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ORIGINAL PAPER

Fluid flow related features as an indicator of potential gas hydrate zone: western continental margin of India

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Abstract Multichannel seismic reflection data from the continental margin of western India suggest the potential presence of fluid expulsion features, which may or may not be associated with gas hydrates. No typical bottom simulating reflector was observed on the reflection seismic section. As a result we look for other evidence in seismic sections in a small corridor of the western continental margin of India in order to establish the presence of gas hydrates. We study features including venting through the seafloor, pockmarks, sea floor collapse, faults acting as migration paths for fluid flow, transparent gas-charged sediment, reduction in amplitude strength, diapirism and mud-volcano. Presence of all these gas-escape features on a seismic section implies the probable presence of methane within the zone of hydrate stability field.

Keywords Western continental margin of India · Gas hydrates · Bottom-simulating reflector · Blanking · Venting of gas · Pockmarks and diapirs

Introduction

Gas hydrates resembling ice are crystalline solids formed of water molecules and methane gas (Sloan 1990). The presence of gas-hydrates changes the geophysical and geochemical properties of marine sediments, and hence can be detected by various proxies or markers. Gas hydrates commonly exist under low-temperature and high-pressure conditions below the seafloor, in water depths of more than 500 m (Kvenvolden et al. 1993; Taylor et al. 2000). The most commonly used marker for the occurrences of gas-hydrates is the identification of a bottom simulating reflector (BSR), which is associated with the base of hydrate stability field, mimics the shape of seafloor and cuts through bedding planes. In the absence of cross-cutting phenomenon the identification of the BSR becomes difficult and it becomes pertinent to use other markers to ascertain the presence of gas hydrate on the western continental margin of India, where few BSRs are reported running parallel to the bedding planes (Reddi et al. 2001; Satyavani et al. 2002). Methane gas, the major constituent of gas hydrates, may be either thermogenic, biogenic or mixed in origin (Kvenvolden 1995; Milkov 2005).

Nearly four decades ago, when petroleum geologists first reported the occurrence of gas hydrates from Siberia, it was believed that their occurrence was possible only in Polar regions. Later, studies proved their occurrence from non-permafrost areas in continents, as well as in offshore areas (Hovland and Curzi 1989; Kvenvolden 1993; Taylor et al. 2000). In view of their potential as an energy source, the exploratory work for marine gas hydrates has intensified all over the world since the 1980s. As a consequence, over the past two decades, numerous papers have been published on the occurrence of gas hydrates in deep-water continental margin areas (Kvenvolden 1988; Hyndman and Davis 1992; Brown et al. 1996; Ginsburg and Soloviev 1997; Vogt et al. 1999). Several estimates of the total organic carbon content in natural gas hydrates have been made and although these numbers are highly speculative, natural gas hydrates may represent a large reservoir of

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hydrocarbons that may dwarf all known fossil–fuel deposits combined (Kvenvolden 1993; Collett 2000). However, the role that 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 accumulations, as well as the concentration of natural gas hydrates in the reservoir sediments (Milkov 2004; Milkov et al. 2003).

As gas hydrate occupies the pore spaces of the host sediment, its presence usually changes the acoustic and geochemical properties of the sediment (Kvenvolden 1993). Due to this acoustic contrast, hydrates in marine environment can best be detected by seismic surveys. Seismic records from known gas hydrate zones display a distinct subsurface reflection, more or less parallel to the seafloor between gas-hydrate layers and gas-hydrate-free sediment layers. The BSRs are believed to be the prime indicator of marine gas hydrates. On the western continental margin of India bedding planes are parallel to the sea floor and detection of BSR is thus not evident on seismic sections. Recent trends (Milkov 2000) in the exploration for gas hydrates reveal the presence of other proxies such as gas venting through the seafloor, pockmarks, seafloor collapse, faults acting as migration paths for fluid flow, transparent sediment due to gas-charging, reduction in reflection amplitude strength, diapirism, and mud-volcanism on seismic records. These identified features all lie in the range of hydrate stability zone predicted by Rao et al. (1998) for Indian continental margins. These are alternative indicators to locate possible gas hydrate zones in deep-water continental margins.

The association of gas hydrates with submarine mud volcanoes has been recorded in the Adriatic Sea (Hovland and Curzi 1989), the Caspian Sea (Ginsburg and Soloviev 1994), the Norwegian Sea (Bouriak et al. 2000), offshore Barbados (Martin et al. 1996) and on the Blake Ridge (Taylor et al. 2000). Milkov (2000) has summarized the association of submarine mud volcanoes and gas hydrates in all the oceans of the world. The publications mentioned above suggest that submarine mud volcanoes (mud diapirs) may be indicators of the subsurface occurrence of gas hydrates.

Karisiddaiah and Veerayya (2002) reported venting and pockmarks in the shallow waters of the western continental margin of India. Venting of gas can be due to gas migration from the deeper sediments in the subsurface, deeper than the gas hydrate stability zone and can be treated as an indicator of the occurrence of gas and possibly gas hydrates. Pockmarks are prominent features on the seafloor formed by the escape of gas from the seabed. These V-shaped depressions are formed by the expulsion of gas from over-pressured shallow gas pockets, dispersing the fluid and gas filled sediments into the water column (Hovland and Judd 1988), or by intensive continuous fluid discharge hindering sediment deposition around the seep. Acoustic blanking underlies the pockmarks. The weakening of reflections is known as blanking, which is caused by the reduction of the impedance contrast because of cementation of sediment by gas hydrate (Lee and Dillon 2001). Acoustic blanking zones below the pockmarks are probably related to the flow of gas. Acoustic disturbances in a narrow vertical column below almost every pockmark can be seen. These disturbances may indicate the upward migration paths of gas and associated pore fluids (Chow et al. 2000).

Geological setting

The western continental margin of India (Fig. 1) has evolved as a consequence of the break up of the eastern Gondwanaland, specifically the separation of Madagascar and later the Seychelles from India about 80–65 Ma (Dietz and Holden 1970). The western margin of India is a typical passive continental margin of Atlantic type, with sedimentation accompanying subsidence in several areas. A number of sedimentary basins dot the western continental margin of India. The margin is also characterized by a dominant hot-spot trace known as the Chagos-Laccadive Ridge, which is emplaced as a consequence of the movement of the

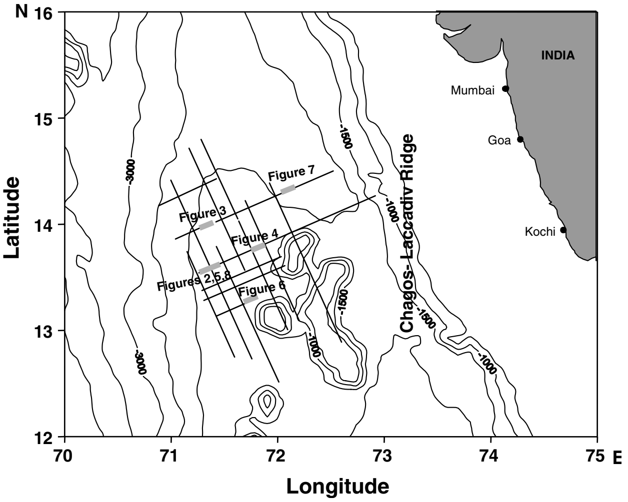

Fig. 1 The study area of western continental margin of India. The solid lines indicate the multi-channel seismic line under study. Shaded portion with figure numbers shows the stack sections presented in this study. Contours represent the bathymetry over the region in meters

Indian Ocean lithosphere over the plume (Ashalatha et al. 1991). Most of the sediments of the western continental margin of India possess >4% total organic carbon (Paropkari et al. 1992); have sedimentation rates of 0.44–0.88 mm/year and a high degree of preservation of organic matter (Nambiar et al. 1991). These parameters are highly favorable for the generation of methane and the formation of gas hydrates. However, few BSRs have been identified in the western continental margin of India, mainly because the reflectors within the gas hydrate stability zone are characterized with reverse polarity and are parallel to the seafloor (Gupta et al. 1998; Rao et al. 2001b; Satyavani et al. 2002). In areas of rapid sedimentation, identification of a BSR becomes difficult due to the absence of cross-cutting characteristics.

Heat flow values inferred from BSRs depths along the western continental margin of India shows a seaward increasing trend, commonly observed in several other margins of the world. High heat flow values varying form 100–130 mW/m^2 are observed in the Bombay and Saursthra offshore areas and along the Goa offshore, heat flow varies from 50 to 90 mW/m^2 moving from east to west (Rao et al. 2001a). We have estimated geothermal gradient and heat flow at the level of BSR as 34.88°C/km and 69.76 mW/m^2 respectively (Fig. 2). Estimated heat flow values for the Kerala offshore area and further south are in the range of 60–80 mW/m^2 (Panda 1985). Published heat flow values (Lee and Uyeda 1965; Pande et al. 1984; Ravi Shankar 1988; Panda 1985) from the Kerala-Konkan offshore area are in agreement with the heat flow estimates made from nearby BSR distributions. Overall, the northern part of the western continental margin of India seems to have higher heat flow compared to southern part. We also note that high heat flow is confined to younger basins and relatively low heat flow is only found in the older basins.

Seismic reflection data, processing and analysis

The seismic reflection data used in this study were collected over the western continental margin of India in the early 1990s for the exploration of hydrocarbons. The data were made available to our institute by the Gas Authority of India Ltd. (GAIL) to reprocess with suitable parameters and identify possible locations of gas hydrate-bearing horizons on the western continental margin of India. The acquisition system included a 96-channel hydrophone streamer with a maximum offset 2575 m active section and air-gun array source for the data acquisition was a tuned array with a total volume of 1650 cubic inches. The 48-fold data were reprocessed for the present study to preserve relative reflection amplitude. Data processing was carried out using ProMAX on SUN workstations using suitable parameters. A band pass filter in the range of 8-10-60-70 Hz was applied to the data. True amplitude recovery was done at 6 db/s.

Velocity analysis was carried out at every 2 km in general and at specific promising locations it was performed at an interval of 1 km. A spiking deconvolution was also applied to data so as to increase resolution. P-wave velocities obtained from the velocity analysis indicate the probable presence of a thin zone of free gas underneath the bottom-simulating reflector. The seafloor reflection is observed at 2590 ms two-way travel time. The depth of this reflection is calculated as being around 2000 m below sea level and the water velocity is of the order of 1550 m/s. This velocity sharply increases to 2050 m/s at a depth of 2280 m, giving a strong reflection observed on data at 2920 ms. Below this point, a sudden decrease in velocity is observed. The interval velocity falls to 1850 m/s and this drop in velocity might suggest the presence of free gas below gas-hydrate bearing sediment (Fig. 2). There is a distinct phase reversal observed and the velocity

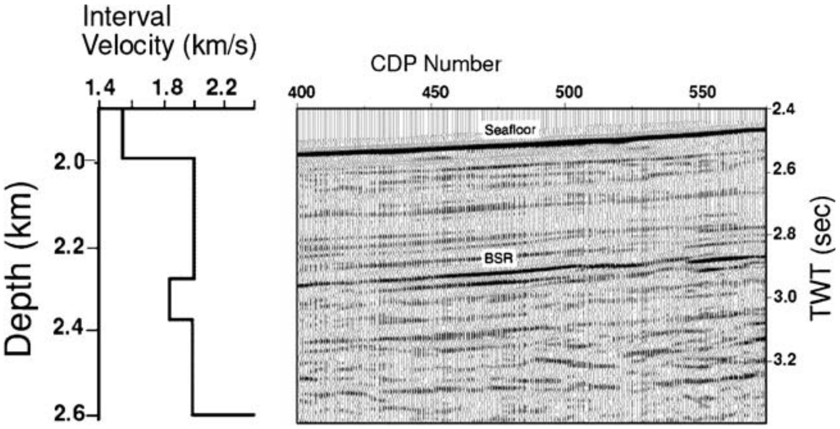

Fig. 2 Multichannel seismic stack sections along the line of study with corresponding interval velocity model

decreases across the reflector, lending support to the idea that this reflection may correspond to the BSR.

Result and discussions

Multi-channel seismic data along a number of lines on the western continental margin of India show parallel bedding planes. The most important evidence of BSRs i.e., the cross cutting of BSR with bedding reflectors is therefore not observed in this area, which makes the proposed BSRs suspect. However the absence of a clear BSR does not necessarily imply the absence of gas hydrates. Recent trends in the exploration for gas hydrates reveal that in the absence of seismic records, there are alternative indicators to locate possible gas hydrate zones in deep water continental margins. The association of gas hydrate with submarine mud volcanoes has been recorded in the Adriatic Sea (Hovland and Curzi 1989), the Caspian Sea (Ginsburg and Soloviev 1994), the Norwegian Sea (Bouriak et al. 2000), off Barbodos (Martin et al. 1996) and on the Blake Ridge (Taylor et al. 2000). In the absence of a clear-cut signature of BSRs, different geological evidence is sought to identify the areas which are prone to gas hydrates. Here we study fluid flow related features on the western continental margin of India in order to explore the probability of the occurrence of gas hydrates, without the clear cut evidence of cross-cutting BSRs and with positive indications of appreciable sediment thickness varies from 200 to 3000 m (Reddi et al. 2001) with high total organic content.

Stacked seismic sections in the western continental margin of India show venting of gas associated with pockmarks and faults, and with the overlying acoustically transparent sediments (Figs. 3, 4). Fluid flow or gas venting is clearly seen through the transparent sediments and reaches the sea floor. The acoustically transparent sediment zone could be due to the presence of hydrate-enriched sediments, fluid-saturated or lithologically homogeneous sediments. The fault can act as a conduit for the upward migration of fluids and gas, which cause thermal instability. The venting of gas may be due to the escape of gas or by the dissociation of gas hydrates. Enhanced fluid migration can result in destruction of the sediment layering, and this usually happens in active fault zones (Riedel et al. 2002). In this region pockmarks could be the direct indicator of the dissociation of gas hydrates, or the escape of free gas from the gas trap below the hydrate layer. This may indicate decomposition of hydrates or the escape of gas/fluid even before the formation of hydrates within the sediments. The blank zones are known to represent conduits for fluids and gas migrating upward.

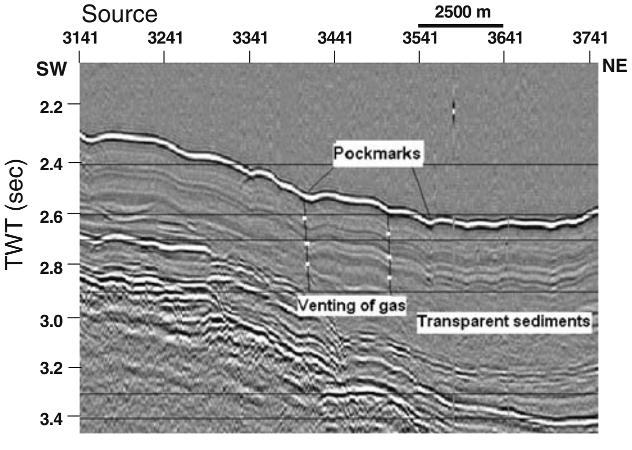

Fig. 3 Venting of gas associated with pockmarks overlain by acoustically transparent sediments

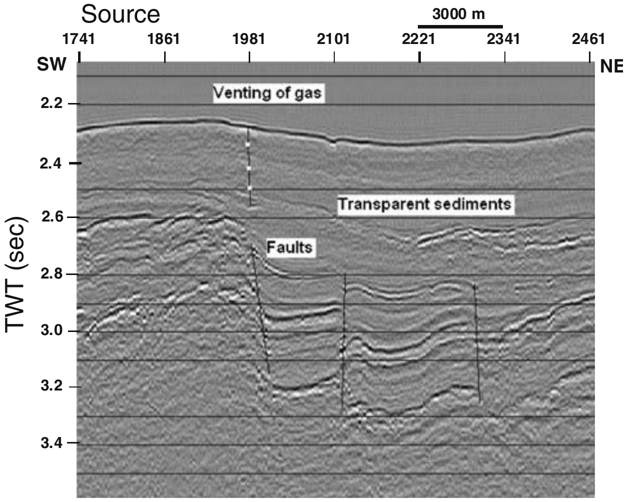

Fig. 4 Venting of gas associated with faults overlain by acoustically transparent sediments

Seismically, mud diapirs are characterized by chaotic reflections, which have higher amplitudes at their rims than at the center. In places, the original layering is preserved within the body of the mud diapir structure. The seismic pattern of the transition zone to the nearby-stratified sediments consists of both layered and chaotic reflections. The internal seismic transparency of the mud diapir could be a result of mud ascent, which leaves the diapir internally homogeneous and hence unreflective. Alternatively, the layering could be masked by gas (Minshull and White 1989). Even in low concentrations, gas in pore fluids causes a distinct reduction in seismic velocity, while leaving the density relatively unaffected. Most of the mud diapirs give rise to doming of the overlying strata, but only a few penetrate the seafloor to become mud volcanoes. The majority rise from below the BSR, thereby interrupting its continuity. In places diapirs are conical in shape, with heights of a few meters to more than 500 m and a width at their base of 1–5 km. However, ridge-like structures also occur with rough mound-like tops of more than 10 km in width.

The driving mechanism for mud diapirism is the existence of a source layer with a density lower than that of the overlying strata and a viscosity sufficiently low to enable upward flow or creep. This is usually the case if salt underlies the denser sedimentary layers, but this is true also when over-pressuring occurs in mud and mudstones. Over-pressuring can be generated by: (1) an increase in compressive stress (i.e. a reduction in pore space) triggered by disequilibrium compaction and tectonic compression, (2) a fluid volume change caused by temperature increase (aqua-thermal pressuring), diagenesis, hydrocarbon generation, and cracking to gas, and (3) fluid movement, as well as processes related to density differences between fluid and gas caused by a hydraulic (potentiometric) head, osmosis and buoyancy (Osborne and Swarbrick 1997). Conditions for over-pressuring are met by the dominance of rapidly accumulated diatomaceous clays and the presence of free gas below the base of the gas hydrate stability zone. Whether the stratigraphic layers below the base of the gas hydrate stability zone or the gas hydrate in the hydrate stability zone serve as a seal for the rising fluids or gas is unknown. That gas hydrates could function as an effective seal appear unlikely because gas migration through the base of the gas hydrate stability zone and within the hydrate stability zone has been reported (Taylor et al. 2000). Diapirism triggering may be due to vertical hydraulic fracturing, when the pore-fluid pressure exceeds the lithostatic pressure (Dimitrov 2002). Faulting in the sediments observed suggests the occurrence of high compressional stresses. This may have led locally to disruption of the impermeable layer, especially on top of anticlinal structures and along fault planes. The mud ascends until the internal pressure and density are in equilibrium with their ambient values.

The present study indicates the association of venting and pockmarks with diapirs (Fig. 5) and pockmarks associated with an igneous seamount may be linked to fluid flux observed in Fig. 6 on a seismic stack section. The thickness of acoustically transparent sediment varies from 200 ms two-way travel time (around 165 m) on top of the diapir to about 300 ms two-way travel time (around 247.5 m) at the western end of the diapir. The seismic segments shown in Figs. 7 and 8 are characterized by venting of gas and pockmarks in association with acoustically transparent sediments visible on stack sections. Here the thickness of transparent sediments is considerably high, about 600 ms two-way travel time (around 495 m). The number of pockmarks is relatively high in this region.

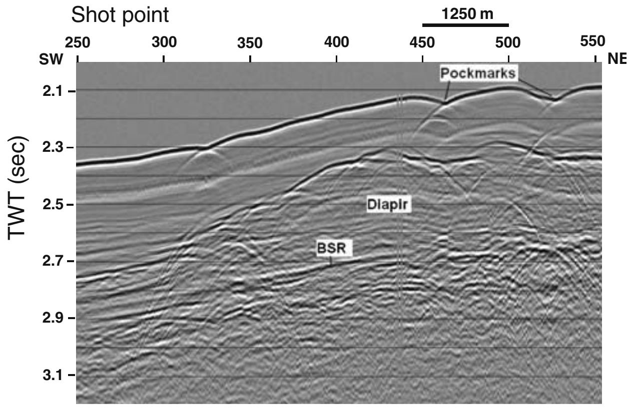

Fig. 5 Pockmarks are seen associated with a diapir and underlain by BSR on migrated section

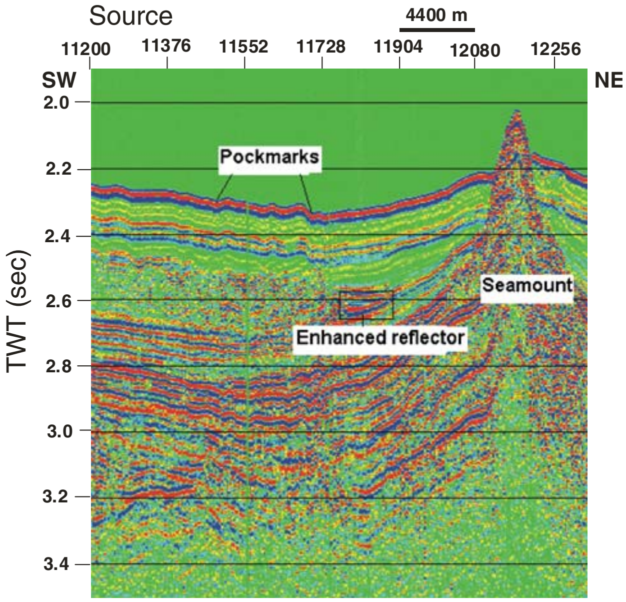

Fig. 6 Pockmarks associated with seamount

Gas chimneys in many cases are located close to faults and fractures but we could not detect these features in our study area. Clusters of chimneys are observed in areas where oil and gas discoveries have been made. These chimneys are believed to result from hydrocarbon migration along faults between source rocks and the seabed. The continental slope shows indications of fluid flow to the seabed through faults. Amplitude anomalies, indicating shallow gas accumulations, are located at faults. Numerous pockmarks can

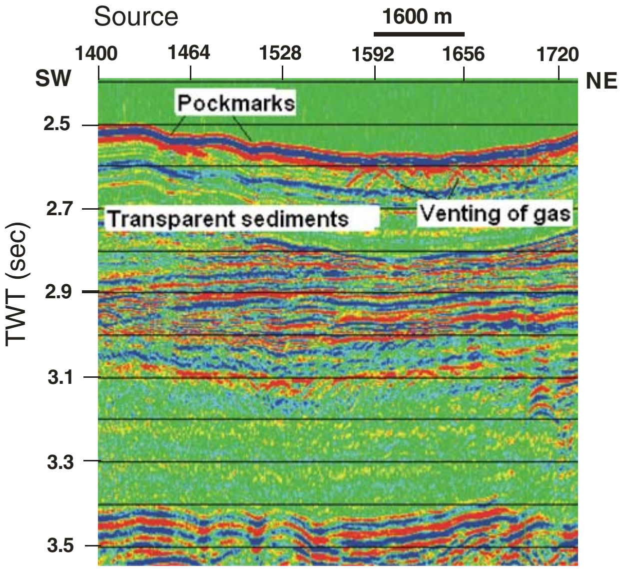

Fig. 7 Venting of gas associated with pockmarks and acoustically transparent sediments

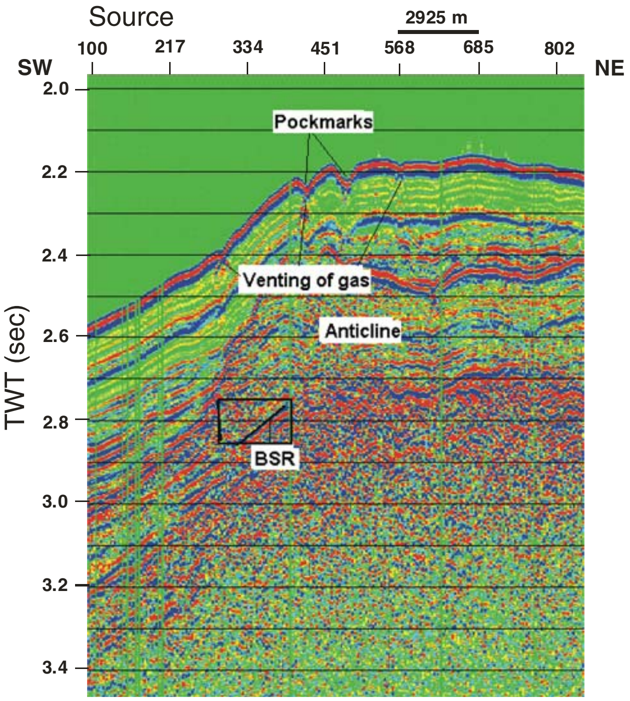

Fig. 8 Venting of gas associated with pockmarks and BSR

be seen along seabed fault lines, and mud volcanoes, recent and ancient, are located at faults.

Vertical hydrocarbon migration cannot be observed directly in seismic data in our study area, and it is not well understood how to distinguish between migration of free gas, and migration of gas-saturated water releasing gas as a result of a drop in the pressure, or in oil. Due to capillary resistance, hydrocarbons cannot move through shales unless there is an open fracture or an open fault. However, water can move through shales and release gas if it is gas saturated and there is a sufficient drop in pressure. This may give rise to chimneys that are not associated with faults. Such chimneys are frequently seen in seismic data in our study area. Seismic data also have the potential to show indications of fluid flow through faults. Whether the flow is gas saturated water, free gas or oil, is not known, but the fluid flow indicators tell us that the faults are or have been, open for fluid migration and, as such, they represent the most likely vertical migration pathway for hydrocarbons. Features that can be seen in seismic data and which can be associated with fluid flow, gas seepage or gas accumulations are chimneys (columnar disturbances), pockmarks, mound structures (carbonate build-ups, diapirs or mud volcanoes) and amplitude anomalies (gas accumulations). The presence of features associated with gas seepage at different stratigraphic levels, indicates different periods of fluid migration.

Gas seepage has been recorded in a variety of geological settings worldwide and often occurs on active mud volcanoes or above mud diapirs (Aloisi et al. 2000). Venting of gas is known to be associated with leakage from gas reservoirs, shallow gas charged sediments, gas hydrates and hydrocarbon bearing sedimentary basins on continental shelves and slopes (Hovland and Judd 1988).

BSRs depict characteristics mimicking the seafloor. Our seismic records show blanking, reversal of the polarity and to an extent, coincidence of the deepening of the reflector with the seafloor depth. These markers are confined to two distinct structural/tectonic configurations, i.e. areas of diapirism, crustal up-warping and areas of parallel bedding. Earlier studies (Karisiddiah et al. 1993) in this region suggest the presence of gas-charged sediments offshore western India. Of particular interest are the acoustic wipeouts noticed at four locations in the western offshore region, which underlie the BSRs (Gupta et al. 1998; Rao et al. 2001b).

Conclusion

Due to parallel-bedding planes, the most clear characteristics of BSR (i.e. the cross-cutting phenomenon of BSR with bedding planes) were not observed on the western continental margin of India. This makes the proposed BSR in our study area not clearly manifest. However, the absence of BSR does not necessarily imply the absence of gas hydrates. Exploration for gas hydrates reveals that in the absence of seismic records, there are alternative indicators to locate a possible gas hydrate zone in the deep continental margin. The presence of fluid flow features in the study area suggests that in this region there is possible gas or gas hydrate accumulations, even without clear-cut evidence of a BSR in the range of the hydrate stability zone. We have analyzed a seismic section to search for evidence of geological features in order to locate a gas hydrate horizon. Some fluid expulsion features such as pockmarks, venting of gas and transparency in sediment may be present as indicated in this study, but gas hydrates may or may not be associated with them, and direct sampling is needed to definitively test gas hydrate presence.

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