Specific character of the bottom simulating reflectors near mud diapirs: Western margin of India

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Multi-channel seismic recording was carried out along the western continental margin of India in the early nineties for the exploration of hydrocarbons. Analysis of seismic data demonstrated a characteristic reflector, which usually coincides with the predicted base of methane hydrates stability field and mimics the seafloor, known as the bottom simulating reflection (BSR) on marine seismic reflection data. Existence of reflections which mimic the seafloor, reverse polarity, seismic blank zone, strong diffraction patterns around the mud diapirs, weak amplitude blocks and pockmarks suggests that gas hydrates are present in deep-water regions. Five characteristic seismic facies associated with bottom simulating reflectors and mud diapirs were identified. In this study, we present the results of seismic surveys which indicate the existence of natural gas hydrates in the western margin of India. These results will be applied to select areas for coring (or drilling) and detailed exploration such as 2D seismic survey with long offset or 3D seismic survey in the future.

Keywords: Bottom simulating reflectors, gas hydrate, mud diapirs, seismic facies.

Natural gas hydrates occur on continental margins worldwide due to the nature of the hydrate stability field. In addition, samples of natural gas hydrates have been recovered on land in the western Prudhoe Bay oil field in Alaska and in the MacKenzie Delta, Canada. Thus far, natural gas hydrates have been recovered at more than 30 oceanic locations, including the northern Cascadia Margin offshore Vancouver Island. Natural gas hydrates have gained interest during the last 20 years because (a) they may represent a future energy resource, (b) they may play a role in global climate change, and (c) they represent a potential geological hazard. Several estimates of the total organic carbon content in natural gas hydrates have been made. Although these numbers are highly speculative, natural gas hydrates may represent a large reservoir of hydrocarbons that may dwarf all known fossil-fuel deposits combined. However, the role of natural gas hydrates may play in contributing to the world’s energy requirements depends on the availability of sufficient gas hydrates and on the costs of production. There is considerable disagreement about the total volume of natural gas hydrate accumulation as well as the concentration of natural gas hydrates in the reservoir sediments. Though natural gas hydrates are known to occur in numerous marine and permafrost regions, little is known about the technology required to separate the gas from the hydrates.

Most oceanic occurrences of gas hydrates in the sedimentary sequence are inferred, based mainly on the presence of an anomalous strong reflector on seismic profiles, termed as bottom simulating reflectors (BSRs). Seismic reflections that parallel the seafloor at sub-bottom depths of several hundred metres appear to be associated with the base of the stability field for methane hydrate. Such BSRs are widespread in the world ocean and can be found, among others, in areas with thick clastic sedimentary accretionary sequences associated with subduction zones. They also occur in divergent margin settings and areas with rapid deposition. Studying the behaviour and character of the BSR and associated seismic facies can provide a better understanding of the processes that form a gas hydrate and reveal the main factors that control the gas hydrate stability. In turn, these controlling factors determine the formation and presence of gas vents and methane flux into the atmosphere.

Analysis of multi-channel seismic reflection profiles (Figure 1) indicates the existence not only of gas hydrates and BSRs, but also of submarine mud volcanoes from the Western Continental Margin of India (WCI). This communication describes in detail (1) the general seismic facies in the vicinity of BSRs associated with mud diapirs, (2) the characteristics and existence of BSRs, (3) BSRs in the vicinity of mud diapirs, and (4) the existence of pockmarks.

The WCI is a passive margin. It is characterized by a complex ridge-graben regime and by the presence of the

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Chagos–Laccadive volcanic ridge (CLR), Pratap, Lakshmi and basement ridges as well as offshore sedimentary basins like Kerala–Konkan, Saurashtra and Bombay1. The regional seismic section of Ratnagiri–Kerala shows that on the slope, the thickness of the sediments gradually increases to 1500–2000 m on the Miocene shelf edge – a few kilometres landwards of the present-day shelf edge. This zone is marked by a sudden thickening of sediments up to 3500–4000 m and shows progradational depositional features25. The shelf edge, which forms a prominent tectonic zone, appears faulted in places with possible deformation of sedimentary cover25. Most of the sediments of the WCMI possess >4% total organic content20, have sedimentation rates of 0.44–0.88 mm/yr and a high degree of preservation of organic matter19.

The margin is characterized by distinct physiographic provinces – continental shelf, slope (shelf margin basin, marginal high) and rise. The shelf is about 345 km wide off Tarapur in the north and narrows down to 60 km off Cochin in the south; it slopes gently to the west. The shelf break occurs between 80 and 145 m water depth. Based on topographic variations and sedimentological characteristics, the shelf is divided into two sub-provinces – an inner shelf and an outer shelf. The inner shelf is marked by an even, gently seaward-sloping topography and is covered by 15–35 m thick, weakly to well stratified or acoustically transparent Holocene muds. This even topography extends up to 50–60 m water depth. Further seaward (deeper than 60–65 m)28,37, the outer shelf is characterized by an uneven or rugged topography variation up to 20 m. Prominent reefs are a common feature at the shelf edge28. Shallow seismic data of the continental slope show a typical sub-bottom penetration of 200–500 m with seaward-dipping cliniforms, outbuilding and up-building. Sediments slups, subsurface faults and gullies are also discernible along some sectors of the slope.

The seismic reflection data used in this study (Figure 1) were collected over the WCMI in the early 1990s for the exploration of hydrocarbons. The data were made available to our institute by the Gas Authority of India Ltd. to reprocess with suitable parameters and identify possible locations of gas hydrate-bearing horizons in this area. The acquisition parameters and processing sequences are given in Tables 1 and 2 respectively.

A general interpretation of the seismic profiles provided essential information on the sedimentary environments, and thus serves as the basis for further discussion of the seismic characteristics of BSRs. Seismic facies units are common features in the vicinity of BSRs with mud diapirs. Five characteristic seismic facies were identified which can provide a geological background and relationships between gas hydrates and mud diapirs are given in Table 3.

Multi-channel seismic reflection profiles from the deep-water area studied showed that some seismic reflections generally mimic the seafloor topography. In Figure 5, one of these events at about 2.95 s TWT (two way travel time) parallels the seabed. The sea-bottom depth of the seismic section is about 2.55 s TWT. Thus a 2.95 s TWT reflection cannot be a multiple reflection of the seabed, since this would occur at about 5.1 s TWT. These

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<th>Table 1. Data acquisition parameters</th>
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<td>Streamer length</td>
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<td>Streamer towing depth</td>
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<td>Number of channels</td>
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<td>Group interval</td>
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<td>Shot interval</td>
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<td>CDP interval</td>
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<td>Near offset</td>
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<td>Far offset</td>
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<th>Table 2. Data processing sequence</th>
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<td>CDP gather</td>
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<td>True amplitude recovery</td>
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<td>Bandpass filter</td>
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<td>Deconvolution operator length</td>
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<td>Deconvolution</td>
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<td>Velocity analysis</td>
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Figure 2. V-shaped pockmarks and acoustic disturbances of narrow, vertical columns below the pockmarks. S1 and S2 are seismic facies units.
Table 3. Seismic facies and its characteristics

<table>
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<tr>
<th>Seismic facies</th>
<th>Characteristics</th>
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<tr>
<td>Facies 1 (S1)</td>
<td>Continuous reflections of high amplitude running parallel to the seafloor and frequently occurring in the uppermost portion of the sedimentary column and in some areas truncated by gullies or disturbed by submarine mud volcanoes (Figures 2 and 3). Lack of disturbance in these well-stratified sedimentary deposits indicates calm hemipelagic sedimentation.</td>
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<tr>
<td>Facies 2 (S2)</td>
<td>Characterized by nearly transparent and white, shaded reflection patterns (Figures 2 and 3).</td>
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<tr>
<td>Facies 3 (S3)</td>
<td>Associated with the development of mud diapirs, i.e. a progradational facies of debris derived from the high land of mud diapirs, with inclined reflectors deformed by diapir uplift.</td>
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<tr>
<td>Facies 4 (S4)</td>
<td>A sub-parallel reflection pattern of high amplitude to the seafloor and usually underlies S2 and S3 at a sub-bottom depth of 200–500 ms two-way travel time (TWT), forming bottom-simulating reflectors.</td>
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<tr>
<td>Facies 5 (S5)</td>
<td>The whole external appearance of seismic facies S5 (Figure 4) is a mud-volcano facies of triangular shape with two sides forming a steep slope. The mud-volcano facies S5 height is about 0.5–1.0 s TWT.</td>
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BSRs are the physical boundaries whose depths are determined by ambient pressures and temperatures\(^ {18,40} \). They are neither lithological nor stratigraphical interfaces. Furthermore, Figure 6 (an enlarged detail of Figure 5) clearly shows the reverse polarity of this reflection, i.e. from the trough–peak–trough of the sea–bottom reflection waveform to the peak–trough–peak of the BSR reflection. The phase shift of 180° is caused by a decrease in the interval velocity below the BSR. Figure 7 is one such example of normal move out (NMO) gather at CDP 500 from the study area along with velocity semblance.

The seismic profiles also show that the stratigraphic reflections above some BSRs are much weaker than those beneath them (Figure 3). The facies S2 has acoustic blanking characteristics. This indicates the absence of any signal because of increased transmission\(^ {11} \) and obliteration of sediment impedance structures owing to the general replacement of pore water by hydrates\(^ {12} \). Therefore, the zone with the acoustic blanking characteristics is also referred to as the hydrate stability zone (HSZ)\(^ {13} \), which is defined as the sedimentary package which contains the gas hydrates (Figure 5). Some of the blanking is not obvious because it is related to the hydrate cementation in the sediments; the degree of blanking is proportional to the amount of hydrate in the pore space\(^ {16} \). The amount of hydrate varies in the deep-water region studied.

BSRs are not always easy to identify in the deep-water area of the WCMI. For example, sometimes the amplitude of the BSRs is low or the signals may be disturbed by other reflections. However, even in the absence of BSRs, the acoustic blanking blocks are usually found in the seismic sections of the deep-water region. This suggests that gas hydrates are distributed widely in the deep-water regions of the study area (Figure 1). The attenuation and disappearance of the BSRs do not necessarily mean that...
the gas hydrates have also thinned and disappeared, but rather that not enough gas is confined under the gas hydrates to decrease $P$-wave velocity markedly and give rise to the BSRs\textsuperscript{6,32}. In the deep-water regions of the WCMI some submarine mud volcanoes\textsuperscript{31} which have extruded from the deep sedimentary beds through to the seafloor, provide numerous conduits through which gas might flow out to the seafloor\textsuperscript{24,26}. These would result in the disappearance of BSRs in some areas. Thus, even in the absence of obvious BSRs, we nonetheless take the existence of weak reflection blocks in the seismic profiles to indicate the possible existence of gas hydrates in the sediments.

Heat-flow values inferred from BSR depth along the WCMI show a seaward increasing trend, commonly observed in several other margins of the world. High heat-flow values varying from 100 to 130 mW/sq. m were recorded in the Bombay and Saurashtra offshore areas\textsuperscript{27}. Along the Goa offshore, heat flow varies from 50 to 90 mW/sq. m as we move from east to west. Estimated\textsuperscript{29} heat flows for the Kerala offshore and further south are in the range of 60–80 mW/sq. m. The estimated\textsuperscript{30} value of heat-flow at BSR level from the study area is 69.88 mW/sq. m. Published heat-flow values\textsuperscript{17,21,22,29} from the Kerala–Konkan offshore are in agreement with the estimates made from near BSR distributions. An increase in heat flow is observed as we move to the west of the CLR. A decrease in sediment thickness\textsuperscript{30} as the ocean–continent boundary is approached could explain the high heat-flow distribution trends west of the Laccadive ridge. Overall, the northern part of the WCMI seems to have high heat flow compared to the southern part. It is also noticed that high heat flows are associated with younger basins and relatively low heat flow with older basins.

Based on the work of Cranston\textsuperscript{5}, the bottom-water temperature and temperature of the subsurface sediments were shown to vary from 2.0°C to 3.0°C. The normal geothermal gradient\textsuperscript{8} is usually 1–4°C per 100 m. The depth of the BSR is approximately 300–500 m below sea level in the study area of the WCMI. Thus, according to the stability diagram of methane\textsuperscript{13}, the BSR is in the stable part of the methane hydrate field. To explain the abnormal uplift behaviour of the BSR, the bottom temperature, geothermal gradient and pressure, i.e. the main factors controlling the formation of gas hydrate\textsuperscript{13} need to be ascertained.

The most interesting and unusual pattern of BSR is manifested in its gradual rising towards the venting area (Figure 3), which is in disagreement with the main char-

![Figure 5](image1.png)

**Figure 5.** Multi-channel seismic stack section with BSR and hydrate stability zone (HSZ).

![Figure 6](image2.png)

**Figure 6.** Enlarged details of the two boxed areas in Figure 5, showing reverse polarity of the BSRs, i.e. from the trough–peak–trough of the seafloor reflection waveform to the peak–trough–peak of the BSR reflection. P. Peak and T. Trough.

![Figure 7](image3.png)

**Figure 7.** Velocity semblance and NMO-corrected gather at CDP no. 500 of Figure 5 showing an interval velocity of 1850 m/s at BSR. Below the BSR there is a drop in interval velocity of 1450 m/s for brine-saturated sediment. Impedance contrast is caused by the presence of methane in the pore space of marine sediments. Free gas of only a few per cent in the pore space can cause the $P$-wave velocity to decrease markedly\textsuperscript{21}. 

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characteristic of BSRs which generally parallel the seabed. Based on the strong reflection of the BSR in this area, the thickness of hydrated sediments should range from a few metres to a few tens of metres\(^{13}\). If an average thickness of hydrated sediments is assumed, it remains uncertain which source can produce such a large amount of methane, bearing in mind\(^{20}\) that the normal concentration of organic matter in the sedimentary cover of the WCMI is more than 4%.

Although there is considerable scattering in the sub-bottom reflection time of the BSRs (Figure 8), it is clear that the BSR (which is not flipped by mud diapirs) depth increases with increasing seabed depth. This is attributed to the following two factors. First, the bottom-water temperature decreases with increasing seabed depth and, therefore, the gas hydrate is stable deeper in the sediments along a given thermal gradient. Secondly, increased hydrostatic pressure gives rise to stability in deeper gas hydrates\(^{15}\). For a more complete picture of the worldwide distribution of BSRs, in Figure 8 we have also plotted data for the Gulf of Mexico, Alaska, California, Nicaragua, Costa Rica, Mexico, Panama, the Blake Outer Ridge area, southern USA and the WCMI\(^{14,15,35,39}\). This plot indicates that there is an affinity between the BSRs not flipped by mud diapirs in the present study area and those in the other areas mentioned above.

Five seismic facies units were recognized in the study area. These are also the general characteristics in the areas of BSRs associated with mud diapirs worldwide. The BSR and weak reflection blocks provide the following evidence that gas hydrates are distributed widely in the deep-water region of the WCMI: (a) bedding planes are parallel in this area, so that the BSR reflections run parallel to the seabed and cross-cutting phenomenon is not observed; (b) BSRs have reverse polarity to the seabed; (c) BSRs occur at sub-bottom depth corresponding to the expected base of methane hydrate stability, and (d) fluid flow-related features such as pockmarks and acoustic blanking suggest that the area is prone to gas hydrate formation.

The depth of the hydrate stability zone (HSZ) increases with increasing seabed depth if the BSRs are not flipped around the mud volcanoes. The high heat flow of mud volcanoes can result in local temperature anomalies which destabilize the gas hydrates and then upturn the base of the HSZ towards the mud volcanoes. Some pockmarks with narrow vertical migration of gas and fluids were also revealed in the seismic facies study of BSRs around mud diapirs. Such unusual behaviour of the BSR and of the hydrate stability field leads to the conclusion that temperature is the most important factor controlling the hydrate stability field, confirming the interpretation of Hyndman and Davis\(^{13}\). Degradation of hydrated sediments causes the formation of vents and is responsible for the flux of methane gas to the water column and atmosphere in this part of the WCMI.


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