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

THE MOHICAN CHANNEL GAS HYDRATE ZONE, SCOTIAN SLOPE: GEOPHYSICAL STRUCTURE

Janette Cullen*
Department of Earth Sciences, Dalhousie University
Halifax, NS, B3H 4J1, CANADA

David C. Mosher
Geological Survey of Canada – Atlantic, Natural Resources Canada
P.O. Box 1006, Dartmouth, NS, B2Y 4A2, CANADA

Keith Louden
Department of Oceanography, Dalhousie University
Halifax, NS, B3H 4J1, CANADA

ABSTRACT

The Scotian margin of the east coast of Canada has a large theoretical gas hydrate stability zone (GHSZ) yet review of extensive industry seismic data reveals a prominent BSR at only one location. 3D seismic reflection and long offset (9 km) pre-stack 2D multichannel seismic data were used to study the velocity structure and geophysical characteristics of the hydrate zone and surrounding regions. The Mohican Channel study area shows a unique double BSR at 300 to 450 m below the seafloor in the western section of the study area immediately adjacent to the Mohican Channel in a water depth range of 1500-1930m. The topmost BSR (BSR 1) is the more extensive of the two covering an area of 150 km^2 in the 3D volume and a calculated area of 280 km^2 using 2D industry and single-channel seismic profiles outside of the study area. BSR 2 covers an area of ~50 km^2 and occurs approximately 80m below BSR 1. A system of polygonal faults is prominent in the area and some faults appear as conduits for gas leakage into the GHSZ. Fluid escape features are common on the surface of BSR 1 but rare on the seafloor suggesting that fluid flux is at lower levels than in the past.

Keywords: Mohican Channel, double BSR, gas hydrate, polygonal faults, pockmarks

INTRODUCTION

Gas hydrate formation occurs under specific conditions of pressure, temperature and optimal gas concentration. On continental margins, these conditions of pressure and temperature, defining the gas hydrate stability zone (GHSZ), occur within the sediment column as a function of water depth, sediment overburden and the Earth temperature gradient. The Nova Scotia margin has an extensive GHSZ with a calculated thickness of 200-400 m over much of the region including the study area in the central Scotian Slope [1]. The most common indicator of gas hydrate in marine continental margin settings is recognition of a bottom simulating reflector (BSR) in seismic reflection data [2]. A BSR results from the acoustic contrast between hydrate-laden sediment formed in the GHSZ and free gas trapped beneath it; thus marking the base of the hydrate zone. This reflector has opposite polarity to that of the

* Corresponding author: E-mail: jcullen@dal.ca

seafloor reflector because of the velocity drop caused by the free gas. It also typically mimics the seafloor and cross-cuts stratigraphic layers because the base of the GHSZ is determined by the local pressure-temperature regime. A distinct BSR has been identified in the study area, adjacent to the Mohican Channel of the central Scotian Slope [3].

An in-depth examination of industry 2D seismic data throughout the Scotian Slope resulted in recognition of BSRs and inference of gas hydrate in formation in three separate locations [3, 4, 5]. Three joint scientific geophysical surveys by the Geological Survey of Canada-Atlantic and Dalhousie University's Department of Oceanography resulted in acquisition of single channel seismic reflection data and 42 OBS deployments in the study area. The study of two OBS deployments is reported in LeBlanc et al (2007) [6].

In the Mohican Channel study area, a double BSR was recognized. The highest amplitude and most extensive BSR appears in levee deposits along both sides of the channel. A large 3D data cube donated by EnCana Corp. allowed detailed examination of the double BSR which occurs on the eastern side of the Mohican Channel. Single channel seismic data acquired by the GSC provided some indication of the physical limits of the BSR on the western side of the channel system (Fig. 1). The primary BSR (BSR 1) is believed to cover an area of approximately 280km^2. This paper provides geophysical characterization of the Mohican Channel gas hydrate field, as determined from 2D and 3D seismic reflection surveys. These characteristics include structural features and seismic attributes identified in the Mohican Channel gas hydrate zone. The intentions of the paper are to understand the geologic circumstances leading to the presence of the BSR in this region and to understand the cause for a double BSR in this situation.

GEOLOGY OF STUDY AREA

The Scotian continental borderland is a passive margin formed during early Mesozoic rifting between the African and North American tectonic plates. The Scotian Basin is divided into a series of subbasins (Orpheus, Abenake, Sable and South Whale) and has a thick sediment accumulation of evaporitic and clastic sequences believed to be 10-12 km in depth [7]. Triassic deposition of evaporites and dolomites was followed by three main periods of subsistence and deposition during the Jurassic, Cretaceous and Early Tertiary when the thickest sedimentary basins formed on the outer shelf and slope [7]. These thick sedimentary basins in association with mobile salt have made the region prospective for hydrocarbons. Mid-Tertiary shales deposited on the slope were deeply incised by Late Tertiary major sea-level low stands. Numerous mass transport flows during the Late Tertiary also deposited sediments several hundreds of meters thick on the continental slope [8]. Shelf-crossing glaciers active during the Quaternary subsequently deposited thick glacial sediment plumes on top of debris flows and deepened pre-existing canyons [9].

The Scotian margin is characterized by a wide continental shelf extending in a NE-SW direction and parallel to the Nova Scotian coastline. Even coarse-scale bathymetric data show two distinct morphologic provinces of the Scotian Slope [3]. East of Verrill Canyon, the slope has a regional gradient of 3–4° and is highly dissected by submarine canyons. West of Verrill Canyon, at 62°W, the general form of the slope is smooth, and the gradient ranges from 3° on the upper slope to 1.5° on the lower slope. The Mohican Channel is the most significant morphologic feature in this western area. The head of the Mohican Channel is at 200 mbsl and is formed from eastern and western branches that converge at 800 mbsl. Below 1200 mbsl, the channel widens to approximately 12 km and the channel walls become less defined towards the base of the slope [10]. The wide base of the Mohican Channel runs through the western section of the study area. The minimal channel cutting in the study area permits tracing of continuous stratigraphic and seismic markers for 10's of km along the slope. Water depths in the study area range from 1000 to 2000m.

METHODS

3D Data

The 3D seismic data volume known as the Torbrook survey covers an area approx. 1500 km^2 (Fig. 1). The seismic system consisted of 6 x 6-km-long multi-channel streamers with 25 m group intervals and 50 m shot intervals, a configuration that gave 60 fold data. Processing on the data cube by EnCana Corp. included interpolation to 12.5x12.5 m grid and pre-stack time migration.

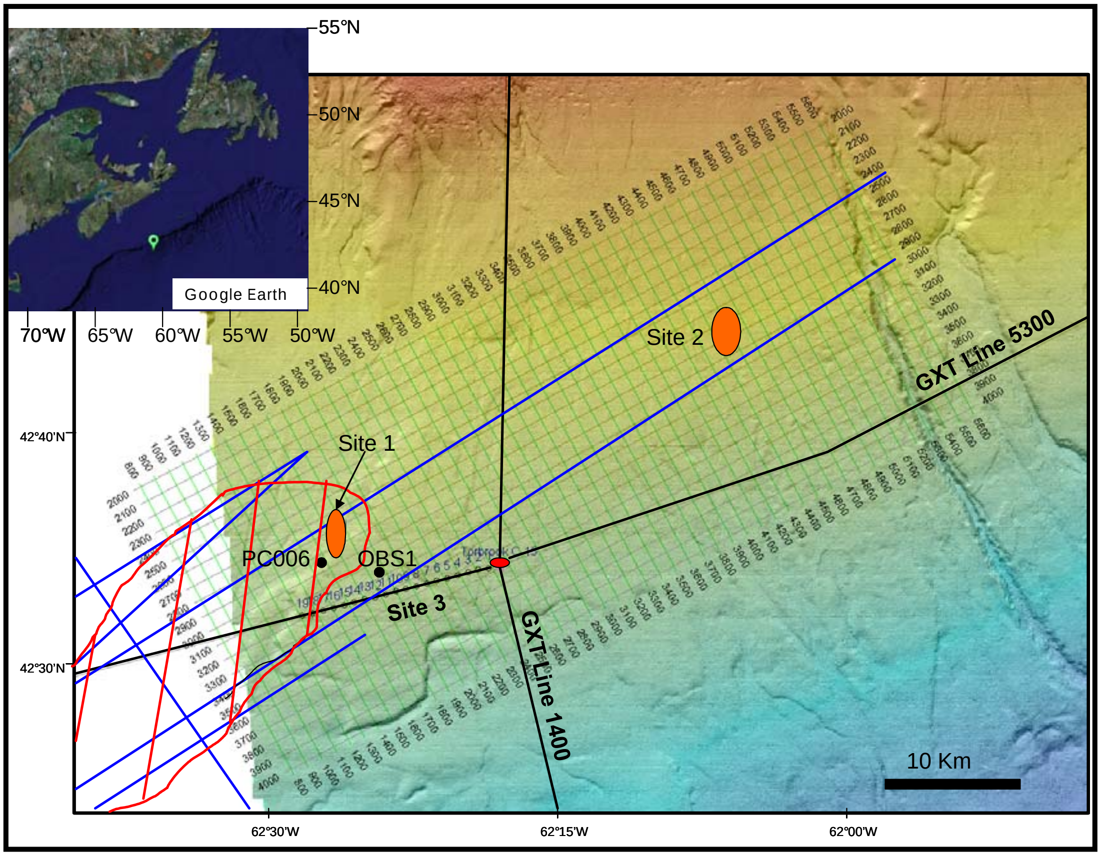

Figure 1: Location map of study area showing outline of 3D Torbrook survey and 2D GXT lines. Sites 1 to 3 mark OBS deployments. OBS 1 marks LeBlanc et al (2007) site. Blue lines mark 2D seismic data acquired by GCS-A. PC006 denotes site of sampled seafloor mound. Red circle marks Torbrook C15 well. Red hatched area shows extent of strongest BSR response in study area.

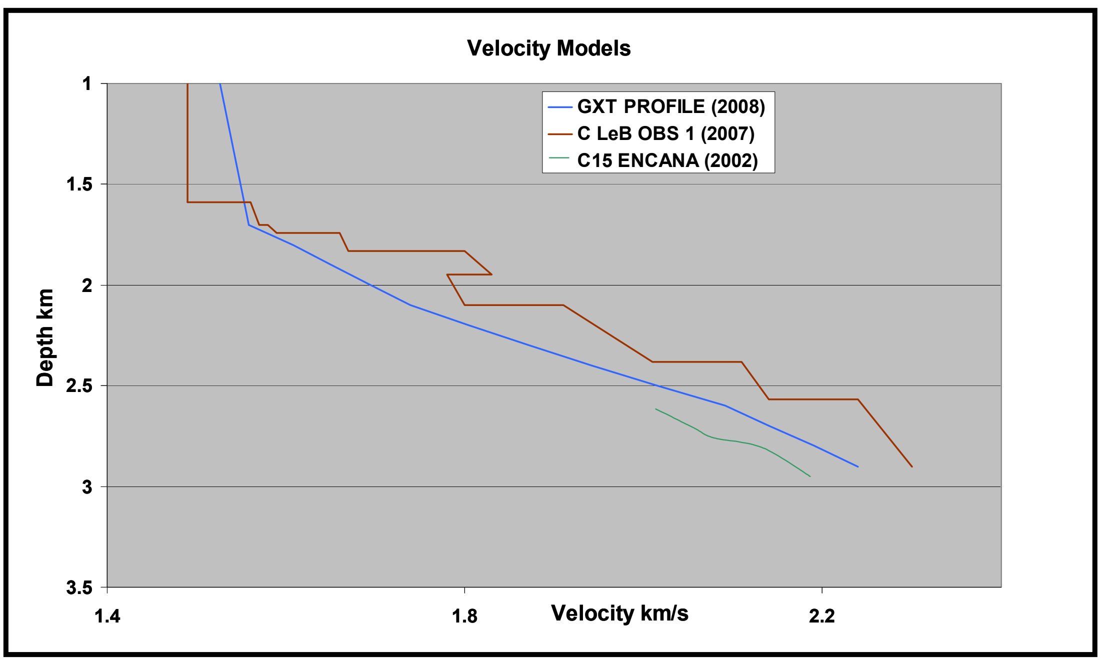

Figure 2: The brown line shows smoothed velocity model from the GXT 2D dataset. The blue line shows velocity model from LeBlanc et al (2007) from a location within the study area (Fig. 1). The green line shows smoothed velocity profile from EnCana C15 Torbrook Well logged from 2.65 to 3.6 km depth. The characteristic high and low velocity zones which mark the location of gas hydrate and free gas are clear on LeBlanc (2007) model. The general trend of the models matches relatively well.

The authors picked horizons of interest using Kingdom Suite™ software. Picking errors of +/- 5 ms are estimated on the basis of the width of the peak amplitude. We found the similarity (coherency) volume to be the most useful for clarifying structural features in the study area. Seismic attributes such as signal phase assisted in definition of the BSR. This attribute was also useful for identifying areas of possible gas-charged sediments.

2D Industry Data

2D multi-channel seismic reflection data were acquired as part of the NovaSpan project by GX Technology (Fig. 1). The authors examined a 100 km section of the 3400 km long offset (9 km streamer) dataset spanning the Scotian Basin, offshore Nova Scotia. Stacking and velocity analysis were completed for this line section crossing the study area using the Globe Claritas software package.

2D Single Channel Data

The Geological Survey of Canada-Atlantic acquired a large volume of 2D high-resolution single channel data in a non-systematic manner along the Canadian east coast margin over the past twelve years (Fig. 1). The single channel data shot over the study sites used a 61 m streamer and a 2 x 210 in^3 GI gun array with approx. 8 s firing rate. Processing consisted of bandpass filtering, gain recovery and F-K time migration.

OBS Data

Velocity profiles from LeBlanc et al (2007) were compared to smoothed velocity profiles from the 2D GX Technology dataset and a smoothed profile from the EnCana C15 Torbrook well. Data for the LeBlanc et al (2007) study was acquired in 2002 along a region of the Scotian Slope near the Mohican Channel and within the study area of this paper. LeBlanc et al (2007) defined the velocity structure of shallow sediments and located velocity anomalies associated with the presence of gas hydrates.

RESULTS

Velocity Models

Initial velocity models from the GX Technology 2D dataset were used to calculate depths and thicknesses of layers of interest in the 3D dataset. The general velocity profile ranged from 1.48 km/s at the seafloor to 2.25 km/s at 3km depth (Fig. 2). The GXT velocity model has a similar profile to the model derived from LeBlanc et al (2007) within the study area and to the velocity model from EnCana C15-Torbrook well data, which was logged from 2650 to 3500 mbsl.

Seismic Reflection

The Mohican Channel BSR is evident on industry exploration 2D and 3D multichannel seismic reflection data and is apparent, although less distinct, on GSC high resolution single channel reflection profiles. This area shows a unique double BSR at 300 to 450 m below the seafloor in the western section of the study area immediately adjacent to the Mohican Channel in a water depth range of 1500-1930m (Fig. 3). A horizon amplitude map of the BSR horizon was derived from the 3D data (Fig. 4). It clearly shows the extent of the strongly negative excursion of the BSR as well as the detailed morphology of this surface.

The topmost BSR (BSR 1) is the more extensive of the two covering an area of 150 km^2 in the 3D volume and a calculated area of 280 km^2 using 2D seismic profiles outside of the study area (Fig. 1). BSR 1 shows lateral changes in reflection amplitude (Fig. 4). BSR 2 covers an area of ~50 km^2 and occurs approximately 80m below BSR 1. The BSRs continue eastwards through the study area where they run parallel to the seafloor and eventually fade into the coincident sedimentary layers (Fig. 3).

Acoustic Blanking

In the study area, a zone of seismic reflections above BSR 1 shows a weakened acoustic response; i.e. low amplitudes, relative to the same horizons correlated laterally away from the BSR (Fig. 3). The zone of acoustic blanking is variable in size from ~100 to 200 m. The largest zone occurs above the sections of BSR 1 with the strongest negative amplitude response. The zone thins rapidly to the west where it is constrained by the Mohican Channel deposits and is cut off in the east by debris flow deposits. Blanking also occurs between BSR 1 and BSR 2.

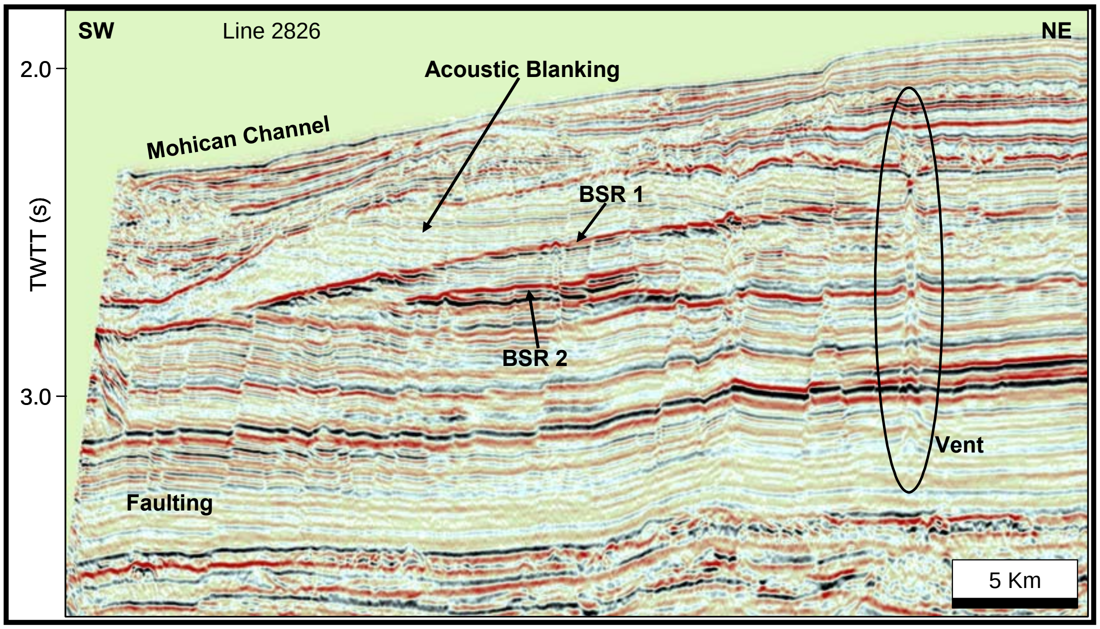

Figure 3: Inline 2826 profile showing double BSR in the west of the study area adjacent to the Mohican Channel. The prominent zone of acoustic blanking is visible above BSR 1 and between BSR1 and BSR 2. BSR 1 fades to the east as it runs parallel to the sedimentary layers in the area. Gas chimneys or vents are common in the study area and show acoustic turbidity associated with fluid flow upwards towards the seafloor. Faulting is prevalent throughout the

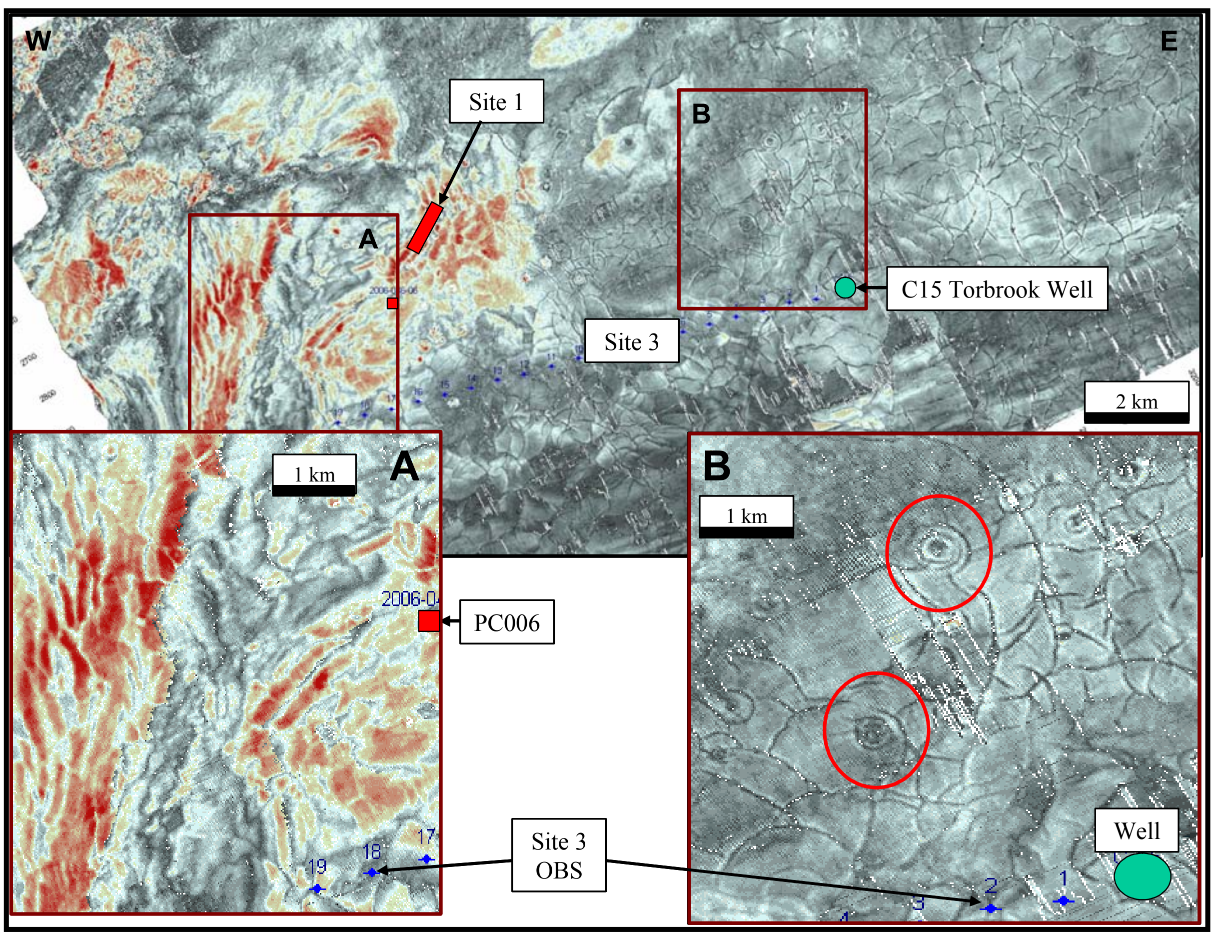

Figure 4: High negative amplitude plot of the surface of BSR 1 in the western section of the study area. The laterally variable amplitude is shown in close up A. The distinctive faulting pattern is shown in close-up B. Also visible are some of the many fluid escape features (red circles, B) visible on the surface of BSR 1.

Fault System

A layer-constrained fault system is clearly visible in the 3D data cube. The lower boundary is at ~3.2 s twt which has been tentatively identified as the Miocene-Eocene Unconformity. The upper boundary of the deformed zone is marked by an increase in thin but widespread and continuous debris flows at ~2.3 s twt, possibly a result of Quaternary glaciation episodes (Figs. 4 and 5).

Fluid Escape Features

Fluid escape features are rare on the seafloor in the study area but abundant on the surface of BSR 1. They fall into a zone running SW to NE along the slope (Fig. 4). The diameters of the features vary from 50 to 500m. This location shows only random distribution of the features throughout the study area although distribution related to buried channels and large faults has been described in other areas such as the Lower Congo Basin [11, 12].

Gas Chimneys

Gas chimneys are distributed throughout the study area and can be identified on seismic profiles as acoustic turbulence which is strong enough to cause 'pull-up' in the acoustic response along a fault (Fig. 3). The data are badly deteriorated at these locations. Vertical extent is highly variable. Gas chimneys which reach the seafloor are rare in this study area although vents and pockmarks have been noted in shallower waters at 500-900mbsl [8, 10]. One rare seafloor mound at the top of a gas chimney was sampled by piston core for gas analyses (Hudson cruise 2006-046-PC006). The gas appears to rise along a fault from a chaotic layer at ~3.2 s twt which shows a laterally variable high negative amplitude response in seismic attribute analyses.

Piston Core and Gas Results

The average depth of piston cores is 10-12m. Subsamples were taken from the cores and stored in a refrigerated container for interstitial gas concentration analyses. Sample analysis at core site 2006-046-PC006 confirms 99.9% methane gas exiting at the seafloor mound (Table 1).

Two methods were used to plot the results to determine source origin. Jeffrey et al (2004) [13]

TDI Brooks Compositional Analyses (ppm)					
Core	**Methane**	**Ethene**	**Ethane**	**Propene**	**Propane**
B/B'	88,185.8	0.17	41.32	0.04	6.57
D/D'	63,051.5	0.15	27.71	0.04	3.42

Stable Carbon Isotopes			
Core	**C1**	**C2**	**C3**
B/B'	-90.6	-56.2	-23.5
D/D'	-99.5	-55.0	-23.3

Table 1: Compositional Analyses results from piston core 2006-046-PC006. 'Stable Carbon Isotopes C1, C2 and C3' refer to methane, ethane and propane respectively.

described analyses using the formula C1/ (C2+C3) plotted against δ^{13}C of methane. Results are inconclusive when using the values from the analyses in Table 1. A flowchart designed by Jeffrey et al (2004) to identify the source of fugitive hydrocarbon gas places the δ^{13}C value at –90‰ to –60‰ within microbial gas that has undergone CO^2 reduction. However our values of δ^{13}C are –90.6‰ and –99.5‰ respectively so this interpretation is not entirely reliable here.

The second method used information provided by Bernard, Brooks and Zumberge (2001) [14]. The authors plotted δ^{13}C of methane vs ethane/ethene ratio using the analyses of 2006-046-PC006 (Table 2). The points derived above plot within the biogenic/mixed zone as determined by the authors of this paper suggesting again that the source of the methane is biogenic rather than thermogenic (Fig. 6).

δ^{13}C methane	Ethane/Ethene ratio
-90.6	243.06
-99.5	184.73

Table 2: δ^{13}C methane and ethane/ethene ratio for analyses from 2006-046-PC006.

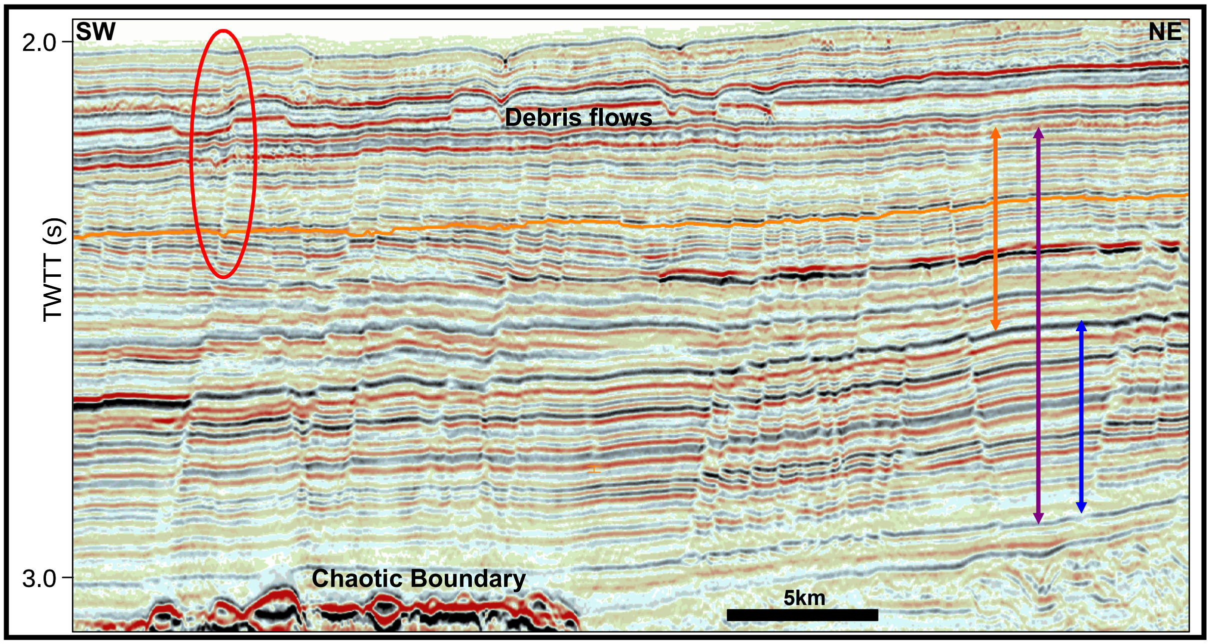

Figure 5: Inline profile 3001 in the eastern section of the 3D cube showing the layer-constrained fault system. Upper boundary is formed by numerous thin debris flows at ~ 0.3 s twt. Lower boundary is marked by a gas-charged chaotic layer at ~ 3.2 s twt. The purple arrow marks the total length of faults within this system. The orange and blue arrows mark possible tiers of faulting as described by Cartwright and Dewhurst (1998). The red oval shows that faults can sometimes extend outside the deformed zone. It is possible that this fault has been reactivated and extended since formation of the layer-constrained system.

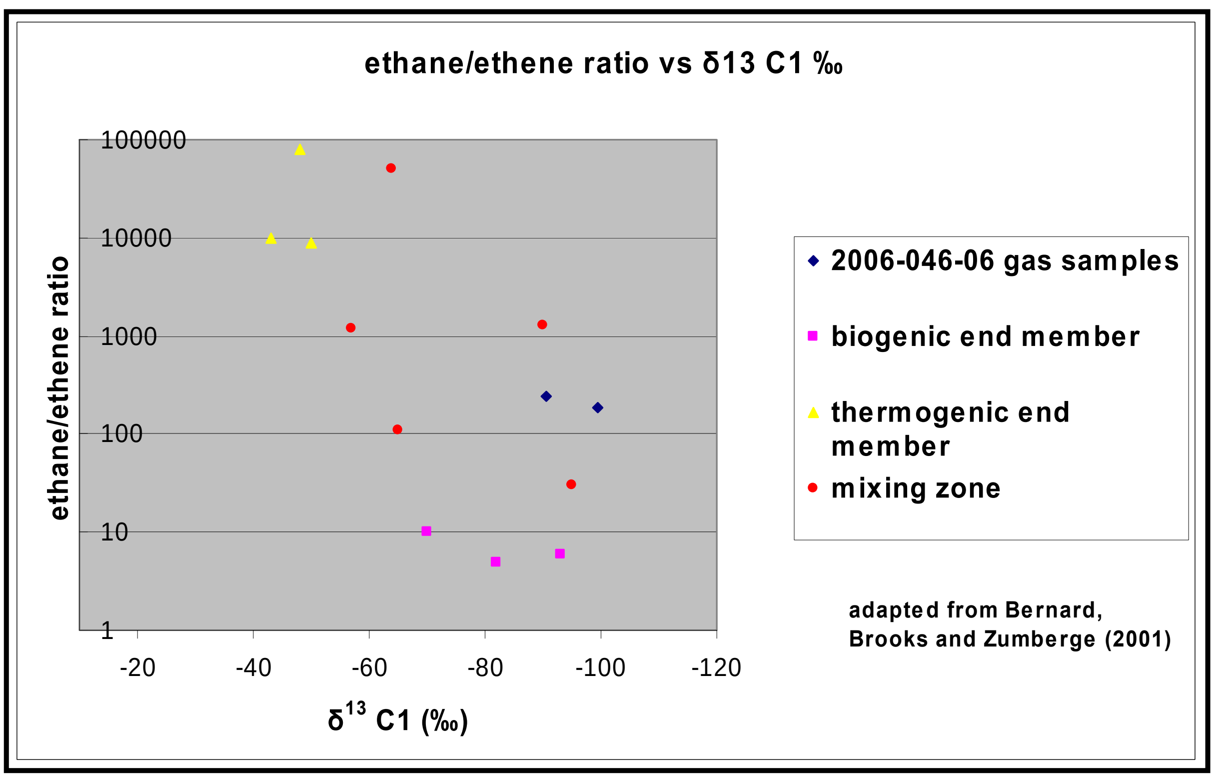

Figure 6: Results from gas analyses on 2006-046-PC006 plotted on graph from Bernard, Brooks and Zumberge (2001). The core results plot at the edge of the mixing zone. This suggests that the gas escaping at the seafloor is a mixture of both biogenic and thermogenic origins.

DISCUSSION

A bottom simulating reflector associated with the Mohican Channel of the central Scotian Slope indicates the likely presence of gas hydrate in the region. The primary BSR maps out on 2D and 3D seismic data to approximately 280 km^2. It is laterally variable in the western section and completely absent in the eastern section of the study area. The presence of two BSRs and their relation to each other may be explained in this area by the remnant of a palaeo-BSR. The Mohican Channel area is an active system and the seismic data clearly shows channel movement and sediment build-up over time. The continental shelf of eastern Canada has undergone several glaciations from mid- to Late Pliocene with lower sea level and cold bottom water temperatures as late as 12 Ka [9]. As the formation of gas hydrate is dependent on the geothermal gradient as well as the pressure regime in an area, any shift in these properties will cause dissociation of hydrate no longer in the optimum GHSZ and subsequent formation of hydrate in the new GHSZ. Seismic attributes studies such as negative amplitude plots show that the area of strongest BSR 2 commonly occurs underneath an area of weak BSR 1 pointing to the dissociation and reformation of hydrate.

Acoustic blanking is commonly observed in areas where BSRs occur [12]. This observation suggests that the acoustic blanking is influenced by sediment composition. Studies by Chand and Minshull (2003) [15] in a variety of locations, including Blake Ridge and Cascadia, support this observation as they show that blanking observed with the GHSZ above the BSR depends on both the nature of the sediments and the concentration of hydrate. Blanking also occurs between BSR 1 and BSR 2 which have a separation of less than 100m. The lack of deep cores in the area of the double BSR means that sediment composition in this area is undetermined.

The faulting pattern throughout the study area is consistent with patterns shown in other areas with potential overpressured sections, so recognition of this phenomenon is important in drilling operations. The faulting pattern meets five out of the seven criteria outlined by Cartwright and Dewhurst (1998) [16] defining a polygonal fault system. These criteria are 1) faults are randomly organised (Fig. 4), 2) faults are layer bound and delimited by regionally correlatable stratigraphic surfaces (Fig. 5), 3) normal faults with small throws 10-100m, 4) closely spaced faults at spacing 10-1000m, 5) deformed interval may be subdivided into 2 or more tiers (Fig. 4). The unproven criteria are beyond the scope of this study as they require a study of fault polarity and confirmation that the fault system is distributed over a large area >150,000 km^2. However the definition of polygonal describes “a plan view geometry where planar, curved and sinuous fault traces are distributed in a wide variety of orientation and connect to form both closed and open multi-sided cells” [17]. This pattern is clearly visible throughout the study area (Fig. 4).

The fault system is believed to be a result of fluid release from overpressured Cenozoic mud rock sequences as commonly seen in the North Sea. Polygonal fault systems are widely developed in passive margin basins that contain thick successions of deep marine sediments. The Scotian slope runs parallel to the present-day coastline of Nova Scotia. During the Mesozoic and Cenozoic however, it formed the landward edge of the Scotian Basin which was itself part of the central North Atlantic Ocean Mesozoic rifted margin [18, 19].

Polygonal faulted intervals such as those described here are commonly found in 2 dominant facies groups 1) biogenic oozes and mudstones, 2) clays and claystones with common properties of ultra-fine grained, very low permeability and high specific surface area [16]. The Torbrook C15 well in the study area was logged from 2650 to 3600 m below sea level, the lower third of the faulted zone. The geological logs describe shales with claystone stringers, claystone units and claystone matrix carrying fine-grained detrital quartz [20]. Occasional claystone and siltstone layers are up to 10m thick. This suggests that the optimal lithological criteria for polygonal fault formation are present.

Fluid flow is an important factor in gas hydrate formation. It is active in the study area as shown by a number of faults displaying acoustic turbidity and seismic “pull-ups” consistent with upwards fluid movement. Gas chimneys are visible in areas where gas or fluid flows along a fault and towards the seafloor. The gas appears to rise from a chaotic layer at ~3.2 s twt and tentatively identified as the Miocene-Eocene Unconformity. Seismic attribute studies show a laterally variable high negative amplitude response from this layer indicating that the sediments are probably gas charged. Gas may migrate up along faults rooted in this layer through the GHSZ.

Circular fluid-escape features, which may be described as pockmarks, are very common on the surface of BSR 1. It is possible that the polygonal fault system and the related pockmarks formed at the time that the top layer confining the deformed zone was at seafloor level. The lack of pockmarks on the current seafloor suggests that there has been a reduction of fluid flux over time. Pockmarks are found worldwide in a variety of depositional environments and with variable sizes and concentrations. The sediments within which these features occur however are relatively consistent [21]. Pockmarks generally form in fine-grained sediments such as clays, muds and silts, sediments which have been found in the lower section of the faulted zone as described in Torbrook C15 logs. Pockmark size varies according to the grain size of the sediment within which it forms e.g. finer sediment host the largest pockmarks [21]. Haskell et al (1999) have observed that finer-grained sediments also have lower concentrations of pockmarks while water depth appears to have minimal impact on formation.

The gas analyses results give very high negative methane carbon isotope values which initially point to the gas being of biogenic origin. This corresponds with the results from the Torbrook C15 well analyzed by EnCana Corp. which concluded that gas shows were of biogenic origin. However when the gas analyses results are plotted using criteria from other authors [13, 14], the final results are inconclusive. It is possible that the gas comes from a deep gas-charged layer, such as the chaotic layer identified at ~ 3.2 s twt, and is reworked in shallower sections before forming gas hydrate. This would account for the data points plotting in the mixing zone on the plots from Bernard et al (2001).

CONCLUSIONS

The BSR adjacent to the Mohican Channel study area is found to be laterally variable in amplitude along its extent. Initial velocity models from a variety of datasets do not indicate a constant zone of high and low velocity at the strongest BSR response as would be expected in an area with relatively constant amounts of both gas hydrate and free gas. These results are consistent with lateral variations in amplitudes seen along the extent of the BSR, suggesting that the free gas beneath the base of the GHSZ is variable. It is possible that the thickness of the bulk hydrate throughout the study area is also laterally variable. Fluid escape features on the surface of BSR 1 and on the top confining layer of the faulted zone show that there was a higher fluid flux through the region in the past. The rarity of fluid escape features reaching the seafloor suggests a low fluid flux in the area today. The double BSR may have been caused by sediment movement along the Mohican Channel zone which in turn caused a change in the optimal position of the GHS, or influences from the last glaciation causing a lower sea level and cold bottom water. Dissociation of gas hydrate from a lower GHSZ to a new optimal GHSZ would account for the location of BSR 2 underneath BSR 1.

REFERENCES

[1] Majorowicz, J.A., and Osadetz, K.G. *Natural Gas Hydrate Stability in the East Coast Offshore-Canada.* Natural Resources Research 2003; 12(2): 93-104.

[2] Tucholke, B.E., Bryan, G.M., and Ewing, J.I. *Gas-hydrate horizons detected in seismic-profiler data from the Western North Atlantic.* AAPG Bulletin 1977; 61(5): 698-707.

[3] Mosher, D., Piper, D.J.W., Campbell, D.C., and Jenner, K.A. *Near-surface geology and sediment-failure geohazards of the central Scotian Slope.* AAPG Bulletin 2004; 88(6): 703-723.

[4] Mosher, D., Louden, K., LeBlanc, C., Shimeld, J.W., and Osadetz, K.G. *Gas Hydrates Offshore Eastern Canada: Fuel for the Future?, OTC 17588. In: Offshore Technology Conference. Houston, Tx. 2-5 May 2005.*

[5] Mosher, D. *Bottom Simulating Reflectors on Canada's East Coast Margin: Evidence for Gas Hydrate. In: 6th International Conference on Gas Hydrates, Vancouver, BC, 6-10 July, 2008*

[6] LeBlanc, C., Louden, K., and Mosher, D. *Gas Hydrates off Eastern Canada: Velocity Models from wide-angle seismic profiles on the Scotian Slope.* Marine and Petroleum Geology 2007; 24(5): 321-335.

[7] Jansa, L.F., and Wade, J.A. *Geology of the continental margin off Nova Scotia and Newfoundland.* In: Offshore Geology of Eastern

Canada. Paper 74-30, pp. 51-105. Geological Survey of Canada, 1975.
[8] Piper, D.J.W. *The Geological Framework of Sediment Instability on the Scotian Slope: Studies to 1999.* Open File 3920, Geological Survey of Canada, 2001
[9] Piper, D.J.W. *Late Cenozoic Evolution of the continental margin of eastern Canada.* Norwegian Journal of Geology 2005; 85: 305-308
[10] Gauley, B.L. 2001. Lithostratigraphy and sediment failure on the central Scotian Slope. M.Sc. Thesis, Dalhousie University, Halifax, Nova Scotia.
[11] Gay, A., Lopez, M., Ondreas, H., Charlou, J.-L., Sermondadaz, G., and Cochonat, P. *Seafloor facies related to upward methane flux within a Giant Pockmark of the Lower Congo Basin.* Marine Geology 2006; 226(1-2): 81-95.
[12] Gay, A., Lopez, M., Berndt, C., and Seranne, M. *Geological controls on focused fluid flow associated with seafloor seeps in the Lower Congo Basin.* Marine Geology 2007; 244(doi:10.1016/j.margeo.2007.06.003): 68-92.
[13] Jeffrey, A., Kaplan, I., Zhang, D., Lu, S.-T., and Nielsen, J. *Fugitive Methane.* Service Summary, p16-19. Zymax Stable Isotope Laboratory, Obispo, CA, November 2004. See also:http://www.dpra.com/File/zymaxstableisotope.pdf
[14] Bernard, B.B., Brooks, J.M., and Zumberge, J. *Determining the origin of gases in near-surface sediments. In: AAPG Hedberg Conference, "Near-surface Hydrocarbon Migration: Mechanisms and Seepage Rates". Vancouver, B.C., Canada. September 16-19, 2001.*
[15] Chand, S., and Minshull, T.A. *Seismic constraints on the effects of gas hydrate on sediment physical properties and fluid flow: a review.* Geofluids 2003; 3(4): 275-289.
[16] Cartwright, J.A., and Dewhurst, D.A. *Layer-bound compaction faults in fine-grained sediments.* GSA Bulletin 1998; 110(10): 1242-1257.
[17] Lonergan, L., Cartwright, J.A., and Jolly, R. *The geometry of polygonal fault systems in Tertiary mudrocks of the North Sea.* Journal of Structural Geology 1998; 20(5): 529-548.
[18] Campbell, D.C., Shimeld, J.W., Mosher, D., and Piper, D.J.W. *Relationships between sediment mass-failure modes and magnitudes in the evolution of the Scotian Slope, offshore Nova Scotia, OTC 16743 In: Offshore Technology Conference. Houston, Texas. 3-6 May 2004.*
[19] Hansen, D.M., Shimeld, J.W., Williamson, M.A., and Lykke-Andersen, H. *Development of a major polygonal fault system in Upper Cretaceous chalk and Cenozoic mudrocks of the Sable Subbasin, Canadian Atlantic margin.* Marine and Petroleum Geology 2004; 21: 1205-1219.
[20] EnCana Corp. *Torbrook C-15 Geological Striplog 1_240*. EnCana Corp., Nova Scotia, Canada, 2002
[21] Haskell, N., Nissen, S., Hughes, M., Grindhaug, J., Dhanani, S., Heath, R., Kantorowicz, J., Antrim, L., Cubanski, M., Nataraj, R., Schilly, M., and Wigger, S. *Delineation of geologic drilling hazards using 3-D seismic attributes.* The Leading Edge 1999; 18(3): 373-382.