Prestack elimination of complex multiples: a Gulf of Mexico subsalt example

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Summary

Since the surface-related multiple elimination technique popularized by the DELPHI consortium is independent of subsurface structure, it can theoretically be used in any complex environment. In practice, however, the limited offset range of field data introduces time-, dip- and offset-dependent amplitude artifacts into the multiple model. This, plus the fact that sources and receivers are located below the water surface, make it impossible to extract a relevant wavelet, which is a critical step in the method. Consequently, this technique is not adaptive enough to provide adequate multiple attenuation.

A new method has been developed that eliminates the need for wavelet extraction in the DELPHI technique. It utilizes the kinematically accurate multiple model and applies a pattern-recognition algorithm to remove the actual multiples. This adaptive technique offers optimum multiple attenuation without damaging the primaries. However, its effectiveness is still somewhat limited by the amplitude inaccuracies of the multiple model.

In areas where first-order multiples can be isolated, it is possible to extract *a posteriori* the seismic wavelet using a simple matching filter between estimated and modeled multiples. Studies of these extracted wavelets have shown that they are indeed offset-dependent, confirming the limitations of the single wavelet approach. Thus, the pattern-recognition technique always gives better results than the costly non-linear wavelet inversion associated with the DELPHI technique.

Introduction

The complexity of salt structures in the Gulf of Mexico imposes the use of prestack depth migration for subsalt imaging. As exploration moves to deeper waters, the presence of surface multiples makes subsalt imaging even more difficult. Standard prestack multiple elimination techniques, such as predictive deconvolution or Radon transforms, fail in the presence of complex structures. The surface multiple elimination technique of Verschuur et al. (1992) offers an attractive alternative in 2D since it is theoretically independent of subsurface structure.

This approach can be summarized by this equation:

$$P_0 = P + W^{-1} P * P + W^{-2} P * P * P + ... \qquad (1)$$

where P is the input data, P_0 is the multiple-free data and W is the seismic wavelet. The * corresponds to the 2D convolution of the prestack data. Practically, the technique has two steps: (1) compute all the relevant convolution terms and (2) find the wavelet W that minimizes the energy of P_0 as expressed in equation (1). Therefore, the technique theoretically provides not only multiple-free data but also an estimate of the seismic wavelet.

The first step of the method constructs a multiple model without any knowledge or assumptions on the subsurface and can therefore handle the most complex structures. However, since this model is based on 2D convolutions, it suffers from edge effects. In particular, it is well known that short offset multiples are poorly modeled for flat events. The second step involves a costly non-linear inversion, where the only adaptive parameters are the wavelet samples. It has been argued that this single wavelet model cannot adequately address the angle-dependency of actual marine sources.

In this paper we show that there are additional artifacts associated with the DELPHI multiple modeling technique. Since the subtraction method is not adaptive enough to take these artifacts into account, it fails to adequately remove all surface-related multiples. We then propose an alternative subtraction technique, based on pattern-recognition, which offers improved multiple attenuation while preserving primary energy.

Impact of limited offset range on multiple modeling

Figure 1 is a schematic illustration of equation (1) for a flat event. The first-order direct multiple is constructed as the convolution of the two primary arrivals that follow the multiple ray-path. This scheme applies twice the original wavelet to the multiple model, which explains the inverse wavelet terms in equation (1). For a flat event, the multiple model at a given offset is constructed using traces of half that offset. For short offsets, these traces may not exist due to the minimum-offset recording limit. Thus, flat event multiples cannot be properly modeled for short offsets.

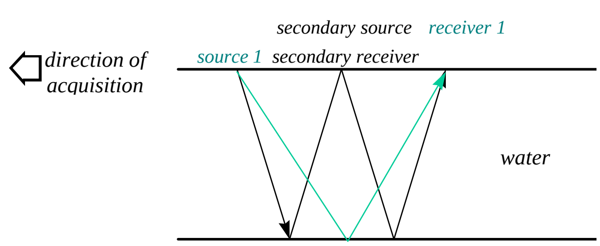

Figure 1: multiple modeling for a flat reflector.

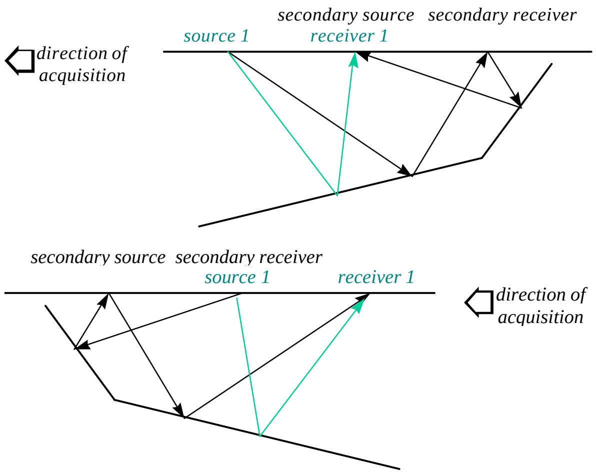

Figure 2: multiple modeling for dipping reflectors.

In the case of dipping reflectors, multiples at a given offset are modeled using traces belonging to a wide range of offsets. The necessary offsets may even 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.

Limitations of the single wavelet approach

Once the multiple field has been modeled through a series of 2D convolutions, it is straightforward to compute the multiple-free data using equation (1), provided that W is known. Since W is generally not known, Verschuur et al. (1992) propose to estimate it via minimization of multiple-free energy, using a costly non-linear inversion scheme. As a consequence, the only adaptive parameters in this multiple elimination process are the wavelet samples.

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. It is also interesting to notice that the 2D 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.

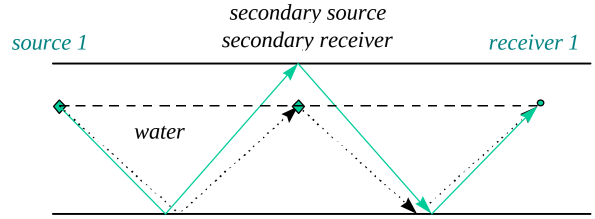

Figure 3: actual and modeled multiple paths.

In addition to the wavelet time- and offset dependency, we have shown in the last section 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. A more adaptive approach needs to be investigated that will address all the model's inadequacies. However, this new technique has to be intelligent enough to distinguish primaries from multiples.

Multiple removal using a pattern-recognition technique

In 1991, Doicin and Spitz described a pattern-recognition technique, particularly effective at removing identified multiple events. The multiple pattern is solely defined as a 3D structural shape, thus real and modeled multiples can have completely different wavelets. Furthermore, the pattern is 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. A subset is defined as a cube in time, CMP and offset. Thus, the method uses both structure and differential moveout to discriminate primaries from multiples, as illustrated in 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 adaptive mechanism which is able to discriminate primaries from multiples.

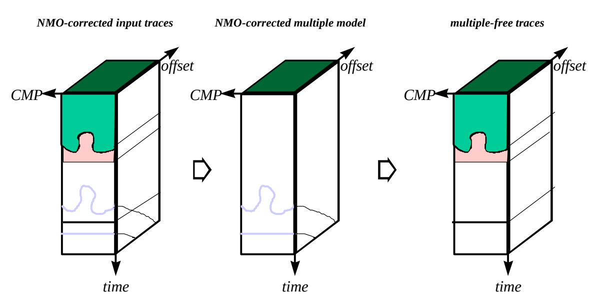

Figure 4: 3D pattern-recognition removal technique.

Time- and offset-dependent model inaccuracies can be effectively handled by this new process. However, in the presence of conflicting dips, relative amplitudes between the different multiple events are not preserved and the pattern loses some of its accuracy. Moreover, the simple 2D 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. To check the relevance of these caveats, we now apply this technique to a real data set from the Gulf of Mexico.

Application to a Gulf of Mexico data set

These 2D Gulf of Mexico data were 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. The purpose of this study is to attenuate multiples prior to prestack depth migration in order to obtain the best possible subsalt image.

Figure 5 first shows the result of prestack depth migration without any attempt to remove multiples. Most of the structure below salt is covered by multiple energy. After multiple suppression using the proposed method, most of this energy has disappeared and the subsalt structure becomes much clearer. However, there is a zone 5 km deep where the geology is still blurred by residual multiples. 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.

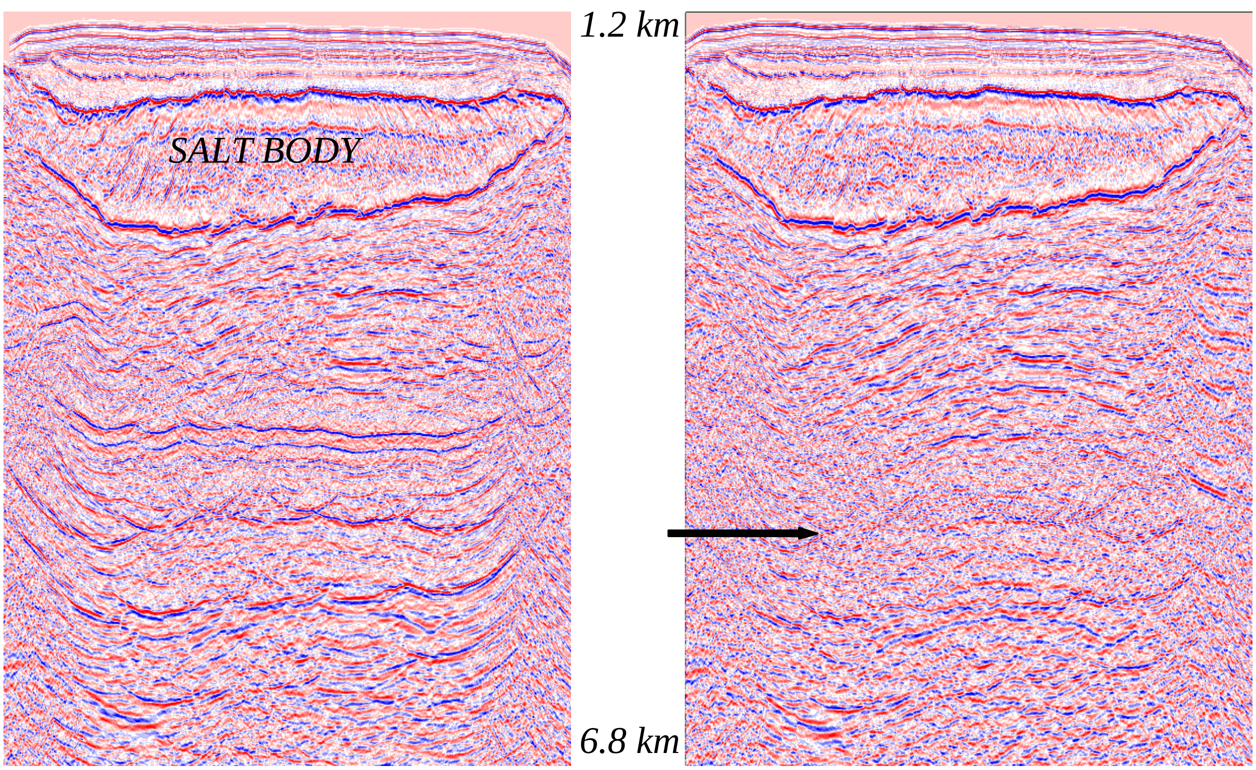

Figure 5: Prestack depth migration before (left) and after multiple attenuation (right). Most of the multiple energy has disappeared and the subsalt geology appears clearly. Some diffracted multiple energy remains as indicated by the arrow. (Data courtesy of Western Geophysical.)

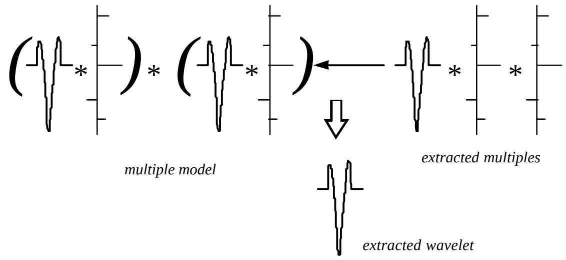

Figure 6: schematic wavelet estimation process.

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 and modeled multiples (Figure 6). When computed on first-order multiples only, this wavelet is identical to what would be obtained from the DELPHI non-linear inversion technique. Yet in our case, the extraction simply amounts to a Wiener-Levinson filter. The depth of the water-bottom in this Gulf of Mexico example makes it possible to isolate areas containing only first-order multiples. The resulting wavelet is displayed in Figure 7.

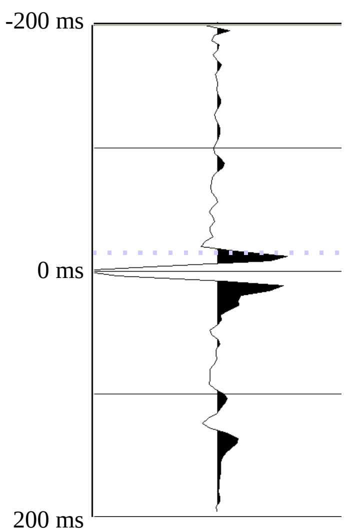

Figure 7: estimated wavelet.

This wavelet 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 kind of a repeat of the wavelet 120 ms below the main lobe. This feature, which was 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. In fact, it is even possible to extract one wavelet per trace although such an estimate would be highly unreliable. Figure 8 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.

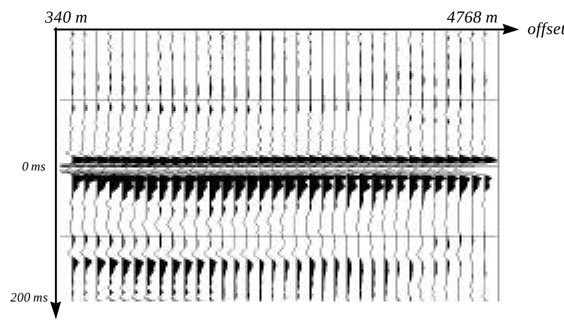

Figure 8: estimated wavelet as a function of offset.

Conclusions

The surface-related multiple elimination technique proposed by the DELPHI consortium provides a kinematically correct multiple model, even for the most complex 2D 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 3D 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 the non-linear wavelet inversion. When first-order multiples can be isolated, it is possible to extract the optimum matching wavelets from the pattern-recognition results. Study of these wavelets show that they are indeed offset-dependent, confirming the limitations of the single wavelet approach.

References

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