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Transformation Noise Suppression for Transmitted Wave VSP Imaging

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SUMMARY

Down going waves are used for seismic imaging in the near-well area additional to the reflected waves. For down going imaging, the transmitted converted waves are used most often. Migration on transmitted converted waves enables obtaining images of the velocity discontinuities, which have not been presented in the velocity macro-model used for imaging. If the sizes of such discontinuities are commensurable with a wavelength, the time delay caused by velocity changes, will be insignificant. At the same time, the converted waves originated on the discontinuity, will have significantly different propagation time compared to compressional waves. We can expect that using of such waves may produce reliable seismic images of such discontinuities with high resolution. At the same time, migrations of VSP data have a low immunity to transformation noise due to the limited apertures. Imaging of seismic boundaries in a wide range of dips sometimes leads to the artifacts that are hard to be distinguished from images of real boundaries. In this paper, the attention is focused on a special way of suppression of transformation noise at Kirchhoff migration. This approach is based on the analysis of a polarization vector of transmitted converted waves.

Introduction

The propagating downgoing waves are widely used in seismic prospecting for studying of the near-well area at vertical seismic profiling (VSP) and in well-to-well survey. Using of these waves allows estimating of wave propagation velocities, parameters of velocity anisotropy, inelastic absorption, etc.

Downgoing waves are used for seismic imaging in the near-well area additional to the reflected waves. For downgoing imaging, the transmitted converted waves are used most often. Migration on transmitted converted waves enables obtaining images of the velocity discontinuities, which have not been presented in the velocity macro-model used for imaging. If the sizes of such discontinuities are commensurable with a wavelength, the time delay, caused by velocity changes, will be insignificant. At the same time, the converted waves, originated on the discontinuity, will have significantly different propagation time compared to compressional waves. We can expect that using of such waves may produce reliable seismic images of such discontinuities with high resolution both in lateral and vertical directions.

Migration on transmitted converted waves was applied to solve various geologic problems. Luo et al, (2006) have shown the principal scheme of Kirchhoff operator for VSP migration on transmitted converted waves. They have applied this migration to image subsurface areas, which image could not be built using reflected waves.

Niheil et al, (2000) used the reverse time migration (RTM) for producing images of vertical fractures. They modified the RTM algorithm in such a way that instead of forward continuation of a compressional wavefield from a source, they used the backward continuation of downgoing compressional wave registered at VSP receivers. It has allowed them to create migration procedure less sensitive to velocity heterogeneities in the area between the source and the target object. Marmalyevskyy et al, (1997) has applied similar approach for producing images of near-vertical boundaries using reflected waves.

Niheil et al, (2002) showed that transmitted converted waves can produce images of layer boundaries and its inner vertical fractures, using mentioned above modified RTM. Migrations on transmitted converted waves possess this property irrespective of their specific realizations. If RTM is more preferable for surface survey data for imaging without any limitation for incidence angles on reflecting boundaries, different migrations of VSP data also possesses the specified property, in particular Kirchhoff migration.

At the same time, migrations of VSP data have a low immunity to transformation noise due to the limited apertures. Imaging of seismic boundaries in a wide range of dips sometimes leads to the artifacts that are hard to be distinguished from images of real boundaries. In this paper, the attention is focused on a special way of suppression of transformation noise at Kirchhoff migration. This approach is based on the analysis of a polarization vector of transmitted converted waves.

Method

Migration on transmitted converted waves is based on the diffraction Kirchhoff-Sobolev formula, which is a solution of the vector wave equation in conditions of medium with smooth changes of properties relative to wavelength (Timoshin, 1978). Generally, ignoring a volumetric term of Kirchhoff-Sobolev integral, in case of migration of VSP gathers, an image is formed at a point $M(\mathbf{x})$ according to the formula:

$$I(\mathbf{x}) = \sum s\big(t_S(\mathbf{x}) + t_R(\mathbf{x})\big) \cdot G_S(\mathbf{x})\,. \tag{1}$$

In this formula $t_S(\mathbf{x})$ and $t_R(\mathbf{x})$ are traveltimes for the defined wave types, calculated from the vector wave equation for point sources located in S and R position accordingly.

Coefficients $G_S(\mathbf{x})$ are determined by the wave amplitudes during the continuation of a synthetic wavefield from source S. This calculation is based on a finite-difference solution of the vector wave equation (Marmalyevskyy, et al, (2005)) and coefficients $G_S(\mathbf{x})$ correspond to the Green's function. For transmitted converted waves migration, traveltime $t_R(\mathbf{x})$ is calculated using a rotor maximum criterion, when traveltime $t_S(\mathbf{x})$ is computed using a maximum divergence criterion. Such approach allows us to build a maximum energy migration operator with the properties close to multi-path operator. Using the vector wave equation to calculate the migration operator enables to take into account thin-layered medium, anisotropy, fracturing, and other wave effects occurring in elastic medium.

Suppression of the migration operator noise is achieved by taking into account direction of the polarization vector with respect to a direction of the wave propagation trajectory. For this purpose, from each point of medium *M*(**x**), ray-tracing is carried out up to a point of the receiver *R* along gradients of the traveltime $t_R(\mathbf{x})$. Spatial derivatives of the traveltime are the components of its gradient. They are calculated using the nearest cell of the traveltime $t_R(\mathbf{x})$ in a direction of differentiation. Ray-tracing is performed by consecutive trajectory calculation on the grid facets of the traveltime $t_R(\mathbf{x})$. The ray path segments between the grid facet points have directions of the traveltime gradients.

During ray-tracing, we determine a direction $\mathbf{n}_R(\mathbf{x})$ of the incident wave to the receiver *R* for the wave originated from a medium point *M*(**x**). If a corresponding wave is compressional then its polarization also should be directed along a vector $\mathbf{n}_R(\mathbf{x})$. For a SV-wave, the polarization vector has direction $\mathbf{m}_R(\mathbf{x}) = \mathbf{f}_R(\mathbf{x}) / \left|\mathbf{f}_R(\mathbf{x})\right|$, where $\mathbf{f}_R(\mathbf{x}) = \mathbf{n}_R(\mathbf{x}) \times \mathbf{e}_z \times \mathbf{n}_R(\mathbf{x})$ and $\mathbf{e}_z$ is the vertical basis vector.

The signal $s(t)$ from the formula (1) is a projection of the registered three-component vector signal $\mathbf{s}_R(t)$ in one of directions $\mathbf{n}_R(\mathbf{x})$ or $\mathbf{m}_R(\mathbf{x})$ depending on a wave type, for which the image (P or SV) is calculated. The projection of the registered signal is calculated according to formulas $s_P(t) = \mathbf{s}(t) \cdot \mathbf{n}_R(\mathbf{x})$ and $s_{SV}(t) = \mathbf{s}(t) \cdot \mathbf{m}_R(\mathbf{x})$.

Using of a vector signal projection to the direction $\mathbf{n}_R(\mathbf{x})$ of the incident wave, or to a perpendicular direction $\mathbf{m}_R(\mathbf{x})$, provides the lower transformation noise.

Synthetic data example

Let us demonstrate the efficiency of the presented noise suppression technique on the model shown in Fig.1. The model represents fault with 200m throw on the bottom boundary. The fault is presented in the form of a 20 m thin layer. Velocity inside of this layer is 2000 m/s that on the average by 25 % differs from velocity in the surrounding medium. The source point is located at the distance 1500 m from the well in which receivers are located with 10m intervals.

Synthetic X- and Z-components have been calculated using the finite-difference continuation of the wavefield. Fig. 2 shows synthetic VSP shot gather and snapshot for X-component of the wavefield. The depth velocity model is presented as a background on the wavefield snapshot. Despite of relative simplicity of the velocity model, wavefield of the transmitted converted waves has a complex structure. Fig.1 shows the initial model, divided into separate areas, which are designated as A, B, C, and D correspondingly. In the VSP shot gather and the wavefield snapshot (Fig.2), the elements of the wavefield related to specific parts of the boundaries are shown with arrows. Transmitted converted waves formed on sites of the boundaries A, B, C, and D accordingly are marked with green, lilac, pink and yellow arrows correspondingly. Transmitted converted wave, which has been originated on a near-vertical fault, is marked with a black arrow. The result of transmitted converted waves migration for Z-components is shown in fig. 3. The velocity model is shown on the image as background. Migration was done without preliminary wavefield separation. Suppression of other types of waves also was not applied. Presence of large quantity of waves of various types in the initial wavefield has led to seismic image substantially distorted by the transformation noise (Fig. 3). Fig. 4 displays the seismic image obtained with the transformation noise suppression technique, described above. This figure demonstrates the considerably lower level of the transformation noise. Thus vertical and horizontal resolution of migration procedure is improved. Let us notice that boundaries in areas A, B and C are well imaged. At the same time, the image of the part D (the bottom boundary) did not come up. On the snapshot, shown in Fig. 2, the transmitted converted wave originated on boundary in D area is present (is shown with a yellow arrow). However, on VSP shot gather this wave is not present because it is not registered in the receivers' interval inside the well and consequently the boundary image in area D is not built.

The image of the fault is, on the contrary, formed in the bottom part of a cross-section, but not formed in its upper part. This is because the compressional wave ray is almost perpendicular to the fault in its upper part; therefore the converted PS-wave is not formed.

The technique of the transformation noise suppression described above is applicable not only to the migration procedure focused on transformation of transmitted converted waves, but also to other types of waves used in VSP migrations. This will be shown in the corresponding presentation.

Conclusions

Migration of VSP data on transmitted converted waves enables seismic boundaries imaging practically without any limitations for their inclination angle. At the same time, large quantity of waves of various types in VSP data both down going and upgoing, leads to significant transformation noise. To suppress the transformation noise, we apply the migration operator, which takes into account distinction in a polarization vector for different waves (P and S). The presented model examples confirm that the offered method improves seismic images by significant suppression of the transformation noise.

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Refereces

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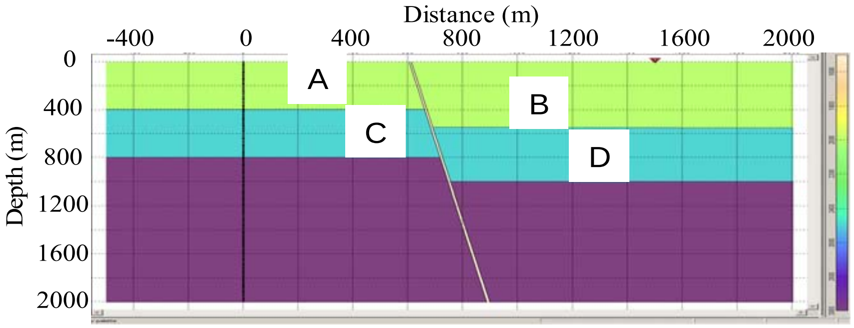

Figure1 Source model

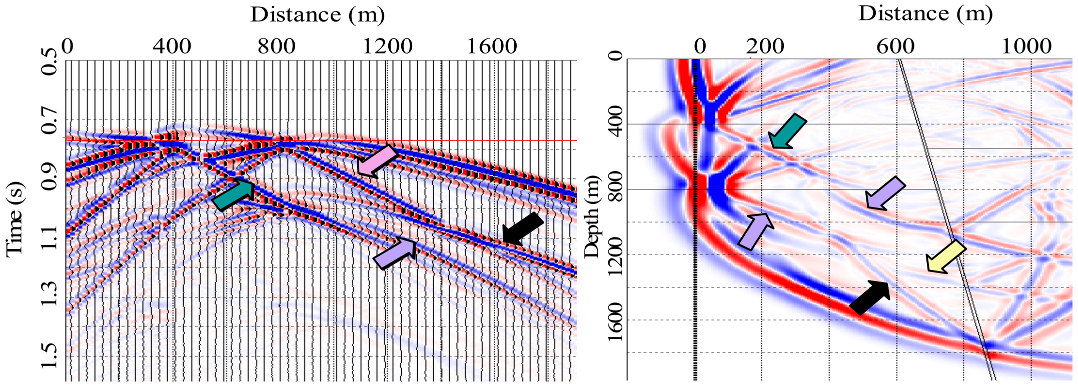

Figure 2 Synthetic VSP shot gather (left) and snapshot (right) received at X-component of the wavefield.

With arrows are shown transmitted PS-waves with conversion on boundaries: A (green), B (lilac), C (pink), D (yellow). With black arrow is shown PS-wave originated on near-vertical boundary.

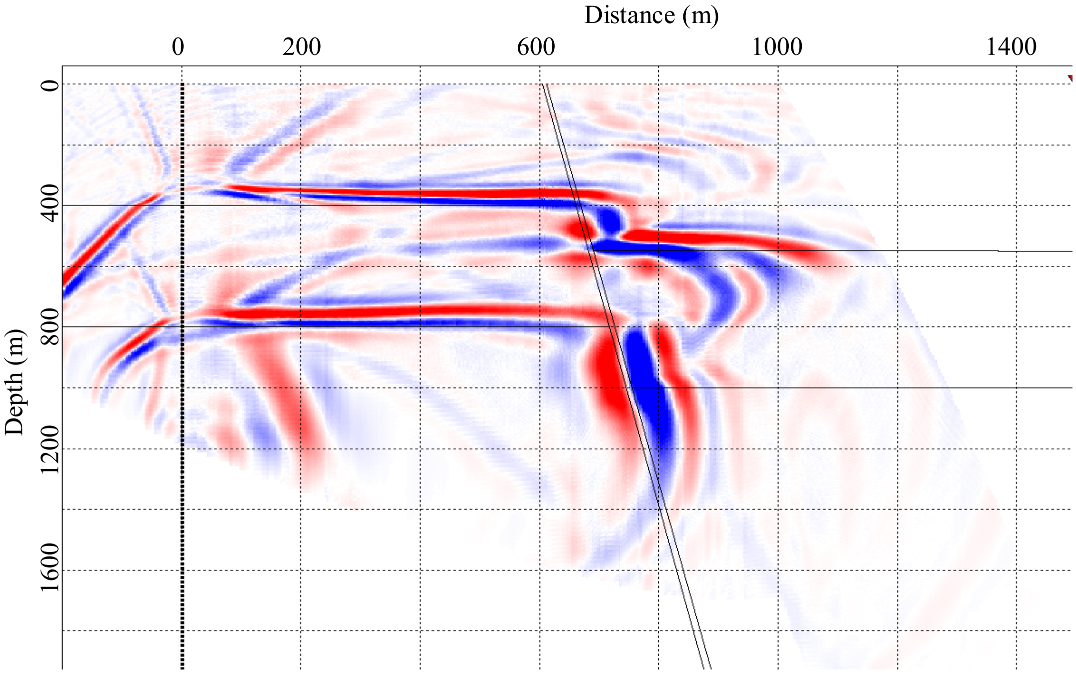

Figure 3 Seismic image obtained with transmitted converted waves without suppression of transformation noises.

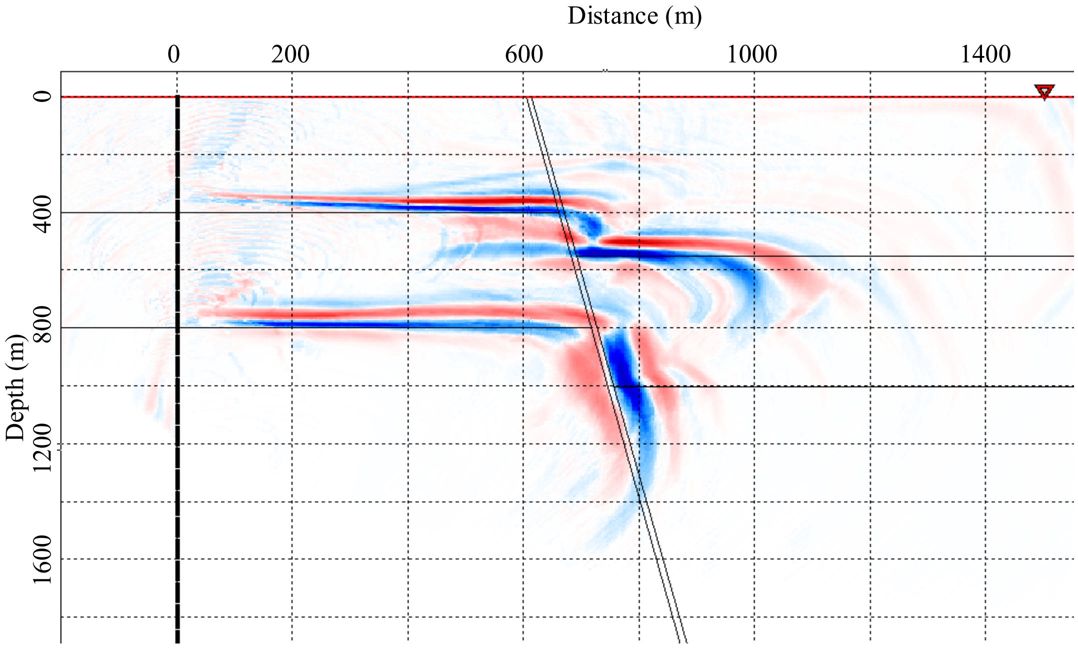

Figure 4 Seismic image obtained with transmitted converted waves and suppression of transformation noises basing on migration operator using a polarization vector of transmitted converted waves.