Multiple elimination using a pattern-recognition technique

ANTOINE GUITTON, CGG, Houston, Texas, U.S., and GUILLAUME CAMBOIS, CGG, Calgary, Canada

Standard prestack multiple elimination techniques, such as predictive deconvolution or Radon transforms, fail in the presence of complex structures.

A technique popularized by the Delphi consortium offers an attractive alternative in 2-D because it is theoretically independent of subsurface structure and can therefore attack all surface-related multiples regardless of their complexity.

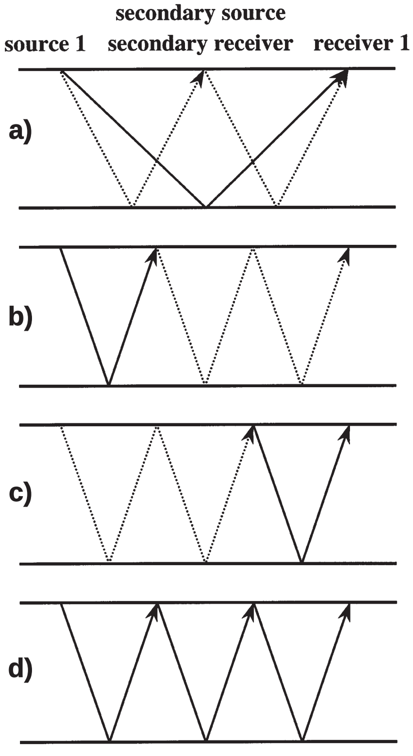

Figure 1. Construction of surface-related multiples by convolution of primary arrivals. (a) For a flat event, the first-order multiple is constructed using primaries from two secondary traces which have either a source or a receiver at the midpoint between the original source and receivers. (b-c) The second-order multiple is constructed twice (b-c) using a combination of primaries (solid lines) and multiples (dotted lines). (d) This multiple is also modeled by the combination of three primary arrivals. Since (d) and (b-c) have opposite polarity, the sum of these three arrivals results in a correct amplitude estimate for the second-order multiple.

The Delphi approach can be summarized by the following equation:

$$P_0 = P + W^{-1} P * P + W^{-2} P * P * P + \ldots$$

(where P is the input data, P_0 is the multiple-free data, W is the seismic wavelet, and * indicates 2-D convolution). Figure 1 illustrates the process for a flat event. The first-order direct multiple is constructed as the convolution of the two primary arrivals that follow the multiple raypath (Figure 1a). The second-order multiple is modeled twice as a combination of primary and first-order multiple arrivals (Figure 1 b-c). The convolution of three primary arrivals (Figure 1d) compensates for this excess modeling. Thus, the first 2-D convolution in the equation models the kinematics of all orders of multiples, but only first-order multiples have correct amplitudes. The further convolution terms are necessary to correct the amplitudes of higher-order terms. Also, each 2-D convolution models multiples with an additional convolution of the original wavelet, which explains the inverse terms in the equation.

In essence, the Delphi technique has two steps: (1) compute all relevant convolution terms and (2) find the wavelet W that minimizes the energy of P_0. Consequently, it theoretically provides multiple-free data and an estimate of the seismic wavelet. The first step of the method constructs a multiple model without any knowledge of or assumptions about the subsurface and can therefore handle the most complex structures. However, since this model is based on 2-D convolutions, it suffers from edge effects. The second step involves a costly nonlinear inversion, where the only adaptive parameters are the wavelet samples. (It has been argued that this single-wavelet approach cannot adequately address the angle-dependency of actual marine sources.)

The problems associated with the limited offset range can be seen in

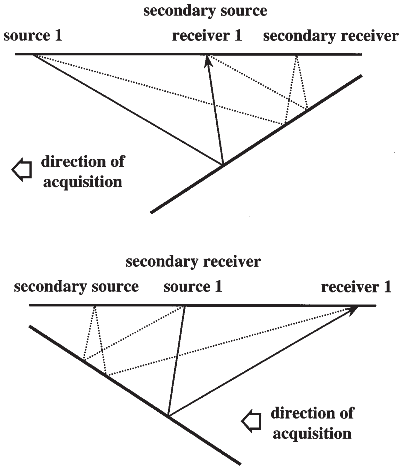

Figure 2. Multiple construction for steeply dipping events. The secondary traces may have larger offsets than the selected primary. These multiples can only be constructed if all secondary offsets are recorded by the spread.

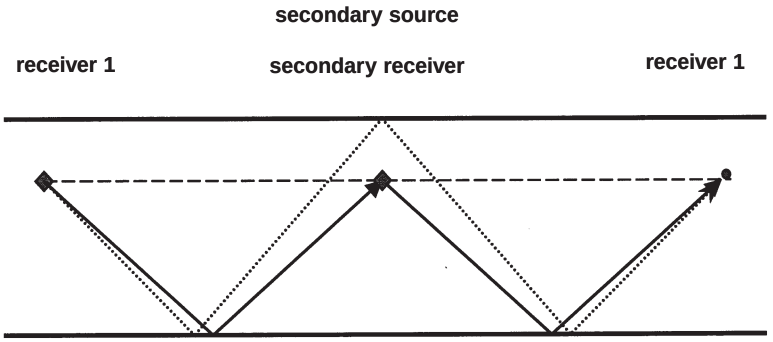

Figure 3. Actual (dotted line) and modeled (solid line) raypaths. At normal incidence, the modeled multiple arrival is ahead of the actual multiple by a ghost period.

Figure 1: If source and receiver correspond to the shortest offset, there are no recorded traces between them to model the multiples. This drawback has long been identified, and numerous schemes to extrapolate the missing offsets have been published. However, the lack of short offsets only affects flat or gently dipping events. The offsets necessary to model the multiples of steeply dipping events may be larger than the targeted offset, as illustrated in Figure 2.

For this particular geometry, multiples are well modeled for short offsets but poorly modeled for large offsets. Depending on the configuration, middle-range offsets are also poorly modeled if one of the multiple legs requires an offset smaller than the minimum. Thus, the quality of multiple modeling at a given offset depends on the depth and dip of the reflectors and the range of recorded offsets. As a consequence, diffracted multiples, which cover the whole range of dips, can never be correctly modeled at any offset. Poorly modeled parts of the hyperbola include the apex for short offsets and the tails for large offsets.

Once the multiple field has been modeled through a series of 2-D convolutions, it is straightforward to compute the multiple-free data using the cited equation, provided that *W* is known. Since *W* is generally not known, the Delphi consortium proposed to estimate it via minimization of multiple-free energy. However, due to source and receiver ghosts, marine wavelets are angle-dependent. Thus, the assumption of one stationary wavelet for the whole survey does not hold. Note that the 2-D convolution modeling implicitly assumes that sources and receivers are located at the surface. Since this is not the case, there is a discrepancy between modeled and actual multiples, as illustrated in Figure 3. At normal incidence, modeled multiples are ahead of actual multiples by exactly a ghost period. In addition to the wavelet time- and offset-dependency, we have shown that the multiple model accuracy is itself time-, dip-, and offset-dependent. It is therefore unlikely that a relatively short wavelet provides enough degrees of freedom to correct for all these modeling errors. As a result, a more adaptive approach that will address all the model's inadequacies, while preserving the integrity of primary energy, is needed.

Multiple removal using a pattern-recognition technique. In 1991, Doicin and Spitz described a pattern-recognition technique that was particularly effective at removing identified multiple events. Since the multiple pattern is solely defined as 3-D structural shape, real and modeled multiples can have completely different wavelets. Furthermore, the pattern is

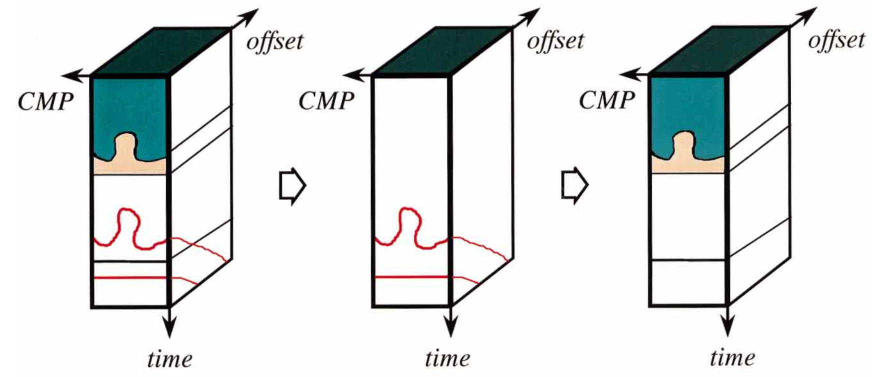

Figure 4. Schematic of the pattern-recognition algorithm. NMO-corrected input traces (left), NMO-corrected multiple model (center), and multiple-free traces (right). The pattern is a 3-D subset in time, CMP, and offset. Everything in the left block that resembles the pattern in the center is removed, leaving the data on the right.

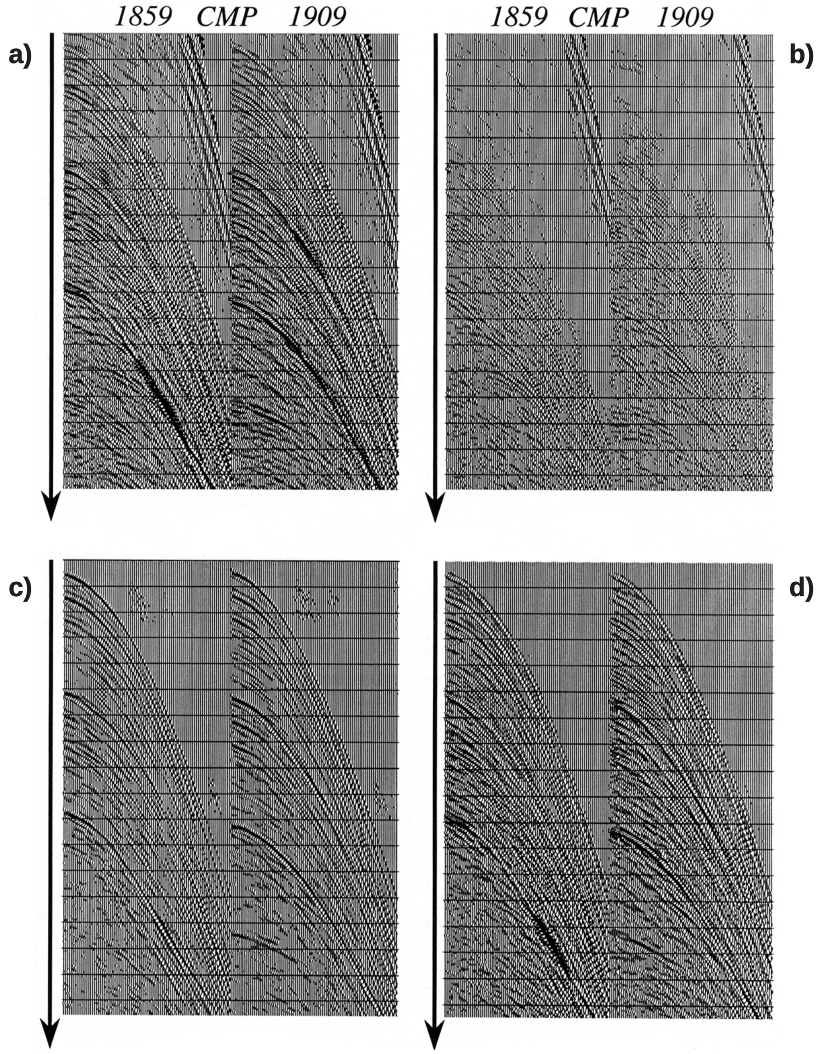

Figure 5. CMP gathers (a) before and (b) after multiple elimination. The multiple model, or pattern (c); has been adapted for optimum removal (d); (b) equals (a) minus (d). The vertical axis ranges from 3500 to 5250 ms.

designed within a sliding cube so that the wavelets do not have to be constant over the whole survey. The method we propose in this paper uses the multiple model derived from the first step of the Delphi approach as the input pattern. Then everything that resembles this pattern within a given subset is removed from the data. Since a subset is defined as a cube in time, CMP, and offset, the method uses both structure and differential moveout to discriminate primaries from multiples (Figure 4). Primaries can only be removed in the unlikely event that they have the same structure and the same moveout as multiples over a significant period of time. Therefore, the proposed scheme offers an improved mechanism for discrimination of primaries from multiples.

This new process can effectively handle time- and offset-dependent model inaccuracies. However, in the presence of conflicting dips, relative amplitudes between the different multiple events are not preserved, and the pattern loses some accuracy. Moreover, as discussed earlier, the simple 2-D convolution models all orders of multiples with correct kinematics, but only first-order multiples have correct amplitudes. Thus, in the presence of conflicting orders of multiples, the pattern suffers from inaccurate relative amplitudes, which subsequently affect the results of our adaptive recognition technique.

Application to a Gulf of Mexico example. This 2-D data set was acquired in a deep-offshore environment over a shallow salt pillow. The particular salt geometry and the water-bottom structure combine to generate surface-related multiples that directly interfere with subsalt geology. Figure 5 shows two CMP gathers before and after multiple elimination. Most multiple energy has been removed. Although these gathers are not NMO-corrected, normal moveout was applied prior to multiple elimination. Figure 5c shows the corresponding multiple model (computed using the Delphi 2-D convolution) and Figure 5d the extracted multiples. The pattern-recognition technique has adapted the amplitudes in a time- and offset-dependent manner for optimum removal. Figure 6 is similar to Figure 5 but shows data after NMO correction and stack. Again, most multiple energy has been removed, and a real dipping event at the bottom of the section clearly appears free of multiples. Figure 6d establishes that the pattern-recognition technique has efficiently adapted the multiple model to match the actual multiples but has not removed any primary events. A significant amount of residual multiple energy remains in the upper part of Figure 6b. Because this corresponds to an area covered with diffracted multiples, we need to assess whether the pattern-recognition technique can cope with the model inaccuracies reported earlier.

Figure 7 shows the same gathers as Figure 5 but after applying an *f-k* filter to common offset planes. The filter was designed to eliminate all flat and gently dipping events, so that the gathers contain only steeply dipping events. The red arrows point to interesting features that are strongly nonhyperbolic because their apex is not at zero-offset. They correspond on the stack to what we have called diffracted multiples, but they obviously have very complex travel paths that are probably associated with the presence of salt. These events are crossed by weaker dipping events in the raw gathers (Figure 7a), and the kinematics of both sets of events have been accurately modeled in the multiple gathers (Figure 7b), confirming that they indeed correspond to multiple energy. However, because these multiples have conflicting dips, their relative amplitudes have not been correctly modeled, and the weaker dipping events are stronger than the nonhyperbolic events. Consequently, the effectiveness of the pattern-recognition technique is limited (Figure 7c). Since most multiple energy in these gathers comes from flat events (compare Figures 5a and 7a), none of the dipping multiple events has been adequately removed. It is nonetheless noteworthy that parabolic Radon

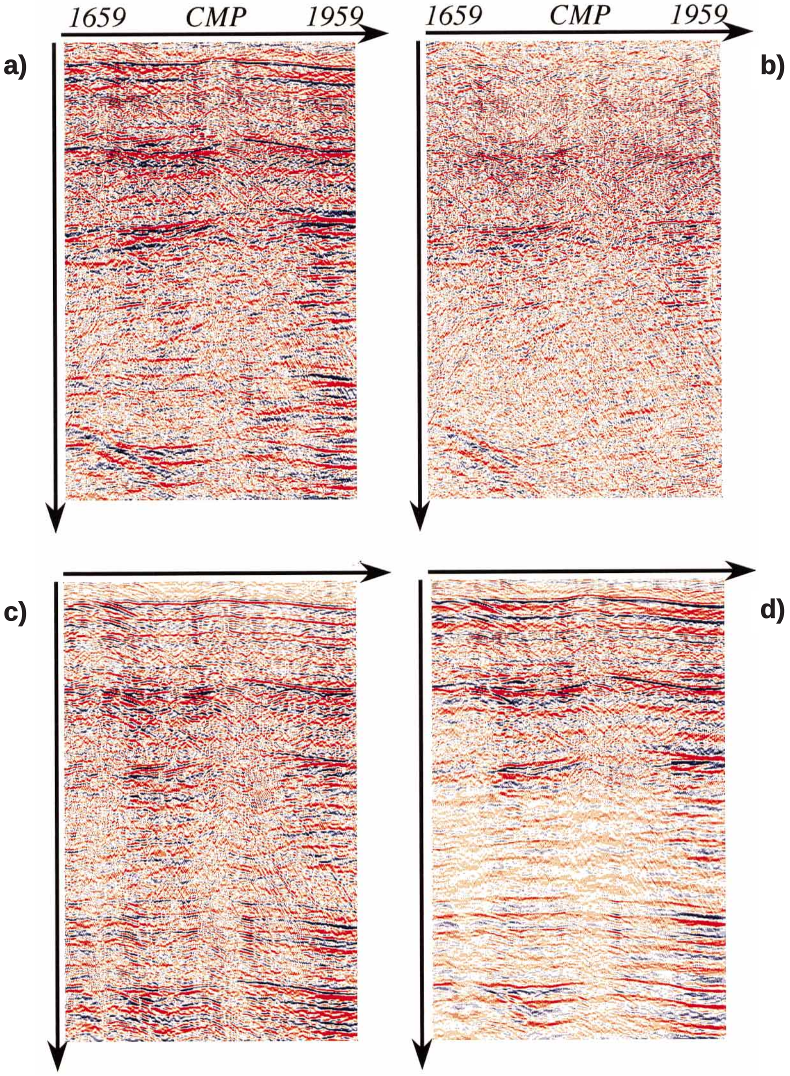

Figure 6. Stack sections (a) before and (b) after multiple elimination. (c) The multiple model has been adapted in a time- and space-variant manner for optimum removal (d). The vertical axis ranges from 3900 ms to 6600 ms.

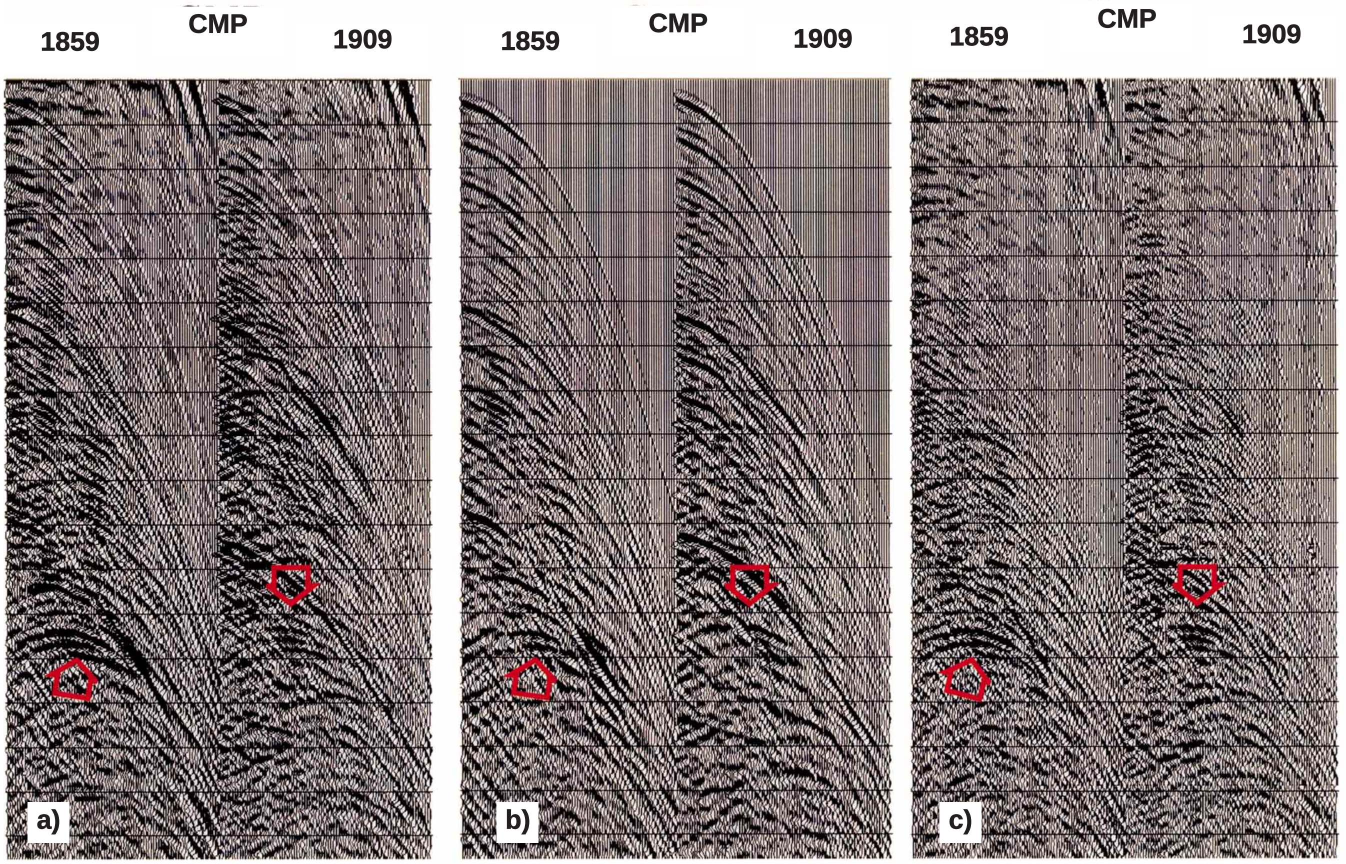

Figure 7. CMP gathers after *f-k* filter on offset planes to remove flat and gently dipping events. (a) compares to 5a, (b) to 5c, and (c) to 5b. The red arrows indicate strong nonhyperbolic multiple events. Conflicting dips have been modeled with correct kinematics but inaccurate amplitudes, which limits the effectiveness of the pattern-recognition technique.

transform would be totally ineffective in the presence of such multiples.

As mentioned earlier, the multiple model is also inaccurate in the presence of conflicting orders of multiples. Figure 8 shows a portion of the section where the third-order multiple of a flat event conflicts with the peg-leg multiple of a dipping event. Because the latter is modeled with abnormally large amplitudes, the pattern-recognition technique fails to adequately attenuate the first-order peg-leg.

Despite its shortcomings, our proposed method successfully removes most multiple energy in the data. Figure 9 shows how the subsalt structure, initially covered with multiple interference, clearly appears after multiple attenuation. The geology is still blurred by residual multiples in a zone at about 5 km. This is due to the presence of strong diffracted multiples that cannot be modeled properly since they contain all possible dips. Other than that, the technique has successfully managed to provide efficient multiple attenuation without damaging the image of primary events.

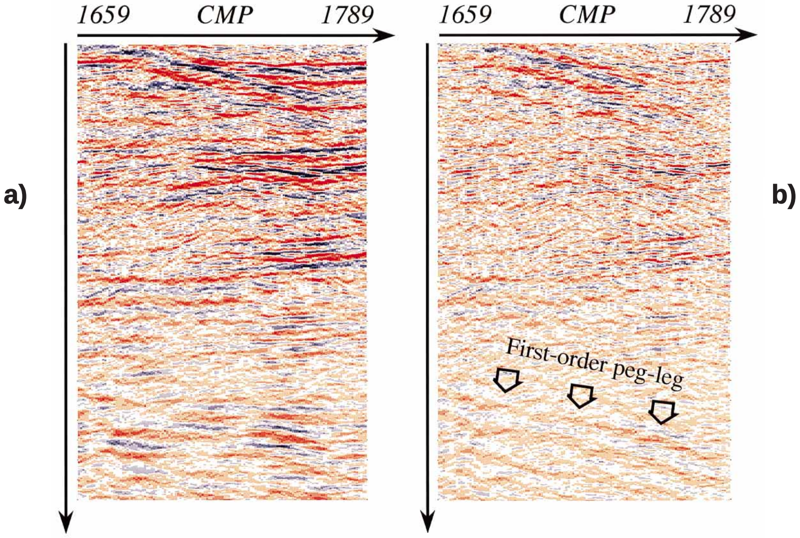

Figure 8. Stack sections (a) before and (b) after multiple removal. The dipping event that appears in the lower part of (b) is a first-order peg-leg multiple of the dipping event in the upper part of (b). The pattern-recognition algorithm was only successful at removing the conflicting third-order multiple because it was modeled with an abnormally large amplitude. The vertical axis ranges from 6200 ms to 8500 ms.

A posteriori wavelet estimation. After calculation of the actual multiples using the pattern-recognition technique, it is theoretically possible to estimate the wavelet by designing a matching filter between extracted

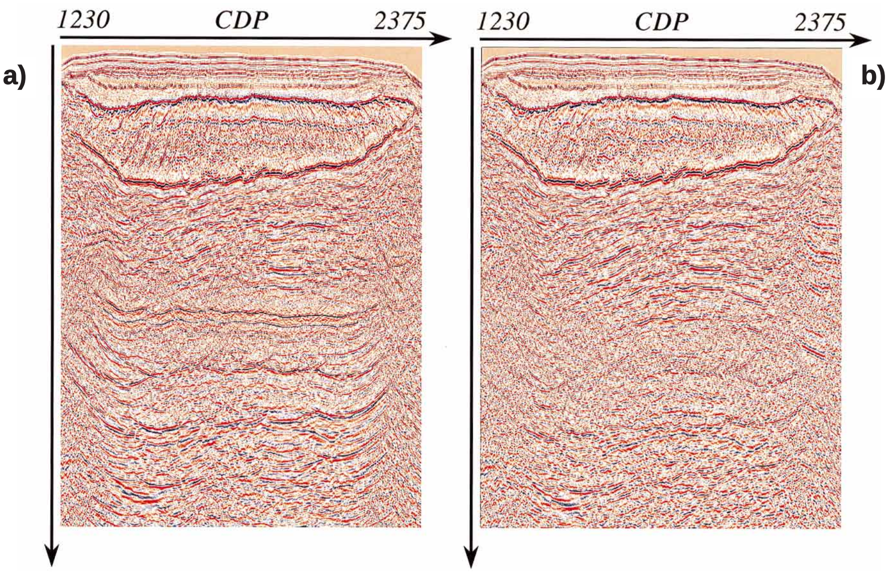

Figure 9. Prestack depth migrated section (a) before and (b) after multiple removal. Even though some diffracted multiple energy remains, the subsalt geology clearly appears after multiple removal. The vertical axis ranges from 1200 m to 6800 m.

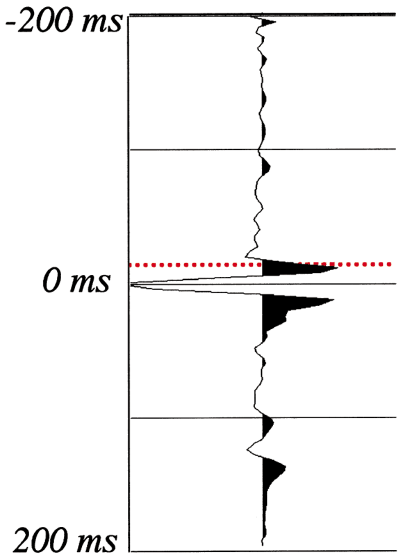

Figure 10. Estimated wavelet. The red dotted line corresponds to the theoretical ghost period that shows the extent of the upward shift.

and modeled multiples (Figure 5). When computed on first-order multiples only, this wavelet is identical to what would be obtained from the Delphi nonlinear inversion technique. Yet in our case, the extraction simply amounts to a Wiener-Levinson filter. The depth of the water bottom in this example makes it possible to isolate areas containing only first-order multiples. The resulting wavelet (Figure 10) looks like a typical causal marine wavelet with its two ghosts. As predicted, it is shifted upward by exactly a ghost period (the dotted line represents the actual ghost period according to theoretical gun and cable depths). There is also some repeat of the wavelet 120 ms below the main lobe. This feature, confirmed by a conventional minimum-phase wavelet extraction technique, is probably an array tuning effect.

Instead of estimating one wavelet for the whole survey, it is possible to extract one wavelet per shot point or per offset plane, or even per trace (although such an estimate would be highly unreliable). Figure 11 shows how the estimated wavelets vary with offset. Even though these estimates are fairly stable, the significant differences are evidence that the single wavelet approach does not provide optimum multiple attenuation.

The upward shift, equal to a ghost period, does not vary with offset as Figure 3 would seem to suggest. In reality, the main trough of the wavelet always arrives at the actual onset time because it is modeled using

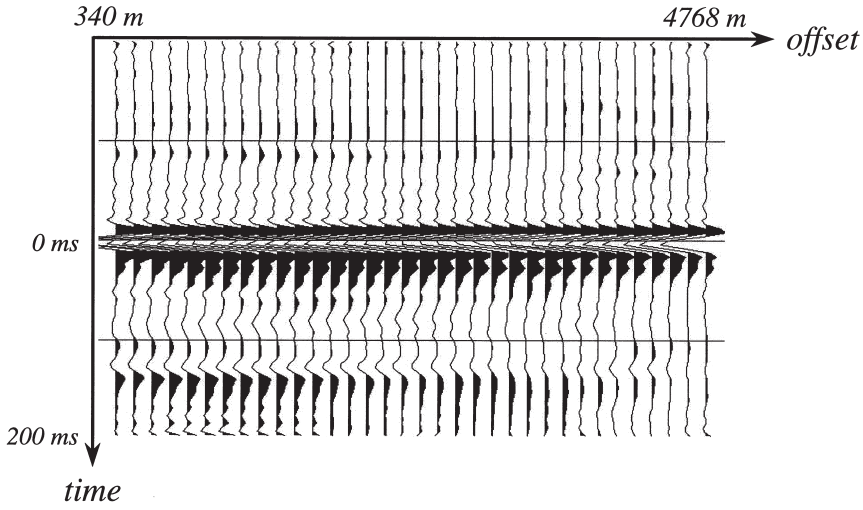

Figure 11. Wavelet variation with offset. Even though the estimates are fairly stable, the significant differences are evidence that the single-wavelet approach does not provide optimum multiple attenuation.

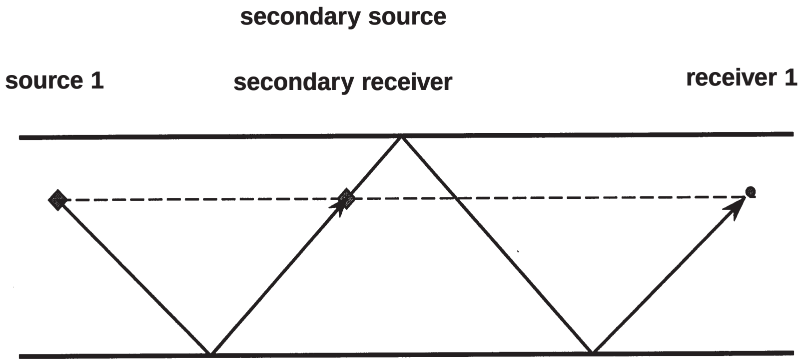

Figure 12. The direct multiple arrival is exactly modeled by a combination of direct and ghosted primaries.

direct and ghosted primary arrivals (Figure 12). Thus, in the Delphi method, the multiple modeling step correctly honors the time- and offset-dependency of the marine wavelet while the single wavelet inversion step ignores it.

Conclusions. The surface-related multiple elimination technique proposed by the Delphi consortium provides a kinematically correct multiple model, even for the most complex 2-D structures. However, the limited offset range of field data introduces time-, dip-, and offset-dependent amplitude anomalies in the model. This, plus the fact that actual marine wavelets are time- and offset-dependent, limits the effectiveness of the multiple removal approach based on the inversion of a single wavelet. Instead, we propose to use a 3-D pattern-recognition algorithm that is much more adaptive than a single wavelet, yet preserves the integrity of primary events. This new method provides optimum multiple elimination as long as the input model (or pattern) accurately describes the actual multiple structure. In case of conflicting dipping events, particularly in the presence of diffracted multiples, the amplitude artifacts associated with the model limit the effectiveness of the method. However, the results are always better (and more cost-effective) than using nonlinear wavelet inversion. When first-order multiples can be isolated, it is possible to extract the optimum matching wavelets from the pattern-recognition results. These wavelets have been shown to be indeed offset-dependent, confirming the limitations of the single-wavelet approach.

Suggestions for further reading. The Delphi multiple attenuation technique is described in numerous Delphi consortium reports. It was published by Verschuur, Berkhout, and Wapenaar in GEOPHYSICS in 1992. Their work has inspired many other authors, such as Ikelle, Amundsen, and Eiken (*TLE*, 1997). The pattern-recognition technique applied to specified peg-leg attenuation was presented by Doicin and Spitz in SEG's 1991 *Expanded Abstracts*.

Acknowledgments: The authors thank Western Geophysical for allowing the use of the data from the Gulf of Mexico.

Corresponding author: G. Cambois, Gcambois@ca.cgg.com.