Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008), Vancouver, British Columbia, CANADA, July 6-10, 2008.

Bottom Simulating Reflectors on Canada's East Coast Margin: Evidence for Gas Hydrate

***David C. Mosher**
Geological Survey of Canada – Atlantic,
Bedford Institute of Oceanography,
P.O. Box 1006,
Dartmouth, NS,
Canada,
B2Y 4A2.

ABSTRACT

The presence of gas hydrates offshore of eastern Canada has long been inferred from estimated stability zone calculations, but the physical evidence is yet to be discovered. While geophysical evidence derived from seismic and borehole logging data provides indications of hydrate occurrence in a number of areas, the results are not regionally comprehensive and, in some cases, are inconsistent. In this study, the results of systematic seismic mapping along the Scotian and Newfoundland margins are documented. An extensive set of 2-D and 3-D, single and multi-channel, seismic reflection data comprising ~45,000 line-km was analyzed for possible evidence of hydrate. Bottom simulating reflectors (including one double BSR) were identified at five different sites, ranging between 300 and 600 m below the seafloor and in water depths of 1000 to 2900 m. The combined area of the five BSRs is 1720 km^2, which comprises a small proportion of the theoretical stability zone area along the Scotian and Newfoundland margins (~635,000 km^2). The apparent paucity of BSRs may relate to the rarity of gas hydrates on the margin or may be simply due to geophysical limitations in detecting hydrate.

Keywords: 'gas hydrates', 'continental margin', 'seismic reflection', 'bottom simulating reflector', 'hydrate stability'

INTRODUCTION

Gas hydrates are believed to represent a large storehouse of methane in sedimentary basins around the world [1]. Canada in particular has a significant potential quantity of hydrate because of extensive northern permafrost and offshore land areas [2,3,4]. Hydrates have been known to exist for some time along the Cascadia margin, offshore of Vancouver Island, initially with the recognition of bottom simulating reflections (BSR) in seismic reflection profiles [5,6,7], followed by Ocean Drilling Program (ODP) sampling (e.g. [8,9]). They have also been recognized for some time in the onshore MacKenzie delta region (e.g. [10,11]). Gas hydrates or clathrates have been recovered through drilling, coring and even fish trawling in the case of Cascadia [12,13]. Estimates of the volume of hydrates in Canada indicate that there may be as much as 10^{12}-10^{14} m^3 of methane gas bound in hydrate [4].

Despite occurrences on the west coast and northern regions of Canada, no physical and little geophysical evidence for hydrates had been published from Canada's East Coast margin,

* Corresponding author: Phone: +1 902 426 3149 Fax +1 902 426 4104 E-mail: dmosher@nrcan.gc.ca

although their presence has been surmised and the calculated stability zone is significant in size [14,15, 16,17,3,4]. It is the intent in this paper to document locations of observations of BSR's on the Atlantic margin of Canada, indicating the possible presence of gas hydrates. The possible existence of hydrate in this petroleum exploration region is significant with respect to exploration for deep-seated gas or oil, it may represent a potential hazard to hydrocarbon exploration and it may also be an indication of an active petroleum generation system. In future, hydrates may also represent a significant hydrocarbon resource. In addition, documentation of global occurrences of methane hydrate has important implications for carbon cycle and climate change investigations.

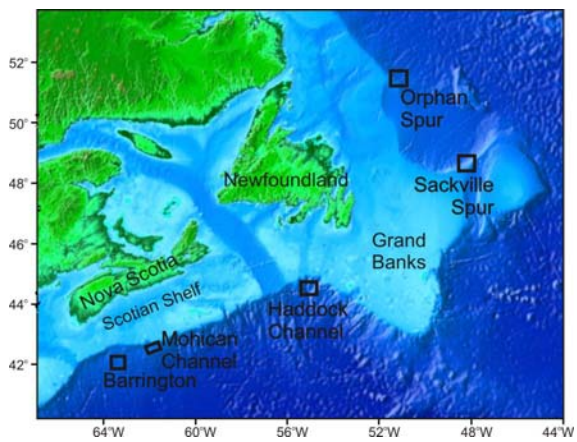

Figure 1. Regional topography of the Canadian east coast continental margin showing locations of areas of identified bottom simulating reflectors (BSR) (boxes).

Background

Geology

The geologic evolution of the continental margin of the east coast of Canada is summarized by [18]. Formation of the North Atlantic by south to north rifting, transform faulting and subsidence occurred in Mesozoic and Cenozoic times with concurrent development of a system of sedimentary basins extending from the southeastern United States to northern Baffin Bay. These sedimentary basins are more than 20 km thick off Newfoundland and 15-20 km thick in the Scotian basin and are prospective for hydrocarbons.

Cenozoic sediments form a variably thick wedge of prodeltaic deep water clastics, predominately mudstones with some chalks and marlstones, overlying rift and synrift sediments [19]. The modern continental margin structure was formed during this period with extensive elongate shelves and a slope with a thick Cenozoic succession that thins towards abyssal depths. Regional unconformities within the succession reflect sea level low-stands, slope sediment mass failure events and contour current erosion and reworking [16,19]. Salt diapirism initiated in the Early Jurassic and continued to the latest Cretaceous. It has since rejuvenated and is presently active beneath some regions of the continental slope [20].

Plio-Pleistocene glaciations figure prominently in the modern margin morphology through erosional, ocean current and sediment delivery processes [19]. Much of the Pleistocene sedimentary sequence in continental slope regions of the east coast margin involve thick (>500 m) sequences of glacial marine sediments, deposited as fine-grained turbidites and mass transport deposits [19,21,22]. Outwash channels and contourite drift deposits may localize coarser grained deposits. Canyon cutting and canyon reoccupation likely occurred during low sea level stands during and immediately following glacial epochs. Large sedimentary drift deposits (spurs) off Newfoundland and Labrador were formed by contour parallel currents. These currents strengthened during low sea level stands and during intensified glacial bottom water generation. Modern sedimentary conditions are pelagic to hemi-pelagic, resulting in a one to two m-thick drape of fine-grained sediment covering much of the seafloor in deep water [21]. The Scotian Slope, from the 350 to 3500 m isobath, represents an area of 120,000 km^2. The Newfoundland continental slope, over the same depth range, represents 515,000 km^2.

Gas Hydrates

The hydrate stability zone on the Canadian Atlantic margin lies beneath the continental slope roughly between water depths of 350 and 3500 m

[4]. This area represents some 635,000 km^2 from Northern Newfoundland to the Southern tip of Nova Scotia. Preliminary methane hydrate volume estimates for the Atlantic margin (including Labrador) are high ($1.9x10^{13}$–$7.8x10^{13}$ m^3) with an inferred mean thickness of 79 m and hydrate saturation of the sediments in the 2-6% range [3].

First predictions that gas hydrate may be present on the Labrador Shelf were given by [14]. These were based on hypothetical assumptions about the geothermal regime for sediments underlying the shelf and low bottom water temperatures in the Labrador Sea (near 0°C). Gas hydrates were interpreted on the basis of petrophysical response in 26 out of 48 wells analyzed, mostly along the Labrador margin [15]. Thurber Consultants Ltd. [15] indicated hydrates in nine out of ten wells analysed from Flemish Pass and Northeast Newfoundland Shelf and slope, extending from 530 to 1090 m subbottom, in 160-1486 m water depth. Several of these perceived occurrences, however, do not fall within the hydrate stability zone and these interpretations are drawn into question (e.g. [22]). Some indications of shallow methane gas, probably related to gas hydrate occurrence, are reported in well reports for the Acadia K-62 and Shelburne G-29 wells in the Scotian basin. Gas hydrate formation at the well head was noted during submersible ROV operations at the Torbrook C-15 well.

Bottom Simulating Reflectors

Interpretations on the presence of gas hydrates on continental margins are largely based on observations of bottom simulating reflections (BSR) in seismic reflection profiles [23]. BSRs ascribed to gas hydrates were first described in the literature in 1977 from the Blake Ridge [24]. A BSR is a phase-reversed reflection event that represents the lower surface of the hydrate. Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program (IODP) sampling, such as conducted during Legs 66 (Mexico),76 (Blake Outer Ridge), 84 (inner slope, Middle America Trench), 112 (Peru margin), 131 (Nankai trough), 146 (Cascadia), 164 (Blake Outer Ridge), 201 (Peru Slope), 204 (Oregon margin – Hydrate Ridge) and most recently Leg 311 (Cascadia margin) have confirmed the presence of hydrate at these locations and have shown that the negative impedance contrast is caused by a low velocity free gas zone below high-velocity ice-bound (hydrate) sediment, resulting in the phase reversal. The depth of occurrence of the hydrate stability zone is a function of pressure and temperature. These properties are dictated by the water depth and bottom water temperature, overburden pressure (sediment density and thickness) and heat flow from the earth. As these properties are largely controlled by depth of burial, the phase reversed reflection event appears to broadly follow the seafloor topography.

Berndt et al. [25] report BSRs related to diagenetic boundaries as opposed to gas phase transitions. They describe BSRs related to opal-C/opal-AT transition and a third type possibly related to smectite illite conversion or to a sudden increase in the abundance of authigenic carbonate. The genesis of these mineral transitions is pressure and temperature dependent as well and therefore, seismic reflections off the interface may mimic the seafloor and could potentially result in cross-cutting reflector relationships. Subtle differences in geophysical signatures are required to discriminate. Typically, diagenetic BSRs are equivalent in phase to the seafloor reflection, while gas hydrate BSRs are phase-reversed; but phase is not always apparent in complex geological situations and gas trapping beneath diagenetic boundaries may cause similar phase reversals. Generally, the diagenesis-related BSR should be at greater depth than the gas hydrate BSR because they develop at about 35-50°C, whereas the gas hydrates are generally not stable above 25°C [25].

Methods

Imaging of BSRs is highly dependent upon the frequency of the seismic system employed (Yuan et al., 1999) and the cross-cutting relationship of the stability window to the inherent stratigraphy (e.g. [25,26]). A variety of seismic reflection imaging systems were used on the continental margin of the east coast of Canada.

Over 45,000 line-km of industry 2D reflection data were investigated for this study to identify BSRs.

In general, these industry data were acquired with airgun arrays of about 6500-7900 in^3 volume. Data were sampled between 2-4 ms and represent frequency ranges between 5 and 100 Hz, with centre frequencies of 30-50 Hz. 3D exploration seismic reflection data used in this study were shot in the Torbrook block (lease block EL2501) of the central Scotian Slope by the vessel *Geco Prakla* for EnCana Energy in June to August 2000. Bin spacing in this 3D data set is 12.5 x 12.5 m. Post processing analysis and interpretation were conducted with 2D/3D seismic interpretation software, including GeoFrame GeoQuest and SMT Kingdom Suite.

Two-dimension (2D) high resolution single channel seismic reflection profiles were acquired in a non-systematic manner over the Canadian east coast margin by the Geological Survey of Canada-Atlantic (GSCA). These data were acquired with smaller airgun arrays and span frequencies between 30 and 250 Hz.

RESULTS

Successful seismic imaging of bottom simulating reflectors is a function of the frequency matching of the thickness of the low velocity zone of free gas beneath a trap such as gas-hydrate laden sediment, and the frequency band of the seismic system. If the zone is thick and the seismic frequencies too high, then the zone will not be imaged as a single phase-reversed reflection but something more complex consisting of a number of brightened reflections (e.g. [27]). This effect makes it difficult to recognize the BSR. If the low velocity zone is too thin and/or the seismic frequencies too low then the transition will not be resolved. As a result, this study has employed both high resolution and low resolution seismic data to investigate the presence of BSRs. Typically, BSRs are best recognized in hydrocarbon exploration scale seismic systems because of their low frequency spectrum and long source-receiver offset. BSR's are also most readily observed if they propagate across other reflection horizons at a dip different from these horizons. 3D data are most useful in this regard, as the seismic data can be profiled in an arbitrary orientation to optimize apparent dips.

Thorough investigation of publicly available data and an extensive grid of modern industry seismic data in combination with the acquisition of new seismic data specific to the purpose of this paper, resulted in recognition of five areas of clearly distinguishable BSRs on the Newfoundland and Nova Scotia margins (Fig. 1): (1) Orphan Spur of the northern Newfoundland margin, 2) Sackville Spur on Flemish Pass of the eastern Newfoundland margin, (3) an area on the southern Newfoundland

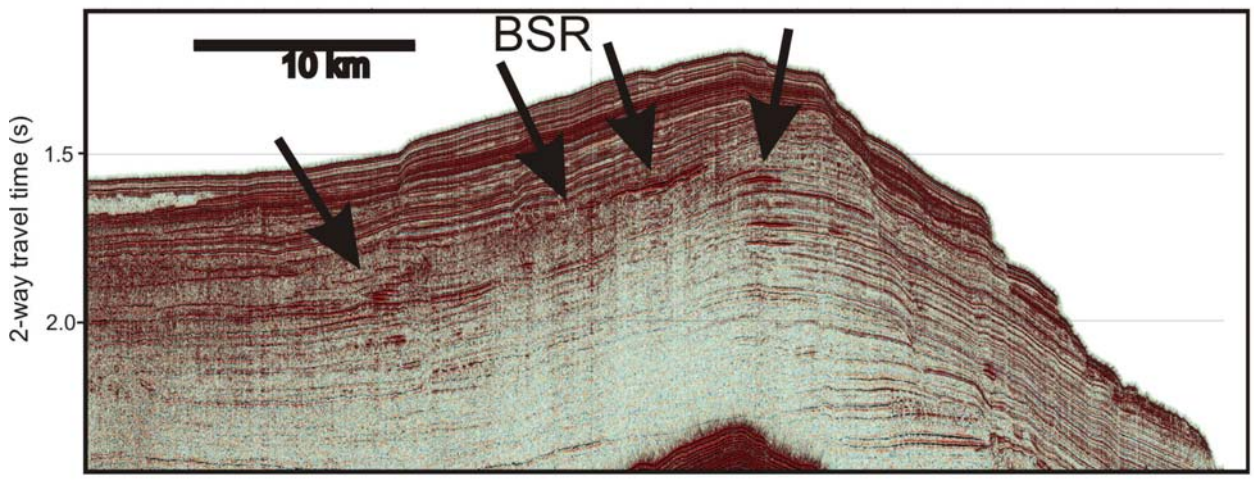

Figure 2. A BSR in the Orphan Spur off the northern margin of Newfoundland is demonstrated on high resolution seismic reflection data by a series of high amplitude (bright) spots on reflectors at specific depths below seafloor.

margin, close to Haddock Channel, (4) an area on the central Scotian Slope east of Mohican Channel, and (5) on the SW Scotian Slope in an area known as the Barrington Block.

Orphan Spur

A BSR was recognized during GSC reconnaissance surveying in 2005 and 2006 on Orphan Spur. This feature is a large drift deposit forming a prograding sedimentary wedge off the northern Newfoundland margin. It forms the northern edge of the prospective Orphan Basin. On these high resolution seismic data (Fig. 2), the BSR appears as a series of anomalously high amplitude portions of reflectors that follows the seafloor gradient at about 350 ms sub-seafloor depth. This brightening of reflectors is recognized in water depths ranging from 900 to 1200 m and crosses the relatively flat-lying stratigraphic sequence of the spur. This characteristic is similar to the BSR described by McConnell and Kendall [26] in the Gulf of Mexico. There is limited seismic coverage of the area, but with existing data the BSR maps to zone of about 370 km^2 in area.

Flemish Pass/Sackville Spur

The BSR under Sackville Spur is similar to that at Orphan Spur. Even on low frequency industry data, it is not a conventional phase-reversed reflection event but rather it appears as a series of brightened (high amplitude) dipping reflectors that dim-out at a common depth below seafloor (Fig. 3). The depth of dim-out of these high amplitudes is 320-360 ms below seafloor and water depths range from 1000-1350 m. In map view, these brightened amplitudes define an area at least 156 km^2 in size.

Haddock Channel

A BSR was noted from a regional grid of 2D industry data on the eastern flank of the Laurentian Channel on the St. Pierre Slope (Figs. 1 and 4) and has subsequently been imaged with high resolution seismic systems. Mapping of the prominent BSR shows it extends over an estimated area of about 82 km^2. The BSR occurs between 450 and 500 ms below the seafloor in water depths between 1700 and 2150 m. There is significant faulting of the shallow sediment column at this site with normal downslope extensional fault displacements. Some

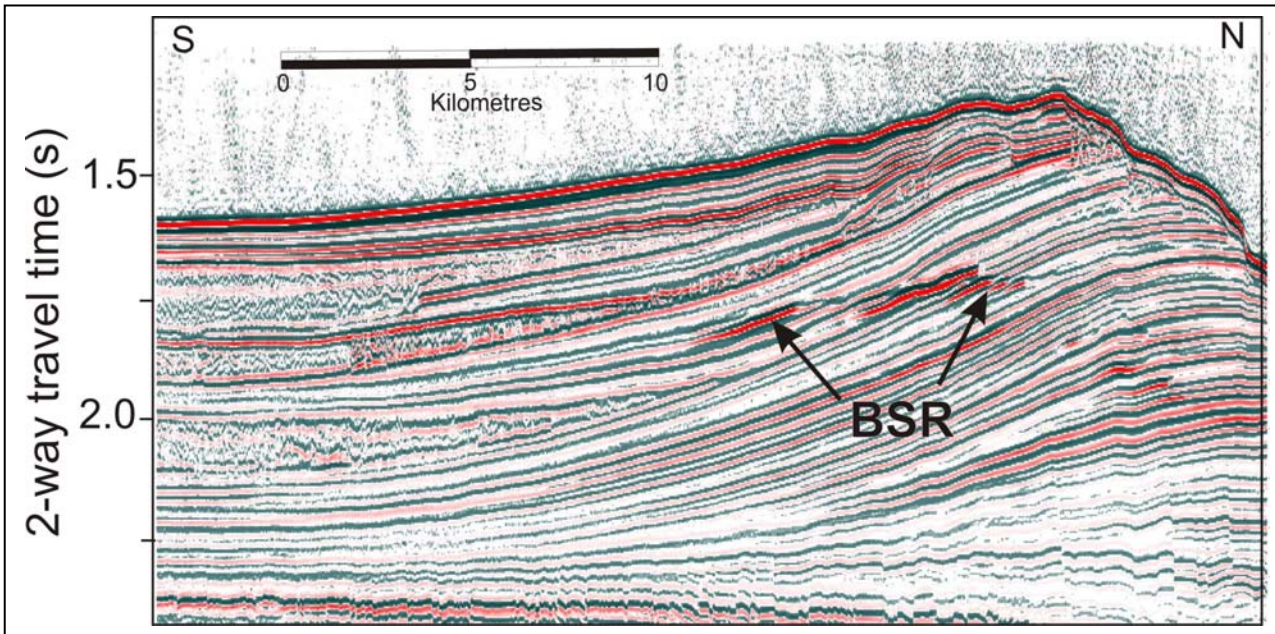

Figure 3. A BSR within the Sackville Spur in the Flemish Pass area off Newfoundland, showing a line of brightened reflections that parallels the seafloor. These data are from a slice of the Mizzen 3D seismic volume, provided by PetroCan.

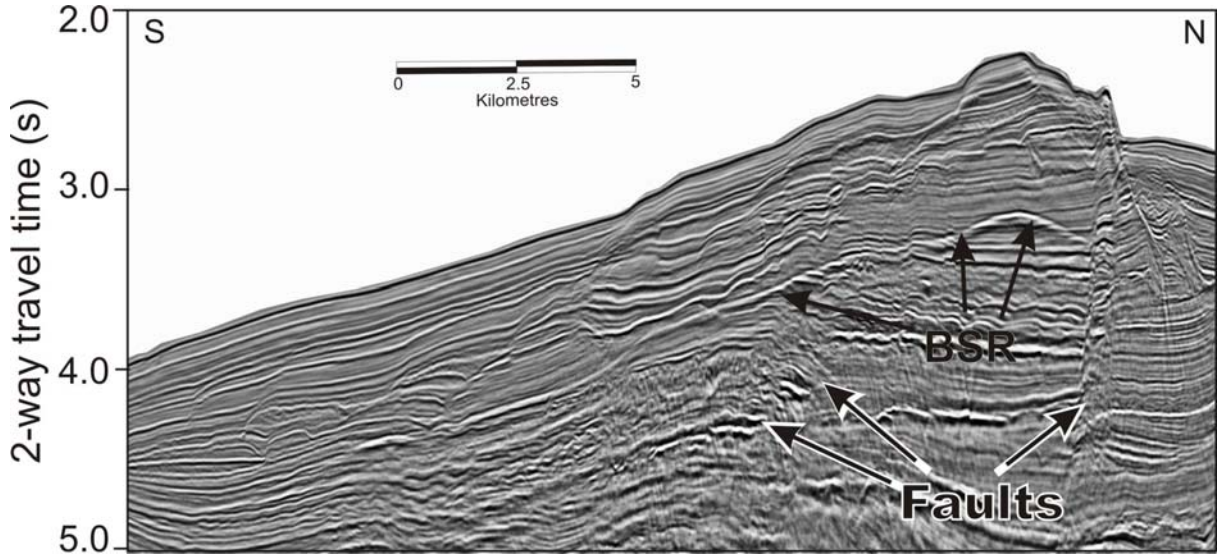

Figure 4. Example of the BSR in the Haddock Channel area of the southern Newfoundland margin. In this orientation, the BSR is clearly seen as a phase reversed reflection that crosses stratigraphy.

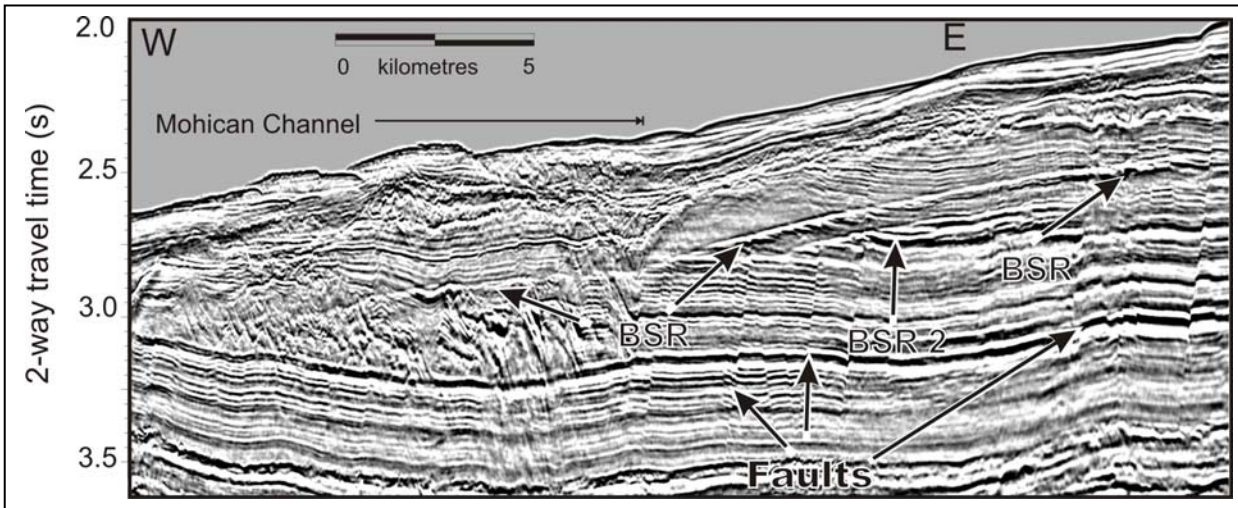

Figure 5. Example of the BSR in the Mohican Channel area of the central Scotian Slope. Note the second smaller BSR below the first and the extensive series of faults.

of these faults clearly pass through the BSR. At the upslope extent, the BSR terminates at a fault that bounds a large (4 km diameter) rotated block.

Mohican Channel BSR

The Mohican Channel BSR is evident on industry exploration 2D and 3D multichannel seismic reflection data and is apparent, although less distinct, on high resolution single channel reflection profiles (Fig. 5). The BSR appears between 400 and 450 ms below the seafloor in a water depth range of 1500 to 1930 m. A second BSR at 500 ms subbottom is apparent as well. The wavelet of the bottom simulating reflector is characterized on industry reflection data by a frequency of about 20-30 Hz, while these data are in general broad band between 5 and 70 Hz. On

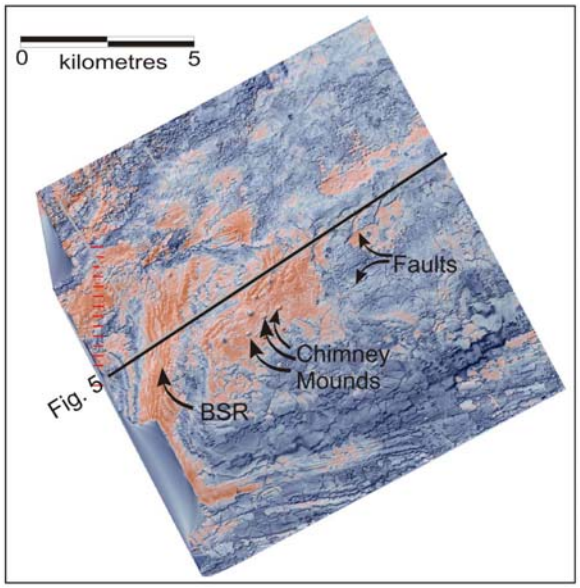

Figure 6. Horizon amplitude map of the BSR from the industry 3D seismic volume, draped over the morphology of that surface. The strong negative amplitudes are mapped in orange and follow the pattern of the Mohican Channel. Faults intersecting this surface show a polygonal pattern throughout the lower half of this image. Note the mounds created by chimneys.

high resolution profiles, the BSR reflector is characterized by a peak frequency of 75 Hz, while the corresponding data are broad band between 35 and 150 Hz. In fact, at the Mohican Channel site, there is a double BSR (*cf.* [28]); a secondary BSR underlies the primary (Fig. 5).

Figure 6 is a horizon amplitude map of the BSR horizon derived from the 3D data. It clearly shows the extent of the strongly negative excursion of the BSR as well as the detailed morphology of this surface. The principal BSR is evident over an area of 280 km^2. A dense system of high angle, small offset normal faults clearly dissects sediments below and sometimes above the BSR (Fig. 5). The fault pattern is clearly visible in plan view (Fig. 6). Occasionally, reflectors surrounding these faults form mounds with diameters of approx. 500 m (Fig. 6). In time-slice these mounds have a concentric ring pattern that forms a chimney or pipe emanating from a zone of high-amplitude reflections 1000 ms below the BSR. These mounds sometimes reach the seafloor. In these cases, shallow piston cores show abundant evidence of gas expansion upon recovery to the surface. Head space gas analyses showed they consisted of 100% methane [29].

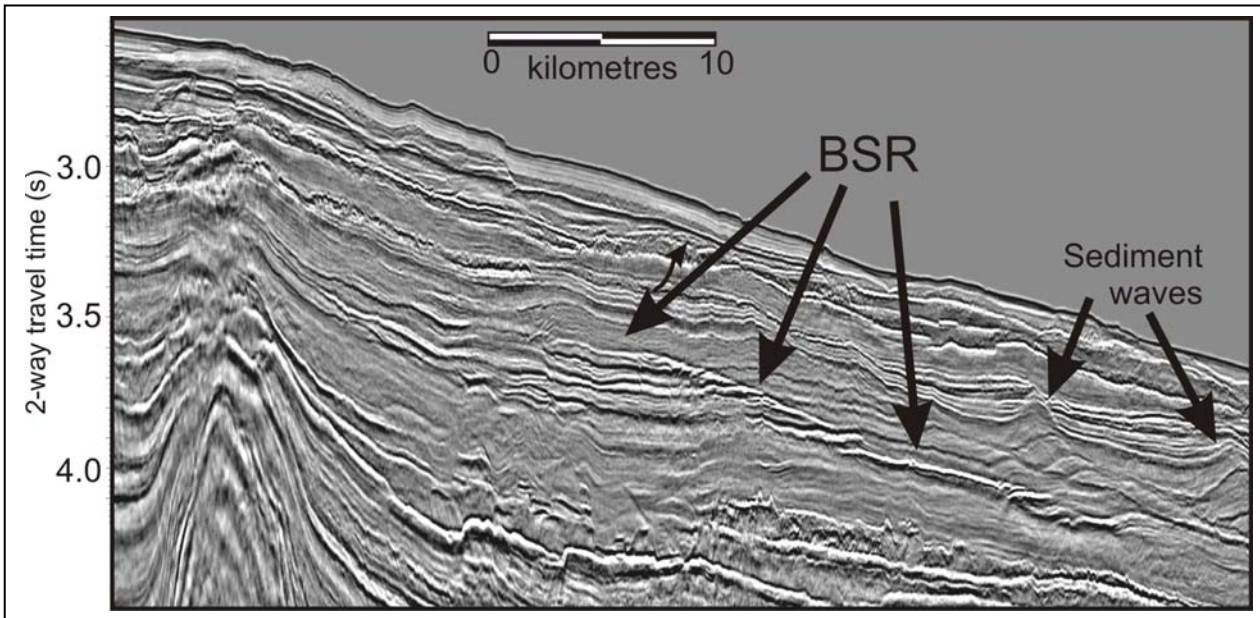

Figure 7. Seismic section showing the BSR at the Barrington site, SW Scotian Slope. Note the presence of possible sediment waves.

Barrington BSR

A BSR is evident in the Southwestern Scotian margin just south of a 3D seismic exploration volume, known as the Barrington block (Fig. 1 and 7). At this site, the BSR occurs in water depths ranging from 2220 to 2890 m and between 500 and 600 ms below the seafloor. From the 2D seismic data grid, a conservative estimate of the area of the BSR is 830 km^2, thus it is by far the largest field identified along the East Coast margin and in the deepest water. The geology of the area is complex with numerous stacked mass transport deposits complicating the stratigraphy. The BSR appears in a stratigraphic interval showing possible sediment waves (Fig. 7).

DISCUSSION

A hydrate BSR represents a low velocity free gas zone trapped beneath hydrate-bound sediment, causing a velocity inversion and a phase-reversed reflection event [23]. The depth of the BSR, therefore, should represent the base of the stability field. It should roughly parallel the seafloor as the stability field is determined by the temperature and pressure gradient below the seafloor. Figure 8 is a plot of the depth of BSR's identified in this investigation. Overlain on this plot are the theoretical depths of the base of the stability field for 100% methane hydrate for each site. This plot shows that in each instance, the BSR depth is near its theoretical base, thus is within the hydrate stability field. This result supports the argument that these BSRs are a result of phase transition of largely methane gas to methane gas hydrate.

Majorowicz and Osadetz [3] estimate the stability zone along the margin running from northern Labrador to SW Nova Scotia in 350 to 3500 m water depth is about 400,000 km^2 in area. In this investigation, the area represented in these water depths off Nova Scotia and Newfoundland was calculated to be 635,000 km^2. Although full seismic coverage of this margin has not been studied as there are regions without data or for which data are not available, mapping of BSR's from available data indicates a total area of only about 1720 km^2.

Gas hydrate formation requires the same criteria as any petroleum system; there needs to be a source of hydrocarbon, reservoir rock with porosity and permeability, and a trapping mechanism. For BSRs, the hydrate itself represents the trap for gas beneath. Interestingly, the five locations of detected BSR's on the East Coast margin correspond in close proximity with conventional exploration blocks where 3D seismic data volumes have been acquired and in some cases drilled. Orphan Spur is on the western flank of the highly prospective Orphan Basin. A large 3D volume was recently acquired within the basin. In closest proximity to the Orphan Spur BSR site are the Blue H-28 well drilled in 1979 in 1486 m water depth and the Great Barasway F-66 well, drilled in 2006 in 2338 m water depth. Flemish Pass/Sackville Spur BSR lies within the area of the Mizzen 3D volume, which was most recently drilled with the Mizzen L-11 well (1153 m water depth) in 2003. Haddock Channel BSR lies close

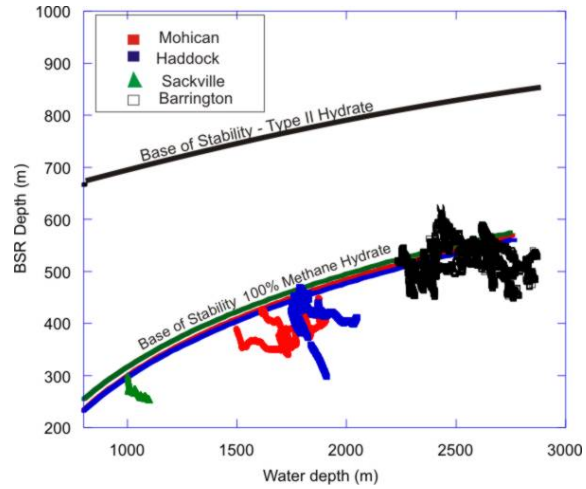

Figure 8. Cross-plot of BSR depth versus water depth with the theoretical base of the hydrate stability zone calculated using Sloan [30] assuming only hydrostatic pressure (i.e. no over-pressures). Velocities used to convert traveltime to depth were derived from LeBlanc et al. [31]. A thermal gradient of 32°C/km was used in these calculations [4]. Seafloor temperatures for each site were taken from the Department of Fisheries and Oceans online data base, using the deepest water temperatures available; 4.15°C for Barrington and Mohican Channel, 4.0°C for Haddock Channel, and 3.5°C for Flemish Pass.

to the prospective South Whale Basin and the Laurentian Sub-basin. The Laurentian East 3D volume is just west of the Haddock Channel BSR. South Whale Basin was drilled in 1986 with the Narwhal F-99 well (1573 m water depth) and drilling in the Laurentian East 3D volume is proposed. The Mohican Channel BSR lies within the Torbrook 3D volume which was drilled with the Torbrook C-15 well in 2002. Finally, the Barrington BSR lies just south of the Barrington 3D volume, which remains undrilled, although the Shelburne G-29 well is in close proximity in 1153 m water depth.

This correspondence of BSR's to areas of exploration interests for conventional hydrocarbons is likely not a coincidence; it demonstrates a probable source for hydrocarbon gas. As indicated, reservoir rock is also a criterion for hydrate formation. Although much of the Pleistocene geology of these deep water sites is represented by fine-grained sediment [19,21] in which porosity is expected to be low, each of the BSR sites demonstrate features that indicate sand may be present. Two of the hydrate occurrences, Orphan Spur and Sackville Spur, are within large sediment drift deposits which likely contain interbedded sand layers due to current winnowing. The seismic character at these sites defining the BSR's supports this interpretation with gas brightening occurring along specific horizons and terminating at the specific depth of the BSR. This echo-character is described by McConnell and Kendall [26]. Presumably, free gas migrates along porous and permeable beds and is trapped below sediment in which permeability is sealed by the hydrate.

Both the Haddock Channel and Mohican Channel BSR sites lie adjacent and beneath or within the channels. It is expected that these channels contain coarse sediment and their associated levee deposits contain sand which presumably decreases in size and abundance away from the channel. In the case of the Mohican Channel BSR, with 3D seismic data available, it is clearly demonstrated that the BSR dissipates distally from the channel (Fig. 6; see [29], possibly corresponding with a decrease in grain size/porosity.

The Barrington BSR appears to be associated with the base of features interpreted to be sediment waves. The waves, possibly generated by along-slope flowing contour currents or downslope turbidity currents, presumable contain high sand percentages and therefore higher porosity than the surrounding medium. This porosity provides the space for hydrate formation.

CONCLUSIONS

Continental margins of Canada represent vast potential for storing hydrocarbon gas (largely methane) in the form of gas hydrate. Along the Scotian and Newfoundland margins, the theoretical stability field for gas hydrate represents ~635,000 km^2. Examination of ~45,000 line-km of industry and GSC 2D seismic reflection data along this margin resulted in identification of five areas with recognizable bottom simulating reflections, totaling about 1720 km^2. These BSR's are noted as clear high amplitude (bright) phase-reversed reflection events and brightened dipping reflectors. In all cases, the brightening of amplitudes and the phase reversal are attributed to free gas trapped beneath a hydrate layer. These results fit with calculations of the base of the theoretical methane hydrate stability zone, supporting the argument that they are evidence of the presence of gas hydrate.

Aside from appropriate temperature and pressure conditions, hydrate formation requires a source of hydrocarbon gas, a trapping mechanism to keep gas in formation long enough to form hydrate and a reservoir within which hydrate can form. There also needs to be pathways through which gas can migrate from its source to the reservoir within the stability field. These criteria are similar to any petroleum system. Each of the BSR's identified on the Canadian east coast margin fall within specific exploration (although not producing) areas, indicating the likelihood of active petroleum systems generating the hydrocarbon gas as a source for hydrate. In addition, each of the areas identified demonstrate geologic circumstances in which the presence of sand is a strong possibility, either as sediment drifts, sediment sandwaves, or channel and levee deposits. The sand presumably provides pore spaces for hydrate to form and

permeability necessary for gas migration. In the case of the Mohican Channel BSR, for which a 3D seismic volume exists, a direct correlation with the channel and its levee is documented. From this volume, it is also possible to identify a complex system of faults and vertical chimneys, providing conduits for gas to migrate from its source to within the hydrate stability window.

Free gas must be present beneath hydrate in order for a BSR to be generated. The hydrate itself acts as a cap to trap gas beneath. This gas zone must be thick enough to be resolved by the seismic system. It has been demonstrated that hydrate exists in regions without the presence of BSRs [9]. It is likely that not all BSRs have been identified on the East Coast margin in this study, but it is clear nonetheless that the summation of areas demonstrating BSRs is small relative to the total area (1720 km^2 relative to 635,000 km^2). This incongruity in area metrics speaks to a fundamental issue concerning hydrate exploration. If we must rely on identification of a BSR to locate hydrate, then gas hydrates are either not as prevalent along this passive continental margin as theoretical models predict, or new exploration techniques are required to identify its presence.

ACKNOWLEDGEMENTS

The authors thank the crew and staff of numerous CGGS Hudson expeditions to acquire data on the Canadian East Coast margin. D.C. Campbell assisted on numerous occasions in this study. Important seismic datasets were provided by EnCana Corporation and by TGS-Nopec Geophysical Company. PetroCan provided images of data shown in Figure 3. Funding was provided by the Earth Sciences Sector of Natural Resources Canada through the "Gas Hydrates: Fuel for the Future" program.

REFERENCES

[1] Kvenvolden KA. *Methane hydrates and global climate.* Global Biochemical Cycles 1988; 2:221–229.

[2] Smith SL, and Judge AS. *Gas hydrate database for Canadian Arctic and selected East Coast wells*. Open File 2746, Geological Survey Canada 1993.

[3] Majorowicz JA, and Osadetz K, *Gas hydrate distribution and volume in Canada.* Am. Assoc. Petroleum Geologists Bull. 1993; 85:1211–1230.

[4] Majorowicz JA, and Osadetz K, *Natural Gas Hydrate Stability in the East Coast Offshore-Canada*. Natural Resources Research 2003; 12:93-104.

[5] Hyndman RD, and Spence GD. *A Seismic Study of Methane Hydrate Marine Bottom Simulating Reflectors*. Journal of Geophysical Research 1992; 97: 6683-6698.

[6] Yuan T, Spence GD, and Hyndman RD. *Seismic velocities and inferred porosities in the accretionary wedge sediments at the Cascadia margin*. Journal of Geophysical Research 1994; 99:4413–4427.

[7] Yuan T, Hyndman RD, Spence GD and Desmons B. *Seismic velocity increase and deep-sea gas hydrate concentration above a bottom-stimulating reflector on the northern Cascadia continental slope*. Journal of Geophysical Research 1999; 101:13655-13671.

[8] Carson B, Westbrook GK, Musgrave RJ and Suess E. *Proceedings of the Ocean Drilling Program, Scientific Results* 146(2): College Station, Texas, Ocean Drilling Program 1995

[9] Riedel M, Collett TS, Malone MJ, and the Expedition 311 Scientists. *Proceedings Integrated Ocean Drilling Program, Leg 311* Washington, DC (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.311.2006 2006.

[10] Dallimore SR, Uchida T, Collett TS. *Scientific results from JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well, Mackenzie Delta, Northwest Territories, Canada*. Bulletin 544, Geological Survey of Canada 1999.

[11] Dallimore SR and Collett TS. *Scientific results from the Mallik 2002 gas hydrate production research well program, Mackenzie Delta, Northwest Territories, Canada.* Bulletin 585 Geological Survey of Canada 2005.

[12] Spence GD, Hyndman RD, Chapman NR and Cleary C. *Fishing trawler nets massive 'catch' of methane hydrates*. EOS Transacations 2001; 82:621.

[13] Chapman NR, Pohlman J, Coffin R, Chanton J and Lapham L. *Thermogenic gas hydrates in the*

northern Cascadia margin. EOS Transactions 2004; 85:361, 366.
[14] Taylor A, Weitmiller R and Judge A. *Two risks to drilling and production off the east coast of Canada-earthquakes and gas hydrates*. In: Denver W, editor, Proc. Symposium Research on the Labrador Coastal and Offshore Region: Memorial Univ. Newfoundland, 1979. p. 91–105.
[15] Thurber Consultants Ltd. *Study of well logs from East Coast offshore wells to delineate gas hydrate occurrence*: Report to Earth Physics Branch, Energy Mines Resources, Ottawa, DSS File: 15SQ.23235-5-0507, 1985.
[16] Piper DJW, Skene KI, Morash N. *History of major debris flows on the Scotian Rise.* Current Research 1999-E:203-212. Geological Survey of Canada 1999.
[17] Gauley B-J. *Lithostratigraphy and Sediment Failure on the Central Scotian Slope.* M.Sc. Thesis, Dalhousie University, 2001.
[18] Wade JA and MacLean BC, *The geology of the southeastern margin of Canada*. In: Keen, MJ. and Williams GL, editors. Geology of the Continental Margin of Eastern Canada, The Geology of North America (1990) I-1, Geological Survey of Canada 1990. p. 169-238.
[19] Piper DJW, *Late Cenozoic evolution of the continental margin of eastern Canada*. Norwegian Journal of Geology 2005; 85:231-244.
[20] Shimeld J, Mosher D, Louden K, LeBlanc C. and Osadetz K. *Bottom simulating reflectors and hydrate occurrences beneath the Scotian Slope, offshore eastern Canada. In: Gas Hydrates: Energy Resource Potential and Associated Geologic Hazards, Program with Abstracts, AAPG Hedberg conference*, Sept. 12-16, 2004, Vancouver, BC. 2004.
[21] Mosher DC, Piper DJW and Campbell DC. *Near-surface geology and sediment-failure geohazards of the central Scotian Slope.* American Association of Petroleum Geologists Bulletin 2004; 88:703-723.
[22] Neave KG, *Shallow seismic velocities on the eastern Grand Banks and Flemish Pass.* Unpublished report Geological Survey of Canada, Terrain Sciences Division, 1990.
[22] Piper DJW and McCall C. *A synthesis of the distribution of submarine mass movements on the Eastern Canadian Margin*. In: Locat J and Meinert J, editors. Submarine Mass Movements and their Consequences. Dordrecht: Kluwer publishing, 2003, p. 291-298.
[23] Shipley TH, Houston MH, Buffler RT, Shaub FJ, McMillen KJ, Ladd JW and Worzel JL. *Seismic reflection evidence for the widespread occurrence of possible gas-hydrate horizons on continental slopes and rises*. American Association of Petroleum Geologists Bulletin 1979; 63: 2204-2213.
[24] Tucholke BE, Bryan GM and Ewing JI. *Gas-hydrate horizons detected in seismic-profiler data from the western North Atlantic*. American Association Petroleum Geologists Bulletin 1977; 61:698-707.
[25] Berndt C, Buenz S, Clayton T, Mienert J and Saunders M. *Seismic character of bottom simulating reflectors; examples from the mid-Norwegian margin.* Marine and Petroleum Geology 2004; 21(6): 723-733
[26] McConnell, D.R. and Kendall, B.A., 2002. Images of the base of gas hydrate stability, Northwest Walker Ridge, Gulf of Mexico. Offshore Technology Conference paper, Houston, TX., 10 pp.
[27] Vanneste M, De Batist M, Golmshtok A, Kremlev A and Versteeg W. *Multi-frequency seismic study of gas hydrate-bearing sediments in Lake Baikal, Siberia.* Marine Geology 2001; 172(1-2):1-21.
[28] Posewang J and Mientert J. *The enigma of double BSRs: indicators for changes in the hydrate stability field.* Geo–Marine Letters 1999; 19:157-163.
[29] Cullen J, Mosher DC and Louden, K. *The Mohican Channel Gas Hydrate Zone, Scotian Slope: Geophysical Structure. In: Proceedings of the 6th International Conference on Gas Hydrates Vancouver, British Columbia, CANADA, 2008.*
[30] Sloan ED. *Clathrate Hydrates of Natural Gases.* New York, Marcel Bekker Inc., 1998.
[31] LeBlanc C, Louden K and Mosher DC. *Gas hydrates on the Nova Scotia Slope: velocity models from wide-angle seismic profiles.* Marine and Petroleum Geology 2007; 24:321-334.