Marine Gas Hydrates: Seismic Observations of Bottom-simulating Reflectors off the West Coast of Canada and the East Coast of India

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Introduction

Deep sea methane hydrates are found several hundred metres beneath the continental slopes of many areas around the world, mainly beneath continental margins having thick sedimentary sections. In this article we describe gas hydrates from a well studied area off the west coast of Canada and provide comparisons with some initial studies of seismic data from the east coast of India.

Naturally occurring gas hydrates are estimated to contain a very large amount of methane, a potential clean hydrocarbon fuel resource (Figure 1). Estimates of total global methane in hydrate exceed the known combustible hydrocarbon reserves, i.e., W Gt (10⁶ tonnes) of carbon or 6 x W Tcf (trillion cubic feet) of methane [e.g., Kvenvolden, 1988; MacDonald, 1990; Kvenvolden, 1993] (Figure 2). Because methane is a very strong atmospheric greenhouse gas, second only to CO₂, natural gas hydrates may also play a role in climate change. For example, release to the atmosphere of methane in hydrates resulting from a climatic warming could strongly enhance the warming trend [e.g., Nisbet, 1990].

Gas hydrates have been known for many years as a problem in natural gas pipelines. They also have been recognised beneath land and shallow sea Arctic regions where they present a drilling hazard. Hydrates have been described as an important gas source in some northern Russia gas fields [e.g. Makogon, 1988]. However, recent studies have indicated that the largest occurrences of gas hydrates lie in horizontal layers several hundred metres beneath the deep seafloor in a few special regions.

The importance of deep sea hydrates is highlighted by the recent Japanese $70 million U.S., five year government-industry program to survey and test-produce methane from gas hydrates off the coast of Japan. There is also important programs in several other countries.

The ice-like clathrate structure of methane hydrate is stable up to a temperature of 10-30 degree C beneath the seafloor at the pressures generated by water depths of greater than about 800 m (Figure 3). Information on marine gas hydrates and underlying free gas has come from

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Fig 1. Clean Burning gas hydrate
(photograph by L.a.Stern, USGS)
Fig 2. Gas hydrate represents the largest global reservoir of organic carbon, a factor of two greater than all conventional hydrocarbons.

Fig 3. Stability fields of deep sea gas hydrate compared to the temperature in the ocean and seafloor.

Fig 4. Deep sea gas hydrate studies from seismic data and international Ocean Drilling Program (ODP)

many sources, but mainly from seismic studies and scientific deep sea drilling. The primary indicator of deep sea hydrate is a bottom-simulating reflector or BSR that parallels the seafloor (Figure 4).

One of the best studied areas of marine gas hydrates is off the west coast of Canada. A hydrate BSR occurs in a 30 km wide band parallel to the coast beneath much to the continental slope off Vancouver Island. The hydrate is concentrated in a layer 50-100 m thick, just above the base of hydrate stability field, which is located 250-300 m below the seafloor. New results from preliminary studies of seismic data from the continental slope off the east coast of India have also revealed strong hydrate BSRs in a few areas. Because such deep sea hydrates represent a very large methane reservoir, its distribution, nature and formation warrant detailed studies.
Formation and Physical Properties of Marine Gas Hydrates

Gas hydrates are an ice-like clathrate structures stabilized by the inclusion of methane gas molecules in the cavities of the crystal lattice formed by water molecules. Natural hydrates can form only under special temperature and pressure conditions. Figure 5 shows in detail the hydrate stability field based on laboratory data and ODP/DSDP in situ borehole measurements. The maximum sub-bottom depth for hydrate stability depends on pressure (water depth), seafloor temperature and vertical temperature gradient (heat flow and thermal conductivity), composition of the enclosed gas, and the pore water salinity. The dissociation temperature is increased by the presence of higher hydrocarbons and CO₂ and decreased by higher salinity. Almost all of the enclosed gas in natural hydrate samples that have been recovered has been methane inferred to be biogenic in origin. The hydrate stability boundary for methane and pure water and for seawater salinity is now well known [e.g., Dickens and Quinby-Hunt, 1996]. The temperatures for marine gas hydrate formation and dissociation may be slightly different, because salt is largely excluded from the hydrate structure, as in the case of normal ice. In situ estimates and measurements of the temperature and pressure in the hydrates at various sites (Nankai off southwest Japan, Peru margin, Vancouver margin, and Blake Bahama) fit the pure- methane and seawater stability field zone within the measurement uncertainties of 1°-4° (Figure 5).

The amount of gas enclosed in the hydrates varies depending on composition, pressure, and temperature conditions. The lattice becomes increasingly occupied at lower temperature and higher pressure. However, laboratory and field data indicate that most of the lattice sites are usually occupied. Thus, hydrates can accommodate nearly 160 times its volume of gas (at standard conditions). A fully saturated methane hydrate has a higher energy density than liquefied methane because the methane sites in the crystal lattice are closer together than the methane molecules in the liquid [Max and Pellenbarg, 1997].

In most deep sea gas hydrates it is concluded that the hydrate replaces the pore fluid and is located within the pore spaces. However, veins and massive bodies of gas hydrates have been found by scientific ocean drilling, such as during DSDP Leg 84 in middle America Trench offshore Guatemala [Mathews and von Huene, 1985]. For seafloor gas hydrates to form sufficient gas must be produced from organic material in the subjacent sediment. The methane in the hydrate may be produced from local sedi
ments. However, organic concentrations in deep-sea sediments usually are not adequate to produce significant hydrate concentrations. Thus, dissolved or free gas generated over a considerable depth interval must migrate upward into the zone of hydrate stability. Although organic concentrations in deep-sea sediments are usually small, approximately 1%, the huge volumes of sediment on continental margins result in very large amounts of methane being produced. It was formerly believed that hydrate formation required free gas, but recent theoretical and laboratory studies have shown that hydrates can be formed from the removal of dissolved gas from rising fluids [e.g., Rempel and Buffett, 1997; Zatsepina and Buffett, 1997]. Extensive hydrates thus can be built up from thick sediment sections where fluid is being expelled upward. Fluid expulsion is well documented in subduction accretionary sedimentary prisms [e.g., Hyndman and Davis, 1992] but it also appears to occur in a number of special locations on passive margins. Two mechanisms are important in forming high concentration of marine gas hydrates: (1) continuing upward fluid expulsion which transports methane rich fluids upward into the hydrate stability field, and (2) the 'gas hydrate concentration cycle', wherein the base of the stability field rises due to ongoing sedimentation or tectonic uplift. The hydrate at the base of the stability field (just above the BSR) is then dissociated, forming gas, which rises to be reincorporated and concentrated as hydrate at a higher level.

The presence of gas hydrates in marine sediments dramatically alters some of the normal physical properties of the sediment, which can be detected by field measurements and by downhole logs. The density of pure methane hydrate is about 0.9 g/cm$^3$ [e.g., Sloan, 1990] which represents only a small change from normal pore water. Hydrates normally exclude the salt in the pore fluid from which it forms, and thus it has high electric resistivities just as water ice and sediments containing hydrates have a higher resistivity compared to unhydrated sediments [Judge, 1982]. The unconsolidated sediments in the upper several hundred metres of marine, sediment section (50% porosity) normally have a very low resistivity of about 1 ohm·m. For 15-20% hydrate saturation in the pore space (7-10% of sediment) the resistivity increases by about a factor of two, to about 2 ohm·m. Several field experiments have been attempted to resolve this difference, but the method is still in a test phase.

The most readily observable change in sediment physical properties resulting from the formation of gas hydrates is an increase in seismic velocity. Pure methane hydrate has a velocity of about 3700 m/s [Pearson et al., 1983; Sloan, 1990]. Laboratory measured seismic velocities for porous media at the maximum hydrate saturation vary from 2700 to 6000 m/s depending on the type of sediment and the method of preparation [Stoll et al., 1971; Stoll, 1974; Pearson et al., 1986]. These laboratory determinations are for sediments of much lower porosity and higher velocity than most continental margin near seafloor sediments. Sediments containing substantial hydrates have enhanced velocities. For example, a hydrate saturation of 10-20% of pore space in unconsolidated sediment (50% porosity at a subbottom depths of a few hundred meters) has a velocity of 1900-2100 m/s, compared to no-hydrate velocities of 1600-1700 m/s. In general, if hydrates occupy 15% of pore space, 15-20% increase of sediment velocity is expected. This increase can be detected in interval velocities from high quality multichannel seismic data and in well calibrated downhole sonic logs.

A small quantity, 1-2%, of free gas in the sediment pore space beneath the BSR will significantly reduce the sediment velocity, while further increase in gas concentration makes little change [e.g., Murphy, 1984; Ostrander, 1984]. The effect of free gas on sediment velocity is highly dependent on water depth (Figure 6), primarily because gas density and compressibility are very sensitive to pressure and temperature.

**Hydrate Bottom-simulating Reflectors**

The primary source of regional information on deep-sea gas hydrates is from seismic reflection data, particularly through the BSR which marks the base of the hydrate stability field at a depth several hundred metres below the sea-
floor. The BSR results from the negative impedance contrast between sediment containing high velocity hydrate and underlying normal sediment that may contain free gas. Sub-bottom isotherms approximately parallel the seafloor, so the base of the hydrate stability field and thus the BSR approximately parallel the seafloor. The BSR is readily apparent if it cuts across stratigraphic reflectors. However, if the BSR is parallel to primary sedimentary bedding, it maybe difficult to identify. That-BSRs are the result of hydrates has been verified by ODP/DSDP drilling, i.e., in downhole measurements, by core measurements, and recently by recovery of sediments containing hydrate in pressurized core samplers [Duncan et al., 1996].

Gas hydrates may be present even where there is no BSR identified from reflection seismic records. The BSR may be especially difficult to recognize if the seismic processing has not been optimized to identify reflection structures in the upper few hundred metres of the sediment section. The BSR can be quite discontinuous, probably reflecting the difference between where gas is developed beneath the hydrate and where little gas is present. For example, hydrate has been indicated by downhole measurements and recovered in cores outside the area of recognized BSR off the southeast U.S. coast [Duncan et al., 1996], confirming that the BSR only provides a minimum or first-order geographic identification of the extent of hydrate development. Other less conclusive criteria include suppression of general reflection amplitudes above the BSR relative to those below referred to as a 'blanking zone', and small scale reflection seismic effects such as the generation of hyperbolae associated with a blocky structure at the base of the hydrate zone.

The BSR reflection is generally a single symmetrical wavelet with a reversed polarity relative to the seafloor (Figure 7), indicating a sharp and negative impedance contrast downward across the BSR. No reflections from the top of the hydrate layer or bottom of the gas layer have been confidently identified (although there are some indications). This behaviour is in contrast to the normal industry experience of “bright spots” at the top of gas layers. It has thus been inferred that the top of the hydrate accumulation and the base of the low-velocity free gas layer beneath the BSR must be gradational.

The characteristic BSRs allow the regional distribution of hydrates to be mapped, and the analyses of the BSRs and of the velocity structure can provide semiquantitative information on the amount and distribution of hydrates and underlying free gas. Seismic analyses have included: (1) determination of BSR reflection coefficients, (2) modelling of the vertical-incidence reflection waveforms, (3) detailed multichannel interval velocity-depth analysis, and (4) analysis and modelling of amplitude-versus-offset (AVO).

![Fig 7](image-url)
Seismic Observations of BSRs and ODP downhole measurements off the West Coast of Canada

The Area of Gas Hydrate offshore Western Canada

In Canada, gas hydrates have been observed in several areas, off the east coast, in the Arctic associated with permafrost, and off the west coast in the accreted sediments of the Cascadia subduction zone. The continental slope off Vancouver Island where there is a strong BSR over a large area has received especially intensive studies. The work has included numerous marine seismic programs, thermal studies, electrical sounding, seafloor sampling, seafloor acoustic imaging, and drill sampling and downhole measurements by the international scientific Ocean Drilling Program (ODP) (Figure 8). Two multichannel seismic reflection surveys were carried out in the region. Other seismo-acoustic surveys have included fine-grid single channel reflection, wide-angle ocean bottom seismograph (OBS) recording, expanded spread profiling, and near hoi-torn deeo-tow multichannel reflection.

Off the Canadian west coast, BSRs are apparent over much of a 20-50 km wide band along the whole southern Vancouver Island continental slope in water depths from about 800 m to 2000 m (Figure 8). Figure 9 shows portions of two orthogonal reflectio lines L89-08 and L89-10 across the ODP drillsite where the BSR is continuous and subparallel to the seafloor at 250-275 ms (~230 metres) below the seabed. On these lines there are clear reflections above the BSR and no reflection blanking effect due to impedance attenuation as seen in an area off the southeast U.S.A. margin.

Comparison of Seismic Data with ODP Downhole Sonic and Other Data

ODP Leg 146 drilled the subduction zone clastic sediment section off Vancouver Island to investigate the nature of the gas hydrate that had been defined by detailed geophysical studies. There was full coring as well as a large number of downhole measurements. The data include sonic logging and vertical seismic profiles (VSP), providing the first high-quality in situ velocity data extending through a BSR. The ODP data have allowed confirmation of the amount of hydrate and gas associated with the BSR estimated from seismic and other field data.

As hydrate density is very close to that of pore water and the amount of free gas below the BSR is usually small, sediment density is
changed very little by the presence of either hydrates or gas. The impedance contrast at the BSR therefore mainly comes from velocity change, which can be estimated from the BSR reflection coefficient. Near the ODP drillsites, a velocity decrease of 300-400 m/s across the BSR is required to produce the impedance contrast representing an estimated BSR reflection coefficient of -0.1. This velocity change appears to come from high-velocity hydrate filling sediment pore space above the BSR and sediment with normal poe,water content containing a small amount of free gas in a thin zone below.

Figure 10 compares the ODP downhole velocity measurements with seismic velocities

![Figure 10](image-url)

**Fig 10**: (a) Interval velocities from 10 Km section provides regional velocity-depth information. (b) Sonic logging and VSP velocity data from ODP Site 889 are shown in comparison with the seismic velocities.

![Figure 11](image-url)

**Fig 11**: Common-depth-point gather with normal moveout and array directivity correction near ODP drillsite, illustrating the seafloor and BSR amplitude-versus-offset behaviour. The offset range is from 183 to 3583 m.
from detailed semblance velocity analyses near the drill sites. In the interval from the seafloor to the BSR depth, the agreement among various velocity data is excellent. Over depths to several kilometres, velocities generally increase smoothly with depth, with the only exception of a high-velocity zone in the ~100 m thick section above the BSR. Below the BSR, the VSP velocity drops sharply to about 1500 m/s indicating a thin free gas layer. No such low velocity was recorded by the sonic data, probably because the drill fluid invasion displaced much of the formation free gas (ODP drilling is with seawater only, no drilling mud). The BSR thus clearly represents a strong discontinuity in formation velocity.

**AVO and Full Wave Inversions**

The characteristics of reflection amplitude-versus-offset (AVO) can be an important indicator of sediment physical properties since AVO depends on the variations of S-wave as well as P-wave velocities across the reflection interface. The AVO analysis is based on the theory and observation that free gas substantially reduces the P-wave velocity with little effect on S-wave velocity. Free gas thus changes Poisson’s ratio, such that the reflection amplitudes increase with increasing reflection angle or offset. In standard AVO analysis, offset-dependent amplitude variations are used to estimate the Poisson’s ratio contrast and hence to provide an indication of free gas. In common industry experience, the reflector occurs at a shale/gas-sand interface for most gas reservoirs. The situation is however quite different for unconsolidated near-surface sediments containing hydrates or free gas. The hydrate BSR does not occur at a lithology boundary, and the gas layer below the BSR is usually thin. Figure II displays an NMO-corrected CDP gather which possesses detailed amplitude characteristics that are uncommon in the standard AVO analysis. The high amplitudes and phase shift at farthest offsets may be the result of turning or diving rays in the high velocity hydrate.

AVO analysis alone is not sufficient to distinguish different velocity structure models across the BSR. However subtle differences in amplitude behaviour and reflection waveform can provide constraint through very careful full waveform inversion since additional information is contained in the detailed waveforms. A well-defined reference velocity-depth profile is also required to represent water-saturated sediment unaffected by either hydrate or free gas.

**Hydrate and Gas Concentrations**

The hydrate concentrations can be semi-quantitatively estimated from several types of geophysical and geochemical data, such as log resistivity, chlorinity from recovered core fluid, and data from pressure core sampler. But so far only the seismic data have provided the most reliable estimates. To calculate the amount of hydrate we must: (1) determine the increase in velocity of the hydrate-bearing sediments relative to the normal water-saturated sediments at that depth determined from a reference velocity-depth profile, and (2) convert the velocity increase to hydrate concentration using a theoretical or a laboratory based relation between velocity increase and concentration. At the ODP Site 889

<table>
<thead>
<tr>
<th>location</th>
<th>data source</th>
<th>hydrate concentration</th>
<th>free gas concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>western Canada off</td>
<td>seismic and ODP</td>
<td>up to ~20% of pore space over 100 m depth interval</td>
<td>~0.3% of pore space over 25 m depth interval</td>
</tr>
<tr>
<td>Vancouver Island</td>
<td>downhole velocities, downhole</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(ODP Leg 146)</td>
<td>electrical log, and core chemistry</td>
<td></td>
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<tr>
<td>eastern US on Blake</td>
<td>downhole velocities, electrical</td>
<td>~5% of pore space over 200 m depth interval</td>
<td>~2% of pore space over 100 m depth interval</td>
</tr>
<tr>
<td>Outer Rise (ODP Leg 164)</td>
<td>log, core chemistry, and pressure core barrel samples</td>
<td></td>
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</tr>
</tbody>
</table>

**Table 1**: Estimates of Hydrates and free gas concentration at ODP Sites offshore Western Canada and Eastern USA.
off Vancouver Island, there is a general increase in the inferred amount of hydrate from near zero at the seafloor to an average of ~20% of the pore space at the depth of BSR. Table I summarizes the concentrations of hydrate and underlying free gas for this site. The estimated hydrate concentration-depth profile indicates a total methane amount of ~200 Tci (trillion cubic feet) in an area of 30 x 200 km where clear BSRs have been observed on the west Canadian continental margin. For comparison, Table I also presents hydrate and gas concentrations from the other best studied area on the Blake Outer Rise off eastern U.S.A. (ODP Leg 164) from a study in progress.

Seismic Observations of BSRs off the East Coast of India

With the increasing interest in marine gas hydrate worldwide and the enormous area of thick continental margin sediments with hydrate potential on the coastal regions of India, programs to explore this alternative energy resource from gas hydrates have been initiated in India. There is a large amount of existing multichannel seismic data, as well as drilling and coring records available for initial evaluation of the hydrate potential for gas hydrates in the offshore Indian basins. A task force was established at Oil and

Fig 12. Reprocessed stack section on the east coast of Indian continental margin where clear BSR is observed.
Natural Gas Corp. Ltd. (ONGC) for gas hydrate evaluation, and a collaborative project for gas hydrate studies offshore India was initiated recently with the Gas Hydrate Study Group in Victoria, BC, Canada. The collaboration, established through the Alberta Research Council which has assisted in evaluating the potential in India of other non-conventional hydrocarbon resources, includes scientists from the University of Victoria (School of Earth and Ocean Sciences) and the Geological Survey of Canada (Pacific Geoscience Centre), who have undertaken extensive gas hydrate research over the past 10 years.

The primary objectives of the initial phase of the project were: (1) to examine existing offshore seismic data over the Indian continental margins (water depths greater than about 750 m where hydrate is stable) and to identify hydrate BSRs for data reprocessing and further investigation, (2) to carry out initial reprocessing of a few selected seismic lines where BSRs are indicated and (3) to make recommendations for more comprehensive studies and future surveys. The available seismic data were originally processed to image deep structures that have potential for conventional hydrocarbons. The processing parameters thus were not optimal for resolving the shallow structure where hydrates may occur. For some of the older data, recent processing methods that were not available at the time of the original processing also allowed better structure resolution. The initial test reprocessing was optimized to improve the images of the sediment structures in the upper several hundred metres below the seafloor. Data from the Andaman continental slope (subduction zone accretionary prism) show evidence for common gas hydrate BSRs. However, the east coast region received the most attention because of its more accessible location to the potential Indian gas users. In that region, BSRs are unambiguous and clearly indicate the presence of gas hydrates.

Data reprocessing of selected sections included predictive gap decon and detailed semblance velocity analysis. Because short-gapped decon can result in wavelet phase rotation which is not desirable for imaging the BSR, a compromise was made between whitening the frequency spectrum and preserving the reflection waveform by using a 16 or 20 ms gap for the predictive decon. Interactive velocity analyses were performed at a 500 m interval to obtain initial stack sections. The newly processed sections helped identify reflections corresponding to BSRs, and with this identification an improved sediment interval velocity field was achieved through a second velocity analysis. The accurate velocities are important in imaging shallow sediment structure and the BSR on the newly processed sections.

The presence of hydrate BSRs off the Indian east coast has been confirmed by several reprocessed seismic sections, as shown in Figure 12. The stack sections clearly image the BSR at 150-300 ms below the seafloor. The warm seawater temperatures, 5-6°C at a water depth of 1200 m, shifts the BSR shallower to the sub-seafloor depth in comparison to the BSR observed on the Canadian margin, and other higher latitude sites. The BSRs shown in Figure 12 clearly cut across other stratigraphic reflections. The strong BSRs closely follow the seafloor topography, and the polarity of the BSRs is opposite to that of the seafloor reflection, as expected for high velocity hydrate over low velocity gas. Interval velocities are 1700-1800 m/s above the BSR and only 1500-1600 m/s below. These reflection characteristics and initial analyses all suggest the existence of hydrate BSRs in the upper 150-250 m sediment sections below the seafloor. The minimum water depth where strong BSRs have been observed so far is about 950 m, which is within the reach of the deep water drilling capacity.

Other sites may be found with more extensive study, but unlikely at water depths less than about 800 m. Reprocessing of these few sections indicate that a more extensive program of reprocessing and study undoubtedly will locate many other regions with substantial occurrence of hydrate BSR along this coast and provide an accurate estimate of the hydrate and gas concentrations.
Gas hydrate Research and its Future

Gas hydrates were originally regarded as a nuisance by the petroleum, natural gas, and petrochemical industries, and as a safety hazard by drilling engineers. The characteristic BSRs, discovered in the deep ocean in the late 1960’s, initially were not understood as marking gas hydrates. There is now extensive research underway around the world. The main hydrate research topics are: seafloor stability, climate change, and energy resource. Of these, the energy resource has immediate economic impact because energy is the basis of world economy. The energy potential of natural gas hydrates is especially of interest to countries that do not have large domestic conventional hydrocarbons. It is now recognized that gas hydrates contain enormous amounts of hydrocarbon, and that they represent a large potential energy resource. However, the transition to economic recovery by the petroleum industry remains uncertain and is still under future development.

Awareness of environmental concerns in increasing in today’s largely coal and oil-based economy which is blamed for much of the apparent global warming and atmospheric pollution. There may be increasing pressure to shift more to less polluting gas as one of the primary energy sources. Gas hydrates have the long term potential to contribute to that energy resource base. Gas hydrates on land in polar regions already contribute in a small way, but exploration and exploitation from the large continental slope occurrences may follow in the future. Many scientific, technical and engineering programs of marine seismic and other field studies, chemical and laboratory studies, and finally deep water drilling are necessary to establish the potential for exploitation of marine gas hydrates. However, hydrates have the potential to develop into a major energy source worldwide for the economies of the next century and beyond.

References


