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TITLE OF PROPOSAL:
The Sackville Spur bottom simulating reflector offshore eastern Canada: indicator of gas hydrates or silica diagenesis?

KEY WORDS
Bottom simulating reflector, gas hydrates, silica diagenesis, Sackville Spur

LIST INNOVATIONS or EXPECTED SIGNIFICANT OUTCOMES
Use of known geophysical and geological indicators of gas hydrate and silica diagenesis, combined with novel application of seismic stratigraphic and geomorphological analysis from three dimensional seismic reflection data, will reveal the origin of the bottom simulating reflector (BSR) that cross-cuts the Sackville Spur.

A set of diagnostic geophysical and geologic criteria will be developed for distinguishing between gas hydrate and diagenetic BSRs in the North Atlantic.

SUMMARY OF PROPOSED RESEARCH

Seismic reflectors that cross cut stratigraphy, mimic the seafloor and do not represent acquisition artifacts are known as bottom simulating reflectors (BSRs). BSRs are present in the upper few hundred metres of the sedimentary section at certain locations along the world's outer continental margins. BSRs represent acoustic impedance contrasts that primarily result from two different post depositional processes: 1) The trapping of free gas below solid gas hydrates and 2) Changes in the physical properties of siliceous sediments at the diagenetic transition of silica. The origin of a BSR identified below the Sackville Spur offshore Newfoundland has been attributed to the presence of gas hydrates by Mosher (2011) and to a diagenetic transition by Statoil (E. Stacey(personal communication 2011)), the operators of the petroleum exploration block that encompasses the BSR occurrence.

This study will aim to determine if gas hydrates are present in the sediments
overlying the BSR through comparison of the BSR depth to the theoretical depth of the base of gas hydrate stability. The study will also use geochemical and geophysical proxies to test for the presence of gas hydrates in the upper few metres of the Sackville Spur sediments. To test the hypothesis of a diagenetic origin, the age of the sediments at the depth of the BSR will be compared to known values for the silica diagenetic transition in the North Atlantic. In addition, the lithology of sidewall cores and cutting from near-by exploration wells will be inspected for the presence of porcelanite and chert which represent the products of the silica diagenetic transitions. Using the results of this study, along with known geologic and geophysical characteristics of gas hydrate versus diagenetic BSRs, a set of key criteria will be developed for distinguishing between the two types of BSRs.

STATEMENT OF PROBLEM
Seismic reflectors that cross-cut stratigraphy, mimic the seafloor and do not represent acquisition artifacts are known as bottom simulating reflectors (BSRs). BSRs represent acoustic impedance contrasts that primarily result from two post depositional processes: 1) The trapping of free gas below solid gas hydrates and 2) Changes in the physical properties of siliceous sediments at the diagenetic transition of silica. Determination of the process responsible for the formation of a given BSR can be problematic. Nevertheless, it is important to distinguish between the two types as gas hydrates represent a geological hazard, a potential future energy source and may contribute to past and future climate changes. In contrast, diagenetic boundaries provide information on the lithology and physical properties of the sediments. A BSR is observed on 3D seismic data acquired offshore Newfoundland. The origin of this BSR, which transects late Cenozoic sediment drift deposits of the Sackville Spur, is currently unclear. This study will use geophysical and geologic observations to determine the origin of the Sackville Spur BSR.

BACKGROUND
Gas Hydrates
Gas hydrates, composed of water and natural gas, form when hydrogen bonded water creates a crystalline lattice that encages guest hydrocarbon molecules. The thermodynamic conditions required for hydrate formation are generally well defined and include regimes dominated by low temperature, typically less than 25 °C and high pressure, normally greater than 0.6 MPa (Sloan 1998). These conditions occur naturally in the first few hundred meters of sediments of the world's outer continental margins. At such locations the zone of hydrate stability extends from the seafloor to the depth at which temperatures become too high for hydrate formation. Below this zone water and free gas occupy the pore spaces. The strongly negative acoustic impedance contrast between the hydrate and underlying gas bearing sediments generates a high amplitude, phase reversed reflector on seismic reflection profiles.

Geophysical indicators of gas hydrate
The negative phase BSR is the primary geophysical indicator of gas hydrates although gas hydrate can occur without a BSR. Also the BSR does not provide information on the distribution and concentration of gas hydrate deposits (Spense et al.
2010). Gas hydrates and underlying free gas modify the physical properties of the shallow sediments which results in characteristic changes in the acoustic response through the sediments. Gas hydrates act to cement the host sediments increasing the velocity through gas hydrate bearing zones as indicated on sonic logs and in refraction studies (e.g. LeBlanc et al. 2007). The presence of gas hydrates also reduces the acoustic contrast through gas hydrate bearing zones (Spense et al 2010), which can result in zones of reduced amplitudes (acoustic blanking) overlying the BSR (e.g. Cullen et al. 2008). Accumulation of free gas below solid gas hydrates commonly results in distinctly elevated seismic reflection amplitudes underlying the BSR. Both gas hydrates and free gas attenuate the seismic signal which can reduce the frequency of the acoustic response from affected intervals (Spense et al. 2010).

Gas hydrates also modify the electrical conductivity of sediments as measured in wells by downhole resistivity tools. Gas hydrates are an electrical insulator that in porous sediments replaces electrically conductive seawater. The presence of hydrates, therefore, results in elevated resistivity values through gas hydrate bearing zones (Collett and Ladd 2000).

**Geochemical proxy for the presence of gas hydrates**

Gas hydrates are difficult to sample as they dissociate at atmospheric temperatures and pressures and are typically only recovered where substantial hydrate deposits occur. Instead, geochemical proxies, such as sulfate concentrations (Browoski et al. 1996) are often used to determine if gas hydrates are present in the upper few hundred metres of marine sediments.

Sulfate \( \text{(SO}_4^{2-} \)\), which is present in seawater, is used as an oxidant by microbes to breakdown organic matter. With increasing depth below the seafloor sulfate is depleted in the sediments. At the base of the sulfate reduction zone sulfate and methane are coconsumed in a process called anaerobic methane oxidation (Browoski et al. 1996). This reaction occurs at a localized depth known as the sulfate-methane interface (SMI). Gas hydrate bearing sediments typically have a higher upward methane flux which increases the co-consumption of sulfate and methane (Chatterjee et al. 2011). This results in a shallowing of the SMI and steep, linear sulfate gradients in the shallow sediments (Browoski et al. 1996).

**Silica Diagenesis**

The diagenesis of siliceous sediments results from the dissolution of biogenic opal-A and the subsequent precipitation of opal-CT. At increased depths opal-CT is dissolved and quartz is precipitated (Williams and Crerar 1985). The diagenetic transition of opal-A to opal-CT significantly increases the density and velocity of the sediments which generates a positive acoustic impedance contrast and a high amplitude, positive phase BSR on seismic profiles. In contrast the opal-CT to quartz transition does not significantly modify the sediment properties (Nobes et al 1992) and if present, the associated BSR typically has reduced amplitude and is poorly developed (Bernt 2004). Guerin and Goldberg (1996) showed that the increases in density and velocity of the sediments result from a reduction in the porosity.
Unlike gas hydrates, which are primarily temperature and pressure dependant, silica diagenesis is complex and controlled by temperature, burial depth, time, pore water chemistry as well as sediment permeability and composition (Hein et al. 1978). In particular, the formation of opal-CT is inhibited in the presence of clay minerals and accelerated in the presence of carbonates (Williams and Crerar 1985). The onset of silica diagenesis is observed throughout the North Atlantic in Miocene and older sediments, which represents a period of increased deposition of siliceous sediments (Riech and von Rad 1979; Vecsei and Hoppie 1996).

BSRs along Canadian East Coast Margin
A regional study by Mosher (2011) identified seven BSR locations along the passive margin of eastern Canada. Mosher (2011) attributed these BSRs to the presence of gas hydrates. To date no hydrate bearing sediments have been recovered along the margin although their occurrence has been inferred from geophysical logs acquired in exploration wells along the margin (Majorowicz and Osadetz 2003).

Figure 1 Locations of BSRs (circles) along the eastern margin of Canada as identified by Mosher (2011). The bold circle shows the location of the Mohican BSR which is attributed to the presence of gas hydrates and represents the only BSR studied in detail along the margin (LeBlanc et al. 2007 and Cullen et al. 2008). The square indicates the location of the Sackville Spur BSR and the extents of Figure 2. Modified after Mosher (2011).
**Sackville Spur BSR**

Mosher (2011) identified a discontinuous BSR that cross-cuts Cenozoic drift deposits of the Sackville Spur offshore Newfoundland (Figures 1 and 2). The BSR crosscuts Pliocene and younger contouritic deposits (Kennard et al. 1990), the lithology of which is not well established due to few samples from exploration wells. The BSR is defined on 3D seismic profiles by the abrupt termination of high amplitude, phase reversed stratigraphic reflections (Figure 3). Mosher (2011) identified a zone of reduced velocities below the BSR that along with the reverse phase of the BSR suggest a gas hydrate origin for the BSR. Resistivity wireline logs acquired in the recently drilled F-09 pilot hole, which intersects the Sackville Spur BSR, were interpreted by the operators of the well as showing no evidence of the presence of gas hydrates. As such, the operators have suggested that the BSR represents a diagenetic boundary (E. Stacey (personal communication 2011)).

![Figure 2](image-url)

**Figure 2** Overview map of the study area showing the preliminary extent of the BSR. The black line through the F-09 pilot hole indicates the location of the seismic profile presented in Figure 3. Refer to Figure 1 for the relative location of the study area along the Eastern Canadian margin.
OBJECTIVES
The main goal of this study is to determine if the BSR imaged on 3D seismic profiles from the Sackville Spur offshore Newfoundland is diagenetic in origin or if it is indicative of the presence of gas hydrates in the shallow sediments. This will be accomplished addressing the following objectives which represent key criteria for distinguishing BSR type in the North Atlantic:

1) Determine if seismic amplitude, frequency, and phase anomalies indicative of the presence of gas hydrates and gas migration occur within the study area;
2) Determine if the BSR depth, as mapped on the Mizzen 3D seismic data, corresponds to the theoretical base of gas hydrate stability;
3) Determine if gas hydrates are present in the shallow sediments of the Sackville Spur through proxy studies of well log data and pore water composition from piston cores;
4) Determine if the age of the sediments at the depth of the BSR correspond to known values for the diagenetic transition of silica;
5) Determine if samples acquired from exploration wells in the vicinity of the study area show indications of the diagenetic transition of silica.

METHODS
3D seismic interpretation
Seismic stratigraphic analysis will be completed for the Mizzen 3D seismic dataset, which covers ~3115 km² on the Sackville Spur and Northern Flemish Pass (Figure 2). The digital, time migrated 3D seismic data was donated in SEG-Y format to Natural Resources Canada by Statoil. The dataset, which extends from the sea surface to approximately 2500 m below sea level, forms the primary dataset for this study. The data will be loaded into the commercial seismic reflection interpretation package Kingdom Suite™ where the structure and amplitudes along the BSR will be mapped. The BSR depth will be determined using a time to depth function derived from refraction
Seismic reflections that intersect the BSR will be mapped to identify amplitude variations indicative of gas migration from depth. Such gas could provide a potential source for the hydrocarbons that form the gas hydrate deposit.

Seismic attributes, which represent the decomposition of seismic traces into constituent characteristics, will be calculated from the 3D seismic data in Kingdom Suite™. In particular, amplitude, frequency, phase, and similarity will be calculated. Amplitude, frequency and phase will be used to identify anomalous values (e.g. values that do not represent primary lithological features) indicative of the presence of gas hydrates and underlying free gas. Similarity, which is the measurement of the likeness of adjacent traces, will be used to identify and map structural features such as faults, which provide potential conduits for the migration of gas from depth.

**Gas hydrate stability**
Under suitable temperature and pressure regimes, gas hydrates will form from water and free gas that are present in the sediment. The temperature and pressures at which this transition occurs is defined by the statistical thermodynamic model provided in Sloan's (1998) freely available CSMHYD software. Assuming the sediment pores are connected to prevent over pressures and that pore pressure equals hydrostatic pressure, a function relating temperature and depth at the base of the gas hydrate stability zone is defined. Using Sloan's (1998) CSMHYD software, Majorowicz and Osadetz (2003) defined the stability function as:

\[
TBHSZ = a \times \ln(DBHSZ) - b
\]

where \(TBHSZ\) and \(DBHSZ\) are the temperature and depth at the base of the hydrate stability zone and \(a\) and \(b\) are constants dependant on the gas composition of the gas hydrate.

Following the method of León et al. (2009) the temperature and pressure at the base of the hydrate stability zone can also be defined by the linear function:

\[
TBHSZ = TSF + \delta g(DBHSZ - DSF)
\]

where \(TSF\) and \(DSF\) are the temperature and depth at the seafloor and \(\delta g\) is the geothermal gradient. Through substitution of Equation (1) into Equation (2) the depth at the base of the hydrate stability zone is defined by the function:

\[
\ln(DBHSZ) = \frac{TSF + \delta g(DBHSZ - DSF) + b}{a}
\]

Where Equation (3) has no real solution, Newton's method, an iterative process, is applied to determine a highly accurate approximation of \(DBHSZ\).

The geothermal gradient will be determined by a line of best fit through a temperature versus depth plot of temperature measurements acquired in exploration wells from within the Flemish Pass. The seafloor temperatures will be obtained from the Fisheries and Oceans Canada's (2011) online database of seawater temperatures while seafloor depths will be determined through depth conversion of the seafloor pick from the Mizzen 3D seismic data. Sensitivity analyses involving systematic variation in the...
seafloor temperature, geothermal gradient and gas composition will be performed to assess the uncertainty in the depth to the base of gas hydrate stability calculations.

To determine the constants a and b of Equation (3) the gas composition will be determined through headspace gas analyses of samples taken approximately every 150 cm from four piston cores (Figure 2) collected in August of 2011 from the CCGS Hudson. The analyses will be performed by TDI Brooks of Texas using gas chromatography which separates and measures concentrations of individual vapor components. Even small quantities of larger molecule gases such as propane and ethane result in a hydrate crystal structure that is stable at higher temperatures and lower pressures than gas hydrates formed from pure methane (Sloan 1998).

**Comparison of gas hydrate stability and BSR depth**

Comparison of the BSR depth to the theoretical depth to the base of the gas hydrate stability will be undertaken in the area below the crest of the Sackville Spur where significant sediment movements are less apparent (Figure 3). Sediment mass movements displace large quantities of sediment resulting in changes to the pressure-temperature regime and the geothermal gradient. A variable geothermal gradient leads to Equation (2) and Equation (3) being invalid. If the BSR and base of gas hydrate stability surfaces correlate below the crest of the spur, it will provide supporting evidence that the Sackville Spur BSR is related to the presence of gas hydrates. On other margins where the presence of gas hydrates is confirmed through recovery in cores, the BSR and base of gas hydrate stability depths are highly correlative (eg León 2009).

**F-09 well logs**

Resistivity, sonic and gamma ray logs were acquired at the F-09 pilot hole, which intersects the western edge of the Sackville Spur BSR (Figures 2 and 3). Once imported into Kingdom Suite the logs are transformed from the depth domain to the time domain to allow for correlation with the seismic data. Generation of a synthetic seismogram; a simulated seismic response obtained by convolving a source wavelet with a reflection coefficient series (White and Simm 2003), will allow for calibration of the correlation between the seismic and well log data. To generate the synthetic seismogram, downhole velocity will be taken from the F-09 sonic log and in the absence of a density log a constant density will be assumed.

To identify possible gas hydrate deposits, the well logs will be inspected for corresponding resistivity and velocity increases in discrete intervals above the BSR. Mosher (2011) showed that velocities derived from refraction studies indicate a velocity reduction below the BSR suggestive of the presence of gas. This observation will be tested through correlation with velocities from the F-09 sonic log, which have a much higher sampling rate than the modeled refraction data.

**Sulfate concentrations**

For this study sulfate concentrations will be determined from 2 mL pore water samples extracted every 60 cm along the four piston cores collected in August of 2011.
Maxxam Analytics of Ontario will use ion chromatography, a process that separates ions based on their charge, to determine the pore water sulfate concentrations in millimoles. The sulfate concentrations will then be plotted versus depth. The occurrence of a linear sulfate gradient would suggest that sulfate reduction is regulated by the upward flux of methane from underlying gas hydrates. If the sulfate gradient is non-linear it will be assumed that the reduction of sulfate is regulated by the presence of organic carbon in the sediment (Browoski et al. 1996).

**Sediment age at the depth of the BSR**
The age of sediments intersected by the BSR will be determined through the correlation of published biostratigraphic age data from the Mizzen L-11 exploration well with the Mizzen 3D seismic. If the BSR represents a diagenetic boundary, the age of the sediments at the depth of the BSR should be Miocene or older (Riech and von Rad 1979).

**Sediment lithology**
Published reports from exploration wells in and around the Flemish Pass will be inspected for lithologic information from sidewall cores and cuttings. Using published biostratigraphic age data the age of occurrences of porcelanite and chert, amorphous forms of quartz (opal) that result from the diagenetic transition of silica, will be determined. Any porcelanite and chert occurrences will then be correlated to the age of the sediments at the depth of the Sackville Spur BSR.

**SIGNIFICANCE AND EXPECTED OUTCOMES**
BSRs occur globally in the upper few hundred metres of marine sediments on the outer portions of passive continental margins, however, the origin of such BSRs is not always apparent. Through determination of the origin of the Sackville Spur BSR this study aims to develop a set of key geophysical and geologic criteria for distinguishing between BSRs formed by gas trapping below gas hydrates and those representing the diagenetic transition of silica.

It is important to identify if a BSR is related to the presence of gas hydrates as changes in the subsurface temperature and pressure regimes, whether due to drilling operations or changes in sea level and thermohaline circulation, can result in hydrate dissociation. This dissociation and the resulting overpressures in shallow marine sediments can lead to sediment instability, a potential geohazard in the marine environment (Sultan et al. 2001). Given gas hydrates represent a significant storehouse of methane, they not only represent a significant potential energy resource but as a greenhouse gas they may also play an important role in past and future climatic change (Krey et al. 2009). If it is determined that the Sackville Spur BSR represents a diagenetic boundary, important information on the sediment composition and sediment properties within the study area will be gained.

**REFERENCES**