Multifocusing-based multiple attenuation

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It is widely considered that, in regions with significant geologic complexity, methods which work directly in the depth domain are superior to methods which operate on prestack time data. So, for example, velocity analysis using depth migration and residual moveout became standard in the industry. The most common depth-velocity analysis attempts to flatten common-image-migrated gathers for main reflectors by measuring depth errors as a function of the offset. At the same time, the fact that most depth-domain algorithms are valid only for correct or nearly correct velocity models should not be underestimated. If this assumption is violated, they can lose their convergence properties or produce wrong results.

Many time-domain methods belong to a group of techniques that can be characterized as macro-model independent methods. These methods, which include conventional NMO or optical stack (de Bazelaire, 1988), MultiFocusing (Gelchinsky, 1998; Berkovitch, 1994) or common-reflection surface (Mann et al., 1999) represent an alternative to the depth-processing sequence and are based upon a transformation of multicoverage prestack data into a simulated zero-offset stack section. In particular, MultiFocusing transformation involves stacking large supergathers of seismic traces, each of which can span many common-midpoint (CMP) gathers. Stacking large supergathers is made possible by the use of a generalized moveout correction. For a given source-receiver pair, in a 2D case, this correction depends on three parameters: the wavefront curvatures of the normal wave, the normal incidence point wave (Hubral, 1983), and the emergence angle of the normal ray. For each supergather and each zero-offset time, T_0, these parameters are obtained through a coherence analysis of the moveout-corrected supergather.

The primary advantage of multifocusing (MF) is the enhancement of the signal-to-noise ratio of stacked sections through stacking a much larger number of traces than in conventional CMP stacking. The use of MF for improved time imaging is widely published (Berkovitch et al., 2008; Korabelnikov, 2008; Landa et al., 2010). At the same time, MF can be considered a method for wavefield analysis which reliably estimates wavefront parameters of each individual seismic event at each observation point. These wavefront parameters may have broad applications in seismic data processing and imaging. The use of the MultiFocusing parameter for prestack signal enhancement and velocity model estimation is described by Berkovitch et al. (2011).

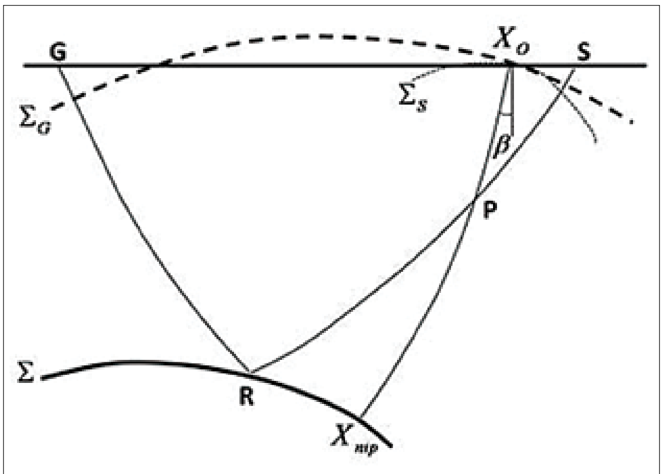

Figure 1. *Ray scheme of MF method.*

In this paper, we present the use of MF technology for multiple attenuation. Multiple attenuation during data processing does not guarantee a "multiple-free" final section. Although a great deal of effort has been invested in trying to resolve the problem of multiple suppression (see detailed review in Weglein et al., 2011), in cases of complex subsurface structure, the remaining multiples will be difficult to recognize, especially after the data have been migrated. In this context, methods that can recognize and attenuate residual multiples are of great importance to seismic processing and interpretation. Keydar et al. (1998) proposed a method for multiple prediction based on the wavefront characteristics of multiple-generating primaries. These attributes can be estimated through an optimization correlation procedure similar to the one used in the MF method. Examples of applications of this approach can be found in Keydar et al. (1998) and Landa et al. (1999a, 1999b). Their method is based on poststack multiple generator picking and estimation of the correspondent wavefront characteristics.

Here we present a modification of the MF-based approach when multiples are recognized directly in the MF attribute domain. First, they are predicted by the MF signal-prediction algorithm and they are then subtracted using adaptive least squares method.

Multiple suppression

The key elements of the proposed procedure are the MF attributes. These attributes, fundamental to multiple attenuation, are determined from the prestack data in a multidimensional optimization procedure. The more accurate the MF attributes, the better the results of the multiple attenuation. Therefore, we briefly describe the MF method as well as physical interpretation of the MF attributes (a detailed description of the method can be found in Berkovitch et al., 1994; Gelchinsky et al., 1999; and Landa et al., 2010).

Multifocusing method. Let us first consider acquisition on a curved surface (Figure 1). The central ray starts at X_0 with an angle β to the vertical. It hits the reflector Σ at the normal incidence point X_{nip}, and returns to X_0. A paraxial ray from the source S intersects the central ray at P, hits the reflector Σ at R, and arrives back at the surface at the receiver location G. These two rays define fictitious focusing waves initiated at point P, namely, the upgoing wavefront Σ_S, and the downgoing wavefront from point P, reflected by the reflector Σ, and emerging again at point X_0 with the wavefront Σ_G. The traveltime difference between the paraxial ray *SRG* and the central ray $X_0 X_{nip} X_0$ (Multifocusing moveout) can be written as

$$\Delta\tau = \Delta\tau^{+} + \Delta\tau^{-},$$

where

$$\Delta\tau^{\pm} = \frac{\sqrt{(R^{\pm})^2 + 2R^{\pm}\Delta X^{\pm}\sin\beta + \Delta X^{\pm 2}} - R^{\pm}}{V_0}.$$

Here

$$R^{\pm} = \frac{1 \pm \sigma}{\dfrac{1}{R_{CEE}} \pm \dfrac{\sigma}{R_{CRE}}}$$

and σ is the so-called focusing parameter given by

$$\sigma = \frac{\Delta X^{+} - \Delta X^{-}}{\Delta X^{+} + \Delta X^{-} + 2\dfrac{\Delta X^{+}\Delta X^{-}}{R_{CRE}}\sin\beta};$$

In the above equations, ΔX^{+} and ΔX^{-} are the source and receiver offsets for a given ray with respect to the central ray, $R^{\pm}$ are the radii of curvature of the fictitious wavefronts Σ_S and Σ_G in the vertical plane, respectively, and V_0 is the near-surface velocity which is assumed known and constant along the observation line. Finally, R_{CEE} and R_{CRE} denote the radii of curvature of the two fundamental wavefronts corresponding to the normal (CEE) wave and normal-incidence-point (CRE) wave, respectively (Hubral, 1983). The CRE wavefront is formed by a point source placed at the point where the zero-offset ray emitted from the central point hits the reflector. The wavefront of the CEE wavefront is formed by normal rays emitted by different points on the reflector (like in an "exploding reflector" scenario).

Most publications on MF are focused mainly on the increased fold and the improved quality of the MF section. However, MF can obtain an increased number of wavefield parameters as compared to a conventional stacking velocity analysis. In fact, estimation of the MF parameters can be considered as MF transforms and can provide optimal wavefront parameters and full distribution of these parameters in the parameter domain when the semblance value plays the role of a probability function.

For stacking or imaging, the physical interpretation and accuracy of the estimated MF parameters are not required. They can be considered as the coefficients of an approximation surface that best fit the actual traveltimes. In applications other than imaging (for example, model building or multiple

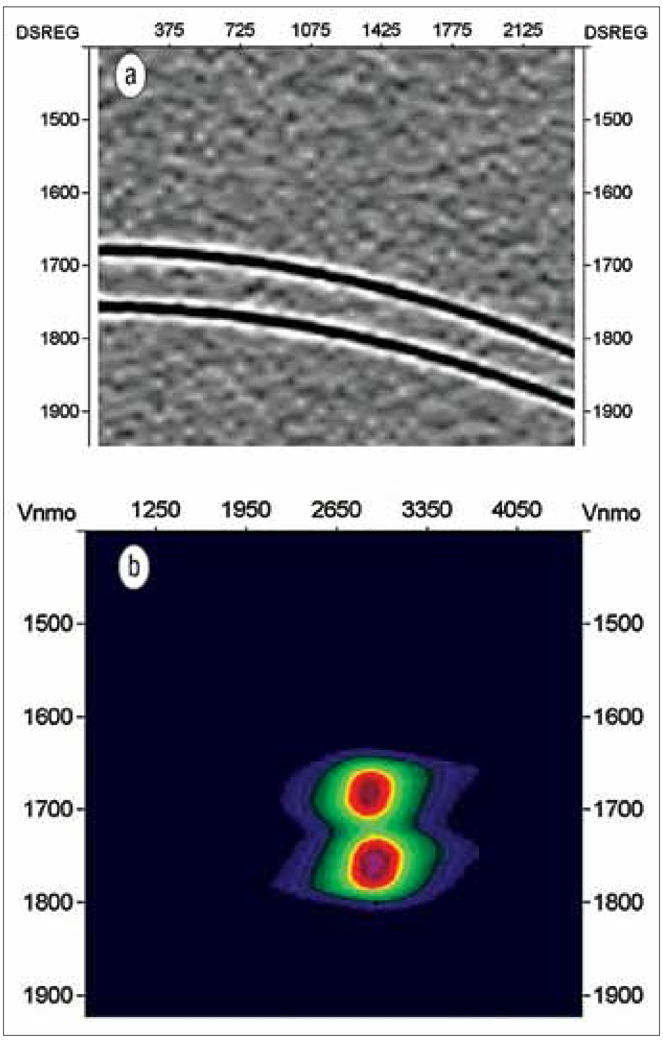

Figure 2. *(a) Synthetic CMP seismogram. Primary and multiple have close zero-offset times. (b) NMO stacking velocity panel. Maximum semblance indicates practically equal velocity values.*

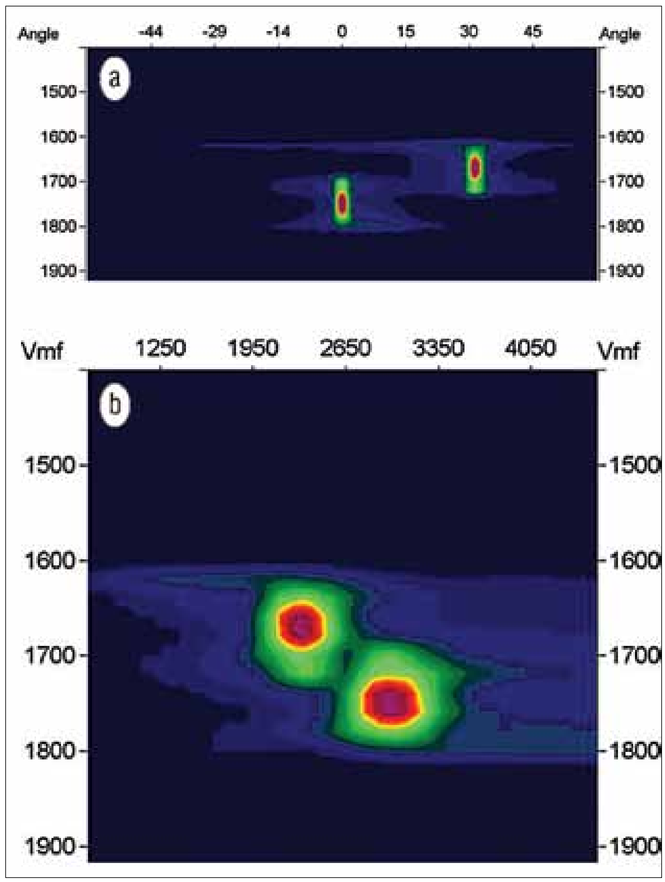

Figure 3. *(a) MF angle panel. Estimations for the primary and multiple are different. (b) MF velocity panel computed from the MF attributes. Estimations for the primary and multiple are different.*

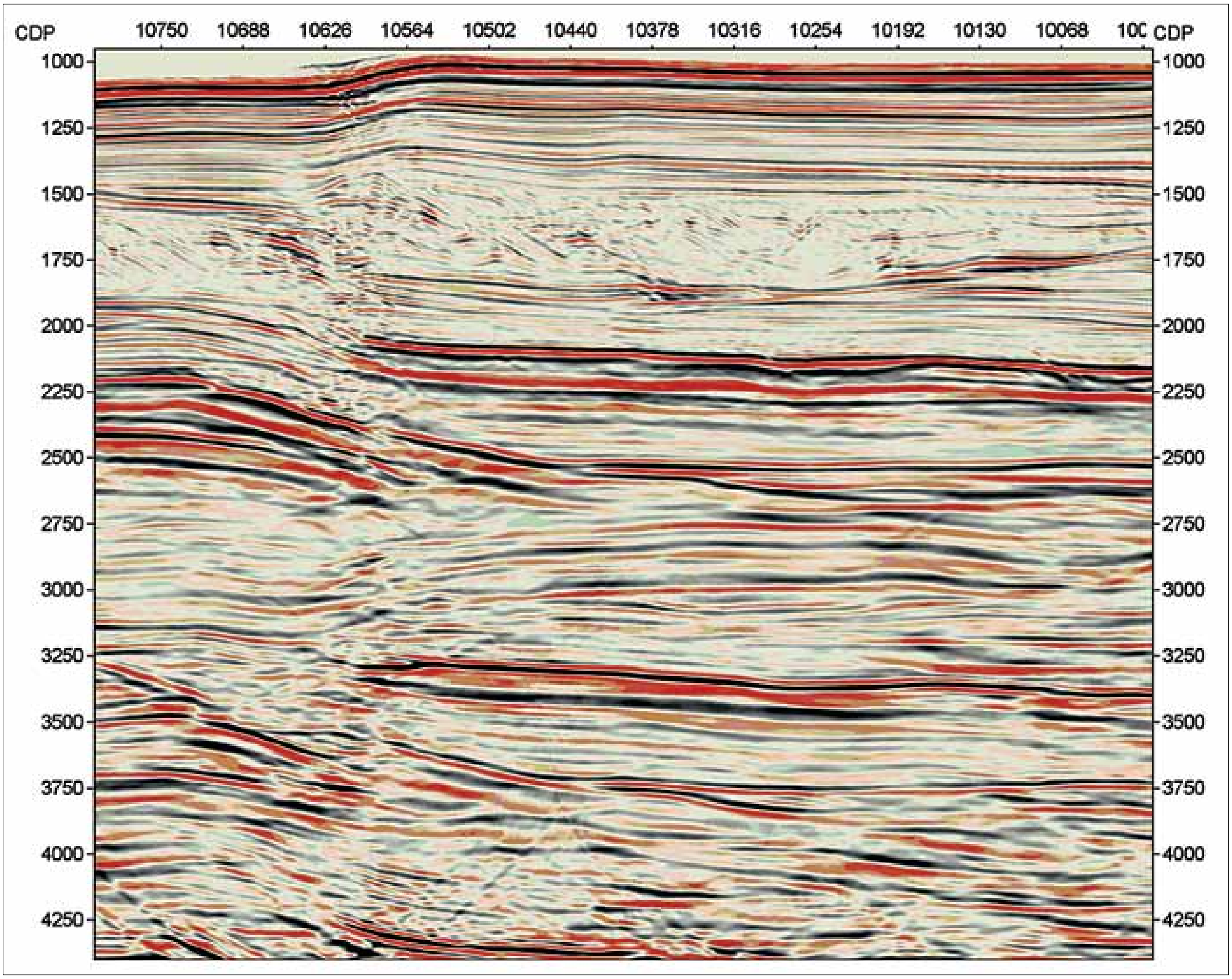

Figure 4. *MF section before multiple attenuation. Target area is below 3250 ms. Due to strong peg-leg multiple energy, primary reflections are practically invisible.*

attenuation), accurate estimate of the attributes is required and a wrong near-surface velocity would lead to erroneous attributes and in turn to errors in the following applications.

Multiple suppression with MF attributes. A method for the identification and removal of multiples using wavefront characteristics was introduced by Keydar et al. (1998) and Landa et al. (1999). Their approach is the target-oriented "predict and subtract" attenuation method, where the objective is to remove multiples of any type (surface-related, interbed, or peg-leg). The multiple-prediction algorithm is based on a simple but powerful concept: the timing of any multiple consists of segments that are primaries. To predict the arrival time for a particular multiple, one should understand the segments of the multiples generating primaries. These segments should satisfy a so-called "multiple condition": emergence angles of the upgoing and downgoing segments are identical. This condition is used to determine arrival times for multiple events which are just simple arithmetic sums of the primary segments. Practically, this procedure requires the accurate estimation of emergence angles for primary reflected events which generate multiples for all source-receiver pairs along the seismic line and finding those traces which satisfy the multiple condition. MF can be used for this purpose because it efficiently estimates emergence angles for the normal ray and wavefront curvatures. After multiple times are predicted, they can be subtracted in the parabolic $\tau - p$ domain (Landa et al., 1999).

Alternatively, multiple prediction can be done directly in the domain of the MF parameters. In many cases, the emergence angle β and radii of curvature R_{CRE} may be sufficiently different for primary and multiple reflections. An appealing option to separate primaries and multiples is to use a dip-independent stacking velocity which can be computed from the definition in the MF emergence angle and wavefront curvature. Let us illustrate the idea schematically on a simple synthetic example. Figure 2a shows a single CMP gather with two events representing primary and multiple reflections from a dipped and a horizontal reflector respectively. Both reflections have close t_0 times with practically the same NMO stacking velocity (Figure 2b). Of course, conventional

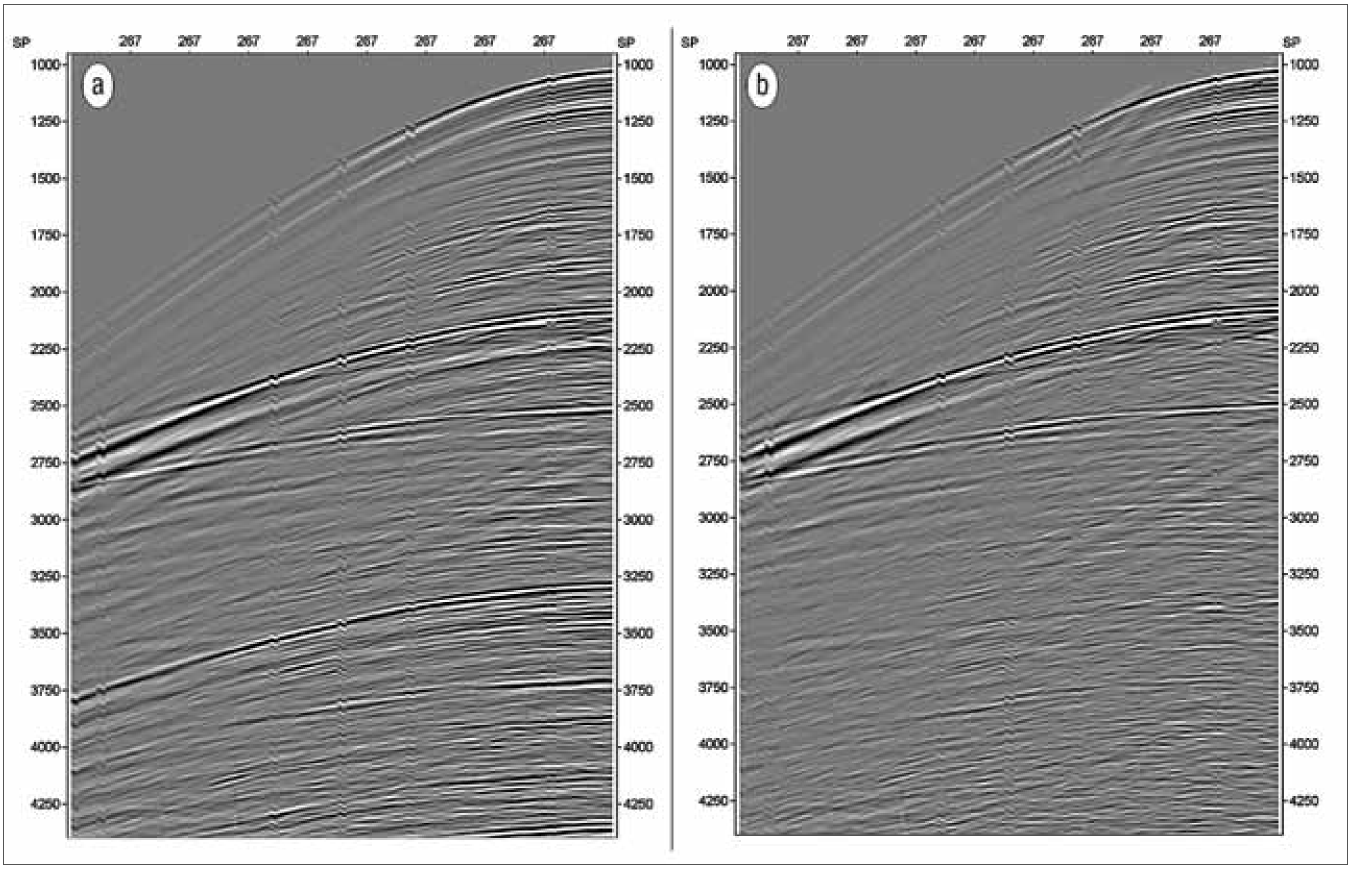

Figure 5. *CMP gather after adaptive subtraction. Multiple energy is attenuated.*

multiple attenuation methods based on velocity separation, such as the $\tau-p$ method, cannot separate between the two events. MF attributes calculated on a supergather around the CMP point easily distinguish between primary and multiple reflections. Figure 3a shows an emergence angle, and Figure 3b, the dip-independent velocity V_{MF} computed from the MF attributes. Now primary and multiple reflections are well separated by different angle and velocity estimations. One method of multiple attenuation is to mute the area where the multiple energy is assumed to be concentrated in the dip-independent velocity domain. Then, an inverse MF transformation should produce "multiple-free" prestack gathers. In practice, it often is desirable to model the multiples and subtract the result from the actual gathers (Hampson, 1986). One reason for this is the necessity to retain in the gathers some energy which cannot be explained by MF transformation, such as strongly nonhyperbolic events. The subtraction in data space actually tends to retain the original texture of the data. As stated by Yilmaz (2001), "Multiple attenuation in the transformed domain is achieved by rejecting a zone that includes the primaries … The inverse transform yields the reconstructed gather that contains presumably only multiples … Again, to preserve data characteristics, rather than modeling the primaries by reconstruction, it is preferable to model the multiples and subtract the modeled gathers from the original … The difference gather should contain the primaries."

In this work, we chose a different way to model the multiples using information obtained in the MF transform domain. Instead of modeling multiples by an inverse MF transform, we compute a multiple model by using a prestack signal-enhancement algorithm (Berkovich et al., 2011).

The idea is to apply the MF traveltime formula to compute new partially stacked traces, when each trace is the result of the summation of data along the MF stacking surface. Prestack traveltimes of the multiples are calculated with the help of the MF attributes of the identified multiples. The resulting traces should be at the positions of the original ones for subsequent subtraction. The algorithm for multiple modeling can be described as follows: according to estimated MF parameters corresponding to multiple events, the partial MF stack calculates a stacking surface around a specified CMP-offset location and performs the summation of data along that surface. The result of summation is assigned to the same CMP, offset, and time coordinates. Repeating this procedure for all desired points generates a new gather that is the MF-enhanced multiple model. Later this gather can be subtracted from the original gather by a least square adaptive subtraction method similar to how it is done in the SRME-type multiple attenuation. Note that multiple events on the resulting multiple model seismograms have increased signal-to-noise ratio compared to the original gathers due to partial coherent summation. It may play a positive role during the adaptive subtraction step.

Example

We illustrate the presented method on real data. Figure 4 shows an MF section before conventional $\tau-p$ (Radon) mul-

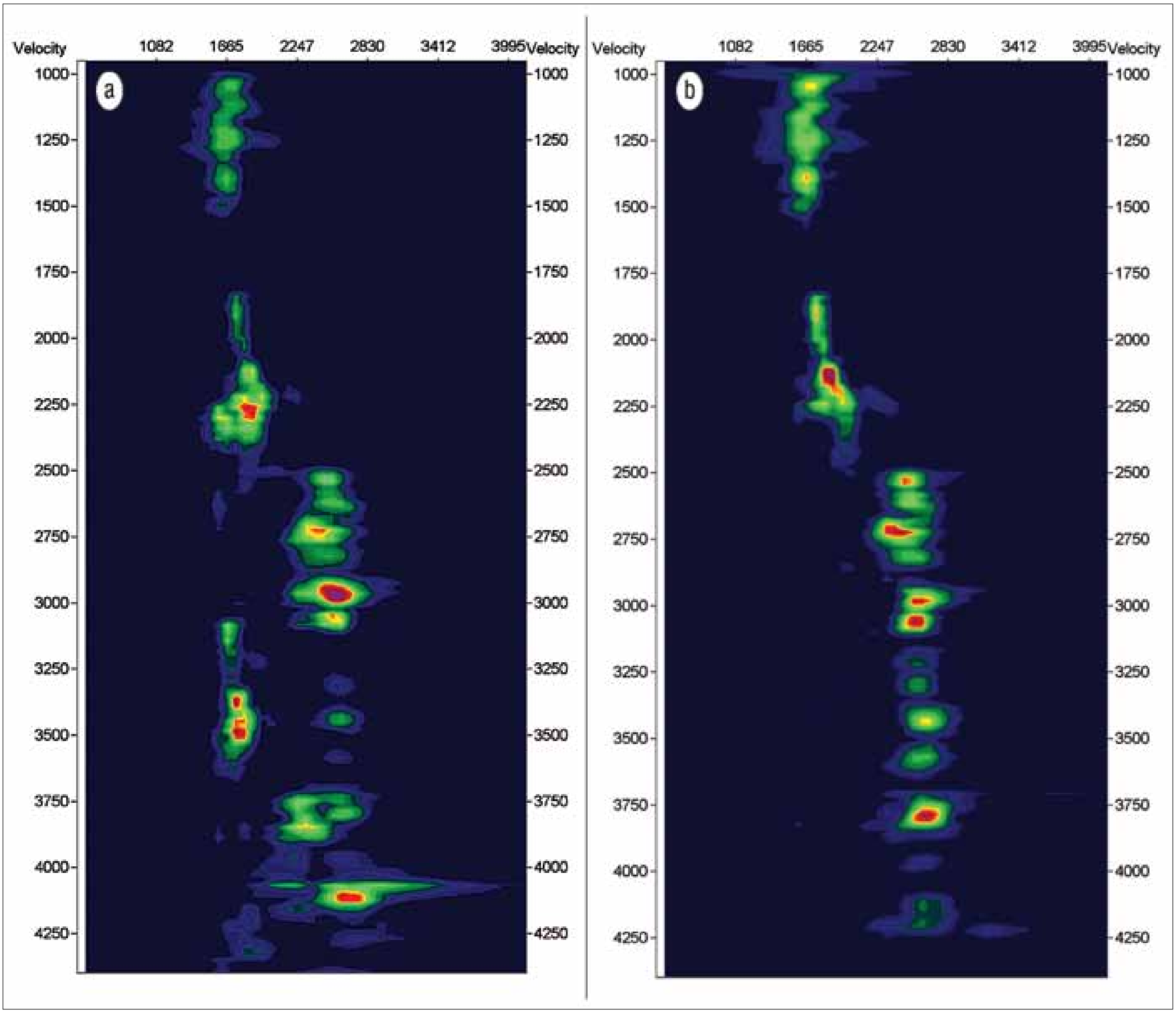

Figure 6. *Velocity panel (a) before and (b) after multiple subtraction.*

tiple attenuation. The target area of this line was imaging reflections below 3000 ms, including a syncline structure at about 3250 ms. Because of a strong peg-leg multiple energy at the target times, primary reflections are practically invisible. The first step in the application of the MF-based multiple suppression method is to trace the multiple events in the MF attribute domain according to the computed R_{CRE} and β information. Next, based on the interpreted corridor for multiples, we compute model seismograms of the multiples by prestack partial summation along the predicted multiple arrival surfaces (MF prestack signal enhancement). Offset traveltimes of the multiples are calculated using the MF attributes (emergence angles and curvatures of the wavefronts) of the identified multiples. Resulting gathers mostly contain multiple energy. In the next step, we subtract these multiple enhanced gathers from the original one. Figure 5a shows an original CMP gather and Figure 5b shows the same gathers after adaptive subtraction. MF velocity panels before and after multiple subtraction are shown in Figures 6a and 6b, respectively.

Comparison between the gathers and velocity panels shows essential attenuation of the multiple energy and better visibility of primary reflections. Figure 7 shows a new MF section obtained from the gathers after multiple attenuation. Primary reflections at the target area including a syncline reflection at 3250 ms are clearly seen. Multiples are successfully attenuated.

Conclusions

We have presented an implementation of a multiple attenuation which can be used within the multifocusing technology. We presented a real data test, which shows the potential of the method. We identified and predicted the multiples in the MF attribute domain through interpretation of the rms velocity and emergence angle panels, which are reliably computed from the prestack data during the MF analysis. We then calculated the offset traveltimes for the multiples using the iden-

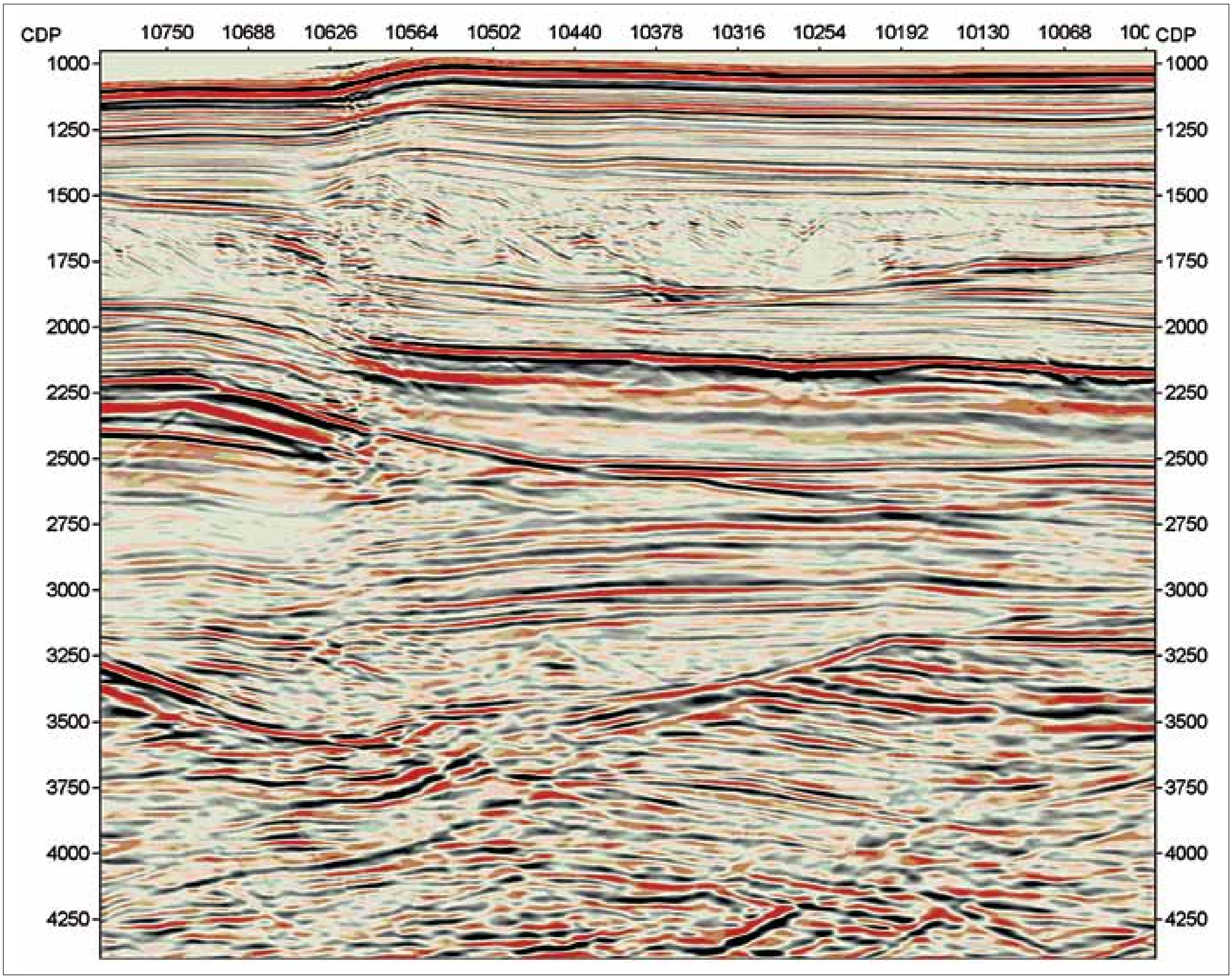

Figure 7. *MF section obtained from the gathers after multiple attenuation. Primary reflections within the target area below 3000 ms are clear.*

tified MF attributes and computed a multiple model based on the partial coherent summation of the original data along the predicted traveltime surfaces. For the final stage, we adaptively filtered the predicted multiples from the original data using a least squares adaptive subtraction procedure.

The proposed procedure is valid for surface-related as well as for interbed types of multiples. It is robust and simple. It is easy to implement and it can predict all kinds of multiples defined by the picked corridors in the MF domain. The multiple suppression approach with MF attributes is not dependent on the regularity of the data. TLE

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