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Combining two seismic experiments to attenuate free-surface multiples in OBC data[1]

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Abstract

The current inverse scattering solution used for multiple attenuation of marine seismic reflection data assumes that sources and receivers are located in the water. To adapt this solution to the ocean-bottom cable (OBC) experiment where receivers are located on the sea-floor, we have proposed combining the conventional marine surface seismic reflection data (streamer data) with OBC data. The streamer data add to the OBC data some of the wave paths needed for multiple attenuation. This combination has allowed us to develop a multiple attenuation method for OBC data which does not require any knowledge of the subsurface and which takes into account all free-surface multiples, including receiver ghosts. A non-linear synthetic data example consisting of pressure and particle velocity fields is used to illustrate the procedure.

Introduction

After several attempts in the 1980s, the technologies for recording seismic data directly from the sea-floor are now well established (e.g. Mjedle 1992; Berg, Svenning and Martin 1994; Mjedle *et al.* 1995; Brink *et al.* 1996; Roed, Dietrichson and Ireson 1996). The expectations are that the interpretation and processing of sea-bottom data will significantly improve reservoir characterization, monitoring and even production. To fulfil these expectations, new seismic processing tools must be developed to accommodate the new acquisition geometry, and in particular the troublesome problem of multiple attenuation must be re-addressed.

The main difficulty arising in the multiple attenuation of ocean-bottom cable (OBC) data is that the receivers are located on the sea-floor which can have a very heterogeneous structure. The bathymetric mapping of the Gulf of Mexico performed by Hilde *et al.* (1991) provides a good illustration of how heterogeneous the sea-floor can be. It is therefore important to develop multiple attenuation methods which do not require a knowledge of the sea-floor and, when possible, any knowledge at all of the subsurface.

Although seismic events in OBC data can consist of direct waves, primaries, ghosts and multiples just as in conventional marine surface seismic data, their wave

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propagation paths are quite different (see Appendix), in particular those of direct waves and receiver ghosts. In the conventional marine surface seismic experiment (throughout this paper, we will refer to this experiment and its corresponding data as the streamer experiment and streamer data, respectively) where sources and receivers are located in the water, the direct wave describes the wave propagation in the water. It does not carry any information about the subsurface and therefore it is generally muted from the data before multiple attenuation. The effect of receiver ghosts is also negligible; it is generally treated as part of an effective source signature because the receivers are very close to the sea-surface. In OBC experiments, the problem is quite different; the direct wave carries information about the structure of the sea-floor and a significant number of reverberations in the water column are categorized as receiver ghosts (Fig. 1 shows typical OBC events). We consider that these physical differences between streamer data and OBC data are important in the formulation of multiple attenuation methods for OBC data. They can be translated into specific questions to be addressed in the formulation of multiple attenuation methods for OBC data: How can we deal with the direct wave and receiver ghosts? Do we try to remove them as a prerequisite step before multiple attenuation or do we include them in the multiple attenuation process?

The current multiple attenuation methods for surface seismic data (e.g. Carvalho, Weglein and Stolt 1991; Verschuur, Berkhout and Wapenaar 1992; Dragoset 1994; Menger, Marek and Heinze 1996; Ikelle, Roberts and Weglein 1997; Weglein *et al.* 1997) take the view that the direct wave must be muted as a prerequisite step to the multiple attenuation process and that receiver ghost events can be treated as part of an effective source signature. The generalization of this approach to OBC data requires a viable method for attenuating receiver ghosts. The idea of using an effective source

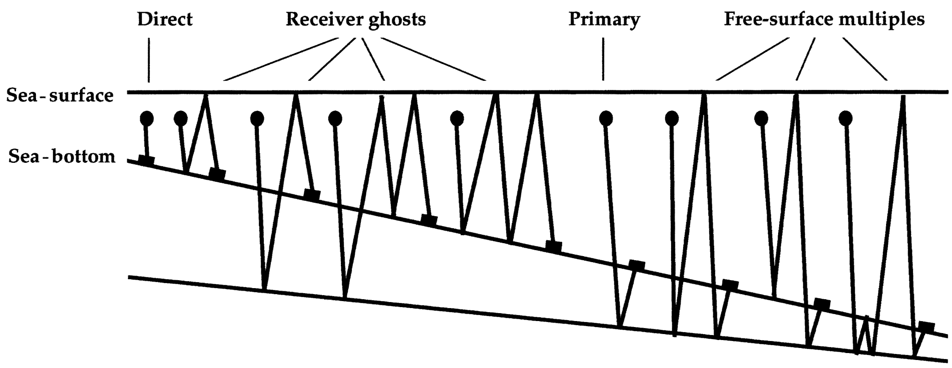

Figure 1. Examples of primary, receiver ghost and free-multiple events in OBC seismic data. ● indicates source positions and ■ indicates receiver positions. Note that a significant number of reverberations in the water column are categorized as receiver ghosts. Also, note that we have defined the receiver-side reverberations as receiver ghosts in accordance with the convention used in streamer data processing, and the source-side reverberations as free-surface multiples.

signature to avoid the deghosting step is no longer practical, especially in deep water, as the duration of receiver ghosts can be very long compared with the actual source and moreover their variations with offset are no longer negligible.

The deghosting of OBC data with the classical deghosting formula (e.g. Fokkema and van den Berg 1996) is a very complex exercise. It is complicated by the potential heterogeneities of the sea-floor and the high number of notches in the data spectrum. For instance, a receiver at 300 m water depth produces a notch almost every 2.5 Hz (see example in Fig. 2).

If the OBC data are multicomponents (e.g. pressure, vertical particle velocity and

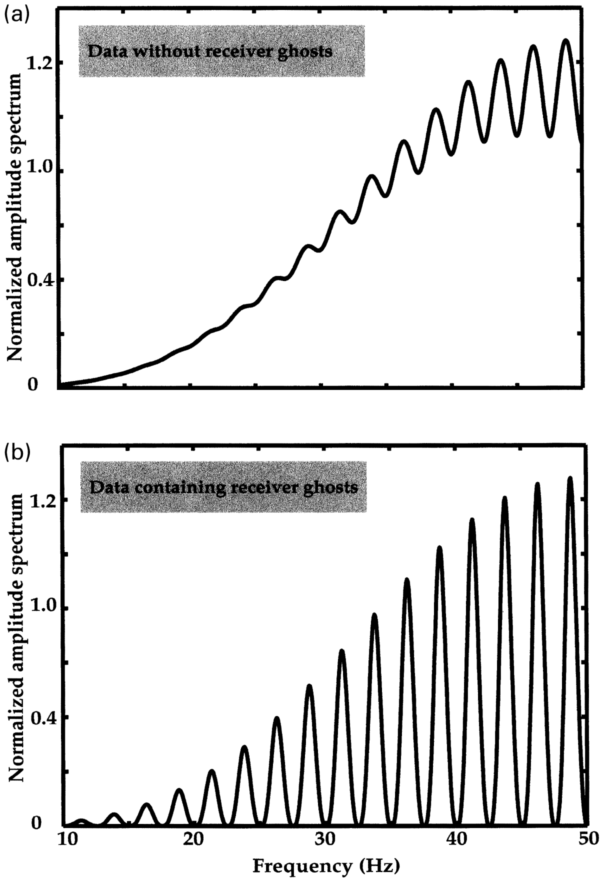

Figure 2. Effect of receiver ghosts in OBC data: (a) data spectrum without receiver ghosts for a fixed wavenumber ($k_x = 0$) and (b) data spectrum containing receiver ghosts. The model of the earth here is one-dimensional. It has two reflectors: the sea-floor at 300 m depth and a second reflector at 700 m. Note the spectrum of the data containing receiver ghosts has a notch every 2.5 Hz. If c_w is the velocity of water and z_b the depth of receiver or sea-floor and if the sea-floor is horizontally flat, the data contained a notch every $\Delta f = c_w/2z_b$.

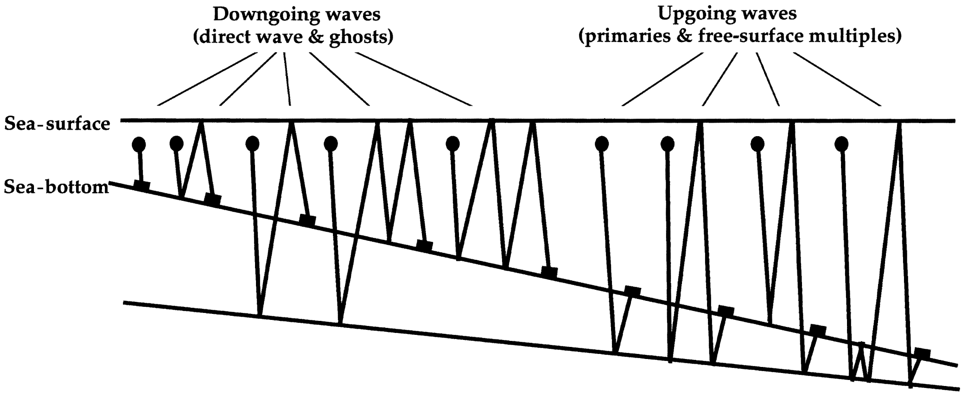

Figure 3. Seismic events in OBC seismic data are grouped into downgoing and upgoing wavefields after an up–down separation at the sea-bottom. ● indicates source positions and ■ indicates receiver positions. Note that the downgoing wavefield contains the direct wave and receiver ghosts while the upgoing wavefield contains the primaries and free-surface multiples.

horizontal particle velocities) and if the properties of the sea-bottom are known, the up/down separation at the sea-bottom is a more attractive deghosting solution. As shown in Fig. 3, seismic events in OBC data can be grouped into downgoing and upgoing wavefields. The downgoing wavefield contains the direct wave and receiver ghosts while the upgoing wavefield, which is the desired field, contains all the primaries and free-surface multiples. The algorithms for performing this wavefield separation have been given by White (1965), Barr and Sanders (1989), Dragoset and Barr (1994), Amundsen and Reitan (1995), Osen *et al.* (1996) and Matson and Weglein (1996). Except for Matson and Weglein's (1996) method which includes free-surface multiple attenuation, the output of the other algorithms is the upgoing wavefield and therefore at least one more processing step is required for free-surface multiple attenuation.

All the methods mentioned above for attenuating receiver ghosts and/or free-surface multiples assume that:
- the sea-floor is flat or that its structure is explicitly known, and
- the elastic properties just below the sea-floor are known.

We formulate here a new method which does not require any knowledge of the subsurface. We will assume that the velocity in the water column is constant.

As stated above, one of the most important problems in the formulation of multiple attenuation for OBC data is how to deal with the direct wave and receiver ghosts. Should they be removed as a prerequisite step before multiple attenuation or should they be included in the multiple attenuation process? Contrary to previous methods, we have chosen to utilize them; the direct-wave arrivals are interpreted as primaries and the receiver ghosts are interpreted as free-surface multiples. Thus, the receiver deghosting is no longer a prerequisite step, it is now an integral part of the free-surface multiple attenuation process.

Our method is formulated as an adaptation, to OBC acquisition geometries, of the inverse scattering series solution used for attenuating free-surface multiples in walkaway VSP data (Ikelle and Weglein 1996). The inverse scattering formulation requires that sources and receivers are located in the water. As in the case of the walkaway VSP data, we overcome this problem by combining the OBC experiment with a streamer experiment which has receivers in the water.

Formulation of an integrated method for free-surface multiple attenuation of OBC data

Multiple attenuation of hydrophone data

We consider two wavefields $\mathbf{E}_0$ and $\mathbf{D}_0$ corresponding to the streamer and OBC experiments, respectively, as shown in Fig. 4. Our objective here is to construct a combination of these two wavefields which allows us to attenuate free-surface multiples and receiver ghosts contained in the OBC wavefield $\mathbf{D}_0$.

We begin by specifying the preprocessing requirements for the multiple attenuation method described below. For streamer data, we assume that the direct wave is muted. As sources and receivers are very close to the sea-surface in this case, source and receiver ghosts are processed as part of an effective source signature. For OBC data, no preprocessing is required; source ghosts are processed as part of an effective source signature while the receiver ghosts are interpreted and processed as free-surface multiples.

Let us now introduce some basic notations and definitions for the description of the

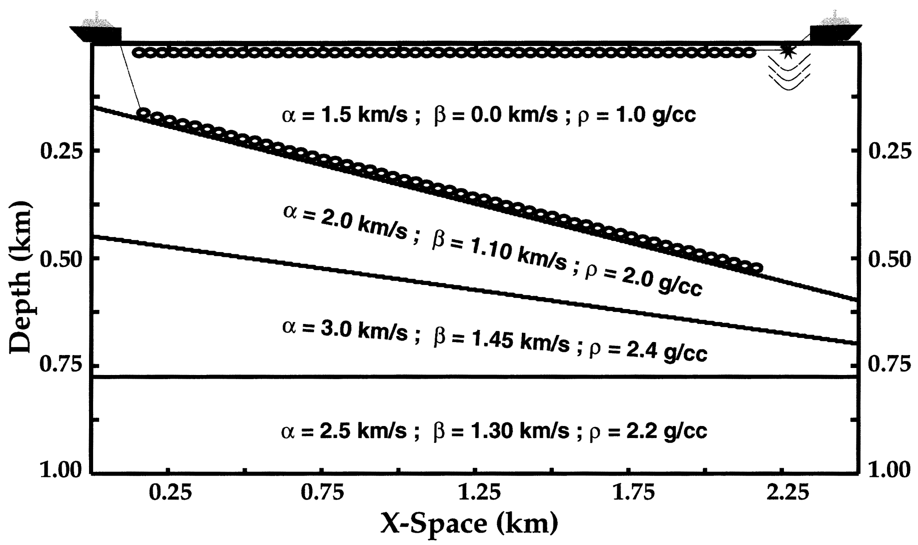

Figure 4. The 2D model used to generate the data in Figs 7 and 11. Note that the sea-floor is not horizontally flat. We also show how the streamer data and OBC data can be recorded simultaneously.

OBC free-surface multiple attenuation. In the OBC situation, it is important to distinguish between the points in the water and those on the sea-floor. Points in the water will be denoted by $\mathbf{x}$, $\mathbf{x}', \ldots$ while points on the sea-floor will be denoted by $\boldsymbol{\xi}, \boldsymbol{\xi}', \ldots$. Using these notations, we define the streamer data $\mathbf{E}_0 = E_0(x_s, x_r, t)$ as the pressure field at the receiver point $\mathbf{x}_r = (x_r, 0)$ and time t for a source point $\mathbf{x}_s = (x_s, 0)$. The OBC data $\mathbf{D}_0 = D_0(x_s, \xi_r, t)$ are defined as the pressure at the receiver point $\boldsymbol{\xi} = (\xi_r, 0)$ (on the sea-floor) and time t for the same source point $\mathbf{x}_s = (x_s, 0)$ in the water. We introduce $D_0(k_s, \xi_r, \omega)$ as the Fourier transform of $D_0(x_s, \xi_r, t)$ with respect to x_s, and t and $E_0(k_s, k_r, \omega)$ as the Fourier transform of $E_0(x_s, x_r, t)$ with respect to x_s, x_r and t. The Fourier-transformed variables corresponding to x_s, x_r and t are, respectively, k_s, k_r and ω.

The inverse scattering series for attenuating free-surface multiples in OBC data can be written as

$$D_p(k_s, \xi_r, \omega) = D_0(k_s, \xi_r, \omega) + A(\omega)D_1(k_s, \xi_r, \omega) + A^2(\omega)D_2(k_s, \xi_r, \omega) + \ldots, \tag{1}$$

where $D_p(k_s, \xi_r, \omega)$ is the data without free-surface multiples and receiver ghosts, and $A(\omega)$ is the inverse of the source signature. If $S(\omega)$ is the Fourier transform of the source signature, assumed to be only time dependent, then $A(\omega) = 1/S(\omega)$. The fields $D_1(k_s, \xi_r, \omega)$, $D_2(k_s, \xi_r, \omega)$, etc. are given by

$$D_n(k_s, \xi_r, \omega) = \int_{-\infty}^{\infty} \mathrm{d}k\, E_0'(k_s, k, \omega)\, D_{n-1}(k, \xi_r, \omega)\,, \quad n = 1, 2, 3, \ldots, \tag{2}$$

with

$$E_0'(k_s, k, \omega) = \frac{\omega}{c} \cos\, \theta E_0(k_s, k, \omega), \tag{3}$$

and

$$\cos\theta = \sqrt{1 - \frac{c^2 k^2}{\omega^2}}\,. \tag{4}$$

The constant c is the velocity of water and k is a generic horizontal wavenumber. From the results given by Ikelle and Weglein (1996) for walkaway VSP data, the proof of (1)–(4) is straightforward. We simply have to replace $D_0(k_s, z_r, \omega)$ by $D_0(k_s, \xi_r, \omega)$ in their equations (A16) to (A20).

The physical interpretation of the scattering Born series, in (1), for removing free-surface multiples is very simple. The series is constructed using the streamer data $E_0(k_s, k_r, \omega)$, the OBC data $D_0(k_s, \xi_r, \omega)$, and the inverse source $A(\omega)$, only. The first term in the series, $D_0(k_s, \xi_r, \omega)$, is the actual data; the second term, with $D_1(k_s, \xi_r, \omega)$, removes free-surface multiples and receiver ghosts which correspond to one reflection at the sea-surface; the next term, with $D_2(k_s, \xi_r, \omega)$, removes free-surface multiples and receiver ghosts which correspond to two reflections at the sea-surface, and so on.

Note that the computation of the terms $\mathbf{D}_1$, $\mathbf{D}_2$, $\mathbf{D}_3$, etc. (equation (2)), which predict the free-surface multiples and receiver ghosts, requires the streamer data $\mathbf{E}_0$.

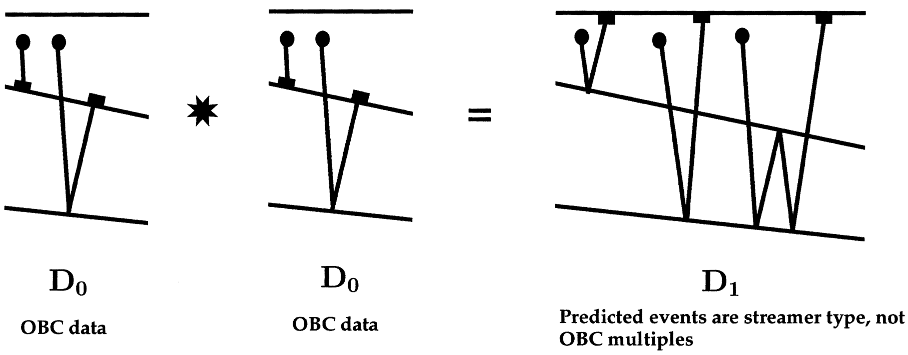

Figure 5. An example of the construction of OBC multiples by combining streamer and OBC primaries (● is the source position and ■ is the receiver position).

The streamer data contain wave paths which are not recorded by the OBC experiment but which are needed for the free-surface multiple attenuation of OBC data. Figure 5 shows the differences between streamer data and OBC data, and how their combination allows us to predict free-surface multiples and receiver ghosts. Figure 6 shows that if the OBC data $\mathbf{D}_0$ are used in the place of the streamer data $\mathbf{E}_0$ in (2), events will be predicted which are not recorded in the OBC experiment and we will obtain a multiple attenuation process which introduces new events into the data in addition to removing the undesired event.

To obtain the $(x-\omega)$ representation of the series we simply perform a Fourier transform of (1) with respect to k_s. This gives

$$D_p(x_s, \xi_r, \omega) = D_0(x_s, \xi_r, \omega) + A(\omega)D_1(x_s, \xi_r, \omega) + A^2(\omega)D_2(x_s, \xi_r, \omega) + \dots, \quad (5)$$

where

$$D_n(x_s, \xi_r, \omega) = \int_{-\infty}^{\infty} \mathrm{d}x\, E_0'(x_s, x, \omega)\, D_{n-1}(x, \xi_r, \omega). \quad (6)$$

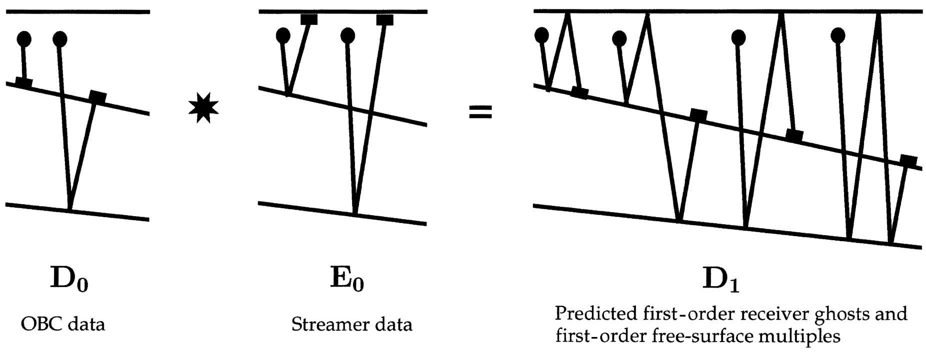

Figure 6. A combination of OBC primary events produces streamer events instead of OBC multiples (● is the source position and ■ is the receiver position).

Equations (2) and (6) are related by Parseval's theorem (Morse and Feshbach 1953). We have used opposite signs in the Fourier transforms of source and receiver coordinates.

In addition to the remarks made above about the computation of the terms $\mathbf{D}_1$, $\mathbf{D}_2$, $\mathbf{D}_3$, etc., it can also be seen that the integral in (6) is carried out over points inside the water ($\mathbf{x}$) and not over points on the sea-floor ($\boldsymbol{\xi}$). Thus, our free-surface multiple attenuation method of OBC data is independent of the structure of the sea-floor.

Multiple attenuation of geophone data

The OBC multiple attenuation solution in (1) and (2) is also valid for particle velocity. We simply have to substitute the pressure field $\mathbf{D}_0$ by the particle velocity $\mathbf{V}_0$ so that

$$V_p^{(i)}(x_s, \xi_r, \omega) = V_0(x_s, \xi_r, \omega) + A(\omega) V_1^{(i)}(x_s, \xi_r, \omega) + A^2(\omega) V_2^{(i)}(x_s, \xi_r, \omega) + \dots, \tag{7}$$

where $V_p^{(i)}(x_s, \xi_r, \omega)$ is the data without free-surface multiples and receiver ghosts corresponding to the ith component of the particle velocity. The fields $V_1^{(i)}(x_s, \xi_r, \omega)$, $V_2^{(i)}(x_s, \xi_r, \omega)$, etc. are given by

$$V_n^{(i)}(x_s, \xi_r, \omega) = \int_{-\infty}^{\infty} \mathrm{d}x \, E_0'(x_s, x, \omega) \, V_{n-1}^{(i)}(x, \xi_r, \omega), \quad n = 1, 2, 3, \dots . \tag{8}$$

Note that multiple attenuation is performed on each component of the particle velocity separately.

It must be emphasized that, despite the fact that the horizontal components of the particle velocity can be discontinuous at a liquid/solid interface (e.g. Amundsen and Reitan 1995), the solution of (7) does not require any knowledge of the subsurface in its application.

As discussed by Ikelle and Weglein (1996), scattering integrals like those in (2), (6) and (8) must be carried out over sources and receivers in the same background medium which here is the water column. Weglein *et al.* (1997) make a similar point: 'inverse scattering theory methods require the support of the perturbation to be on one side of the measurement surface'.

Let us assume that the sea-floor is a perfect liquid/solid interface and that particle velocity recordings are made with the receivers in the solid and the sources in the liquid. If the scattering integral is carried out over receivers of OBC data, the background must include the solid medium in which the receivers are located (see Matson and Weglein 1996). Note that the scattering integrals in (2), (6) and (8) are not carried out over receivers of OBC data but over receivers of streamer data (which are located in the water column) and over sources of OBC data (which are also located in the water column). In other words, we can choose the background medium to be the water column as in the streamer case. Thus, we have avoided any difficulties related to discontinuities of horizontal components of the particle velocity (e.g. any slipping that may occur along the liquid/solid interface) and any other problem related to the sea-floor heterogeneities.

Numerical synthetic example

We now present a numerical example to illustrate the applicability of the series in (5) and (7) for attenuating receiver ghosts and free-surface multiples in OBC data. We simulate a numerical example where OBC data and streamer data are available.

We consider a two-dimensional earth, described as an inhomogeneous solid half-space overlain by a homogeneous fluid (water) layer. The solid half-space consists of three homogeneous layers (Fig. 4). Note that the sea-floor is not horizontally flat. We have generated synthetic streamer and OBC data using a finite-difference modelling scheme. Due to finite-difference gridding of the geological model, the receivers cannot be located exactly on the sea-floor. We put them 5 m above the sea-floor for the pressure field and 5 m below for the particle velocity fields. The streamer has 161 receivers corresponding to offsets between 0 m and 2000 m. We also put 161 receivers on the sea-floor for recording pressure and particle velocity. Figure 7 shows one of the shot gathers of the OBC data corresponding to the pressure field. We have indicated by arrows some receiver ghosts and free-surface multiples. In fact, this data set contains source and receiver ghosts, and all types of multiple.

Multiple attenuation of hydrophone data

Figure 8 shows the results of the multiple attenuation process based on the series in (5);

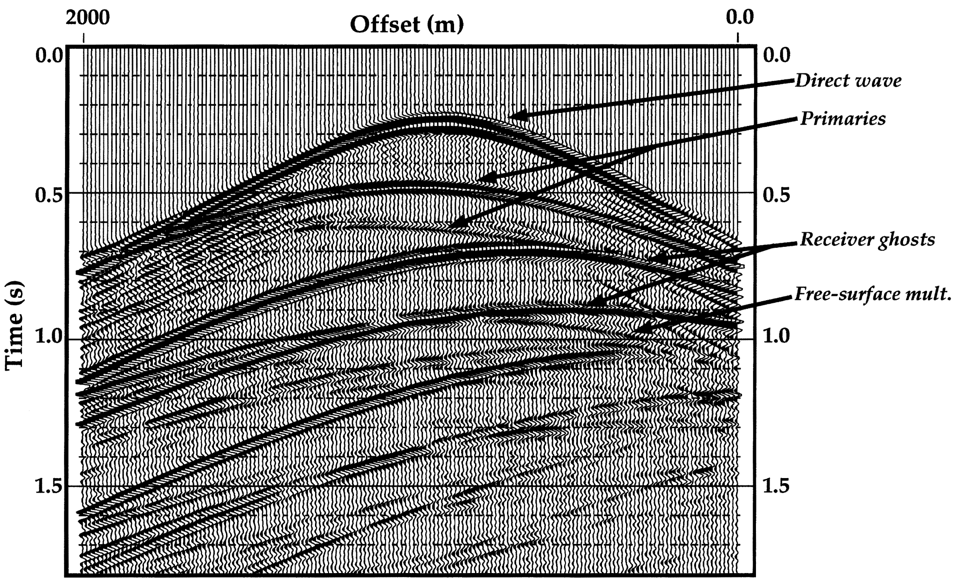

Figure 7. The OBC pressure wavefield corresponding to the 2D model in Fig. 4. The shot position is at 1.25 km. The data contain receiver and source ghosts, free-surface and internal multiples, and primaries. We have indicated the three P-to-P primaries and some of the corresponding first-order free-surface multiples and receiver ghosts.

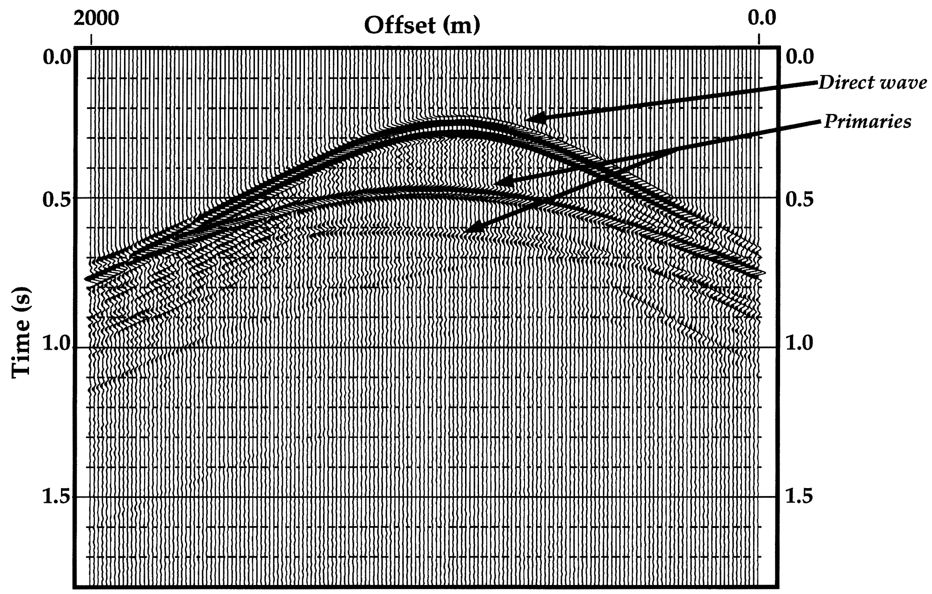

Figure 8. Result of multiple attenuation of the OBC pressure wavefield in Fig. 7 with the shot at 1.25 km.

only the first four terms of the series were used. The exact source signature was known but it was not used in the estimation of $A(\omega)$ because finite-difference modelling generates other events such as source ghosts which contribute to the change in the apparent source signature. (We recall that the series in (1), (5) and (7) assume that the data have been corrected for source ghosts.) In this respect, our tests are closer to real data environments. The usual solution to the problem of estimating $A(\omega)$ is to seek an effective source which permits the attenuation of free-surface multiples thus indirectly compensating for modelling assumptions which affect the source signature. The algorithm for estimating the source signature described by Ikelle *et al.* (1997) solves this problem. We have used it to estimate $A(\omega)$. By comparing Figs 7 and 8, we can see that the multiple removal procedure is quite effective even with a laterally varying sea-floor. However, we can see that the results after multiple attenuation (Fig. 8) are not totally clean. The reason is as follows: the finite-difference data contained source ghosts, internal multiples, events due to the imperfection of boundary conditions and noise relative to the gridding of geological models. The series described in (1), (5) and (7) do not take into account these modelling effects.

Let us emphasize that in the multiple attenuation method of OBC data presented here, the up–down separation of the wavefield for the purpose of receiver deghosting is not required. The receiver ghost events are treated as free-surface multiples. The modelling of the multiples is a confirmation of this. Figures 9 and 10 show the $D_1(x_s, \xi_r, \omega)$ and $D_2(x_s, \xi_r, \omega)$ terms which correspond to first-order and second-order

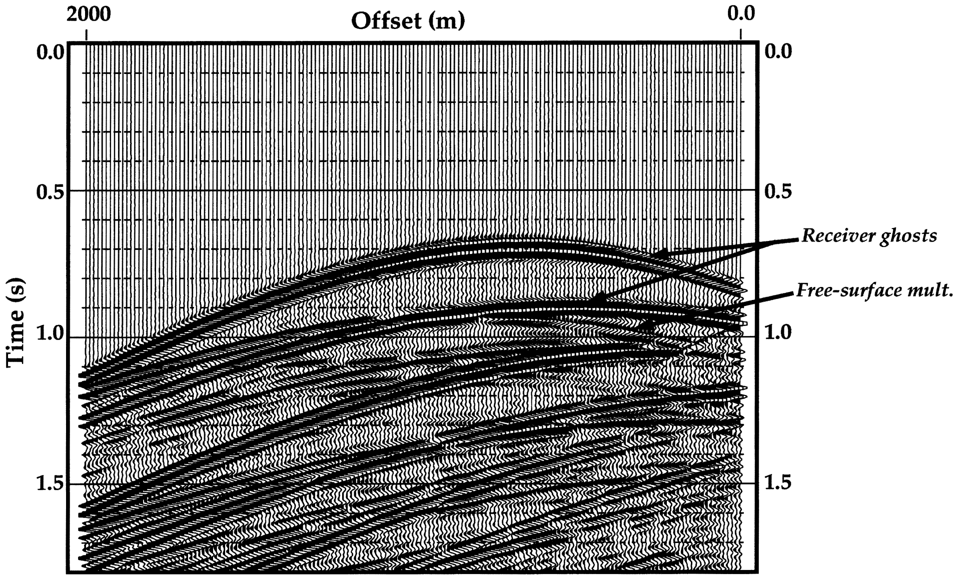

Figure 9. Predicted first-order multiples using the data in Fig. 7 for the shot at 1.25 km.

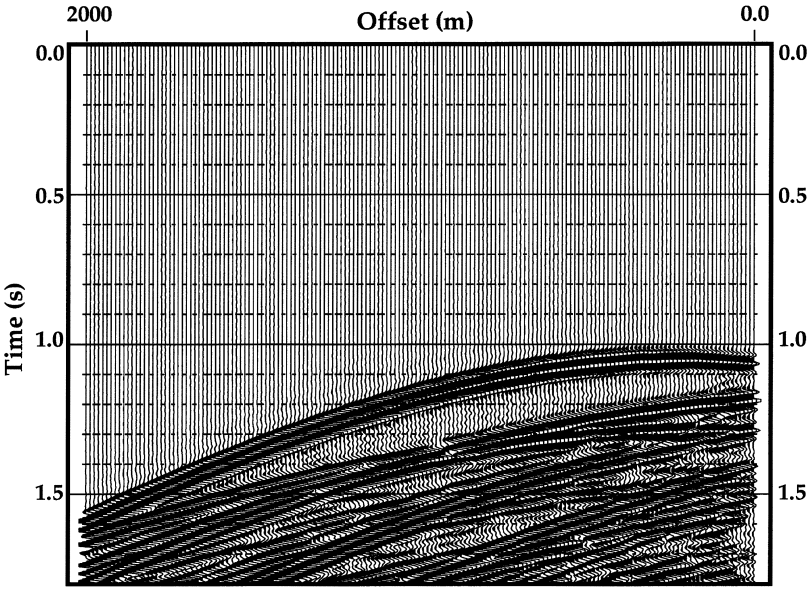

Figure 10. Predicted second-order multiples using the data in Fig. 7 for the shot at 1.25 km.

predicted free-surface multiples, respectively. We can see that the receiver ghosts and free-surface multiples are all well predicted by this method.

Multiple attenuation of geophone data

We have also tested the case where OBC data correspond to the particle velocity. Figure 11 shows, for instance, the horizontal component of the particle velocity before multiple attenuation and Fig. 12 shows the results of multiple attenuation obtained using the series (7). By comparing Figs 11 and 12, we can see that the multiple attenuation procedure described here is also effective for the particle velocity.

Conclusions

A construction of the inverse scattering series for attenuating free-surface multiples and receiver ghosts in multicomponent OBC data was presented. It combines streamer data and multicomponent OBC data. Multiple attenuation of each component of the OBC data is performed separately.

This multiple attenuation method does not require any knowledge of the subsurface nor any up–down separation of the wavefield.

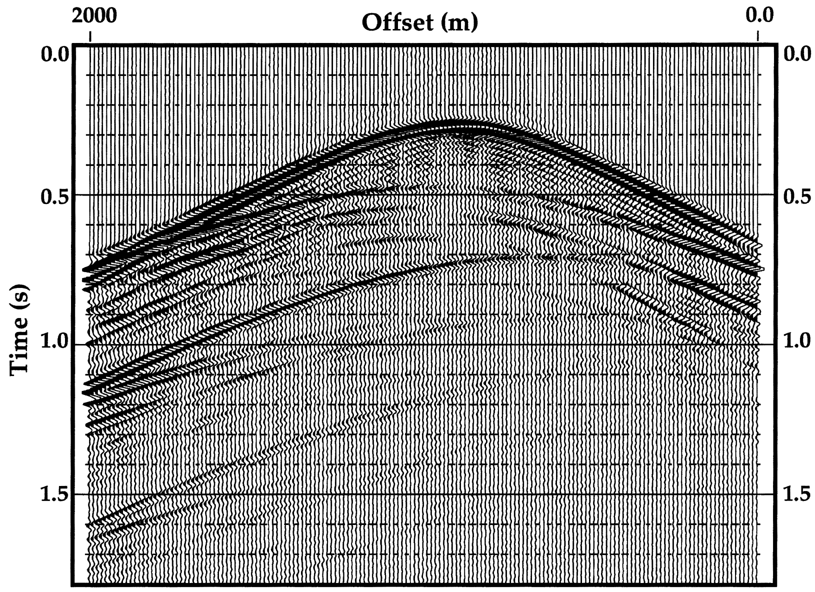

Figure 11. The OBC horizontal particle velocity wavefield corresponding to the 2D model in Fig. 4. The shot position is at 1.25 km. The data contain receiver and source ghosts, free-surface and internal multiples, and primaries.

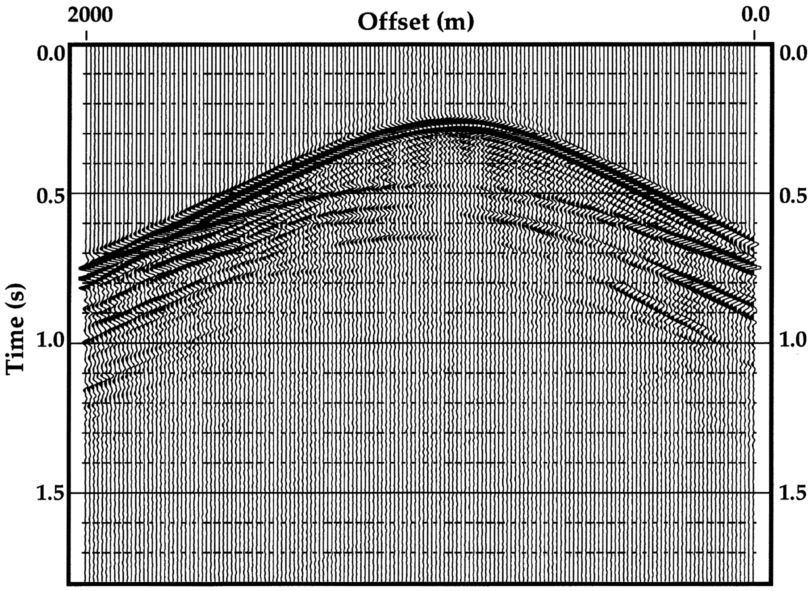

Figure 12. Result of multiple attenuation of the OBC horizontal particle velocity wavefield in Fig. 11 with the shot at 1.25 km.

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Appendix: OBC terminology

A number of terms, such as direct wave and receiver ghost, have evolved different meanings in the respective analysis of towed streamer and OBC data. As the meanings of these terms are critical to the understanding of this paper, we would like to elaborate on their definitions.

OBC direct wave

The 'OBC direct wave' is the wave that propagates in the background medium (here, the water column) from the source position to the receiver without hitting any reflector other than the sea-surface and the sea-bottom. Just as in the streamer experiment, for the case where the source is above the streamer, the OBC direct wave can include source ghosts. But contrary to the direct wave in the streamer experiment, for the case where the source is below the streamer, it does not include receiver ghosts.

To define the OBC direct wave completely, we need to distinguish between the 'pressure OBC direct wave' and the 'velocity OBC direct wave' because the OBC pressure field is recorded just above the sea-floor while the OBC velocity fields are recorded just below the sea-floor. Thus the 'velocity OBC direct wave' contains a transmitted wave while the 'pressure OBC direct wave' contains a reflected wave.

Let us expand the definition of pressure OBC direct wave because it involves two events. When the recorded OBC wavefield is a pressure field, in addition to the wave that propagates in the water column from the source position to the receiver, there is a sea-bottom reflection arriving almost at the same time as the direct wave. In this paper, we treat these two events as one single event which we call the 'pressure OBC direct wave'.

OBC receiver ghosts

A receiver ghost is generally defined as an event whose last reflection was from the sea-surface (Sheriff 1991). This is exactly the case for OBC receiver ghosts as shown in Fig. 1. However, we have to distinguish between the 'pressure OBC receiver ghost' and the 'velocity OBC receiver ghost'. The pressure OBC receiver ghost contains the sea-bottom reflection while the velocity OBC receiver ghosts includes a transmitted wave through the sea-floor.

In streamer data, the effect of receiver ghosts can be treated approximately by adding to the actual source signature its virtual, inverted image with respect to the sea-surface because receiver depths are generally small ($\leq$10 m). Contrary to streamer data, the receiver ghosts in OBC data are clearly distinct from the source signature just like free-surface multiples. In this paper, we treat receiver ghosts as free-surface multiples.

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