oceanic crust (POC). The deep reflectors visible on line AA′ (figure 3A) and line CC′ (figure 3B) possibly indicate continental Moho. Seaward Dipping Reflectors (SDRs) visible on line EE′ (figure 3B) act as characteristic evidences of magmatic occurrence on this segment of margin. The Cretaceous rift related faults (RF) are distinctly seen on the seismic sections (figure 3A–C). The basement morphology is imprinted by set of half graben features associated with break-away normal faults in the northern part of the study area, parallel to the present-day coastline (figure 3B, C). Further, six major horizons, viz., Water Bottom, Miocene, Oligocene, Paleocene, Cretaceous and Basement were interpreted on these seismic sections (figure 3A–C) based on the correlation of seismic lines with the well markers identified in the surrounding offshore basin areas. The interval and average velocities for these identified marker horizons is summarized in table 1. It is observed that the seismic velocities in the VB area (1600–3500 m/sec) are lower than that of K–G area. This is mainly because of the faster sedimentation due to Ganges influx and less accommodation space in shallower portion, which makes sediments more unconsolidated.

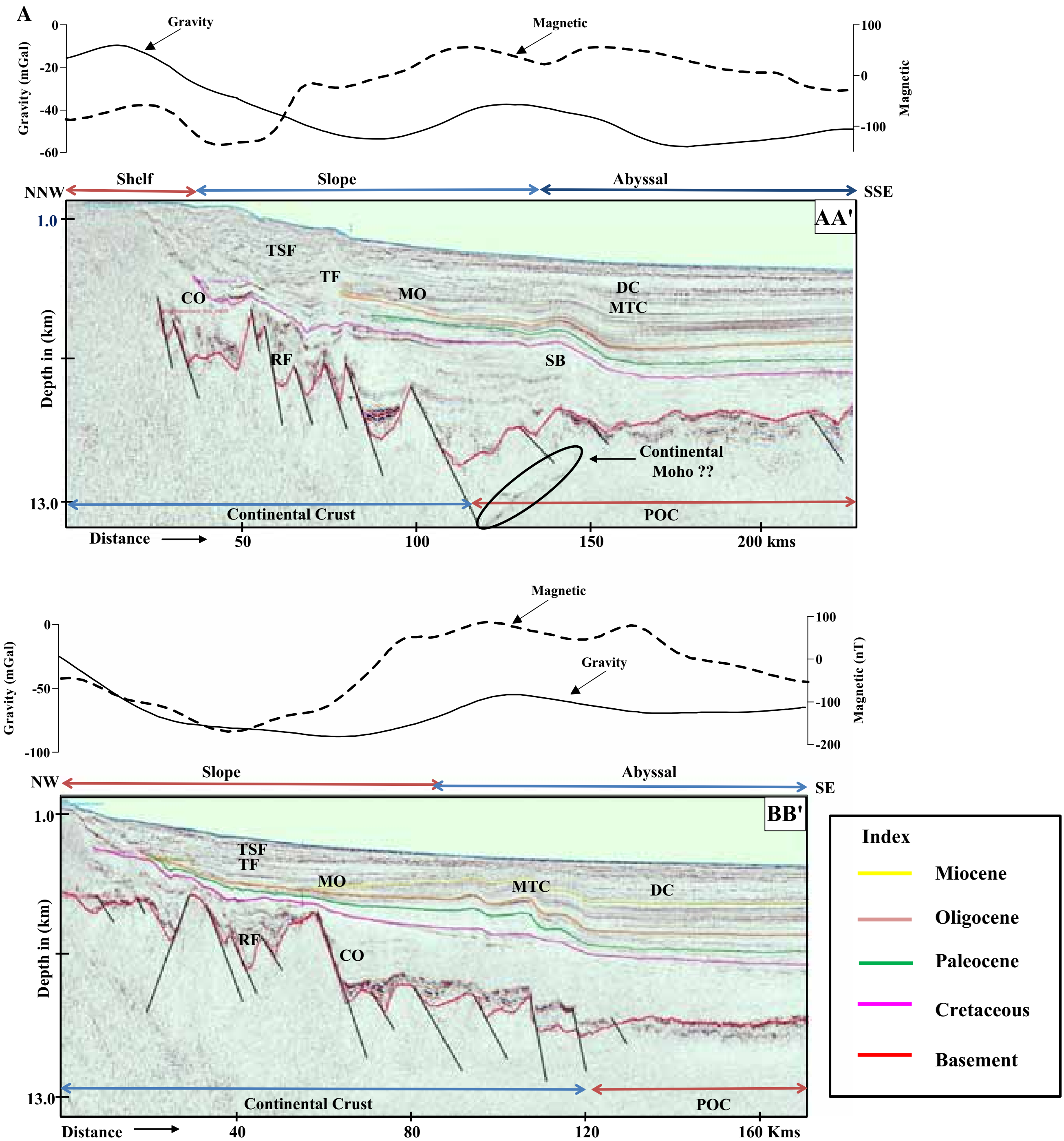


Figure 3. (**A–C**). Interpreted multi-channel seismic lines AA′–FF (see figure 1B for location) across the VB basin showing the basement morphology, rift related structuration and the sediment layer pattern overlying the basement. Basement high and Mesozoic rifts observed in abyssal plain area, Seaward Dipping Reflectors (SDR) and rift related break-away faults also marked on these sections: TF: Toe Thrust Regime; TSF: Tertiary sediment fill; SB: shale bulge; CO: Cretaceous depositional onlap; DC: sediment Depo-center; MTC: Mass Transport Complex; RF: Rift related faults; POC: Proto-Oceanic Crust.

Based on the interpretation of all available seismic lines in the offshore and the regional structural interpretations of important marker horizons along with their interval velocities described in the present study (table 1), we further prepared isopach maps for five different stratigraphic periods between (i) Water bottom–Miocene, (ii) Miocene–Oligocene, (iii) Oligocene–Paleocene, (iv) Paleocene–Cretaceous and (v) Cretaceous–Basement to understand the sedimentation history in space and time along the margin (figure 4A–E). The maximum thickness of

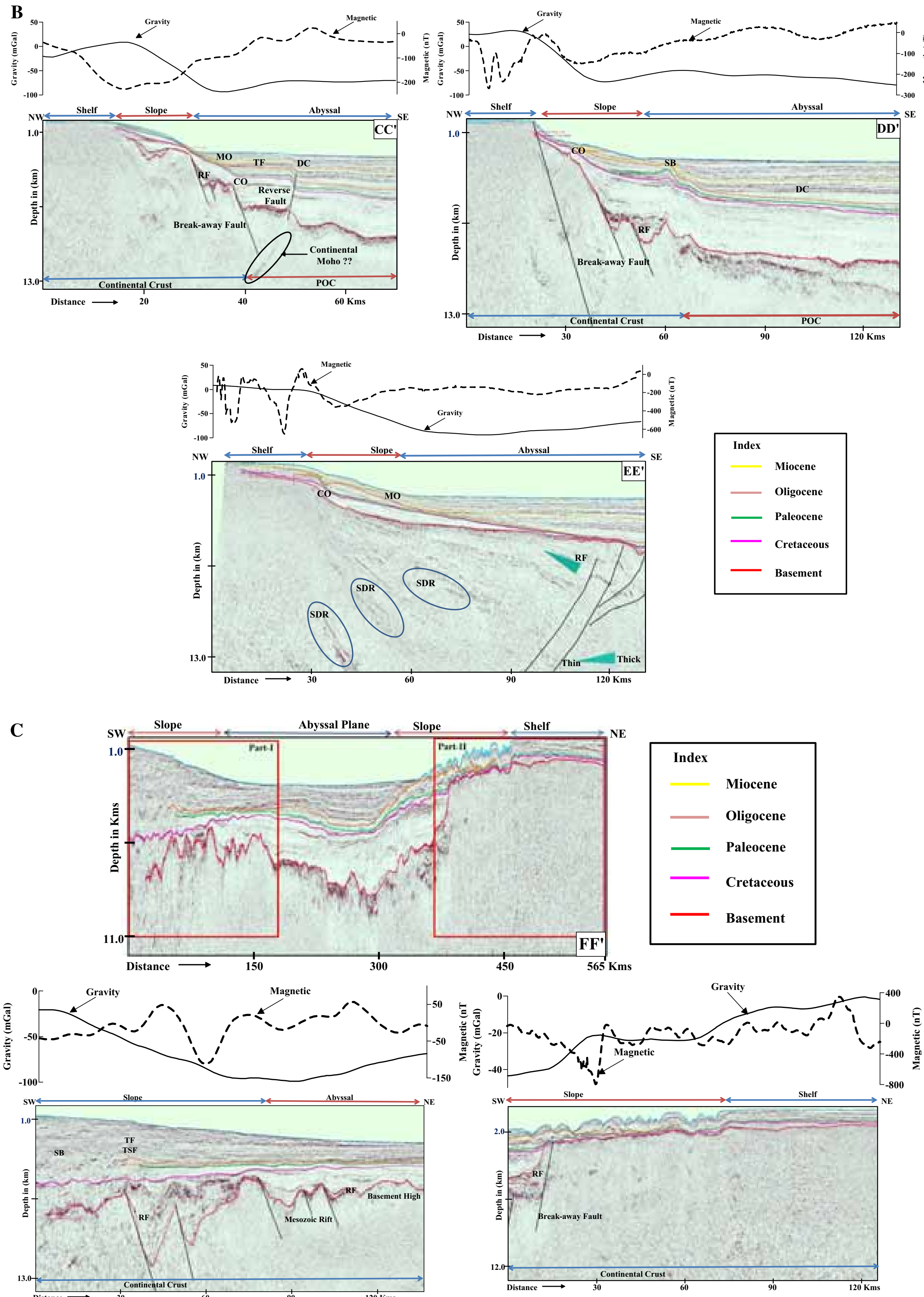


Figure 3. (*Continued.*)

Table 1. *Ages of different stratigraphic horizons and its corresponding interval and average seismic velocities in the VB area.*

Layers	Interval velocity (m/sec)	Horizon tops	Average velocity (m/sec)
Water Column	1500	–	–
Sea Bed–Miocene	1600–2450	Sea bottom	1530
Miocene–Oligocene	1900–2600	Miocene top	1950
Oligocene–Cretaceous	2250–3050	Oligocene top	2100
Cretaceous–Basement	2300–3500	Basement top	2500
Deeper than Basement	3000–6500	–	–

Cretaceous sediments lie in the VB basin compared to the K–G region (figure 4E). In contrast to this, Paleocene thickness is relatively more in the western part towards offshore K–G basin (figure 4D). In the continental slope area, the Paleocene thickness is still less and varies from east to west (figure 4D). It is also observed that Oligocene thickness is much less as compared to other stratigraphic intervals (figure 4C). Due to less sediment thickness, the effect of volcanic highs related to the 85°E Ridge bears impression on the thickness of Oligocene sediments towards eastern part of the study area. Further, the thickness of Miocene sediments goes till a kilometer in the study area with a regional dip towards southeast (figure 4B).

5. Interpretation of potential field data

The composite gravity anomaly map (figure 2A) of the region shows subdued gravity high (–20 to 35 mGal) associated with the Eastern Ghat mobile belt (EGMB) rocks and a typical bi-polar gravity signatures (30 to –70 mGal) associated with shelf-slope regions of the margin. The composite magnetic anomaly map (figures 2B and 5A) of the region reveals the NE–SW trending magnetically disturbed region related to the EGMB rocks which abuts the coast north of Visakhapatnam and continue across the coast into the offshore. The continuation anomaly signatures is noticed in both gravity and magnetic anomaly maps (figures 2A and 5A). In the offshore region, two distinct magnetic anomaly characters were observed: (i) subdued magnetic anomalies in the SW part and (ii) high amplitude (–800 to 1000 nT) coast parallel magnetic anomaly pattern in the northern part of the basin (figures 2B and 5A). Murthy *et al.* (1993) interpreted these anomalously high magnetic anomalies as rift-related dyke intrusions in the crust.

In order to enhance the shallow structural features observed in figures 2 and 5(A) and also to map the structural continuity across the coast, the image enhanced maps of gravity and magnetic data (figure 5B and C) have been prepared using the first vertical derivative (FVD) and the tilt derivative (TDR) methods (Blakely 1995). The TDR map of total magnetic anomalies (figure 5B) shows that the high amplitude magnetic anomalies observed over the EGMB basement rocks continued across the coast and also highlights the several rift-related dyke intrusions in extended crustal domain of VB basin. In the offshore region, Kakinada trough in the northern part of Krishna–Godavari basin is marked by low gravity and high magnetic anomalies (figure 5A–C). The long curve linear trends on the TDR map (figure 5B) indicate the offshore extension of Pudimadaka (PKL) and Vizianagaram (VZL) lineaments as reported by the earlier workers (Subrahmanyam *et al.* 2007; Murthy *et al.* 2010). Further, these workers suggest that the low-to-moderate seismicity observed off Vizianagaram shelf could be due to the reactivation of these pre-existing structural lineaments. It is also evident from the TDR map that PKL limits the VB basin from the adjacent Krishna–Godavari rift basin (figure 5B). Towards deep offshore area of the basin, a zone of high amplitude gravity and magnetic anomalies having width varying from 60 to 90 km correlates with the POC beyond the continental crustal rocks (figure 5A–C).

5.1 *2-D constrained gravity and magnetic modelling*

In order to compare the variations in the crustal geometry and rift characteristics between the thick sedimentary basin and non-basinal areas, we have performed the joint gravity–magnetic modelling along two regional transects (MM′ and NN′ shown

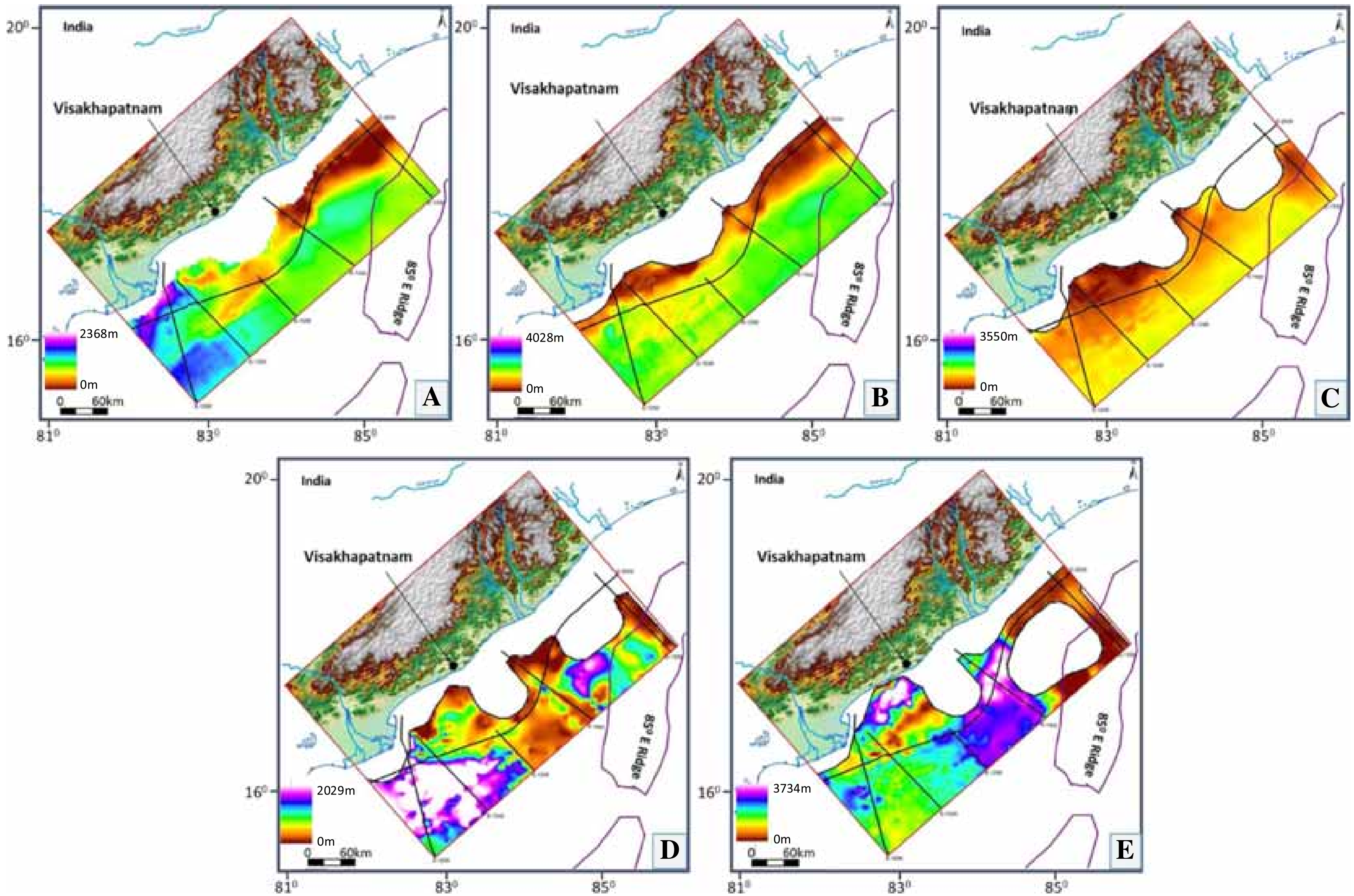


Figure 4. Isopach maps (in meters) of five major sedimentary sequences **(A)** from Water bottom–Miocene, **(B)** Miocene–Oligocene, **(C)** Oligocene–Paleocene, **(D)** Paleocene–Cretaceous, and **(E)** Cretaceous to Basement derived from the MCS data shown in figure 1(B).

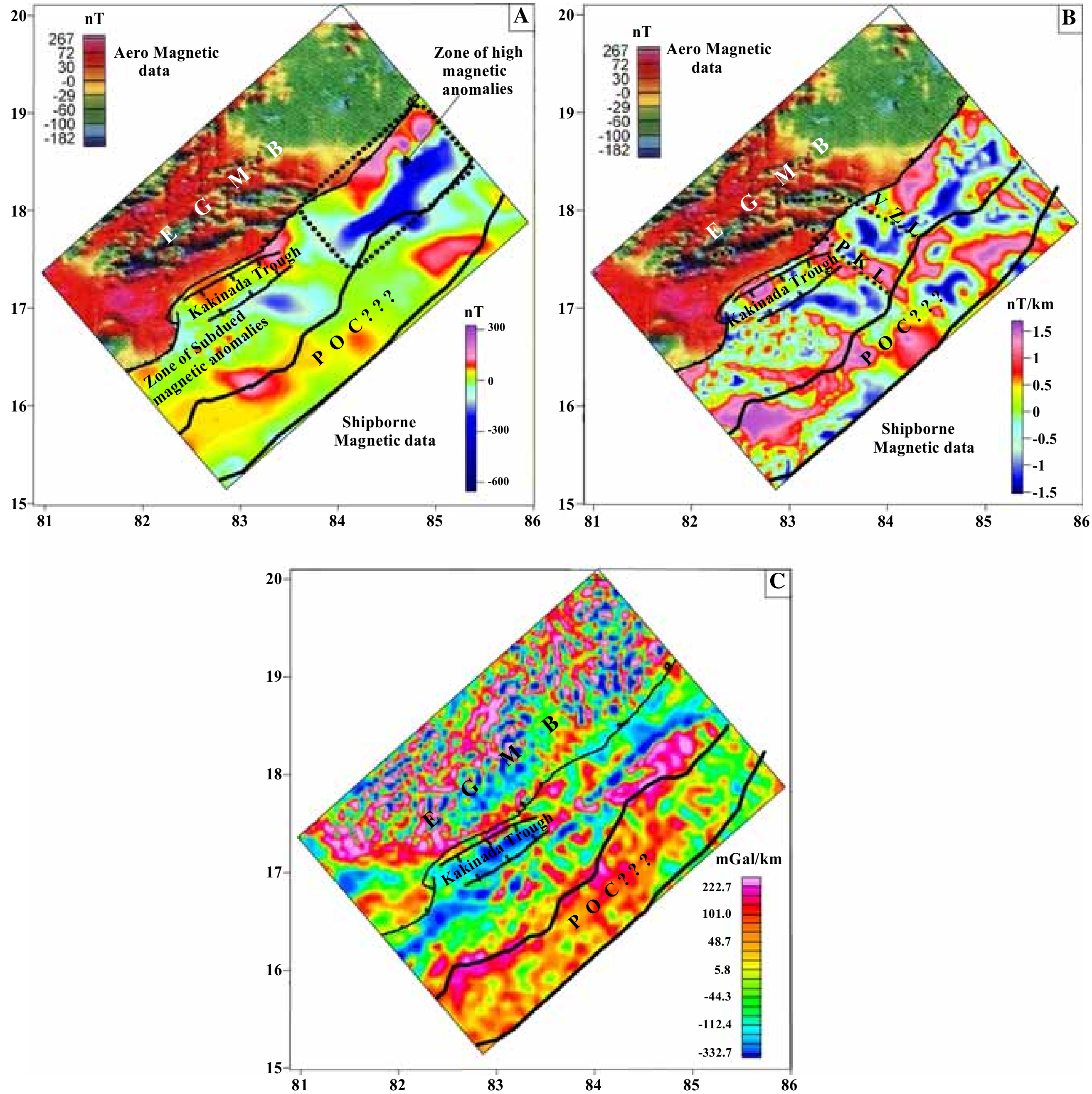
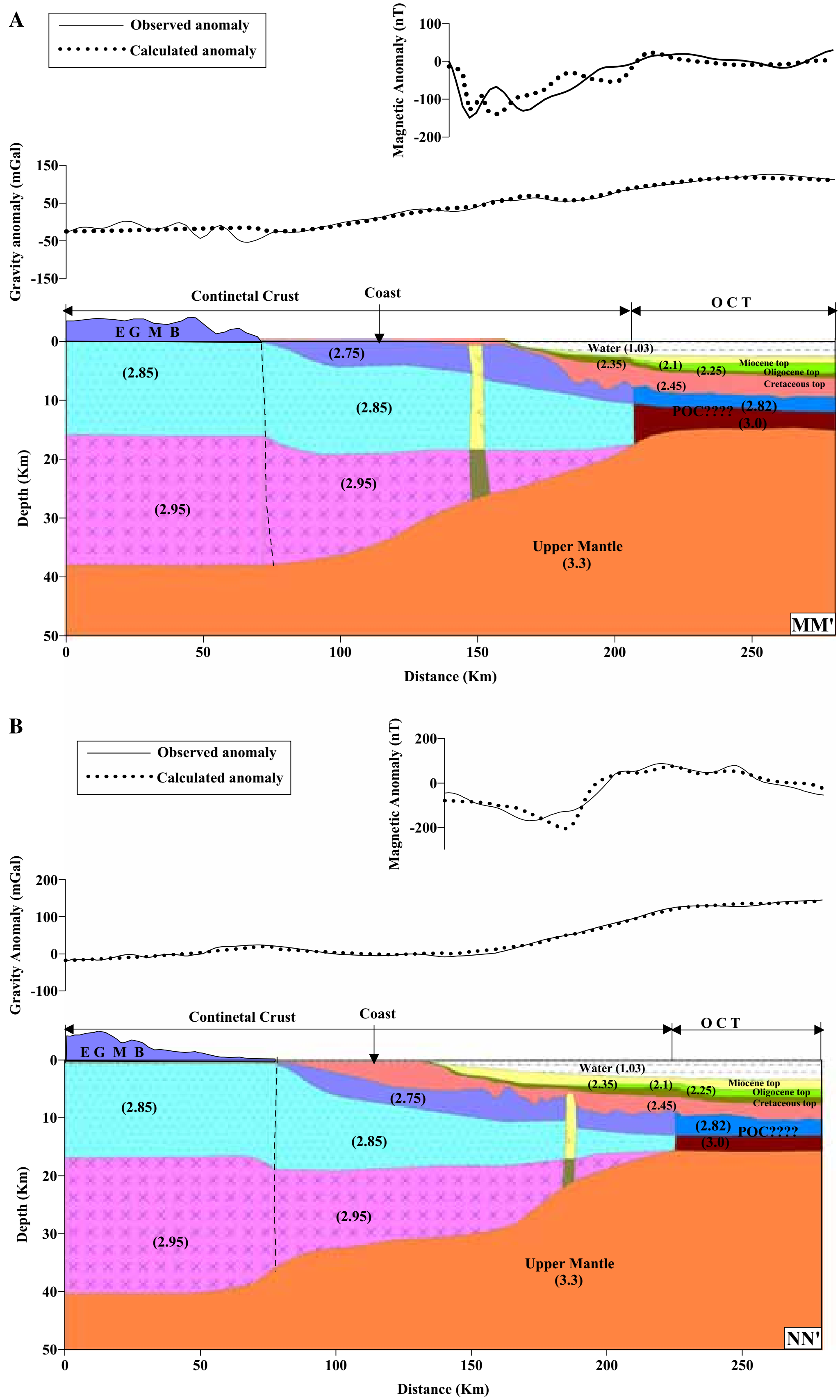


Figure 5. **(A)** Composite total field magnetic anomaly map and its **(B)** tilt derivative (TDR) map of VB Basin. **(C)** First vertical derivative (FVD) map of Complete Bouguer anomalies. Offshore continuity of Pudimadaka (PKL) and Vizianagaram (VZL) lineaments (dotted lines) are from marked after Murthy *et al.* (2010). The extent of POC (solid black lines) in the offshore is adopted from Nemcok *et al.* (2012).

in figure 2A). The transect MM′ is located in the non-basinal region and it is constructed by extending the offshore MCS line DD′ onto the onshore up to the crystalline region. While the transect NN′ pertaining to the thick sedimentary region in the south (in the close vicinity of the K–G basin) is constructed by utilizing the MCS line BB′ in the offshore and deep seismic sounding data (DSS) (Kaila *et al.* 1990) in the onshore region. The gravity anomalies from the Bouguer anomaly grid and magnetic anomalies from the ship-borne data were projected along these profiles for performing the 2-D joint gravity–magnetic modelling along these transects. The 2-D forward gravity and magnetic modelling was carried out using the GM-SYS module of Geosoft commercial software which is primarily based on the algorithms of Talwani *et al.* (1959) and Talwani and Heirtzler (1964). The


A
Observed anomaly
Calculated anomaly
Magnetic Anomaly (nT)
100
0
-100
-200
Gravity anomaly (mGal)
150
50
-50
-150
Continetal Crust
Coast
O C T
E G M B
Water (1.03)
(2.75)
(2.85)
(2.85)
(2.35)
(2.1)
(2.25)
(2.45)
Miocene top
Oligocene top
Cretaceous top
POC????
(2.82)
(3.0)
(2.95)
(2.95)
Upper Mantle
(3.3)
MM'
Depth (Km)
0
10
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Observed anomaly
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Magnetic Anomaly (nT)
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POC????
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Upper Mantle
(3.3)
NN'
Depth (Km)
0
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30
40
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0
50
100
150
200
250
Distance (Km)

◀Figure 6. **(A–B)**. Crustal models along transects MM′ and NN′ (see figure 2 for location) obtained from the integrated interpretation of Multi-channels seismic data (BB′ and DD′) and joint gravity-magnetic modelling. The upper and middle panels in **(A)** and **(B)** are the observed (thick line) and calculated (dashed line) gravity and magnetic responses of the crustal model shown in the bottom panel. The numbers in brackets shown on the model represents the density values used to derive the crustal structure shown in the bottom panel. EGMB: Eastern Ghat Mobile Belt; POC: Proto-Oceanic Crust; OCT: Ocean continent transition zone.

initial model geometry up to the basement is based on the MCS reflection data and crustal layering below the basement is constructed partly based on the results obtained from DSS data (Kaila *et al.* 1990). Further, velocity information for various sedimentary and crustal layers was utilized to constrain density values required for gravity modelling. In the case of magnetic modelling, large anomalies along the profiles were interpreted as intrusive structures with varying magnetic susceptibility and remnant magnetization properties. The total intensity of Earth's magnetic field is considered as 43,000 nT, and the inclination and declination of the induced magnetization in this region are 23° and –1.35°.

6. Results and discussion

The integrated interpretation of MCS reflection and potential filed data aided with the isopach maps of different sedimentary horizons have provided valuable insights on the sedimentation pattern (both in space and time), rift and crustal architecture in the VB basin, which is the non-basinal segment of the east Indian margin. Some of these details are given below.

6.1 *Sedimentation history*

The isopach maps of the offshore VB basin indicate that maximum Cretaceous sediment thickness concentration is around the present-day coast implying river-delta system was active during this time in the Mahanadi area (figure 4E). The Cretaceous sediments onlap (CO) onto the uplifted basement highs is seen in all dip lines from AA′–EE′ (figure 3A, B). Marine transgressive and regressive phases were also observed during end of Paleocene to Late Eocene. Absence of Oligocene in the shelf and part of the upper slope of the Mahanadi Basin (figure 4C) suggest regression in the Oligocene period. During this period, rate of subsidence of Mahanadi shelf was faster than the rate of sea level fall to produce Type-II unconformity (Posamentier *et al.* 1988). This major regressive cycle present at the onset of Late Eocene which continued till end of Oligocene causing absence of Late Eocene–Oligocene sediments in a vast area including the shelf and parts of upper slope in the study area (figure 4C). In the basal part of Miocene, a major transgressive phase is observed with small pulses of regressive and transgressive faults/toe thrusts (TF) which are evident in lines AA′ to CC′ (figure 3A and B) and line FF′ (figure 3C). As Miocene wedges towards the continental shelf, Miocene Onlaps (MO) on the Early Miocene décollement surface is also seen in the proximal part. With the onset of collision of the Indian and Eurasian plates, the major sedimentation activities prevailed during the post-Oligocene period and recent channel activity was the major contributor of sediments in the deeper part of the basin. The onset of activity of the Ganga–Brahmaputra feeder systems during Mid-Miocene along with older Mahanadi–Brahmani river system led to the huge influx of clastics into the basin, and prograding deltaic sediments built out over Mio-Pliocene period (figure 4A and B). Further, the sediment depo-center (DC) shifts from Miocene to Pliocene from proximal to distal part of basin (AA′ and BB′ in figure 3A) and (CC′ and DD′ in figure 3B) and Pliocene Mass Transport Complex (MTC) is observed on line AA′ (figure 3A) in distal part (Roy *et al.* 2015). The dominance of sediments from Godavari River in the proximal part and possible influence of Ganges sediments in the distal part is observed in the Tertiary deposition. It results in the high energy Tertiary sediment fill (TSF) in the proximal part, while relatively passive basin fills as we go to distal side (Choudhuri *et al.* 2017).

6.2 *Crustal and rift architecture*

The crustal models derived from the joint interpretation of gravity and magnetic data reveal that the crustal configuration in the non-basin region (profile MM′ in figure 6A) is distinctly different from the basin region (profile NN′ in figure 6B). In the non-basin area, the crustal model shows that crust is 36–38 km thick below the EGMB and gradually thins to 16–20 km at the COT in the offshore area (figure 6A). Whereas, in the basin region, the model reveals that crust below the EGMB is 38–40 km thick which thins laterally within the basin (figure 6B). The significant crustal thinning is observed at the offshore basin boundary compared to the boundary between EGMB and onshore part of the basin. Based on the geological correlation of EGMB rocks with Elan bank and NW–SE fracture zone trends in the Bay of Bengal, Radhakrishna *et al.* (2012a, b) suggested that the Elan Bank is juxtaposed to the EGMB rocks at the central part of ECMI in the pre-breakup scenario. Therefore, the observed crustal thinning in this region can be attributed to the second phase of rifting that took place between the ECMI and Elan Bank micro-continent. Further, the crust seems to have been punctured by the volcanic intrusives and the magnetization characteristics of this volcanism are similar to the Rajmahal volcanics indicating their emplacement during the continental breakup (figure 6A–B).

In the central segment of the ECMI, the MCS reflection profiles (Sinha *et al.* 2010; Nemcok *et al.* 2012; Radhakrishna *et al.* 2012a) have eminently revealed the seismic signatures related to the upper and lower continental crust, of exhumed upper mantle rocks and the oceanic Moho boundary, and inferred POC rocks at the COT in the K–G offshore basin. Extending this interpretation, Nemcock *et al.* (2012) have proposed the presence of POC boundary all along the ECMI. The interpreted seismic reflection profiles as well as crustal models (figures 3, 6) in the present study also indicate the POC rocks that were imaged by them. The detailed crustal transect modelling (further south of the present study) carried out by Radhakrishna *et al.* (2012a) also indicated the presence of POC rocks forming the continent–ocean transition in the K–G offshore, however, opined that sufficient density contrast is required between the POC rocks and the adjoining crust in order to meaningfully interpret the POC through potential field data. This requirement may vary from place to place depending on the tectonic setting in which POC rocks are emplaced. The modeled POC rocks required higher densities of $\sim$3.0 g/cc (Radhakrishna *et al.* 2012a). The crustal model from the present study (figure 6A–B) also suggests such higher densities for POC rocks indicating that rock types belonging to POC do not significantly vary along the ECMI. Several workers suggest wide variation in crustal types and emplacement process for the POC based on its seismic characteristics observed elsewhere, in the passive margin segments of the world oceans (Meyers *et al.* 1996; Wilson *et al.* 2003). Though the present study would not be able to resolve such fine-scale structural variation, the modeled POC in different segments of the ECMI (Radhakrishna *et al.* 2012a; Twinkle *et al.* 2016), and the model from the present study together do not indicate significant variations in POC emplacement process along the ECMI.

Based on detailed synthesis of the MCS reflection data, Nemcok *et al.* (2012) inferred a basic breakup scenario for the ECMI, which was subsequently refined by Sinha *et al.* (2015). Based on this framework, the ECMI is divided into six segments along which the continental breakup took place and the central ECMI (the present study region) forms part of the Krishna–Godavari rift and the Vizag transfer zones. From the gravity and magnetic images in the VB Basin, the extension of EGMB rocks in the offshore areas can be inferred (figure 5A–C). Further, the seismic sections in VB area (CC′–EE′) are devoid of rift related structuration (horst-graben morphology) in the extended part of the upper crust in the shelf areas (figure 3B–C). However, minor rift structures are noticed in the distal part of the margin within deepwater areas (figure 3B–C). The proximal and distal margins are clearly separated by the high angle break-away normal faults with large offset associated with sedimentation. It is also noticed that crustal thinning in the VB area occurs over a very short distance of 40–80 km (figures 3B and 6A). These observations indicate that it occurs as strike-slip-dominated margin connecting the K–G and Mahanadi rift zones. Similar nature of crustal thinning and rift architecture was noticed in the southern part of ECMI in the Palar Basin (Krishna *et al.* 2009; Nemcok *et al.* 2012) where Sinha *et al.* (2015) proposed Coromandal transfer zone between K–G and Cauvery Rift Zones.

7. Conclusions

Integrated analysis of MCS reflection and potential field (gravity and magnetic) datasets along the central segment of ECMI have brought out the following new insights on the crustal architecture with implications on the India-east Antarctica breakup:

- Seismically constrained crustal models obtained in the present study indicate that there is distinct variation in the crustal geometry both along and across margin. The thickness of the continental crust ranges 36–40 km below the EGMB and these rocks further extended into the offshore. The COT zone mapped in this region is 60–90 km wide and probably associated with high-density POC rocks.

- The composite magnetic anomaly map of the study region shows exceptionally high amplitude (–800 to 1000 nT) magnetic anomalies in the northern part of VB basin which could be due to dyke intrusions emplaced during the continental breakup.
- Comparison of the crustal and rift architecture across the VB basin with adjacent thick sedimentary area of the K–G basin suggests that VB basin segment of the margin acts transfer zone between K–G and Mahanadi rift zones.
- Image enhanced maps of gravity and magnetic data clearly delineate the offshore extension of Pudimadaka Lineament (PKL) and Vizianagaram Lineament (VZL). Further PKL forms the southeastern limit of the VB basin.

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References

Amante C and Eakins B W 2008 ETOPO1 1 Arc-Minute Global Relief Model: Procedures, data sources and analysis; National Geophysical Data Center, NESDIS, NOAA, U.S. Department of Commerce, Boulder, CO.

Bastia R 2006 An overview of Indian sedimentary basins with special focus on emerging east coast deepwater frontiers; *The Leading Edge* **25** 818–829.

Bastia R, Radhakrishna M, Srinivas T, Nayak Satyabrata, Nathaniel D M and Biswal T K 2010 Structural and tectonic interpretation of geophysical data along the eastern continental margin of India with special reference to the deep water petroliferous basins; *J. Asian Earth Sci.* **39** 608–619.

Biswas S K 1993 Major neotectonic events during the Quaternary in Krishna–Godavari Basin; *Cur. Sci.* **64** 797–803.

Blakely R J 1995 *Potential Theory in Gravity and Magnetic Applications*; Cambridge University Press, 437p.

Chand S, Radhakrishna M and Subrahmanyam C 2001 India–East Antarctica margins: Rift-shear tectonic setting inferred from gravity and bathymetry data; *Earth Planet. Sci. Lett.* **185** 225–236.

Choudhuri M, Nemcok M, Melichar R and Sinha N 2017 Propagation of hotspot volcanism driven flexure in oceanic crust-85° E Ridge case study; *Mar. Pet. Geol.* **82** 134–153.

Fuloria R C, Pandey R N, Bharali B R and Mishra J K 1992 Stratigraphy, structure and tectonics of Mahanadi Offshore Basin; *Geol. Soc. India Spec. Publ.* **29** 255–265.

Gibbons A D, Whittaker J M and Müller R D 2013 The breakup of East Gondwana: Assimilating constraints from Cretaceous ocean basins around India into a best-fit tectonic model; *J. Geophys. Res. Solid Earth* **118** 808–822, https://doi.org/10.1002/jgrb.50079.

Jarvis A, Reuter H I, Nelson A and Guevara E 2008 Hole-filled SRTM for the Globe Version 4, CGIAR-CSI SRTM 90 m Database; http://srtm.csi.cgiar.org.

Kaila K L, Murthy P R K, Rao V K and Venkateswarlu N 1990 Deep seismic sounding in the Godavari graben and Godavari (coastal) basin, India; *Tectonophys.* **173** 307–317.

Krishna K S, Laju Michael Bhattacharyya R and Majumdar T J 2009 Geoid and gravity anomaly data of conjugate regions of Bay of Bengal and Enderby Basin – new constraints on breakup and early spreading history between India and Antarctica; *J. Geophys. Res.* **114** B03102, https://doi.org/10.1029/2008jb005808.

Lal N K, Siawal A and Kaul AK 2009 Evolution of the east coast of India – a plate tectonic reconstruction; *J. Geol. Soc. India* **73** 249–260.

Meyers J B, Rosendahl B R, Groschel-Becker H, Austin J and Rona P A 1996 Deep penetrating MCS imaging of the rift-to-drift transition, offshore Douala and North Gabon basins, West Africa; *Mar. Pet. Geol.* **13** 791–835.

Murthy K S R, Rao T C S, Subrahmanyam A S, Malleswararao M M and Lakshminarayana S 1993 Structural lineaments from magnetic anomalies of eastern continental margin of India (ECMI) and northwest Bengal Fan; *Mar. Geol.* **114** 171–183.

Murthy K S R, Subrahmanyam V, Subrahmanyam A S, Murty G P S and Sarma K V L N S 2010 Land-ocean tectonics (LOTs) and the associated seismic hazard over the Eastern Continental Margin of India (ECMI); *Nat. Hazards* **55(2)** 167–175.

Nemcok M, Sinha S T, Stuart C J, Welker C, Choudhuri M, Sharma S P, Misra A A, Sinha N and Venkatraman S 2012 East Indian margin evolution and crustal architecture: Integration of deep reflection seismic interpretation and gravity modelling; *Geol. Soc. London, Spec. Publ.* **369** 477–496, https://doi.org/10.1144/sp369.6

Pavlis N K, Holmes S A, Kenyon S C and Factor J K 2012 The development and evaluation of the Earth Gravitational Model 2008 (EGM2008); *J. Geophys. Res.* **117(B04406)**, https://doi.org/10.1029/2011jb008916.

Posamentier H W, Jervey M T and Vail P R 1988 Eustatic controls on clastic deposition I – Conceptual framework; In: Sea level changes: An integrated approach: Tulsa (eds)

Wilgus C K, Hastings B S, Kendall C G St C, Posamentier H W, Ross C A and Van Wagoner J C, *Soc. Econ. Paleontol. Mineral. Spec. Publ.* **42** 109–124.

Powell C M, Roots S R and Veevers J J 1988 Pre-breakup continental extension in East Gondwanaland and the early opening of the eastern Indian Ocean; *Tectonophys.* **155** 261–283.

Prabhakar K N and Zutshi P L 1993 Evolution of southern part of Indian east coast basins; *J. Geol. Soc. India* **41** 215–230.

Radhakrishna B P 1989 Suspect tectono-stratigraphic terrane elements in the Indian subcontinent; *J. Geol. Soc. India* **34 (1)** 1–24.

Radhakrishna M, Twinkle D, Nayak S, Bastia R and Rao G S 2012a Crustal structure and rift architecture across the Krishna–Godavari basin in the central Eastern Continental Margin of India based on analysis of gravity and seismic data; *Mar. Pet. Geol.* **37** 129–146.

Radhakrishna M, Srinivasa Rao G, Nayak S, Bastia R and Twinkle D 2012b Early Cretaceous fracture zones in the Bay of Bengal and their tectonic implications: Constraints from multi-channel seismic reflection and potential field data; *Tectonophys.* **522** 187–197.

Rajaram M, Anand S P and Balakrishna T S 2006 Composite magnetic anomaly map of India and its contiguous regions; *J. Geol. Soc. India* **685** 569–576.

Ramakrishnan M, Nanda J K and Augustine P F 1998 Geological evolution of the Proterozoic Eastern Ghats Mobile Belt; *Geol. Surv. India. Spec. Publ.* **44** 1–21.

Rangaraju M K, Aggarwal A and Prabhakar K N 1993 Tectono-stratigraphy, structural styles, evolutionary model and hydrocarbon prospects of Cauvery and Palar Basins, India; In: Proceedings of the second seminar on petroliferous basins of India (eds) Biswas S K, Alak D, Garg P, Pandey J, Maithani A and Thomas N J, *Indian Pet. Publ.,* Dehradun, pp. 331–354.

Rao G N 2001 Sedimentation, stratigraphy and petroleum potential of Krishna–Godavari basin, east coast of India; *Am. Assoc. Pet. Geol. Bull.* **85(9)** 1623–1643.

Roy S, Choudhuri M and Gupta P 2015 Rift Grabens and Crustal Architecture of the offshore North East Coast-Mahanadi Basin, Eastern Continental Margin of India, In: *Petroleum Geosciences: Indian Context* (ed.) Mukherjee S, Springer International Publishing, Switzerland, **294** 145p.

Sandwell D T, Müller R D, Smith W H F, Garcia E and Francis R 2014 New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure; *Science* **346** 65–67, https://doi.org/10.1126/science.1258213.

Sastri V V, Sinha R N, Singh G and Murti K V S 1973 Stratigraphy and Tectonics of sedimentary basins on east coast of Peninsular India; *Am. Assoc. Pet. Geol. Bull.* **57** 655–678.

Sastri V V, Venkatachala B S and Narayanan V 1981 The evolution of the east coast of India; *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **36** 23–54.

Sinha S T, Nemcok M, Choudhuri M, Misra A A, Sharma S P, Sinha N and Venkatraman S 2010 The crustal architecture and continental break up of East India Passive Margin: An integrated study of deep reflection seismic interpretation and gravity modelling; *Am. Assoc. Pet. Geol.* Annual Convention and Exhibition, New Orleans, Louisiana, USA, April 11–14, 2010.

Sinha S T, Nemcok M, Choudhuri M, Sinha N and Rao P D 2015 The role of break-up localization in microcontinent separation along a strike-slip margin: The East India–Elan Bank case study. Transform Margins: Development, Controls and Petroleum Systems; *Geol. Soc. London, Spec. Publ.* **431**, http://doi.org/10.1144/SP431.5.

Subrahmanyam A S, Murty G P S, Sarma K V L N S, Mohana Rao K, Reddy N P C, Malleswara Rao M M, Subrahmanyam V, Suneetha Rani P, Anuradha A and Murthy K S R 2007 Qualitative assessment of tectonic lineaments over the coastal and inner shelf of Kakinada and Kalingapatnam, central east coast of India; *J. Geol. Soc. India* **69** 1328–1334.

Subrahmanyam C, Thakur N K, Gangadhara Rao T, Ramana M V and Subrahmanyam V 1999 Tectonics of the Bay of Bengal, northeastern Indian Ocean: New insights from satellite-derived gravity and mshipborne geophysical data; *Earth Planet. Sci. Lett.* **171** 237-251.

Talwani M and Heirtzler J R 1964 Computations of magnetic anomalies caused by two-dimensional bodies of arbitary shape; In: Computers in the mineral industry. Part I (ed.) Parks G A, *Stanford Univ. Publ. Geol. Sci.* **9** 464–480.

Talwani M, Worzel J L and Landisman M 1959 Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone; *J. Geophys. Res.* **64** 49–59.

Twinkle D, Srinivasa Rao G, Radhakrishna M and Murthy K S R 2016 Crustal structure and rift tectonics across the Cauvery–Palar basin, Eastern Continental Margin of India based on seismic and potential field modelling; *J. Earth Syst. Sci.* **125** 329–342, https://doi.org/10.1007/s12040-016-0669-y.

Veevers J J 2009 Palinspastic (pre-rift and pre-drift) fit of India and conjugate Antarctica and geological connections across the suture; *Gondwana Res.* **16** 90–108.

Wilson P G, Jonathan P, Turner Graham K and Westbrook 2003 Structural architecture of the ocean–continent boundary at an oblique transform margin through deep-imaging seismic interpretation and gravity modelling: Equatorial Guinea, West Africa; *Tectonophys.* **374(1–2)** 19–40.

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