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Exploring the Passive Margins–a case study from the Eastern Continental Margin of India

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ABSTRACT
The Eastern Continental Margin of India (ECMI) is a passive margin, evolved due to the break-up of India from East Antarctica during Late Cretaceous (140–120 Ma). Over the last three decades extensive marine geophysical data (bathymetry, magnetic, gravity and multi-channel seismic reflection) was collected over the ECMI. These data sets were analyzed to understand the structure, tectonics and the geodynamic evolution of this passive margin.

This paper presents the synthesis of the results obtained from marine geophysical studies spanning over a period of nearly two decades, mainly related to the geomorphology, tectonics, coastal seismicity, Holocene sea level history and marine geohazards of the margin. The geodynamic evolution of this passive margin is explained based on the major tectonic lineaments like Continent-Ocean Boundary (COB), the NE-SW horst and graben trend of the continental basement and the rift related dyke intrusions within the continental basement. Land – Ocean Tectonic lineaments (LOTs) identified from the data reveal neotectonic activity associated at the three locations over the ECMI. Holocene sea level history has been traced from the high resolution seismic reflection data. Marine geohazards over the basinal and non basinal areas of ECMI have been demarcated. Scope for future studies is also discussed.

INTRODUCTION

Passive continental margins are formed within a single lithospheric plate, in which continental crust adjoins the oceanic crust. Earthquake activity is minimal but sediment deposition dominates at these margins. Passive margins form initially at divergent plate boundary following break-up of the continent and they presently bound the oceans formed by the spreading involved in the break-up of the Paleozoic super-continent. Passive margins are potential targets for exploitation of a variety of non-living resources including petroleum and natural gas (Morelock et al, 2006). A thorough assessment of the geological potential of these areas requires a comprehensive knowledge on the history of the ocean from the time of pre-rifting events to the present. Although pre-rift fits of continents, around most Atlantic-type oceans are reasonably well known, the precision with which published fits are defined is generally lower than desirable for exploration purposes and further effort in assessing the most probable fit is needed for two reasons. Firstly, the exact continental fit plays an important part in understanding the structure of the continental margins and secondly the orientation of buried basement structures under the continental shelf can be better estimated if the pre-rift fit is accurately known.

Rifting events that precede continental rupture are perhaps the most important single influence in controlling continental margin structure and a major effort in mapping these rifts is generally rewarding.

The Eastern Continental Margin of India (ECMI) has evolved due to the break-up of India from East Antarctica during Late Cretaceous (140–120 Ma) (Curray et al. 1982; Ramana et al, 1994; Gopal Rao et al, 1997; Krishna et al 2009). The initial break-up seems to have occurred at the bight of the present day Krishna–Godavari (K–G) basin (Murthy, et al, 1995a), in two major stages along two different segments; the northern (K–G) rifted segment and the southern (Cauvery) sheared or transform segment (Subrahmanyam et al., 1999a).

The Indian Plate has undergone an eastward tilt during its initial break-up and for this reason we find that most of the South Indian rivers along the Gondwana Grabens have an eastward trend, though most of these major rivers have originated far west. The tectonic fabric in the south Indian shield, south of Son–Narmada Lineament has a predominantly NW–SE or W–E trend (Vita-Finzi, 2004; Roy, 2006).

The earliest study on the stratigraphy, structure and tectonics of the Bengal Fan, including the ECMI from geophysical data collected during the International Indian Ocean Expedition (IIOE; 1960-1965) evoked considerable interest in the study of this region (Rao and Rao, 1986). These preliminary observations, based mostly on four widely spaced seismic sections (along 10°, 14°, 17° and 20°N) in the northern Bengal Fan provided significant information on the geodynamics of this strategic region, considered to have been evolved due to the break-up of Indian Plate from Antarctica during Late Cretaceous (120 Ma) and its subsequent collision with the Asian counterpart around Eocene time (54 Ma). Extensive geophysical coverage

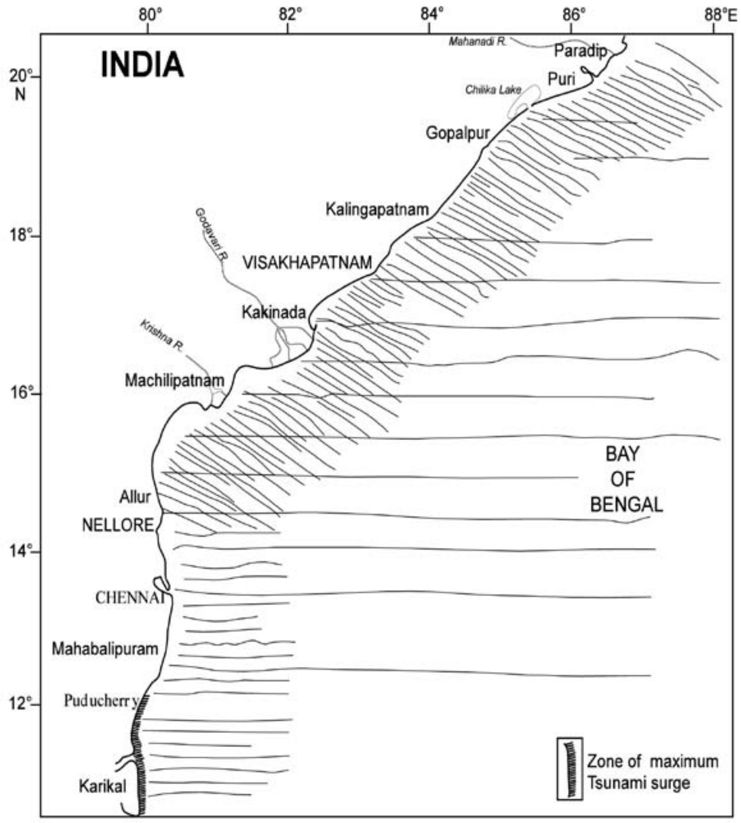


Figure 1. Survey tracks of geophysical data over the Eastern Continental Margin of India (ECMI) and the Bengal Fan.

during the period from 1980 to this date led to several theories on the evolution of the Bengal Fan including the aseismic ridges in this region. Detailed studies during the last two decades, with extensive satellite and ship-borne gravity data sets along with multi-channel seismic data added significant new information on the structure, tectonics and evolution of the Bengal Fan and resolved some of the ambiguities on the break-up of continents and spreading history of the Indian Ocean, in general and on the nature and origin of 85°E and Ninetyeast Ridges, in particular. The Cauvery, Krishna-Godavari and Mahanadi offshore basins are now potential targets for exploitation of hydrocarbons (Rabi Bastia and Radhakrishna, 2013, Sain et al, 2014), including the gas hydrates (Mazumdar et al, 2008, Dewangan, et al, 2010, 2011, 2013, Ramana, et al, 2010, Ramprasad et. al., 2011). This paper is a synthesis of the results from the marine geophysical studies carried out over the ECMI over a period of nearly two decades.

Since 1985, the Marine Geophysics Group of the CSIR-National Institute of Oceanography (NIO) at Visakhapatnam has carried out extensive geophysical surveys over the ECMI and the Bengal Fan. These surveys generated bathymetry, magnetic, gravity and high resolution shallow seismic data over the ECMI (Fig.1). In addition, the offshore basins (Cauvery, Krishna-Godavari and Mahanadi) and non-basinal areas (Visakhapatnam-Kalingapatnam shelf) of ECMI were covered by detailed studies. These data sets were utilized to explain the evolution, tectonics and associated hazards of a passive margin (Murthy, et al, 2012). While the detailed data over the offshore river basins have been used to delineate the offshore extension of some of the Pre-Cambrian Tectonic Lineaments, the data over the inner shelf have been analysed to infer the seismic hazard associated with some of the Land-Ocean Tectonic Lineaments.

GEOMORPHOLOGY

Morphologically the ECMI represents a mosaic of basinal and non-basinal segments. The depth contours of the eastern continental margin nearly follow a N-S trend in the southern part between Karaikal (10°55'N) and Nellore (14°30'N) from where they take a NE-SW trend up to Paradip (20°15'N) in the north, thus running sub parallel to the coast line. The contours indicate in general a narrow shelf in the south from Karaikal (10°55'N) to Nellore (14°30'N), also off Krishna and Godavari river basins and a relatively wider shelf to the north from Kakinada to Paradip (Figs.2a and b). The shelf/slope characteristics at different locations of the margin are summarized in Table1.

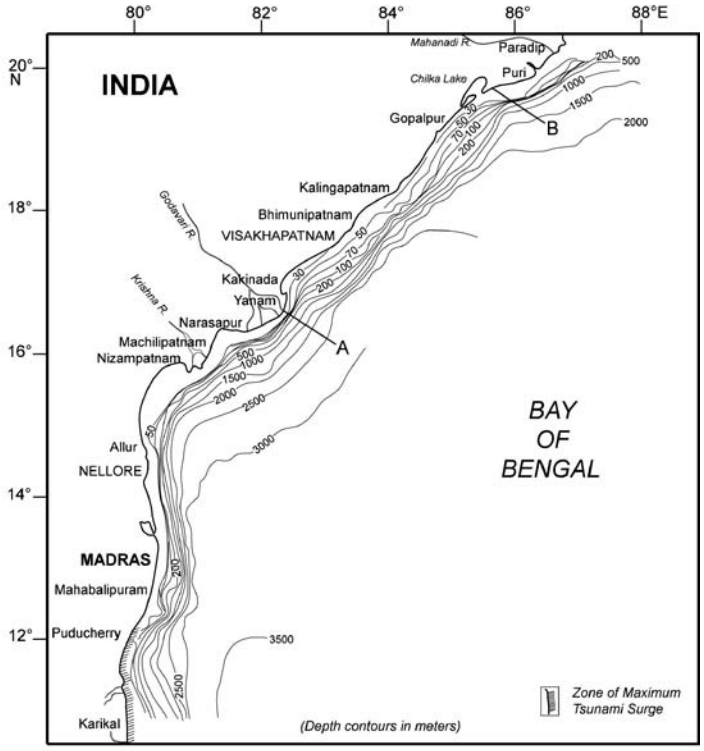


Fig.2a Bathymetry map of the Eastern Continental Margin of India (ECMI) A and B represent offsets in the bathymetry contours (Murthy, et al, 2006)

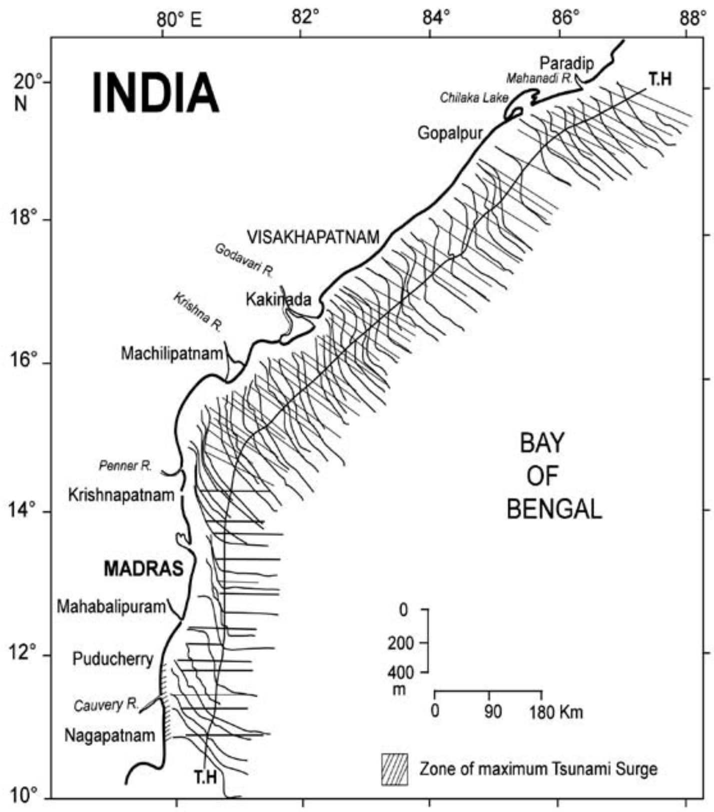


Fig.2 b) Bathymetry sections plotted along the track over the Eastern Continental Margin of India. (Murthy, et al, 2006). (Note the Topographic high (TH) marked at the foot of the continental slope)

Table 1. Shelf / slope characteristics off selected places over the eastern continental margin of India (ECMI) (Murthy, et. al., 1993)

	Water depth at shelf break (m)	Shelf edge distance from coast (km)	Shelf gradient (ratio)	Slope gradient (ratio)	Depth at which marginal high (T.H.) is recorded (metres)	Remarks (only relative terms)
1. Paradip	100	50	1:320	1:50	Not clear	Wide shelf, gentle slope
2. Puri	130	40	1:300	1:43	Not clear	Wide shelf, gentle slope
3. Chilika Lake	220	40	1:200	128	800 ?	Wide shelf, gentle slope
4. South of Chilika Lake	220	40	1:200	1:35	Not clear	Wide shelf, steep slope
5. South of Gopalpur	220	44	1:200	1:16	1500-2000	Wide shelf, steep slope
6. Kalingapatnam	120	35	1:280	1:16	1800-2000	Narrow shelf, steep slope
7. Kalingapatnam	130	45	1:345	1:15	2000-2100	Wide shelf, steep slope
8. Visakhapatnam	200	50	1:250	1:12	1900-2100	Wide shelf, steep slope
9. North of Kakinada	200	45	1:225	1:12	2400-2600	Wide shelf, steep slope
10. Krishna River	70	21	1:300	1:25		Narrow shelf, gentle slope
11. Nizampatnam	70	22	1:300	1:25	Not clear	Narrow shelf, gentle slope
12. Chennai	200	43	1:200	1:8	2700	Wide shelf, very steep slope
13. North of Puducherry	90	35	1:400	1:6	3000	Narrow shelf, very steep slope
14. Karaikal	70	16	1:200	1:19	3000	Narrow shelf, steep slope
15. Nagapattinam	70	24	1:340	1:17	3000	Narrow shelf, average slope

The foot of the continental slope occurs at a depth of 3000 m in the south but decreases to less than 2000 m depth in the north. A topographic high (TH) is observed at the foot of the continental slope in some of the profiles. The topographic high is broader (about 20 km) over the southern part compared to the northern part where it is recorded as a sharp peak. The relief of this high varies from a few tens of metres to as much as 300 m. Based on the analysis of other geophysical data, this topographic high was interpreted as the edge of the continental crust (Murthy, et al., 1993)

Bathymetry and high resolution seismic reflection data also indicate that the morphology of the basinal areas is influenced by both deltaic and ocean processes, while that of the non-basinal areas is dominated by eustatic sea level changes. Recent studies revealed that the morphology has considerable impact on the ocean processes such as the storm/cyclone and Tsunami surge. The Indian Ocean Tsunami of 26th December, 2004 caused extensive damage over Cuddalore-Puducherry (also called as Pondicherry) part of the Tami Nadu shelf, which has a concave morphology. In a similar way, the concave shelf of Nizampatnam, Machilipatnam of Andhra coast and the Paradip shelf of Orissa coast are also vulnerable for cyclone/storm surge (Murthy, et al, 2006a and b, Murthy, et al, 2011).

TECTONICS

Magnetic and free-air gravity data (Fig.3 and 4) and Bengal Fan have been used to infer the major structural lineaments (Fig.5.) and to understand the tectonics of this passive margin, since its break up from eastern Antarctica (Murthy. et al.,1993):

The Continent-Ocean Boundary (COB) is delineated from bathymetry, magnetic and free-air gravity data at the foot of the continental slope running parallel to the coast in the southern part between Chennai(13°N) and Kakinada (17°N). Further north, its expression is not clear, probably obscured by the thick sediments of the Bengal Fan. Subsequent results from multi-channel seismic data confirmed the trend of COB, inferred from gravity and magnetic data. The model derived for COB (Fig.5a) also suggests a folded and faulted oceanic crust at its contact with the continental crust (Murthy, et al, 1993). Linear trends of dyke intrusions landward of COB are identified from magnetic data, which might represent the rift-phase volcanism associated with the evolution of ECMI (Fig.5a). The present data reveals such intrusives off Chennai and also off Visakhapatnam to Chilika Lake, and it needs a detailed study regarding the nature and extent of these intrusives and their relation to the land

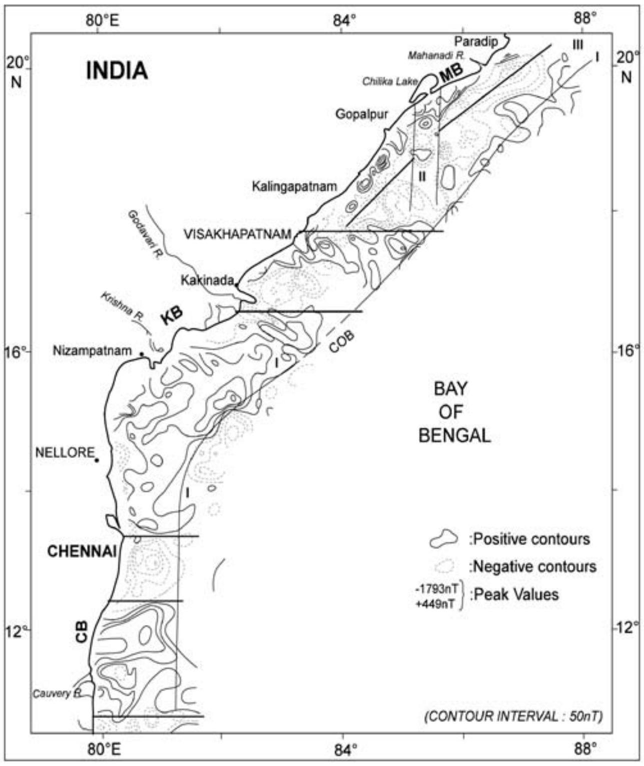


Fig.3 Magnetic anomaly map of the ECMI (Murthy, et al., 1993). I, II and III are the major structural trends delineated from the magnetic anomaly map. Trend I represents the Continent-Ocean Boundary (COB); II represents 85° E Ridge and III represents horst and graben trend (Murthy, et al.,1993; Subrahmanyam, et al., 1994 and 1997)

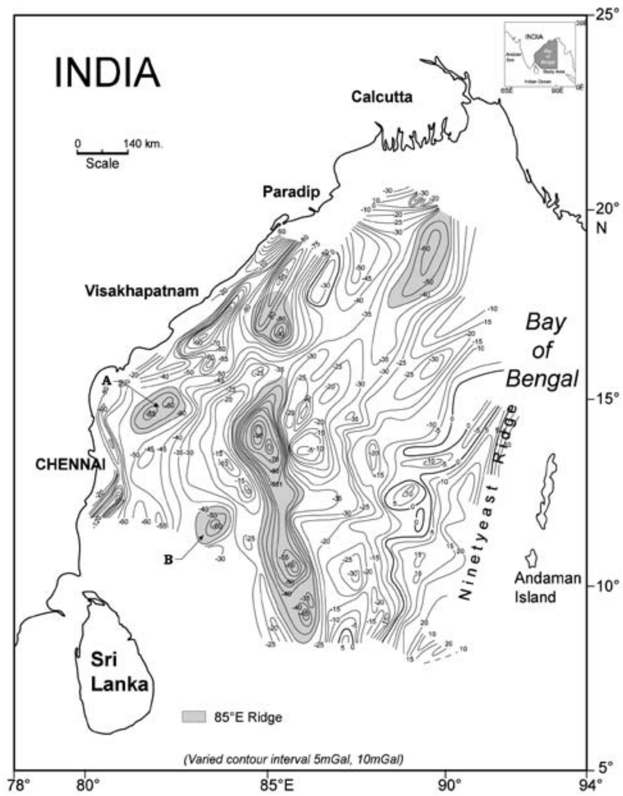


Fig.4 Free air gravity anomaly map of the ECMI (Subrahmanyam, et al, 2001)

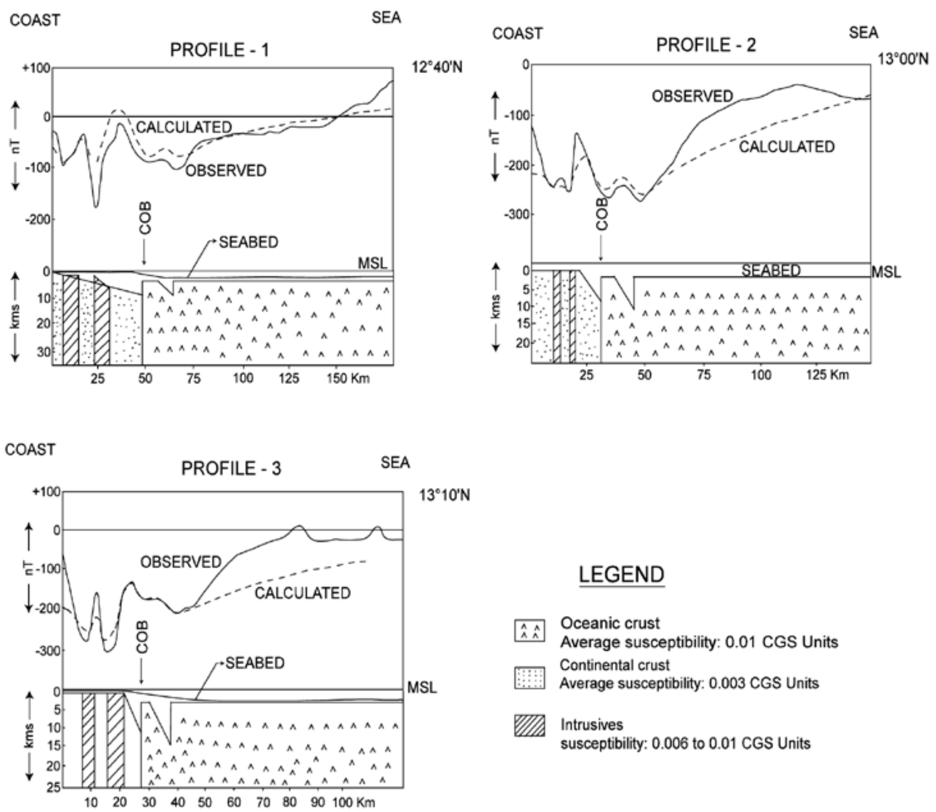


Fig.5 a) Model derived for the crustal structure across the ECMI (Profiles located off Chennai, Fig.1)

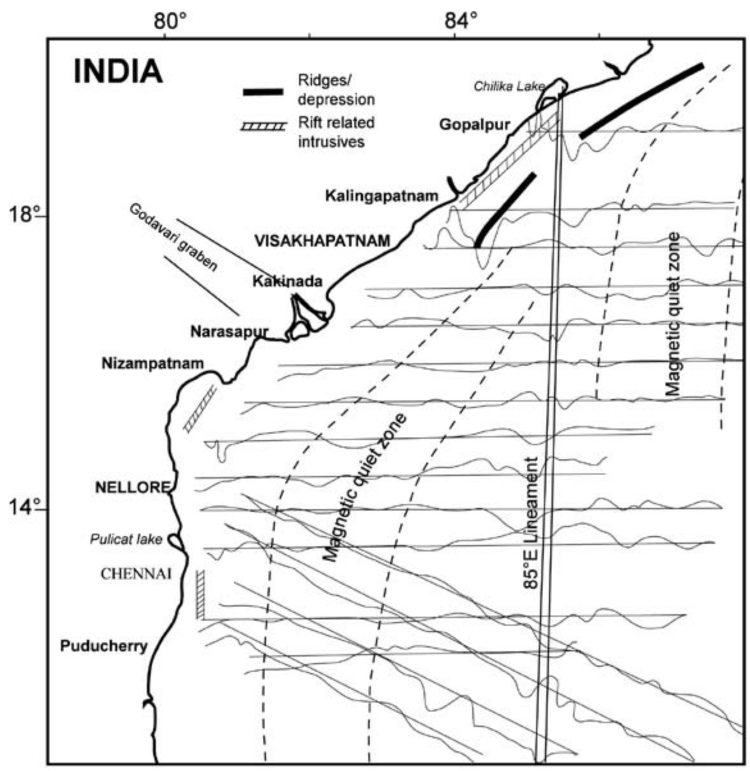


Fig.5 b) Major Structural lineaments identified from the geophysical data of ECMI.

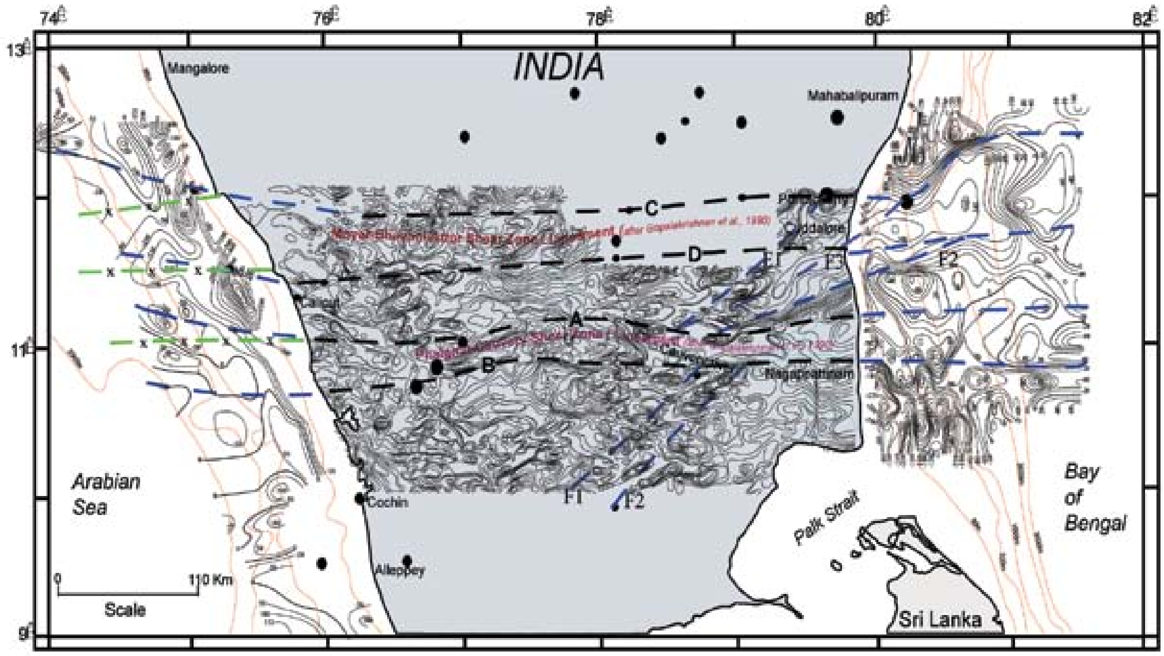


Fig.6.a Pre Cambrian mega lineaments in the South Indian Shield (Subrahmanyam et al, 2006)

geology (Fig.5b). These intrusions are associated with very high amplitude magnetic anomalies in the northern part between Visakhapatnam and Gopalpur, reaching at places to nearly 1500 nT.

Magnetic and gravity data also delineated horst and graben configuration within the continental basement that might be related to the vertical tectonics in the post-rift stages of the evolution of ECMI. This type of basement configuration is more prominent beneath the continental shelf between Visakhapatnam and Paradip (Fig.5b).

The present study also derived a two stage evolution of the eastern margin of India: a) Rift phase represented by the coast parallel dyke intrusions and b) Post rift stage represented by horst and graben configuration over the region (Subrahmanyam, et al., 1994). The study also proposes possible extension of 85° E Ridge into the land area near Chilika Lake, adjacent to the eastern continental margin of India. Correlation between tectonic lineament map of the ECMI with the granulite facies distribution map of India and Antarctica indicates a structural link between the east coast of India and the Enderby Land of Antarctica (Murthy, et al, 1997a).

Magnetic and free-air gravity data in the Bengal Fan indicate the northern extension of the 85°E Ridge up to 20°N. The negative magnetic anomaly associated with this ridge has been explained in terms of mantle depressions (Subrahmanyam, et al, 2001). Magnetic data also demarcated another major lineament along 80°E, located over the Cauvery offshore basin. A magnetic quiet zone of Cretaceous Period is demarcated over the Bengal Fan seaward of the COB between 13° and 17°N, although further north it appears to have been distorted due to the emplacement of the 85°E Ridge. An integrated study of bathymetry, magnetic, gravity and multichannel seismic reflection data of Mahanadi shelf by Srinivasa Rao and Radhakrishna (2014) demarcated the northward extension of the 85° East Ridge abutting the coast at Chilika Lake.

Geophysical data (magnetic, free-air gravity and high resolution seismic) collected over the Cauvery, Krishna-Godavari and Mahanadi offshore basins of the Eastern Continental Margin of India (ECMI) have been used to demarcate the offshore extension of the Pre-Cambrian mega lineaments delineated earlier from land based geophysical studies.

Pre-Cambrian Mega Lineaments off Cauvery Basin

The qualitative study of the airborne and marine magnetic data sets of the South Indian Shield, including the eastern and western continental margins revealed two major tectonic lineaments across the south Indian continent (Subrahmanyam. et al, 2006). One of the lineaments starts approximately at 1500 m isobath in the western offshore region of south India, runs across the southern peninsular India and passes through the Cauvery offshore basin of the Eastern Continental Margin (ECMI) of India up to a water depth more than 3000 m. It covers a horizontal distance of approximately 750 km. This lineament runs almost parallel to 11°N and can be considered as a mega lineament hitherto unmapped (Fig.6a).

This mega lineament referred to as Palghat– Cauvery Lineament (PCL) is characterized by elongated and isolated closures of magnetic anomalies trending approximately in E–W direction. This zone is also associated with high magnitude earthquake epicenter locations, suggesting significant tectonic activity.

Similarly, towards north of this mega lineament/zone, another east west trending lineament is present, which was earlier marked as Moyar–Bhavani–Attur lineament. In the present study the offshore extension of this lineament was identified and marked in the total intensity magnetic data of the adjoining eastern and western continental margins of India. This lineament also starts at approximately 1500 m isobath in the western offshore region of southern India and runs across the southern peninsular India, passes through the eastern continental shelf of India up to a water depth of more than 3000 m (Fig.6a). It covers a distance of approximately 800 km. This lineament almost runs parallel and close to12° N, in an E–W direction cutting across the south Indian continent. The Dharwar Craton is separated from the Southern Granulite Terrain (SGT) by two prominent shear zones known as the Moyar–Bhavani shear zone and Palghat–Cauvery shear zone, a transition zone marked by gradation in metamorphism from gneisses in the north to charnockite in the south. Perhaps this phenomenon is reflected as an east– west trending tight band of total intensity magnetic contours over the south Indian Peninsula. These two mega lineaments act as major tectonic/structural boundaries of the south Indian continent.

The presence of these mega lineaments on the Peninsular shield as well as on the eastern and western margins of India suggest that, the south Indian land mass and the adjoining offshore regions in the east and west are genetically linked and also indicate that these lineaments may be of Precambrian age. Some of the earlier reported lineaments over the western continental shelf are well correlating with the presently inferred westward extension of the mega lineaments.

In the present study, by revising the aeromagnetic data over southern Peninsular India, three major faults were delineated**.** Two of these faults appear to be dislocated at PCL boundary, suggesting westward shearing along the southern east– west mega lineament. The three faults are associated with some earthquake epicentres.

South of Cuddalore on the east coast of India, the westward bend/bite of the coastline can be related to a tectonic movement. The present study revealed that the bend/bite is controlled and bounded by the NE–SW trending fault lineaments running from the land mass and passes through the eastern continental shelf of India. One of these delineated faults is associated with an earthquake of magnitude 5.5 that occurred on 25th September 2001, off Puducherry (Fig.6b).

The present study concludes that the regions between the latitudes 10° N and 12° 30 N of the south Indian continent are characterized and controlled by two mega lineations and associated tectonics suggesting that the area is tectonically active. The presence of continental magnetic anomalies and the oldest mega lineaments of Precambrian origin, up to 3000 m isobath over the ECMI perhaps suggest that the continent–ocean boundary/transition exists beyond this point.

Tectonics of Krishna-Godavari offshore basin

Detailed analysis of geophysical data of offshore Krishna-Godavari Basin has revealed significant information on the geodynamics of this petroliferous basin (Murthy et., al., 1995a, Subrahmanayam, et al., 2010) Bathymetry and magnetic data suggest the offshore extension of the two major Pre-Cambrian tectonic lineaments, viz., the Avanigadda and Chintalapudi cross trends (ACT and CCT). The Continent-Ocean Boundary (COB) appears to be the seaward limit of these two trends. However the present data are insufficient to confirm the extension of these two trends seaward of COB (Fig.6b). The Chintalapudi cross trend (CCT) appears to be fault related, as evidenced form the significant offsets in the magnetic and bathymetry contours. The weak magnetic anomalies associated with these two trends may be due to subsidence of the offshore basin.

An intense magnetic anomalous zone located near the COB off Machilipatnam is confined between the two Pre-Cambrian cross trends. A model derived for this anomaly suggests an inclined rectangular prism at an average depth of 7 km having remnant magnetic characteristics (Murthy, et al., 1995a)**.** The width of the body is approximately 60 km. An explanation was given for this volcanic source within the hotspot reference frame work. In earlier reconstructions of the trace of the Crozet hotspot, the Marion hotspot was positioned at about the bight of India, i.e. near the curved portion of the present Krishna-Godavari basin. However, the trace of this hotspot is uncertain for the period from 140 Ma to about 96 Ma. The isolated magnetic anomaly off Machilipatnam, located near the COB might be related to the location of the Marion hotspot at the time of initial rift. The paleo-latitude (-49.5°) obtained from the model studies supports this assumption. The two cross trends ACT and CCT on either side of this anomaly extend across the entire onshore and offshore basin. These two trends are therefore tectonically significant and appear to be much older than the other structural features of Krishna-Godavari basin. However, their relationship to the hotspot is not clear. One possibility is that the two trends might represent the trace of the hotspot. However, such an

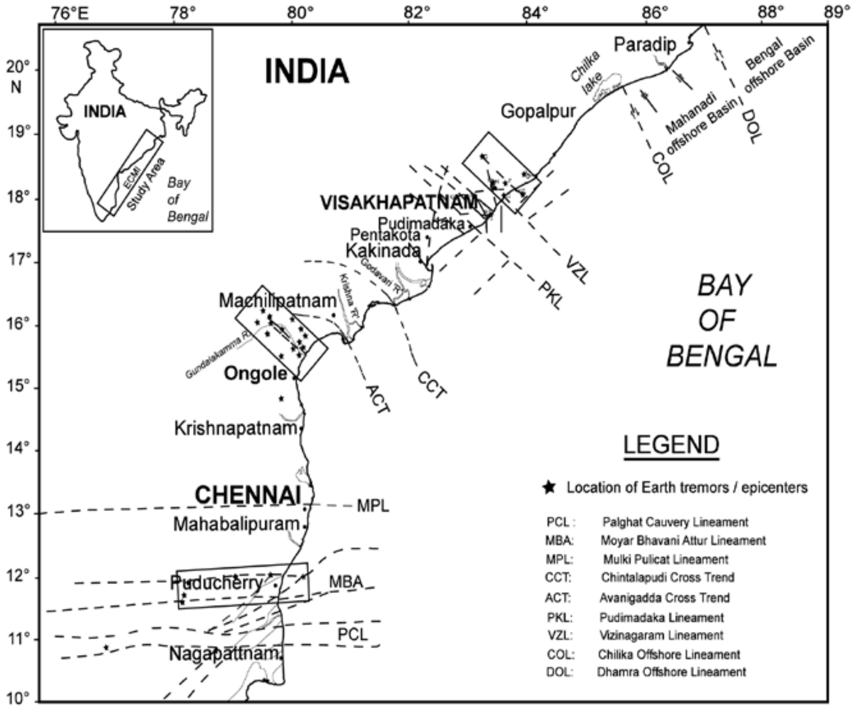


Fig.6 b) Land-ocean tectonic Lineaments over the ECMI (Murthy et al., 2010)

assumption requires a south to southeast till of this part of the hotspot beneath Peninsular India.

The study also suggested the offshore extension of the Kaza ridge. However, an alternative interpretation indicates that this trend might represent dyke intrusions within the continental trust. Model studies support the latter view. Such dyke intrusions were reported earlier over the inner shelf of Tamil Nadu and Orissa coast of the eastern continental margin and their origin was attributed to the rift phase volcanism.

Tectonics of Mahanadi offshore basin

Mahanadi is another major sedimentary basin located along the east coast of India. It extends over an area of 1,41,589 sq.km, which is nearly 4.3% of total geographical area of the country. The coastal geomorphic province is drained by the Mahanadi River system (Mahanadi, Brahmani, Baitarani and Dhamara Rivers) with a sediment load to the basin of the order of 7.10 × 109 kg/yr (Subrahmanyam, et al., 2008) . Due to more pronounced deltaic activity during the mid-late Miocene period, a wider continental shelf evolved in the Mahanadi Basin. All the major rivers of India viz. Ganges, Mahanadi, Godavari, Krishna and Cauvery are attributed to the initial rifting of the Gondwanaland and the subsequent motions of the Indian plate, which presently subducts along the Andaman–Nicobar–Sumatra Arc and enjoys a convergent setup. The study of the deltas of these major rivers helps in understanding the Indian plate motions and the associated effects. The Mahanadi basin is typically suited for this purpose, as its onshore geology significantly differs from that of its offshore.

The basement configuration inferred from the bathymetry, magnetic and gravity data resembles a series of coast-parallel structural highs and depressions and their shearing pattern in the Mahanadi offshore Basin (Subrahmanyam, et al. 2008). The Chilika offshore lineament and Dhamara offshore lineament constitute the southern and northern boundaries of the offshore basin respectively (Fig.6b). In this sector, the inferred Continent Ocean Boundary (COB), around 170 km from the coast, approximately mimics the 2000 m isobath. The width of the inferred offshore basin between the Chilika Offshore Lineament and Dhamara Offshore Lineament is around 240 km and it extends approximately up to 170 km from coast to offshore (perhaps up to the COB). The inferred tectonics of the north eastern continental margin of India suggests pull-apart and sheared/transform mechanisms during the breakup of India from Antarctica. The model studies suggest that the northern part of the 85°E Ridge abuts the coast at Chilika Lake.

The shape of 2000 m isobath over the northeastern continental margin of India closely resembles to that of 2000 m isobath off the Lambert Graben of East Antarctica. This inference appears to further support the theory that the eastern continental margin of India and East Antarctica are closely aligned in the pre-breakup tectonic setting of the eastern Gondwanaland.

NEOTECTONICS AND COASTAL SEISMICITY

Passive margins, also called as Atlantic type of margins, by definition are generally the sites of negligible tectonic activity like earthquakes, volcanoes, mountain building, etc. The Eastern Continental Margin of India (ECMI) is considered as a passive margin, though the geodynamic processes and the resultant seismo-tectonics prevalent in the vicinity of the ECMI are quite different compared to other passive margins. The tectonic fabric in the south Indian shield, south of Son–Narmada Lineament has a predominantly NW–SE or W–E trend (Roy, 2006).

The South Indian (Peninsular) Shield has been experiencing moderate seismicity (Mw 5.0), which indicates the ongoing neotectonic activity or reactivation of existing Pre-Cambrian faults in this region. However, some of the earthquakes that occurred in this Stable Continental Region (SCR) are quite devastating, for example the Latur (1993; Mw 6.3), Jabalpur (1997; Mw 6.0) and Bhuj (2001; Mw 7.7) events. New data has been added during the last two decades to understand the process of crustal deformation and fault reactivation taking place in the South Indian Shield.

The east coast of India is more prone for natural hazards like cyclones, storm surges. However, the Sumatra earthquake of 26th December, 2004 has added another unusual hazard to the Indian Ocean Rim countries in the form of a Tsunami. During the months of December 2004 to July 2005, the coastal areas all along the east coast of India have experienced aftershocks, of few seconds duration, of the 26 December 2004 earthquake, and also of 28 March 2005 (Mw 8.3) and 24 July 2005 (Mw 7.3) mega events. It is also important to note that the Andaman – Nicobar convergent margin is experiencing continuous aftershocks even today and the impact of these aftershocks is felt on the east coast of India. This implies that the coastal regions have to take note of this new seismic hazard.

Marine geophysical studies were carried out during the last few years with the main emphasis of identifying the seismic hazard associated with the coastal regions of ECMI. Analysis of magnetic, gravity and shallow seismic data, combined with reported seismicity data, indicate moderate seismicity associated with some land–ocean tectonic lineaments (LOTs) of ECMI (Murthy, et al., 1995b; 1997b; 2010, Murty et al., 2002, Subrahmanyam et al., 1995; 1999b; 2007). The coastal/offshore regions of Visakhapatnam, Vizianagaram and Ongole of Andhra Pradesh margin and the Puducherry shelf of Tamil Nadu margin have been identified as zones of weakness where neotectonic activity has been established (Fig.6b). While Earthquake data over the coastal and offshore areas of Vizianagaram (Subrahmanyam, et al., 2007) and Ongole (Reddy and Chandrakala, 2004, Sarma, et al., 2010) indicate moderate seismicity (with magnitude of tremors of the order of 3–4.5), the Puducherry offshore experienced an earthquake of magnitude 5.5, in 2001, which was a fairly larger event for the South Indian shield (Murty et al., 2002). A continuous monitoring of coastal seismicity, through geophysical studies is essential. The rapid industrial scenario currently taking place along the east coast of India must contemplate this aspect of natural hazards for a sustainable development. The tectonic setting with predominantly W–E, NW–SE lineaments extending from the coast to offshore resulting in a basinal to non-basinal mosaic suggest that the ECMI is more vulnerable to the neotectonic activity, compared to the WCMI (Murthy. et al. 2011).

HOLOCENE SEA LEVEL HISTORY

Geophysical data (mainly bathymetry and high-resolution seismic records) over the continental shelf regions help in delineating the relict (or paleo) strandlines, which in turn could give us a clue about the sea level history. Bathymetry and high resolution seismic data (Figs.7 a and b.) collected over the inner and outer shelf of Visakhapatnam (30 to 150 m water depth), east coast of India, revealed linear trends of relict strandlines between 30 to 130 m water depths. Sediment samples were collected over the relict features (hard rock outcrops) associated with these strandlines.

Another section of high resolution seismic data over the Visakhapatnam shelf, east coast of India (Fig. 7b.) revealed a faulted and rugged subsurface layer (marked as Lower Unconformity) approximately 100m below the present shelf. Though sediment samples could not be collected over this buried layer, it was estimated that this unconformity might represent a paleo-shelf corresponding to1.5 kya, based on the sedimentation rates in this part of the coast and the ages determined from the surface sediment samples (Murthy, 1989, Mohana Rao, et al., 2000).

Radio-carbon dating of the samples collected from the outcropped relict sediments helped in understanding the history of sea level changes during the period of late Quaternary (Mohana Rao, et al., 2000). Based on these observations, a sea level curve for the period from the Last Glacial Maximum (LGM) to the present (18, 000 years to the present) was drawn for the coast of Visakhapatnam (Fig.7c)

MARINE GEOHAZARDS

The morphology of ECMI from Karaikal in the south to Pardip on the north is essentially a mosaic of basinal and non-basinal areas. The Cauvery, Krishna-Godavari, Mahanadi form the major off shore basins, apart from the minor basins like Palar, Varaha, Tandava, Gosthani, Vamsadhara, etc that join the Bay of Bengal. The Swatch

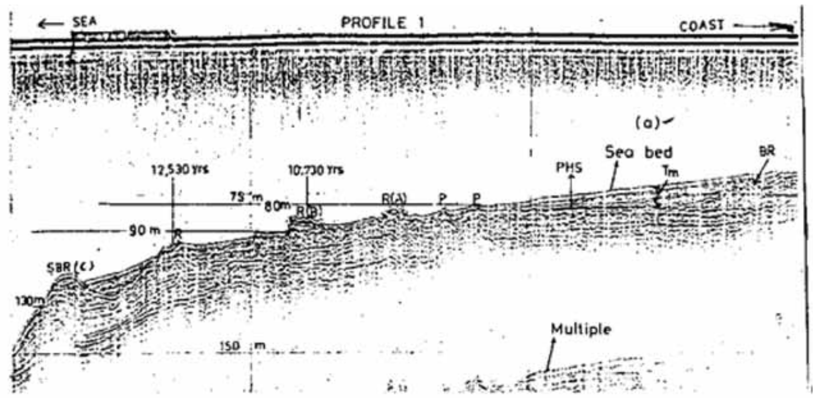


Fig.7.a) High resolution seismic reflection data over the continental shelf of Visakhapatnam, east coast of India indicating relict features associated with paleo-shore lines at 80, 90 and 130 m water depth (Murthy, 1989, Mohana Rao et al., 2000). The sediment samples collected at 80 and 90 m water depth were subjected to radio-carbon dating (ages indicated at the top of these features).

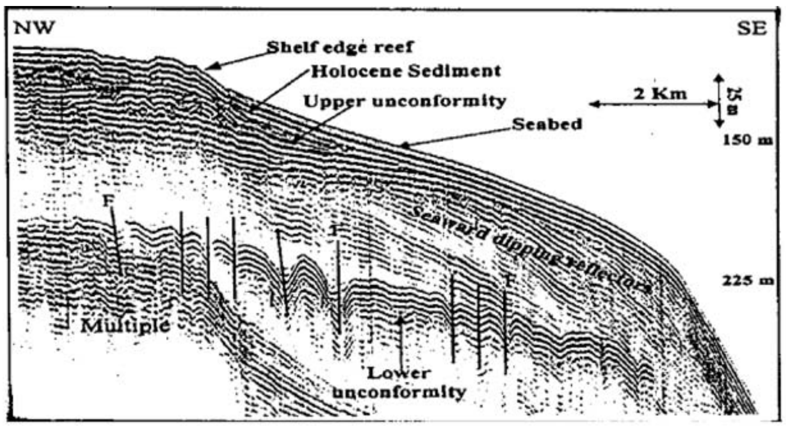


Fig.7b High resolution seismic record over the continental shelf of Visakhapatnam, east coast of India (Murthy, 1989; Mohana Rao et al., 2000). The faulted layer approximately 100m below the present seabed indicates another paleo-shoreline with an estimated age of about 1.5kya (Late Pleistocene)

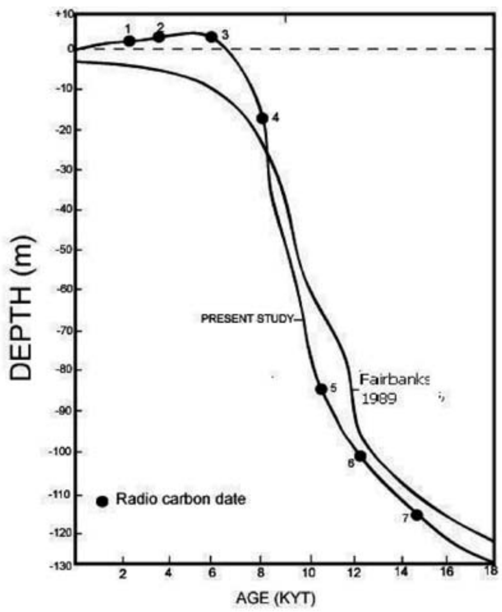


Fig.7c Tentative sea level curve (with thick circles) since Last Glacial Maximum (LGM) for the coast of Visakhapatnam, India (Mohana Rao, et al, 2000). Continuous line is the global eustatic sea level curve derived by Fairbanks (1989) for LGM to present

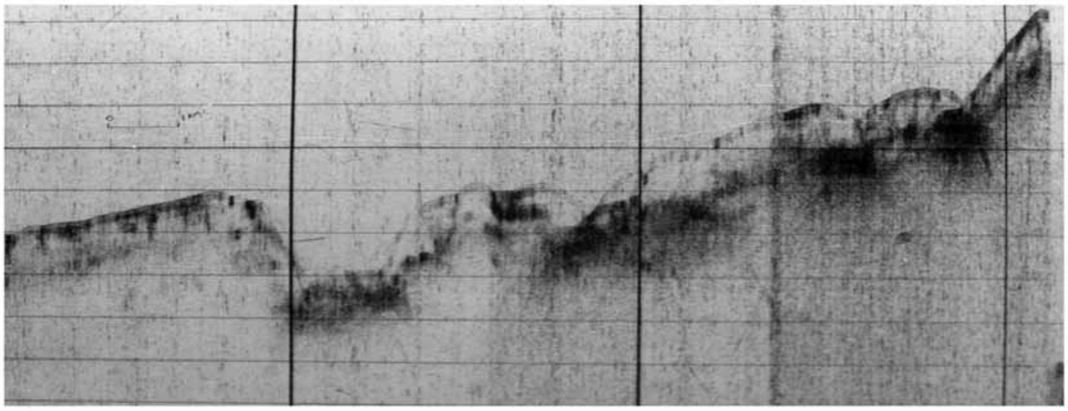
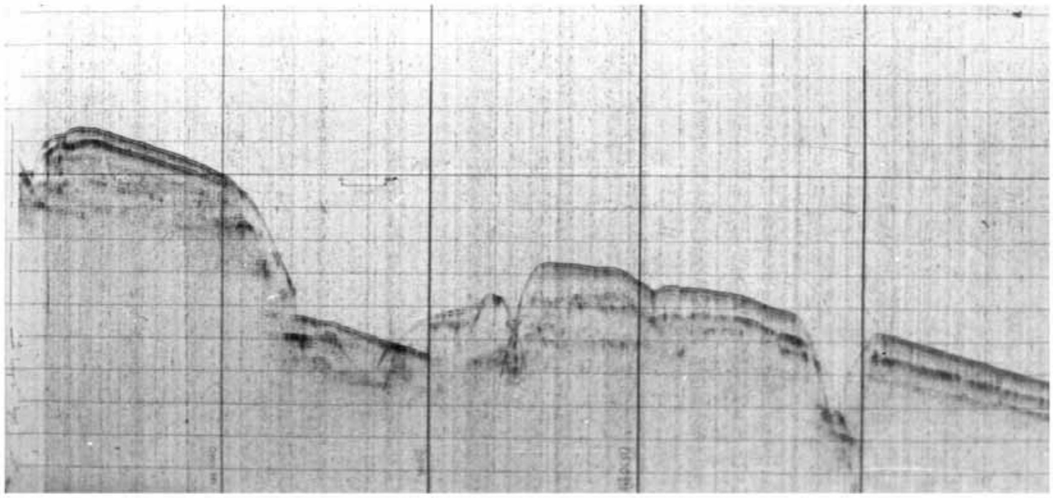
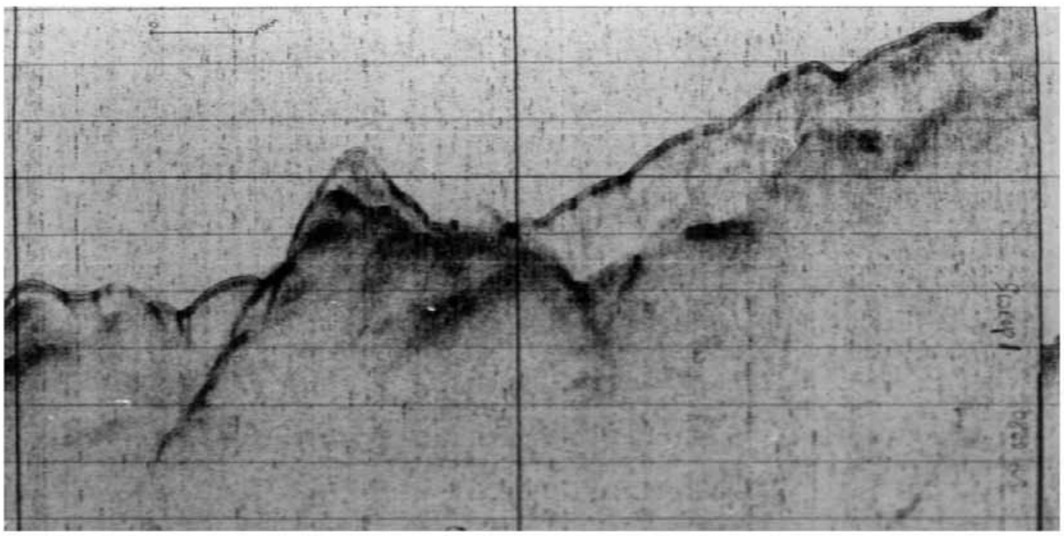


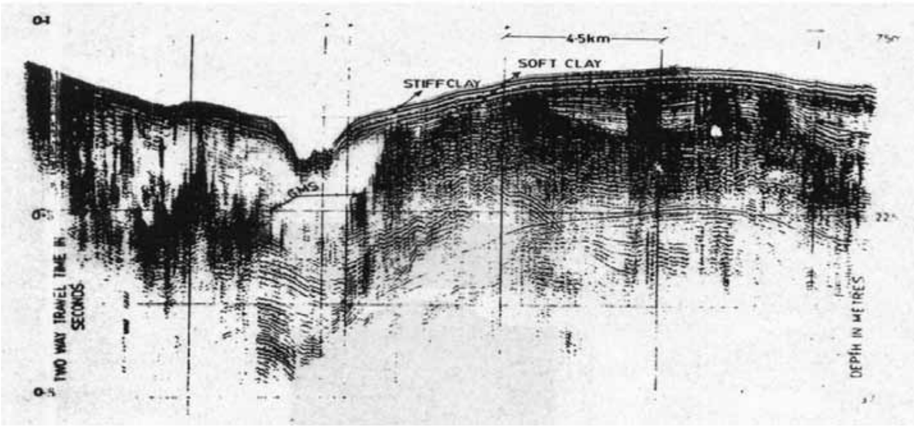
Fig.8. Some examples of marine geohazards identified from the high resolution seismic records (Murthy and Rao, 1993; Mohana Rao, 2005) of ECMI. a) Seismic record showing V-cut Channels associated with gas charged sediments



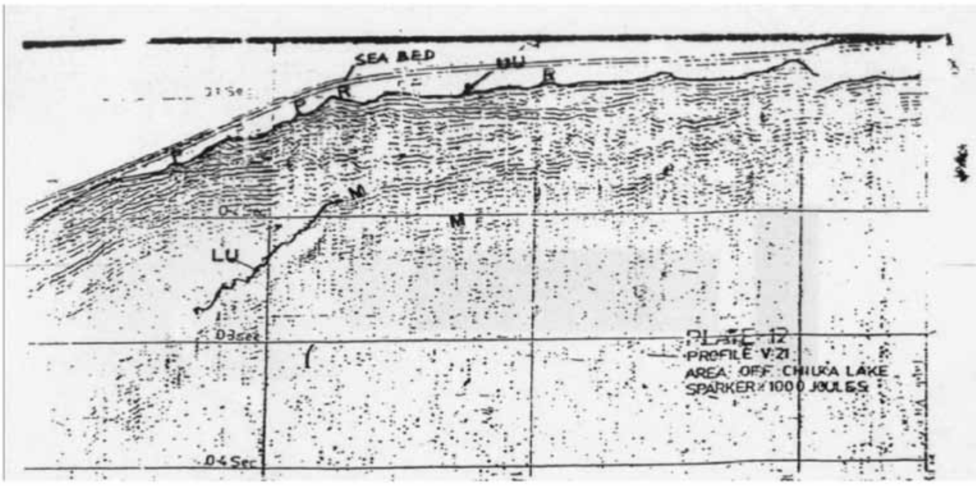
b) Seismic record showing fault valley, slump and gas charged sediments in Cauvery basin



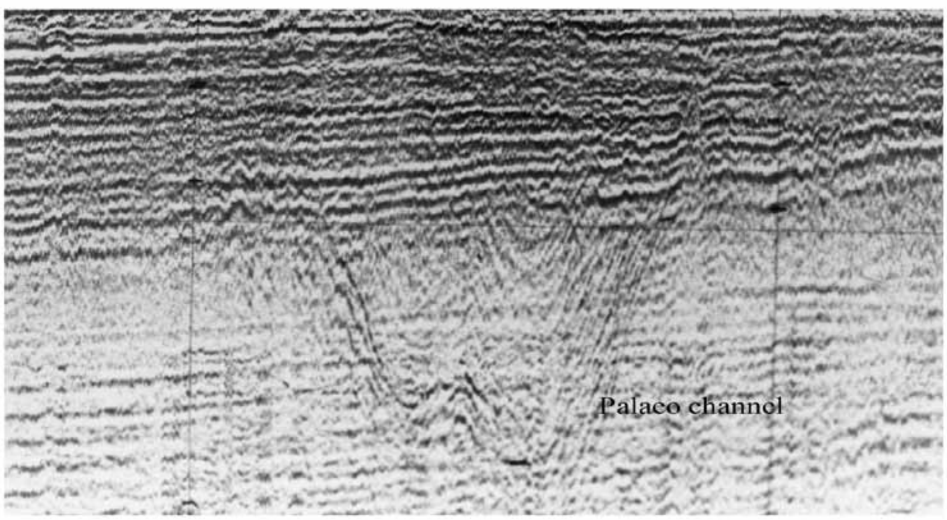
c) Seismic record showing Diapric structure in Cauvery basin.



d) Seismic record showing Columnar and hummocky structures off K-G Basin (Profile taken parallel to the coast).



e) Morphological features of late Pleistocene period off Gopalpur shelf. (The rugged palaeo-shelf is buried by thin sediments of Recent Period)



f) Seismic record showing Paleo-channel off Pudimadaka, Visakhapatnam (Profile taken parallel to the coast).

of No Ground represents a major canyon at the apex of the Bengal Fan and forms the gateway for the influx of sediments from Ganges and Brahmaputra. The Chennai shelf and the Visakhapatnam-Gopalpur shelf represent the non basinal part of the ECMI. A preliminary study on the acoustic wipeouts over the Krishna-Godavari basins was made by Murthy and Rao, (1999); Mohan Rao, (2005); Anitha et al, (2014), while detailed study on the marine goehazards of ECMI from multi-beam bathymetry, side scan sonar and 3D high resolution seismic reflection data was made by Rabi Bastia et al., (2011).

In general, the basinal areas of the ECMI are associated with marine geohazards like sediment slumps, diapiric structures, v-cut channels, gas mixed sediments and other such hazards mainly related to the deltaic processes (Figs.8 a to d for example). The non-basinal areas provide an excellent record of relict strandlines related to eustatic sea level changes (Figs.7a and b and Fig. 8e and f for example), with associated rugged sea bed morphology and other subsurface hazards like buried channels, neotectonic faults.

FUTURE WORK

The extensive geophysical data collected over the ECMI for the last three decades helped to understand the structure, tectonics and evolution of this passive margin to some extent. However, there is need for future studies particularly on the following aspects:

The COB needs a detailed study. The nature of the continental, oceanic and transitional crust at COB is least understood.

The Chilika Lake – Paradip margin needs a details study. This part of the margin is associated with a complex tectonics with the intersection of continental crust, oceanic crust, the 85 E Ridge trend abutting at the Chilika Lake and the NE-SW horst-graben trend over the continental shelf. The possibility of a tectonic origin of Chilika Lake due to these complex geodynamic processes is to be analyzed. The interaction of different physical processes (the deltaic process off river basins and the eustatic sea level changes over the non basinal areas) on the morphology and Quaternary stratigraphy of ECMI is least attempted. We need to collect considerable number of sediment cores over the ECMI for this purpose.

The relation between tectonics and the submarine canyons particularly over the Cauvery Basin is to be studied in detail.

Quantitative studies on the Land-Ocean Tectonics (LOT) and the associated neotectonic activity need to be taken up. The impact of offshore exploitation for hydrocarbons (including the gas hydrates) on the geo-environment of Krishna-Godavari as well as other offshore basins need to be studied.

The economic feasibility of exploitation of relict carbonate deposits off Visakhapatnam shelf and the placer deposits of north Andhra shelf need to be studied.

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