FRESNEL-VOLUME-MIGRATION OF SINGLE-COMPONENT SEISMIC DATA

S. Buske, M. Heigel, and S. Lüth

email: *buske@geophysik.fu-berlin.de*
keywords: *migration*

ABSTRACT

Kirchhoff prestack depth migration (KPSDM) distributes the recorded wavefield along two-way-traveltime isochrones. An image is generated by constructive interference of these isochrones along the actual reflector elements. This method is considered as a state-of-the-art technique in obtaining high-quality images of the subsurface. However in the case of sparse sampling or limited aperture the resulting image is affected by significant migration noise due to the insufficient constructive interference of the back-propagated wavefield. Some modifications have been proposed which aim at reducing these artefacts. These modifications consist in the construction of a specular path of wave propagation derived from the slowness of coherent phases in the seismogram section and the mainly heuristic restriction of the imaging operator to that wave path.
In this paper we propose another approach by using the concept of Fresnel-Volumes to restrict the migration operator in a physically frequency-dependent way. We have implemented this Fresnel-Volume-Migration (FVM) scheme for single-component seismic data. The emergence angle at the receiver is determined by a local slowness analysis. Using the emergence angle as the starting direction a ray is propagated into the subsurface and the back-propagation of the wavefield is restricted to the vicinity of this ray according to its approximated Fresnel-Volume. We describe the procedure and discuss the limitations of the approximation. Furthermore we show the properties of the FVM scheme with the help of a simple synthetic model as well as a real data set over a salt pillow in North Germany. Compared with standard KPSDM the image quality of FVM is significantly enhanced due to the restriction of the migration operators to the region near the actual reflection point.

INTRODUCTION

Seismic imaging comprises the reconstruction of subsurface structures from seismic wavefields. A number of imaging algorithms have been developed over the past decades, mainly by back-propagation of the recorded wavefield using either finite-differences (Claerbout, 1971), frequency-wavenumber methods (Stolt, 1978) or Kirchhoff theory (Schneider, 1978). One of the most widely used imaging methods is Kirchhoff prestack depth migration (KPSDM) (Bleistein and Gray, 2001). The basic principle behind this procedure is to construct an image by a weighted summation through the wavefield along diffraction surfaces. Alternatively it can be described by distributing the wavefield along the corresponding two-way-traveltime isochrones (migration operator). The image itself is generated by constructive interference of these isochrones along the actual reflector elements.

KPSDM is considered as a state-of-the-art technique for producing high-quality images of the subsurface, especially in complex geological settings. It is easy and straightforward to implement, flexible with respect to acquisition parameters and several extensions have been proposed to incorporate attenuation, anisotropy, etc. Its areas of application include a wide range of scales from engineering seismology over hydrocarbon exploration to deep seismic soundings.

However in certain cases the condition for a sufficiently good interference of isochrones is not fulfilled. This situation includes surveys with e.g. low coverage or limited aperture. In these cases the image result can be affected by significant migration noise and artefacts due to the less constructive interference of the back-propagated wavefield. Furthermore steeply dipping reflectors almost always pose problems since the corresponding migration operators are often artificially limited in dip by muting near the acquisition surface.

Some modifications have been proposed which aim at reducing these artefacts. These modifications consist in the construction of a specular path of wave propagation, which can be derived from the slowness of coherent phases in the seismogram section, and the mainly heuristic restriction of the migration operator to that wave path (Takahashi, 1995; Tillmanns and Gebrande, 1999; Sun and Schuster, 2003).

We propose another approach by using the concept of Fresnel-Volumes in order to restrict the migration operator in a physically frequency-dependent way. For this purpose we initially determine the emergence angle of the wavefield at the receiver. Using this angle as the starting direction we propagate a ray into the subsurface and we restrict the back-propagation of the wavefield to the vicinity of this ray according to its approximated Fresnel-Volume. This so-called Fresnel-Volume-Migration (FVM) can be regarded as an extension of KPSDM where the migration operator is restricted to the area around the specular reflection point. The procedure itself resolves spatial ambiguities and results in strongly reduced migration artefacts, particularly in the case of low-coverage data. The final image comprises a significantly higher image quality and consequently a better resolution.

We have already implemented the FVM scheme successfully for multicomponent seismic data, where the emergence angle can be computed from the polarization of the wavefield, and applied it in a hard-rock environment for seismic imaging and prediction ahead of a tunnel construction site (Goertz et al., 2003; Lüth et al., 2005). Here we describe the application to single-component surface seismic reflection data. In this case the emergence angle at the receiver is determined from a local slowness analysis using a cross-correlation of neighbouring traces. In the following section the methodology and the numerical implementation is described in detail. Afterwards the concept is tested on a simple synthetic model which illustrates the basic properties and advantages over standard implementations of KPSDM. Finally the method is applied to an exploration data set acquired over a salt pillow in North Germany. This example demonstrates the above mentioned benefits of FVM over standard KPSDM, i.e. increased image quality and resolution.

METHODOLOGY

Principle

KPSDM can be formulated as a weighted diffraction stack over the recorded wavefield U (Schneider (1978); Schleicher et al. (1993); Bleistein and Gray (2001)). The image value M at an image point located at $\mathbf{r}$ is obtained by integrating the wavefield along the corresponding diffraction surface $(t_S + t_R)$:

$$M(\mathbf{r}) = \iint\limits_A W(\mathbf{r}, \mathbf{r}')\dot{U}(\mathbf{r}', t_S + t_R)d\mathbf{r}'. \tag{1}$$

t_S and t_R denote the traveltimes from the source (S) and the receiver (R) to the image point $P(\mathbf{r})$, respectively. The weighting function W accounts for the correct amplitude treatment based on Kirchhoff theory. The wavefield itself is differentiated with respect to time in order to recover the true source pulse after migration.

Although equation (1) is an adequate basis for a numerical implementation the migration procedure can alternatively be considered as a *smearing* of the wavefield along the corresponding TWT (two-way-traveltime) isochrones. An image of the actual reflector is generated by constructive interference of these TWT isochrones along the reflector. According to equation (1) the wavefield U is smeared throughout the subsurface along the whole TWT isochrones although usually only small parts of the isochrones actually contribute constructively to the image of the reflector. In particular for spatially sparsely sampled data with low coverage this may cause strong artefacts and significant migration noise. The reason for this unlimited smearing is that normally the migration is performed as a single-trace operation and no further information is used from which part of the isochrone the reflected energy originates.

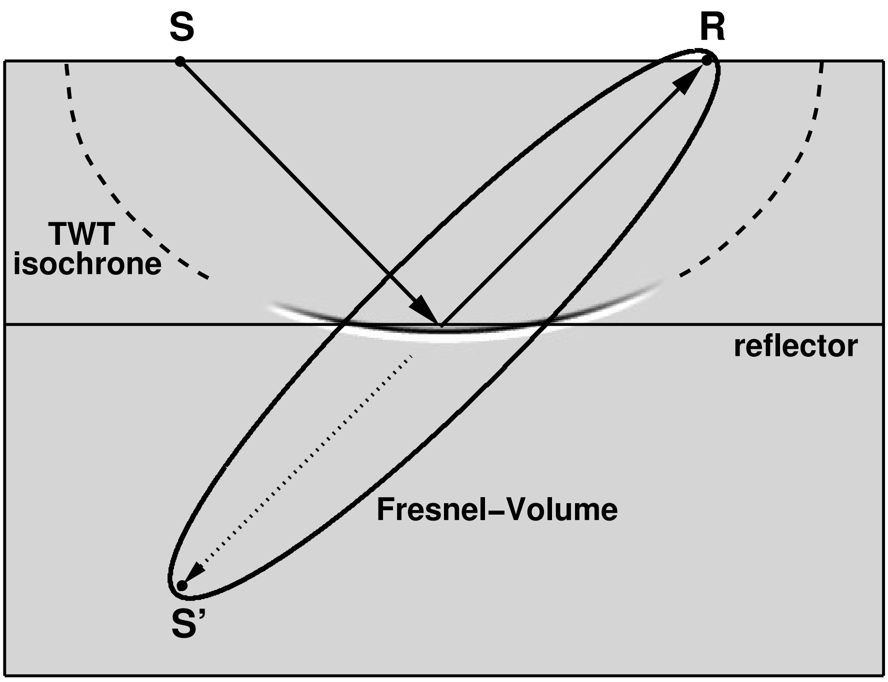

Figure 1: Fresnel-Volume-Migration scheme. The migration operator is limited along the TWT isochrone to the area near the reflection point using the Fresnel-Volume of that ray which starts at the receiver with the estimated emergence angle and ends after the TWT at point S'.

We propose to limit the smearing along the TWT isochrone to the vicinity of the actual reflection point by using the corresponding Fresnel-Volume (Kravtsov and Orlov (1990); Kravtsov (2005)). The concept is illustrated schematically in Fig. 1. Consider a source (S) and a receiver (R) along the acquisition surface as well as a plane horizontal reflector at depth. KPSDM would smear the reflected signal along the corresponding TWT isochrone (indicated by the dashed line in Fig. 1). However only the part of the TWT isochrone in the vicinity of the actual reflection point contributes effectively to the image of the reflector. Therefore we limit the smearing to this region by the following procedure, which is performed for every trace and for every time sample (t_0) of this trace.

- Estimate the emergence angle at the receiver. This can be done either by analysing the polarisation of multi-component data (see Lüth et al. (2005)) or by a slowness analysis of neighbouring traces. Here we use an efficient and robust cross-correlation procedure (Haslinger (1994)).

- Trace a ray into the subsurface using the estimated emergence angle as the starting direction until the time t_0 is reached. This ray (continued as a dotted line below the reflection point in Fig. 1) will ideally pass the actual reflection point and continues to the point S'. For a homogeneous model with no velocity contrast at the reflector the point S' is given by the actual source position (S) mirrored at the reflector.

- Calculate the Fresnel-Volume of this ray. The concept of Fresnel-Volumes transforms the mathematically infinitely thin ray to a physically frequency-dependent ray of finite thickness. This is performed during the previous step by a slightly modified version of Fresnel-Volume-Ray-Tracing (Cerveny and Soares (1992)). At every point $\mathbf{r}$ along the ray the Fresnel-Radius r_F (i.e. the size of the Fresnel-Zone perpendicular to the ray) is given by:

$$r_F(\mathbf{r}) \approx \sqrt{\frac{T}{\Pi_{13}^{-1}(\mathbf{r}) - (\Pi_{13}(\mathbf{r}) - \Pi_{13}(\mathbf{r_0}))^{-1}}} \tag{2}$$

  where T denotes the dominant period. $\mathbf{r_0}$ is the endpoint of the ray at time t_0 and Π_{13} is a ray-propagator element which can be computed along with the standard ray tracing procedure (for details see Lüth et al. (2005)).

- Smear the recorded wavefield amplitude along the corresponding TWT (t_0) isochrone (migration operator) but weight the amplitude such that inside the Fresnel-Volume the weight is one and outside it is tapered to zero with increasing distance from the Fresnel-Volume. Mathematically the procedure results in an additional weighting factor within the Kirchhoff integral

$$M(\mathbf{r}) = \iint_A V(\mathbf{r}, \mathbf{r}', t_S + t_R) W(\mathbf{r}, \mathbf{r}') \dot{U}(\mathbf{r}', t_S + t_R) d\mathbf{r}', \tag{3}$$

  where the weighting function is given by

$$V = \left\{ \begin{array}{ll} 1 \quad \text{if} \quad d \leq r_F & \\ 1 - \frac{d - r_F}{d} \quad \text{if} \quad r_F < d < 2r_F & \\ 0 \quad \text{if} \quad d \geq 2r_F & \end{array} \right\}. \tag{4}$$

  d is the distance between the image point under consideration and its nearest point on the corresponding TWT (t_0) ray. r_F denotes the Fresnel radius at this nearest point on the ray. The weighting function passes all image points within the Fresnel-volume of the corresponding ray with full weight and applies a linear taper outside to the double Fresnel radius.

This procedure is in principle performed for all samples of all traces. Within the time window of the reflected signal the wavefield is back-propagated along the corresponding emergence angle, which leads to the actual reflection point. Outside this time window the emergence angle is randomly distributed according to the characteristics of the noise so that the noise itself is randomly distributed in the subsurface.

The weighting using the Fresnel-Volume leads to a restriction of the smearing process around the actual reflection point. Migration noise produced by smearing the amplitudes too far away from the reflection point is therefore avoided. For standard seismic surveys this means that less migration noise appears with large dips near the acquisition surface. Some advanced implementations of KPSDM also try to tackle this problem by artificially limiting the migration operator near the surface or for steeply dipping parts. However, this implies the dangerous assumption that no steeply dipping reflectors are present and that they do not reach the surface. Here no such a-priori dip limitation has to be included, the procedure accounts for arbitrary dips whether they are near the surface or at greater depths.

Validity of approximations

The procedure described above limits the smearing to the region around the reflection point by using the Fresnel-Volume of the ray which starts at the receiver, passes the reflection point and continues until the TWT t_0 is reached. This *direct* Fresnel-Volume of the transmitted ray (dotted line in Fig. 2a) is used as an approximation of the Fresnel-Zone on the reflector. The *reflected* Fresnel-Volume (solid line in Fig. 2a) describes the region around the reflected ray between source (S) and receiver (R) which physically contributes to the recorded wavefield. The intersection between the reflector and the *reflected* Fresnel-Volume defines the true Fresnel-Zone on the reflector. For vanishing velocity contrast at the reflector as in Fig. 2a both Fresnel-Volumes span the same Fresnel-Zone on the reflector. Hence the approximation is well justified.

Fig. 2b shows the case of significantly different travel distances from the source and the receiver to the reflector, but also vanishing velocity contrast. This example is equivalent to the case of a dipping reflector (acquisition surface as a straight line trough source and receiver). Here the approximation is also well justified, i.e. both Fresnel-Volumes coincide on the reflector.

Fig. 2c finally illustrates the difference for non-vanishing velocity contrast at the reflector. For increasing velocity in the lower layer the *direct* Fresnel-Volume (dotted line in Fig. 2c) is expanded and the Fresnel-Zone on the reflector is slightly overestimated. On the other hand for decreasing velocity the *direct* Fresnel-Volume (dashed line in Fig. 2c) becomes smaller and the Fresnel-Zone on the reflector is slightly underestimated. However, the center of the estimated Fresnel-Zone is in both cases still correct since the position of the reflected ray does not depend on the velocity contrast. Furthermore the migration operator itself is tapered at the boundary of the *direct* Fresnel-Volume so that a slightly wrong estimate of the Fresnel-Zone due the actual velocity contrast does not significantly influence the migration results.

APPLICATION TO SYNTHETIC DATA

The principal features are illustrated with the help of a single shot migration applied to a simple synthetic data set (see Fig. 3). The model consists of a plane horizontal reflector at a depth of 3 km between to homogeneous layers. 501 receivers are distributed along the x-axis ($z = 0$) with a spacing of 10 m and the source is located at the center of the model ($x = 2.5$ km).

Fig. 3a shows the result of standard KPSDM. The reflector is well imaged at its correct depth but significant migration smiles centered at the boundaries of the covered reflector area ($x = 1.25$ km and $x = 3.75$ km) can be observed. Fig. 3b shows the result of FVM. Again the reflector is well imaged at its correct depth but now the migration smiles are effectively suppressed. Almost no migration smile can be seen at depths less than 2.8 km. The smiles do not reach the lateral boundaries of the model, although they still exist at the boundaries of the illuminated reflector area due to the fact that the migration operator is tapered outside of the Fresnel-Volume.

This comparison of KPSDM and FVM demonstrates how migration smiles are suppressed even in the case of a simple synthetic model. The following real data example demonstrates the gain of image quality due to this suppression.

APPLICATION TO REAL DATA

The data set was acquired over a salt pillow in North Germany. Fig. 4a shows the corresponding P-wave velocity model consisting of a high velocity salt inclusion embedded within dipping sedimentary layers. A total of 107 shots distributed along the surface with a symmetric split-spread configuration of 120 receivers

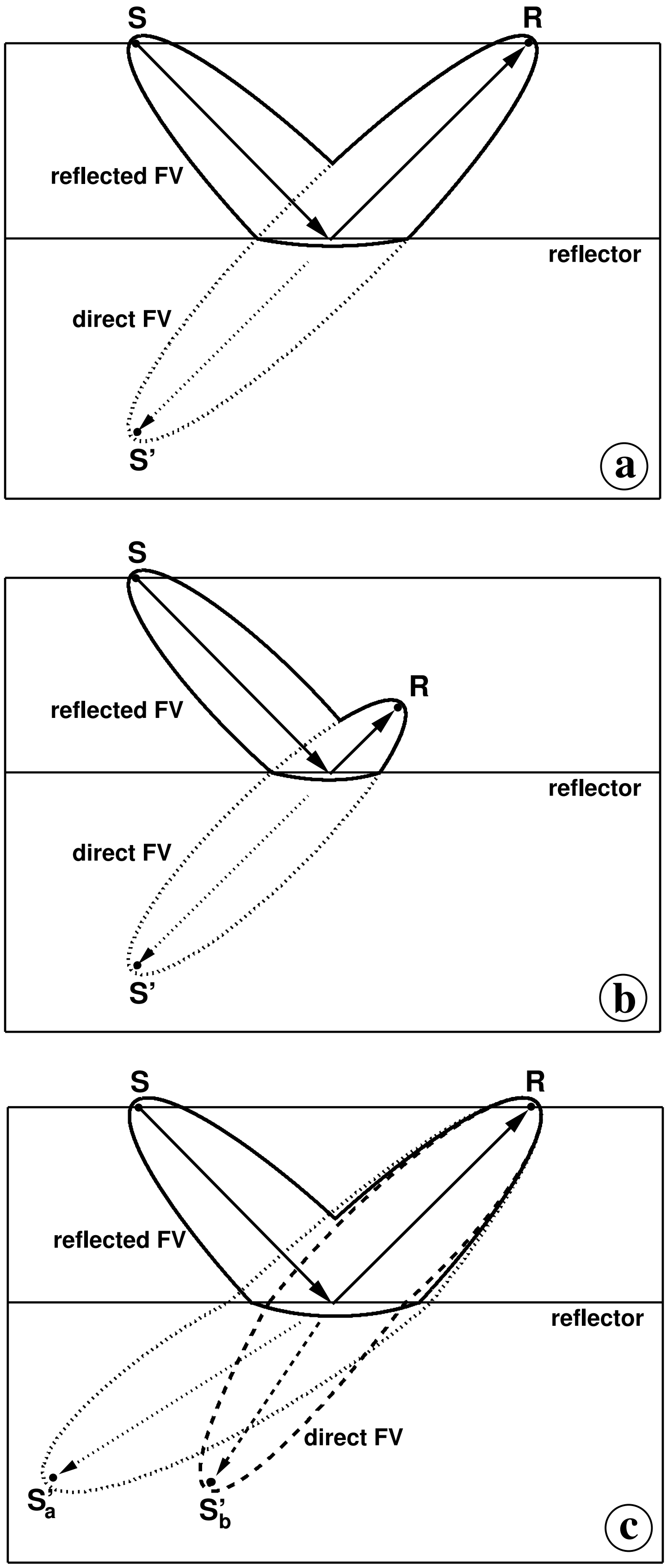

Figure 2: Validity of the approximation. (a) FV of the reflected ray versus FV of the direct ray for (a) symmetric source and receiver locations and vanishing velocity contrast (b) asymmetric source and receiver locations ("dipping reflector") and vanishing velocity contrast (c) symmetric source and receiver locations and non-vanishing velocity contrast.

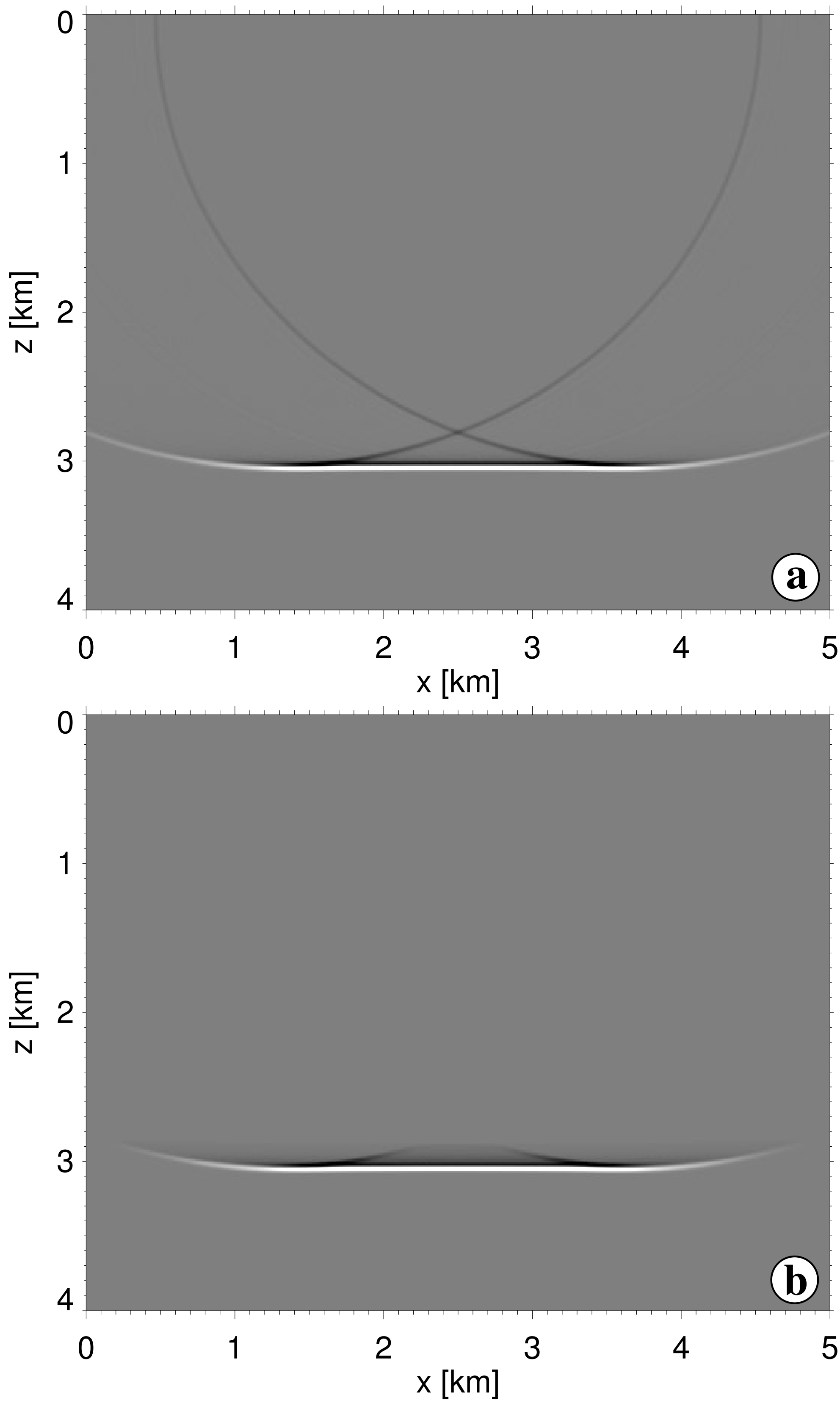

Figure 3: Comparison of KPSDM (a) and FVM (b) for the synthetic example. Note the suppressed migration smiles at the edges of the illuminated reflector area in the FVM result.

and an effective aperture of 4.8 km per shot were used here. The traveltime computation of the diffraction curves was performed using a FD eikonal solver (Podvin and Lecomte (1991).

The results of KPSDM and FVM are shown in Fig. 4b and 4c, respectively. The basic structural features and the layer interfaces can be identified in the KPSDM result (Fig. 4b). Nevertheless significant migration noise is present because no artificial dip limitation was applied to the migration operators. In comparison the FVM result (Fig. 4c) provides a much cleaner image with almost no migration smiles. The interfaces can be better traced troughout the model in particular below the salt pillow in the center of the model.

This behaviour becomes also evident for single migrated shot gathers. Figure 5 (top) shows the comparison of KPSDM and FVM for such a gather from the left part of the model. The KPSDM result (Fig. 5a) allows to identify the major interfaces but strong migration noise appears especially at the lateral boundaries as well as at deeper parts of the section. On the other hand the FVM result (Fig. 5b) still contains some of these smiles but they are strongly suppressed so that the overall image quality is enhanced.

Figure 5 (bottom) shows a zoomed portion of the lower right part of the model just below the salt pillow. Again the FVM result (Fig. 5d) is superior to the KPSDM result (Fig. 5c) in terms of image quality. The reflectors are more continuous and most of the migration smiles have been removed. That not only allows for a better reflector visibility and characterization but in turn also prevents a misinterpretation of smiles as structural features.

CONCLUSIONS

We presented an extension of Kirchhoff prestack depth migration (KPSDM). The basic idea is to restrict the migration operator to the area around the actual reflection point using the concept of Fresnel-Volumes and emergence angles at the receiver estimated from a local slowness analysis. This so-called Fresnel-Volume-Migration (FVM) limits the back-propagation of the recorded wavefield to the physically relevant part of the subsurface. No dips are a-priori excluded by any artificial muting of migration operators. The image quality is significantly enhanced over standard KPSDM by the inherent suppression of migration smiles. This is shown on a simple synthetic example as well as on a real data set over a salt pillow in North Germany.

The FVM procedure shown in this paper is described, valid and fully implemented in 3D. The method can also be applied in a straightforward way to migration algorithms using later arrivals which is sometimes beneficial for sub-salt-imaging. The extension to anisotropic media is also valid as long as the traveltime computation of the diffraction surfaces is performed using an appropriate anisotropic scheme and the computation of the Fresnel-Radius is replaced by the corresponding anisotropic formula.

ACKNOWLEDGEMENTS

We are grateful to Yury Kravtsov for discussions and valuable advice and to Gaz-de-France (Lingen, Germany) for the permission to publish the results of the real data set.

REFERENCES

Bleistein, N. and Gray, S. (2001). From the Hagedoorn imaging technique to Kirchhoff migration and inversion. Geophysical Prospecting, 49:629–645.

Cerveny, V. and Soares, J. (1992). Fresnel volume ray tracing. *Geophysics*, 57:902–915.

Claerbout, J. F. (1971). Towards a unified theory of reflector mapping. *Geophysics*, 36:467–481.

Goertz, A., Müller, C., Buske, S., and Lüth, S. (2003). Elastic Fresnel-volume true-amplitude multicomponent migration. *65th EAGE meeting, Stavanger, Expanded Abstracts*.

Haslinger, F. (1994). Ein Verfahren zur automatisierten Bestimmung von Scheingeschwindigkeiten aus Mehrspurseismogrammen. Master's thesis, Ludwig-Maximilian-Universität München, 80 pages, in german.

Kravtsov, Y. A. (2005). *Geometrical optics in Engineering Physics*. Alpha Science International, Harrow, UK.

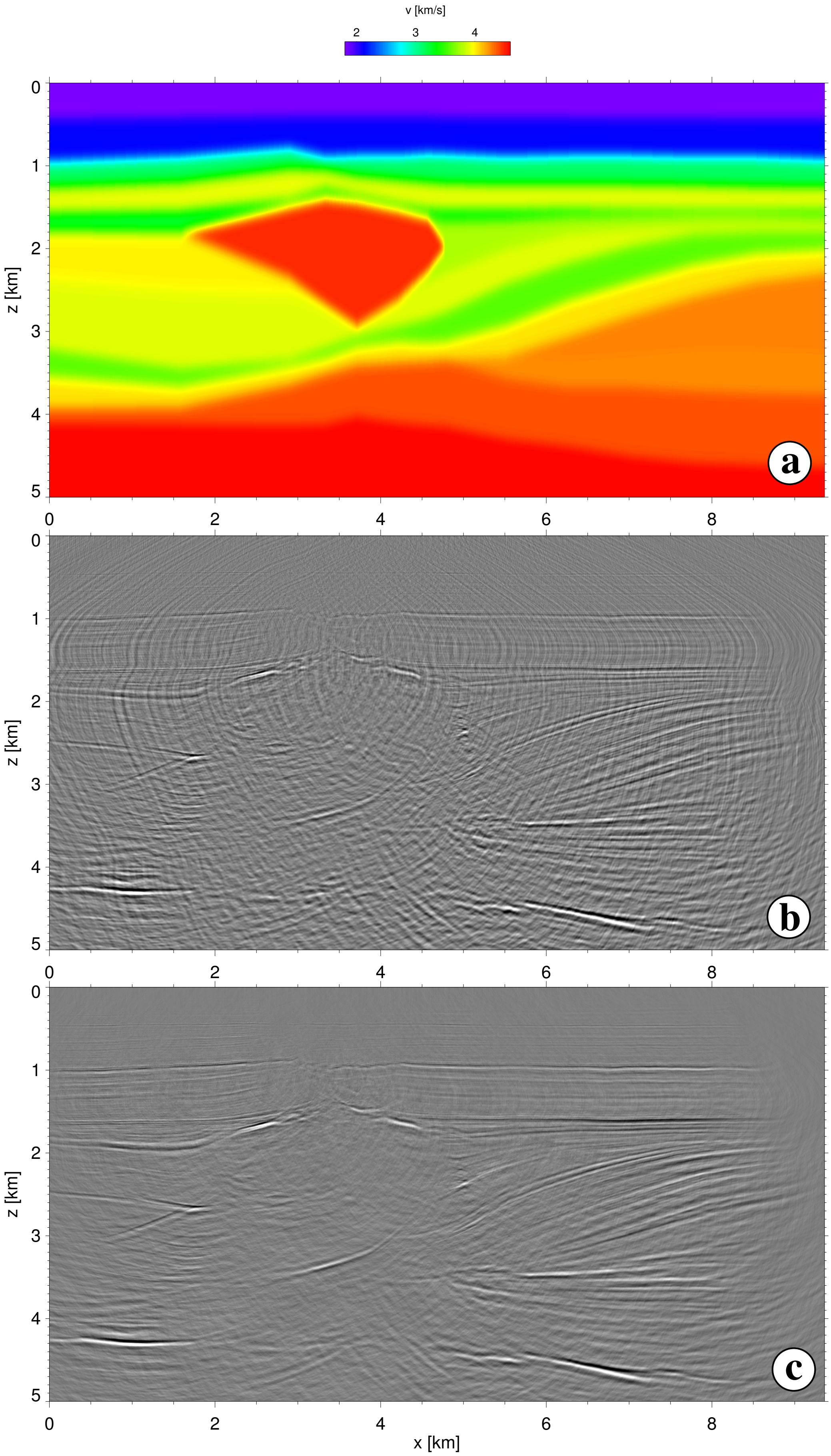

Figure 4: Real data set: (a) P-wave-velocity model (b) KPSDM result (c) FVM result.

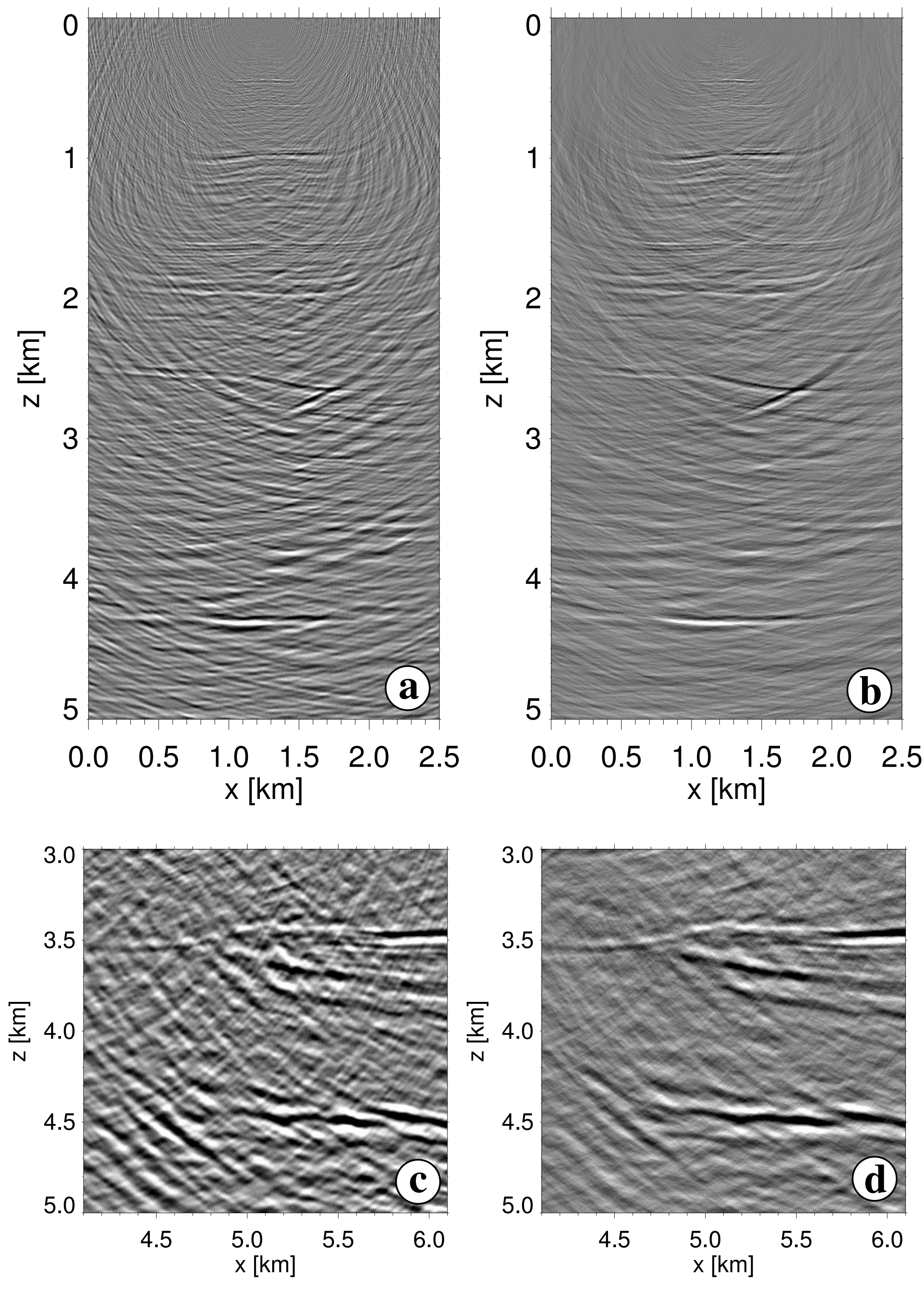

Figure 5: Top: Comparison of single migrated shot gather using (a) KPSDM and (b) FVM. Bottom: Zooms into sections of (c) KPSDM result (see Fig. 4b) and (d) FVM result (see Fig. 4c).

Kravtsov, Y. A. and Orlov, Y. I. (1990). *Geometrical optics of inhomogeneous media*. Springer Verlag, Berlin, Heidelberg.

Lüth, S., Buske, S., Giese, R., and Goertz, A. (2005). Fresnel-volume migration of multicomponent data. *Geophysics*, 70:S121–S129.

Podvin, P. and Lecomte, I. (1991). Finite difference computation of traveltimes in very contrasted velocity models: a massively parallel approach and its associated tools. *Geophys. J. Int.*, 105:271–284.

Schleicher, J., Tygel, M., and Hubral, P. (1993). 3-D true-amplitude finite-offset migration. *Geophysics*, 58:1112–1126.

Schneider, W. A. (1978). Integral formulation for migration in two and three dimensions. *Geophysics*, 43:49–76.

Stolt, R. H. (1978). Migration by Fourier transform. *Geophysics*, 43:23–48.

Sun, H. and Schuster, G. (2003). 3D wavepath migration. Geophysical Prospecting, 51:421–430.

Takahashi, T. (1995). Prestack migration using arrival angle information. *Geophysics*, 60:154–163.

Tillmanns, M. and Gebrande, H. (1999). Focusing in prestack isochrone migration using instantaneous slowness information. PAGEOPH, 156:187–206.