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# Occurrence of pockmarks and gas seepages along the central western continental margin of India

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**High-resolution seismic reflection profiling has revealed the occurrence of acoustic masking, pockmarks, gas seepages and plumes on the inner shelf, middle shelf and upper continental slope of western India, between 20 and 50 m, 60 and 75 m, and 170 and 260 m water depths, respectively. A typical 40-km long seismic section trending in a NW-SE direction – from the upper slope is characterized by anticline–syncline structure and culminates toward the NW. In some places fluid or gas escape features and plumes appear 2–12 m above the seafloor. Active and relict-type pockmarks are noticed. Out of thirty well-recognized pockmarks along the section, six are buried. In general, the pockmarks are 80–130 m in diameter and 0.75–2.5 m deep. Biogenic gas due to organic-rich sediments in the slope or thermogenic gas emanating from deep-seated faults, fractures and lineaments in the region may have given rise to these features.**

POCKMARKS are increasingly being recognized as widespread morphological phenomena on the seabed and are often indicative of the venting of natural gas, mainly methane[1]. Pockmarks found at the bottom of lakes and oceans around the world[2] are somewhat v-shaped depressions that form from the escape of natural gas and interstitial water from unconsolidated muddy sediments[3]. They range from a few metres to several hundreds of metres in diameter, with a maximum relief of 30 m. Pockmarks have been considered as indicators of subsurface petroleum deposits[1,4], offshore geologic hazards[5], contributors to global warming through greenhouse gas (methane) release[6,7], index of enhanced biological pro-

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ductivity[8] and as regions of significant sediment redistribution in temperate estuaries that may mark sites of past seismic activity[9]. Recently, we have reported different types of acoustic masking due to gas-charged sediments and their distribution pattern in the inner shelf of western India[10].

Although pockmarks are reported extensively worldwide, very little is known about their occurrence along the Indian margins. Here, we describe the occurrence of these features along the central part of the western margin of India (Figures 1 and 2), which may provide clues on the presence of hitherto untapped natural gas hydrate[11] resource potential, further offshore.

## Physiography and sedimentary facies

Regionally, the western margin (Figure 1) is characterized by distinct physiographic provinces–continental shelf, slope (shelf margin basin, marginal-high) and a rise. The shelf is about 345 km wide off Tarapur (close to Mumbai) in the north, narrows down to 60 km off Cochin in the south and 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, inner and outer shelves. The inner shelf is characterized by an even and gently seaward sloping topography (to about the 50–60 m isobath) and is covered by recent terrigenous silts and clayey silts, whereas the outer shelf (deeper than 60–65 m) is marked by an uneven-to-rough topography with 2–20 m relative variations and is composed of relict oolitic sands, coral reefs, algal knolls, bioherms or lithified sediments[12,13]. Further seaward, the upper continental slope is relatively smooth and steeper than the lower slope. However, the middle–lower slope region in some places is occupied by prominent flat-topped marginal highs preceded by a basin. The upper slope and marginal highs[14] are carpeted by sand–silt–clay facies, whereas the middle to lower slope, shelf margin basin and the rise are dominated by silty clays and/or fine-grained laminated mud and olive-grey to dark-brown mud[15].

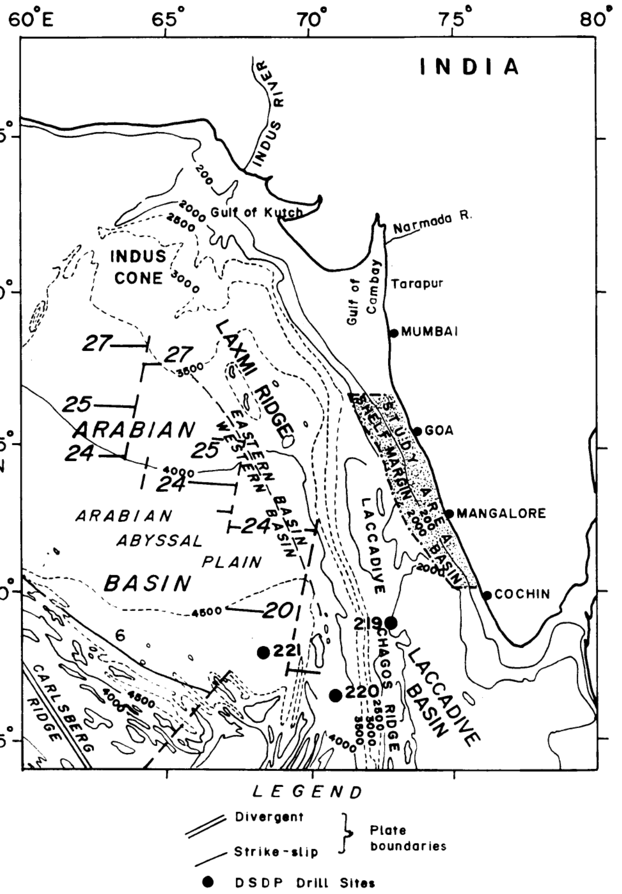


Figure 1. Location map showing the study area, regional bathymetry (m), and tectonics of the Arabian Sea (modified after refs 26, 36).

## Material and methods

During the 30th and 71st cruises of R.V. *Gaveshani* high-resolution seismic reflection profiler data were collected normal to the coast, along the central western margin of India with a spacing of 20 km (Figure 2). The data were obtained using a Huntec Hydrosonde (main pulse: 5 kHz), and an ORE sub-bottom profiler (3.5 kHz) together with side-scan sonar (EG&G Mark IB, dual channel recorder: 259-3 and tow fish 272), and Kelvin and Hughes MS-45 (30 kHz) echosounder. Positions were

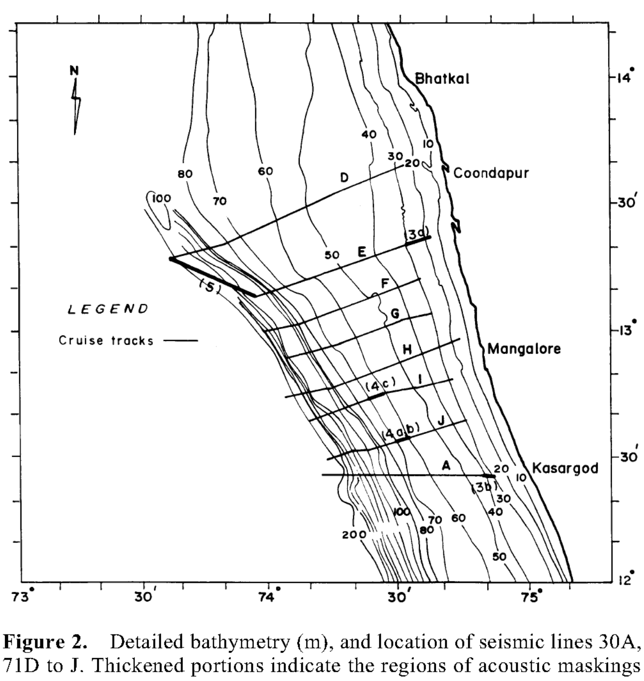


Figure 2. Detailed bathymetry (m), and location of seismic lines 30A, 71D to J. Thickened portions indicate the regions of acoustic maskings (< 60 m water depth) and pockmarks, seeps and plumes (> 60–300 m water depth). Also shown are the locations of profiles (numbers in brackets) presented in Figures 3 to 5.

obtained using satellite navigation and Global Positioning Systems.

## Results and discussion

We focus here mainly on the presence of typical acoustic anomalies indicating gas-related features on seismic profiles (Figure 2) of the area.

### *Inner shelf*

The seismic reflection profiles revealed the presence of 5–35 m thick, weakly-stratified and acoustically transparent clays on the inner shelf. Within these sediments, the presence of anomalous seismic signatures in the form of acoustic masking due to gas-charged sediments is conspicuous[10,16].

Characteristic seeps are noticed in the near-shore at water depths of 20–25 m off Coondapur (Figure 3 *a*). Here the shallow sub-bottom is marked by 3 seismo-stratigraphic units; Unit 1 being the uppermost acoustically transparent clayey layer; Unit 2, underlain by the somewhat dense silty-clay; and Unit 3, the lowermost compact sandy layer. The seeps pierce through Unit 3 and are mostly confined to Unit 2. Sonographs reveal the presence of isolated as well as clustered pockmarks at a water depth of 25 m off Kasargod (Figure 3 *b*).

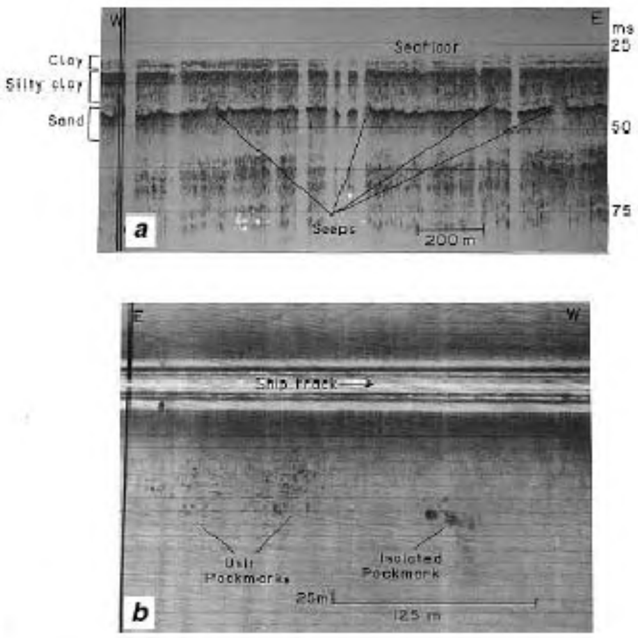


**Figure 3 *a*.** High-resolution ORE sub-bottom seismic profile (3.5 kHz) from the inner shelf off Coondapur, showing major seismic stratigraphic units and prominent seeps. Seeps are confined to the bottom-most sandy horizon; and (***b***) Side-scan sonograph of the inner shelf (water depth: 25 m) showing probable unit as well as isolated pockmarks off Kasargod. For location see Figure 2.

### *Middle shelf*

Distinct v-shaped notches are noticed on echograms as well as on the corresponding seismic records at water depths of 60–70 m between off Mangalore and Kasargod (Figure 4 *a* and *b*). These depressions are 100–200 m wide and 2–3 m deep. Sonographs along a parallel line confirm their presence (Figure 4 *c*). These v-shaped notches on the seafloor appear to be isolated pockmarks and are circular enclosed depressions as opposed to down-slope channels observed elsewhere within the mid-shelf.

### *Upper continental slope*

Farther seaward, a typical stretch of 40 km seismic section along the upper slope trending NW to SE is characterized

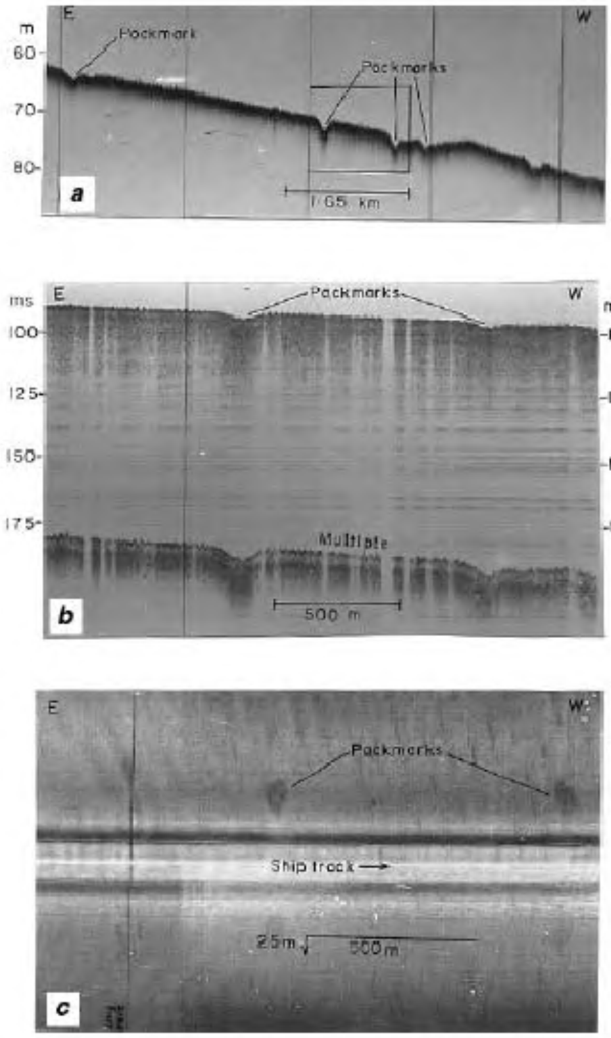


**Figure 4 *a*.** Echogram showing pockmarks on the mid-shelf between Mangalore and Kasargod; (***b***) Corresponding ORE sub-bottom profile confirms the occurrence of pockmarks (water depth: 65 m); and (***c***) Side-scan sonograph (105 kHz) of a parallel line (Line I) depicting pockmark-like features in the mid-shelf off Mangalore. For location see Figure 2.

by an anticline (Figure 5). Along this section the water depth varies from 170 m in the SE to 260 m in the NW with a maximum of 275 m at the centre, forming a prominent syncline structure. Echograms (not presented) of this section corroborate the characteristic seeps observed in Figure 5. The seismic profile shows three characteristic sub-bottom reflectors: the first one at 8–20 m, the second at 45 m and the third at about 55–60 m below the seafloor (mbsf) (Figure 5). Acoustically transparent sediments mostly characterize the sub-bottom immediately below the seafloor. The first sub-bottom reflector (R1) is continuous in the NW and can be traced as it deepens towards the syncline centre and apparently disappears at a depth of 50 mbsf, whereas in the SE, below this unit, the other two sub-bottom reflectors R2 and R3 are parallel, discontinuous and faulted (Figure 5).

## Distribution of pockmarks

The seafloor along the seismic section is generally smooth. However, prominent pockmarks and seeps are present (Figure 5). Out of thirty pockmarks recorded in this section, six are buried. The pockmarks are mostly confined between the first sub-bottom reflector and the seafloor, while some formed 2–12 m deep (?) depressions on the seafloor; a few others lie on the anticline. On the other hand, buried pockmarks lie 2–8 mbsf (Figure 5).

The pockmarks in general are 80–130 m in diameter and 0.75–2.5 m deep, while the smaller-sized buried pockmarks are 20 m in diameter and < 1 m deep. Their side walls are relatively steep. These pockmarks occur as conical and dish-shaped incisions, often truncating the strata above the second sub-bottom reflector. Occasionally, distinct gas plumes rise from a few metres to about 70 m above the seafloor (Figure 5).

### *Formation of pockmarks*

The existence of an acoustic turbid zone underneath the pockmarks (Figure 5) suggests that there is a continuous supply of gas from below and that at present the sediments within the migration path are gas-charged[17]. The release of gas under the side walls allows continuous mass wasting and reworking all around and causes the maintenance of steep slopes. Similar pockmarks were observed in muddy and sandy sediments over wide depth ranges elsewhere[2,18,19]. They can be buried and hence relict, or actively venting gas at the seafloor (Figure 5). The venting of gas and pockmark formation is a continuous process[18]. The pockmarks along the seismic profile (Figure 5) show features similar to craters with raised rims in the order of 0.75 to 1.5 m; thus they might have interacted in the redistribution of sediments[1].

A characteristic, well-marked suspected gas front with high scattering return is conspicuous and lies ~ 70–120 m above the anticline (Figure 5). In contrast, reflection returns from below the gas front are markedly somewhat weak. This is also typical for gas in sediments, where attenuation is increased and acoustic energy dissipates more rapidly than would be the case in gas-free sediments[1,20].

Uchupi *et al.*[21] reported that pockmarks tend to occur in fine-grained sediments with their size varying according to sediment texture; the finer the sediment, the larger the size of the pockmark. They tend to be smaller in stiff, fine sediments and are poorly developed in coarse sediments. Their number decreases with decreasing grain size as a result of diminishing permeability[21]. However, the size or spatial density of pockmarks shows no relationship to the water depth[2]. Instead, the size of the pockmark structures is controlled by the texture of the sediments and the volume of the escaping gas[22]. It is inferred that relatively fine-grained sediments in the syncline, which are acoustically transparent, might have led to larger-sized pockmarks. Although the features formed due to erosion by bottom currents and by the escape of water often appear as v-shaped notches[21,23,24], the pockmarks under consideration may not fall in this category. In some places, the shape of the pockmarks may later have been influenced by water currents[2].

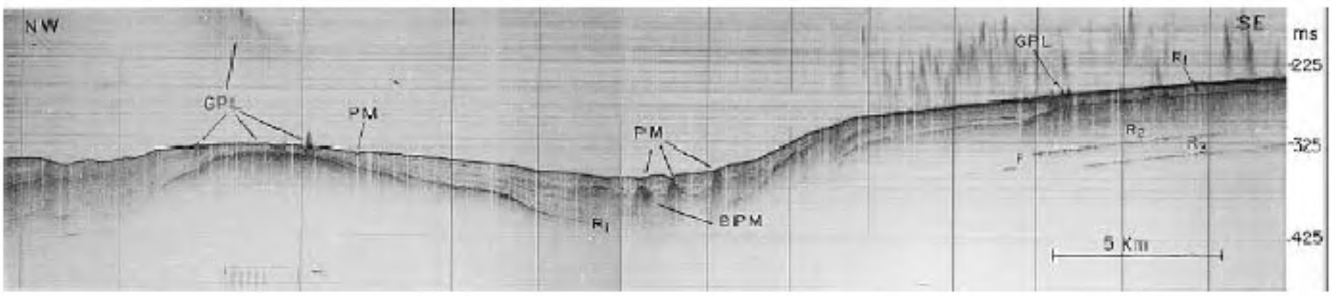


**Figure 5.** High-resolution ORE sub-bottom seismic profile (3.5 kHz) showing intricate details of gas-related features, such as distinct gas plumes, pockmarks, gas seepages and gas fronts (marked by water column reflections) on the continental slope off Coondapur. Gas plumes (GPL) are seen emanating from the subsurface horizon into the water column. Pockmarks (Pm), buried pockmarks (BPm), fault (F), prominent reflectors (R1, R2 and R3) are identified in the area. For location see Figure 2.

### *Migration pathways of hydrocarbons*

For gas generated deep within the seafloor to be expressed at shallow depths, upward migration pathways must exist[20]. Vertical faults and tilted permeable sedimentary layers are two common examples of such migration paths. This has been supported by detailed study of underway-geophysical data, wherein the basic structural framework of the western continental margin[25] was considered to be influenced by the pre-existing Precambrian structural fabric of the continent. Further, the gently undulating morphology of the seafloor and the underlying anticline structure in the study area seem to be a result of weak folding that probably resulted from differential movements caused during the Last Glacial Maximum (LGM) and/or compressional forces acting on the margin[26].

### *Sources of hydrocarbon gases*

The continental slope off western India is considered to be one of the modern analogues for the environment of formation of organic-rich sedimentary facies that are common in the geological record[27]. The northeastern Arabian Sea is characterized by an exceptionally stable oxygen minimum zone (OMZ) between 200 and 1200 m water depths and a strong, seasonal, monsoon-controlled variability of primary productivity[28]. Sediment cores from the northeastern Arabian Sea show laminated, organic-rich bands, reflecting monsoon-induced biological productivity[29]. The concentration of organic matter is < 1% by weight in the relict outer-shelf sedimentary environment, but increases dramatically to a maximum of 6–7% in the silty clay and clayey silt zone in the (upper) slope of the present study area[14,27]. Stable carbon isotope ($\delta^{13}C_{org}$ – 18.03 to – 23.86) data, $C_{org}/N_{total}$ (5.83 to 11.77) ratios and $I/C_{org}$ (25 to 270) ratios all suggest that the organic matter in the sediments of the deeper parts of the present study area (slope) is of marine origin[27].

A major climate change[26,30] with an accompanying increase in the erosion rate of flanking onshore Western Ghats could produce the sudden input of clastic sediments to the continental margin, which might be the source for the methane-rich sediments. This enormous sediment supply during 18,000 yr BP eustatic sea level low of – 120 m, might have resulted in significant sediment input to the continental slope of the study area. In addition to this terrestrial organic source, thermogenic gas migrating through the deep-seated faults[25] may form another possible source. Cyclic loading and unloading of soft marine seabed sediments may also trigger bursts of gas and low-density liquid expulsions through weak zones in the seafloor and thus reactivate the dormant pockmarks[31].

Mechanisms proposed for submarine pockmark formation are: (1) excavation by freshwater seepage[19], (2) venting of interstitial gas[9,32], (3) pore-water escape during sediment compaction[33], (4) sediment rafting by methane hydrates[34], and (5) freshwater ice rafting not associated with hydrocarbon deposits[35]. Besides, two models proposed for the formation of pockmarks are: (1) an equilibrium model, wherein pockmarks are thought to have been formed slowly over thousands of years, and (2) a catastrophic model, for pockmarks that might have been formed during an earthquake, tsunami and/or a storm, with large quantities of muddy sediments being transported during the formation[9].

In the absence of any major earthquake events (except the recent reports on the tectonic spurt in the continental crust within the Indian craton) in the area under investigation, it appears that the pockmarks described so far on the western margin are of equilibrium-type. Further, we attribute that pockmarks were formed (i) by localized gas or fluid seeps which dewatered the sediment and caused collapse structures and (ii) possibly due to the dissociation (?) of underlying gas hydrates[11], further offshore.


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# MEETINGS/SYMPOSIA/SEMINARS

**III Indian Pineal Study Group (IPSG) Symposium**

Date: 1–3 March 2002
Place: Varanasi

Topics include: Pineal and livestock reproduction, Pineal and livestock production, Pineal and livestock health, Pineal and biological clock, Pineal and photoperiodism, Pineal and geroprotection, Pineal and behaviour, Pineal and intermediary metabolism, Neuroendocrinology, Comparative pineal physiology.

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**The 39th IUPAC Congress and 86th Conference of The Canadian Society for Chemistry**

Date: 10–15 August 2003
Place: Ottawa, Canada

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**International Conference on Discotic Liquid Crystals**

Date: 25–26 November 2002
Place: Bangalore, India

Topics include: Chemistry, physics and applications of discotics, including discotic oligomers, polymers and networks.

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**Twelfth User Interaction Meet (Remote Sensing)**

Date: 30–31 January 2002
Place: Hyderabad

During this meet, NRSA Data Centre will provide information regarding the following topics/area: Status and update of data product and services, New services like data dissemination through electronic network, Advances in data dissemination and introduction of e-commerce, High resolution data availability and ordering procedures, Details of future satellite missions, Aerial remote sensing and photogrammetry, New and emerging applications of satellite data.

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