Shot-profile migration of multiple reflections

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ABSTRACT

A shot-profile migration algorithm is modified to image multiple reflections at their correct location in the subsurface. This method replaces the impulsive source with an areal source made of recorded primaries and multiples. In addition, the extrapolated wavefield at the receivers consists of recorded multiples only which have been previously separated from the primaries. Migration results with 2-D synthetic and field data prove that the migration of multiples can bring valuable structural information of the earth with or without separation.

INTRODUCTION

Seismic migration aims to move recorded seismic wavefield at the surface back into the earth at the reflector location from which they have originated. Multiple reflections, which are also recorded, are usually not accounted for in the migration process. Therefore, as a prerequisite to any correct imaging of the subsurface, multiples are traditionally attenuated (Guitton et al., 2001).

In this paper, I try to treat the multiples like signal rather than noise. My goal is to show that multiples can be easily imaged with a conventional shot-profile migration algorithm (Jacobs, 1982; Rickett, 2001). This migration is carried out in the (ω,x) domain. I will assess if the migration of multiple reflections adds any type of structural information and if it can increase the signal-noise ratio of the final image.

In the first section, I review theoretical aspects of shot-profile migration and expand its concepts to image multiples. In the second part, I show migration results with 2-D synthetic and field data. In the last section, I discuss practical aspects of multiple migration.

THEORY OF REFLECTOR MAPPING WITH SHOT-PROFILE MIGRATION

In this section, I review basic principles of earth imaging as pioneered by Claerbout (1971). Then I generalize these principles to reflector mapping with multiple reflections with a shot-profile migration algorithm.

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Imaging of primaries

Shot-profile migration aims to produce an image of the subsurface by extrapolating both the source and receiver wavefields into the interior of the earth. The imaging condition (Claerbout, 1971) consists of crosscorrelating the two wavefields at each depth-step. Reflectors are formed where the two wavefields correlate. Figure 1 illustrates this principle.

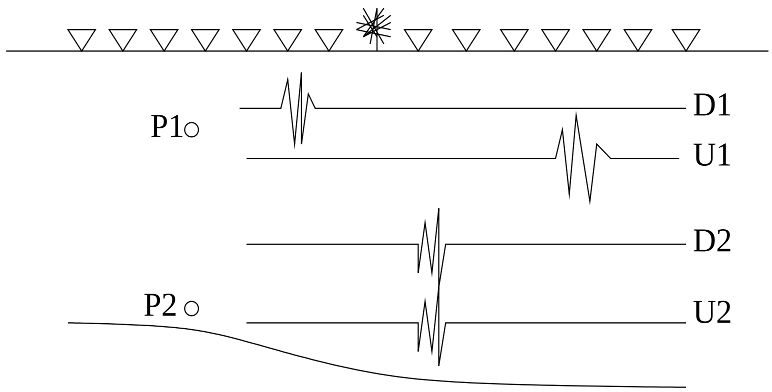

Figure 1: The up-going wavefield is recorded everywhere at the receiver locations (shown as triangles). The down-going wavefield is emitted at the source location in the center of the survey (shown as a star). At earth location P1, the two extrapolated wavefields do not crosscorrelate because the down-going wavefield arrives at a much earlier time than the up-going wavefield. At earth location P2, which is the reflector depth, the two wavefields crosscorrelate and an image is formed. Adapted from Claerbout (1971). updown [NR]

In general shot-profile migration is performed in the (ω,x) domain one frequency at a time and one shot at a time. The final image is formed by adding all the different contributions of every shot together.

Imaging of multiples

A similar machinery can be effectively used to image multiples at their correct location in the subsurface. I keep the same imaging principle as developed by Claerbout. The differences stem from the choice of up- and down-going wavefields I extrapolate.

Figure 2 illustrates the basic idea behind the migration of the multiples. In Figure 2(a), a wavefield generated at S is recorded at the receiver R_n. The reflector location r_a is imaged by extrapolating both the primary wavefield recorded at R_n and the source wavefield at S simultaneously in the subsurface and by crosscorrelating them at each depth step.

Similarly in Figure 2(b), a multiple recorded at R_n can be used to image the reflector location r_b if we use the primary wavefield recorded at the receiver R_1 as a source function. Hence a multiple reflection recorded at any receiver location can be used to image the subsurface if a primary is utilized as a source.

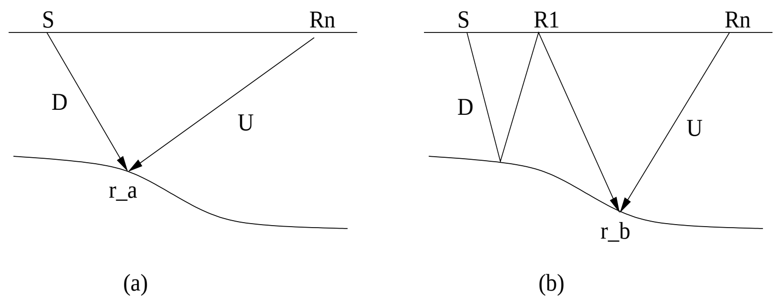

Figure 2: Illustration of the basic idea of reflector mapping with (a) primaries and (b) multiples. In (a) the primary images the reflector location r_a and the source is impulsive. In (b) the multiple helps to image the reflector location r_b and the source is a primary recorded at R_1. primult [NR]

Finding the exact location of R_1 for each multiple and each receiver position R_n would require an earth-model and many tedious computation steps. Fortunately, the imaging condition tells us that the image is formed if and only if the up- and down- going wavefields correlate. Therefore for a given receiver position R_n, we can use as a source function every single primary recorded on the seismic array since only relevant receiver positions R_1 would produce constructive crosscorrelations.

Now if we expand this idea to every receiver position R_n on the seismic array, we can produce an image of the earth by simply taking every recorded primary as the source function and every recorded multiple as the up-going wavefield. The impulsive source becomes an areal-shot record. In theory, any order of multiples can be properly imaged if their corresponding source path exists in the down-going wavefield. Hence first order multiples need primaries as sources, second order multiples need first order multiples, and so on.

Note that the source function needs to be time-reversed before the extrapolation. This is done in the (ω,x) domain by computing the complex conjugate of the source wavefield.

A similar approach has been presented by Berkhout and Verschuur (1994) using the so-called “WRW” model. Notice that so far, this approach works for surface-related multiples only but could be easily extended to internal-multiple migration.

A SYNTHETIC DATA EXAMPLE

In this section I use a modified version of the 2.5-D Amoco dataset (Etgen and Regone, 1998; Dellinger et al., 2000) to illustrate the migration of multiples. This data example proves that multiples can provide structural information on the earth.

The Amoco dataset

The synthetic dataset I use consists of a modified version of the 2.5-D Amoco velocity model. Figure 3 displays the velocity model. I have added a 500 meters water layer to generate water column reverberations. Two finite-differences modelings were done with and without free-surface conditions in order to easily extract surface-related multiples. The data were recorded with a split-spread geometry. 32 shots were acquired and processed for the final images.

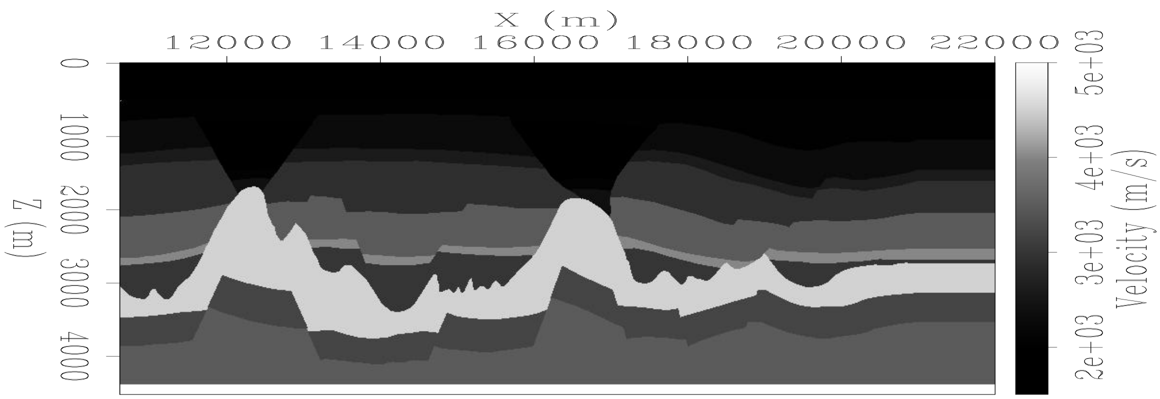

Figure 3: The velocity model used to generate the synthetic data. velamoco [NR]

Migration of one shot record

I illustrate the migration of multiples with one shot. In Figure 4 I display the source function on the left panel, and the recorded wavefield on the right panel. The recorded wavefield is the superposition of primaries and multiples. The migration result for this shot location is shown in Figure 6a.

Figure 5 displays the source function and the up-going wavefield for the migration of multiples. As proposed in the preceding section, the source function is not impulsive but areal. The recorded wavefield contains the surface-related multiples only. The migration result is shown in Figure 6b and compares favorably with the output of the migration of primaries.

It is interesting to note that the water-bottom is illuminated with a wider aperture when multiples are used. As illustrated in Figure 2, for a given receiver R_n, the primary illuminates the reflector in r_a at a closer location to the source in S than does the multiple in r_b. Therefore, for one given shot, the multiples migrate with a wider aperture but with smaller angles.

As a final result, I display in Figures 6c and 6d the different illumination patterns for both the impulsive and areal sources (Rickett, 2001). These maps are obtained by simply computing the amplitude (squared) of the down-going wavefield at each depth and for each frequency. These Figures illustrate the aperture and illumination effects of the multiples.

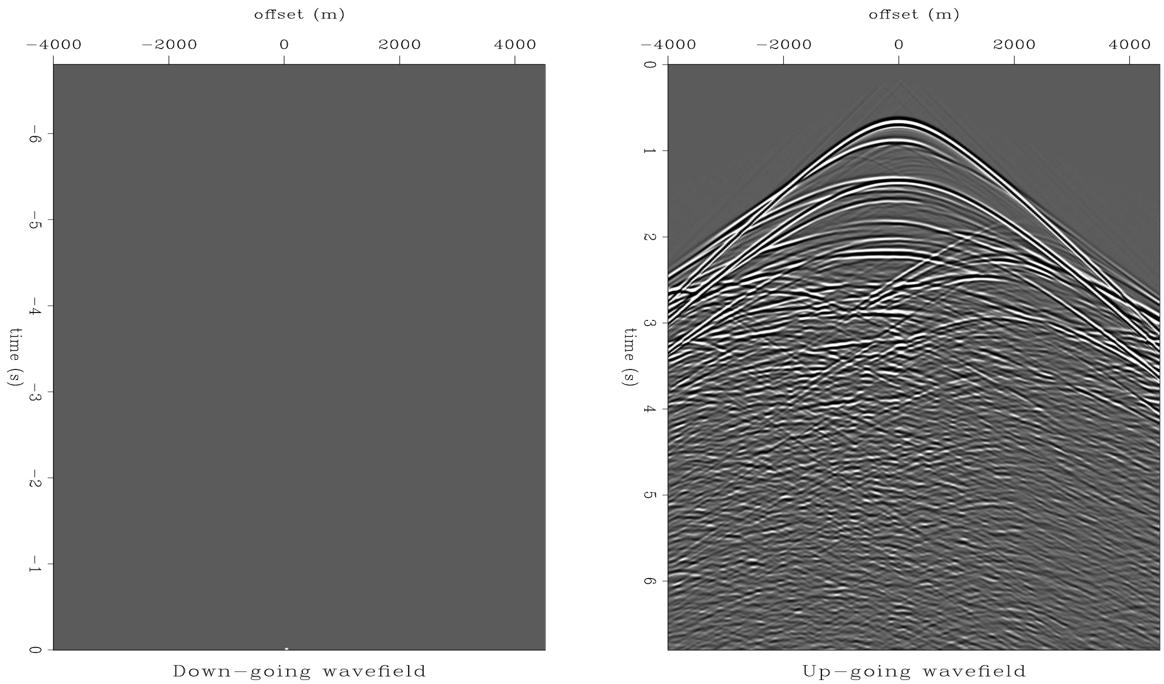

Figure 4: Shot-profile migration of the primaries. Left: Impulsive source function. Look closely at offset 0. meter and time 0. second to see the impulse. Right: Recorded primaries and multiples. shotprim14 [NR]

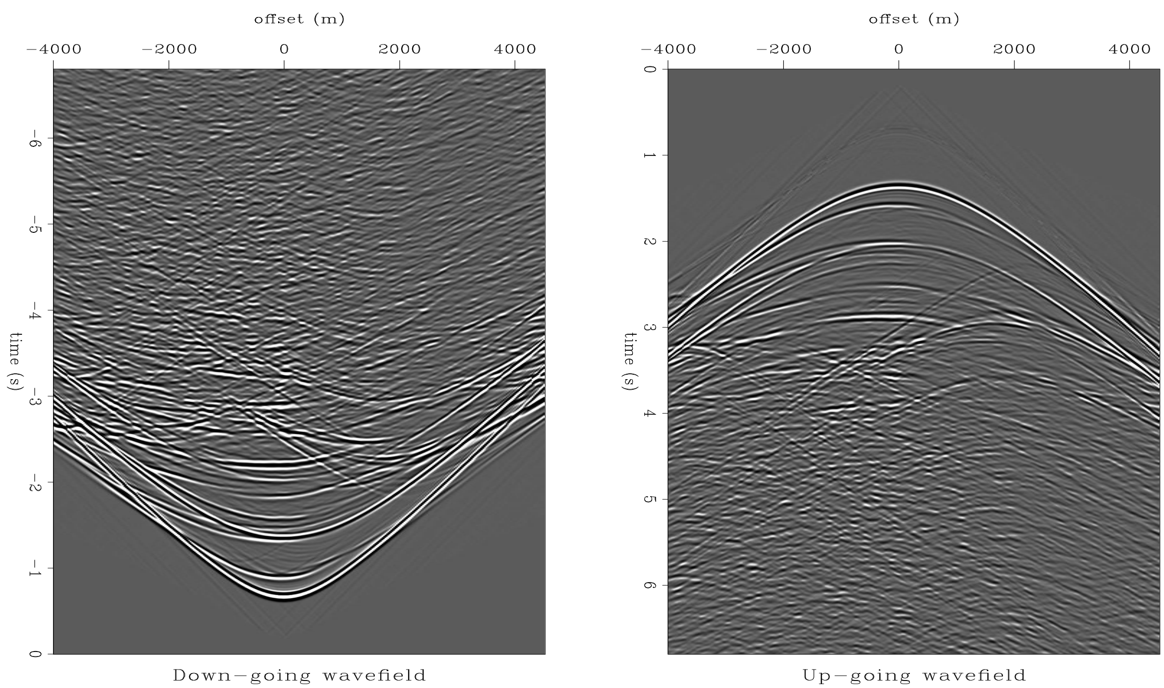

Figure 5: Shot-profile migration of the multiples. Left: Areal source function. Right: Recorded multiples only. The source function is plotted upside-down to represent the computation involved by the time-reversed process. shotmig14 [NR]

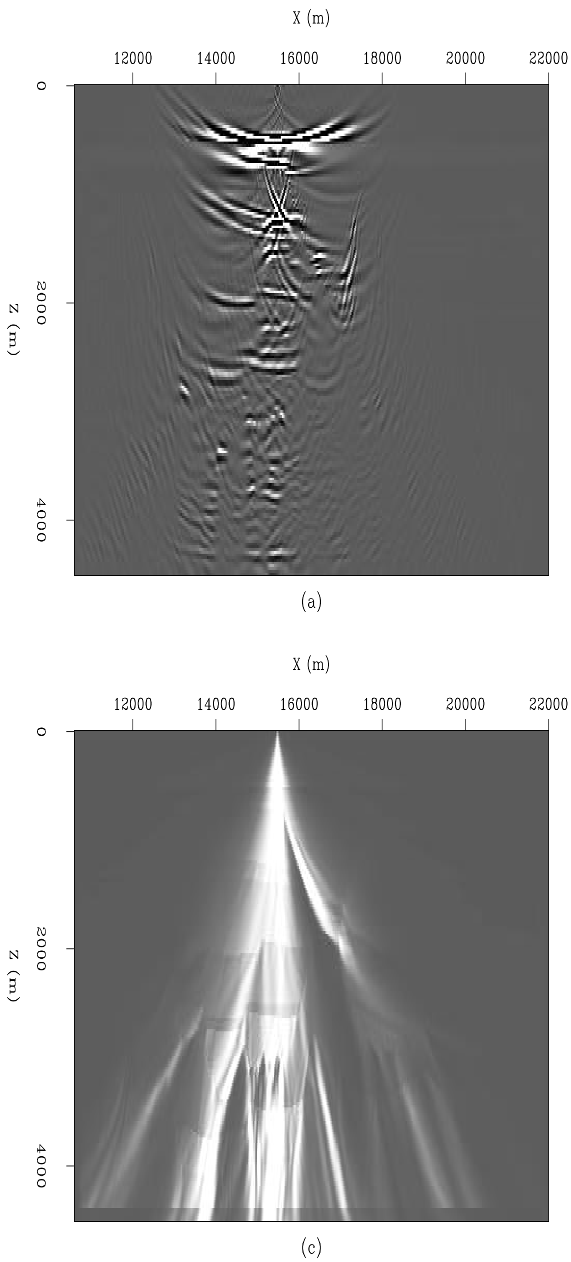

Figure 6: Migration results and illumination maps of the down-going wavefields for the imaging of multiples and primaries. (a) Migration of the primaries. (b) Migration of the multiples. (c) An illumination map for the impulsive source. (d) An illumination map for the areal source. compil14 [NR,M]

Migration of the survey

I now proceed to the final imaging steps of migrating every shot record and summing them. Figures 7a and 7b show the final migration result for both primaries and multiples. The two final images are quite similar although the migration of the primaries with the impulsive source is crispier and less noisy than with multiples. Nevertheless the migration of multiples yields an accurate image of the earth. After closer inspection, it seems that the flanks of the canyon in the middle above the salt dome is better defined with the multiples.

The illumination maps displayed in Figures 7c and 7d are almost identical after summation of all shot contributions. This comes from the acquisition geometry at the two ends of the survey. This first result is rather encouraging and shows that multiples can be used to image the earth.

Other migration results with multiples

I see two fundamental problems with the migration of the multiples. First, the final image is noisy, blurring precious information in some areas. Second, multiples need to be extracted from the data.

A good trick to decrease the noise level in the migration result is to use the water-bottom reflection only for the source. This can be done most of the time by applying a simple mute to the data. Figure 8 shows the up- and down-going wavefields if the water-bottom reflection is used as a source. Figure 9 displays a comparison of the migration of multiples with all the primaries as the source (Figure 9a) and the water-bottom as the source (Figure 9b). The noise level has decreased without loosing structural information. This result proves that for these data, most of the surface-related multiples are water-column reverberations.

The need for separating multiples might be quite dissuasive when field data are imaged because it might involve heavy computations and/or an earth model that might not be known in advance. Let us consider for a moment that we do not want to do the multiple attenuation but still want to do some imaging with multiples. This goal requires that the recorded data with primaries and multiples are used for both up- and down-going wavefields (Figure 10). Now I compare in Figure 11 the migration results when only multiples (Figure 11a) and multiples plus primaries (Figure 11b) are extrapolated in the up-going wavefield. The migration of primaries and multiples yields a noisy image but never-the-less structurally interpretable.

In the next section I migrate multiples for two 2-D lines. One survey comes from the Gulf of Mexico and the other from the North Sea. They demonstrate potential strengths and weaknesses of the proposed method for multiple migration.

TWO 2-D FIELD DATA EXAMPLES

I illustrate the multiple migration with field data. The first dataset is a deep-water survey with a shallow salt body. The second dataset is a North Sea survey with a relatively thick basalt

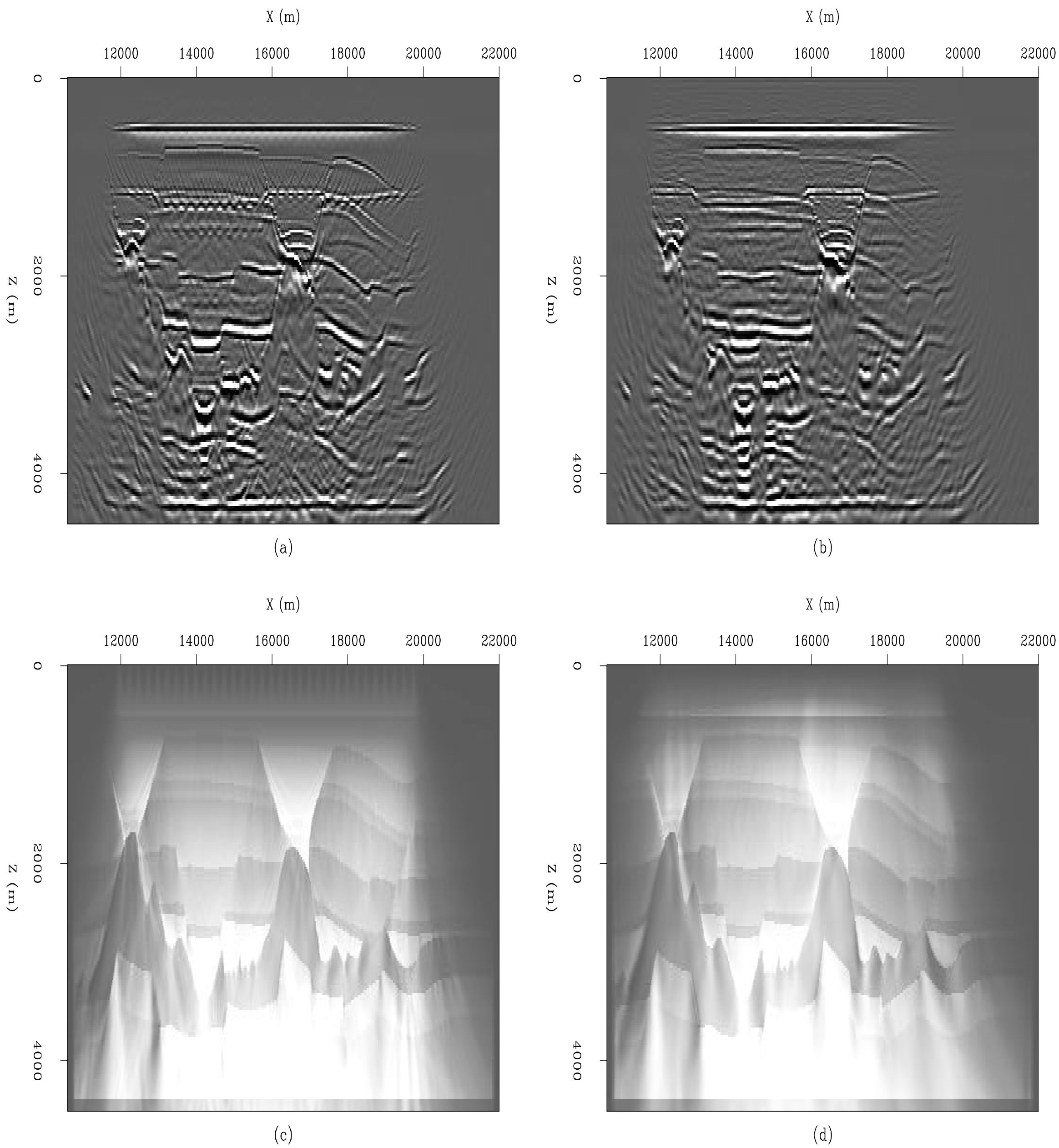

Figure 7: Final migration results and illumination maps. (a) Migration of the primaries. (b) Migration of the multiples. (c) An illumination map for all the impulsive sources. (d) An illumination map for all the areal sources. compmig [CR,M]

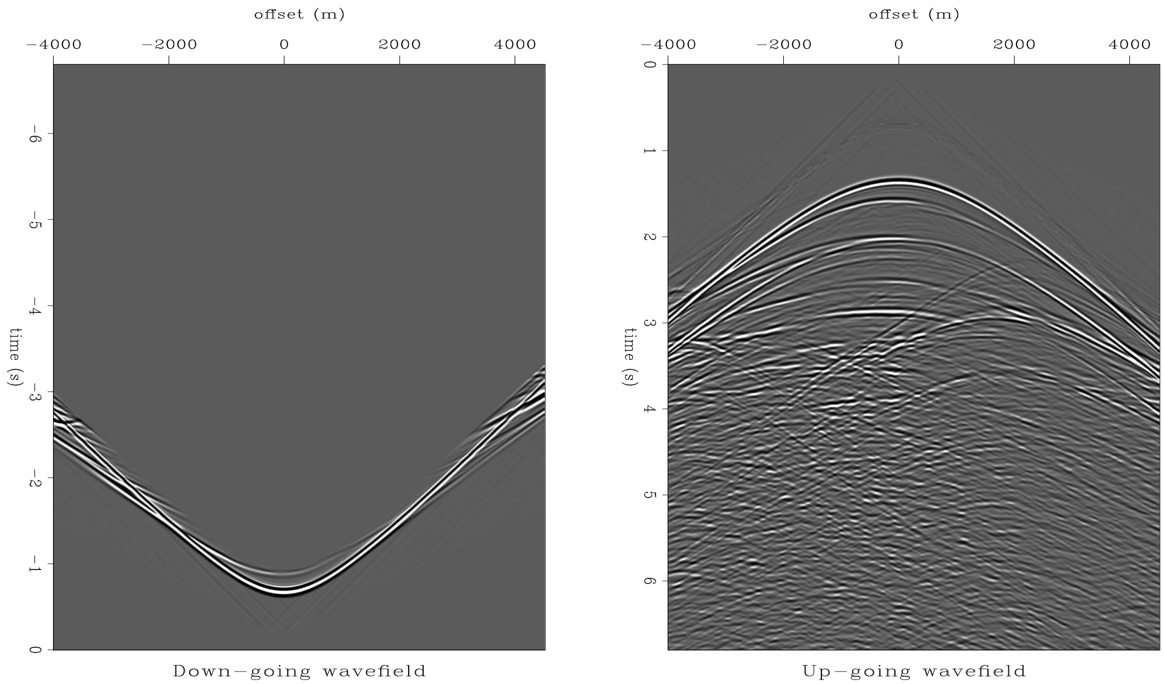

Figure 8: Shot-profile migration of the multiples. Left: Areal source function with the water-bottom reflection only. Right: Multiples. wbmig14 [NR]

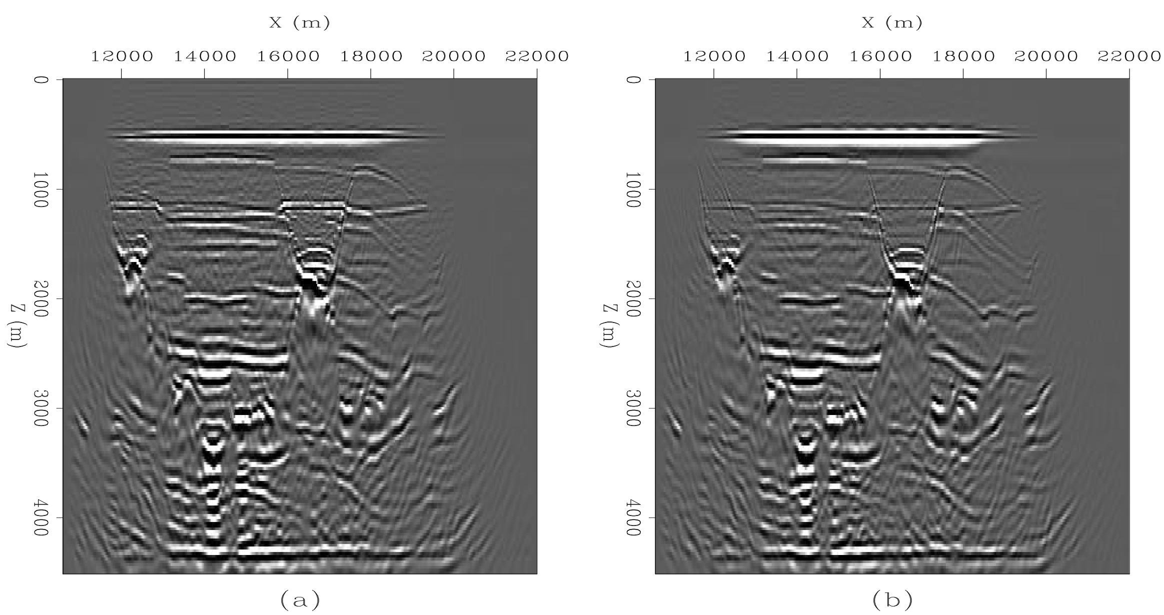

Figure 9: Migration results. (a) Multiples and primaries are used as a source. (b) The water-bottom reflection is used as a source. compwb [CR,M]

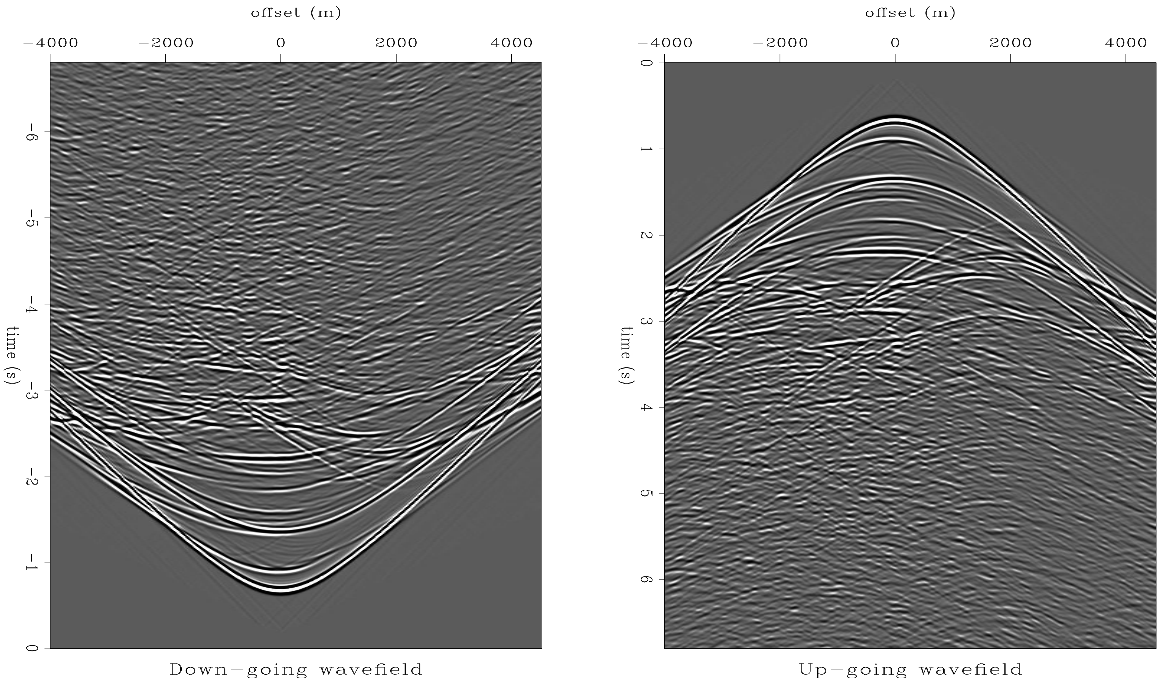

Figure 10: Shot-profile migration of the multiples. Left: Areal source function with primaries and multiples. Right: Multiples and primaries are extrapolated. allall14 [NR]

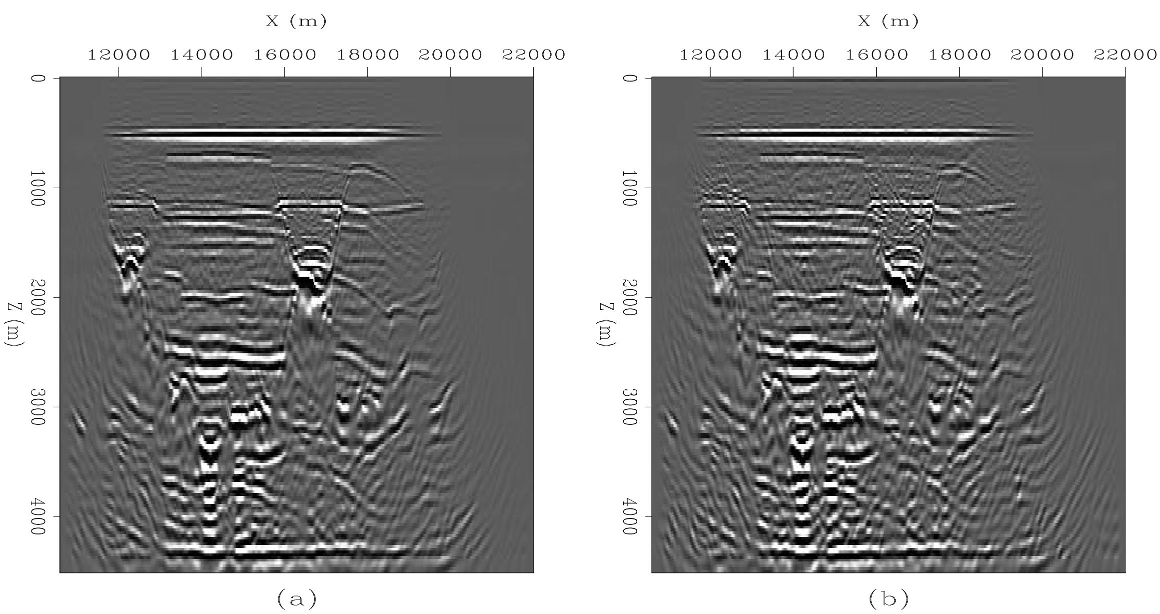

Figure 11: Migration results. (a) Same as Figure 7(b). (b) Imaging of multiples with primaries and multiples in the up-going wavefield. compall [CR,M]

slab.

A Gulf of Mexico example

This dataset has been intensively used for testing multiple attenuation techniques (The Leading Edge, January 1999). Figure 12 shows the velocity model that is used for the migration (Gratwick, 2001).

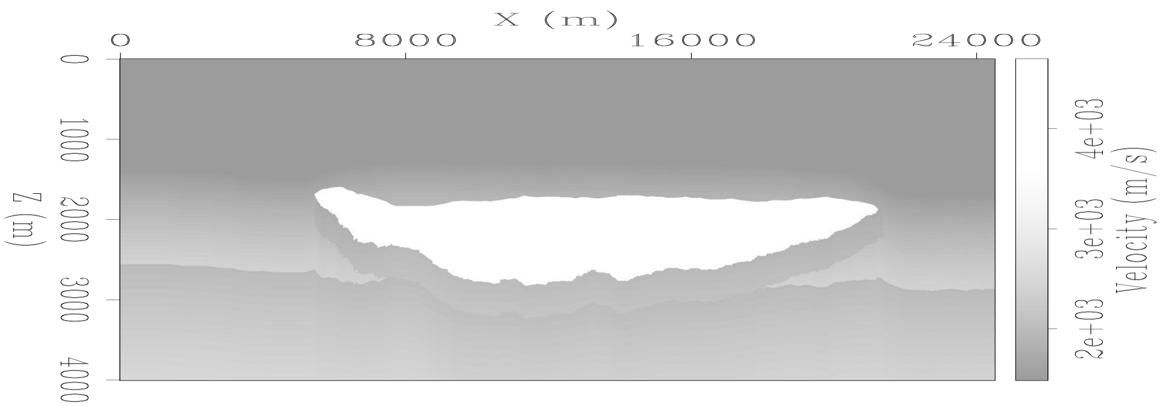

Figure 12: Velocity field for the Gulf of Mexico 2-D line. velgom [NR]

For this data set I did not separate primaries from multiples as required by the theory. As an approximate solution, I decided to mute everything above the first surface-related multiple for the up-going wavefield. Therefore the down-going wavefield is made of the complete shot and the up-going wavefield is made of the complete shot minus the primaries above the first surface-related multiple (Figure 13).

The migration results are displayed in Figure 14. Figures 14a and 14b show the migration results for primaries and multiples respectively. The two migrations produce similar results. Despite the approximations made, the multiple migration gives a very accurate image of the salt body and of the sediments.

A North Sea example

The North Sea dataset illustrates how challenging basalt imaging can be. The data are infested with internal and surface-related multiples. In addition, the internal layering of the basalt layer caused by repetitive basalt flows interlaced with sedimentary deposits make the identification of the bottom of the basalt very difficult. Kostov et al. (2000) attempted P-wave imaging with long-offset streamer data. Brown et al. (2001) tried imaging locally-converted shear waves.

Because multiples are so strong in this dataset, multiple migration might unravel some useful information. Again I did not separate multiples from primaries. I muted the up-going wavefield, as with the Gulf of Mexico data, to remove all the data above the first surface-related multiple.

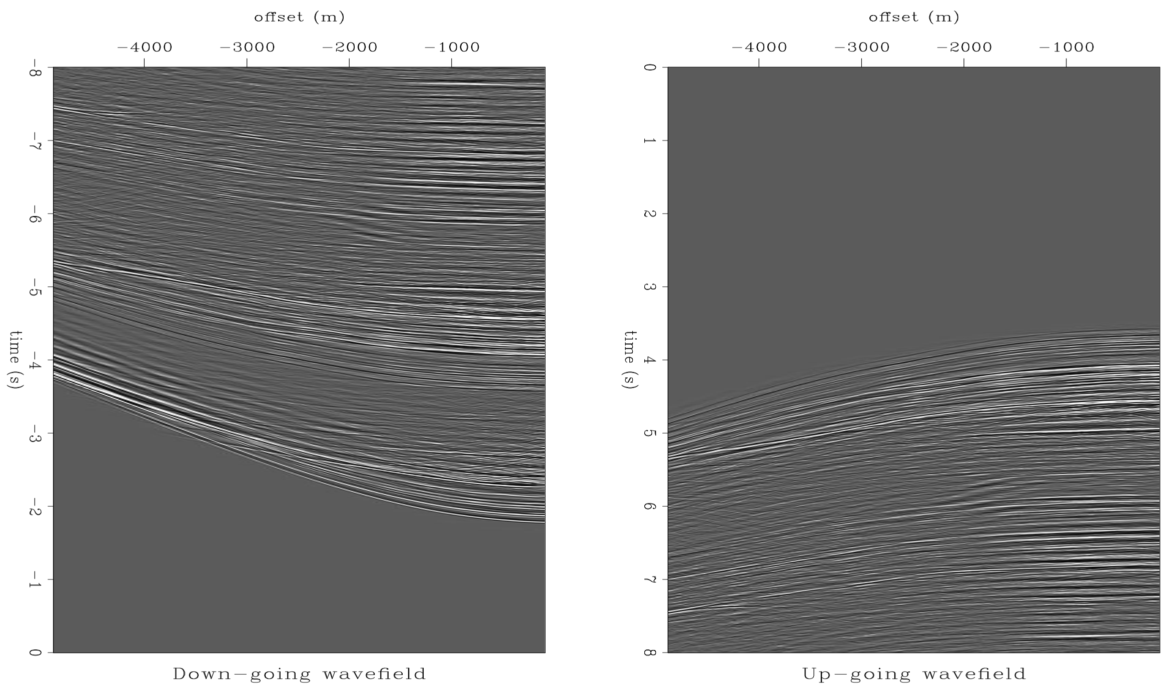

Figure 13: Left: The source function with primaries and multiples. Right: Same as the source function but with a mute above the first surface-related multiple. gom_ud_mult500 [NR]

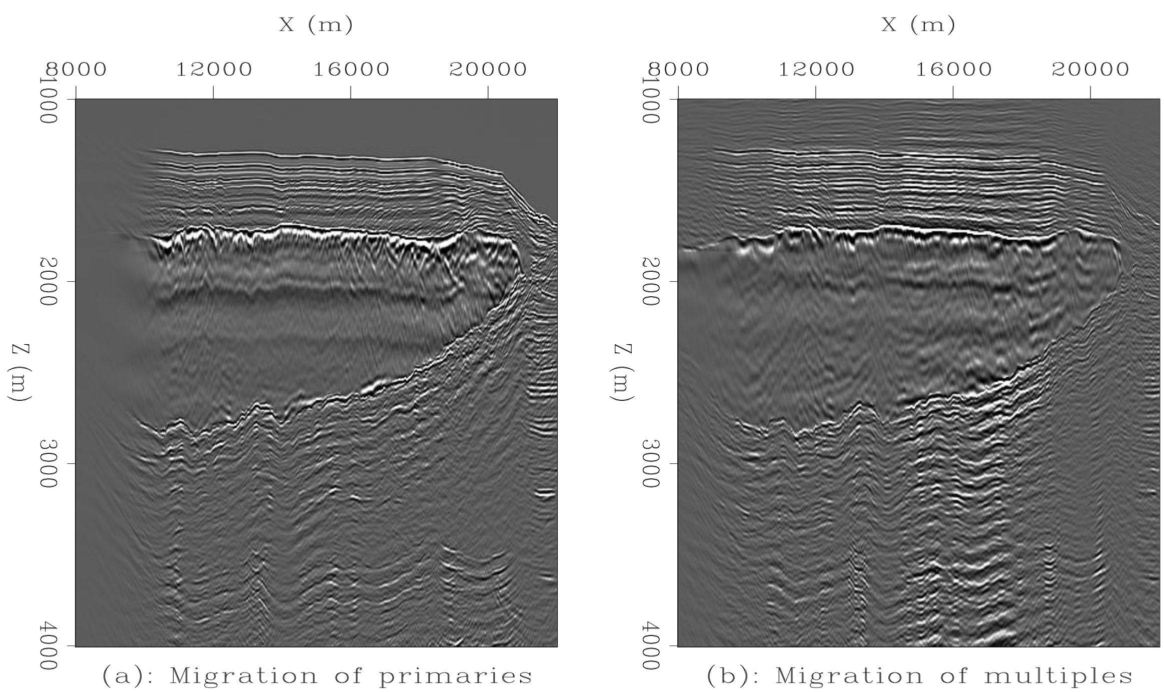

Figure 14: (a) Migration of the primaries. (b) Migration of the multiples. The two images are comparable. The salt body is clearly visible in the multiple migration result. gom_comp [CR,M]

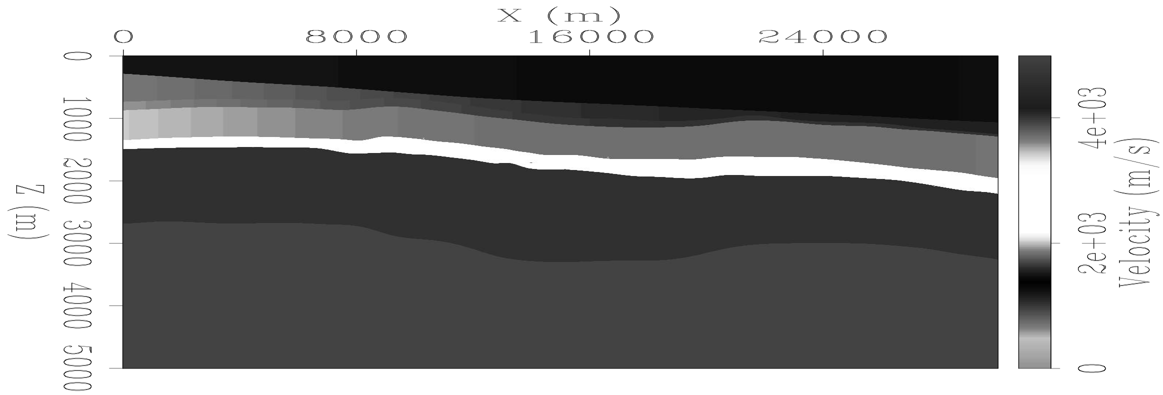

Figure 15: Velocity field for the North Sea 2-D line. The top of the basalt corresponds to the top of the white layer. The bottom of the basalt corresponds to the bottom of the next layer, around 2500 meters. velns [NR]

The velocity model for the North Sea dataset is displayed in Figure 15. I show one example of up- and down-going wavefields in Figure 16. Notice the strong reverberations of the water column plus other surface-related/internal multiples.

I migrated the North Sea data without large offsets and for a small portion of the survey only. Figure 17 shows the imaging results when primaries (Figure 17a) and multiples (Figure 17b) are migrated. It appears that the multiple image is less focused than the primary image. In addition the water-bottom is not at the correct location for both images. What happened ?

The answer is simple: cable feathering. Kostov et al. (2000) indicates that cable feathering was quite strong for the subset I migrated. Therefore the shot S, R_1 and R_n in Figure 2 are not in the same plane anymore introducing positioning errors in the migration.

DISCUSSION AND CONCLUSION

I have shown that migrating multiples at their correct location is possible. Results with a complex 2-D synthetic model and field data examples prove that multiples can bring valuable structural information. Although very encouraging, multiple migration has some limitations.

First, we need to generate a multiple model with correct kinematics and amplitudes. This can be quite a computation burden. Nonetheless, multiple attenuation is a prerequisite to any imaging step. Thus, instead of trashing these multiples, we might simply use them for migration. As an intermediate solution, I propose to use both primaries and multiples in the up-going wavefield. This is a cheap alternative to the full multiple attenuation that yields an interpretable image of the subsurface.

Second, the final image after migration of multiples is more noisy than the migration of primaries. In the synthetic data example I proposed using the water-bottom reflection for the source function. In practice the amount of muting depends on the subsurface, i.e., the main

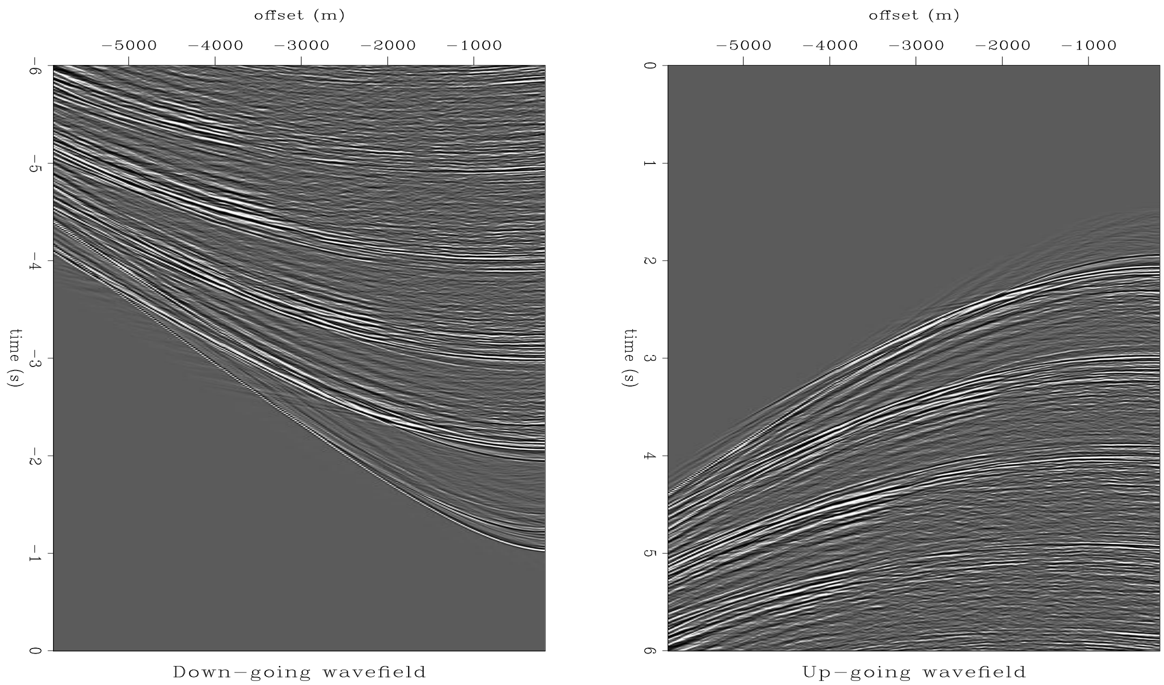

Figure 16: Left: The source function with primaries and multiples. Right: Same as the source with a mute. ns_ud_mult100 [NR]

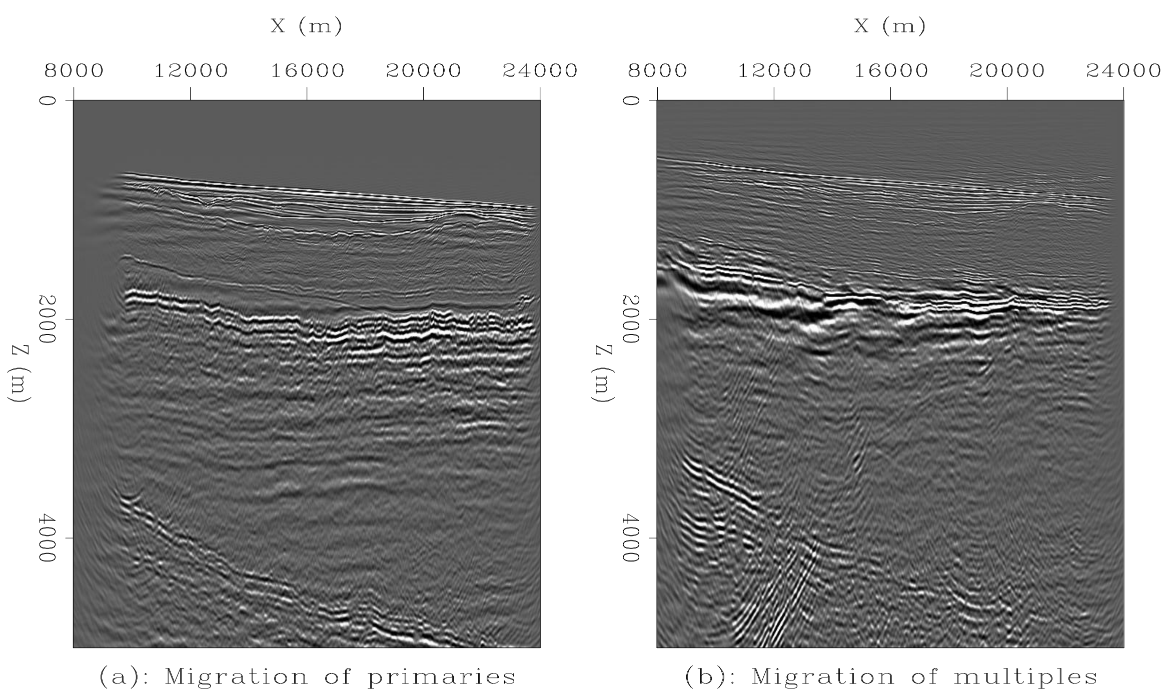

Figure 17: (a) Migration of the primaries. (b) Migration of the multiples. The two images are different because of cable feathering. ns_comp [CR,M]

"generators" of multiples.

Last, we might not be able to simply add the different images in order to increase the signal-noise ratio. When primaries are migrated, we use a synthetic source that is not the true seismic source. When multiples are migrated, the source is perfectly taking into account because we use the recorded wavefield as a source. Hence a direct addition of the migration results of primaries and multiples must be done with care.

As a final comment, the North Sea example perfectly illustrated the need for a targeted preprocessing of the data. In this case I should have corrected for cable feathering before multiple migration. Similar preprocessing steps are needed for the surface-related multiple attenuation technique (Verschuur et al., 1992).

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