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Comparison of single- and multichannel high-resolution seismic data for shallow stratigraphy mapping in St. Lawrence River estuary, Quebec

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Abstract: During the summer of 2004, over 1150 km of high-resolution marine seismic-reflection data were acquired along 28 profiles in the St. Lawrence River estuary. The main objectives of the survey were to study the stratigraphy of unconsolidated Quaternary sediments, to locate areas with natural gas, and to provide information on shallow structures and rock types of the basement. The seismic data were acquired with a single-channel and a multichannel streamer to assess improvements and differences between seismic images resulting from the two acquisition geometries. In general, the single- and multichannel data display very similar regional geological information. The multichannel data locally provides additional details for some geological structures within the unconsolidated sediments and underlying bedrock.

Résumé : Pendant l'été de 2004, nous avons obtenu des données de sismique-réflexion haute résolution sur plus de 1150 km répartis en 28 profils dans l'estuaire du Saint-Laurent. Les principaux objectifs de ce levé étaient l'étude de la stratigraphie des sédiments meubles du Quaternaire, la localisation de zones renfermant du gaz naturel et la collecte d'information sur les structures à faible profondeur et la lithologie du socle. Les données sismiques ont été recueillies au moyen de flûtes sismiques monocanal et multicanal afin d'évaluer les améliorations et les différences entre les images sismiques obtenues en utilisant les deux géométries d'acquisition. En général, les données monocanal et les données multicanal fournissent des informations géologiques régionales très simiIaires. Par endroits, les données multicanal fournissent des précisions additionnelles pour certaines structures géologiques dans les sédiments meubles et le substratum rocheux sous-jacent.

INTRODUCTION

Shallow, high-resolution, marine seismic-reflection surveys are often conducted with single-channel streamers. Although high-resolution, 3-D multichannel acquisition systems have been developed (Mueller, 2005; Scheidhauer et al., 2005), single-channel 2-D data are still acquired because of their low cost and low postprocessing requirements. Two- or three-dimensional multichannel data usually improve the signal-to-noise ratio and the imaging of complex structures, but such data requires processing that increases the cost and delay accessibility to interpretable sections. Many recently published, shallow, high-resolution marine research results used only single-channel data or a combination of single- and multichannel data (Orange et al. 2005; Duck and Herbert, 2006; Karp et al., 2006), indicating that the benefit of multichannel data for this type of application remains questionable for many marine geoscientists. Here, the authors compare 2-D single-channel and multichannel data acquired with a low-energy seismic-reflection source in the St. Lawrence River estuary to assess improvements and differences between seismic images resulting from the two acquisition geometries.

The high-resolution marine seismic-reflection data were acquired in the St. Lawrence River estuary as part of the 'Appalachians' phase of the Targeted Geoscience Initiative (TGI-2). The main objectives of the survey were to study the stratigraphy of unconsolidated Quaternary sediments, to locate areas with free gas and to provide information on shallow structures and rock types of the basement. During the summer of 2004, the Geological Survey of Canada (GSC) and the Institut National de la Recherche Scientifique-Eau-Terre-Environnement (INRS-ETE) collected over 1150 km of single-channel and multichannel seismic-reflection data along 28 profiles (Fig. 1). Most of the profiles are perpendicular to the main northeast-southwest St. Lawrence River axis and intersect the Laurentian Channel where water depth reaches the 350 m isobath. Three longer profiles were also acquired parallel to the main river axis. Results from northwest-southeast lines 04C-5 (southeast of Forestville) and 04C-15 (northwest of Matane) are shown in this paper.

DATA ACQUISITION

The seismic lines were shot with a 2-8 kJ EG&G sparker that provided seismic-reflection images to maximum depths of approximately 200 m to 500 m of seismic-reflection data in the sediments and bedrock (M.J. Duchesne and B.F. Long, unpub. report, 2004). This depth range is sufficient to map the unconsolidated sediments in the Laurentian Channel and the top of underlying bedrock, but it is not adequate to image regional geological structures or deeper targets of potential interest to the oil and gas industry. In the St. Lawrence River, seismic-reflection surveys using a source generating pressure of less than 275.79 kPa at 1 m are not subject to environmental impact review. The pressure produced by the 8 kJ sparker at 1 m is 130 kPa, significantly less than the 275.79 kPa limit. Details about the EG&G sparker source are shown in Figure 2a.

Two separate streamers were towed 25 m behind the source located 25 m from the stern of the vessel (Fig. 2b). The single-channel streamer combines the signal of 23 hydrophones distributed over 12 m (M.J. Duchesne and B.F. Long, unpub. report, 2004). The multichannel streamer comprised 48 receivers separated by 5m and provided a

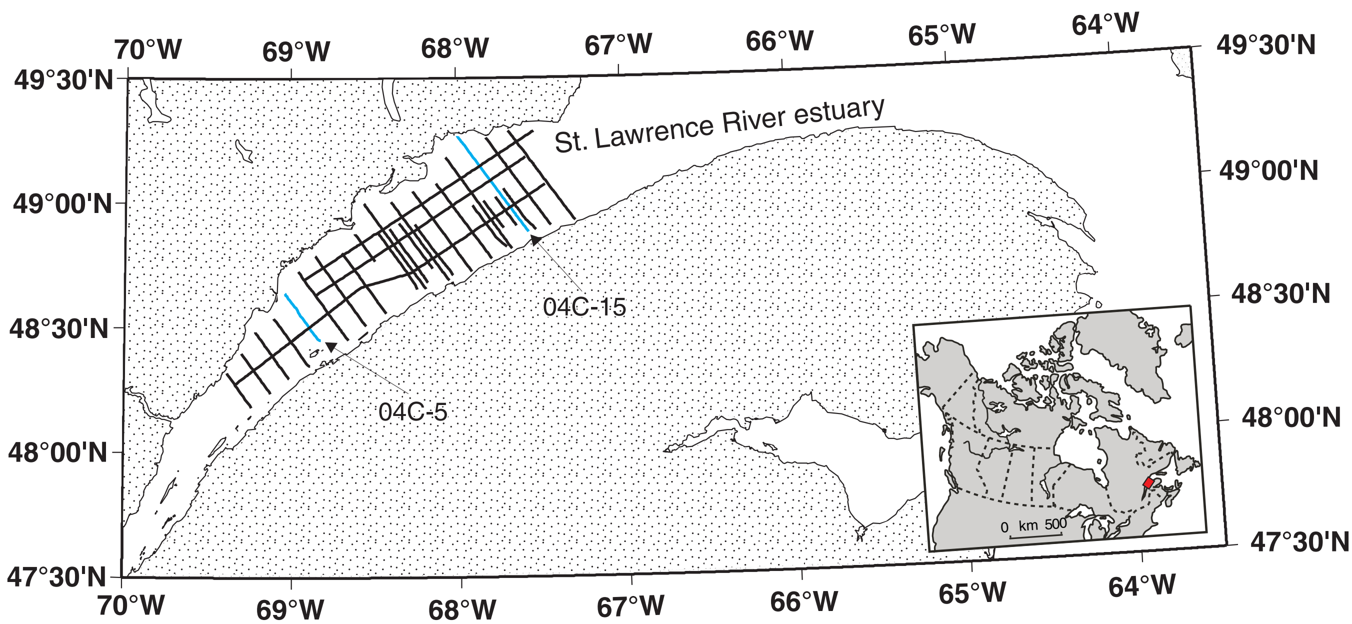

Figure 1. Location of the 2004 seismic profiles in the St. Lawrence River estuary. Data from profiles 04C-5 and 04C-15 are shown in this paper.

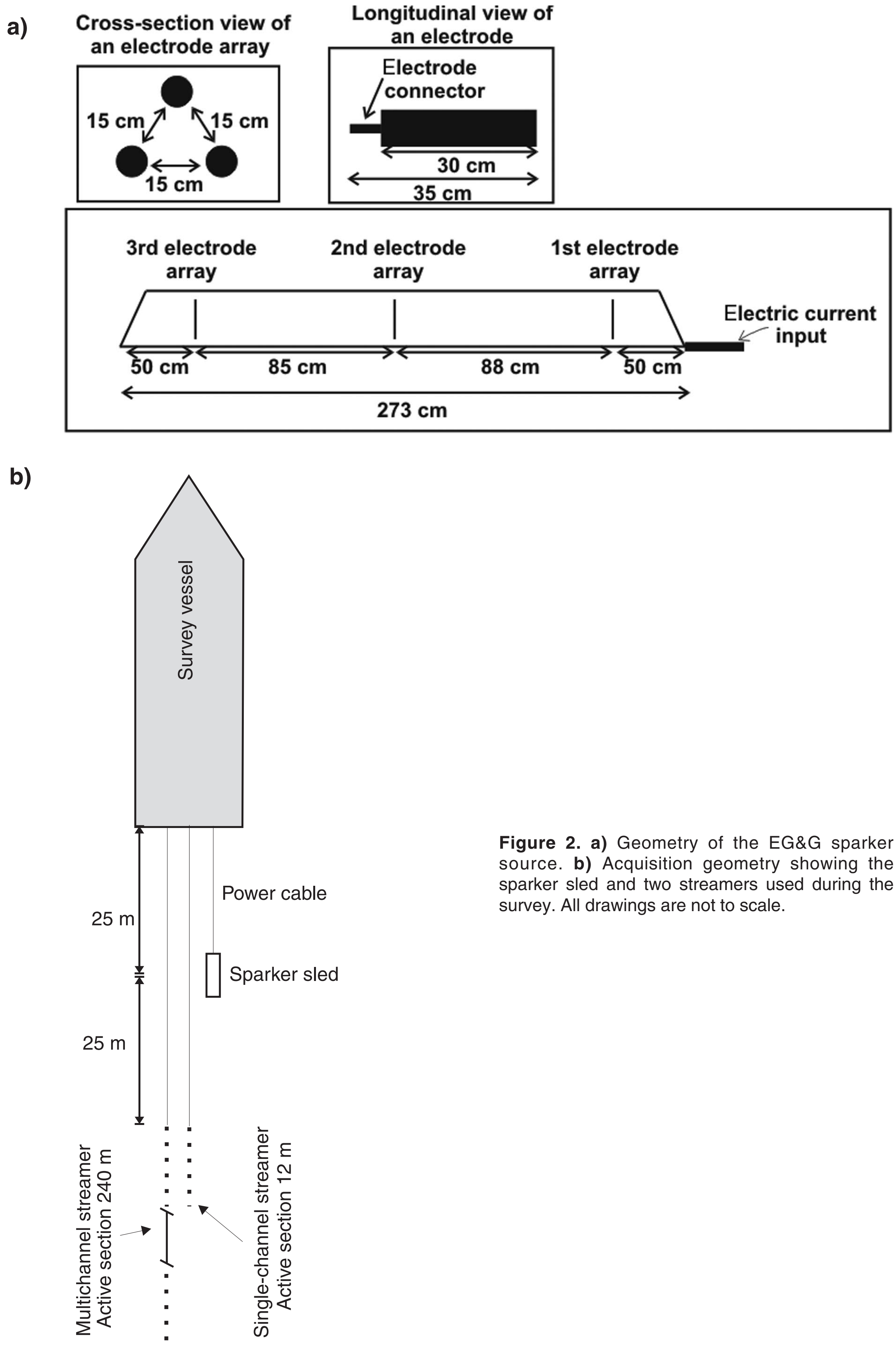

Figure 2. a) Geometry of the EG&G sparker source. **b)** Acquisition geometry showing the sparker sled and two streamers used during the survey. All drawings are not to scale.

maximum source-receiver offset of 260 m (Fig. 2b). The signals from the two streamers were recorded with different parameters on different seismographs. The monotrace data were sampled every 20 µs with a total record length of 1.250 s, whereas a sample rate of 250 µs with a record length of 1.8 s were used for the multichannel data. The shot spacing was controlled by time (every 4 s) and averages 10 m for all profiles. All positions were provided by Differential Global Positioning System.

An example of two shot gathers acquired with the multichannel system is shown on Figure 3. The sparker introduced well known secondary bubble pulses (Buogo and Cannelli, 2002) that complicate separation of reflections from closely spaced geological interfaces. A similar source signature is also observed on the single-channel data. Figure 4 shows a comparison of the amplitude spectrum for single- and multichannel field records from the northern part of line 04C-5. The sparker generated a broad spectrum with frequencies ranging from 30 Hz to 450 Hz, but characterized by multiple peaks and troughs. This reveals another complexity introduced by the sparker source. It is also important to note that the sparker source signature was not consistent throughout the survey due to the progressive, but systematic deterioration of the electrodes and lateral variations in the electrical conductivity of the water.

PROCESSING

Both single- and multichannel seismic-reflection data required processing. Some processing steps were common or similar for both acquisition geometries. These steps included source signature deconvolution, band-pass filtering, data gaining, and migration. Other processing steps were required for the multichannel data. Table 1 shows the simplified processing sequences used for single- and multichannel data. Most of the processing effort was directed towards the attenuation of the strong secondary pulse produced by the sparker. Without this, the processing of the multichannel data could have been done in a timely and cost-effective manner. A modern seismic source such as the double-chamber GI air gun should be considered in future surveys to minimize any source-related problems.

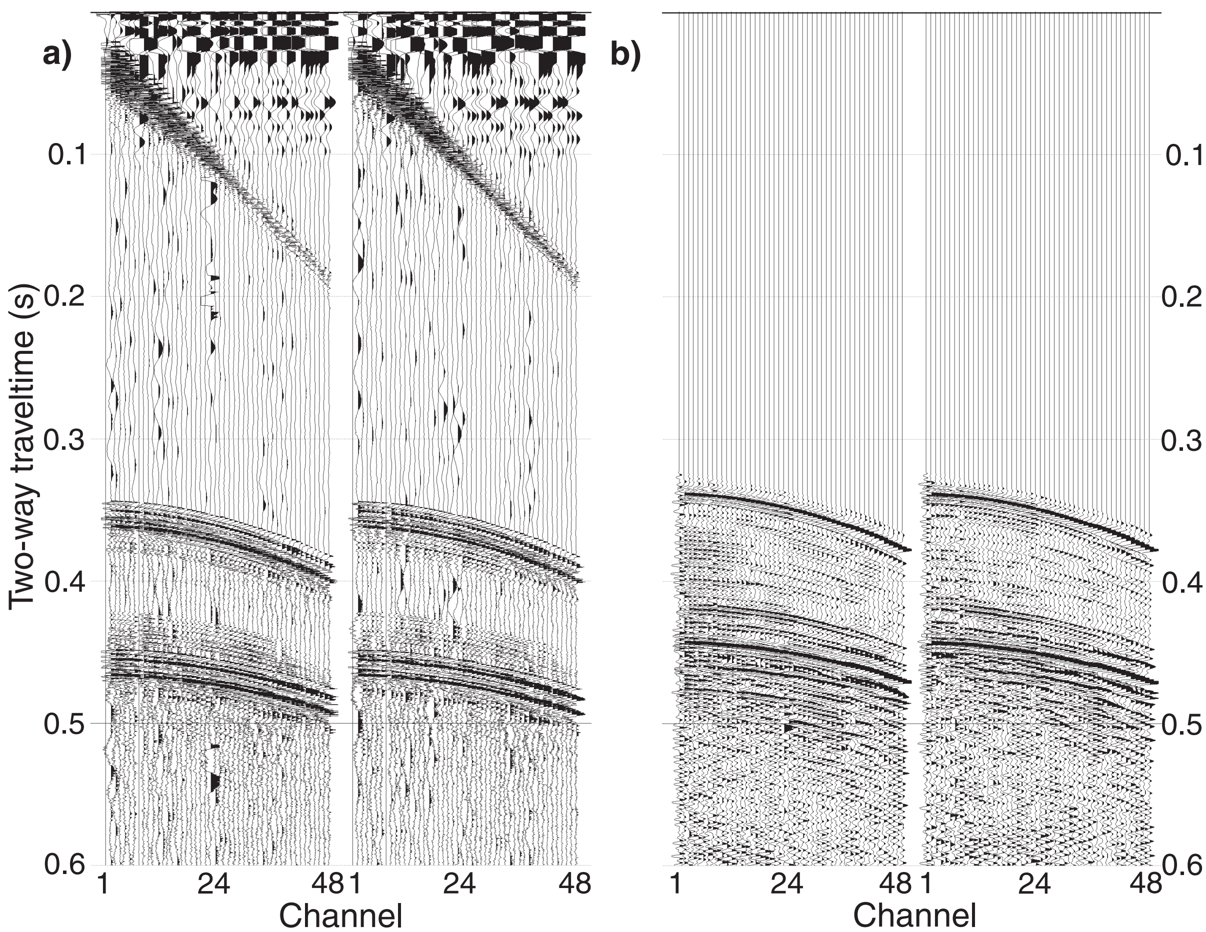

Figure 3. a) Two raw field gathers from the multichannel data (line 04C-15). **b)** The same gathers after source deconvolution, bandpass filtering, and gaining (AGC). The water-bottom reflections near 0.35 s are sharper after processing.

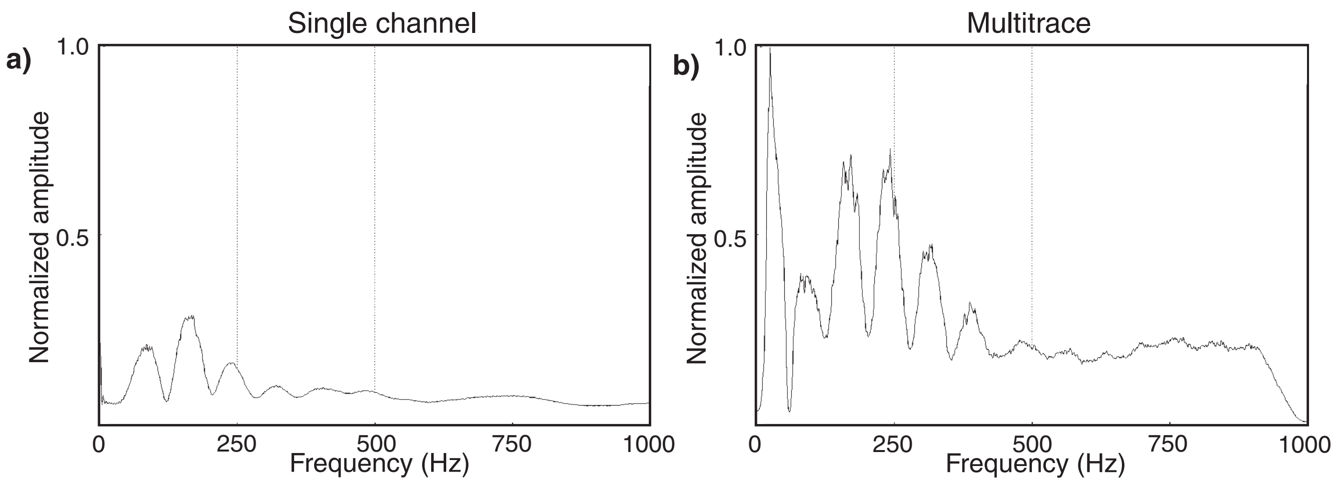

Figure 4. **a)** Normalized amplitude spectrum for the single-channel data from line 04C-5. **b)** Normalized amplitude spectrum for the same profile for the third channel of the multichannel data. Both data are characterized by strong amplitudes at very low frequencies which explain the general amplitude level difference between a) and b). The strong amplitude for the single-channel is located close to DC component. In both cases, the low frequencies were removed with a bandpass filter. The spectra are characterized by multiple peaks and troughs, showing a real complexity introduced by the sparker source.

Table 1. Simplified processing parameters used for the single- and multichannel data.

Single channel	Multichannel
Mute above water-bottom reflection	Geometry
Spherical divergence corrections (1500 m/s)	Amplitude trace balancing (1000 ms window)
Ormsby band-pass filter (30-60-330-380 Hz)	Matched-filter to minimum phase (operator 80 ms)
Trace-by-trace deconvolution operator design (operator 40 ms)	Spiking deconvolution (operator 80 ms)
Predictive decon (operator length 1000 ms)	Butterworth band-pass filter (35-60-330-380 Hz)
TV spectrum balancing Bandwidth: 30 Hz Slope: 50 Hz Maximum frequency: 380 Hz	Mute above water-bottom reflection
	Spectral balancing (30 Hz window)
Automatic gain control C- 500 ms window (output shown in Fig. 8)	Automatic gain control (250 ms window)
	Common-depth-point sorting
	Normal moveout
	Stack (output shown in Fig. 8)
Fk-migration with 1520 m/s (output shown in Fig. 7)	*Fk*-migration with 1520 m/s (output shown in Fig. 7)

Attenuation of sparker signature

Marine deconvolution processes assume some consistency in the source wave form and usually produce better results when the source signature is minimum phase (Yilmaz, 2001). Unfortunately, the sparker does not produce such a minimum phase signal (Allessandrini and Gasperini, 1989). Hence, the application of two filters was required to efficiently attenuate the strong sparker bubble pulse (Fig. 5a). Similar approaches, but different tools were used for the single- and multichannel data.

For the multichannel data, the first filter transformed the source signal to a minimum phase equivalent wavelet (Fig. 5b). This filter reduced the amplitude of the bubble pulse and made the phase of the wavelet suitable for subsequent Weiner filtering. A spiking deconvolution was then applied to the minimum phase wavelet to efficiently attenuate the secondary pulse (Fig. 5c). The sparker source signature was removed from the single-channel data by applying a traceby-trace spiking deconvolution algorithm initially designed for vertical seismic profiles that also permitted elimination of problems associated with the poor shot-to-shot repeatability of the source. Both approaches produced satisfactory results.

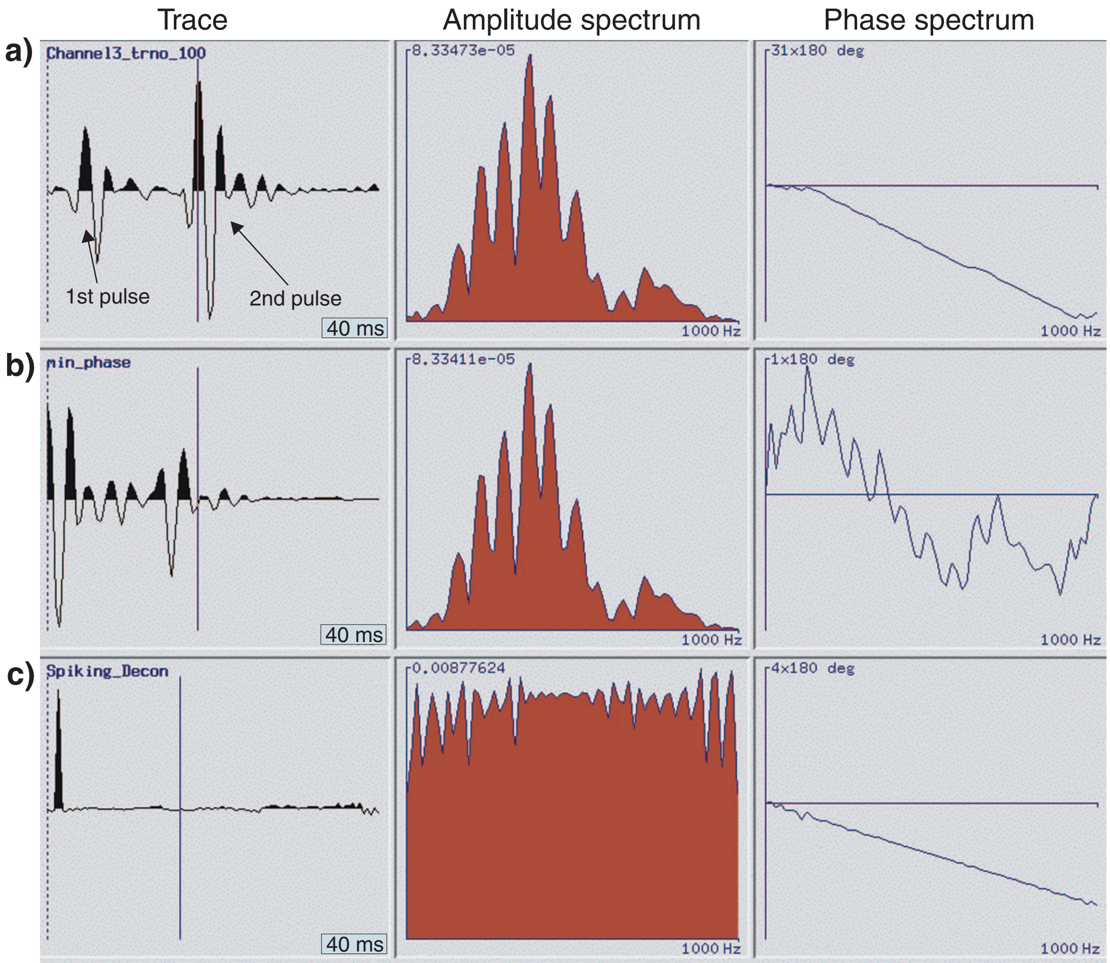

Figure 5. a) The water-bottom reflection observed on one trace of the multichannel data. The sparker bubble pulse (second event) is stronger the initial energy pulse. **b)** The same trace after conversion to a minimum phase and **c)** results after spiking deconvolution.

The deconvolution filters were designed on the water-bottom reflection in a 40 ms window that included both primary and secondary pulses. The authors choose to design the filters on the water-bottom reflection because this event is clear on all channels from all shot points. The direct arrivals do not display such consistency. A disadvantage of this approach is that it will tend to homogenize the water-bottom reflections throughout the profile and will attenuate effects related to natural variations in composition and compaction of the sediments at the bottom of the St. Lawrence River estuary. On the other hand, consistency of seismic-reflection wave form is required for an efficient stacking of the multichannel data.

For the multichannel data, the source deconvolution process was followed with a bandpass filter and the application of an automatic gain control (AGC). Figure 3b shows two shot gathers before and after the application of these three steps, whereas Figure 6 shows a similar comparison for traces recorded on a common hydrophone from the multichannel streamer (channel 3).

Multichannel processing

The multichannel data processing also included geometry, CDP (common depth point) gathering, velocity analysis, normal moveout corrections, and migration. A spacing of 10 m was used between CDPs. This provides final trace spacing similar to the average single-channel spatial sampling, but with an average fold of 50. Velocity analysis was critical to improve images from the top of the bedrock and deeper structures. The stacking velocities for water, unconsolidated sediments, and top of bedrock reflections ranged between 1485 m/s to 1600 m/s. This limited velocity range indicates that depths or bed thicknesses could be approximately determined without significant distortion with a constant velocity of 1520 m/s. The deeper bedrock structures sparsely distributed on the profiles have stacking velocity ranging from 1600 m/s to 2025 m/s. The constant velocity approximation would provide inaccurate time-to-depth conversion for these structures.

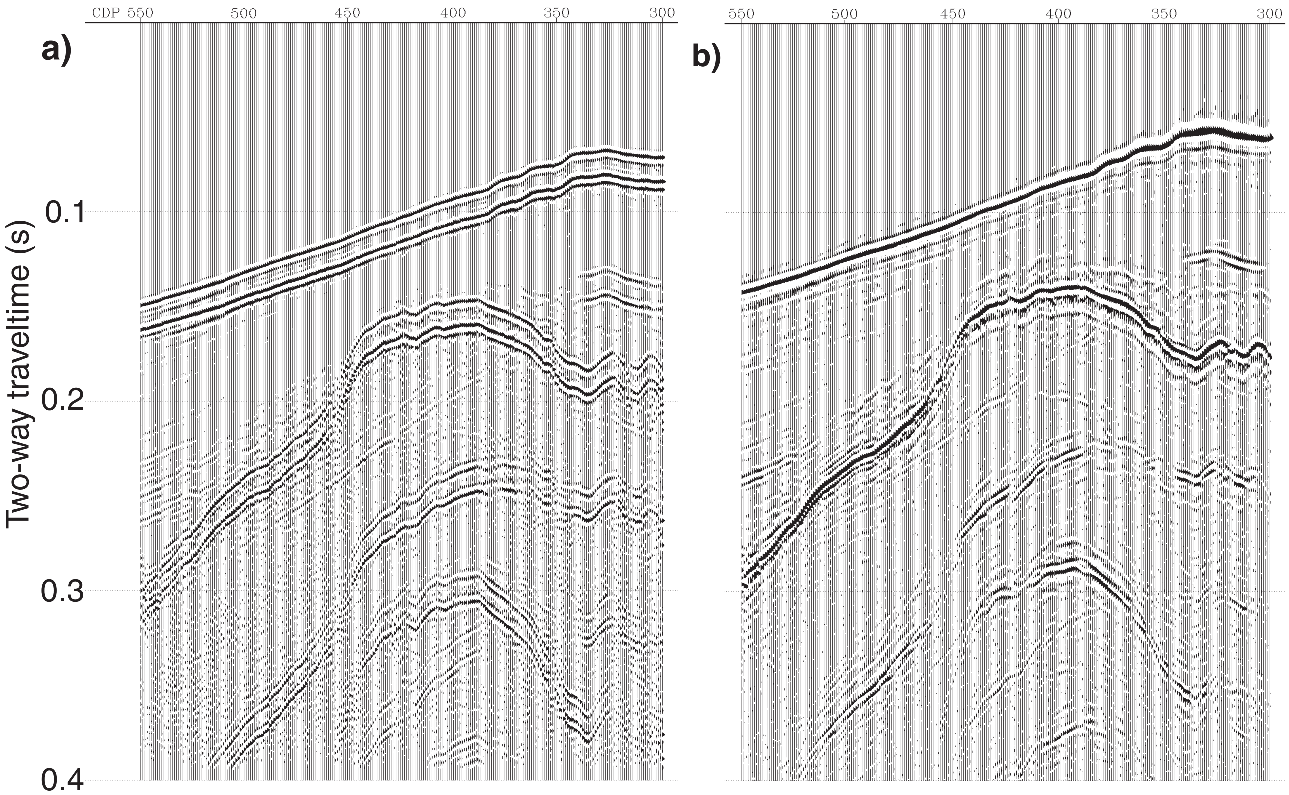

Figure 6. Comparison of a part of a single-channel from line 04C-5 **a)** before and **b)** after source signature deconvolution.

The stacked section (part of it is shown in Fig. 8) reveals numerous diffractions within the unconsolidated sediments and bedrock, indicating that migration of the data is required. A constant velocity *Fk*-migration (1520 m/s) was used to produce the final section shown in Figure 7. The migrated single-channel section is also shown on this figure for comparison purposes. The main difference between the two sections is the stronger signal-to-noise ratio of the multichannel data. At this regional scale, both sections mostly display the same geological features. Some discrepancies are revealed by showing a subset of the data (a subset of the stacked sections is shown in Fig. 8). The multichannel section provides some additional details in the bedrock not well imaged with the single-channel data.

Both migrated sections in Figure 7 are also characterized by strong water-bottom and peg-leg multiples. There were no serious attempts to remove or attenuate the multiples observed in the shallow parts of the single- and multichannel profiles. The higher velocity used to stack bedrock reflections locally helped to attenuate the first water-bottom multiple on the multichannel data; however, the limited source-receiver offsets provided by the survey configuration (maximum of 260 m) combined to the limited velocity contrast between water and top of basement rocks makes them a difficult processing challenge. Predictive deconvolution was applied with some success to the single-channel data. The multiple reflections only overprint primary reflections in the shallow-water areas of the survey, whereas the main target reflections beneath the Laurentian Channel (two-way traveltime of the water-bottom reflection ~ 400 ms) are not affected by this problem.

MAIN RESULTS

Several other single-channel high-resolution seismic profiles were previously acquired in the St. Lawrence River estuary to determine the different seismostratigraphic units of the Quaternary marine sediments (Massé, 2001; Tremblay et al., 2003). These surveys allowed the determination of up to seven units of irregular thicknesses for the Quaternary sediments (Massé, 2001). Most of these units are also observed on the 2004 profiles that fill gaps between profiles from previous programs and allow a pseudo-3-D analysis of the sediment distribution in the estuary.

The seafloor and basement topography produced prominent reflections on the single- and multichannel data from line 04C-15 (Fig. 7). Reflections from the bedrock reveal complex topography especially at both extremities of this profile where they likely originate from the continuation of geological units located onshore. The bedrock reflections on

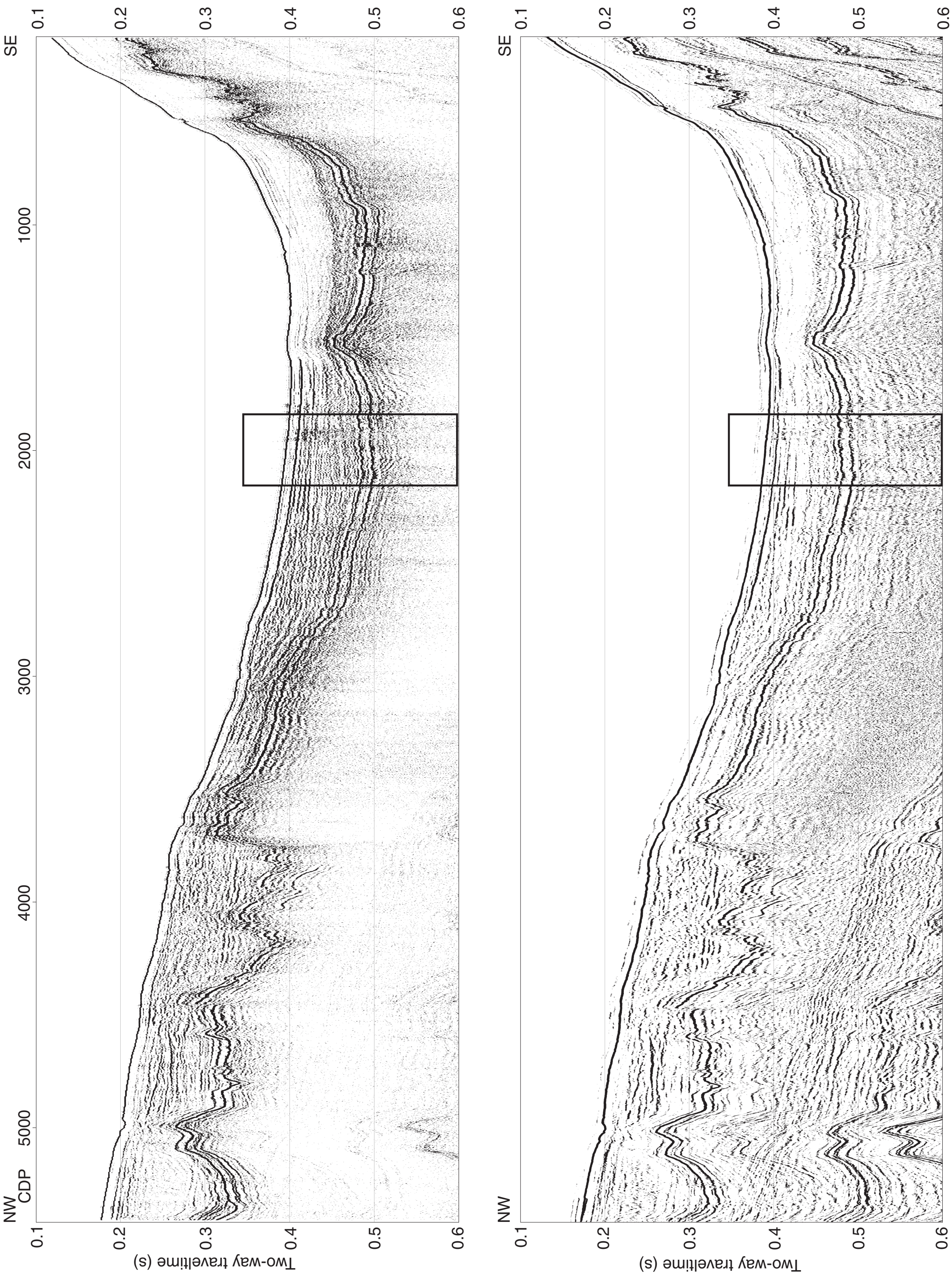

Figure 7. Comparison of single-channel (top) and multichannel data (bottom) from line 04C-15 after processing. The rectangles show the location of seismic data presented in Figure 8. The main difference between the two sections is the stronger signal-to-noise ratio of the multichannel data. The length of the profiles is approximately 50 km. CDP = common depth point.

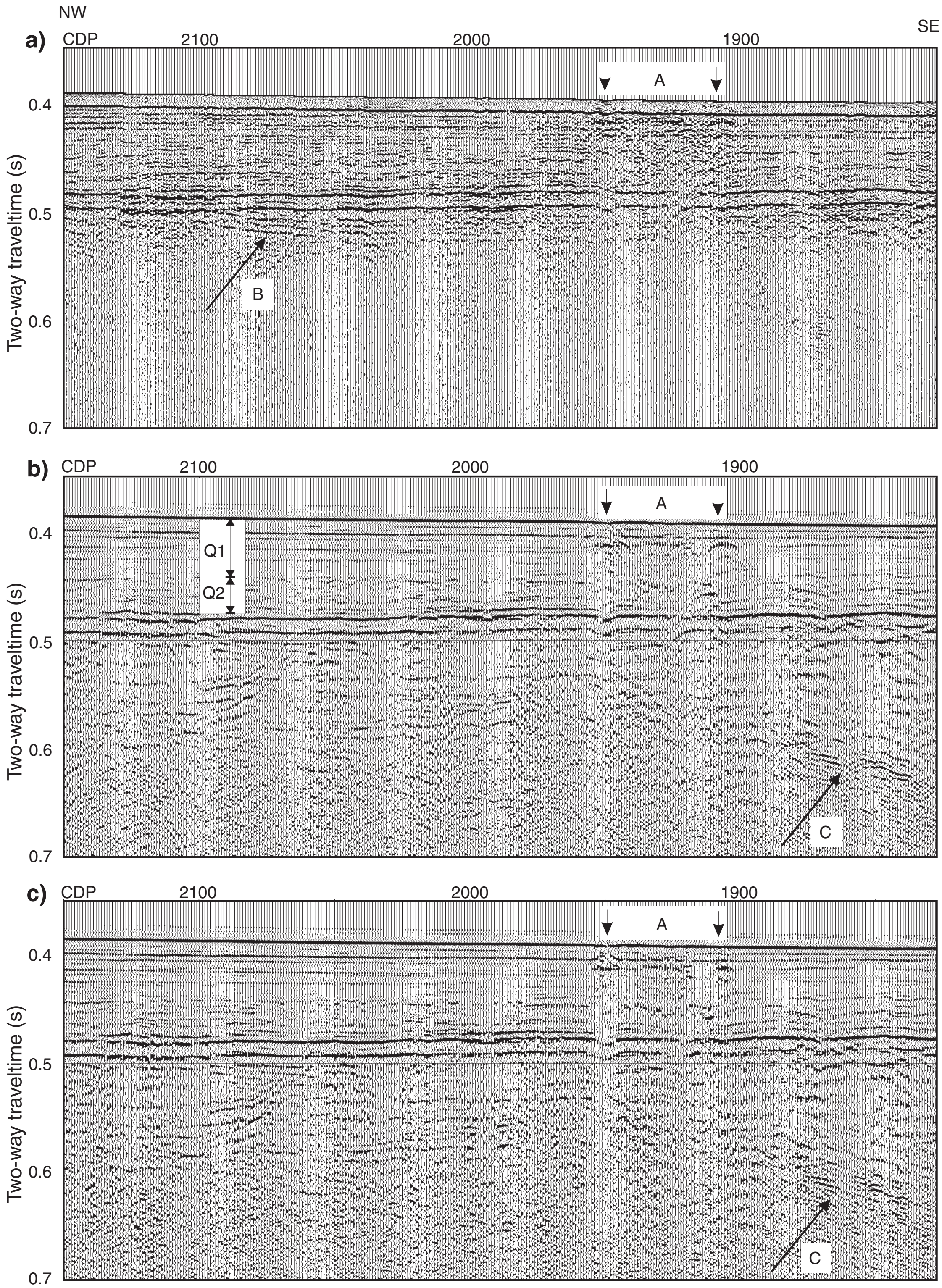

Figure 8. Comparison of single-channel data **a)** before migration, **b)** stacked multichannel data, and **c)** migrated multichannel data. Arrows A show events possibly related to free gas. The diffraction hyperbola beneath the water-bottom reflections and velocity pull-downs on the basement reflections suggest free gas trapped in the unconsolidated sediments. Arrow B points to shallowly dipping reflections on the single-channel data. These reflections do not appear on the stacked and migrated multichannel data. This is explained by the higher velocity used to stack the multichannel data. Arrow C indicates deeper basement reflections not well defined on the single-channel data. CDP = common depth point.

the northeast part of the profile correspond to Grenvillian metamorphic rocks found on the north shore (Tremblay et al., 2003). Similarly, the Applachian units mapped in Gaspésie likely produce the bedrock reflections on the southwest part of the section. Tremblay et al. (2003) speculated that basement rocks in the Laurentian Channel consist of St. Lawrence Lowlands or Appalachian rocks unconformably overlying rocks from the Grenville Province. Unfortunately, neither the single- or multichannel data from lines 04C-5 (not shown) and 04C-15 provide enough information at depth to confirm this hypothesis.

Other reflections are also observed within the unconsolidated Quaternary sediments and locally from shallow structures in the bedrock. The Quaternary sediments are relatively thin in this area of the St. Lawrence River and can be divided into two different units (Q1 and Q2 on Fig. 8b). The lower unit is characterized by discontinuous reflectivity and numerous diffraction hyperbolae on the stacked section. Reflections in the upper unit are more continuous. Diffractions possibly related to escaping gas are also locally observed in the upper sediments (Fig. 8). The pull-down of bedrock reflections underneath the diffractions suggest that the latter may result from highly reflective, low-velocity gas pockets trapped within the sediments. The diffractions just beneath the water-bottom reflection are not as well defined on the single-channel data; however, the single-channel data shows a chaotic pattern crosscutting reflections on either side that suggest the presence of a gas chimney. It is not clear if the gas originates from organic-rich sedimentary deposits or it migrated from petroleum occurrences in the basement.

Figure 8 also shows deeper structure in the bedrock (event C). The single-channel data shows hints of higher seismic amplitudes, whereas this reflection is well defined on the multichannel data. The origin of this reflection is still unexplained.

SUMMARY

The single-channel data offer a rapid and accurate image of the sedimentary sequence in the St. Lawrence River estuary. It comprises most of the information present in the multichannel section, but with a notably lower signal-to-noise ratio. The multichannel data provide clearer details for some geological structures within the unconsolidated sediments and underlying bedrock. Diffractions within the shallow unconsolidated sediments and low-velocity pull-down of the bedrock reflections, two signatures potentially produced by natural gas, are clearly observed on the multichannel stacked section. The higher signal-to-noise ratio of the multichannel data also helps to improve confidence in the interpretation of the seismic section. Future work should include a detailed pseudo-3-D interpretation of the 2-D marine profiles of the St. Lawrence River estuary.

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