

Gas hydrates as alternative energy resource – seismic methods

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In view of the strenuous demand–supply oil and gas scenario, extensive efforts are being made to search for alternative forms of energy, which could substitute and fill the projected gap. The probable energy resources, which are likely to fill the gap are nuclear energy, coal bed methane, coal gasification/liquefaction, gas hydrates and hydrogen. Presently, the share of nuclear energy is insignificant in the energy basket contributing only 6% at the world level and about 2% in India. With the estimated large quantity of coal reserve all over the globe, efforts are being made to evaluate and extract methane trapped in coal beds and workout efficient use of coal through its liquefaction and gasification.

Gas hydrates with immense resource potential is being considered as a viable alternative to overcome the present oil and gas demand–supply crunch. It is estimated that gas hydrates can provide 50% of organic carbon of the earth or twice the energy resource when compared to the conventional form of energy. Current estimates of gas in gas hydrate accumulations in the world's marine and permafrost appear relatively well constrained and are expected to be in the order of about 20,000 trillion m³. Initial estimates of amount of gas in the identified gas hydrate locations on the continental margins of India are likely to attain a figure of 2000 trillion m³. The advantage of gas hydrates holding vast quantity of methane gas as reserve makes this form of hydrocarbons lucrative for exploration and exploitation.

In this article, I briefly present the conventional oil and gas scenario and describe seismic methods, which are commonly used to identify presence of gas hydrates in the region of investigation.

Keywords: Amplitude, energy resource, gas hydrates, simulating reflectors.

THE primary forms of energy that are being consumed have limited reserves. These resources are not renewable, as these reserves came into existence due to geological processes over a long period of time and cannot be replenished easily. Other energies such as wind, solar, water and geothermal are renewable, which means that these energies are inexhaustible. However, renewable resources are presently not economically viable.

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The estimated oil in place of the world is of the order of 6000 billion barrels (BB, barrel ~ 159 l) including the producible and nonproducable oil in the reservoir. However, owing to the present day technology and the characteristics of the reservoirs only a portion of the oil can be brought to the surface. This producible fraction is considered as the reserve. At present, 2500 BB reserve is an optimistic figure.

The present oil reserve estimates have remained mainly unaltered and no major oil fields were discovered in the last couple of decades. There are no giant oil field discoveries after the late sixties.

Natural gas because of its higher fuel efficiency and low order pollutants may work out to be a good energy prospect for the generation of electricity and as the main constituent in industrial production. It is expected that in future, industry will consume 40% of the total gas production. The projected estimated reserves of the world are of the order of 10,000 TCF, out of which around 6200 TCF are proven reserves.

The consumption of conventional form of energy leads to contamination of the atmosphere, either by emission of many gases during combustion or their free escape to the atmosphere, resulting in the greenhouse effect.

The discouraging oil and natural gas scenario necessitates looking at alternative forms of energy. In recent times, coal bed methane (CBM), coal gasification, coal liquefaction, nuclear energy, hydrogen and gas hydrates have emerged as possible viable energy sources. The alternative forms of energy, which will replace the present fossil fuel energies, must be economically viable, cost efficient and long lasting; in this regard gas hydrates are emerging as a viable energy resource of the future.

Gas hydrates

Gas hydrates are naturally occurring solid compounds composed of methane gas and water. Gas hydrates are an ice-like structure in which methane gas molecules are caged in a lattice of water molecules under elevated pressure and low temperature. The maximum amount of methane that can be trapped depends on the geometry and free space available in the lattice of the water molecule. Methane, the prime constituent of gas hydrates, is formed in the earth by different biological, chemical and physical

processes. Microbial methane is likely to migrate only to short distances to form gas hydrates occurring at or near the surface¹. In deeper parts of the earth, methane is generated by thermal degradation of organic matter². Most of the gas hydrates in the marine environment have been contributed by biogenic methane. However, in regions of the earth, gas hydrates may have been partially contributed by thermogenic methane.

Initially, it was thought that gas hydrates may occur only in the outer regions of the solar system, where the temperatures are appreciably low and water in the form of ice is quite common³. However, the pressure on the outer planets is quite low and it is expected that these planets will hold clathrates with a compound mixture of different gases.

The stability condition for the formation of hydrates in the earth's crust is in general prevalent in the deep-sea marine environment and in the permafrost and polar regions. Gas hydrates occur in less than 10% of the total oceanic area, as they are restricted to slopes and rises of outer continental margins, where water depth exceeds 300 m. Figure 1 shows P–T regimes for permafrost and tropical marine environment under which hydrates can be stable⁴. The lower temperatures in the permafrost region, almost touching about 1°C, permit formation of gas hydrates few hundred metres below the surface of the earth. In the tropical regions, the sea-surface temperature in the tropical countries is around 20°C and gas hydrates can be stable up to 300 m when the sea floor attains 0°C temperature. The thickness of gas hydrate stability zone (GHSZ) depends on the sea floor depth, geothermal gradient, gas composition, ionic content of water and geology of the region. In the presence of heavier gases along

with methane, such as H₂S and CO₂, gas hydrates can be stable at higher temperature, whereas those containing nitrogen and dissolved salts in water require lower temperature for stability.

Geophysical indicators

Bottom simulating reflectors

The presence of gas hydrates in the subsurface of earth as thick layers, veins, nodules as well as pore filling, cementing the sediment grains, increases the stiffness of the sediments. The stiffening of the sediments results in increase of the compressional velocity, V_p and cementation of sediment grains by hydrate will lead to increase in shear modulus and thereby shear wave velocity V_s . Normal oceanic sediments underlying the gas hydrates have lower velocities and if gas is trapped in underlain sediments, the velocity of the layer will still be lower⁵. Because the strength of the reflected signal is proportional to the change in acoustic impedance (product of velocity and density) across the interface, the base of hydrate cemented zone produces a strong reflector, which has reverse polarity to that of the sea floor. As this reflector marks the phase boundary and runs parallel to the sea floor, it has been termed as bottom simulating reflector (BSR)⁶ and owing to the relevance of phase boundary being dependent on the thermobaric conditions, this associated reflector cuts across the dipping sedimentary beds. The identification of BSR on the seismic reflection data has become important to drawing inference for the presence of gas hydrates in a region.

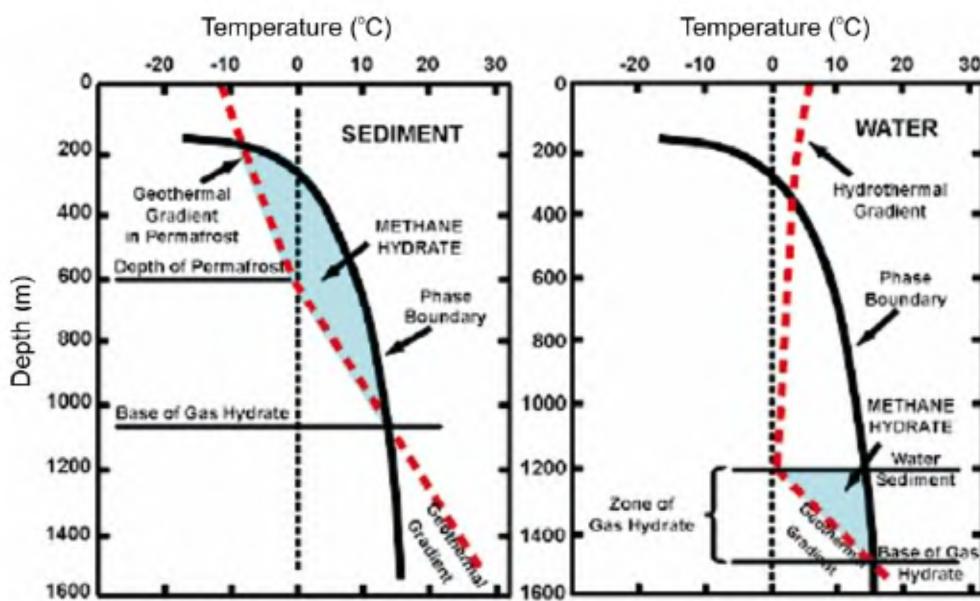


Figure 1. Phase diagram showing thermodynamic stability range of hydrates in a pure water/methane system (area highlighted with the blue colour) in permafrost and deep-sea sediments. (After Kvenvolden⁴.)

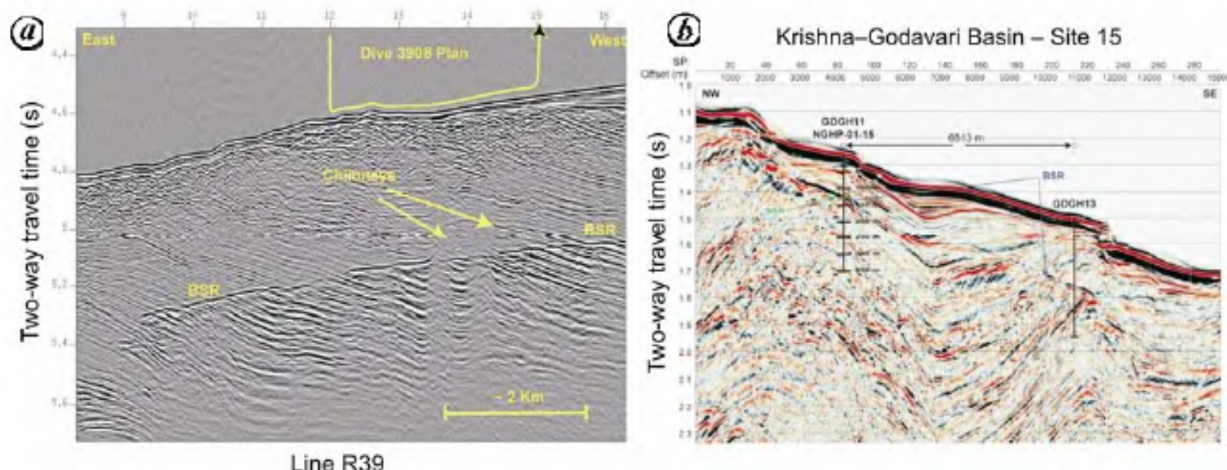


Figure 2. Typical bottom simulating reflector (BSR) over the Blake Ridge in the Atlantic Ocean (a) and in the Krishna–Godavari basin off the eastern coast of India (b).

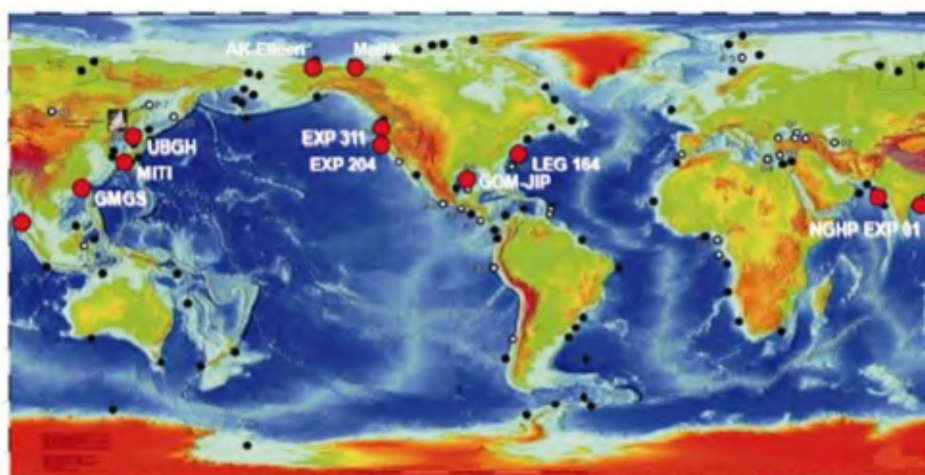


Figure 3. Global distribution of identified gas hydrate-bearing locations. Solid circle (black) indicates where hydrates have been identified based on seismic and other geophysical data and circles in white indicate where hydrates have been recovered. Red thick solid circles indicate the regions covered under Ocean Drilling Program.

Figure 2a and b shows a typical BSR satisfying most of the characteristics mentioned above over the Blake Ridge in the Atlantic Ocean and in the Krishna–Godavari basin off the eastern coast of India.

Occurrences of gas hydrates have been identified in many places all over the globe (Figure 3). Their presence has been inferred by the analysis of seismic reflection data and from drilling. It has been established that gas hydrates can be found in the submarine continental shelf and slope setting as well as in the permafrost regions. The presence of gas hydrates has been ground toothed by samples taken from about 20 sites on the globe. About 80 locations have been established on the inference drawn from evidences of the seismic data⁷.

Plunging BSRs: In recent times, some of the identified BSRs do not have all the characteristics of a typical BSR.

These BSRs do not show the main characteristic of running parallel to the sea floor (Figure 4). Gas hydrate-bearing sediments are sometimes associated with features like wipe outs, termination of reflectors and seeps probably suggesting the vertical fluid flow patterns. Approximately three-quarters of the gas hydrate-bearing sites in the database (including seabed and sub-seabed sites) are within or proximal to features that may promote upward migration of gas or gas-rich fluids. The upward movement of the fluids perturbs the thermal region locally, thereby perturbing the stability condition of the gas hydrates. Faults act like conduits for flow of fluids and often disturb the pattern of BSRs⁸. As such, BSRs not showing any parallelism to seafloor are termed as plunging BSRs. Blanking associated over narrow zones with such features are attributed to the vertical movement of fluids and gases. These features in seismic reflection data

in the Gulf of Mexico provide inference about the presence of gas hydrates as well gases emanating from deep (thermogenic) sources.

Double BSRs: In some regions of the world, the movement of phase boundary upward or downward during the periods of climatic changes has altered the position of old (relic) and new BSRs and have formed with the present stability conditions producing two BSRs (Figure 5), i.e. double BSR (DBSR). The DBSR pattern observed in the Oregon continental margin was interpreted⁹ as a temporary feature caused by changing sediment thickness due to tectonic processes. Norwegian continental margin DBSR was interpreted¹⁰ to have been caused by different gas compositions forming hydrates at different stability zones. The occurrence of DBSR in the Nankai slope is suggested as due to the present day active stability conditions and the second one is a relic of ancient physical conditions prevailing in this region¹¹. In recent times¹², it

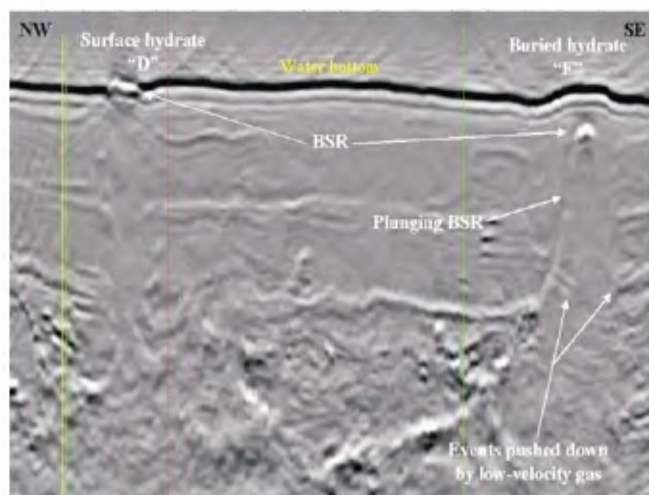


Figure 4. Observed plunging bottom simulating reflectors (BSRs) with gas escape features in the Gulf of Mexico. The observed BSRs are controlled by the events of fluid flow.

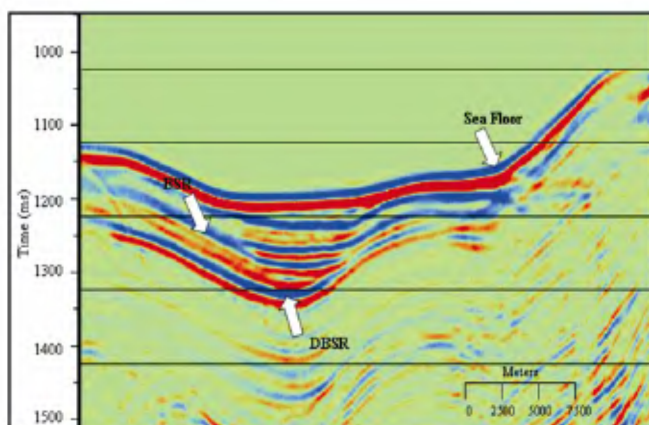


Figure 5. Double bottom simulating reflector identified on the Green Canyon in the Gulf of Mexico.

has been reported that presence of fluids in the sediment and hydrate matrix will alter characteristics of the medium. The presence fluids may reduce the velocity of the medium. Layering of fluids may produce low velocity layer in the hydrated zone and thereby this may also result in the formation of DBSRs.

Blanking

One more interesting feature that provides vital information on the inference about the presence of gas hydrate in a region of investigation is the blanking observed in seismic reflection data. It has been observed that hydrate-bearing sediments are devoid of reflections (Figure 6) when compared to the sediments below the stability zone. It is argued that cementation of sediment grains with gas hydrates may lead to uniformity within the sediment strata and thereby showing no reflection in this zone. The observed blanking in many parts of the world has been attributed to the presence of gas hydrates in the region^{13,14}. However, Holbrook *et al.*¹⁵ did not observe significant increase in seismic velocity, an indicator of the presence of gas hydrates and suggested that lack of impedance contrast within the zone of stability may indicate the homogeneity of the sediments. Wood and Ruppel¹⁶ suggest that 'blank zone' in seismic data may imply a paucity of horizontal reflections rather than lack of impedance contrast. It was argued that the vertical seismic reflection profiling (VSP) results did not show significant changes in velocities over the Blake Ridge in the presence of gas hydrates, probably suggesting causes other than homogeneity for the observed amplitude reduction. Homogeneities lower than the resolvable spatial wavelengths are averaged out and due to scattering result in lower reflectivity¹⁷. Modelling results¹⁸ have indicated enhancement in the blanking pattern with increase in saturation of gas hydrates in sediments.

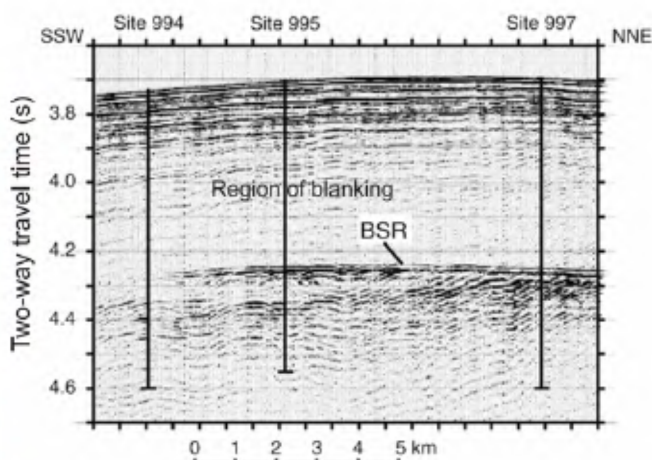


Figure 6. The blanking (area of no reflections) observed over the Blake Ridge, in the north Atlantic, suggesting the presence of gas hydrates in this region.

Velocity amplitude pull-downs

Velocity amplitude pull-downs (VAMPS) are pseudo-structures observed in the seismic reflection data indicating the presence of high concentration (massive) of hydrates. VAMPS primarily mark variation of velocity values (amplitudes) underlain by sediments saturated with free gas in the region of investigation. The high concentration of hydrates at the base of hydrated layer significantly alters the seismic velocity. Owing to the high velocities, the seismic waves travel faster in this region, thereby reducing the travel times when compared to adjoining regions. The reduction in travel time results in pseudo-structures as if the structure is upwarped (pulled up) when compared to normal stratigraphy. The low-velocity medium of free gas under the hydrated layer produces a pull-down pseudo-structure owing to the large travel times in the region. The push-pull pattern as seen in the seismic reflection stacked data suggests that appreciable changes occur in the velocity amplitude due to massive presence of hydrate underlain by free gas layer. Distinctive VAMPS are displayed on the seismic records as vertical columns (1–2 wide) of down flexed horizon commonly stacked directly beneath the crestal region of series of arched or domed horizons. VAMPS are most commonly recorded within the flat lying beds and non-structural settings. Massive accumulation of hydrates deposits is generally identified by means of occurrence of VAMPS structures in the Bering Sea Basin¹⁹ and Sea of Okhotsk²⁰. Figure 7 shows seismic stack section of VAMPS identified in the Bering Sea Basin.

Velocity

The main quantitative constraint on hydrate and gas concentrations can be obtained from a detailed analysis of

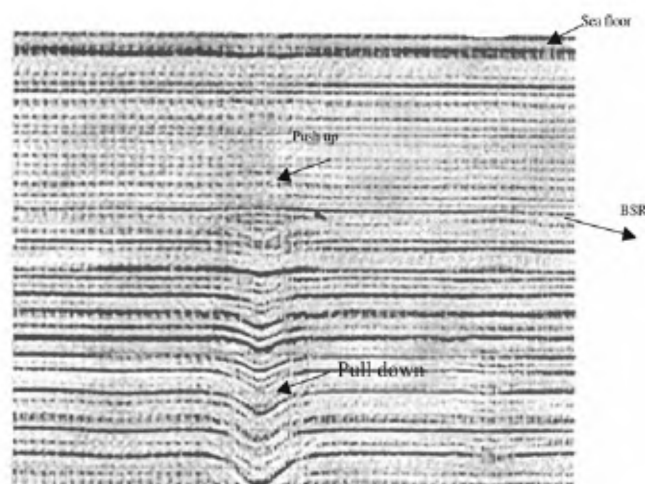


Figure 7. Seismic stack section depicting velocity amplitude pull-downs anomalies identified in the Bering Sea Basin has been interpreted to be caused by the presence of massive hydrates.

seismic velocities estimated from multi-channel seismic data. The conventional multi-channel data are collected with hydrophone array exceeding 2 or 3 times the depth of the target zone. The velocity-depth obtained for deeper parts may be extrapolated upward in the shallower parts and this may be used as the reference velocity field for the quantification of gas hydrates²¹. Based on the down-hole velocity data at the ODP Site 889, about 2/3 velocities from the high-velocity hydrate and about 1/3 from the low-velocity gas, relative to a no-hydrate no-gas reference velocity-depth contribute towards formation of BSR²². This ratio is undoubtedly highly variable. For example, on the Blake Ridge, the BSR reflection appears to be primarily due to the low-velocity free gas²³. The estimated RMS velocity values could be converted to interval velocity by Dix equations, which provide detailed information about the velocity variations in each layer. The presence of gas hydrates and free gas is identified in the region based on the high and low velocity pattern (Figure 8)²⁴.

Frequency attenuation

Free gas is known to highly attenuate the seismic P-waves. Instantaneous frequency enables us to delineate the regions of high attenuation (i.e. absorption of energy due to internal friction). For a given region of high attenuation, the shorter wavelength energy will be attenuated. Seismic attenuation is high in case of free gas-bearing zones rather than hydrates and hence helps in differentiating the gas-bearing zones from hydrate bearing and/or sediments lacking free gas. Saturation of sediments with hydrates increases the rigidity and thereby the seismic velocity. The attenuation of seismic velocity decreases when the rigidity of sediment is enhanced due to compaction. However, on the contrary, sediments saturated with hydrates show higher attenuation for higher frequencies with increase in saturation¹²; such behaviour is attributed to presence of pore fluids in the hydrate and sediment matrix. In this context, it is expected that existence of fluids in the hydrate and sediment matrix may lead to the absorption of higher frequencies (Figure 9)²⁵.

Hydrates without BSR

A BSR is generally not distinctly observed in the regions covered with thick well-bedded sediments, slope basin sediments, which may cast doubts on the presence of hydrates. Analysis of multi-channel seismic data from many regions of the world has revealed that gas hydrates may be present in many locations where BSR was not distinctly identified^{26–28}. Hydrates may not be present because well-bedded sediments reduce permeability compared to the deformed accreted sediments, thus inhibiting vertical fluid and methane flow. Alternatively,

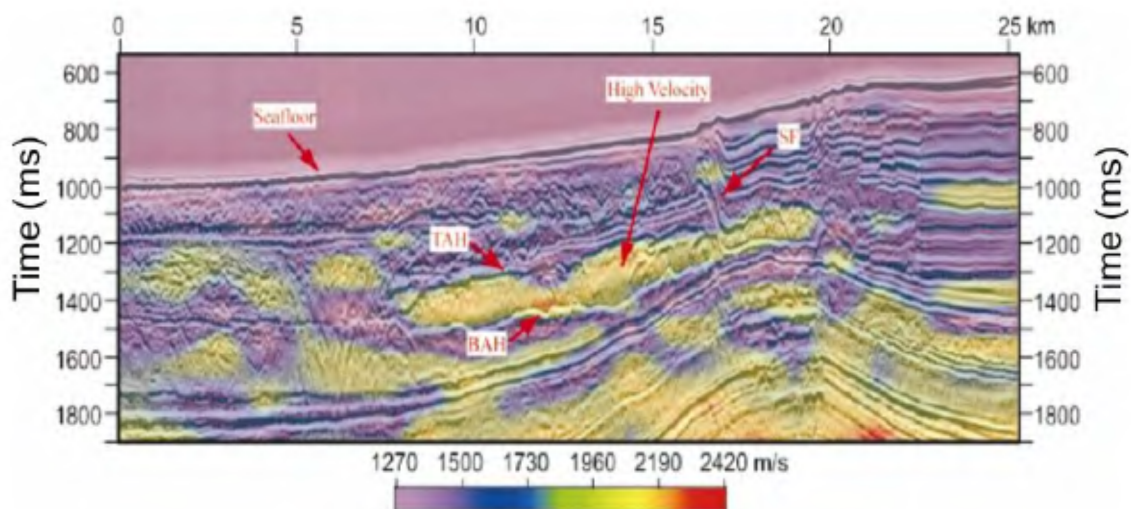


Figure 8. Interval velocity variation obtained from a seismic profile in Caspian Basin in Azerbaijan. The presence of light coloured regions (high velocity zone) suggests the presence of gas hydrate underlain by free gas with lower velocities. The top of hydrates (TAH) and bottom of hydrate zone (BAH) are indicated.

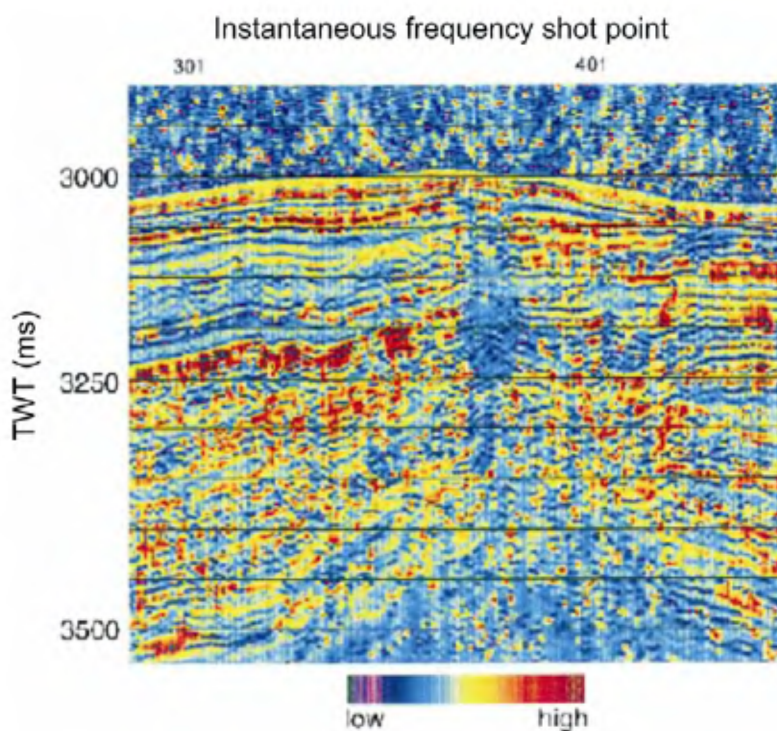


Figure 9. Attenuation of higher frequencies in the free gas and gas hydrate layers (after Taylor *et al.*²⁵). The absence of red coloured dots in some regions indicates attenuation of high frequency signals suggesting the escape of gases.

hydrates may be present but tectonic subsidence and sediment deposition in the slope basin result in downward movement of the base of the stability field, so that the gas layer is transformed to hydrate and the BSR is much diffused²⁹. The absence of BSR can also be attributable to rate of methane supply and the top of methane layer not in coincidence with the base of gas hydrate stability zone^{16,30}. The results from ODP Leg 164 over the Blake

Ridge in the Atlantic suggested that hydrates might be present in this region in spite of the absence of BSR in some parts of the Ridge²⁶. The absence of BSR in some regions off Costa Rica was interpreted in terms of the geothermal gradient, which makes the BGSZ deepen to the extent of basement rocks and not confined to the sediment column²⁸. Interpretation of multi-channel seismic data in the Nankai Trough region suggested that BSR

can easily be identified in the sediments covering the anticlinal and at the flanks of anticline, whereas it was not clearly traced in the basin slope¹¹.

Discussion

The identification of BSR on the multi-channel seismic data has led to the inference of locating gas hydrate reserves in many parts of the world^{31–33}. It is not yet fully understood what causes the formation of BSR. Is it the positive impedance due to the presence of gas hydrate or the negative impedance contrast across the interface due to the presence of free gas below the hydrated layer? With development in seismic data acquisition and processing/modelling, the causative mechanism of formation of BSR is being debated extensively^{34,35}. In earlier studies, BSR marked the interface between high velocity hydrate-bearing sediments underlain by normal velocity oceanic sediments or low velocity gas saturated sediments^{36,37}. Hyndman and Spence³⁸ suggested that the identified BSRs over the Cascadian margin might be due to higher saturation of gas hydrates. On the contrary, it was argued that weaker BSRs may be caused by gas hydrates in the absence of free gas^{39,40}. Many evidences are emerging to suggest that free-gas below the hydrate stability zone may be the prime cause^{36,40,41}, for the formation of BSR. Singh *et al.*⁴² contended that BSR in Cascadian margin is mainly due to the lower impedance associated with underlying free gas layer. Further studies⁴³ in this region have suggested that BSR occurs due to the high velocity hydrated layer underlain by low velocity free gas layer.

The analysis of wide range frequency seismic data²² indicated that BSR emerges as a strong reflector for low frequencies and practically disappears in the very high frequency range. The modelling³¹ of frequency response of this data set suggested that maximum gradient changes in the velocity profile occur near BSR and the thickness where the maximum change occurs is in the order of 6–8 m.

The information contained in the amplitude versus offset (AVO) (distance) is generally utilized to model the configuration which governs the formation of BSR. The concentration of gas hydrates and free gas in the lower layer will affect the Poisson's ratio and thereby results in different AVO patterns depending on the contribution from these two layers. It has been observed that the amplitude increases with offset in the presence of gas below the BSR (Figure 10)⁴⁴.

To arrive at the possible cause for the AVO pattern, extensive modelling has been attempted in many parts of the world^{45,46}. Andreassen *et al.*⁴⁴ suggested that the AVO pattern in the Beaufort region can be accounted in terms of only free gas layer. On the contrary, Hyndman *et al.*³³ suggested that the pattern of AVO in Cascadian margin does not require free gas layer. All these models consider

a gradational increase in the hydrate concentration in the hydrated layer and thereby there is a sharp fall in velocity due to the presence of free gas layer. It is argued that the hydrate saturation controls the AVO pattern significantly rather than the free gas below the BSR once the gas saturation exceeds 1%. Therefore, it is felt that the AVO pattern gives little information about the gas saturation below BSR^{45,47,48}. However, estimates of hydrate saturation to account for the strength of BSR itself is not unique. Hyndman and Spence³⁸ estimated that 30% pore hydrate saturation is required for the amplitude of BSR observed in the Cascadian margin, whereas for the same region, Singh *et al.*⁴² postulated that amplitude of BSR in this region could be accounted in terms of free gas below the BSR. Guerin *et al.*⁴⁹ estimated that 5–10% saturation of hydrate and 5% saturation of free gas in the underlying layer is enough to produce the amplitude of BSR in the Blake Ridge area. When the causes of variations in the velocity become speculative, it casts a doubt on the quantification of gas hydrates and free gas reserves estimated from modelling the AVO response of BSR.

The identification of DBSRs from many regions of the world has led to many interpretational aspects to account for their formation. The causative mechanism for formation of DBSR has been interpreted in terms of climatic change and tectonic activity. It has been reported that the presence of fluids in the sediment and hydrate matrix produces physical characteristics of the medium¹². The presence of pore fluids may reduce the velocity of the medium. Layering of fluids may produce low velocity layer in the hydrated zone and thereby this may also result in the formation of DBSRs. On the contrary, laboratory experiments have indicated that BSR forms the top of the free gas and not the base of the gas hydrate stability zone and some of hydrates may also exist along with gas⁵⁰. Existence of such conditions in nature is also likely

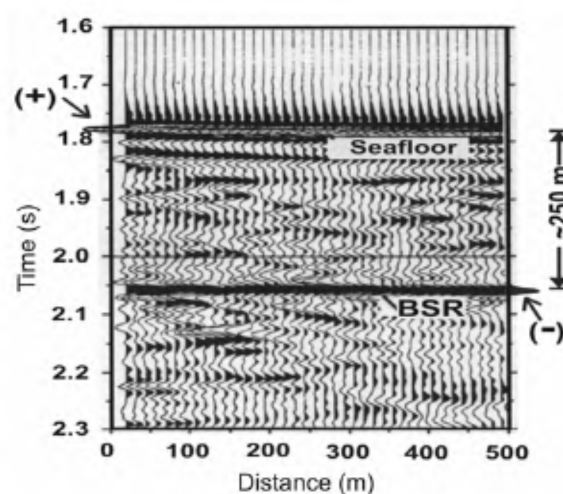


Figure 10. The observed amplitude versus off-set pattern for Cascadian margin, exhibiting increase in amplitude with offset suggesting possible presence of high velocity hydrate layer underlain by free gas layer.

to generate DBSR owing to presence of hydrates and free gas in this complex pattern. Under these considerations it is felt that presence of heavier hydrocarbons¹¹, fluids¹² in the hydrated layer and presence of hydrates in the free gas layer are more likely to be the causes for the generation of DBSR.

Detailed velocity analysis of seismic data constraints the quantitative estimates of gas hydrates and the underlying free gas³⁸. P-wave velocities estimated for different regions of the world show quite a large variation. Waveform inversion of data offshore Vancouver Island has given a value of 1700 m/s for the hydrated layer⁴². In the region of Blake Ridge, a velocity 2500 m/s was obtained⁵¹. Similarly for free-gas layer, the estimated velocities also show appreciable variation. The values range from as high as 1650 m/s (ref. 33) for the Indian region to as low as 1240 m/s for Cascadian margin⁴³. The results from ODP Site 889 indicate that the appreciable velocity increase of the hydrated layer contributes significantly to that of the drop in velocity in the free gas layer for the generation of BSR in this region. The results indicate that there is no definite pattern in impedance contrast across the hydrated-free-gas layers to produce BSR. P and S wave velocities differ significantly from one rock matrix to other. Hydrates have affinity to form in coarse-grained rocks. However, coarse-grained rocks in general have high velocities compared to fine-grained rocks. The saturation of high velocity hydrates in fine-grained rocks shows appreciable increase in velocity when compared to the coarse-grained rocks. In this regard, an estimate of the reference velocity of host rock matrix is a prerequisite to characterize the increase/decrease in velocity due to presence of hydrate or free gas.

Irrespective of the mode of formation of BSR, it still remains the main diagnostic character for locating gas hydrates in a region^{31–33,43}. Recent studies on the eastern continental margin of India have identified potential gas hydrate zones in the Krishna–Godavari offshore basin as well as in the Andaman Sea based on the identification of BSR in multi-channel seismic and anomalies in the multi-parameter data^{52–54}. Drilling and coring results have established the ground truth for the massive deposits of gas hydrates and these regions have emerged as few of the most prominent gas hydrate reservoirs on earth^{55,56}.

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ACKNOWLEDGEMENTS. I thank the Director, NGRI for providing infrastructural facilities and to CSIR for granting the Emeritus Scientist Scheme.

Received 17 July 2009; revised accepted 4 June 2010