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Structural and tectonic interpretation of geophysical data along the Eastern Continental Margin of India with special reference to the deep water petroliferous basins

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ABSTRACT

The study area encompasses the Eastern Continental Margin of India (ECMI) and the adjoining deep water areas of Bay of Bengal. The region has evolved through multiple phases of tectonic activity and fed by abundant supply of sediments brought by prominent river systems of the Indian shield. Detailed analysis of total field magnetic and satellite-derived gravity data along with multi channel seismic reflection sections is carried out to decipher major tectonic features, basement structure, and the results have been interpreted in terms of basin configuration and play types for different deep water basins along the ECMI. Interpretation of various image enhanced gravity and magnetic anomaly maps suggest that in general, the ENE–WSW trending faults dominate the structural configuration at the margin. These maps also exhibit a clear density transition from the region of attenuated continental crust/proto oceanic crust to oceanic crust based on which the Continent Ocean Boundary (COB) has been demarcated along the margin. Basement depths estimated from magnetic data indicate that the values range from 1 to 12 km below sea level and deepen towards the Bengal Fan in the north and reveal horst–graben features related to rifting. A comparison of basement depths derived from seismic data indicates that in general, the basement trends and depths are comparable in Cauvery and Krishna–Godavari basins, whereas, in the Mahanadi basin, basement structure over the 85°E ridge is clearly revealed in seismic data. Further, eight multichannel seismic sections across different basins of the margin presented here reveal fault pattern, rift geometries and depositional trends related to canyon fills and channel–levee systems and provide a basic framework for future petroleum in this under explored frontier.

1. Introduction

The Eastern Continental Margin of India (ECMI) is a divergent type of margin that evolved as a consequence of break-up of eastern Gondwanaland between India and east Antarctica during early Cretaceous (Powell et al., 1988). It is observed that the Precambrian structural trends viz., the Godavari and Mahanadi rifts, shear zones and granulite terrains at the east coast of India have close linkages with similar features along the east Antarctica (Fedorov et al., 1982; Yoshida et al., 1999). Reconstruction models considering the pre-rift and drift extensions (Reeves et al., 2004; Veevers, 2009) provided further constraints on rifting scenario between India and Antarctica. Ship-borne as well as the satellite-derived gravity and magnetic investigations along the eastern Indian offshore (Bay of Bengal) and the conjugate Enderby basin, east Antarctica were very useful in understanding the margin evolution and have provided valuable information on structural fabric as well as nature of the crust (Chand et al., 2001; Ramana et al., 2001; Rotstein et al., 2001; Golynsky et al., 2002; Krishna et al., 2009). Based on the requirement of accommodating the Elan Bank microcontinent lying on the western margin of Kerguelen Plateau (Ingle et al., 2002; Borissova et al., 2003; Gaina et al., 2003, 2007), Krishna et al. (2009) proposed a two stage rifting history for the ECMI, first, an Australia–Antarctica separation with greater India during early Cretaceous, second, the separation of Elan Bank from the present day ECMI at about 120 Ma. Though the position of Elan Bank as well as the timing of breakup is still debated, the rifting and drifting history of these two continents has left its imprints both at the coast as well as the surrounding deep ocean floor in terms of structural features and formation of sedimentary basins along the present day ECMI. The Precambrian structural grain of the Indian shield (Fig. 1) controlled to a larger extent the continental fragmentation and the subsequent tectonic reactivations that led to the present day basement trends as well as margin segmentation.

The ECMI is characterized by the presence of five major sedimentary basins in the onshore areas and detailed geophysical studies over these basins reveal that the basins extend offshore and

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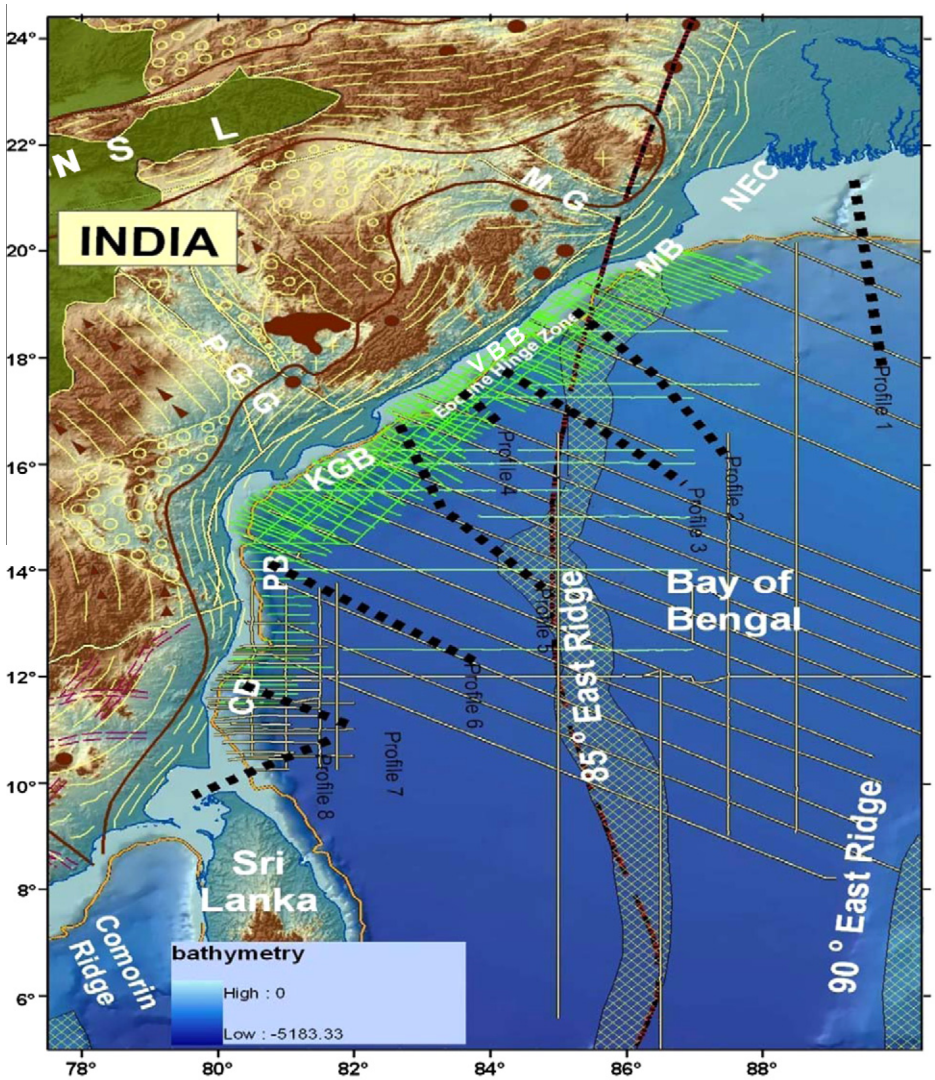

Fig. 1. Tectonic sketch map of east coast of India and the adjoining areas. Precambrian basement tectonic fabric of the Indian shield is adopted from Naqvi and Rogers (1987). Location of ship-borne gravity and magnetic data (thin lines) and regional seismic reflection lines (bold dashed lines, profiles 1–8) utilized in the present study are shown. NSL – Narmada-Son Lineament; MG – Mahanadi Graben; PGG – Pranahita-Godavari Graben; CB – Cauvery Basin; PB – Palar Basin; KGB – Krishna–Godavari Basin; VBB – Visakhapatnam Bay Basin; MB – Mahanadi Basin; NEC – North East Coast Basin.

merge with the deep-sea Bengal Fan. The underlying basement in the basins is typically dominated by alternating set of NE–SW trending ridges and depressions (Sastri et al., 1981; Prabhakar and Zutshi, 1993; Fuloria, 1993; Bastia, 2006). Marine magnetic studies in the nearshore regions of the margin revealed offshore extension of structural trends and dyke intrusions related to rift-phase volcanism (Murthy et al., 1993; Subrahmanyam et al., 1995, 2006). In this paper, we present a detailed analysis of gravity, magnetic as well as seismic data in order to discuss the structural fabric, basement trends and rift tectonics that gave rise to the present day basin configuration along the ECMI. High resolution regional seismic sections are further used to identify various geological features and play types within the sedimentary strata so as to understand the depositional history and petroleum systems in the deep water sedimentary basins along the ECMI.

2. Regional tectonic setting and evolution

Major geological and tectonic features underlying the ECMI and the adjoining Bay of Bengal are inherited from the breakup of eastern Gondwanaland during early Cretaceous and subsequent spreading of the Indian Ocean floor. The ECMI has a strike-length of about 2000 km extending from the Sri Lanka shelf on the far south to the Bengal basin on the north and consists of five major river based sedimentary basins: the Bengal, Mahanadi, Krishna–Godavari, Palar and Cauvery, of which, the later four basins are believed to have originated as pull-apart basins during the breakup of Gondwanaland (Talukdar, 1982). Geophysical investigations along the ECMI suggest that the margin can be considered as a composite of two segments, the northern part (north of 16°N) having rifted margin character, and the southern part developed as a consequence of shearing in the early stages of continental separation (Subrahmanyam et al., 1999; Chand et al., 2001). We therefore believe that the basins in the southern part of the ECMI might have evolved into the rift basins from the initial pull-apart basins. The basement rocks along the east coast of India belong to the Eastern Ghats Mobile Belt in the northern part and the Southern Granulite Terrain in the south. The NE–SW trending ridge-depression basement configuration underlying the ECMI basins typically demonstrates that they developed over a highly faulted and rifted continental crust probably during late Cretaceous time. These basins consist of Mesozoic sediments in their deeper parts. The thickness of sediments in these basins varies from 3 to 5 km in the onshore depressions to more than 10 km in the offshore (Sastri et al., 1973). The sediments attain a maximum thickness of 22 km at the apex of the Bengal Fan in the offshore Bengal basin (Curray, 1991). The oldest sediments in the Bay of Bengal were deposited on the seafloor probably from early Cretaceous to middle Paleocene (Curray et al., 1982).

The lithosphere in the eastern Indian Ocean experienced three major phases of seafloor spreading; NW–SE spreading until mid-Cretaceous, N–S until early Tertiary and continuing in NE–SW direction. Different views persist on the timing of breakup and rifting between India and east Antarctica and based on magnetic anomaly identifications it ranges between 132 Ma (Ramana et al., 1994; Desa et al., 2006) and ~120 Ma (Gopala Rao et al., 1997). Observation of M2 to M9 anomalies and identification of fossil ridge in the Enderby basin of east Antarctica (Gaina et al., 2003) suggests younger magnetic lineations of M1 and M0 in the Bay of Bengal.

The Bay of Bengal lithosphere during its evolution encountered two major hotspots, Kerguelen and the Crozet and gave rise to the emplacement of linear N–S trending aseismic ridges, the Ninety east and the 85°E ridges respectively which separate the present day Bengal Fan into three major sub-basins (Curray et al., 1982; Curray and Munasinghe, 1991). Analysis of geophysical data at the margin indicates that 85°E ridge meets the ECMI at Mahanadi basin and continues northward up to Rajmahal traps (Curray and Munasinghe, 1991; Subrahmanyam et al., 1999; Krishna, 2003; Subrahmanyam et al., 2008). In the Mahanadi offshore, the 85°E ridge was aerially exposed during early Paleogene period and acted as local provenance for sediments (Dangwal et al., 2008). Initial collision of India with Asia occurred in Eocene times, at approximately 55 Ma which had a significant effect on the clastic input to the basins along ECMI particularly the Krishna–Godavari, Mahanadi and Bengal basins.

3. Data and analysis

Different geophysical data sets pertaining to the eastern Indian offshore and the deeper parts of the Bay of Bengal are utilized in the present study in order to delineate the structural and tectonic features, basin configuration and to understand the hydrocarbon potential in different basins of the ECMI. These include the satellite-derived gravity data (Andersen and Knudsen, 1997), shipborne gravity and magnetic data, basement information compiled from 2D as well as 3D seismic reflection data. Fig. 1 shows the location of gravity and magnetic profiles and regional seismic lines utilized in the present study. Satellite-derived gravity field KMS-02, an update of its earlier version KMS-01 (Andersen and Knudsen, 1997) is known to have a higher resolution than the contemporary global gravity datasets and provides dense (1 min grid) and uniform coverage in the offshore areas. Apart from the satellite-derived gravity, nearly 33,000 line km of gravity and 18,000 line km of magnetic data available from the National Institute of Oceanography (NIO) marine trackline data base along with the National Geophysical Data Center (NGDC) trackline data are utilized for the present study. The line spacing for gravity trackline data was too large and the profiles extend far into the Bay of Bengal, whereas, the magnetic data have a different spatial coverage to gravity, line spacing is more regular and dense, and does not extend into the Bay of Bengal (Fig. 1). The gridded magnetic data is used for the purpose of qualitative analysis as well as to derive basement structure. A number of 2D seismic lines and 3D grids acquired for exploration purpose have been used to understand the basement structure and give an indication of the type of tectonic and sedimentary features at depth.

3.1. Data enhancement techniques

The objective of gravity and magnetic interpretation was to delineate structural and tectonic features in the offshore by improving desired anomaly features. The data were interpreted through qualitative analysis by applying various image enhancement methods such as filters, derivatives, gradients, Reduction-to-Pole (RTP) and prepare maps for each one of them. For this purpose, the satellite-derived gravity data set is used instead of trackline gravity data due to its dense and uniform coverage. The dense magnetic trackline data in the offshore is also used for this analysis.

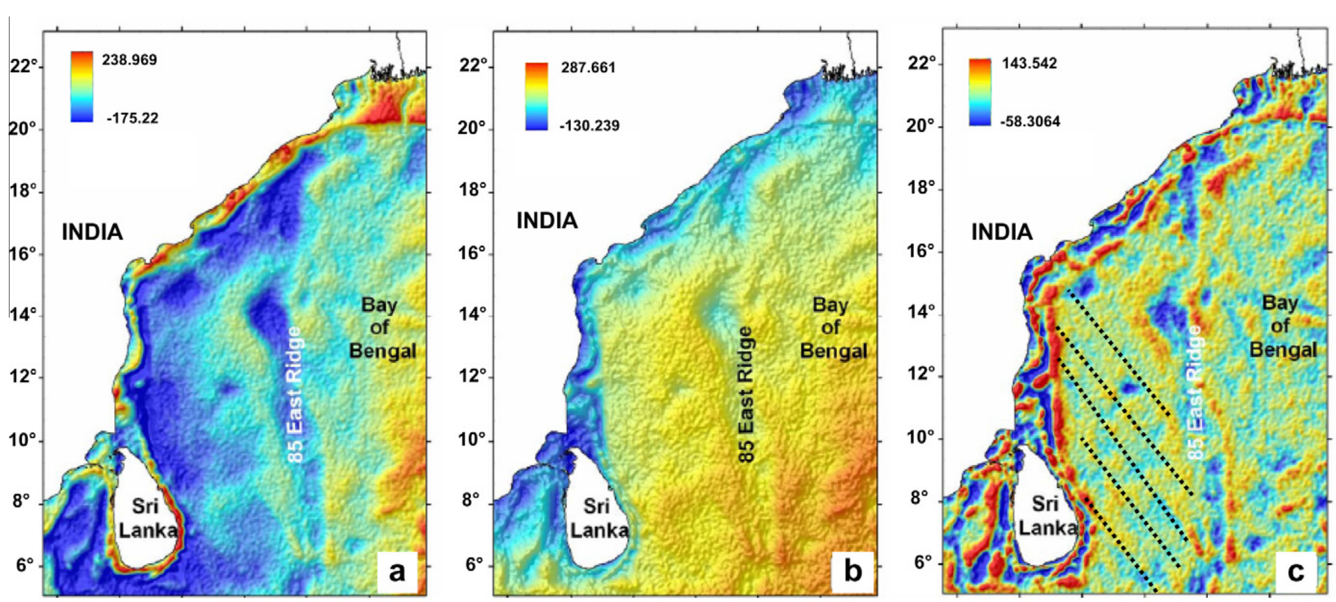

Fig. 2. Shaded relief maps showing (a) free-air gravity anomalies, (b) Bouguer gravity anomalies, (c) Band-pass filtered (10–200 km) Bouguer gravity anomalies along the ECMI and the adjoining Bay of Bengal region. High-resolution satellite-derived gravity data, KMS-02 (Andersen and Knudsen, 1997) has been used for this purpose. The NW–SE trending dashed lines shown in Panel C are fractures zones from Krishna et al. (2009).

3.1.1. Gravity anomaly maps

Free-air anomaly map prepared from the KMS-02 satellite gravity data is presented in Fig. 2a and as characteristic of all free-air gravity maps, it shows a strong correlation with bathymetry having a prominent shelf edge effect. Other prominent anomaly seen on the map is the N–S trending gravity low in the Bay of Bengal due to 85°E ridge which merges with the gravity low at the margin. As much of the sharp free-air gravity anomaly at the shelf edge can be explained directly in terms of changing water depth, the Bouguer anomaly is computed by replacing the water column with a density equal to the average density of the sediments at the seafloor. For Bouguer reduction, a value of 2.67 gm/cc, the average density of crustal rocks is generally used. This value is higher for the water bottom sediments where density contrast with the water column directly exists. As the present interest is to study variations in gravity anomalies due to localized structural trends, faults and sedimentary structures, a realistic density value of 2.0 gm/cc for the water bottom sediments is considered for calculation of Bouguer gravity anomaly. A 3-D Bouguer correction was calculated taking into consideration the terrain correction and then applied directly to the free-air anomaly. The resultant complete Bouguer anomaly map is shown in Fig. 2b. As the Bouguer anomaly map often contains features that are barely visible due to their low amplitude or low frequency, or high amplitude anomalies with a dominant strike direction, different data enhancement methods are used. As a first step, the band-pass filter (10–200 km wavelength) is applied to the Bouguer anomaly map and the resultant map (Fig. 2c) defines anomalies better than free-air and Bouguer anomaly maps. Krishna et al. (2009) identified several NW–SE trending fracture zones in the Bay of Bengal region west of 85°E

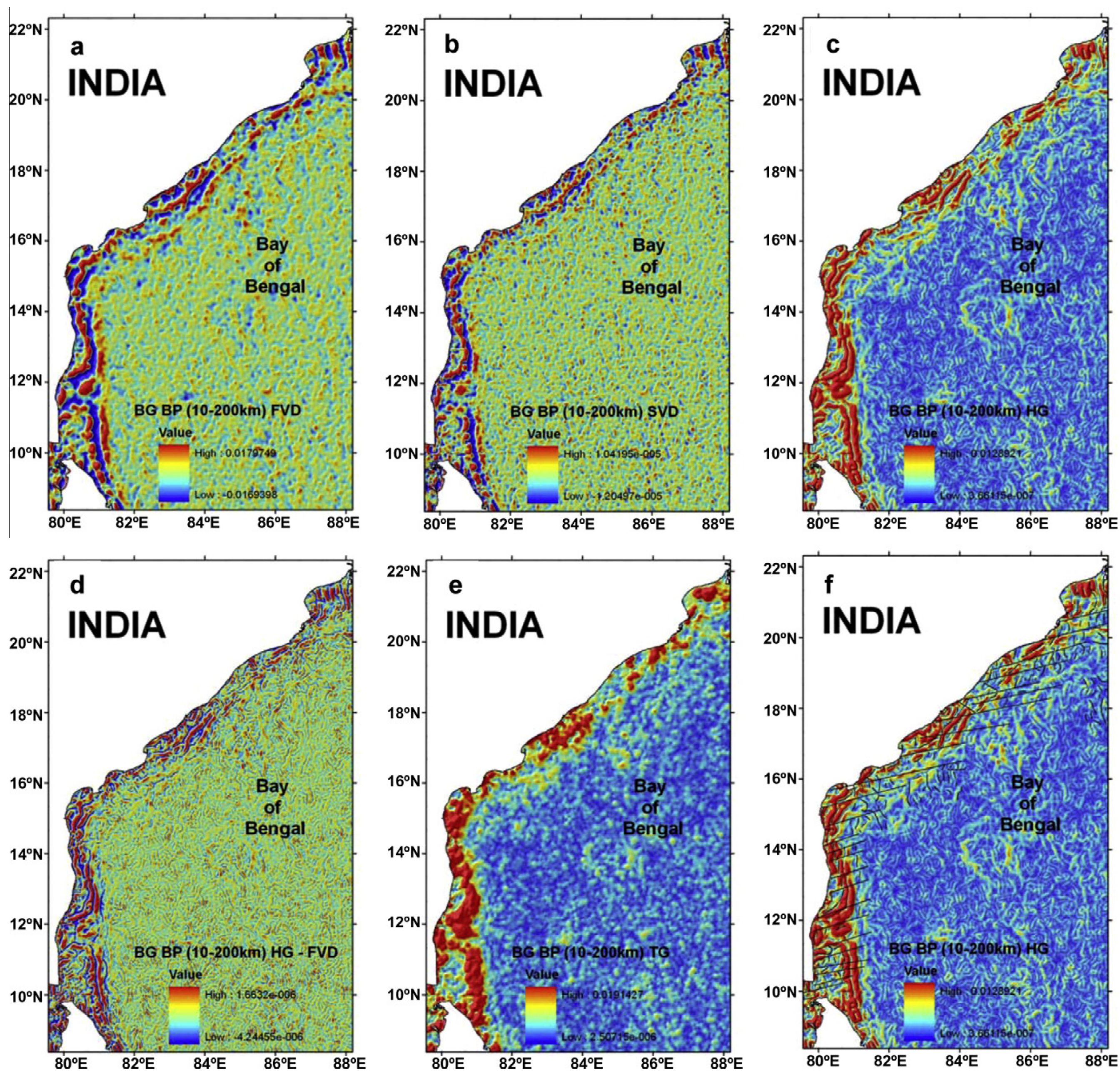

Fig. 3. Image enhanced maps prepared from the band-pass filtered Bouguer anomaly map (Fig. 2c) (a) first vertical derivative (FVD), (b) second vertical derivative (SVD), (c) horizontal gradient (HG), (d) horizontal gradient of first vertical derivative, (e) total gradient (TG), (f) the lineaments, trends and faults identified from the gravity and magnetic data analysis in the offshore region are superimposed on (c).

ridge (Fig. 2c). Though not all, some of these trends could be recognized in the band-pass filtered Bouguer anomaly map. The band-pass filtered data is subjected to further filtering using first vertical derivative (FVD), second vertical derivative (SVD), horizontal gradient (HG), FVD of HG and total gradient amplitude in order to resolve various features such as basement highs, faults, edges of geological features and the resultant maps are shown in Fig. 3a–e. Using these enhanced maps, several lineaments, faults, gravity trends identified along the margin (Fig. 3f) suggests that in general, the ENE–WSW trending faults dominate the structural configuration.

3.1.2. Magnetic anomaly maps

The magnetic trackline data obtained from NIO (Fig. 1) is gridded to produce the total magnetic intensity (TMI) map along the margin (Fig. 4a). The map shows considerable range of anomaly wavelengths and amplitude variations reflecting numerous magnetic sources at different depths. In many instances, it represents

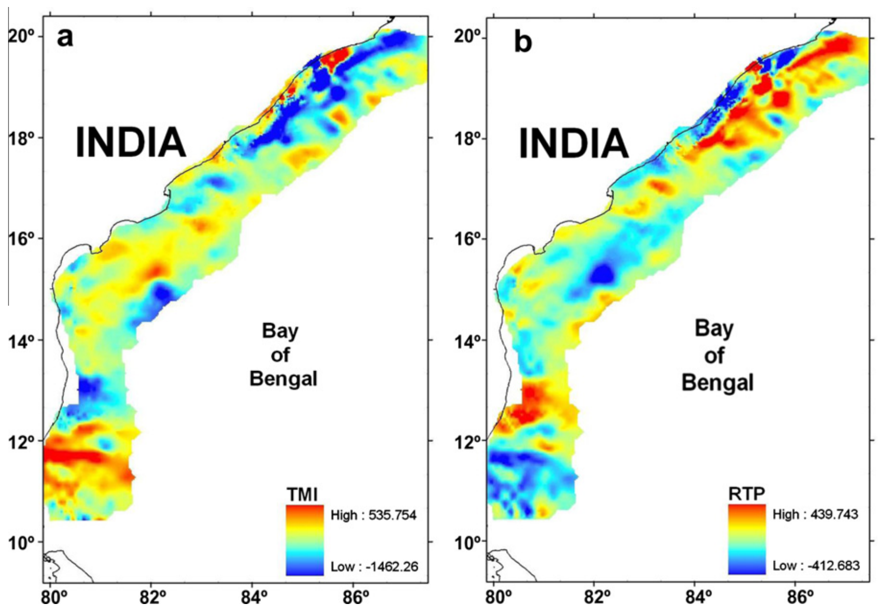

Fig. 4. Color coded images showing (a) total magnetic intensity (TMI) anomalies (b) Reduction-to-Pole (RTP) map of (a) along the ECMI. The NIO magnetic data is used for this purpose.

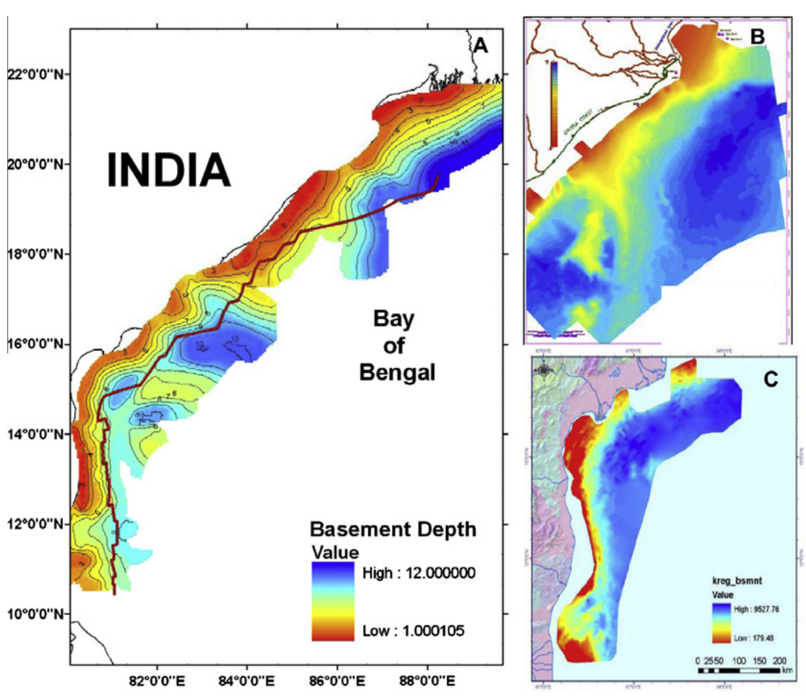

Fig. 5. Map showing (a) depth to magnetic basement obtained from magnetic data (Fig. 4a) for the ECMI. Inferred COB is shown as red line on the map. Depth to basement obtained from offshore seismic data is presented for, (b) Mahanadi and NEC basins, (c) Cauvery and Krishna–Godavari basins along the margin.

a composite signal or sum of the anomalous magnetization of these sources. In order to assist further analysis, the magnetic anomaly data were transformed using the Reduced-to-Pole (RTP) operator. The RTP software developed by Fugro Robertson Inc. (FRI) is used for this purpose. The magnetic field inclination and declination at the survey area are necessary input parameters for the RTP procedure along with the date of measurement. The software enables differential RTP calculations, which is useful for large survey areas that will have significantly variable magnetic parameters. The RTP map derived from the magnetic data is shown in Fig. 4b. Comparison of TMI anomaly and RTP maps show that the anomalies are migrated in a certain direction. High-low pairs of anomalies tend to exhibit dominant positive anomaly features. In RTP broader anomalies move further than the narrow anomalies. The majority of positive anomaly zones are usually related to basement/structural highs and/or volcanic zones.

Magnetic anomalies TMI and RTP of TMI prepared from NIO ship track data have shown the linear magnetic trends following the boundary of continental/proto oceanic to oceanic crust matching with the gravity enhancements viz., Bouguer gravity band pass (10–200 km) and its vertical and horizontal derivative maps (Fig. 3). The Continent Ocean Boundary (COB) identified from the potential field enhancements has been compared with the seismic data. Filter maps derived from gravity data exhibit a clear density transition from the region of attenuated continental crust and is indicated by the linear Bouguer gravity high trend (Bandpass 10–200 km) in the offshore. Total magnetic intensity and Reduction-to-Pole maps (Fig. 4) prepared from ship track magnetic data indicate the intensity of crustal attenuation to be maximum with gradually fading magnetic anomalies in Mahanadi, Northeast Coast (NEC) and northern part of Krishna–Godavari basin suggesting that the extension to be more orthogonal. The southern part of Krishna–Godavari, Palar and Cauvery basins show abruptly ending magnetic anomalies in both maps indicating minimal crustal attenuation and abrupt transition between continental and oceanic crust characterising oblique transform movement.

3.1.3. Basement depth estimation

NIO magnetic data is further utilized to estimate the basement depth and sediment thickness in order to interpret structures in specific regions which could be useful in hydrocarbon exploration. In the areas where the NIO magnetic data are absent, the NGDC tracklines are used. Magnetic anomalies can be produced by a number of causative features and different methods are in use to estimate depth from the magnetic data which are mostly manual in nature. MAGPROBE, the 2-D magnetic depth estimation software developed by FRI is used in the present study for estimation of magnetic depth. It is versatile and utilizes several automatic algorithms, including the Werner and Euler deconvolution methods along with a variety of empirical approaches. In this study, the depth estimation is carried out using the total magnetic field data (Fig. 4a) primarily by means of Werner deconvolution, Euler deconvolution and Peters half slope methods. Basement depths estimated from the above analysis and the COB identified along the margin are shown in Fig. 5a. In general, basement depths estimated from magnetic data is ascribed uncertainties of 10–15% in the case of ideally shaped magnetic source bodies. As such conditions are of exception, in the present study, a realistic range of 10–30% is suggested for uncertainties in estimated depths. The basement depth ranges from 1 to 12 km below sea level and deepens towards the Bengal Fan in the north of the region. In the southern part of Cauvery basin close to Point Calimere, two E–W trending basement lows are observed which are truncated at the COB, whereas, the basin to the north is characterized by a more N–S depositional axis. The COB is much closer to the onshore area at this location. NE–SW strike-slip faults are the predominant structures in the basin and continue across the COB. In the northernmost portion of the basin there is a WNW–ESE trending

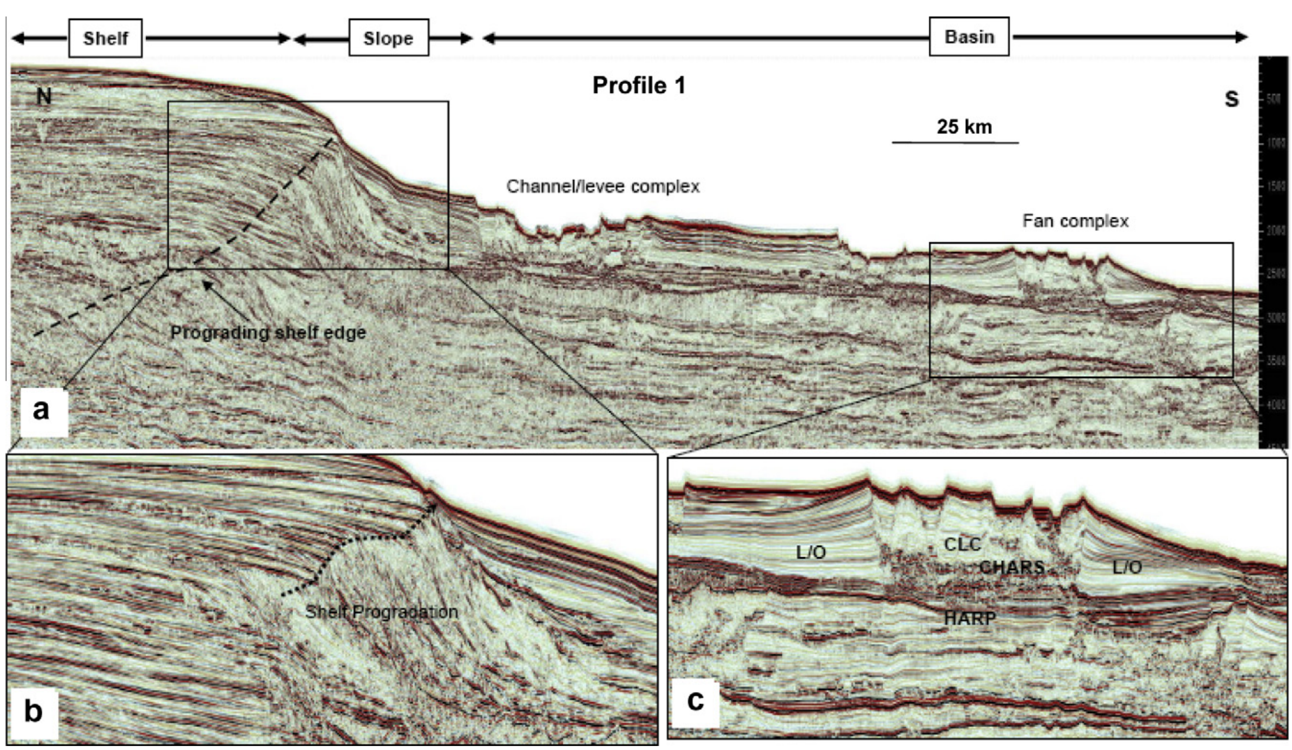

Fig. 6. (a) Seismic section representing shelf-slope system and depositional elements of Ganga–Brahmaputra (Bengal) basin. (b) Prograding shelf edge in younger Tertiary time, (c) morphology of present day channel–levee complex. L/O – Levee/Overbank, CLC – channel–levee complex, CHARS – Chaotic high amplitude reflectors, HARP – high amplitude reflection package.

basement high. In general, the NE–SW strike-slip faults are predominant structures in the Krishna–Godavari basin and continue into deeper oceanic areas. The COB follows these faults in some areas and is close to the coastline in the Machilipatnam bay area and the main basement low areas actually fall on oceanic crust. These are oriented E–W and form as series of basement highs and lows truncated against attenuated continental crust. This abrupt change in the basement trends from N–S in Cauvery basin to ENE–WSW in Krishna–Godavari basin marks the basin boundary. Further north, the deepest portion of magnetic basement is indicated by ENE–WSW trending basement low (>10 km). Such local depressions on oceanic crust may represent structures formed by subsidence due to sediment loading as clastic sediments are carried to the coast from the hinterland, bypass the shelf and are deposited as deep water fans on oceanic crust. In Mahanadi basin, the basement contours parallel the coastline probably reflecting the early syn-rift geometry of the basin prior to the breakup. Basement highs and lows in the northern part of the basin are NW–SE. The structures truncate against COB in the northernmost area indicating that these axes are perhaps controlled by pre-existing rift geometry. In the NEC basin, dominant structures are N–S trending features probably related to the Bengal Fan. The depth to basement increases towards the Bengal Fan throughout the basin. For comparison, the colour coded basement depth maps prepared from large volume of seismic data for the northern (Mahanadi and NEC basins) and southern (Cauvery and Krishna–Godavari basins) parts of ECMI are presented in Fig. 5b and c) respectively. It may be noted that both magnetic and seismic data have different spatial coverage and resolution in different parts of the ECMI. The general observations made from these maps are presence of some horst and graben features related to rifting. A comparison of basement depth derived from magnetic as well as seismic data indicates that basement trends and depths in general are comparable in Cauvery and Krishna–Godavari basins. In the Mahanadi basin, however, the basement structure over the 85°E ridge is more clearly revealed in seismic data. Besides these macro tectonic features, various small scale features which could well act as play types for hydrocarbon exploration are identified in respective basins from regional seismic profiles. A detailed description of these play types is presented in the next section.

4. Geological and tectonic features, and play types in the deep water basins along the ECMI

The exploration activities until recently were concentrated within the water depth of 100 m primarily due to technological considerations. Recent discoveries of giant sized oil and gas fields around the world in general and Krishna–Godavari basin in particular have shifted the focus towards the vast unexplored deep water sediments of Bay of Bengal. Sedimentary accumulations of Indian East Coast range in age from Mesozoic to Recent. These were deposited when continental rifting and subsequent drifting of India away from Antarctica ushered in the accumulation of marine sediments along the east coast. In the Oligocene period, a major shelf edge developed all along the coast which caused thick accumulation of sediments on the basin-ward side during the subsequent Neogene period. It also marks a facies change from carbonates on the platform side, to argillaceous rocks on the basinal side, which further suggests a break in the continental slope that occurred during the Eocene period.

Large volumes of seismic, gravity-magnetic, multi-beam surveys and seabed logs acquired recently along the eastern Indian

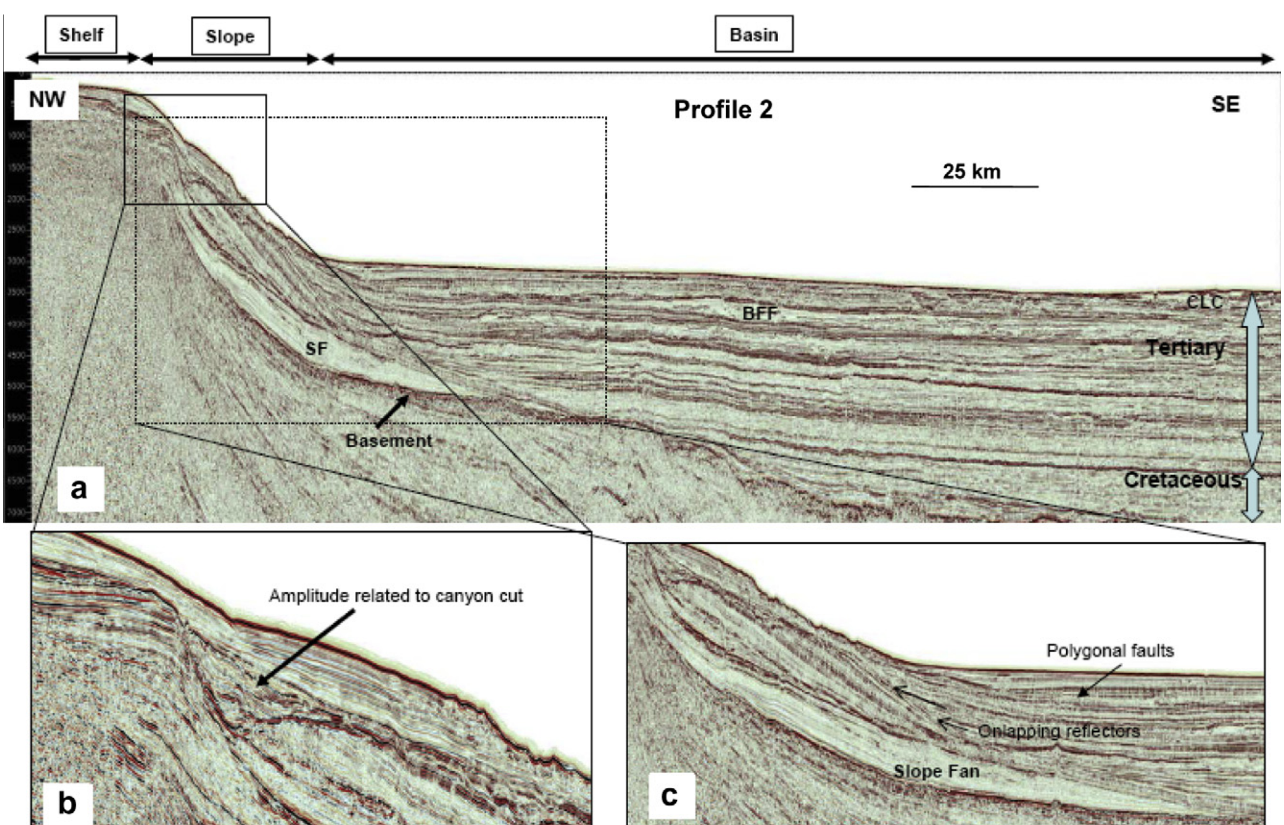

Fig. 7. (a) Regional seismic section through the Mahanadi basin. SF – slope fan; BFF – basin floor fan; CLC – channel–levee complex. (b) High-amplitude associated with canyon cut. (c) Transparent zone represents the slope fan. Also shown are the polygonal faults and onlapping reflectors.

offshore brought out considerable knowledge of the individual basin configuration. In the light of this new data set, the earlier classification of ECMI into five river based sedimentary basins (Sastri et al., 1973) has been revised on the basis of tectonic style, sedimentation and basin geometry from the shelf to deep water areas by Bastia (2006). From north to south, these are: (i) Ganga–Brahmaputra basin (Bengal offshore), (ii) Mahanadi basin, (iii) Visakhapatnam Bay Basin, (iv) Krishna–Godavari basin, (v) Palar–Pennar basin, (vi) Cauvery basin and (vii) Gulf of Mannar. The main depositional elements observed in the deep-sea basins of the east coast of India can be broadly subdivided into (i) Tertiary formations which include all types of depositional systems (clastic to carbonates and fluvial to deep water) consisting of delta-distributary channel complex, shelfal canyon cut-and-fill sequences and deep-water channel complex, (ii) Mesozoic rift related structural plays.

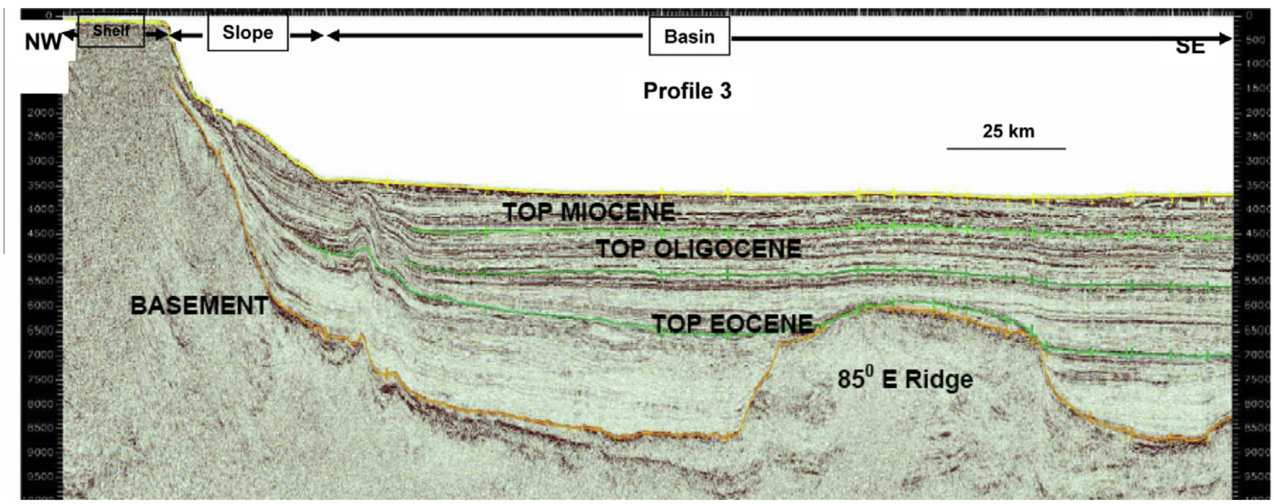

Fig. 8. The seismic section depicting the expression of 85°E ridge.

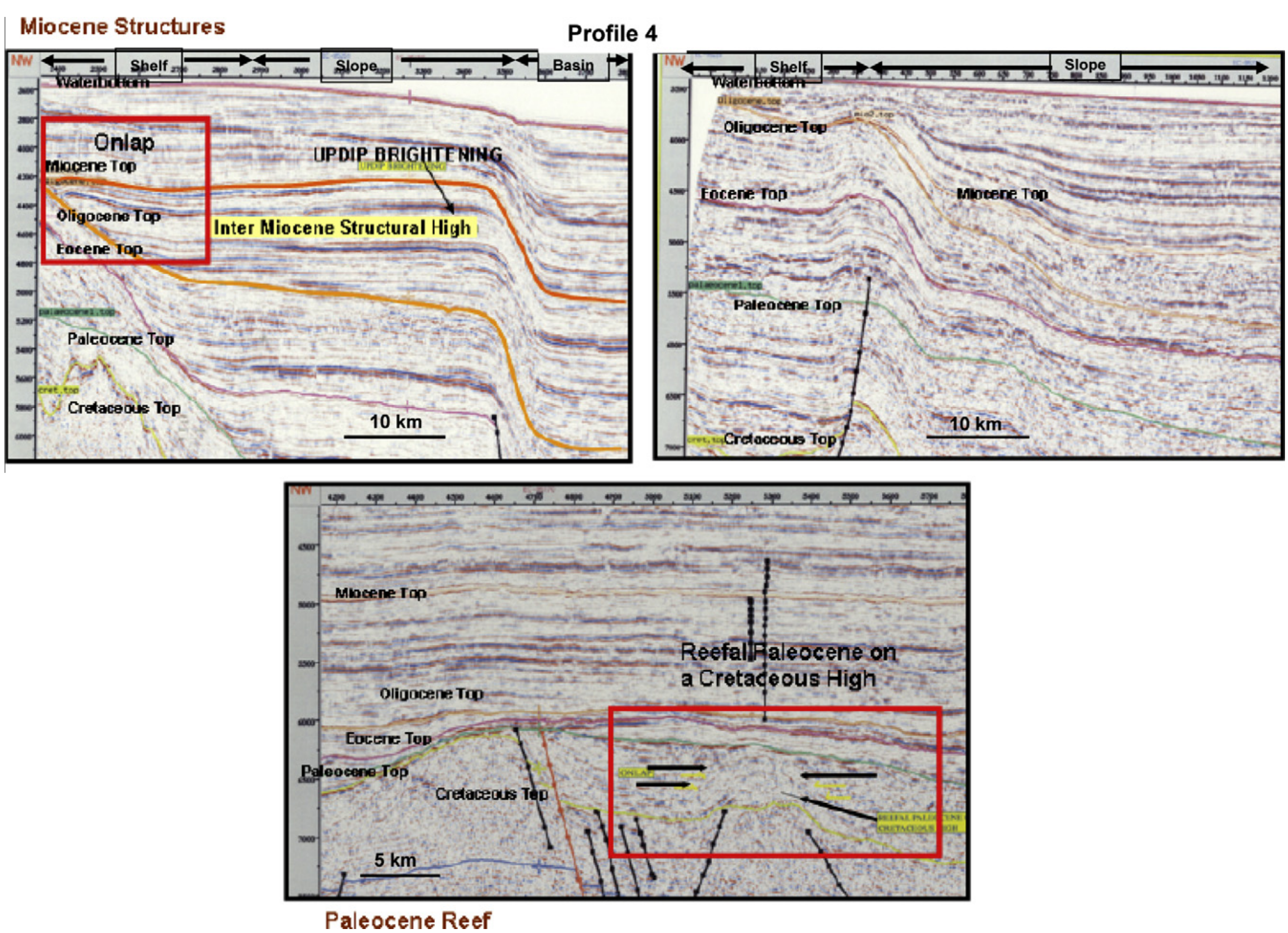

Fig. 9. Seismic section across Visakhapatnam Bay Basin showing structural traps associated with reactivated basement faults. High amplitudes in the Tertiary sequence suggests presence of channel–levee complex. In the post Oligocene strata there are few onlapping wedges against structural highs.

We present here eight regional seismic sections (profiles 1–8 in Fig. 1) to mark various depositional elements in the eastern offshore basins. Except profiles 4 and 8, all other sections are from newly acquired multichannel regional seismic lines (acquired by GX Technology for Reliance Industries) covering shelf to abyssal plains in the eastern offshore. Some salient observations made from these data in reference to petroleum systems in the deep water basins along the ECMI are presented basin-wise.

4.1. Ganga–Brahmaputra basin (Bengal offshore)

The basin is fed by two major river systems of Ganges and Brahmaputra, and extends in the east into Bangladesh and, in the south, into the deep waters of the Bay of Bengal (Curray and Moore, 1974). The depositional elements in the offshore part of the basin are typically represented by numerous repeated canyon cuts caused by mass-wasting, with intervening fills in the form of deep water to sub-aerial channels and progradational deltaic deposits. An example of the shelf-slope system with prograding shelf edge with time is shown in Fig. 6. The section also images the morphology of the present day channel–levee over bank system, which are prominent play types in deep water basins around the world.

4.2. Mahanadi basin

The evolution of Mahanadi basin started in the Jurassic period as a result of the break-up of Gondwanaland. The eastern boundary of the Mahanadi offshore basin with the Bengal basin is represented by a major fault (Fuloria, 1993), and in the southwestern part, the basin is limited by the 85°E ridge. The regional seismic section (Fig. 7) shows the shelf and slope fan extending to basin floor. The dominant depositional elements are separated by the channel–levee complex characterized by bright amplitude package. The transparent zone in the section documents a different acoustic envelope suggesting a slope fan. Possibility of this transparent zone being a mudflow cannot be ruled out. The younger sediments are cut by numerous vertical to subvertical polygonal fault systems associated with differential compaction and fluid expulsion. Onlapping reflectors suggest the presence of wedge out plays. High amplitude bodies within canyon cuts represents deep-water channel complex, a well proved play type around the world. Another prominent feature identified in the basin which needs to be discussed is the 85°E ridge.

4.2.1. 85°E ridge

The 85°E ridge is a N–S trending ridge passing through the Bay of Bengal which is believed to have been formed as a trace of Crozet hotspot (Curray and Munasinghe, 1991). North of 5°N, the ridge is completely buried structure below thick Bengal Fan sediments with a characteristic gravity low and complex magnetic signature (Krishna, 2003). High resolution seismic imaging of the offshore Mahandi basin revealed the presence of ridge at the margin abutting the Mahanadi coast south of Chilka Lake (Bastia et al., 2010). The ridge played a significant role through geologic times in confining and distributing the sediments from the coast to deep-sea. Part of the ridge was aerially exposed during Early Paleogene

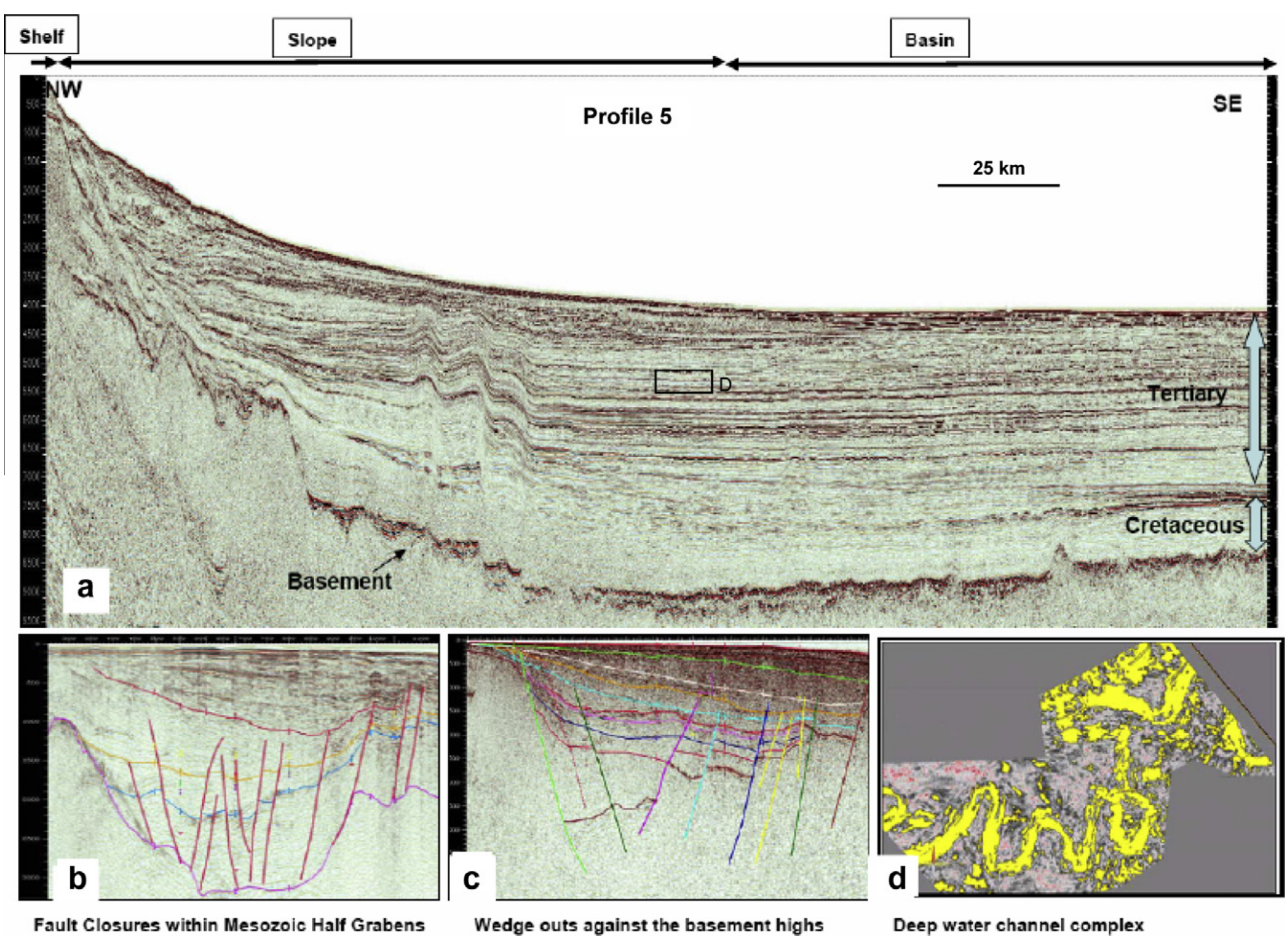

Fig. 10. (a) Seismic section through the Krishna–Godavari basin showing Mesozoic and Tertiary sedimentary sequences. (b) Interpreted fault geometry depicting the Mesozoic rift. (c) Time structure map at the top of basement also suggest horst–graben rift architecture. (d) Horizon slice extracted from a high amplitude reflection package of Tertiary sequence images the sinuous deep-water channel/levee complex.

period and acted as local provenance for sediment (Dangwal et al., 2008). The thin sedimentary cover over the ridge top (Fig. 8) gives a good picture of orientation of ridge within this area and provides the eastward limit of the sediment distribution.

4.3. Visakhapatnam Bay Basin

The Visakhapatnam Bay is a narrow basin located between Mahanadi on the north and Krishna–Godavari on the south. The basin probably represents a failed arm which is confined to the western limit of the offshore continuation. The basin is a major intracratonic rift and is marked by exposed late Cretaceous rocks. The basin is fed by relatively weak river systems.

The composite rifted grabens are filled with post-rift sediments which in turn are overlain by a thick Tertiary sequence. Seismic section (Fig. 9) represents structural highs associated with reactivation of basement. Possible carbonate build ups on these highs may be good play types to be tested. Few onlapping wedges against structural highs are another promising play types. High amplitude bodies identified in the Tertiary section may suggest presence of deep-water channel complex/splays. Similar high amplitude patterns tested in the adjoining region are found to be representing channel–levee systems.

4.4. Krishna–Godavari basin

The evolution of the Krishna–Godavari basin started as a composite rifted horst–graben feature in the Late Jurassic period. It was part of the development of the east coast divergent margin. The horsts and grabens were separated by vertical or steeply dipping faults. Rifting during early part of lower Cretaceous resulted in the formation of pericratonic basin (Rao, 2001). The initial rift-drift phase during this time initiated a number of fluvio-lacustrine sediments throughout the basin. However, the transport of material was limited to short distances and, therefore, clastics from that time are poorly sorted, mainly argillaceous and arkosic sandstones. Deposition was rapid; graben subsidence was active and contemporaneous with the sedimentation.

The basin is fed by two major river systems namely Krishna and Godavari. The regional seismic section (Fig. 10a–d) depicts thick pile of Mesozoic and Tertiary sedimentary sequences. The early Cretaceous sequence represents rifted geometry where as the Tertiary sequence is characterized by occurrence of few very bright amplitude packages suggesting numerous vertically stacked sinuous deep-water channel–levee complex (Bastia, 2006). Drill well results show the sand to shale ratio within these channels is very high providing an excellent reservoir facies for petroleum accumulation.

4.5. Palar–Pennar basin

Palar–Pennar basin is sandwiched between Krishna–Godavari in the north and Cauvery basin in the south. The major north–south structural grain continues downward from Krishna–Godavari to Palar–Pennar basin (Rangaraju et al., 1993). Two smaller river systems, Palar and Pennar bring sediments from the basement highs to the sea. The regional seismic section (Fig. 11a–c) depicts lower Cretaceous rift with associated half-grabens and high ampli-

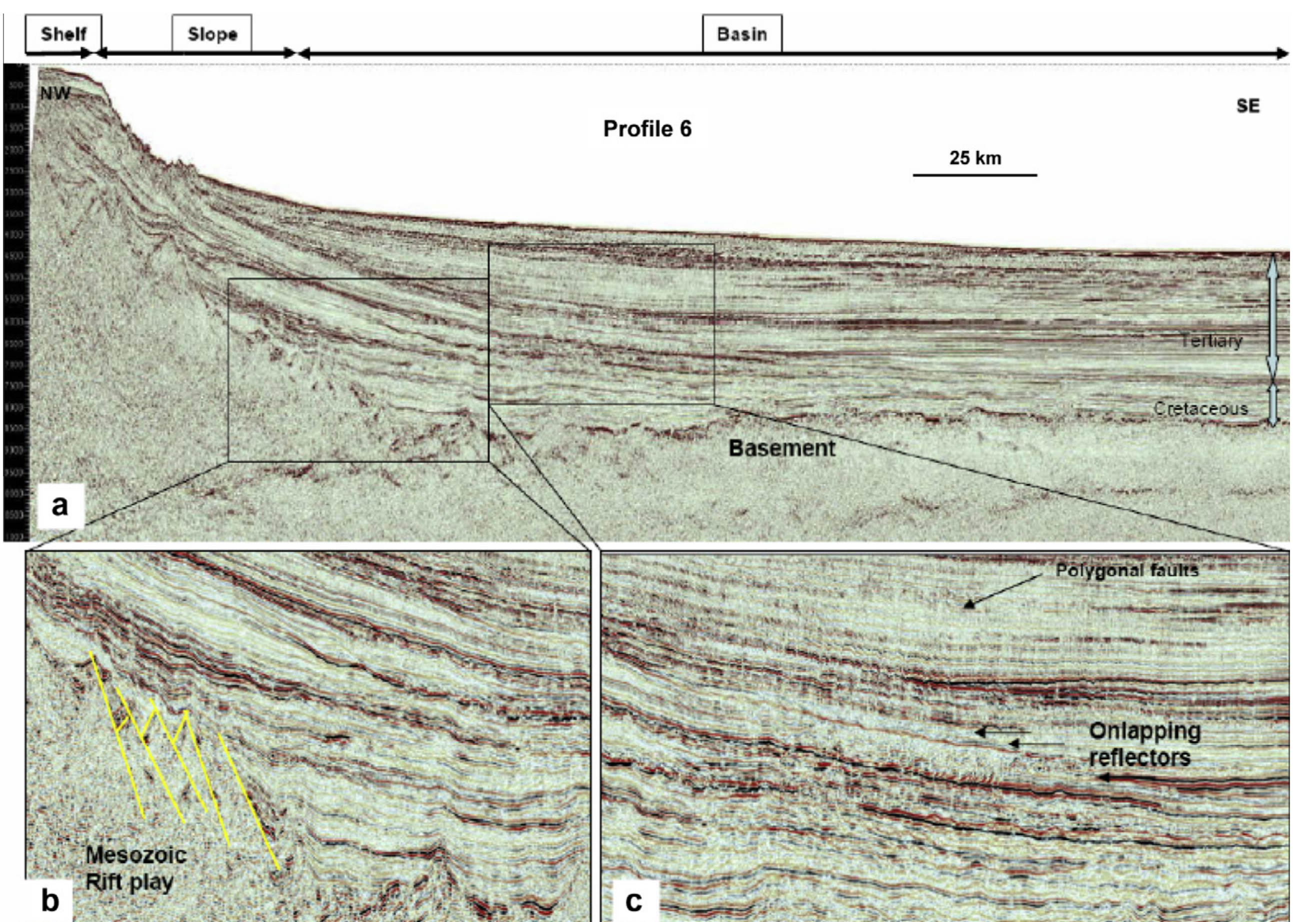

Fig. 11. (a) Seismic section through the Palar–Pennar basin connecting the shelf to abyssal plain across the margin, (b) Mesozoic rift with associated half-grabens. (c) High amplitude onlapping reflectors. Also shown are number of closely placed polygonal faults.

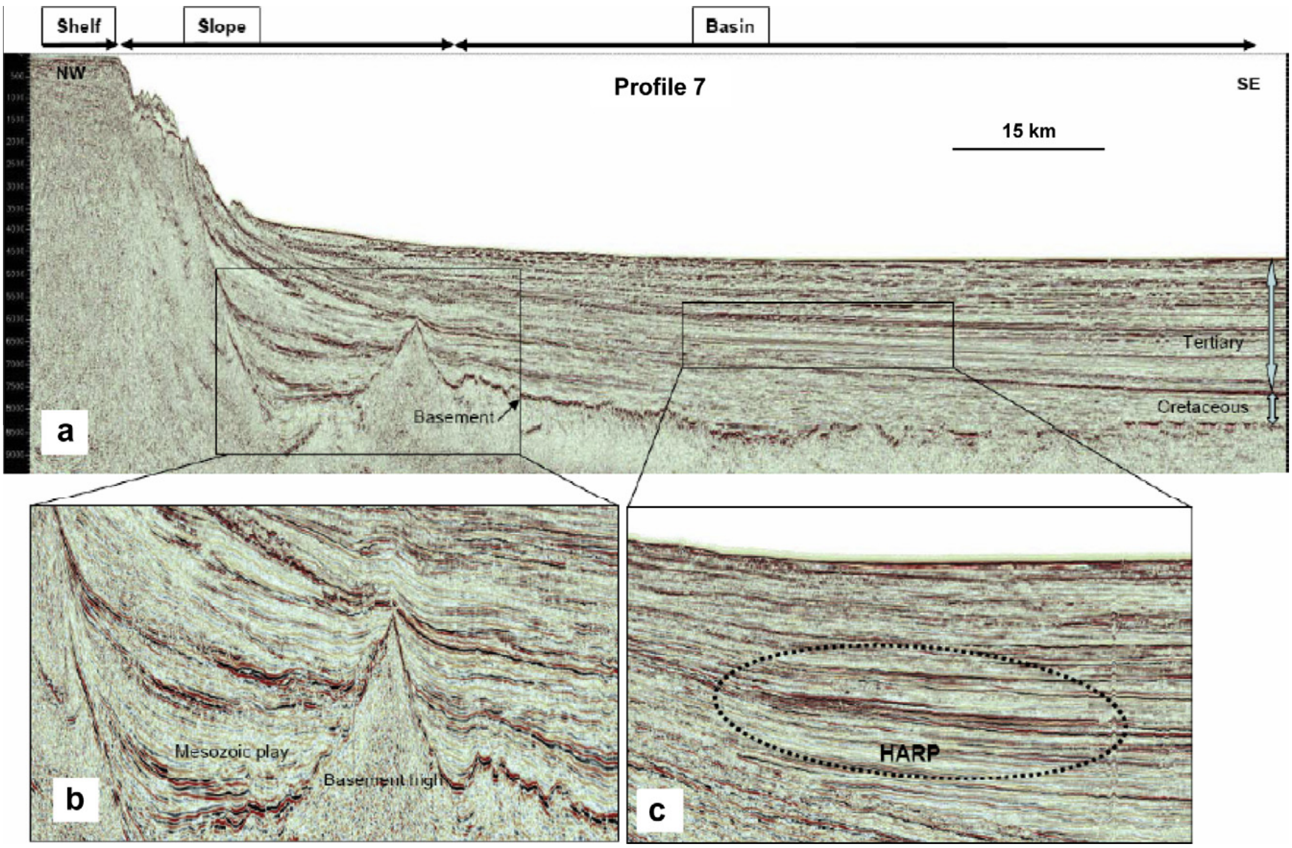

Fig. 12. (a) Seismic section across the Cauvery basin showing prominent basement highs and associated Mesozoic-Tertiary sequences. (b) Showing Mesozoic play abutting against basement high. (c) Tertiary high amplitude reflection package (HARP) representing channel fills.

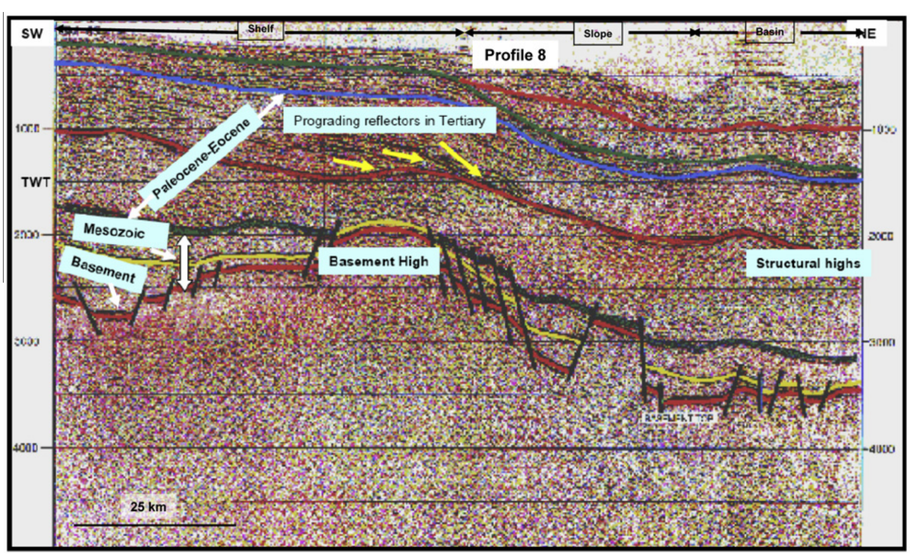

Fig. 13. Seismic profile shows horst graben tectonic setting in the basin and subsequent post-rift sequences. Prograding events in the Tertiary sequence are also marked.

tude onlapping Tertiary sequence. Numerous polygonal faults are also observed in the younger Tertiary section.

4.6. Cauvery offshore and Gulf of Mannar

This basin represents a series of horst–graben features that are oblique to the coast like the Palar basin in the north (Balakrishnan and Sharma, 1981). The grabens are filled with Mesozoic rocks. Thick Tertiary sediment pack mostly contributed by Cauvery river system is accumulated as a thick wedge on the uniformly eastward sloping platform. The regional seismic section (Fig. 12a–c) shows the prominent basement highs and the Mesozoic sediments abutting against the highs. The Tertiary high amplitude packages identified here are proved to be channel fill/splay sediments. Gulf of Mannar is the southern most basin in the east coast located between the cratonic mass of India and Sri Lanka (Prabhakar and

Zutshi, 1993). Fig. 13 shows the horst graben tectonic setting of the basin with post-rift fill sequences. As can be seen, Tertiary wedge outs against the basement highs are also common.

5. Conclusions

Interpretation of gravity, magnetic and multichannel seismic data in the offshore east coast of India suggest that the ECMI represents a passive continental margin setup marked by prominent tectonic features with horst–graben basement morphology related to rifting. Interpretation of various image enhanced gravity and magnetic anomaly maps suggest that in general, the ENE–WSW trending faults dominate the structural configuration at the margin and some of these faults cut across the COB inferred from these maps. Basement depths estimated from magnetic data indicate that the values range from 1 to 12 km below sea level and deepen towards the Bengal Fan in the north. The multichannel seismic sections across different basins of the margin analysed in the present study reveal fault pattern, rift geometries and depositional trends related to canyon fills and channel–levee systems and provide a basic framework for future petroleum in this under explored frontier. The Cauvery–Palar and Krishna–Godavari basins can be thought to represent two tier petroleum systems; the Mesozoic rift related plays and Tertiary deep-water channel–levee plays, whereas, in the Bengal offshore and Mahanadi basins, the Tertiary channel–levee complexes of are predominant.

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