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ORIGINAL RESEARCH PAPER

A seismic study to investigate the prospect of gas hydrate in Mahanadi deep water basin, northeastern continental margin of India

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Abstract The presence of gas hydrates, one of the new alternative energy resources for the future, along the Indian continental margins has been inferred mainly from bottom simulating reflectors (BSR) and the gas stability zone thickness mapping. Gas hydrate reserves in Krishna Godawari Basin have been established with the help of gas-hydrate related proxies inferred from multidisciplinary investigations. In the present study, an analysis of 3D seismic data of nearly 3,420 km^2 area of Mahanadi deep water basin was performed in search of seismic proxies related with the existence of natural gas hydrate in the region. Analysis depicts the presence of BSR-like features over a large areal extent of nearly 250 km^2 in the central western part of the basin, which exhibit all characteristics of a classical BSR associated with gas hydrate accumulation in a region. The observed BSR is present in a specific area restricted to a structural low at the Neogene level. The coherency inversion of pre-stack time migration (PSTM) gathers shows definite inversion of interval velocity across the BSR interface which indicates hydrate bearing sediments overlying the free gas bearing sediments. The amplitude versus offset analysis of PSTM gathers shows increase of amplitude with offset, a common trend as observed in BSR associated with gas hydrate accumulation. Results suggest the possibility of gas hydrate accumulation in the central part of the basin specifically in the area of structural low at the Neogene level. These results would serve as preliminary information for selecting prospective gas hydrate accumulation areas for further integrated or individual study from geophysical, geological, geochemical and microbiological perspectives for confirmation of gas hydrate reserves in the area. Further, on the basis of these results it is envisaged that biogenic gas might have been generated in the region which under suitable temperature and pressure conditions might have been transformed into the gas hydrates, and therefore, an integrated study comprising geophysical, geological, geochemical and microbiological data is suggested to establish the gas hydrate reserves in Mahanadi deep water basin.

Keywords Gas hydrate · Bottom simulating reflection · Seismic proxies · Mahanadi deep water basin · Coherency inversion of PSTM gather

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Introduction

The ever-increasing demand for sustained industrial growth has forced all of us to look for renewable and alternate energy resources such as coal bed methane in coal seams, gas found in shale, and gas hydrates found below or on the ocean floor in form of ice-like substances. Natural gas hydrates do have the potential of becoming an alternate energy resource due to their huge deposits envisaged worldwide (Kvenvolden 1993a; Collett 2002). Gas hydrates have received much attention because they are a possible future alternative non-conventional energy resource, and because their destabilization on the continental shelf may play a role in global climate change. There are a number of studies describing the significance of gas hydrates, occurrence and genesis of this valuable deposit both in permafrost regions and marine sediments of continental slopes (e.g. Kvenvolden 1993b; Holbrook et al. 1996; Lee et al. 1996; Sloan 1997; Ginsburg and Soloviev 1998; Collett et al. 1999; Collett and Ladd 2000; Milkov and Sassen 2001; Collett 2002; Tréhu et al. 2002, 2004; Bunz et al. 2005; Ghosh and Sain 2008; Hornbach et al. 2008; Westbrook et al. 2008; Hustoft et al. 2009: Ramana et al. 2009).

Gas hydrates are white, crystalline, ice-like materials composed of a methane molecule surrounded by a cage of water molecules. The hydrates are mostly methane rich, but are sometimes associated with ethane, propane, butane, carbon dioxide and hydrogen sulfide. The gas hydrates are generally found in the permafrost and outer continental margins of the world where the methane concentration exceeds its solubility limit (Sloan 1997; Kvenvolden 1993b, 1995, 1999). Moreover, samples of natural gas hydrates have been recovered on land in the western Prudhoe Bay oil field in Alaska (Collett 1993) and in the Mackenzie delta of Canada (Dallimore et al. 2002). These are formed at high pressure (8–30 MPa) and low temperature (10°–20°C) in shallow sediments, and are stable up to a few 100 m below the sea floor. Methane trapped in hydrates and free gas below the hydrate-bearing sediments is found in huge amounts. India has also begun active research in establishing gas hydrate reserves in its east and west coasts by collecting geophysical, geological, geochemical and microbiological data under its Natural Gas Hydrate Program (NGHP) initiated and funded by the Ministry of Petroleum and Natural Gas, Government of India.

Gas hydrates are mostly identified by mapping bottom simulating reflectors (BSR) on seismic sections (Shipley et al. 1979; Yuan et al. 1996; Sain et al. 2000; Dewangan and Ramprasad 2007). A BSR is recognized based on its characteristic features such as; (1) mimicking the shape of the sea floor as a BSR follows isotherms which are nearly parallel to the morphology of the sea floor, (2) cutting across the underlying/overlying dipping strata and (3) exhibiting large amplitude but opposite polarity to that of the seafloor reflections. The presence of gas hydrates reduces the permeability of the sediments and hence traps free gas underneath. Thus the bottom simulating reflector is an interface between gas-hydrate-bearing sediments above and free-gas-saturated sediments below the interface and is often associated with the base of the gas hydrate stability field. The BSR may not be continuous but patchy, indicating an upward gradational hydrate layer above and downward gradational free gas layer below the BSR. Most of the gas hydrates worldwide have been inferred from BSR and Gas Hydrate Stability Zone (GHSZ) thickness maps. The Gulf of Mexico, Blake Ridge, Cascadia Margin, Mackenzie Delta and Nankai trough are some of the excellent examples of this category (Dallimore et al. 1999; Wood and Ruppel 2000; Hyndman et al. 2001; Ashi et al. 2002; Holbrook et al. 2002; Hornbach et al. 2008). On the other hand, some of the BSR proven areas yielded no gas hydrates on drilling, for example some of the areas covering Blake Ridge, Nankai trough, offshore Goa and west coast of India, are examples of this category. Moreover, at many places in the world, the gas hydrates have been reported without BSR (Holbrook et al. 1996). This implies that every inferred BSR does not necessarily indicate the presence of gas hydrates; sometimes lithology gives such pseudo-reflections. The presence of double BSR on seismic sections is also reported by Posewang and Mienert (1996), which causes an enigma to the hydrates stability zone calculation. Therefore, in addition to geophysical anomalies, such as BSRs, pockmarks, gas up-thrust zone, vents, blanking zones, etc., other non-geophysical (geochemical and microbial) proxies are also very important and should be examined for ascertaining the gas hydrates and mitigating the exploration risk for gas hydrates.

Almost all giant oil fields in the Gulf of Mexico, Caspian Sea, and Mediterranean Sea are proven to be associated with gas hydrate accumulation in the upper few hundred meters of sediment. The permafrost regions (Siberia in Russia, Mackenzie delta in Canada and Alaska) known for their conventional hydrocarbon reserves are also associated with gas hydrate deposits. Therefore, it is believed that the areas of conventional hydrocarbon prospects could be locales of gas hydrate deposits provided geological formations meet the requirements of high pressure and low temperature. Some of the offshore basins of India such as Saurastra, Mumbai, Kerla-Konkan, Krishna-Godavari, Cauvery and Mahanadi along the Indian continental margins are well known petroliferous basins. A map of gas hydrate accumulation along Indian continental margins (Fig. 1) has been prepared by the National Institute of Oceanography (NIO), Goa. The gas hydrate stability zones thickness map of the east coast of India and Bay of Bengal (Fig. 2) have been prepared by NIO, Goa, using Miles (1995) concept on the basis of available data for bathymetry, heat flow, seabed temperature and geothermal gradient etc., within the EEZ of India (Rastogi et al. 1999; Sethi et al. 2004; Ramana et al. 2007). Geophysical, geochemical and microbiological proxies observed along the east coast of India have suggested a strong indication for gas hydrate deposits in Krishna Godawari (KG), Cauvery, and Andaman Basins (Ramana et al. 2006; Satyavani et al. 2008). The drilling by the *JOIDES Resolution* drill ship under NGHP Expedition-1 has confirmed the presence of massive gas hydrate accumulation (>80 m thick) in KG Basin (Collett et al. 2008). In Mahanadi deep water basin, BSR-like anomalous features are reported in many areas, but a thorough analysis of data for other geophysical and

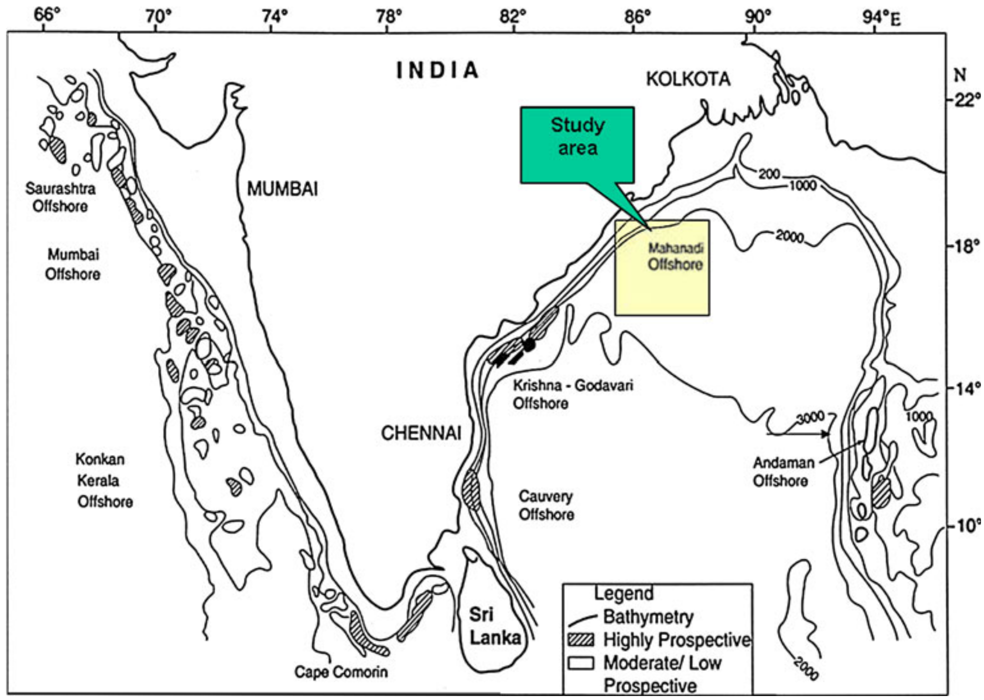


Fig. 1 Map depicting prospective area for gas hydrate along Indian margins (after Ramana et al. 2006)

non-geophysical (geochemical and microbiological) proxies are needed to establish the presence of gas hydrate accumulation. Therefore, in the present study, an attempt is made to analyze the 3D seismic data of Mahanadi deep water areas in a search for BSR-like features which are present conspicuously in a certain part of the basin area. The velocity and amplitude (VAMP) study of BSR is performed and the velocity inversion is carried out to examine whether these BSRs are due to gas hydrate accumulation in the basin.

Geological setting

The Mahanadi Basin is one of the several sedimentary basins developed along the east coast of India as a result of rifting and break-up of Gondwanaland during the Jurassic period. This basin covers an estimated area of over 50,000 km^2 of which nearly one fourth is onshore and the rest is offshore. Tectonically, these basins are developed around a triple junction between the NE-SW trending east coast of India (which represents an Atlantic type passive continental margin) and the NW–SE trending Mahanadi graben within the Indian shield (Fuloria 1992; Subrahmanyam et al. 2008). The Mahanadi Basin is separated from KG Basin by 85°E Ridge. The major tectonic features are shown in Fig. 3 (Fuloria 1992). The hydrocarbon prospects of the offshore basin are rated good and it belongs to a petroleum province (Jagannathan et al. 1983; Fuloria 1993; Bastia 2006). The deep-water part of Mahanadi Basin has attracted much exploration attention because of its proximity to the deep-water area of KG Basin which has proven to have huge gas reserves and is an area of recent gas discoveries.

Paleogene and Neogene sections in the Mahanadi deep-water basin exhibit channel complexes that are highly sinuous and often stacked vertically due to shifting of a depositional axis both in space and time (Nath et al. 2006). A sinuous channel-levee complex often results in submarine fan lobes towards the deeper part of the basin. Incised valley and valley fill sequences are also prevalent during Paleogene and Neogene periods.

Data and methodology

A multi-streamer 3D seismic survey was carried out in an area of 1,820 km^2 with a grid of 12.5 by 25 m. The acquisition parameters are given in Table 1. Standard 3D seismic data processing, consisting of the processing sequence as stipulated in Table 2, has been carried out. Special data processing care has been taken to preserve true amplitude of the reflectors. Very close velocity analysis on PSTM gathers has been carried out to obtain the best estimate of the interval velocity field in the specified areas depicting BSRs. Amplitude versus offset (AVO) analyses of BSR are also performed. An areal mapping and delineation of these bottom simulating reflectors are carried out to examine the correlation between the structural low at the Neogene level and probable gas hydrates accumulation. Post-stack data analyses were also carried out to look for BSR in the adjoining areas which were covered by 3D Q

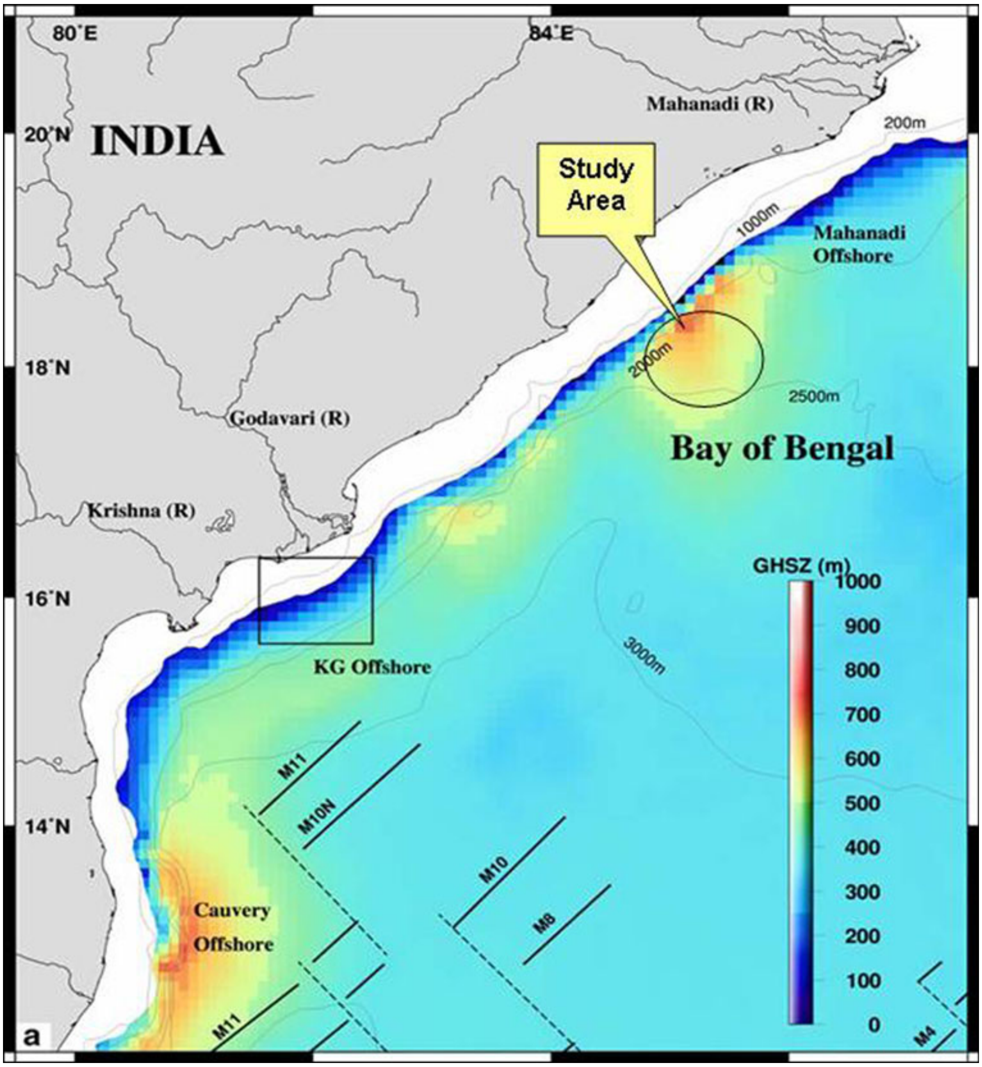


Fig. 2 Gas hydrate stability zone (GHSZ) map showing the thickness of gas hydrate stability zone (in meters) for the eastern continental margin of India (NIO 1997). Thin continuous *lines* are depth contours (m), *dashed lines* and *thick lines* are oceanic fracture zones and magnetic anomaly lineation, respectively (Ramana et al. 2001). The map shows the GHSZ thickness in study area in Mahanadi deep water basin (*encircled*) of the order of 600–700 m

marine technique keeping the same acquisition and processing grid. A total of 3,420 km^2 3D data were analyzed for the study.

Results and discussion

The study area covers the mid slope to abyssal region of the eastern continental margin of India. Depth of the sea bed varies from 200 to 2,700 m with steep slope from 200 to 2,200 m in the northern part and a gentle increase in water depth up to 2,700 m in the southern part. The Neogene section in the area comprises predominantly clay-stones with minor sand and silts. Polygonal faults are dominant in upper few hundred meter sections (Fig. 5). The 85° East Ridge passes through the middle of the study area. The gas escape features such as gas chimney, zones of gas masking/saturation, and mud diapirs are not seen clearly on the seismic sections of the area. The possible reason for this could be the low frequency seismic data (3–120 Hz) acquired for hydrocarbon exploration with deeper interest. The seismic sections in the area show the presence of BSR-like anomalous reflections 300–400 ms below the seabed. These BSR-like features are distinct and follow the characteristic features such as mimicking the seafloor, polarity reversal, cross-cutting the lithological formations, and blanking above and below the BSR. Figure 4 shows a PSTM gather depicting BSR reflection with opposite polarity to the sea bottom reflection. The bottom simulating reflections are very strong at some locations and feeble at

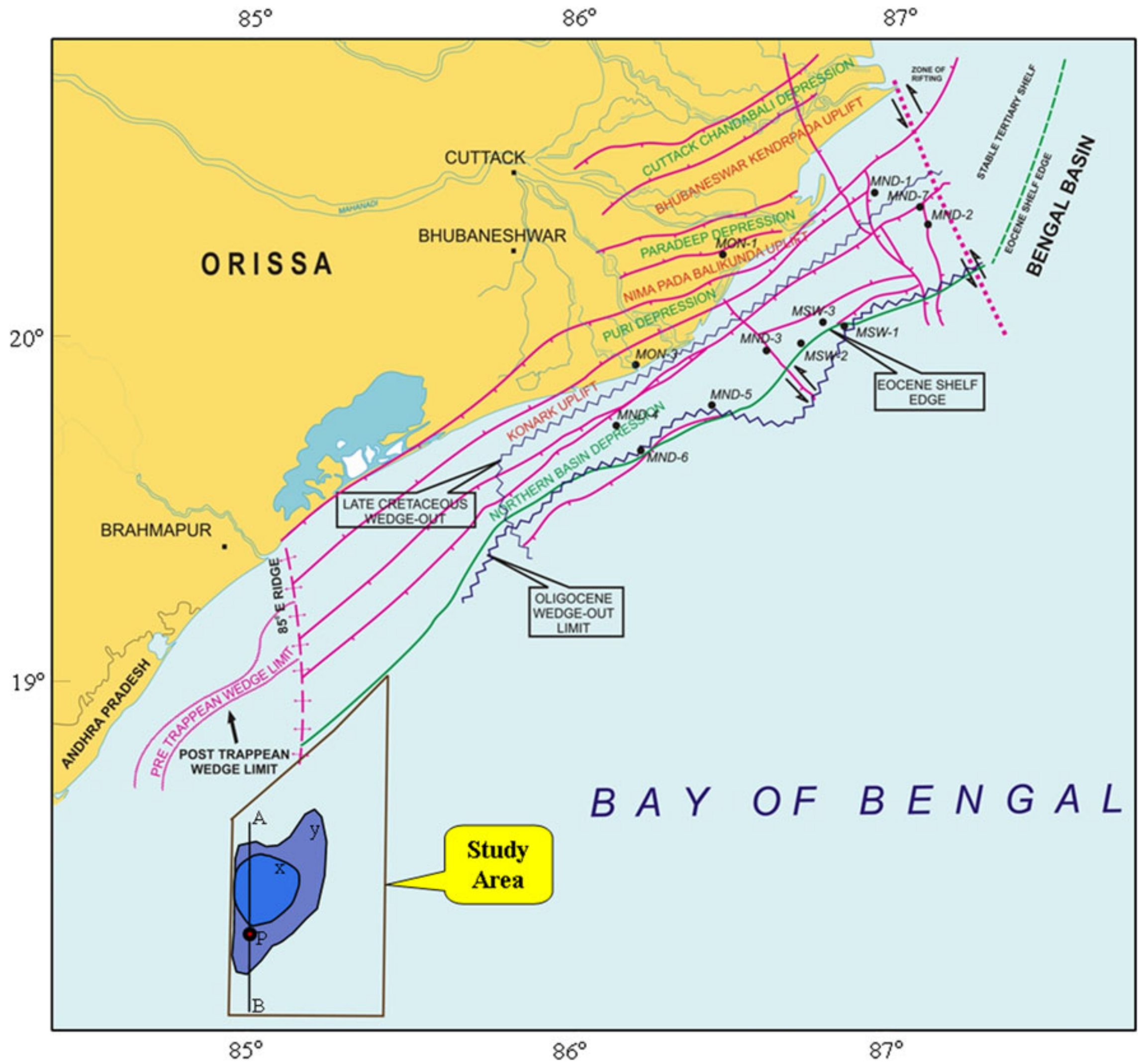


Fig. 3 Map showing the major tectonic features in Mahanadi Basin (modified after Fuloria 1992). Point P shows location of the velocity analysis panel shown in Fig. 7. *Line AB* indicates the location of the seismic section shown in the Fig. 5. The area X shows the low at the Neogene level and the depositional centre. Area Y depicts the gas hydrate deposits based on the mapping of BSR

other places. The reflection strengths of BSRs may be attributed to the saturation of free gas beneath the reflector as well as upward gradation of gas hydrate and its saturation level.

Seismic sections in the western middle part of the area show very strong BSR (Fig. 5), but in the eastern part of the area BSR-like reflections are absent, although the seafloor depth is of the same order. The analysis of 3D seismic data in the area reveals that these BSR reflections are present in the region of structural low at the Neogene level, indicating thereby that the gas hydrate accumulation may be restricted in and around the depositional center. In these areas, the sedimentary thickness is more than the usual thickness in the area and therefore the methane gas generation might be restricted to this depositional center. The gas hydrate stability zone thickness calculated using these BSRs (Fig. 4) is found to be of the order of 350–450 m, which is lower than the GHSZ thickness (600–700 m) in Mahanadi Basin area estimated by Rastogi et al. (1999) and NIO (1997) on the basis of geothermal gradient, sea bed temperature, and bathymetry data (Fig. 2). The difference may be attributed to the estimation errors of geothermal gradient, sea temperature, heat flow, interval velocity, etc. However, the estimate of GHSZ thickness calculated by seismic methods should be more reliable. On the basis of mapping of GHSZ thickness, it can be envisaged that the thin GHSZ areas might be indicative of fluid flow, and thus likely areas of methane flux that could generate gas hydrate deposits. The BSRs are mapped and delineated throughout the area and the areal extent of these features is quite large, of the order of 250 km^2 in the central western part of the area. The areal distribution of

Table 1 Seismic data acquisition parameters

No. of streamers	6
Receiver interval	25 m
Fold	62
Record length	10 s
Low cut filter	3 Hz @ 12 dB/oct
Gun depth	6 m
Recording format	SEGD
No. of receivers	240
Shot interval	25 m flip-flop
Bin size	12.5 × 25 m
Sample interval	2 ms
High cut filter	206 Hz @27 dB/oct
Cable depth	7 m

Table 2 Conventional seismic data processing sequence

Bad SP and traces editing
Band pass filter
Automatic de-spiking
Navigation data merge
Spherical divergence correction
Swell noise attenuation
Radon linear noise attenuation
De-signature to minimum phase and reverse polarity
Tidal correction
Deconvolution
Radon anti-multiple flex binned
Gun/cable static correction
Spherical divergence correction removal
Kirchoff PSTM for velocity analysis
Velocity field generation
Full volume Kirchoff PSTM
Residual velocity analysis
Final stack
Final scaling/filtering

the BSRs in the study area is shown in Fig. 3. The area in blue colour (Fig. 3) depicts the possible gas hydrate deposits in the block. Figure 6 shows the distribution of the BSRs which is restricted to the central-west part of the area. Our findings predict that this area is the most promising for the detailed gas hydrate exploration in this part of the Mahanadi Basin.

Coherency inversion of PSTM gathers (Fig. 7), indicates a velocity inversion at the base of the BSR. The interval velocity reduces from 1,750 to 1,520 m/s across the BSR. The interval velocity of hydrate bearing sediment above the BSR is lower than the interval velocity usually encountered in the classic cases. This might be due to the low hydrate saturation in the sediments and/or the presence of clay

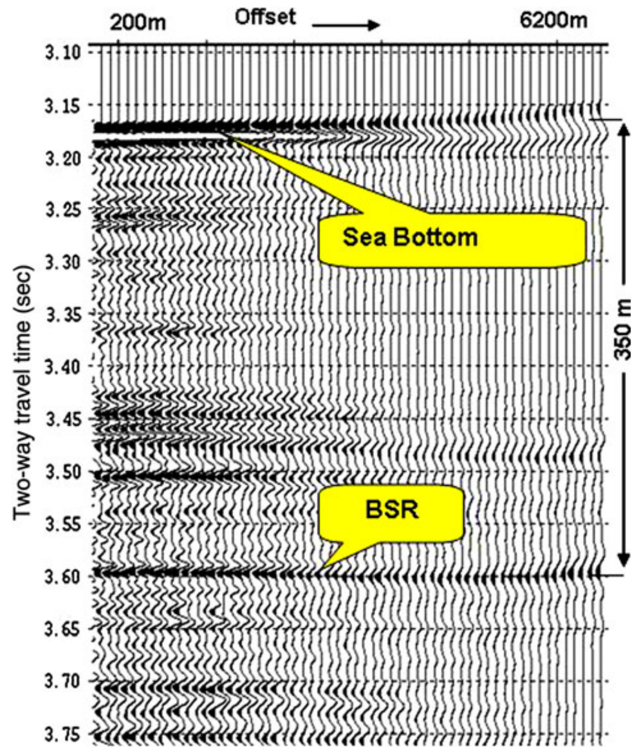


Fig. 4 PSTM gathers showing BSR polarity opposite to that of sea *bottom* reflection

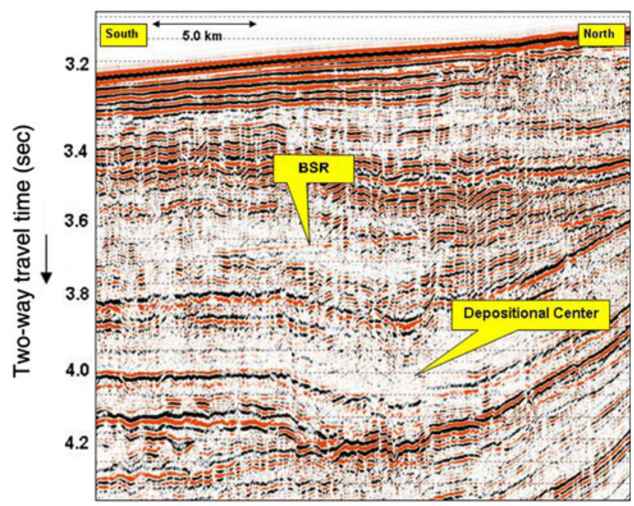


Fig. 5 Seismic section showing BSR and sagging at Neogene level (Inline-A)

sediments in the host rock. The drilled wells in the area also confirm the presence of clay in the top few hundred meters from the sea bed. However, the presence of very good reflection events in Fig. 5 may be due to some silt content, fine sand layers, and laminated clay layers in the top few hundred meters of lithological section. Extensive faulting in the shallow seismic section is polygonal in nature and may be the result of fluid expulsion during the

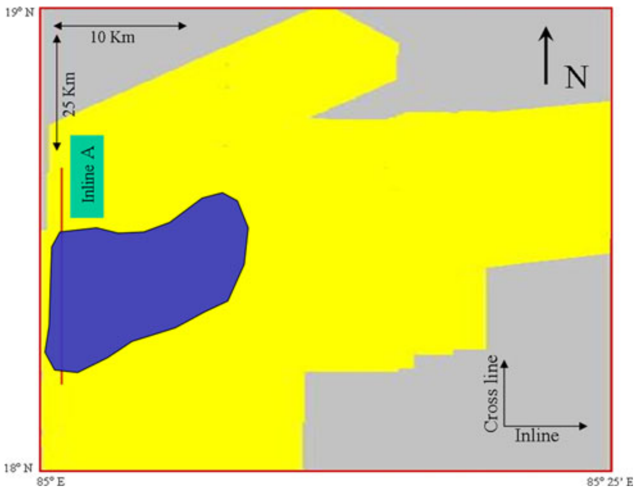


Fig. 6 Base map of the study area (shown in yellow) showing the areal extent of the BSR (in blue) corresponding to the area marked Y in Fig. 3

digenetic processes and neo-tectonics in the area. Further, a correlation of a depositional model in the area with the GHSZ thickness reveals that the clay-dominant depositional center, the possible gas hydrate deposition area in Mahanadi deep water basin, is associated with a thin gas hydrate stability zone.

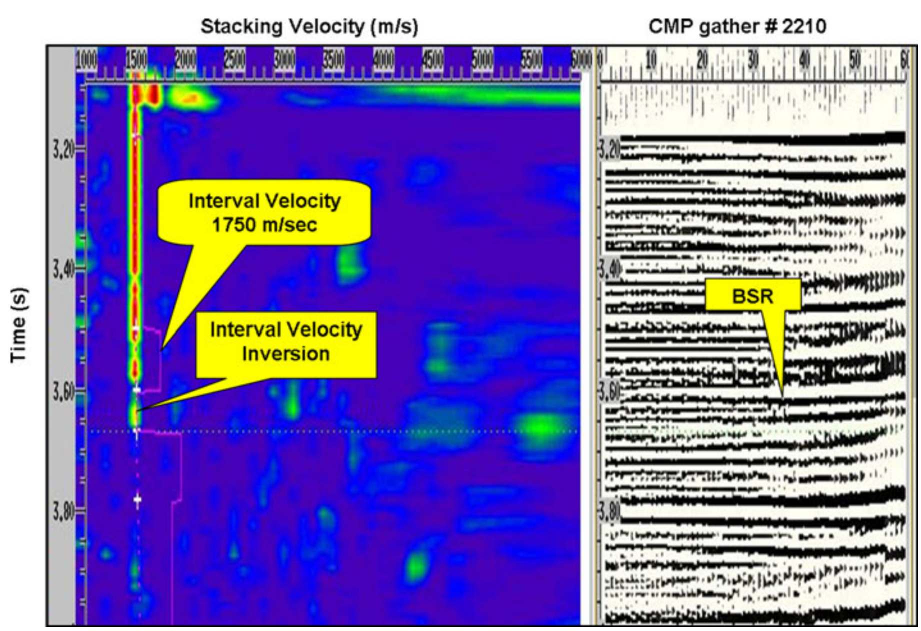
AVO analysis of PSTM gathers show increase of amplitude with offset, which indicates that sediments below the hydrate might be saturated with free gas. Similar results are also reported by Ecker and Lumley (2001) in the Blake Outer Ridge area. AVO analyses of BSR have been carried out by many geoscientists (e.g. Ecker and Lumley 1993; Uma Shankar et al. 2004; Xun et al. 2004; Chen et al. 2007; Rajput et al. 2010). Figure 8 shows AVO response of a particular PSTM gather. From Fig. 8, it can be observed that the BSR shows noticeable increase of amplitude with angle. Normally, the BSR shows increase in amplitude with offset; therefore, the observed AVO response for BSR is similar to that expected.

Conclusion

In order to investigate the prospect of exploration of natural gas hydrate in northeastern continental margins of India, 3-D seismic data of the Mahanadi deep water basin covering an estimated area of approximately 3,420 km^2 were analyzed in search of geophysical proxies, viz. bottom simulating reflectors (BSR), associated with the gas hydrate accumulation in the area. Special processing, such as velocity and amplitude study (VAMP) and velocity inversion were carried out to examine the characteristics of BSR and inspect whether these BSR are due to the gas hydrate accumulation in the area.

The analysis of 3-D seismic data depicts BSR-like features, a proxy for gas hydrate accumulation, in the central part of the area confined to the areas of structural low at the Neogene level. The BSR observed in this area fulfill all the characteristics of a classic case of gas hydrate accumulation, such as polarity reversal, cross-cutting the formation, velocity inversion across the BSR, and blanking above and below the BSR. The coherency inversion of PSTM gathers shows definite inversion of interval velocity below the BSR (i.e. 1,750 m/s above the BSR and 1,520 m/s below the BSR). The geological preconditions such as high rate of sedimentation, adequate depth and temperature coinciding with the

Fig. 7 Velocity panel showing interval velocity inversion below BSR. The interval velocity across the BSR reduces from 1,750 to 1,520 m/s



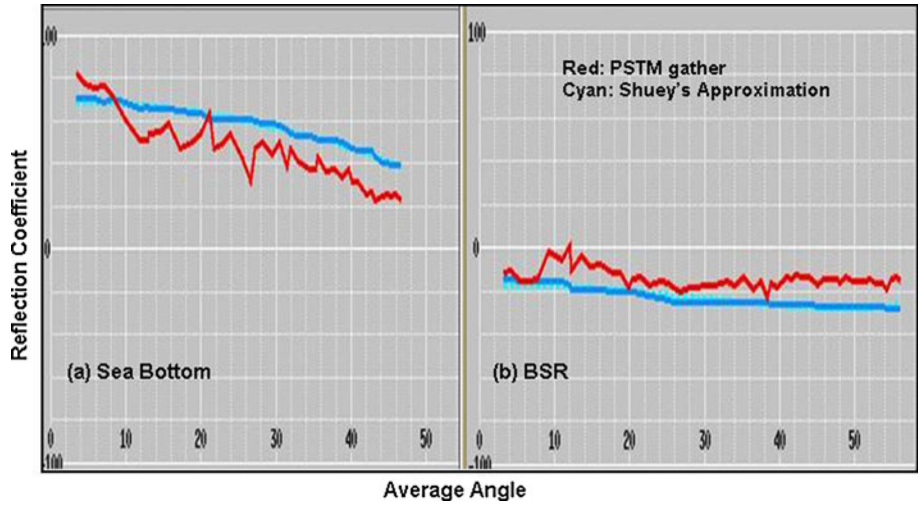


Fig. 8 AVO response showing amplitude variation with average angle θ for (**a**) Sea bottom reflection, (**b**) BSR reflection. Theoretical calculation using Shuey (1985) approximation matches the observed trend

delineated BSR indicates gas hydrate accumulation in Neogene sediments in Mahanadi deep water basin. Delineation and mapping of bottom simulating reflectors indicate a large area of the order of 250 km^2 in the central part of the basin as a probable gas hydrate accumulation area in Mahanadi deep water basin. The AVO responses of BSR suggest the presence of free gas below the hydrate sediments. The low order of interval velocity (1,750 m/s) of the hydrate layer might be due poor saturation of hydrate in the sediments.

These results would furnish a basis for further studies in the area for exploration of gas hydrates. Therefore, on basis of these results, an integrated study of geophysical and non-geophysical (geological, geochemical and microbiological) data is recommended for confirmation and exploration of gas hydrates in the Mahanadi deep water basin area.

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