Origin and significance of a bottom simulating reflector (BSR) in the Choshi Spur Depression of the Offshore Chiba Sedimentary Basin, central Japan

Hiroyuki Arato*
Hiroshi Akai**
Satoshi Uchiyama***
Tetsuro Kudo* and Kaichi Sekiguchi*

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* Technical Research Center, Teikoku Oil Co., Ltd. 9-23-30 Kitakarasuyama, Setagaya-ku, Tokyo, 157 Japan
** Teikoku Oil De Venezuela, C.A., Torre Seguros Caracas, 3 Piso Av. FCO. De Miranda, Los Palos Grandes, Caracas 1060, Venezuela
*** Exploration Department, Teikoku Oil Co., Ltd. 9-23-30 Kitakarasuyama, Setagaya-ku, Tokyo, 157 Japan

Abstract

A bottom simulating reflector (BSR) is present in the Miocene-Pliocene Miura Group in a small depression at the tip of the Choshi Spur in the Offshore Chiba Sedimentary Basin, central Japan. We adopt the assumption that natural gas hydrate BSRs always co-occur with layer-formed gas hydrates at the base of gas hydrate stability (BGHS), and with underlying free gas. The layered natural gas hydrates suggested by this BSR are thought to have formed from natural gases of thermogenic origin accompanied by an upward shift of the BGHS. These latter gases were presumably supplied continuously from yet undiscovered, underlying, mature, organic-rich source sediments. The upward movement of the BGHS was related to large-scale tectonic uplift that accompanied development of the Kurotaki unconformity, to rapid continuing deposition of the Kazusa Group, and/or possibly to an increase in the geothermal gradient.

A large volume of the estimated natural gas reserves may not be expected as energy resources from the BSR area of the Choshi Spur Depression. However, this is an excellent research site for studying BSR geophysics, the geophysical responses of natural gas hydrates, the geological occurrence and formation mechanisms of a natural gas hydrate-bearing zone, and for evaluating additional operational concepts for reserve evaluation and gas recovery in the near future.

Key words: bottom simulating reflector (BSR), natural gas hydrate, Offshore Chiba Sedimentary Basin, Choshi Spur, hydrate stability zone, base of gas hydrate stability (BGHS)

Introduction

A bottom simulating reflector (BSR) is present in MITI (Ministry of International Trade and Industry, Japan) seismic profiles of the Offshore Chiba Sedimentary Basin, which is located in the southern fore-arc of the northeastern Japan Arc (Fig. 1). The geologic setting and origin of this BSR are discussed here.

Occurrence of the BSR in the Offshore Chiba Sedimentary Basin

Two seismic surveys were carried out on the eastern shelf of the Boso Peninsula in water depths of less than 1,000 meters by Teikoku Oil-Gulf Oil in 1974, but no BSRs were detected. Seismic profiles from deeper-water sites acquired by MITI in 1977, however, show a BSR present where two profile lines intersect over a bottom feature called the Choshi Spur (Fig. 2). The BSR occupies the tip of the Choshi Spur and is located about 80 kilometers east of the Boso Peninsula. The tip of the Choshi Spur forms a relatively flat terrace at a water depth of about 1,600 meters (Fig. 3, 4). Time-depth conversion data are not available, because no offshore exploratory wells have been drilled in this basin, but the depth of the BSR below the sea floor is estimated to be roughly 600 meters, based on the interval velocity values of seismic velocity analysis data. The geothermal gradient in this area is assumed to be about three degrees Celsius per 100 meters, which falls well within the range of values for a basin in a forearc setting. Based on this assumption, the base of gas hydrate stability (BGHS) was anticipated to be 600 meters below the sea floor. The actual presence of the BSR about 600 meters below the sea floor, noted above, closely approximates this model, where the bottom sea water temperature assumed to be 4.0 degrees Celsius.

Seismic reflectors in profile 18 delineate a small
Submarine geological maps for the area east of the Boso Peninsula (Tanahashi and Honza, 1983; Okuda, 1985) also provide some stratigraphic information applicable to the study area. These maps do not directly cover the study area, but they show depositional patterns similar to those seen in the MITI seismic profiles of the Choshi Spur area. Tanahashi and Honza (1983) constructed a seismic stratigraphic framework for the offshore eastern Boso Peninsula, on the basis of seismic facies analysis and on the traces of some salient discontinuities. They also provided correlations between the offshore stratigraphic framework, based in part on analysis of dredged samples, and the onshore stratigraphy of the Boso Peninsula.

Their study demonstrated that three layers, labeled C, B and A in ascending order, are identifiable by seismic characteristics, and can be correlated with the Miura Group, the Kazusa Group and the Shimosa Group, respectively, of the Boso Peninsula.

Sediments in the Choshi Spur Depression may be divided into two parts:

i) the lower part may correlate with part of Layer C (Miura Group), and

ii) the upper part of Layer B (Kazusa Group), and underlying basement rocks, may correlate with Permian through Paleogene strata (Fig. 5).

Geological model for accumulation of gas hydrate and free gas

Nature of BSRs

Bottom simulating reflectors (BSRs), which lie approximately subparallel to the sea floor and have high amplitude and reverse polarity (Kvenvolden and Barnard, 1983), are one of the most significant indicators of natural gas hydrate accumulation. The amplitude characteristics of natural gas hydrate BSRs are determined by the contrast of acoustic impedances associated with the combination of a high acoustic velocity for natural gas hydrate layers, and a low acoustic velocity for underlying free-gas-bearing layers (Dillon and Paull, 1983; Hyndmann and Davis, 1992; Hyndmann and Spence, 1992). The subparallel alignment of BSRs with the sea floor is controlled by the subbottom depth to the base of gas hydrate stability (BGHS), which is a product of pressure and temperature conditions. A BSR ideally indicates the presence of a natural gas hydrate layer at the base of gas hydrate stability (BGHS) that is associated with underlying natural free gas.

Association of gas hydrates

The existence of gas hydrates in subbottom ocean conditions requires the following three conditions (Matsumoto, 1995):

1. sufficient intergranular space in sediments for the formation of clathrate cages,
2. sufficient methane and water, and
3. pressure-temperature conditions that stabilize
Fig. 2. Map showing bathymetry, the locations of seismic lines, and the studied BSR. The thin lines indicate seismic lines on the outer shelf and upper slope acquired by Teikoku Oil and Gulf Oil in 1974. The thicker lines indicate MITI regional seismic lines (Shimokita–Tokai Oki region) acquired in 1977. The thickest bars along MITI seismic lines 18 and T show the observed BSRs, and the shaded area inside the dotted line indicates the approximate area of the BSR.

Fig. 3. MITI seismic profile 18 (shot points 0–970) of the Shimokita–Tokai Oki region. The series of open triangles indicates the location of the BSR. Modified from Japan National Oil Corporation (1977).

Gas hydrates. Strata in the Choshi Spur Depression are thought to have sufficient porosities and water content, because they consist of young and relatively uncompacted marine clastic sediments which lack a thick overburden. In addition, the space between the BSR and the sea floor of the Choshi Spur is considered to have favorable pressure–temperature conditions for gas hydrate stability. Consequently, the methane sources control occurrences of natural gas hydrates.

The two major sources of methane for producing gas hydrates are:

1. organic material decomposed biogenically at shallow subbottom depths, producing mainly methane, or
2. natural gases introduced into the field of gas hydrate stability produce gas hydrates at the BGHS.
Fig. 4. Close-up view of MITI seismic profile 18 (shot points 100–530) of the Shimokita-Tokai Oki region. The series of open triangles indicates the location of the BSR. Modified from Japan National Oil Corporation (1977).

Fig. 5. Diagrammatic section of east–west trending seismic profile 18 in the Offshore Chiba Sedimentary Basin. The darker shaded layer area indicates the distribution of Permian–Paleogene deposits. The medium shaded layer fine dots and overlying lightest shaded layer show the distribution of the Miura Group and Kazusa Group, respectively. Thick double lines show the location of the BSR.

The former case will result in dispersive gas hydrates, and the latter case in layered gas hydrates.

**Accumulation of natural gas hydrates**

The accumulation of natural gas hydrates expectably forms a tight layer at the BGHS that is accompanied by underlying natural free gas. The following two processes are thought to produce natural gas hydrates at the BGHS:

1. a continuous supply of natural gas to the hydrate stability zone from underlying mature source sediments, and
2. an upward migration of the BGHS against natural gas hydrate–bearing strata.

The former case occurs when organic–rich sediments reach maturity in a gas window below the hydrate stability zone. In such a case, natural gas supplied into the hydrate stability zone must be of thermogenic origin. The latter case occurs when sediments within the hydrate stability zone originally contain natural gas hydrates, irrespective of whether the supplied natural gases are thermogenic or biogenic in origin, or whether the natural gas hydrates are dispersive, massive or layered.

**Shifts in the position of the BGHS**

The position of the BGHS is controlled by pressure–temperature relations, assuming that gas and water content remain constant (Claypool and Kaplan, 1974; Field and Kvenvolden, 1985). Either a decrease
in pressure or an increase in temperature will result in an upward shift of the BGHS. A number of geological phenomena will lead to a pressure reduction or a temperature rise. Reduced pressure may result from decreased water depth caused by either a eustatic fall or tectonic uplift. Increased temperature may result from greater burial depth, a steeper geothermal gradient, or higher sea water temperature.

**Effects of glacioeustatic changes**

In the simplest case, a decrease in pressure may result from lesser water depth owing to eustatic sea level fall. Glacioeustatic changes are reflected in the oxygen isotopic ratios of planktic foraminifera (Shackleton and Opdyke, 1973), upon which the oxygen isotope curve for the Quaternary is based (Williams, 1990). Using this curve and the known relationship that a 0.11–0.1 per mil shift in oxygen isotopic values indicates an approximate 10-meter change in sea-level (Fairbanks and Mathews, 1978), glacioeustatic changes in the Quaternary probably did not exceed 150–200 meters. Based on the dissociation curve of methane hydrates (Field and Kvenvolden, 1985), an approximate 30-meter upward shift in the BGHS would be an acceptable maximum case, since Quaternary glacioeustatic fall evidently was less than 200 meters at the Choshi Spur (Fig. 7).

**Effects of tectonic uplift**

Tectonic uplift may also reduce water depth, and both tectonic uplift and eustatic fall result in relative sea-level fall. Two hundred meters of tectonic uplift produces the same effect on the position of the BGHS as 200 meters of glacioeustatic sea level fall. However, several thousand meters of tectonic uplift may produce an upward shift of several hundred meters, which is beyond the possible amplitude of a glacioeustatic fall. The conclusion is that glacioeustatic falls are not as effective as are large scale tectonic uplifts for affecting large upward movements of the BGHS.

**Effects of deposition**

Rises in temperature may result from increases in burial depth. Continuous deposition upon the sea floor causes an increase in burial depth at a given site that may be accelerated by basin subsidence. Both deposition and subsidence lead to an increase in temperature and an upward shift of the BGHS if the geothermal gradient is constant. Assuming a constant geothermal gradient, an additional 200 meters of sediment would produce more than 200 meters of upward movement in the BGHS (Fig. 8). However, the same amount of deposition associated with synchronous subsidence would also result in about 200 meters of upward shift of the BGHS (Fig. 9). Compared to eustatic fluctuations, additional deposition results in a greater accumulation of gas hydrates at the BGHS.
Fig. 8. Phase diagram showing the field of methane hydrate stability and the effect of additional deposition on upward movement of the base of gas hydrate stability (BGHS). Based on the phase boundary curve of Field and Kvenvolden (1985), about 230 meters of upward movement of the BGHS results from an additional 200 meters of deposition at a water depth is roughly 1,600 meters.

**Effects of shifts in the geothermal gradient**

An increase in the geothermal gradient also causes an increase in temperature. In the Choshi Spur, the geothermal gradient is thought to be approximately 3.0 degrees Celsius per 100 meters. In comparison, some fore-arc sedimentary basins in the northern part of Northeastern Japan have geothermal gradients ranging from 1.0 to 2.0 degrees Celsius per 100 meters. Three degrees Celsius per 100 meters may be a not unreasonable value for the Choshi Spur, given its location close to the triple junction of trenches called the “Boso Triple Junction” (Ogawa et al., 1989). However, if the geothermal gradient were to increase from 2.0 to 3.0 degrees Celsius per 100 meters, as it seemingly did at the Choshi Spur, then more than 300 meters of upward movement of the BGHS would be expected (Fig. 10). An increase in the geothermal gradient, therefore, affects a greater accumulation of gas hydrates at the BGHS.

**Effects of changes in the temperature of sea water**

Increases in sea water temperature produce concurrent increases in formational temperature. Oxygen isotopes shifted a maximum of about 2.0 per mil from glacial to interglacial stages in the Quaternary (Williams, 1990), owing to an approximate 10 degree Celsius increase in sea surface temperature (Morley and Shackleton 1984). If the sea surface temperature rose at least 5 degrees Celsius and the temperature profile of the ocean did not change, then an approximate 200-meter upward shift of the BGHS would be expected (Fig. 11). The rise in formational temperature resulting from a sea water temperature increase would reduce any pressure increase due to elevated sea levels during interglacial stages (Fig. 12).

In summary, large-scale tectonic uplift, increases in the geothermal gradient, and additional deposition are thought to be the main causes of the accumulation of gas hydrates related to upward movements of the BGHS.

**The association of gas hydrates and free gas layers in the Choshi Spur**

**Major controls on gas hydrate association in the Choshi Spur Depression**

The inferred burial history of the Choshi Spur Depression (Fig. 13) includes deposition of the Miura Group between 16.0 Ma and 3.0 Ma (Okada et al., 1991; Saito et al., 1991). The overlying Kazusa Group ranges in age from about 2.5 to 0.5 Ma and is separated from the Miura Group by the Kurotaki Unconformity (Ito, 1992). The depositional environments of both groups in the Choshi Spur Depression are not directly
observational, because no exploratory or research wells have been drilled in the Offshore Chiba Sedimentary Basin. However, paleo-bathymetry has been inferred from benthic foraminiferal assemblages in subaerial exposures on the Boso Peninsula. The lower and middle parts of the Miura Group are thought to have been deposited in the middle bathyal zone, and the upper part in the lower bathyal zone (Saito et al., 1991). The Kazusa Group, on the other hand, is thought to have been deposited in depths similar to those of the present Choshi Spur. If the paleo-bathymetry of the Miura Group on the Boso Peninsula is applicable to the Choshi Spur, this means that large-scale uplift was associated with the Kurotaki Unconformity and with rapid additional deposition of the Kazusa Group. If such large-scale uplift was closely connected to changes in the tectonic setting of the nearby “Boso Triple Junction” (Seno and Maruyama, 1984; Niitsuma, 1991) (although there is no direct evidence for this), then an increase in the geothermal gradient may have happened concurrently and resulted in upward movement of the BGHS. Smaller fluctuations in the BGHS may have been related to eustatic cycles (Haq, 1988; Williams, 1990).

Geological models

A biogenic origin would have produced dispersive gas hydrates in both the Miura and Kazusa Groups. But, there would have been major differences in the geologic setting of the gas hydrates between the center and margins of the Choshi Spur Depression. The area of greatest subsidence, at the center of the depression, would have experienced the maximum upward shift of the BGHS. This maximum upward movement of the BGHS resulted in the accumulation of natural gas hydrates and underlying free gases at the center of the depression, which coincides with the highest amplitude of the BSR (Fig. 15). In a thermo-genic-origin scenario, however, lesser amounts of gas hydrate would originally have been present in both groups, and natural gases would have been supplied from a deeper part of the Choshi Spur. The natural gases might then have migrated to a structurally higher marginal area of the depression. As a result, the combination of a layered gas hydrate and a free-gas-bearing layer would have appeared in areas of minimal subsidence (Fig. 14). No significant accumulation of layer-formed natural gas hydrates occurs at the center of the Choshi Spur Depression, because the BGHS evidently moved up through strata lacking
dispersive gas hydrates. The occurrence of the BSR in the Choshi Spur Depression suggests a thermogenic origin.

**Estimated natural gas reserves in place**

Matsumoto (1995) estimated that natural gas hydrate reserves in place for the Nankai Trough area amount to 0.8 trillion cubic meters. This estimate was made by using the calculated BSR area (14,000 square kilometers), a methane hydrate volume factor of 170, and the following assumptions from the worldwide literature on natural gas hydrates:

1. the average thickness of the natural gas hydrate-bearing layer is one meter,
2. the average effective porosity of the sediments is 40 percent,
3. the average gas hydrate saturation of the pore space is 12 percent, and
4. the average occupation ratio of methane within clathrate cages is 70 percent.

Using this same approach, the authors conclude that natural gas hydrate reserves in place for the BSR area of the Choshi Spur Depression are 1.8 billion cubic meters.

One survey of the literature on free gases beneath hydrate-bearing layers concluded that such gases have approximately 40 percent of the volume of the layered hydrates (The Institute of Applied Energy, 1992). If this summation of empirical data is accepted, then about 2.5 billion cubic meters of natural gas hydrates and related free gases would be the inferred total gas reserves in place in the Choshi Spur depression. However, the degree to which assumptions based on this literature survey apply to the Choshi Spur Depression is unknown.

**Conclusions**

A BSR in the Miocene–Pliocene Miura Group in the Choshi Spur Depression is inferred to be an indication of gas hydrates. The combination of layer-formed gas hydrates and associated free gases, which generated the BSR, may have been produced by large-scale tectonic uplift, by rapid deposition of the Kazusa Group in the Choshi Spur Depression, and/or by an increase in geothermal gradient related to changes in overall tectonic setting of the nearby triple-junction.

Glacioeustatic changes probably are not effective causes of gas hydrate accumulation related to upward movement of the BGHS, even though they may influence the association and disassociation processes of methane hydrate crystals.

There is no expectation of significant natural gas reserves in place in the BSR area of the Choshi Spur Depression. On the other hand, this is an excellent research site for studying BSR geophysics, the geophysical responses of natural gas hydrates, the geological occurrence and formation mechanisms of a natural gas hydrate-bearing zone, and for evaluating further operational concepts for reserve evaluation and gas recovery.

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Fig. 13. Inferred burial history diagram, showing eustatic sea level fluctuations (Haq, 1988; Williams, 1988) and estimated paleobathymetry of the Miura Group (Saito et al., 1991) and the Kazusa Group.

(A) after deposition of the Miura Group

(B) after deposition of the Kazusa Group

Fig. 14. Conceptual model showing the accumulation process of layer-formed gas hydrates related to thermogenically mature source material following rapid deposition of the Kazusa Group in the Choshi Spur Depression.
Fig. 15: Conceptual model showing the accumulation process of layer-formed gas hydrates related to biogenic disseptive-formed gas hydrates within the Miura and Kazusa Groups, following rapid deposition of the Kazusa Group.

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