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ORIGINAL PAPER

Identification and characterization of marine geohazards in the deep water eastern offshore of India: constraints from multibeam bathymetry, side scan sonar and 3D high-resolution seismic data

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Abstract The eastern offshore of India covers a vast stretch of sedimentary tract fed by major rivers like Ganges, Brahmaputra and Mahanadi in the north, Krishna and Godavari in the center, and Cauvery and Palar in the south, which led to variations in shelf-slope characteristics, degree of slope and hence slope instability. The structure as well as seismic attribute maps prepared from multibeam bathymetry and high-resolution 3D seismic data set has been analyzed to identify various geohazards in the deep water offshore regions of the east coast of India. These can be categorized as slope instability, slope canyons, shallow gas, mass transport complexes, sediment waves, gas hydrates, gas chimney, mud volcanoes and shallow faults. The slope instability is primarily related to rapid sedimentation by the active river systems while the other geohazards are often developed in association with shallow gas flows and leakages. The bottom simulating reflectors (BSRs) identified in the seismic sections indicate the presence of gas hydrates. Rapid sedimentation, BSR formation, dissolution and expulsion of water as well as gas and their subsequent vertical migration are responsible for the formation of shallow gas-related hazards. The results from the above analysis are of immense help in minimizing the risk of shallow hazards during exploration, drilling and subsurface installation activities along the eastern Indian offshore.

Keywords Marine Geohazards · 3D seismic · Multibeam bathymetry · Eastern offshore of India · Indian Ocean

1 Introduction

The eastern offshore region of India has evolved as a consequence of rifting and breakup of India and east Antarctica during early Cretaceous (Powell et al. 1988). Major onshore

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river-based sedimentary basins along the east coast such as the Cauvery, Palar, Krishna–Godavari and Mahanadi basins consisting of typical horst-graben structural configuration (Sastri et al. 1973; Fuloria 1993) continue into deep offshore regions of the Bay of Bengal (Curray et al. 1982). The offshore basins along the margin have proved to be highly prospective in terms of occurrence of potential oil- and natural gas-bearing structures and have become one of the most promising petroliferous regions of the world (Bastia 2006; Gupta 2006). As a result, the eastern offshore region of India witnessed immense exploration and production activity in the recent times extending well into the deep water areas. Drilling and other related activities in marine areas particularly in the deeper waters is very challenging and risky as the safety, suitability and stability of drilling rigs and other subsea installations should be taken very seriously. So, as a precautionary measure, regions of potential geohazards along the eastern offshore need to be identified, understood and analyzed in order to have an a priori knowledge on such locations before deep marine operations are undertaken. Geohazards can be simply defined as the seabed features or near-surface events that create problems for drilling or seabed installations (Bonnell and Mullee 2000; Yahaya-Joe et al. 2000). The characteristic geomorphic features related to geohazards vary from place to place depending upon the regional geology, tectonic history and sediment dispersal pattern. In this paper, we present results of geohazard analysis and discuss various shallow hazards as well as their characteristics along the eastern offshore areas of India. The present study area is mostly confined to continental slope region though few of the features identified continue into the abyssal plain.

2 Shelf-slope morphology along the margin

The shaded relief map of topography along the east coast and the adjoining offshore region prepared from the ETOPO5 database (Fig. 1a) suggest that the margin is characterized by a relatively narrow continental shelf and a relatively wide area comprising the continental slope and rise. Detailed bathymetric investigations along the margin carried out by many previous investigators (Rao et al. 1988; Murthy and Rao 1990; Murthy et al. 1993) indicate that (i) the depth contours run subparallel to the coastline throughout the margin with a very narrow shelf between Karaikal to Nellore (10°–14° N) and a wider shelf between Kakinada to Paradip (17°–20° N), (ii) steeper gradients in the slope at Pondicherry (12° N) and Madras (13° N) and gentle gradients off Krishna–Godavari basin as well as off Chilka Lake and Paradip in Mahanadi basin (iii) depth to the foot of continental slope increases from ~2,000 m in the north to ~3,000 m in the south occasionally marked by a topographic high.

The drainage pattern of major river systems along the east coast (Fig. 1a) brings huge amount of sediments into the offshore and is the main contributing factor to the morphological variations along the margin. For the purpose of the present study, based on this river system, the margin has been divided into three segments namely Cauvery–Palar, Krishna–Godavari and NEC–Mahanadi for easier depiction of data and potential geohazard zones.

3 Data

In the present study, different geophysical data sets pertaining to the eastern Indian offshore and the deeper parts of the Bay of Bengal are utilized in order to delineate various

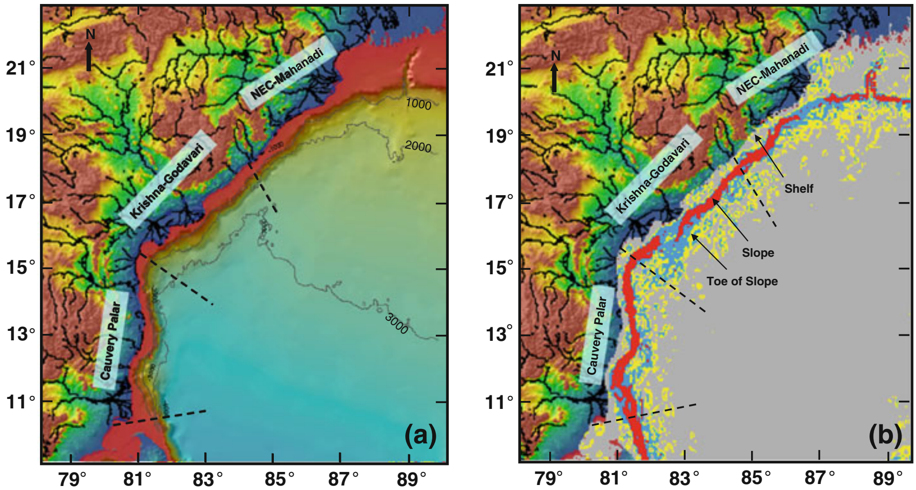

Fig. 1 **a** *Shaded* relief map of topography along the east coast and the adjoining offshore of India. The prominent river systems are also overlaid on topographic map. The *black dotted straight lines* roughly demarcate the boundaries of three major basins namely NEC–Mahanadi, Krishna–Godavari and Cauvery–Palar basin used for morphological classification. **b** Slope attribute calculated from bathymetry data shown on topography map. *Gray color* represents very low slope while *red* represents steep slope. *Blue and yellow* represents intermediate slope. This map is used for better delineation of shelf-slope and basin

deepwater geomorphic features. Apart from extensive 2D and 3D seismic data acquired under the exploration program of Reliance Industries Ltd., which forms the main basis for geohazard identification, multibeam bathymetry and side scan sonar data have also been used. Both multibeam bathymetry and side scan sonar data provide a rapid means of determining the high-resolution morphology that cannot be revealed clearly in seismic reflection data and nature of sediments on the seafloor. Though coverage and resolution of these data sets differ, integrated interpretation of them under GIS platform allowed us to characterize the features better. For this purpose, a number of time structure maps and various seismic attributes have also been used.

4 Identification of various geohazards and their characteristics

Based on the interpretation of available data, a number of geomorphic features that could be categorized under geohazards have been identified. Detailed description of these and their characteristics are presented below.

4.1 Slope instability

A slope map calculated from the bathymetry data is shown in Fig. 1b. Based on the slope map, the shelf-slope break and the toe of the slope that are important boundary markers between different depositional regimes have been identified. Steeper gradient along the slope causes more erosion and bypass of sediments while toe of the slope characterized by smoother seafloor is the area for ponding or deposition of sediments. The slope region shows failure features, whereas toe of slope may show depositional elements. All these features may pose risk to subsurface installations or drilling equipment. Slope instability is considered the most serious offshore threat on both local and regional scales. In case of eastern offshore, average slope is about 0.5° in the shallow water area having depth less than 60 m, 1.5 to 2° between 100 and 200 m water depth and increases further to 2.5 to 3° on the continental slope. While the slope is steepest in Cauvery–Palar basin, it is least steep in the NEC–Mahanadi basin.

4.2 Slope canyons

Deep water canyons are conduits for high sediment flows and strong turbidity current as evident from the events like the 1929 Grand Banks and the 1971 Nice/Var canyon-related submarine cable breakages (Day 2002). The stability of submarine canyon systems is related to seabed slope angles and the canyon walls and depends on the processes modifying the slopes and external triggering mechanisms causing them to fail. As large mass of sediments flow through these canyons, strong currents of the sediments would pose problems for the subsea installation. Based on maps prepared from the multibeam and 3D seismic data, a large number of deep canyons have been identified (Fig. 2) along the eastern offshore of India. Steep walls of the canyons show scar marks related to canyon wall failure.

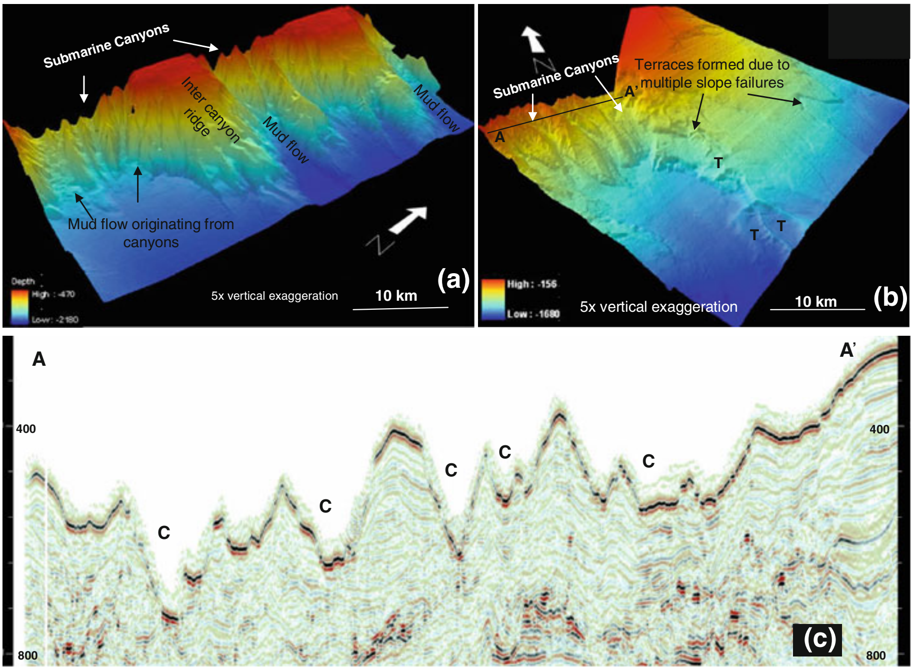

Fig. 2 Shows slope canyon systems along the eastern offshore. **a** Three-dimensional visualization of bathymetry from KG basin. A number of well-developed submarine canyon systems can be seen on the slope region. **b** Bathymetry map from another part of KG basin showing canyons and slope failure scraps. The terraces are formed due to multiple failure events. **c** Seismic depth section showing nature of the submarine canyon systems. Position of the *line* is shown in (*b*). Some of the canyons are 200 m deep. Poor imaging of the canyon walls is due to steep slope angle

4.3 Submarine channels

Besides canyons, a number of straight to highly sinuous submarine channels are identified in the region (Fig. 3). These are present in both slope and abyssal plain region. Active turbidity current movement along these channels would be hazardous for subsea engineering activities.

4.4 Mass transport complexes/mud flow

The phrase 'mass transport complex' refers to deposits or features resulting from submarine mass movement processes like slides, slumps and flows with plastic behavior, all of which are mass flows that are supported primarily by cohesion (i.e. the matrix has a finite

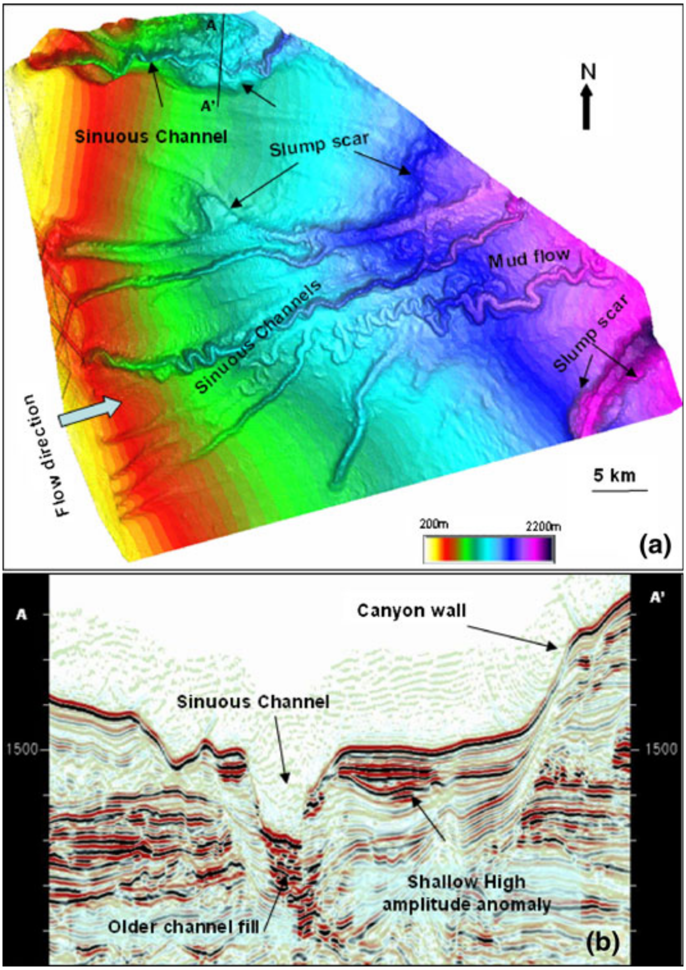

Fig. 3 **a** Three-dimensional visualization of bathymetry map prepared from 3D seismic data. The area is a part of deep water Cauvery offshore. A number of canyons, sinuous and *straight* channels are identified. **b** Few high-amplitude seismic reflectors are identified beneath water bottom. If they correspond to *shallow* gas-charged sands, then these could be hazardous

yield strength) and/or by skeleton stresses (i.e. contact between grains) (Hampton et al. 1996; Iverson 1997). In a seismic section, these are represented by chaotic reflectors and transparent zones. The surface morphology of mass transport deposits exerts an important control on sediment pathways during the subsequent sedimentary system, until the topography created on top of the mass transport deposit is covered (Dykstra and Kneller 2002; Dykstra 2005). Large-scale deposits can redirect sediment pathways hundreds to thousands of square kilometers of area on the seafloor (Kneller and Dykstra 2003). Hence, any installation along the path of mass transport movements can be affected. A present-day sea bottom map prepared from 3D seismic data shows the presence of mass transport complexes which are active today. Figure 4 shows similarity attribute extracted from the 3D seismic data demonstrating various features associated with mass movements in Krishna–Godavari basin. Similar features are also identified from other basins off the east coast. These areas could be termed hazard-prone.

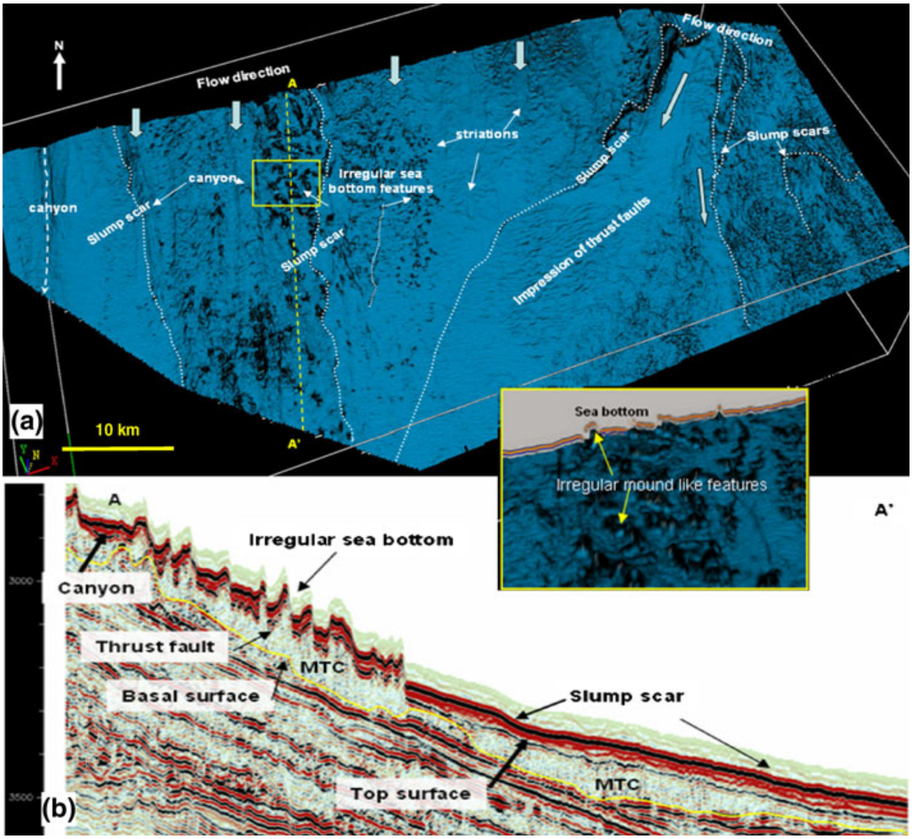

Fig. 4 **a** Semblance attribute overlaid on a seabed relief map *bottom* is presented to describe the geomorphic features of the eastern offshore. Presence of slump scars and striation marks are characteristic features of a mass transport movement. *Block arrow* marks represent different inlets for sedimentation. The *inset* shows a zoomed feature of the sea mounds, and the seismic section shows the irregular mound-like features. **b** Seismic section showing the nature of the irregular water bottom formed due to toe thrust related to mass transport movement. *MTC* mass transport complex

4.5 Sediment waves

Conspicuous wavy-shaped seismic reflectors are identified in 3D seismic data from deep water areas in the eastern offshore (Fig. 5) and can be termed as sediment waves. These features form in response to spillover and flow stripping from channels of the predominantly dilute fine-grained turbidity flows. Sediment waves are common features on submarine channel levees (McHugh and Ryan 2000; Normark et al. 2002; Wynn and Stow 2002). Study of present-day deep water sediment waves can be used in predicting hazardous area, which should be avoided during any subsurface installation. These can be related to active submarine flows which should be identified and characterized for hazard identification. Sediment waves are identified from a number of locations along east coast of India. Seismic sections shows well-developed sediment waves at various places. At some places, these are related to channel-levee complexes and at other places are associated with mass transport complexes. In both cases, these features show active sediment movement and remobilization. Due to their significant height and length, sediment movement of this scale can be hazardous to subsea installation.

4.6 Shallow faults

Very small scale faults could be identified near to the water bottom in the area between the outer shelf and the inner slope off the Godavari delta, which could be interpreted as synsedimentary listric faults and associated gravitational sediment loading. A representative seismic section shown in Fig. 6 depicts these faults. These faults are small in size and are not deep rooted. Hence, these faults are therefore not associated with tectonic movements and seismicity. The scarps they produce on the seafloor are much steeper and hence can trigger slumps. In some cases, these faults can also act as failure surfaces along which a large mass of younger sediments can move down. Hence, any drilling or heavy subsea installation in this zone can lead to mass failure.

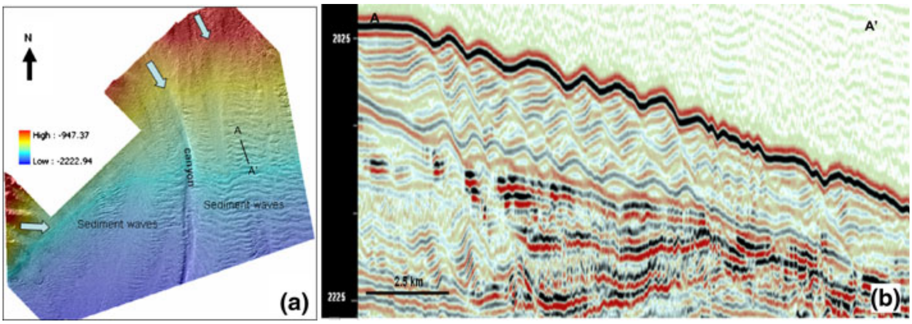

Fig. 5 **a** Multibeam bathymetry map from deep water region in the Mahanadi offshore showing the presence of sediment waves. A well-developed submarine canyon is seen to be running from north to south. The sediment waves, which form due to flow stripping, are present on the flank of the canyon features. **b** Seismic section (TWT) showing seismic signature of the sediment waves. As can be seen from the section, each wave is having a length of around 1 km and height of 30 to 50 m. This *huge* shape of the waves describes the high energy associated with the formation

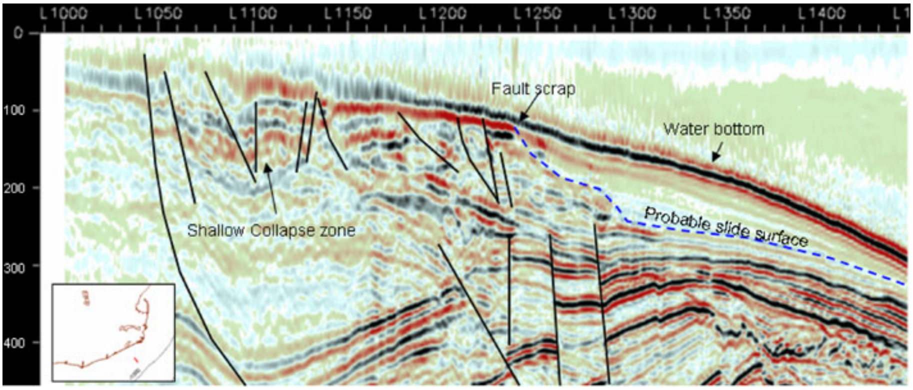

Fig. 6 A depth section from *shallow* water region of Godavari offshore showing interpreted shallow faults. These faults can act as conduit for gas seep or planes for sliding. In both cases, the faults can create hazards to drilling or any subsea installation

4.7 Gas hydrate

Gas hydrates are being studied around the world as a future source for gas reserve as well as a geohazard which can create problem during drilling. Kvenvolden (1999) summarized the connection between gas hydrate and slope failures in various continental margins. Gas hydrates are stable under low temperatures and high pressures. The hydrate stability zone in marine environments is a function of the water depth, the seafloor temperature and the geothermal gradient. The hydrate stability zone maps for the east coast of India have been prepared by several researchers. A number of areas identified based on the presence of BSRs in the eastern offshore of India (e.g. Chaudhuri et al. 2002; Mathur et al. 2007) reveal potential zones for gas hydrate accumulation (Fig. 7). A representative seismic section showing such BSR is shown in Fig. 7. Detailed analysis should be made using seismic data and shallow core before concluding the presence of gas hydrate zone. Gas hydrates could significantly reduce the submarine slope stability (Nixon and Grozic 2006), and the presence of shallow gas in the above zones can also be hazards, especially when over-pressured, then constituting a significant drilling hazard.

4.8 Mud volcanoes

Mud volcanoes have been reported from both passive as well as active margin setups (Milkov 2000). Bathymetry maps from 3D seismic as well as multibeam data set have brought out mound-like features, which have been interpreted as mud volcanoes. On a seismic section, it presents as a vertical zone with transparent seismic signature and looks like a pillar-type structure (Fig. 8). The amplitudes within the pillar are wiped out with a mound sitting above it. This vertical reflection-free zone below the center of the mud volcano can be interpreted as the feeder dike (Graue 2000; Stewart and Davies 2006). Submarine mud volcanic activity may impact drilling operations, ring installations and pipeline routings. The mud volcano structure affects wells drilled for oil and gas production as the mud is associated with poorly constrained pore pressure and fracture strength which in turn affect the stability of boreholes (Ebrom et al. 2004).

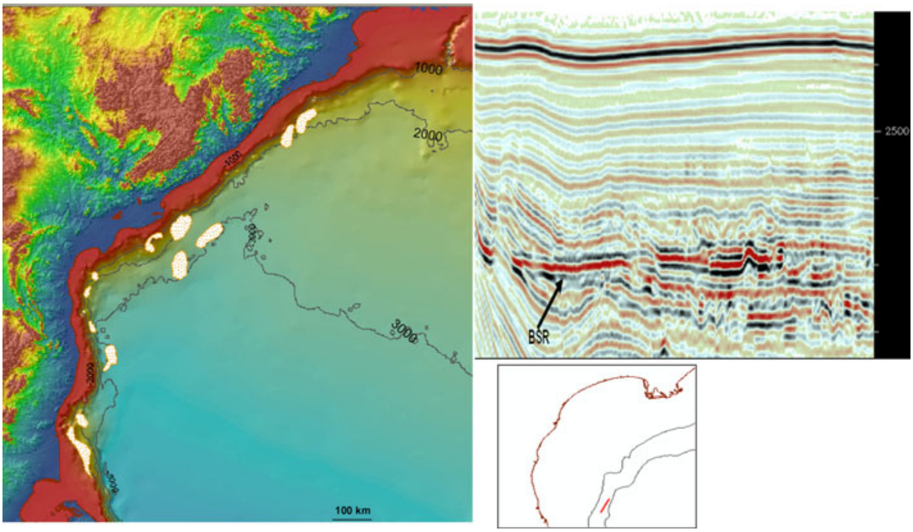

Fig. 7 *Map* showing potential areas of gas hydrates based on interpretation of BSR in the eastern offshore of India (modified after Mathur et al. 2007). Seismic section showing the presence of BSR in the east coast of India (location shown in the *inset*)

4.9 Pock marks

Seabed pockmarks are concave, crater-like depressions that are found to be associated with the release of gas or fluids from the subsurface (King and MacLean 1970; Hovland and Judd 1988). A number of pockmarks have been identified from the multibeam map off eastern offshore of India (Fig. 9). Pockmarks are generally formed in soft, fine-grained seabed sediments by the escape of fluid or gas into the water column (Hovland and Judd 1988). These represent an important global mechanism for degassing deeply buried sediments and contribute significant volumes of fossil methane to the atmospheric budget (Judd 2005; Kvenvolden and Rogers 2005). These can be identified from high-resolution multibeam maps as high backscatter values due to the presence of calcareous material produced from organisms which live on seeped gas from the seafloor.

4.10 Gas chimney

Chimneys indicate upward migration of gas from the deep to the shallow prospect (Heggland 2004), and shallow gas can cause problems during drilling. An interpreted gas chimney is indicated on a seismic section from the eastern offshore of India (Fig. 10). The chimney is of inverted cone-type shape with low amplitude. The nearly ubiquitous gas blanking shows that there is active fluid flow occurring in the area evidenced by observations of possible gas seeps in the water column. The gas probably is transported upwards in solution with migrating pore water that is being expelled as sediments undergo compaction due to rapid sedimentation. As the pore water rises, pressure decrease releases gas. Few high-amplitude anomalies identified near to the gas chimney indicate charging of reservoir facies through the fault. This high amplitude indicates a risk of a gas

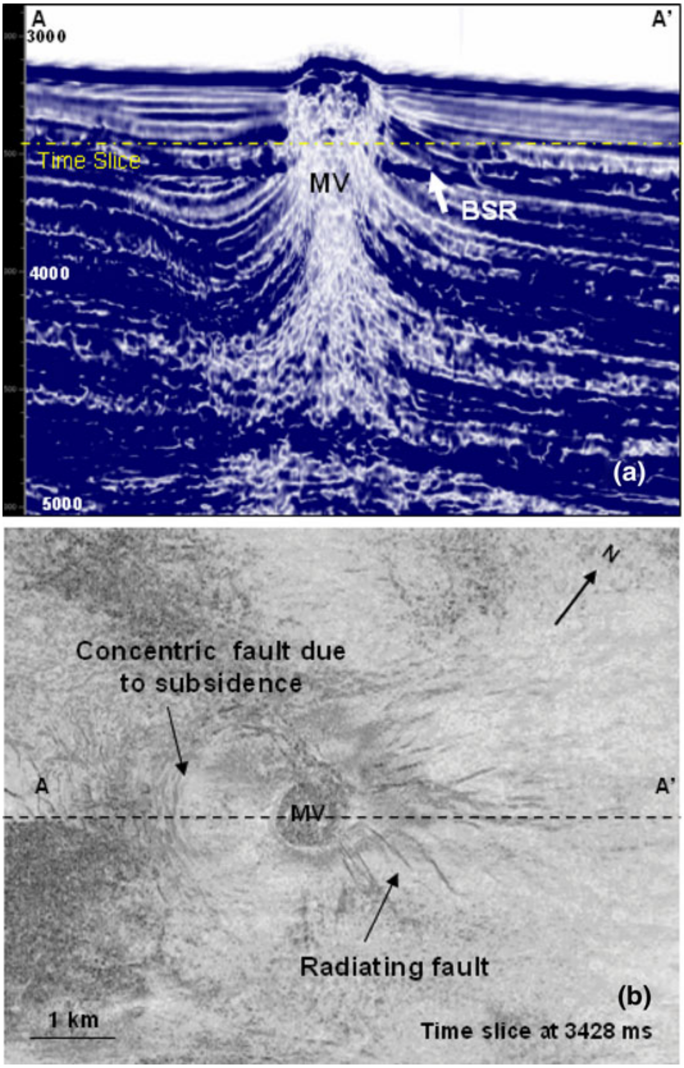

Fig. 8 **a** Reflection strength extracted along a seismic section showing a *white-colored plume*-shaped feature corresponds to loss of amplitude zone identified as the mud volcano. At around 3500 ms, a seismic reflector cross-cutting other reflectors is seen and is interpreted to be a BSR. **b** Presents a time slice derived from coherency attribute showing the mud volcano and related features. In the time slice, the circular feature depicts the mud volcano. It can be seen that there are a number of faults encircling it while there is another set that seems to radiate from the volcano. The concentric faults are supposed to be originated due to collapse of the surrounding sediments, while the radiating ones are generated due to the piercing effect of the volcano

accumulation in the shallow reservoir. Amplitude maps are used to identify amplitude anomalies representative of shallow gas accumulations as well as identify faults. As the gas chimneys cause active gas seepage, any drilling activity near to this can lead to disastrous events.

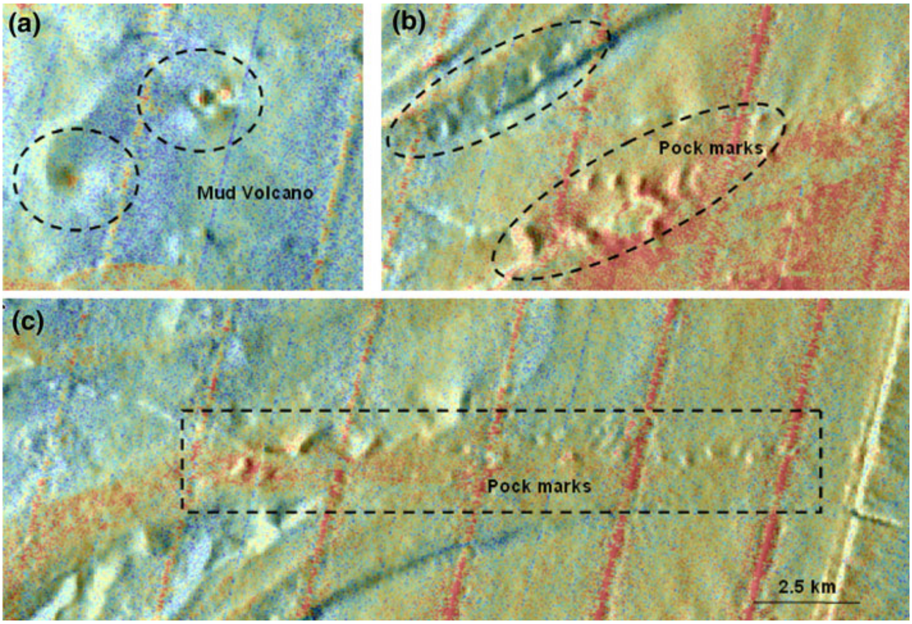

Fig. 9 *Backscatter* image overlaid on multibeam bathymetry data from deep water area of Krishna basin shows identified mud volcanoes and pockmarks. **a** Two topographic positive mounds interpreted to be mud volcanoes are denoted. In figure **b** and **c**, small depressions on sea bottom are interpreted as *pock marks*. Some of these also show high *backscatter* values

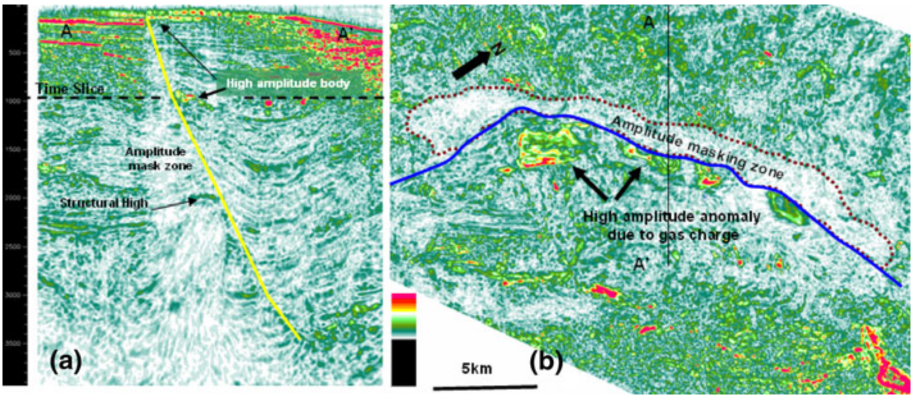

Fig. 10 **a** Reflection strength along a seismic section from Godavari offshore showing the presence of amplitude blanking zone associated with a well-defined fault. A high-amplitude anomaly near the fault points out probable gas charge along the fault. A time slice extracted along 1,000 ms (TWT) is also shown in figure. **b** Shows the spatial disposition of the amplitude masking zone and high-amplitude anomaly related to the fault

5 Summary and conclusions

The present paper brings out a simple and generalized picture of various geohazards found on the east coast of India based on available seismic, mulitbeam and side scan sonar data

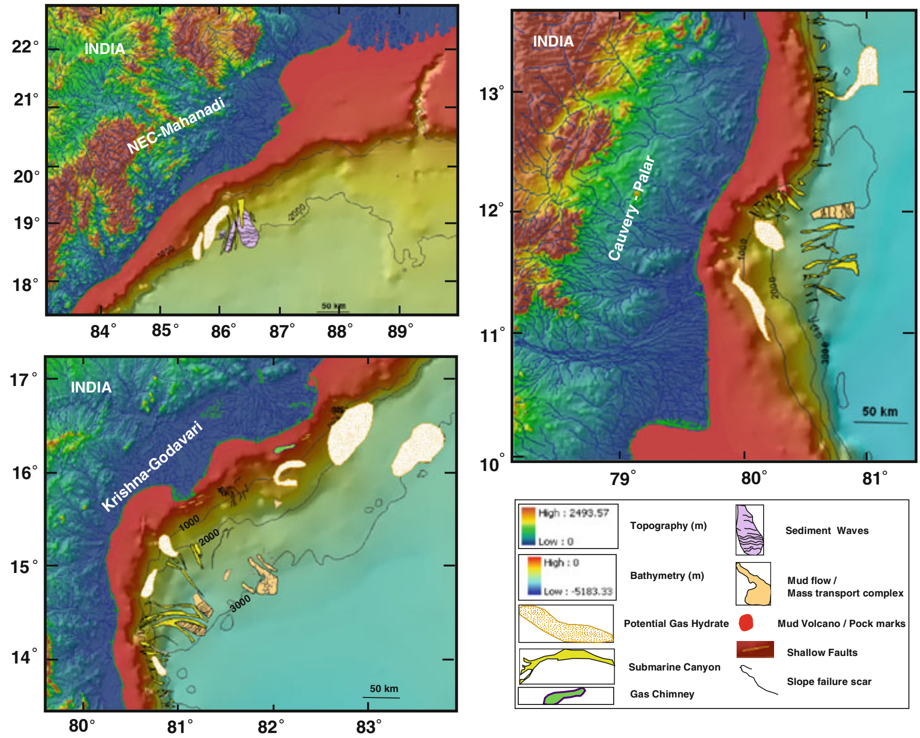

Fig. 11 Maps summarizing the identified submarine geohazards in the eastern offshore of India

set. Three different maps summarizing various geohazards along the eastern offshore have been presented for Cauvery–Palar, Krishna–Godavari and NEC–Mahanadi basins in Fig. 11. From these maps, it can be concluded that the slope stability and slope canyons are the important geohazards throughout the east coast of India. The presence of large mass of transport complexes off the Krishna–Godavari should be treated with utmost care. Gas chimneys, mud volcanoes or gas seep-related features are not so common in the area. A number of locations prone to the presence of gas hydrate are also present in the offshore. With no lithologic information available for interpretation, the study is purely based on seismic and published analogues. Shallow core analysis would be more useful for detailed study. Further, the study does not rule out the presence of any other type of geohazards due to the lack of detailed data in many areas.

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