GEOPHYSICS, VOL. 73, NO. 6 (NOVEMBER-DECEMBER 2008); P. Q59–Q63, 6 FIGS., 1 TABLE.
10.1190/1.2976117

# Optimal seismic-data acquisition in very shallow waters: Surveys in the Venice lagoon

Luca Baradello[1] and José M. Carcione[1]

## ABSTRACT

Acquiring large amounts of data in very shallow waters of the immediate subtidal zone using a multichannel technique is unaffordable because moveout correction and a standard stacking procedure are required. The conventional inline longitudinal deployment of source and streamer leads to a phase difference along the hydrophone array for nonvertical arrivals. The array in this system is hard wired, so these phase differences cannot be accounted for and the summed output is attenuated as a result. We propose a transverse configuration, whereby the variation in phase along the array is smaller. The summed output improves because pairs of hydrophones with equivalent absolute offset are stacked in phase as a result of the symmetric configuration; however, all of the hydrophones are out of phase in the conventional geometry. Even at depths of 40 m, a better image is obtained. The technique has been used during surveys in the Venice lagoon, where the water depth ranges from 40 cm to 2 m.

## INTRODUCTION

Seismic data acquisition in exceptionally shallow waters is very sensitive to several factors, especially source-receiver configuration. Usually, the conventional acquisition geometry (streamer towed behind a source) generates poor results when using a single-channel streamer with a multihydrophone hard-wired group. This is because the streamer can be much longer than the dominant wavelength, a condition that implies large phase differences between the elements of the receiver array (e.g., McGee, 1995).

We acquired high-resolution seismic data from geologic mapping of the Venice lagoon and a study of the sedimentary structures of Alpine Italian lakes. In many cases, very shallow waters are present. The surveys used a boomer source, chosen for its short pulse, good repeatability, and directivity (e.g., Verbeek and McGee, 1995). The acquisition system consisted of a power-supply unit connected to an electrodynamic transducer (Figure 1a). The source consisted of a plate mounted on a catamaran frame, suspended at a constant depth of $z_s = 10$ cm to reduce dragging turbulence (Figure 1b). Besides the boomer, other sources can be used as high-resolution acoustic subbottom profilers (pinger, sparker, chirp), which generally are utilized within the marine surveying community for Quaternary geologic studies.

The signals were acquired by a multihydrophone (MH) streamer whose active section (2.8 m) consisted of eight equidistant piezoelectric elements housed in an oil-filled tube (Figure 1c). The frequency bandwidth was 0.4–9 kHz; therefore, the streamer length was about 17 wavelengths long at the top of the band of interest and 0.8 wavelengths at the bottom. To avoid destructive interference between reflected signals and multiple events from the air/water interface, suitable floaters kept the streamer as shallow as possible. However, the source ghost was located inside the frequency band.

The source ghost is the energy pulse that travels upward from the gun. It is reflected from the sea surface with a reversal in polarity. This ghost will interfere destructively at a particular frequency that depends on the depth from the source to the sea surface. That frequency is given by $f = v/(2z_s)$, where $v$ is the water sound velocity. This gives a notch frequency of nearly 7.5 kHz. Note that the dominant frequency of the seismograms is approximately 5 kHz. These characteristics, under favorable conditions, permit decimetric-scale resolution. Another alternative to the MH streamer is to use a single hydrophone, but generally it has poor signal-to-noise ratio (S/N).

In conventional acquisition geometry, the streamer is towed behind the plate with a longitudinal offset. The pulse has a very short wavelength, and most of the surveys involve water depths between 40 and 100 cm; thus, the single hydrophones of the MH streamer collect data in a destructive phase because the signals cannot be summed by applying NMO correction. To overcome this problem, we propose a transverse geometry that can collect more coherent events as a result of the minimum NMO traveltimes.

Our method was tested by generating synthetic seismograms and was later applied to surveys in the Venice lagoon. The seismograms

Manuscript received by the Editor 21 March 2008Manuscript received by the Editor 3 June 2008; published online 15 October 2008.
[1]Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy. E-mail: lbaradello@ogs.trieste.it; jcarcione@ogs.trieste.it.
© 2008 Society of Exploration Geophysicists. All rights reserved.

showed remarkable improvement in the coherence and S/N of the reflection events. Plets et al. (2007) used a similar acquisition configuration for shallow waters (<5 m). In their study, a marine survey was conducted using a square quadratic array of four baffled chirp transducers and a single-channel receiver array consisting of a group of eight hydrophone elements placed at the side of the transducers. The analysis performed in our paper can also be applied to the system of Plet et al..

## ACQUISITION GEOMETRIES

The conventional (longitudinal) and transverse geometries are shown in Figure 2. Figure 2a and b represents horizontal plan views, Figure 2c represents a vertical section, and Figure 2d represents a perspective view of the second geometry, where $o$ is the near offset, $h$ is the water depth, and $o + x$ is the offset, i.e., the distance between the source and a given receiver. The near offset during the acquisition was $o = 1.5$ m, and the length of the streamer was 2.8 m. As indicated in Figure 2, $x$ ranged from 0 to 2.8 m in the longitudinal geometry and from $-1.4$ to 1.4 m in the transverse geometry. The nearest and farthest receivers were located at 1.5 and 4.3 m, respectively, in the first case and at 1.5 and 2.05 m in the second case. The data were acquired simultaneously, with the source located at the same position for both configurations, according to the relative distance described above. The model described below uses the same parameters.

The vessel moved at a given velocity (usually 3.6–5.4 km/h) along the direction of the streamer. The dashed line indicates the optimal geometry (Figure 2b), which is a circle of radius $o$ with its center in the source. In this case, the signal arrived at all of the hydrophones of the streamer in-phase. The raypath was equal to $\sqrt{o^2 + 4h^2}$ for all of the receivers. However, this geometry was impractical because of the turbulence generated by the motion of the vessel on the streamer.

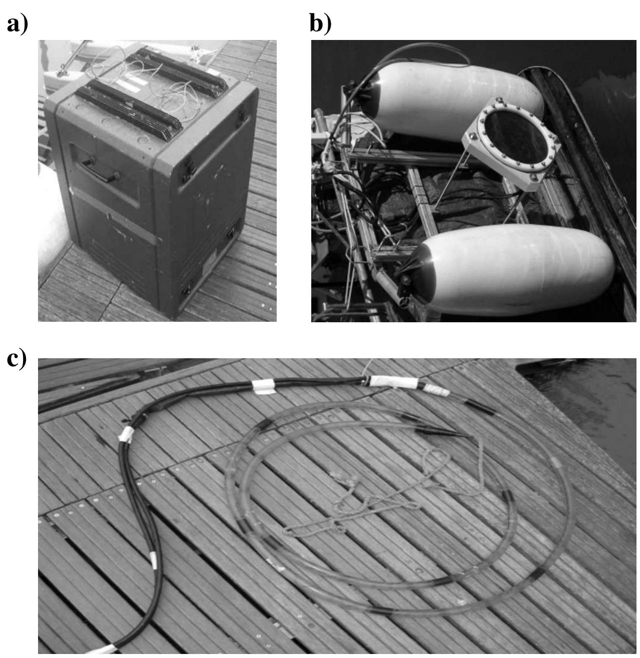


Figure 1. High-resolution seismic system composed of (a) Pulsar 2002 (power unit), (b) UWAK05 (source), and (c) EG&G streamer, consisting of a single-channel multihydrophone group.

In the transverse case, pairs of hydrophones with equivalent absolute offset were stacked in-phase on account of the symmetric configuration, and all of the hydrophones were out-of-phase in the conventional geometry. If the layers were planar and parallel to the lagoon bottom, as is usually the case in very shallow waters, the transverse geometry would be optimal for data acquisition. The turbulence noise was minimal because the streamer was straight and in both cases was in line with the towing direction.

There are arguments against longitudinal acquisition systems. McGee (1995) claims that for a longitudinal geometry in very shallow waters, all of the elements of the streamer array are approximately in-phase under the condition $L \ll 2\sqrt{h\lambda}$, where $L$ is the length of the streamer, $\lambda = v/f$ is the wavelength, $v$ is the sound velocity of water, and $f$ is frequency. For parameters typical in the Venice lagoon, such as $h = 1.5$ m, $f = 5$ kHz, and $v = 1500$ m/s, we have $2\sqrt{h\lambda} = 1.34$ m, a condition that is not fulfilled for the 2.8-m-long streamer. Despite this, the transverse geometry greatly improves the stack by reducing phase differences.

To study the problem quantitatively, it is appropriate for this type of environment to consider the layer-cake model (Brouwer and Helbig, 1998) to obtain the traveltime as a function of offset for an interface below the bottom of the sea. The model consists of a stack of $n$ homogeneous plane layers of arbitrary thickness. Taking Figure 3 as

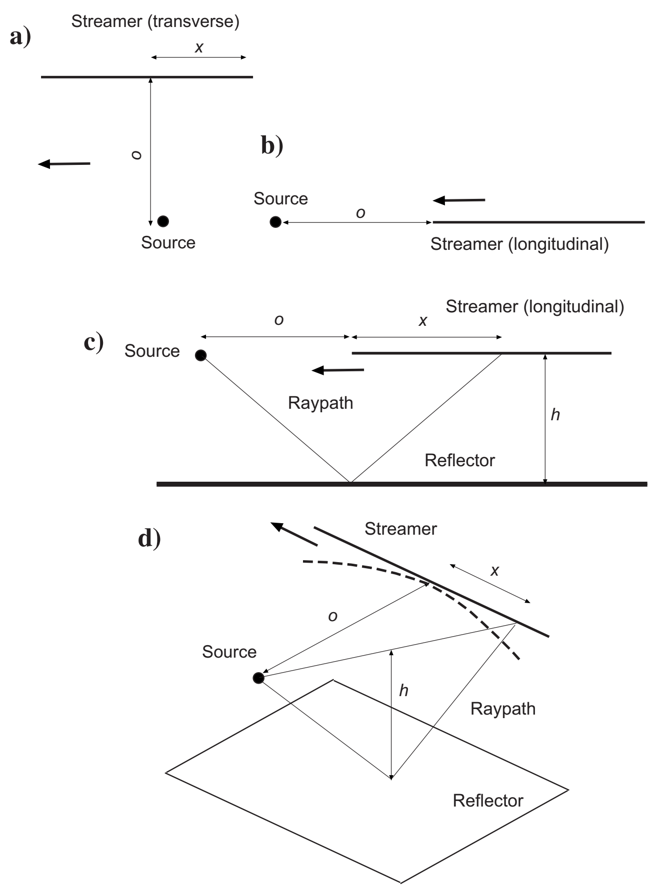


Figure 2. Conventional (longitudinal) and transverse acquisition geometries, where (a) and (b) represent plan views, (c) is a vertical section, and (d) is a perspective view of the second geometry. The dashed line is the optimal geometry, corresponding to a circle of radius $o$ centered at the source. The arrow indicates the towing direction. Source and streamer move together.

a reference, corresponding to $n = 3$ for clarity, the exact offset and two-way traveltime of the reflection event coming from the $n$th interface are

$$X_n = 2p \sum_{i=1}^{n} \frac{v_i h_i}{\sqrt{1 - p^2 v_i^2}} \quad (1)$$

and

$$T_n = 2 \sum_{i=1}^{n} \frac{h_i}{v_i \sqrt{1 - p^2 v_i^2}}, \quad (2)$$

where

$$p = \frac{\sin \theta_1}{v} = \frac{\sin \theta_i}{v_i} \quad (3)$$

is the ray parameter, which is a constant, and $v_1 = v$. We have $X_n = o + x_n$ for the longitudinal case and $X_n = \sqrt{o^2 + x_n^2}$ for the transverse case.

For $n = 1$, we obtain the equations for the lagoon bottom. The two-way traveltime curves for the longitudinal and transverse cases are given by

$$T = \frac{1}{v} \sqrt{(o + x)^2 + 4h^2} \quad (4)$$

and

$$T = \frac{1}{v} \sqrt{o^2 + x^2 + 4h^2}, \quad (5)$$

respectively, where in equation 5 the distance $x$ is taken from the center receiver.

We consider the layered model (velocity and thickness) shown in Table 1 to obtain the traveltime and amplitude of the reflection events corresponding to layer 5 (15-m depth) and layer 7 (41-m depth). This velocity profile is typical of very shallow environments, where muddy sediments have a lower velocity than water because of their higher density (e.g., Carcione and Poletto, 2000). Figure 4 shows the traveltime $T$ as a function of $x_n$ for the two configurations. As can be seen, the transverse geometry in Figure 2b has much smaller NMO times than the conventional geometry, and pairs of hydrophones with equivalent offset are stacked in-phase. The phase differences between the two configurations are smaller for layer 7.

Let us consider a Ricker wavelet with a central frequency of 5 kHz and perform a stack of the eight hydrophone traces of the streamer. The propagation effects are approximately the same for both geometries because the reflection and transmission coefficients and phase angles are an almost constant function of $\theta$ for the small

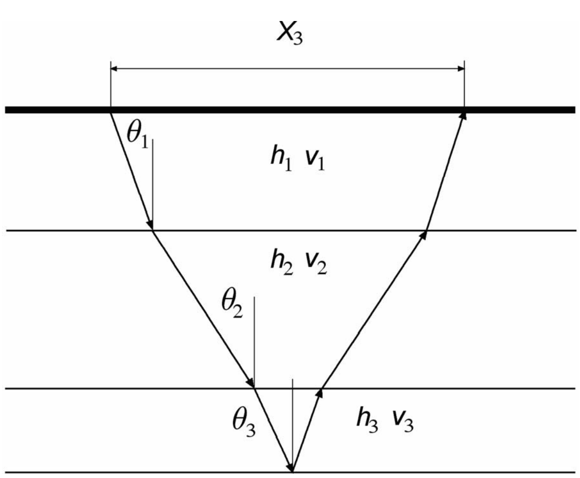


Figure 3. Layer-cake model used to compute the traveltime curves corresponding to the longitudinal and transverse geometries.

**Table 1. Layer-cake model.**

| Layer | $v$ (km/s) | $h$ (m) | Depth of base (m) |
|---|---|---|---|
| 1 | 1.5 | 1.5 | 1.5 |
| 2 | 1.2 | 2.0 | 3.5 |
| 3 | 1.3 | 3.0 | 6.5 |
| 4 | 1.5 | 3.0 | 9.5 |
| 5 | 1.6 | 5.5 | 15.0 |
| 6 | 1.7 | 15.0 | 30.0 |
| 7 | 1.8 | 11.0 | 41.0 |

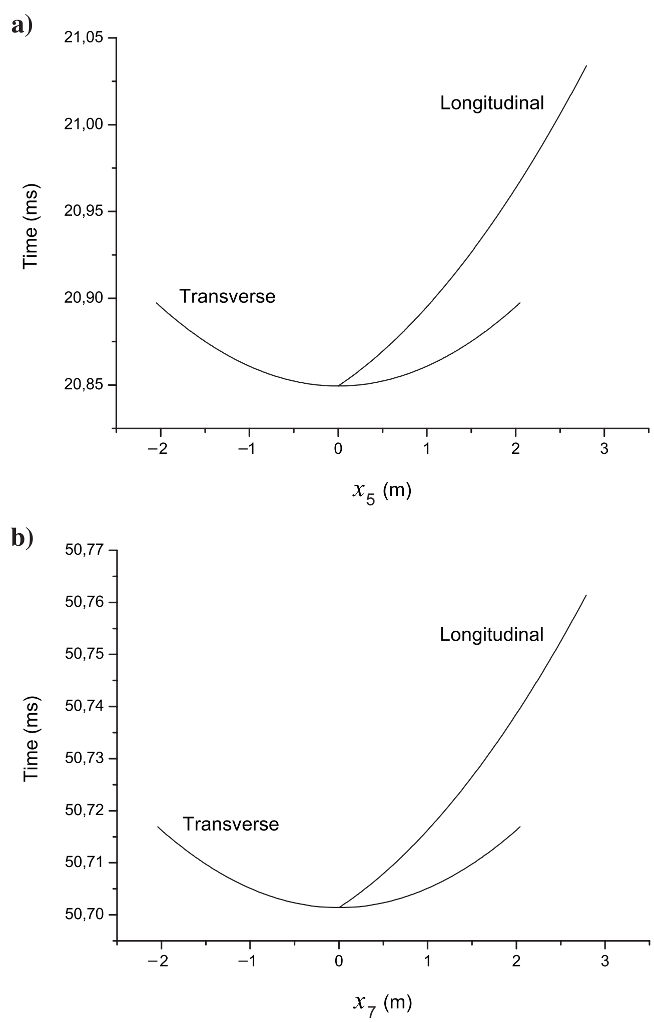


Figure 4. Traveltimes of (a) layer 5 and (b) layer 7 (see Table 1) as a function of $x_n$. The water depth is 1.5 m, the near offset is 1.5 m, and the streamer length is 2.8 m.

velocity contrasts reported in Table 1. Each single trace is corrected for geometric spreading by the factor $T_1/T_i$, $i = 1, \ldots, 8$, where $T_1$ is the two-way traveltime of the nearest hydrophone.

The stacked signals are displayed in Figure 5, where the dashed line corresponds to the longitudinal geometry. The maximum NMO time (relative to the nearest receiver to the source) decreases for increasing depth, from 0.2 ms (Figure 5a) to 0.066 ms (Figure 5b). The amplitude of the deep reflection ($T_1 = 50.70$ ms) is affected little by the phase differences. On the other hand, the shallow event ($T_1 = 20.84$ ms) is stacked much better with the transverse geometry. Although the deep layer (41 m depth) has a traveltime of 50 ms, there is still an improvement; this explains why the method works for deep layers. Even if there are small NMO differences, the transverse geometry provides better images.

One could argue that the velocity reversal in the model shown in Table 1 is responsible for the improvement when using transverse geometry. The reasoning can be that a significant part of the raypath goes through the material with velocity lower than that of water. This results in a low apparent velocity in the water layer, a short apparent wavelength, and therefore a large array effect. This would not happen with a normal velocity profile.

To investigate this, we considered a profile where the velocity increased monotonically with depth. The traveltimes were approximately similar to those shown in Figure 4, and the respective stacks showed similar differences between the amplitudes obtained with the transverse and longitudinal configurations. The shallow reflector had a maximum amplitude 3.5 times stronger in the first case, as in the case of the model in Table 1 (see Figure 5a). Hence, transverse geometry was equally effective when the velocity profile increased monotonically.

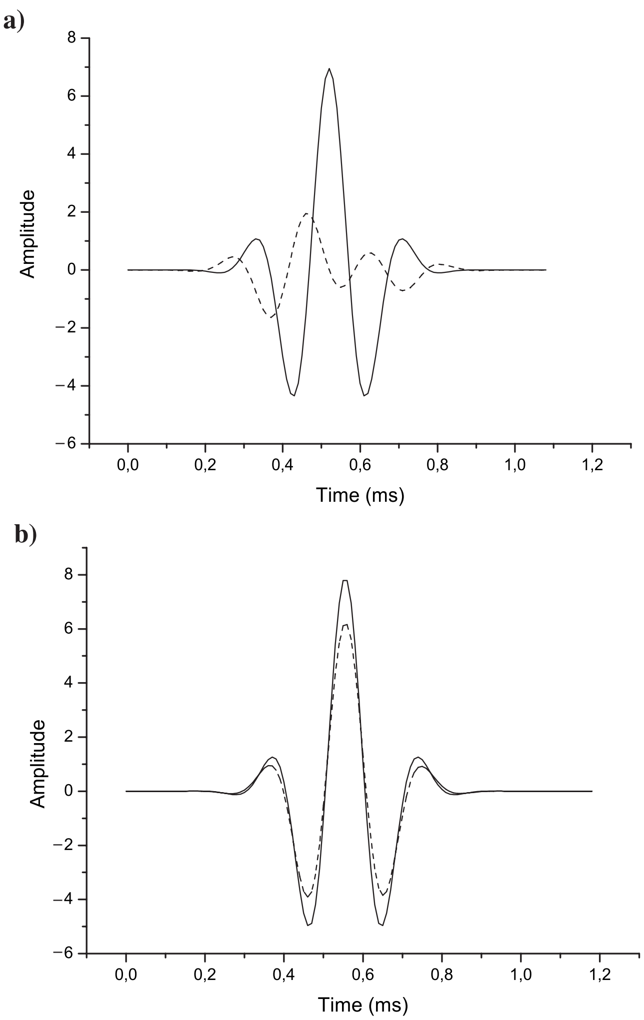


Figure 5. Stacked signal received by the eight hydrophones of the streamer, where (a) refers to layer 5 and (b) to layer 7 (see Table 1). The dashed line corresponds to the longitudinal geometry. The time is relative to that of the nearest receiver, i.e., 20.84 ms for layer 5 and 50.70 ms for layer 7.

## SEISMIC ACQUISITION IN THE VENICE LAGOON

We tested the transverse configuration in the Venice lagoon. Nearly 100 km of high-resolution profiles have been acquired outside the navigation channels in the southern part of the lagoon. The seismic data were processed with a conventional sequence: The spherical divergence was removed and a time-variant band-pass filter was applied. In several profiles, the direct wave degraded the reflections. We removed this effect in both the longitudinal and transverse geometries by computing a mean trace in a given interval, crosscorrelating it with the near traces, and applying the corresponding time shift as a static correction.

Figure 6 compares seismic profiles acquired simultaneously, using conventional (longitudinal) and transverse geometry. The sections are displayed using the same amplitude scale. Because they were obtained under the same conditions and were processed with

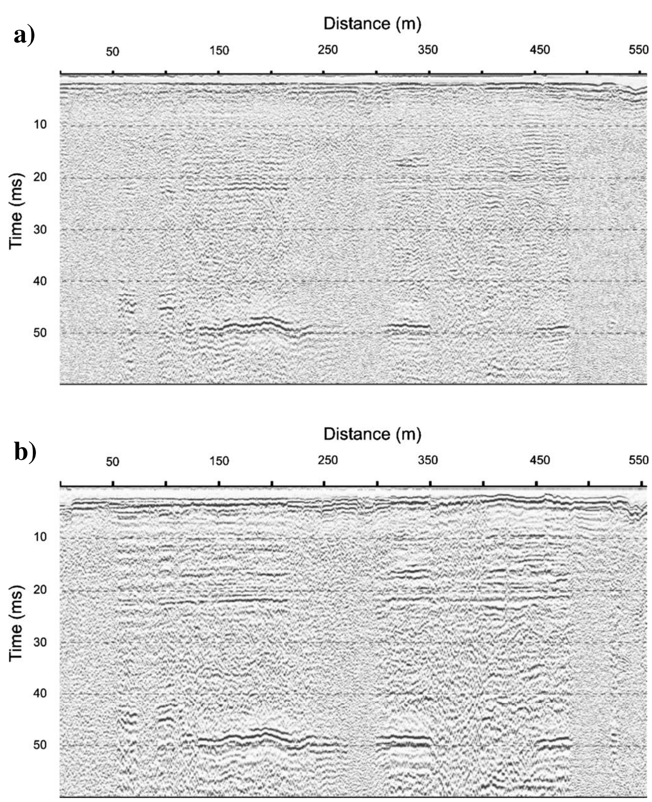


Figure 6. Seismic acquisition at the Venice lagoon. (a) Conventional (longitudinal) geometry survey. (b) Transverse geometry survey. Horizontal distance versus two-way traveltime is shown.

the same sequence, the differences are the sole result of the source-streamer configurations, not the location of the streamers with respect to a random-noise source, e.g., the engine. Note that the noise-dominated areas at the ends of both sections appear to have approximately the same amplitude. In particular, the transverse configuration is a little closer to the engine than the longitudinal one, so the noise should greatly affect the seismogram displayed in Figure 6b. However, this is not the case: The transverse configuration has a better S/N. The improvement using the transverse geometry is noticeable, as predicted by the stacks shown in Figure 5. The shallow event is imaged better than the deeper one. It appears that gas zones block penetration in several patches, but the tops of the gas patches are well imaged.

Therefore, studies based on transverse geometry allow us to obtain a detailed sequence stratigraphic analysis of the Venice lagoon, providing an opportunity to recognize the lateral variability in the architecture of these sequences as well as recent human impact on sedimentation.

## CONCLUSIONS

It is possible to perform high-resolution seismic surveys with a single-channel, multihydrophone streamer in shallow water using a transverse source-receiver configuration. In this case, the signals recorded by the array of hydrophones are stacked to produce a more coherent signal than achievable with a longitudinal configuration.

This new acquisition geometry allows us to obtain hundreds of kilometers of high-resolution seismic profiles with high-quality results. Such large amounts of data cannot be obtained by using a conventional multichannel technique, which requires NMO correction and a standard stacking procedure because it is impractical and unaffordable. A fast, efficient method such as the one we propose could acquire nearly 50–60 km of seismic profiles per day and process the data in a few hours.

Data acquired in the Venice area reveal a high S/N that can be used to perform reliable interpretations of the formations and evolution of the lagoon.

## ACKNOWLEDGMENTS

This work was supported in part by Co.Ri.La (Consorzio Ricerche Laguna) in subproject 3.16 of the 2004-06 Research Programme, “New very-high resolution seismic methods in shallow waters to study the Venice lagoon subsoil.” Thanks go to Luigi Tosi (ISMAR-CNR), Giuliano Brancolini (OGS), and Daniel Nieto Yabar (OGS) for their support during data acquisition. We are grateful to Monika Breitzke and the editor, who provided useful comments.

## REFERENCES

Brouwer, J., and K. Helbig, 1998, Shallow high-resolution reflection seismics: Elsevier Science Publ. Co., Inc.

Carcione, J. M., and F. Poletto, 2000, Sound velocity of drilling mud saturated with reservoir gas: Geophysics, **65**, 646–651.

McGee, T. M., 1995, High-resolution marine reflection profiling for engineering and environmental purposes: Part A — Acquiring analogue sesimic signals: Journal of Applied Geophysics, **33**, 271–285.

Plets, R. M. K., J. K. Dix, J. R. Adams, and A. I. Best, 2007, 3D reconstruction of a shallow archaeological site from high resolution acoustic imagery: The Grace Dieu: Applied Acoustics, doi: 10.1016/j. apacoust.2007 .04.004.

Verbeek, N. H., and T. M. McGee, 1995, Characteristics of high-resolution marine reflection profile sources: Journal of Applied Geophysics, **33**, 251–269.