Multiple attenuation for shallow-water surveys: Notes on old challenges and new opportunities

Clement Kostov[1], Frederico Xavier de Melo[1], Abhishek Raj[1], Alexander Zarkhidze[1], Alex Cooke[1], Glenn Miers[1], and John Bacon[1]

Abstract

Challenges are reviewed for multiple-attenuation workflows for shallow-water surveys, including the 3D surface-related multiple elimination (3D SRME) workflow as well as workflows that combine wavefield extrapolation and 3D SRME. A proposed workflow improves on 3D SRME results for shallow-water surveys while aiming to remove all surface-related multiples rather than just a subset from those multiples. The key step in this workflow is a 3D SRME prediction of free-surface multiples using two input data sets — the recorded data and another data set preprocessed to remove a subset of water-layer-related multiples. This approach reduces some of the amplitude distortions in the SRME model and leads to overall improvement in results. Properties of the proposed workflow are illustrated with data from two shallow-water surveys acquired in the North Sea with multimeasurement steamers. Processing of the densely sampled 3D shot gathers obtained by joint interpolation and deghosting using the multimeasurement data provides more accurate wavefield extrapolation, better constrained adaptive subtraction, and overall better multiple-attenuation results than processing data from each streamer independently.

Introduction

Industry-standard processing for marine seismic data typically includes attenuation of free-surface multiples with 3D surface-related multiple elimination (SRME), a method consisting of data-driven prediction of multiples followed by adaptive subtraction (Verschuur, 2012). Accurate attenuation, or separation, of free-surface multiples is needed before predicting internal multiples with data-driven methods and before imaging/inversion of primaries. Generally, applications that motivate the acquisition and processing of broadband seismic data also imply high expectations for accurate removal of free-surface multiples.

The 3D SRME method performs well when sampling and data-conditioning requirements are met (Dragoset et al., 2010). However, 3D SRME faces several challenges in shallow-water surveys. The two main challenges specific to such surveys are the reconstruction of seismic traces at offsets smaller than the nearest offset and the adaptive subtraction of the predicted multiples. For the purposes of our discussion, we will consider as "shallow water" the areas in a survey where water depth is less than about 200 m. For typical acquisition geometries, such water depths correlate broadly with the transition from successful to marginal results when processing data with standard 3D SRME.

In shallow-water surveys, methods based on wavefield extrapolation are often successful (Lokshtanov, 2001; Verschuur, 2012; Wang et al., 2014) in removing a class of high-amplitude multiples that has bounces (e.g., reflections, refractions, diffractions) on the water bottom. Figure 1 provides decompositions of free-surface-related and water-layer-related multiples into subsets, including the subset of multiples modeled by wavefield-extrapolation methods (water-layer multiples with bounces in the water layer on the shot or receiver side, i.e., WLM-SL-LS, with the notation introduced in Figure 1).

Moore and Bisley (2006) propose to follow the attenuation of WLM-SL-LS multiples with modeling of free-surface multiples that are not related to the water layer (FSM-LL in Figure 1a). The approach of Moore and Bisley (2006), known

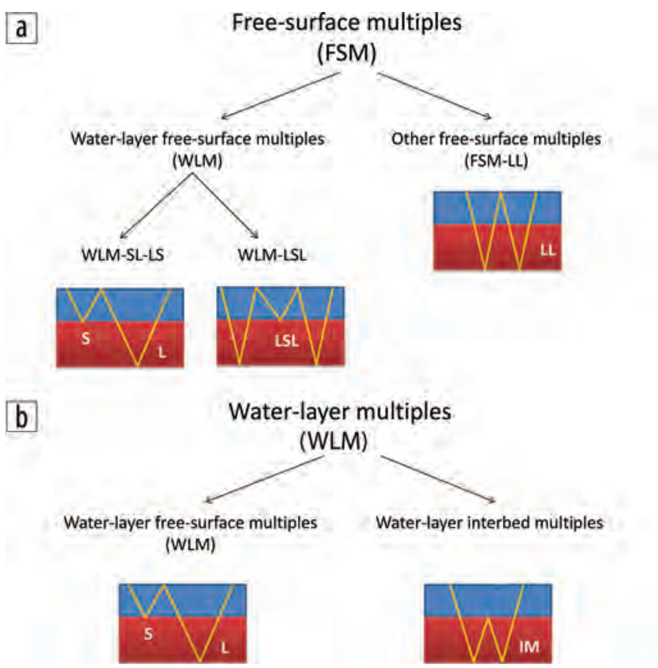

Figure 1. (a) Free-surface multiples (FSM) are split in two groups: multiples that include an upward bounce on the water bottom (WLM) and multiples that do not bounce upward on the water bottom (FSM-LL). The first set (WLM) is split further into two groups, depending on whether the bounce occurs on the source or receiver side (WLM-SL-LS) or not (WLM-LSL). The notation S refers to short path bounces from the water bottom, whereas L refers to long path bounces from deeper interfaces. (b) Water-layer multiples split into two subsets, one grouping events with upward bounce on the water bottom (free-surface multiples, as in Figure 1a), the other grouping events with downward bounce on the water bottom (interbed multiples).

[1]Schlumberger.

http://dx.doi.org/10.1190/tle34070760.1.

as deterministic water-layer demultiple (DWD), extends significantly the class of free-surface multiples being attenuated, but it leaves in the data multiples of the WLM-LSL type (van Groenestijn et al., 2012).

We propose a workflow that has the same first step as DWD, i.e., attenuation of WLM-SL-LS-type multiples by a wavefield-extrapolation approach using a model of the water layer. Next, we use general surface multiple prediction (GSMP), a particular implementation of 3D SRME (Moore and Dragoset, 2008), to predict all free-surface multiples. This prediction uses the results from the earlier DWD step to obtain a model of free-surface multiples that has better properties than a standard 3D SRME model does. In a third step, we subtract from the data the models obtained at each of the two previous steps.

This workflow is applicable to any streamer data, but it benefits in the prediction and subtraction phases from multimeasurement data that are deghosted and reconstructed with dense inline and crossline sampling of receivers (Özbek et al., 2010).

After introduction and formal description of the method, the proposed workflow is applied to a data set from the North Sea with challenging shallow channels. An application to a second North Sea data set illustrates recent developments in the prediction of water-layer-related multiples of type WLM-SL-LS with wavefield-extrapolation methods. The final section reviews current results versus challenges and further opportunities.

Methodology

We describe a workflow that aims to attenuate all free-surface multiples while performing better than standard SRME in shallow-water surveys. The workflow has three main steps, starting with the prediction and attenuation of WLM-SL-LS multiples (Figure 1). Predictions are carried out by wavefield extrapolation of data D through the water layer. For instance, wavefield extrapolation of a common-shot gather with a Green's function for water layer W_R produces a model of multiples M_R where events have a water-bottom reflection at the receiver side. Similarly, a model for source-side water-layer multiples M_S is obtained by wavefield extrapolation of common-receiver gathers with a Green's function W_S. Formally,

$$M_R = W_R * D \text{ and } M_S = W_S * D, \tag{1}$$

with symbol * denoting multidimensional convolution in space and time (Verschuur, 2012).

Multiples that have reflections in the water layer on both the source and receiver sides are present in both models (M_R and M_S) and would be predicted twice if we were simply to sum the source-side and receiver-side models. Following Lokshtanov (2001), equation 2 includes correction terms for such multiples,

$$M_{WLM} = M_R + M_S - W_R * D * W_S - D_W * W_S, \tag{2}$$

where the notation D_W is used for the water-bottom primary reflection.

Note that terms in equation 2 can be grouped in different ways to reduce the number of wavefield extrapolations needed. The four terms in equation 2 can be reduced to three terms by combining, for instance, M_S and $D_W * W_S$, i.e., modeling multiples with bounces on the source side by wavefield extrapolation of common-receiver gathers where the water-bottom reflection has been removed.

Moore (2004) further reduces the number of wavefield extrapolations to two by removing the receiver-side multiples from the data before wavefield extrapolation with the source-side operator, as follows:

$$M_{WLM} = M_R + (D - D_W - f * M_R) * W_S, \tag{3}$$

where f is a linear filter indicating that the receiver-side multiples M_R are being removed by adaptive subtraction from the data.

Figure 2 further illustrates different types of multiples using finite-difference 2D synthetic data.

Having predicted and attenuated WLM-SL-LS-type multiples, Moore and Bisley (2006) compute a model for LL-type multiples by muting the primaries corresponding to the shallow generators used in modeling the WLM-SL-LS multiples. As mentioned previously, this approach does not attenuate multiples of the LSL type, which might or might not be a concern in specific practical situations.

Here, we propose an alternative approach using the estimate of primaries after DWD, denoted P_{WLM}, to improve the predictions of free-surface multiples. The P_{WLM} estimate of primaries still contains multiples (WLM-LL) that do not reflect on the water bottom or other shallow generators included in the DWD water-layer model. Formally,

$$P_{WLM} = P + M_{LL},$$

with P denoting primary reflections.

We compute a 3D SRME model of free-surface multiples (M_{FSM}) from two input wavefields (Verschuur, 2012), as follows:

$$M_{FSM} = P_{WLM} * D = (P + M_{LL}) * D = M + M_{LL} * D, \tag{4}$$

where M denotes a multiple model with correct amplitudes (without overprediction for high-order multiples). When computing 3D SRME models, deconvolution of the model of multiples with the acquisition wavelet is performed typically as part of the prediction (Dragoset et al., 2010). However, for simplicity of notations, we omit this step in equation 4 and in the following equations that involve SRME-type predictions of multiples.

A similar decomposition of the SRME model as in equation 4, separating the exact prediction of the multiples from the term responsible for overprediction of the high-order multiples, is as follows:

$$M_{SRME} = D * D = (P + M) * D = M + M * D. \tag{5}$$

Although the M_{FSM} model still contains overpredicted multiples of order higher than one, as per equation 4, these multiples involve deeper generators than the ones included for modeling WLM multiples. Hence, the corresponding multiples are separated better in time and space than water-layer-related multiples (WLM) and therefore are attenuated better by adaptive subtraction. For this reason, we expect that the M_{FSM} model (equation 4) provides an improvement with respect to the M_{SRME} model (equation 5).

When the data are separated into upgoing and downgoing components, we have the option to remove WLM-SL-LS

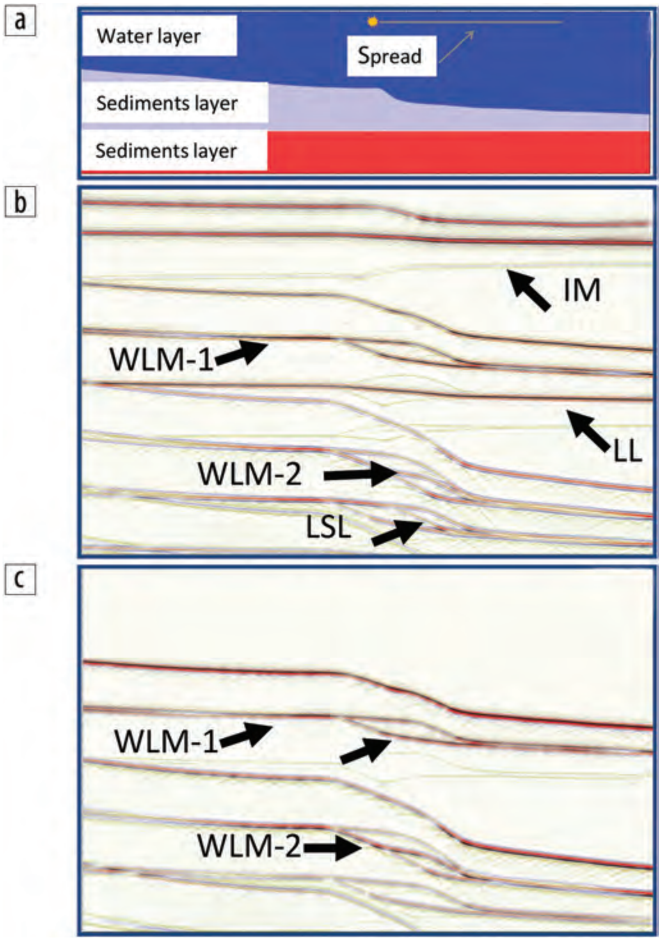

Figure 2. (a) Three-layer model used to compute an acoustic finite-difference synthetic data set. The top layer is water. The water bottom has a moderate dip and an escarpment feature at the center of the model. The deeper reflector below the water bottom is horizontal. (b) Common-offset section from the finite-difference data set. The top two events are the primary reflections. The annotations point to IM (interbed multiple); WLM-1 peg-leg multiples with upward reflections on the water bottom and on the deeper reflector; WLM-2 event that has upward reflections in the water layer at the source and receiver sides; LL, a free-surface multiple from the reflector below the water bottom (no reflection on the water bottom); and LSL, a multiple in which the reflection on the water bottom is neither at the source nor at the receiver side. (c) Wavefield-extrapolation methods based on equation 2 predict water-layer multiples with reflections in the water layer on the source or receiver side. Note the splitting of events, especially below the escarpment, with the implication that both source- and receiver-side models are needed for accurate predictions of multiples.

multiples from the upgoing component (e.g., by DWD) and predict an M_{FSM} model of free-surface multiples by multidimensional convolution of these upgoing data with the downgoing data.

The third and final step in the workflow is to subtract the models computed in the first two stages, for instance, using simultaneous adaptive subtraction, as follows:

$$P = D - f_1 * M_{WLM} - f_2 * M_{FSM}. \tag{6}$$

Field data examples

Free-surface multiple attenuation in a shallow-water survey with complex shallow structure. Our first example is with data from a multimeasurement survey from the North Sea. The data were acquired with eight streamers, each 3 km long, separated by 75 m in the crossline direction and towed at 18-m depth. The nearest receivers are 150 m from the sources. The source was a multilevel source, with subarrays at three depth levels to attenuate the source ghost. The data acquired by each streamer are multimeasurement data including three components (pressure and two particle velocity components). Using these multimeasurement data, we reconstruct shot gathers with virtual streamers at 6.25-m nominal crossline spacing and receivers at 6.25-m spacing along the virtual streamers (Özbek et al., 2010).

Figure 3a displays a stack along an inline before attenuation of multiples. The data have been processed for 3D receiver-side deghosting; no residual source-side deghosting has been applied. The main generators of multiples are the water bottom, the complex channels in the near surface, and the base Cretaceous unconformity (BCU). Figure 3b displays a stack after attenuation of WLM multiples by DWD, where the DWD model of source-side and receiver-side WLM multiples is computed according to equation 2.

In this example, wavefield extrapolations are run with data from one streamer at a time, assuming a horizontal water bottom and mild structural variations in the subsurface. Figure 4a displays the stack section obtained by attenuating multiples predicted by GSMP with two input data sets, as in equation 4. The free-surface multiple of type LL reflecting from the shallow channel is now removed, but there are residual first-order free-surface multiples with reflections from the BCU and the seafloor. This residual most likely is related to the missing near offsets and incomplete reconstruction of the water-bottom primary reflection. To better attenuate such residual multiples, we perform a simultaneous subtraction of the DWD and GSMP models, according to equation 6, and show the results in Figure 4b.

Water-layer-related multiples: Examples of model-based, general deterministic water-layer demultiple (GDWD). Our second field data example is from the Bruce field area in the U. K. continental-shelf sector of the North Sea, approximately 340 km northeast of Aberdeen, in a water depth of about 120 m. The acquisition parameters are similar to the ones quoted in the first example: eight multimeasurement streamers 3 km in length and with 75-m crossline separation towed flat at a depth of 18 m, near offset of 150 m, multilevel source array, and 37.5-m shot interval. The reconstructed shot-gather data are a densely sampled grid of receivers with nominal inline and crossline receiver spacings of 6.25 m. For the multiple-attenuation tests, we selected three input sail lines covering an area of 12.5 km × 1.5 km.

In this example, we compare prediction and attenuation of WLM-SL-LS-type multiples by two implementations of the DWD method (Moore and Bisley, 2006). The first implementation is called general DWD (GDWD). It uses data preconditioning and true-azimuth 3D predictions similarly to GSMP and takes advantage of the densely reconstructed common-shot data for adaptive subtraction (Figure 5b). The second implementation applies DWD to each virtual streamer separately, assuming a locally horizontal water bottom (Figure 5c).

Figures 5 and 6 compare the two methods on shot gathers. These 3D shot gathers (time and two space dimensions) are obtained by reconstruction of the acquired multimeasurement streamer data on a dense grid, such that the data are organized in virtual streamers (85 per shot gather, sampled 6.25-m inline, and 6.25 separation between streamers crossline). The GDWD result using the 3D shot gathers is consistently better (in predictions on Figure 5 and after subtraction on Figure 6) than the DWD result obtained by processing each streamer independently.

Note that the 3D adaptive subtractions in the GDWD case use shorter windows in time than the 2D adaptive subtractions in the DWD case, thus reducing the number of cases in which

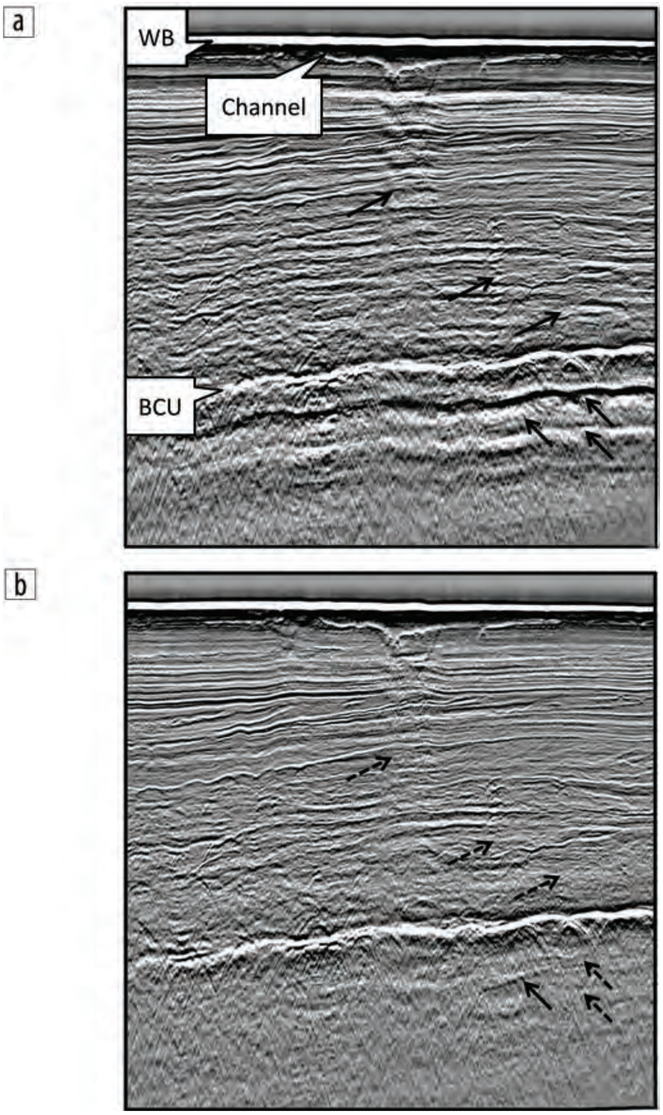

Figure 3. (a) Input stack, inner cable. Boxes point to the main generators of multiples. Arrows point to some of the most prominent multiples. (b) Stack after removal of WLM multiples (of WLM SL-LS type) by the DWD method. WLM multiples are well suppressed. For comparison with the input data, arrows pointing to WLM are repeated in dashed lines. A residual non-WLM multiple, indicated by the solid arrow, is now apparent below the base Cretaceous unconformity.

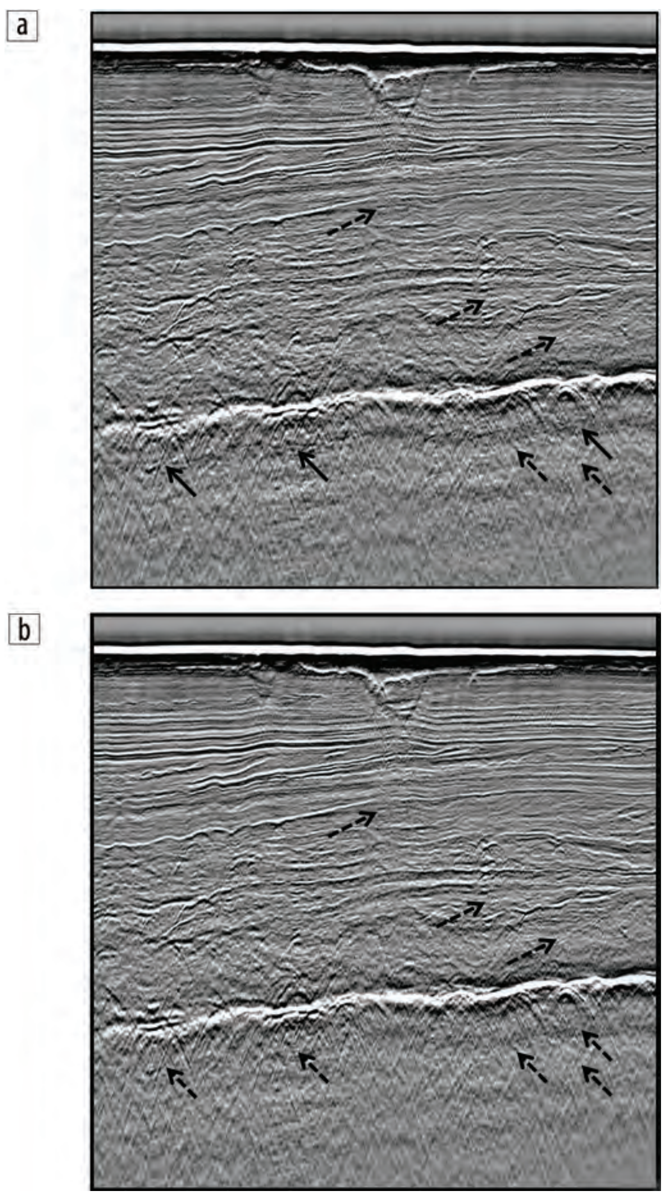

Figure 4. (a) Stack result, removal of free-surface multiples by GSMP with two inputs, DWD upgoing and downgoing data. (b) Stack result, after simultaneous subtractions of two models: DWD model (Figure 3b) and GSMP with two inputs (Figure 4a). In Figure 4b, note overall good attenuation of all free-surface multiples (WLM and LL).

events within a window would require different adaptive-filtering corrections.

Figure 7 displays an inline stack before attenuation of multiples (Figure 7a), a GDWD stack (Figure 7b), and their difference section (Figure 7c). The multiples are well attenuated on the GDWD stack, from shallow to deep parts of the section (Figure 7b), with no attenuation of primaries noted on the difference section (Figure 7c).

Windows from the stack sections (top left corner of Figure 7a, near the water bottom) are zoomed and displayed in Figure 8. Figure 8a compares the stack of the input data (Figure 8a, top panel), the stack from the GDWD workflow (Figure 8a, middle panel), and the stack from the DWD workflow (Figure 8a, bottom panel). Figure 8b (top panel) shows the corresponding stacks of the GDWD model of multiples, and Figure 8b (bottom panel) shows the DWD model of multiples. Again, these results illustrate the high quality of multiple removal by the GDWD method and the improved performance of GDWD with respect to DWD, implemented here as a streamer-by-streamer processing flow.

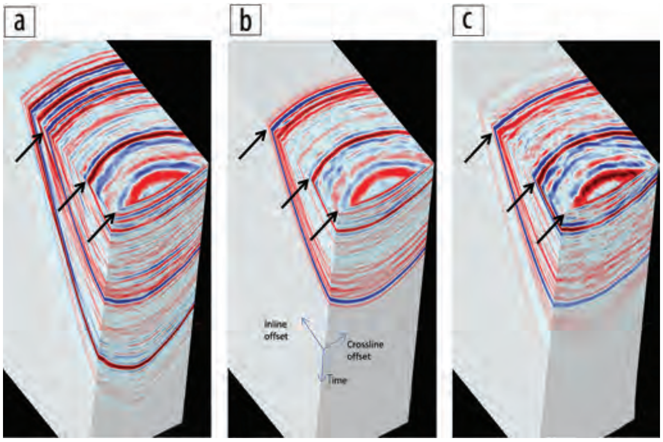

Figure 5. Displays of common-shot data cubes as follows: (a) input shot-gather data; (b) multiples predicted with GDWD; (c) multiples predicted by the DWD method, in which each virtual streamer is processed independently. Arrows point to some strong multiples.

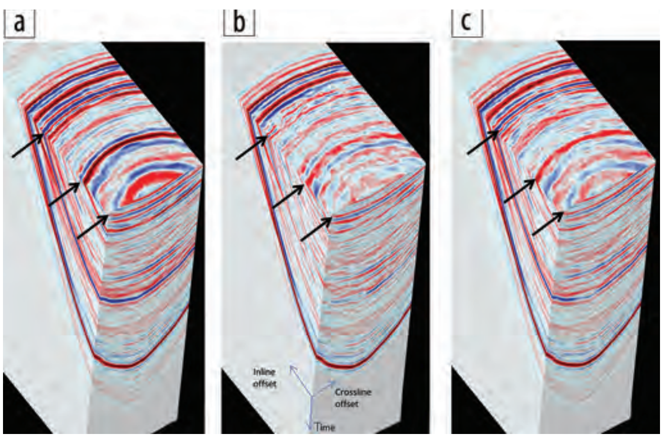

Figure 6. Displays of common-shot data cubes as follows: (a) input shot-gather data; (b) result after multiple prediction with GDWD and adaptive subtraction with 3D windows (time and two space coordinates); (c) result after adaptive subtraction, with each virtual streamer processed independently (DWD). Arrows point to strong multiples on the input in panel (a) and to residuals after adaptive subtraction in panels (b) and (c).

Conclusions

We described a workflow that combines the strengths of wavefield extrapolation and 3D SRME approaches and aims to attenuate all free-surface multiples rather than a subset of those multiples. This workflow includes a 3D SRME step which avoids to a large extent the issues of prediction and subtraction of high-order multiples in the standard 3D SRME workflow. Still, the results of 3D SRME are sensitive to the reconstruction of the

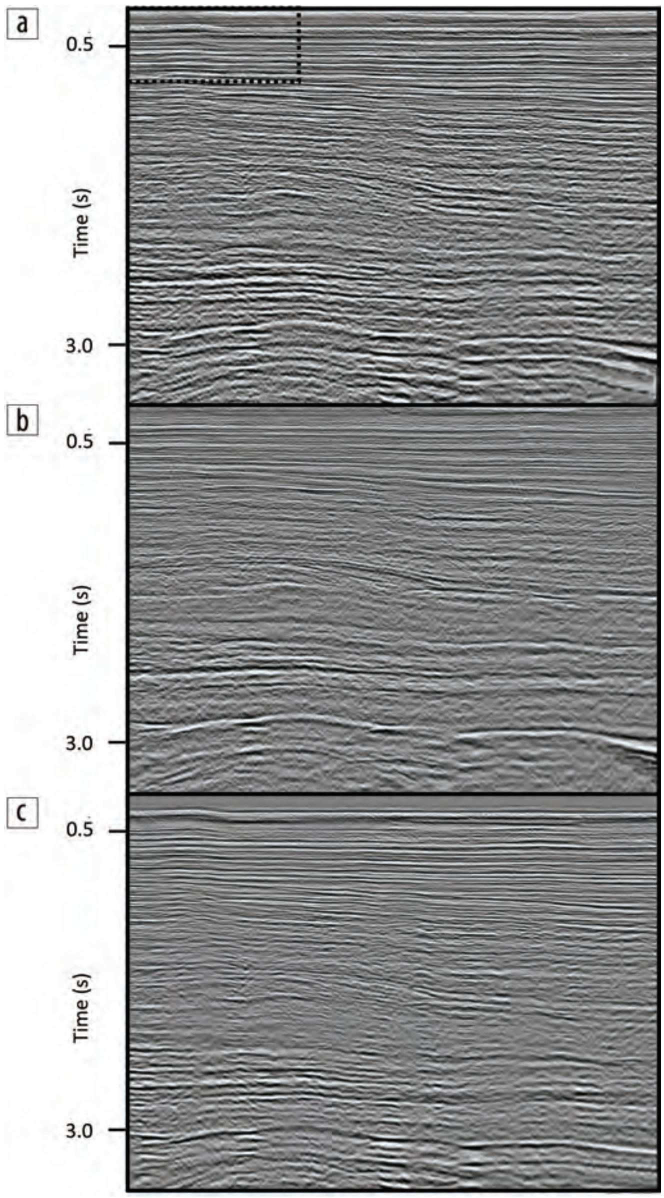

Figure 7. Inline stacks; the vertical axis is time from 0.2 to 3.5 s, and the horizontal axis is midpoint positions, with an extent on the order of 10 km. (a) Stack of the input data. The rectangle indicates the area shown in Figure 8. (b) Stack of the data, after attenuation of multiples by GDWD (GDWD stack). (c) Difference of the stacks shown in panels (a) (input) and (b) (GDWD).

near offsets, and therefore a simultaneous subtraction of DWD/GDWD, along with the 3D SRME model, provided the best results in a first field data example. The reconstruction of near offsets remains a challenge and an important area of improvement for shallow-water towed-streamer surveys.

In both of our field data examples, the water-bottom reflectors have simple structure, and the construction of a velocity-depth model limited to the water-bottom reflector, as needed for kinematically accurate Green's functions for the water layer, was straightforward. However, in the first example, we noted a shallow channel that generates strong free-surface multiples that do not reflect on the water bottom.

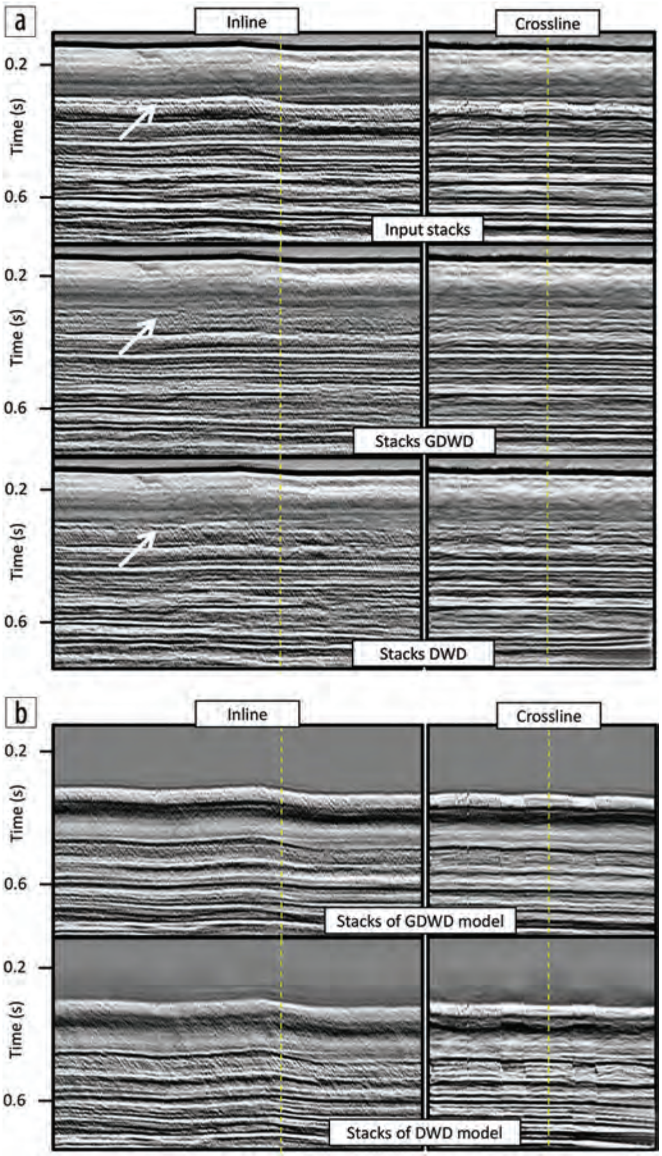

Figure 8. (a) Inline and crossline stacks of shallow portions of the input stacks (top panel), stacks with multiples suppressed by GDWD (middle panel), and stacks with multiples suppressed by DWD (bottom panel). (b) Inline stack of the GDWD model of multiples (top panel) and inline stack of the DWD model of multiples (bottom panel).

In such cases, we might want to extend the model-based approach to include multiples from shallow structures below the water bottom. Recent advances in imaging with multiples and in full-waveform inversion applied for shallow structure characterization could lead to a step change in model-based predictions for multiples generated from complex shallow structures.

In our second field data example, we illustrated the removal of water-layer-related multiples by wavefield-extrapolation methods. We compared streamer-by-streamer processing with processing that takes advantage of data that are densely reconstructed in shot gathers. The significant improvements in the second approach are attributed to more accurate wavefield extrapolations carried out in a 3D sense and to better constrained adaptive subtractions. TLE

Acknowledgments

The authors thank Statoil and Schlumberger for permission to publish. We thank Statoil U.K. Limited, JX Nippon Exploration and Production (U.K.) Limited, and Dyas B.V. for permission to use the data for the first field data example. We thank our colleagues Richard Bisley, Ian Moore, Zhiming Wu, Scott A. Slaton, Dave Clark, Chris Cunnell, and Bill Dragoset (consultant) for their contributions to various aspects of the work reported here.

Corresponding author: kostov1@slb.com

References

Dragoset, B., E. Verschuur, I. Moore, and R. Bisley, 2010, A perspective on 3D surface-related multiple elimination: Geophysics, **75**, no. 5, 75A245–75A261, http://dx.doi.org/10.1190/1.3475413.

Lokshtanov, D., 2001, Suppression of water-layer multiples and peg-legs by wave-equation approach: 63rd Conference and Exhibition, EAGE, Extended Abstracts, IM-1.

Moore, I., 2004, Method for attenuating water-layer multiples: U. S. Patent 1,6832161B1.

Moore, I., and R. Bisley, 2006, Multiple attenuation in shallow-water situations: 68th Conference and Exhibition, EAGE, Extended Abstracts, F018.

Moore, I., and B. Dragoset, 2008, General surface multiple prediction: A flexible 3D SRME algorithm: First Break, **26**, no. 9, 89–100.

Özbek, A., M. Vassallo, K. Özdemir, D.-J. van Manen, and K. Eggenberger, 2010, Crossline wavefield reconstruction from multicomponent streamer data: Part 2 — Joint interpolation and 3D up/down separation by generalized matching pursuit: Geophysics, **75**, no. 6, WB69–WB85, http://dx.doi.org/10.1190/1.3497316.

van Groenestijn, G.-J., W. Ross, and G. N. Cumaran, 2012, Connecting deconvolution and SRME: 82nd Annual International Meeting, SEG, Expanded Abstracts, http://dx.doi.org/10.1190/segam2012-1274.1.

Verschuur, D. J., 2012, Seismic multiple removal techniques: Past, present and future: EAGE Publications, Education Tour Series.

Wang, P., H. Jin, M. Yang, and S. Xu, 2014, A model-based water-layer demultiple algorithm: First Break, **32**, no. 3, 63–68, http://dx.doi.org/10.3997/1365-2397.2014002.