Kirchhoff prestack depth migration in 3-D models: Comparison of triclinic anisotropy with simpler anisotropies

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Summary

We apply the Kirchhoff prestack depth migration to the calculation of migrated sections in 3-D simple anisotropic homogeneous velocity models. We generate recorded wave field in models composed of two homogeneous layers separated by one non-inclined or inclined curved interface. The anisotropy in the upper layer is triclinic. We test Kirchhoff prestack depth migration in velocity models with different types of anisotropy: a triclinic anisotropic medium, an isotropic medium, transversely isotropic media with a horizontal (HTI) and vertical (VTI) symmetry axis. We show errors of migrated interface caused by inaccurate velocity models used for migration. The study is limited to P-waves.

Keywords

3-D Kirchhoff prestack depth migration, anisotropic velocity model

1. Introduction

Inaccurate velocity models used for migration can lead to position errors of interfaces in migrated sections. Anisotropy-induced distortions in imaging have been analyzed mostly for 2-D transverse isotropic media (Larner and Cohen, 1993; Alkhalifah and Larner, 1994; Behera and Tsvankin, 2009).

Tsvankin et al. (2010) mention that TI models with a vertical (VTI) and tilted (TTI) axis of symmetry have become practically standard in prestack imaging projects all over the world. On the other hand, Tsvankin et al. (2010) write that many sedimentary formations including sands and carbonates, however, contain vertical or steeply dipping fracture sets and should be described by effective symmetries lower than TI, such as orthorhombic.

We approximate the recorded wave field by ray-theory synthetic seismograms, and then we apply ray-based Kirchhoff prestack depth migration to the calculation of the migrated sections. To calculate the recorded wave field, we use 3-D simple anisotropic velocity model composed of two homogeneous layers separated by one curved interface that is non-inclined or inclined. The anisotropy in the upper layer is triclinic (the lowest symmetry). The bottom layer is isotropic.

We test the 3-D Kirchhoff prestack depth migration in homogeneous models without the curved interface with different types of anisotropy: a triclinic anisotropic medium, an isotropic medium, transversely isotropic media with a horizontal (HTI) and vertical (VTI) symmetry axis. We show misposition, distortion and defocusing of migrated interface caused by inaccurate velocity models used for migration. We use 3-D migration

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because the reflected two-point rays propagate in triclinic media in a 3-D volume. The study is limited to P-waves.

The first tests of this migration algorithm on 2-D and 3-D models of various anisotropy were shown by Bucha (2010).

The GOCAD program has been used to visualize the 3-D model with curved interface, shot-receiver configurations and computed two-point rays.

2. Anisotropic velocity models

The dimensions of the 3-D velocity models and measurement configurations are derived from the 2-D Marmousi model and dataset (Versteeg & Grau, 1991). The horizontal dimensions of the model are 9.2 km x 10 km and the depth is 3 km. The velocity model is composed of two homogeneous layers separated by one curved interface. We use two models, one with non-inclined curved interface and one with inclined curved interface (see Figure 1).

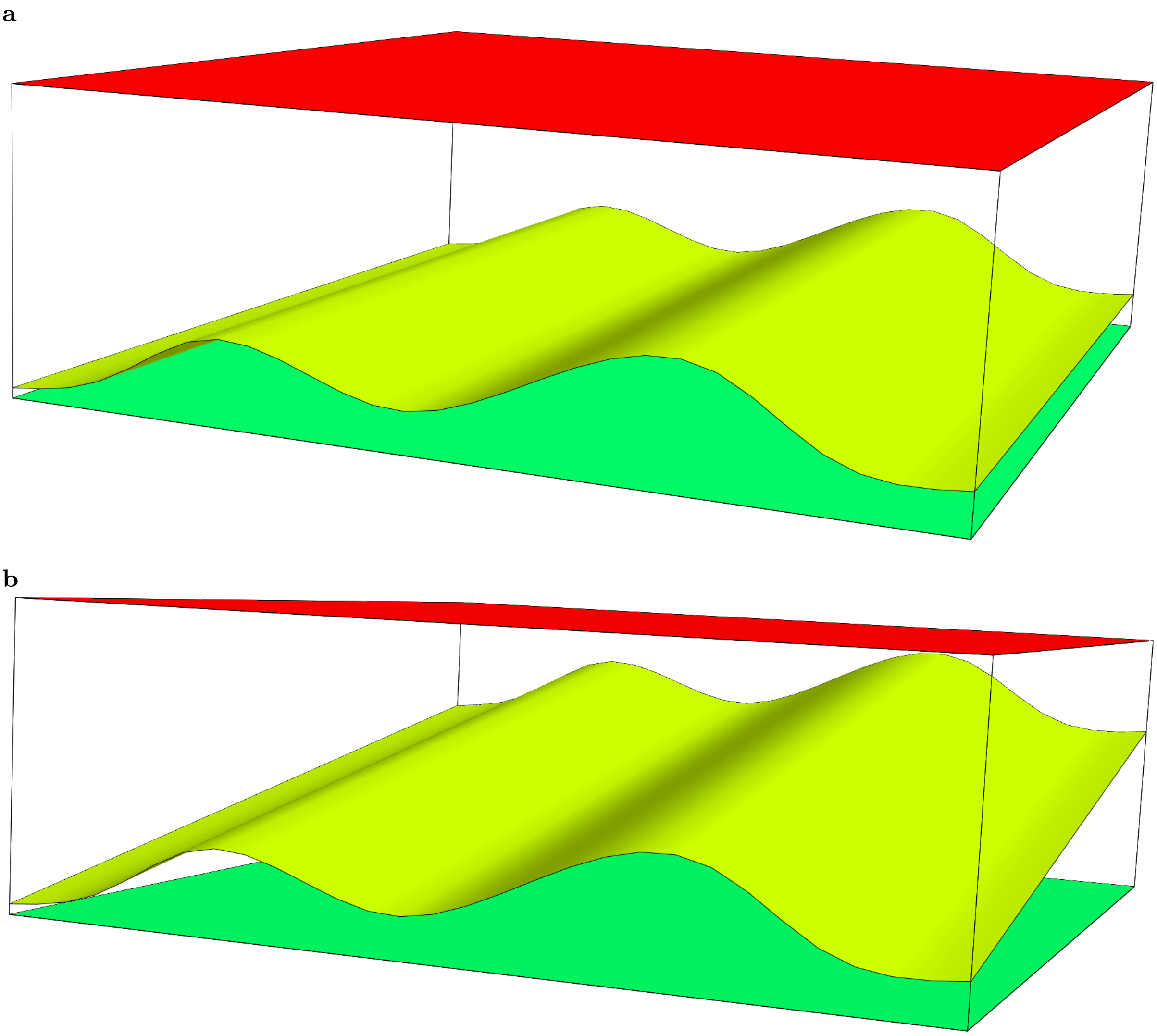

Figure 1. 3-D models with a non-inclined curved interface (**a**), an inclined curved interface (**b**). The horizontal dimensions of the models are 9.2 km x 10 km, the depth is 3 km. Models consist of three interfaces: one curved interface, top and bottom model planes. Interfaces are coloured according to the indices of surfaces.

We compute the **recorded wave field** in the model with triclinic anisotropy in the upper layer:

a) Triclinic anisotropy (TA) representing dry Vosges sandstone (Mensch & Rasolofosaon, 1997). The reflected two-point rays propagate in a 3-D volume. The matrix of elastic moduli reads

$$\begin{pmatrix} 10.3 & 0.9 & 1.3 & 1.4 & 1.1 & 0.8 \\ & 10.6 & 2.1 & 0.2 & -0.2 & -0.6 \\ & & 14.1 & 0.0 & -0.5 & -1.0 \\ & & & 5.1 & 0.0 & 0.2 \\ & & & & 6.0 & 0.0 \\ & & & & & 4.9 \end{pmatrix} \frac{\mathrm{km}^2}{\mathrm{s}^2} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} \\ & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} \\ & & A_{33} & A_{34} & A_{35} & A_{36} \\ & & & A_{44} & A_{45} & A_{46} \\ & & & & A_{55} & A_{56} \\ & & & & & A_{66} \end{pmatrix}$$

Elastic moduli are reduced, divided by density ρ. The bottom layer is isotropic and has P-wave velocity $V_p = 3.6$ km/s.

We perform the **migration** in homogeneous models (without curved interface) with triclinic anisotropy specified in item a) and also in the following isotropic and anisotropic models:

b) Isotropic medium (ISO) with P-wave velocity ${V_p}^2 = 14.1$ km^2/s^2 (equal to the vertical P-wave velocity in the TA model, matrix element A_{33}),
and S-wave velocity ${V_s}^2 = 5.55$ km^2/s^2 (mean of matrix elements A_{44} and A_{55} in the TA model).

c) VTI-1 is a transversely isotropic medium with a vertical symmetry axis (VTI). The matrix of elastic moduli reads

$$\begin{pmatrix} 10.45 & 0.65 & 1.7 & 0.0 & 0.0 & 0.0 \\ & 10.45 & 1.7 & 0.0 & 0.0 & 0.0 \\ & & 14.1 & 0.0 & 0.0 & 0.0 \\ & & & 5.55 & 0.0 & 0.0 \\ & & & & 5.55 & 0.0 \\ & & & & & 4.9 \end{pmatrix} \frac{\mathrm{km}^2}{\mathrm{s}^2} = \begin{pmatrix} A_{11} & A_{12} & A_{13} & 0 & 0 & 0 \\ & A_{11} & A_{13} & 0 & 0 & 0 \\ & & A_{33} & 0 & 0 & 0 \\ & & & A_{44} & 0 & 0 \\ & & & & A_{44} & 0 \\ & & & & & A_{66} \end{pmatrix}$$

with $A_{12} = A_{11} - 2 * A_{66}$

We optimized velocities for vertical and near vertical P-waves to obtain the best results of the migration. We fitted matrix element A_{33} for vertical P-waves and elements $A_{13} = A_{23}$ (mean of triclinic elements A_{13}, A_{23}) for near vertical P-waves according to elastic moduli of triclinic anisotropy.

Horizontal P-wave velocities (elements A_{11}, A_{22}) are equal in both directions and the value is mean of triclinic elements A_{11}, A_{22}.

d) VTI-2 is similar to VTI-1, we only decreased matrix element A_{33}, which is responsible for vertical P-wave velocity, to $A_{33} = 11.6$ km^2/s^2.

e) VTI-3 is similar to VTI-1, we only decreased matrix elements A_{11} and A_{12}, which are responsible for horizontal P-wave velocity in the direction parallel with measurement lines, to $A_{11} = 8.95$ km^2/s^2 and $A_{12} = -0.85$ km^2/s^2.

f) HTI-1 is a transversely isotropic medium with a horizontal symmetry axis (HTI). The symmetry axis is parallel with the x_1 coordinate axis. The matrix of elastic moduli reads

$$\begin{pmatrix} 10.3 & 1.3 & 1.3 & 0.0 & 0.0 & 0.0 \\ & 14.1 & 3.9 & 0.0 & 0.0 & 0.0 \\ & & 14.1 & 0.0 & 0.0 & 0.0 \\ & & & 5.1 & 0.0 & 0.0 \\ & & & & 6.0 & 0.0 \\ & & & & & 6.0 \end{pmatrix} \frac{\mathrm{km}^2}{\mathrm{s}^2} = \begin{pmatrix} A_{11} & A_{13} & A_{13} & 0 & 0 & 0 \\ & A_{33} & A_{23} & 0 & 0 & 0 \\ & & A_{33} & 0 & 0 & 0 \\ & & & A_{44} & 0 & 0 \\ & & & & A_{55} & 0 \\ & & & & & A_{55} \end{pmatrix}$$

$$\text{with } A_{23} = A_{33} - 2 * A_{44}$$

We fitted matrix element A_{33} for vertical P-waves and element A_{23} for near vertical P-waves according to the elastic moduli of triclinic anisotropy.

The horizontal P-wave velocity, perpendicular to the profile lines (A_{22}), is equal to the vertical P-wave velocity (A_{33}) of the triclinic (TA) model.

g) HTI-2 is a transversely isotropic medium with a horizontal symmetry axis (HTI). The symmetry axis is parallel with the x_2 coordinate axis. The matrix of elastic moduli reads

$$\begin{pmatrix} 14.1 & 2.1 & 2.1 & 0.0 & 0.0 & 0.0 \\ & 10.6 & 2.1 & 0.0 & 0.0 & 0.0 \\ & & 14.1 & 0.0 & 0.0 & 0.0 \\ & & & 5.1 & 0.0 & 0.0 \\ & & & & 6.0 & 0.0 \\ & & & & & 5.1 \end{pmatrix} \frac{\mathrm{km}^2}{\mathrm{s}^2} = \begin{pmatrix} A_{33} & A_{23} & A_{13} & 0 & 0 & 0 \\ & A_{22} & A_{23} & 0 & 0 & 0 \\ & & A_{33} & 0 & 0 & 0 \\ & & & A_{44} & 0 & 0 \\ & & & & A_{55} & 0 \\ & & & & & A_{44} \end{pmatrix}$$

$$\text{with } A_{13} = A_{33} - 2 * A_{55}$$

We fitted matrix element A_{33} for vertical P-waves and element A_{13} for near vertical P-waves according to the elastic moduli of triclinic anisotropy.

The horizontal P-wave velocity, parallel with the profile lines (A_{11}), is equal to the vertical P-wave velocity (A_{33}) of the triclinic (TA) model.

3. Shots and receivers

The measurement configuration is derived from the Marmousi model and dataset (Versteeg & Grau, 1991). The profile lines are parallel with the x_1 coordinate axis. One profile line has the following configuration: The first shot is 3 km from the left-hand side of the velocity model, the last shot is 8.975 km from the left-hand side of the velocity model, the distance between the shots is 0.025 km, the depth of the shots is 0.008 km. The total number of shots is 240. The number of receivers per shot is 96, the first receiver is at offset 2.575 km left of the shot location, the last receiver is at offset 0.2 km left of the shot location, the distance between the receivers is 0.025 km, and the depth of the receivers is 0 km.

The 3-D measurement configuration consists of 81 parallel profile lines, see Figures 2 and 3. The distance between the parallel profile lines is 0.025 km.

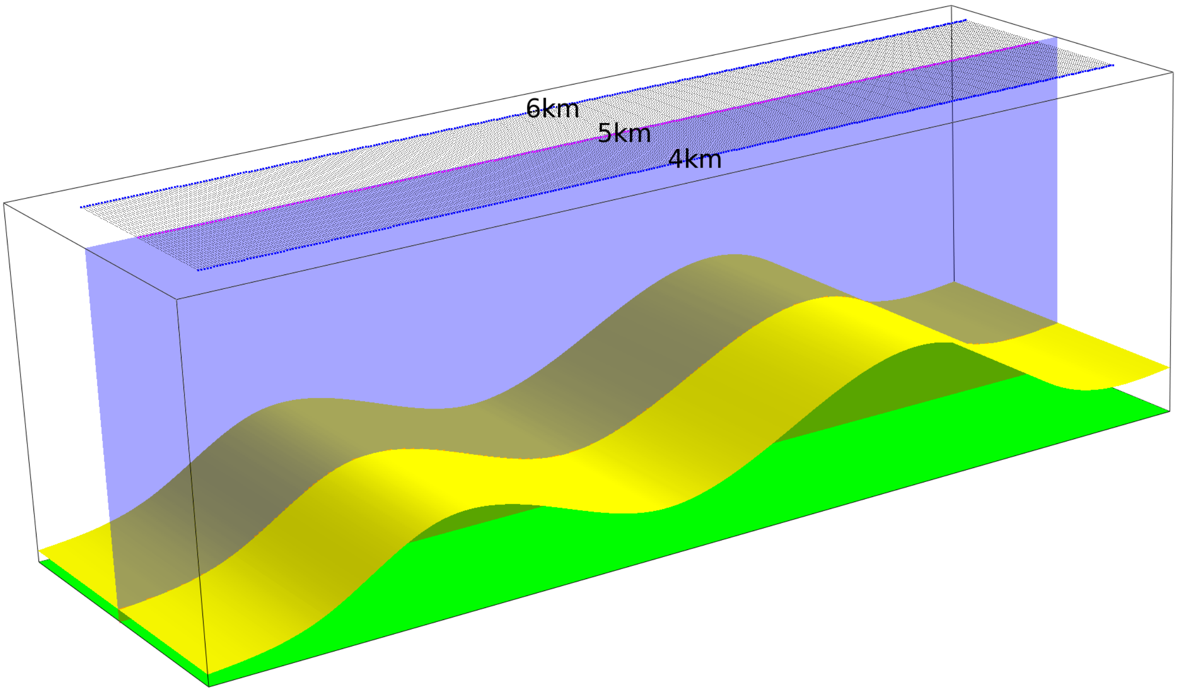

Figure 2. Slice of 3-D model with 81 parallel profile lines, the non-inclined curved interface and the bottom model plane. The horizontal dimensions of the model slice are 9.2 km x 3 km, the depth is 3 km. We compute and stack migrated sections in the 2-D plane located in the middle of the shot-receiver configuration (at horizontal coordinate x_2=5 km).

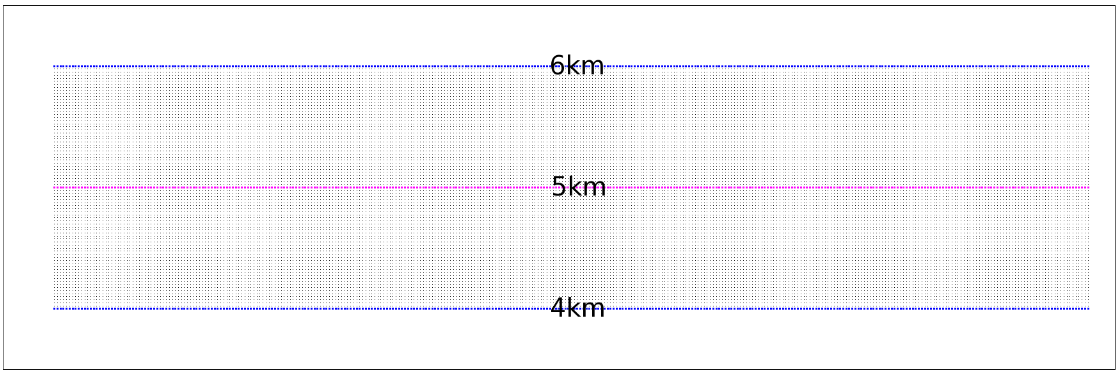

Figure 3. Top view of the slice of 3-D model with 81 parallel profile lines parametrized by the x_2 coordinate.

4. Recorded wave field

The recorded wave field in the triclinic velocity model was computed using the ANRAY software package (Gajewski & Pšenčík, 1990).

3-D ray tracing is used to calculate the two-point rays of the reflected P-wave. We then compute the ray-theory seismograms at the receivers.

In the velocity model with the non-inclined curved interface, the recorded wave field is equal for all parallel profile lines, since the layers are homogeneous and the non-inclined curved interface is independent of the distance x_2 perpendicular to the profile lines (see Figures 1a, 2).

In the model with inclined curved interface the recorded wave field should be calculated for each profile line independently (see Figure 1b).

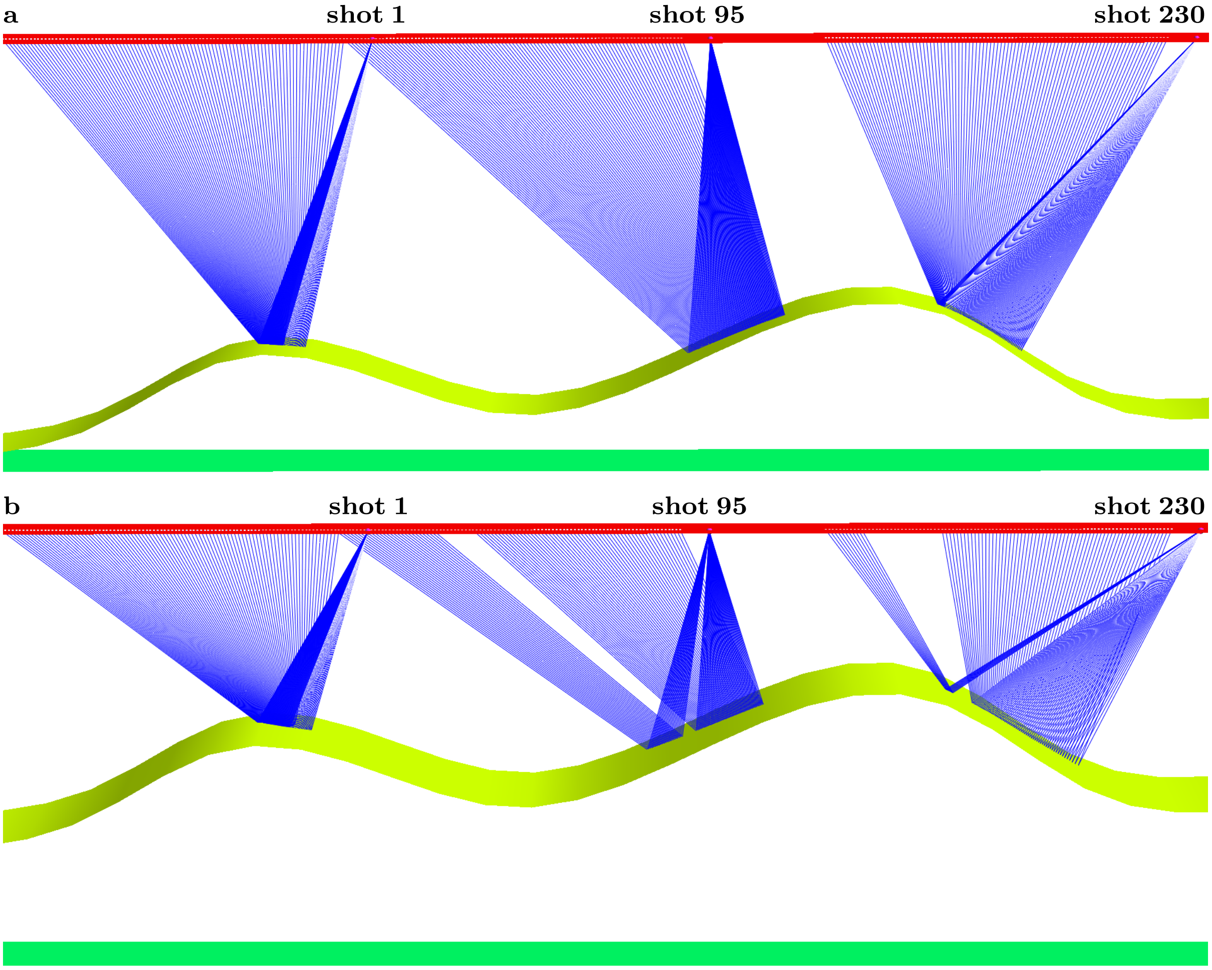

Figure 4. Selected two-point rays computed in the model with triclinic anisotropy (TA) in the upper layer. The curved interface is non-inclined (**a**) and inclined (**b**). The two-point rays of the reflected P-wave propagate in a 3-D volume. Shots 1, 95 and 230 are located at horizontal coordinates x_1=3 km, 5.35 km and 8.725 km. The profile line is located at horizontal coordinate x_2=5 km.

Figure 4 shows two-point rays of the reflected P-wave for one selected profile line and three shot-receiver configurations. The selected profile line is in the middle of 81 profile lines.

5. 3-D Kirchhoff prestack depth migration

We use the MODEL, CRT, FORMS and DATA packages for the Kirchhoff prestack depth migration (Červený, Klimeš & Pšenčík, 1988; Bulant, 1996). The migration consists of two-parametric ray tracing from the individual surface points, calculating grid values of travel time and amplitude, common-shot migration and stacking of migrated images. The shot-receiver configuration consists of 81 parallel profile lines at the intervals of 0.025 km (see Figures 2, 3). We compute and stack 81 migrated sections calculated in the 2-D plane located in the middle of the shot-receiver configuration (at horizontal coordinate x_2=5 km, see Figure 2). The first profile line starts at horizontal coordinate x_2=4 km and the last profile line ends at horizontal coordinate x_2=6 km.

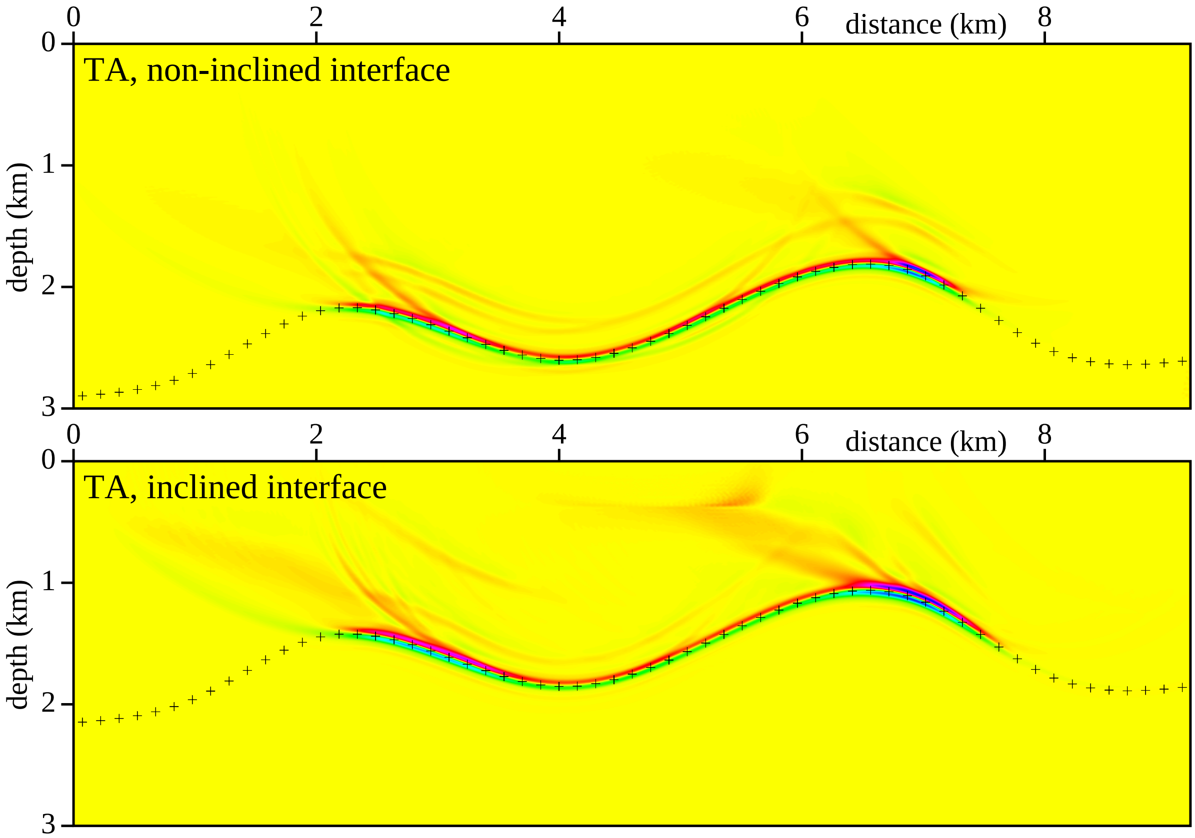

Figure 5. Stacked migrated sections calculated in the models with non-inclined and inclined curved interface. The triclinic anisotropy in the upper layer of the velocity model used to compute the recorded wave field is the same as the anisotropy in the homogeneous velocity model used for migration. The crosses denote the interface in the velocity model used to compute the recorded wave field.

5.1 Anisotropy for migration equal to the anisotropy for the recorded wave field

We first choose the anisotropy in the homogeneous velocity model for migration equal to the triclinic anisotropy in the upper layer of the velocity model used to compute the recorded wave field. Figure 5 shows the stacked migrated sections calculated in the models with non-inclined and inclined curved interface. The migrated interface coincides nearly perfectly with the interface in the model used to compute the recorded wave field. The migrated sections in Figure 5 demonstrate that the migration algorithm works well. These migrated sections may be used for comparison with migrated sections calculated for inaccurate velocity models.

We compared individual migrated sections for separate profile lines in the model with non-inclined curved interface and we observed asymmetry in migration caused by triclinic anisotropy that is asymmetric. Figures 6 and 7 display migrated sections of selected individual profile lines. Note the differences between pairs of sections (lines 4.6 and 5.4, lines 4.4 and 5.6, etc.) located at the equal distances symmetrically from the middle profile line at horizontal coordinate 5 km, where the vertical stacked sections are calculated. In comparison with Figure 6, the migrated interfaces in Figure 7 are shifted, distorted and poorly displayed in the horizontal range approximately 4 - 6 km. These migration distortions are stronger with the greater distance from the middle profile line. The crosses denote the interface in the velocity model used for computation of the recorded wave field.

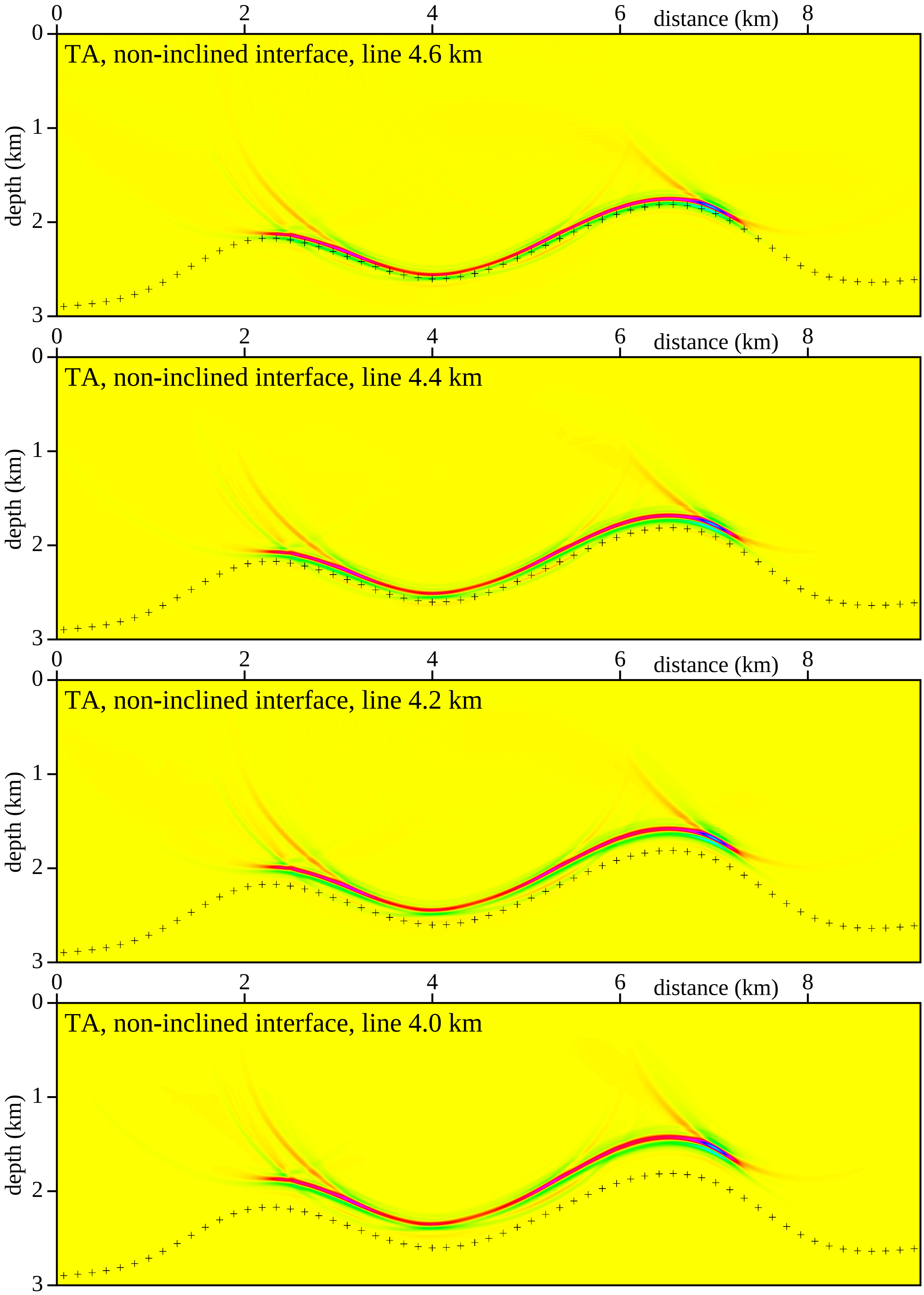

Figure 6. Individual stacked migrated sections corresponding to profile lines 4.6, 4.4, 4.2 and 4.0 km. The triclinic anisotropy in the upper layer of the velocity model used to compute the recorded wave field is the same as the anisotropy in the velocity model used for migration. The crosses denote the interface in the velocity model used to compute the recorded wave field. The curved interface is non-inclined.

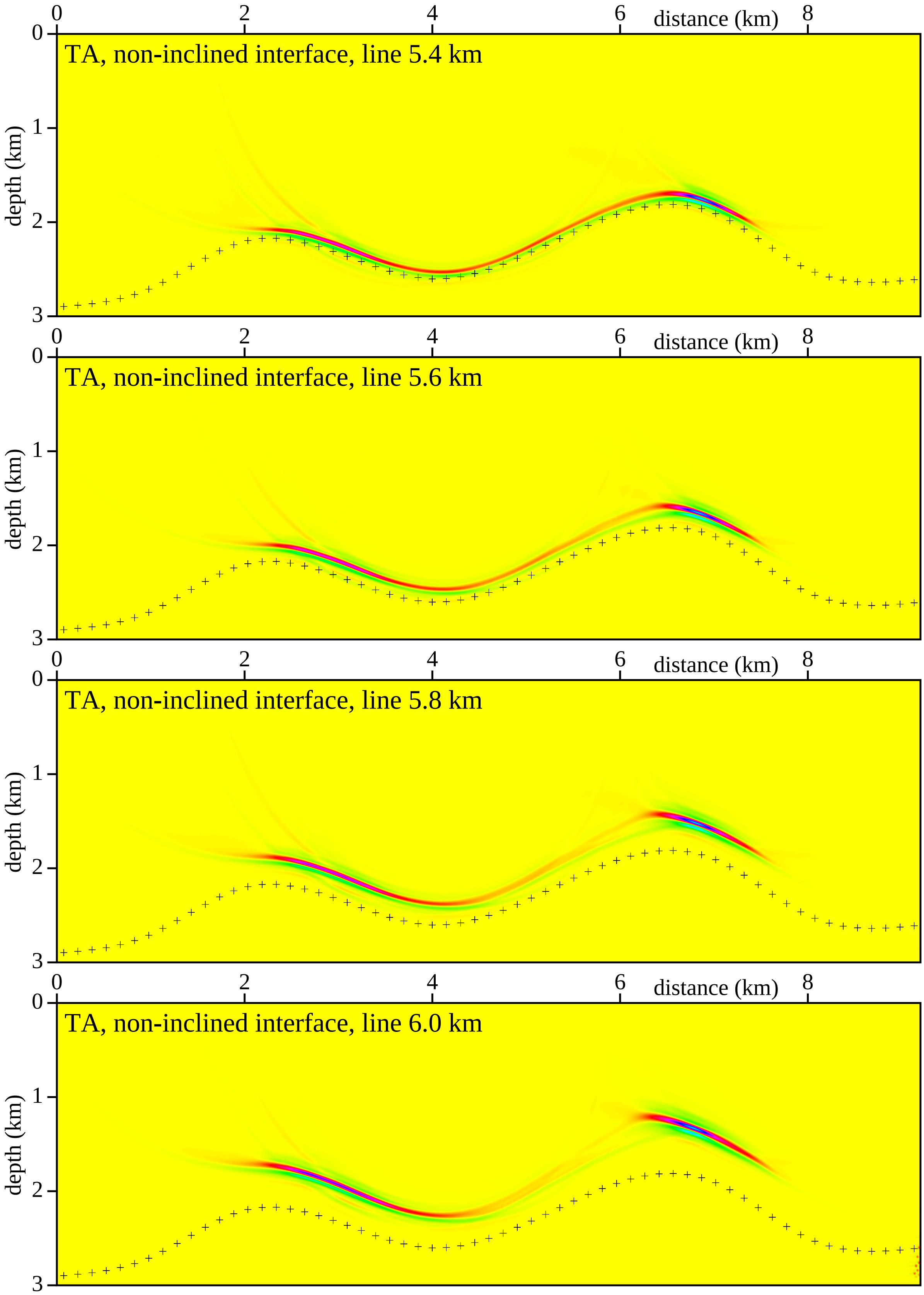

Figure 7. Individual stacked migrated sections corresponding to profile lines 5.4, 5.6, 5.8 and 6.0 km. The triclinic anisotropy in the upper layer of the velocity model used to compute the recorded wave field is the same as the anisotropy in the velocity model used for migration. The crosses denote the interface in the velocity model used to compute the recorded wave field. The curved interface is non-inclined.

Another effect of the triclinic asymmetry is the shift of the profile line, recording the wave reflected at given position x_2: The vertical migrated section is situated at x_2=5 km. For a non-inclined interface and a symmetric anisotropy with respect to x_2, the wave reflected at x_2=5 km is recorded along the profile at x_2=5 km. For the triclinic anisotropy, the profile line recording the wave reflected at x_2=5 km is shifted from coordinate x_2=5 km towards coordinate x_2=4.9 km. This effect of the triclinic anisotropy is thus similar to the effect of an inclined interface in an isotropic medium.

We also compared individual migrated sections for separate profile lines in the model with non-inclined curved interface for the isotropic medium, VTI and HTI media (described in the next Section 5.2) which are symmetric. We observed negligible differences between pairs of sections located at the equal distances symmetrically from the middle profile line at horizontal coordinate 5 km.

5.2 Anisotropy for migration different from the anisotropy for the recorded wave field

Figures 8-11 show stacked migrated sections when the anisotropy in the homogeneous velocity model used for migration is different from the anisotropy in the upper layer of the velocity model used to compute the recorded wave field. We compare the triclinic anisotropy used for the recorded wave field with the isotropy (ISO), transversely isotropic media with a vertical and horizontal symmetry axis (VTI-1,2,3 and HTI-1,2) used for the migration. These tests should simulate situations when we have made a bad guess of the velocity model for migration. We shall divide results of our tests according to the values of vertical and horizontal P-wave velocities.

a) Vertical P-wave velocity (matrix element A_{33}) in VTI-1 and HTI-1 models is the same as analogous velocity (A_{33}) in the triclinic (TA) model. Horizontal P-wave velocity, parallel with the profile lines (matrix element A_{11}), in VTI-1 model is nearly the same and in HTI-1 model the same as horizontal P-wave velocity (A_{11}) in the triclinic (TA) model. We optimized velocities in models VTI-1 and HTI-1 for vertical and near vertical rays to obtain the best results of migration.

   Migrated sections are very similar either we migrate in model with VTI-1 or HTI-1 anisotropy (see Figure 8). Note the poorly displayed migrated interface in the horizontal range approximately 4 - 6 km. The displaying of the discussed segment of the interface (4 - 6 km) is worse for the model with the inclined curved interface. The migrated interface is slightly mispositioned.

b) Vertical P-wave velocity (matrix element A_{33}) in the isotropic (ISO) and HTI-2 models is the same as analogous velocity (A_{33}) in the triclinic (TA) model. Horizontal P-wave velocity, parallel with the profile lines (matrix element A_{11}), in ISO and HTI-2 models is equal to vertical P-wave velocity (A_{33}) in the triclinic (TA) model (see Figure 9). We optimized velocities also in models ISO and HTI-2 for vertical and near vertical rays to obtain the best results of migration.

   Migrated sections are very similar either we migrate in model with isotropy (ISO) or HTI-2 anisotropy. In this case the migrated interface in the horizontal range approximately 4 - 6 km is displayed much better. The segments of the interface in the horizontal ranges approximately 2 - 4 km and 6 - 8 km are defocused and mispositioned.

c) Vertical P-wave velocity (matrix element A_{33}) in the VTI-2 model is lower than vertical P-wave velocity (A_{33}) in the triclinic (TA) model (see Figure 10). Migrated interface is shifted vertically upwards (undermigrated) and is slightly distorted. The vertical shift is smaller and the distortion is greater for the model with inclined curved interface. Migrated interface in the horizontal range approximately 4 - 6 km is poorly displayed for the inclined curved interface, analogously to the migration in the VTI-1 model.

d) Horizontal P-wave velocity, parallel with the profile lines (matrix element A_{11}), in the model VTI-3 is lower than horizontal P-wave velocity (A_{11}) in the triclinic (TA) model (see Figure 11). In this case we can observe the poorly displayed migrated interface in the horizontal range approximately 4 - 6 km (as in Figure 8). Compared with the migration in model VTI-1 (Figure 8), the image of the interface is slightly worse in the horizontal range of 4 - 6 km.

The computing time of the 3-D Kirchhoff migration for 81×240 stacked sections computed on a grid of cells 16×16 metres and interpolated to a grid of cells 4×4 metres, is approximately 27 hours for the model with inclined curved interface (approximately 5 seconds per one shot-receiver configuration). The time of the computation corresponds to an Athlon six-core 3.2 GHz processor.

6. Conclusions

We have applied the 3-D Kirchhoff prestack depth migration to the calculation of migrated sections in 3-D simple anisotropic homogeneous velocity models. The recorded wave field was generated in the models composed of two homogeneous layers separated by one non-inclined or inclined curved interface. The anisotropy in the upper layer is triclinic (the lowest symmetry). The bottom layer is isotropic.

We have tested 3-D Kirchhoff prestack depth migration in homogeneous velocity models without the curved interface, a) with the same triclinic anisotropy, b) with different types of simpler anisotropies: isotropic medium, transversely isotropic media with a horizontal (HTI) and vertical (VTI) symmetry axis. The study has been limited to P-waves.

a) We have computed the stacked migrated sections when the anisotropy in the homogeneous velocity model for migration is equal to the triclinic anisotropy in the upper layer of the velocity model used to compute the recorded wave field. In this case, the migrated interface coincides nearly perfectly with the interface in the model used to compute the recorded wave field.

   Individual migrated sections are compared for separate profile lines in the model with non-inclined curved interface. The pairs of migrated sections located at the equal distances symmetrically from the middle profile line at horizontal coordinate 5 km (used for stacking of 81 sections) are different. One half of the sections in the horizontal range 5 - 6 km (perpendicular to profile lines) has shifted, distorted and poorly displayed migrated interface in comparison with the sections in the horizontal range 4 - 5 km. These distortions are stronger with the greater distance from the middle profile line. The observed asymmetry in migration is caused by triclinic anisotropy that is asymmetric.

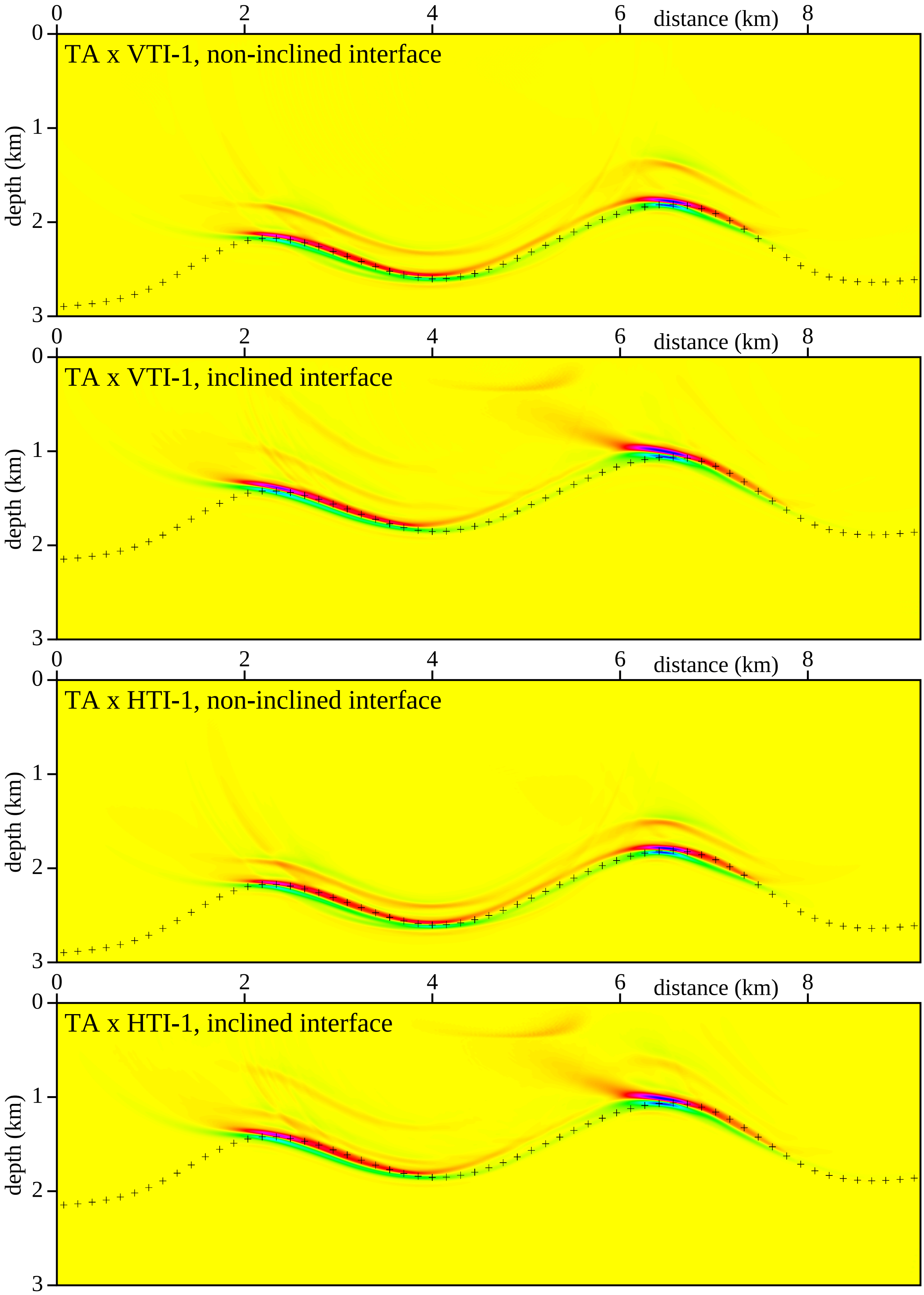

Figure 8. Stacked migrated sections when the triclinic anisotropy is used for the recorded wave field and the transversely isotropic media with a vertical and horizontal symmetry axis (VTI-1 and HTI-1) are used for the migration. The crosses denote the interface in the velocity model used to compute the recorded wave field.

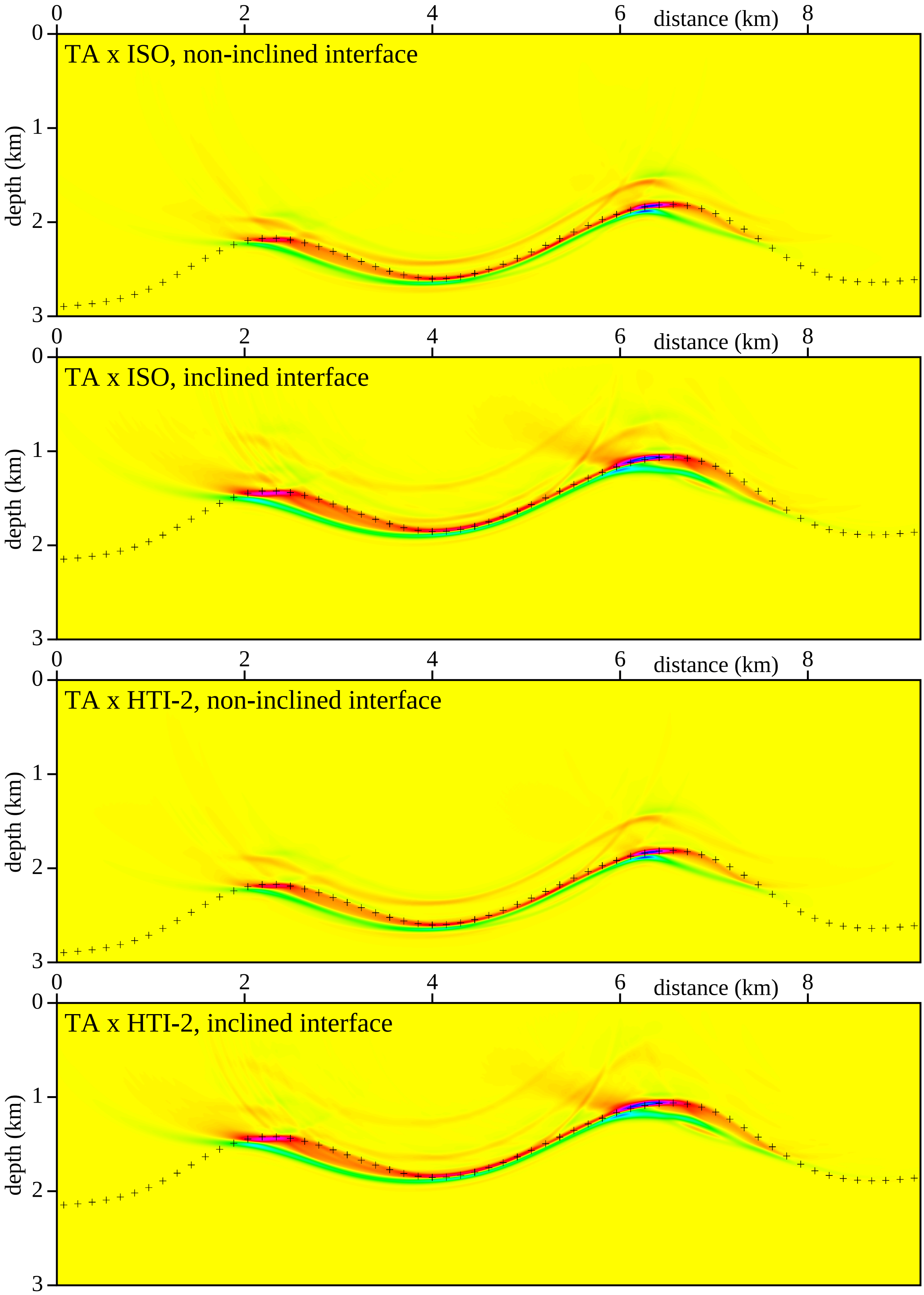

Figure 9. Stacked migrated sections when the triclinic anisotropy is used for the recorded wave field and the isotropic medium (ISO) and the transversely isotropic medium with a horizontal symmetry axis (HTI-2) are used for the migration. The crosses denote the interface in the velocity model used to compute the recorded wave field.

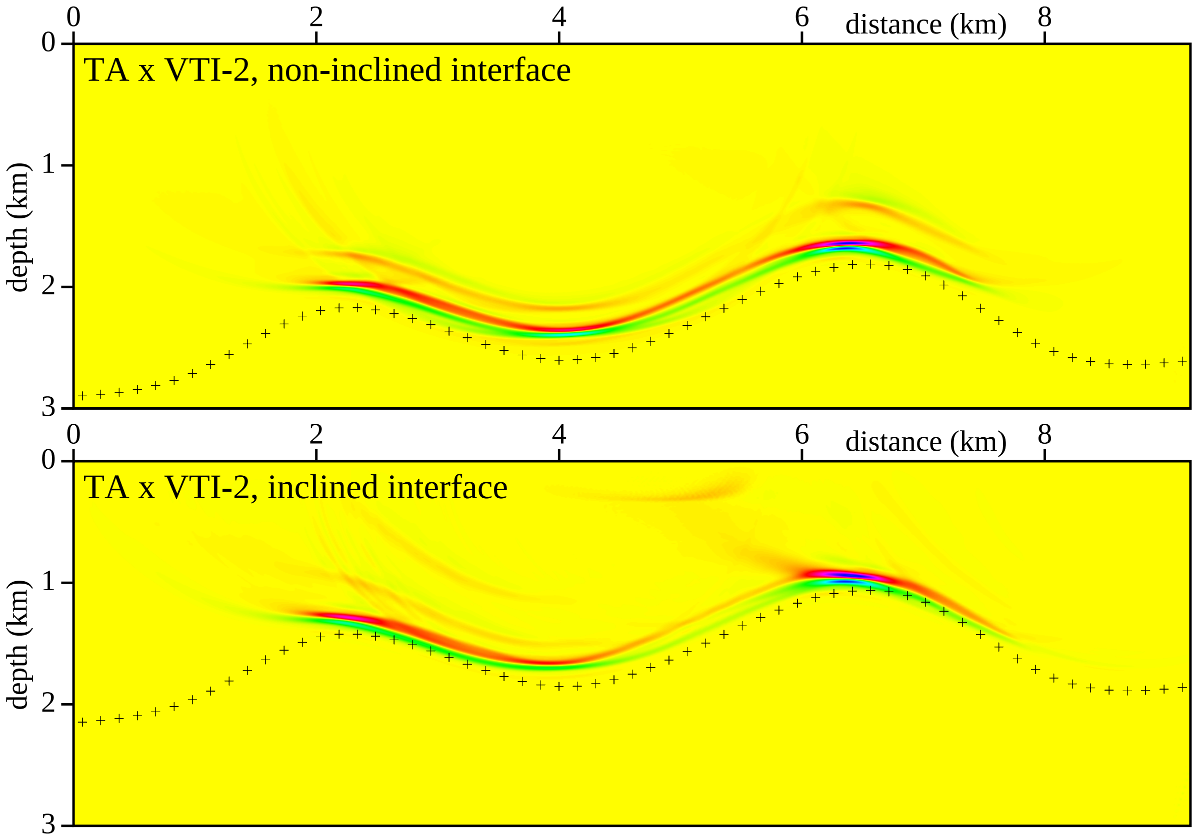

Figure 10. Stacked migrated sections when the triclinic anisotropy is used for the recorded wave field and the transversely isotropic medium with a vertical symmetry axis (VTI-2) is used for the migration. The crosses denote the interface in the velocity model used to compute the recorded wave field. Compare to Figure 8.

b) We have compared the stacked migrated sections when the anisotropy in the homogeneous velocity model used for migration is different from the anisotropy in the upper layer of the velocity model used to compute the recorded wave field. The triclinic anisotropy is used for the recorded wave field and the isotropic medium, transversely isotropic media with a vertical (VTI) and horizontal (HTI) symmetry axis are used for the migration. We tested isotropic, VTI and HTI migration models with optimized P-wave velocities for vertical and near vertical rays to obtain the best results of migration. We performed migration in VTI models with lower vertical or horizontal P-wave velocities than in the triclinic model. Misposition, distortion and defocusing of migrated interface caused by inaccurate velocity models used for migration are presented. The migration errors are slightly different for models with non-inclined or inclined curved interface.

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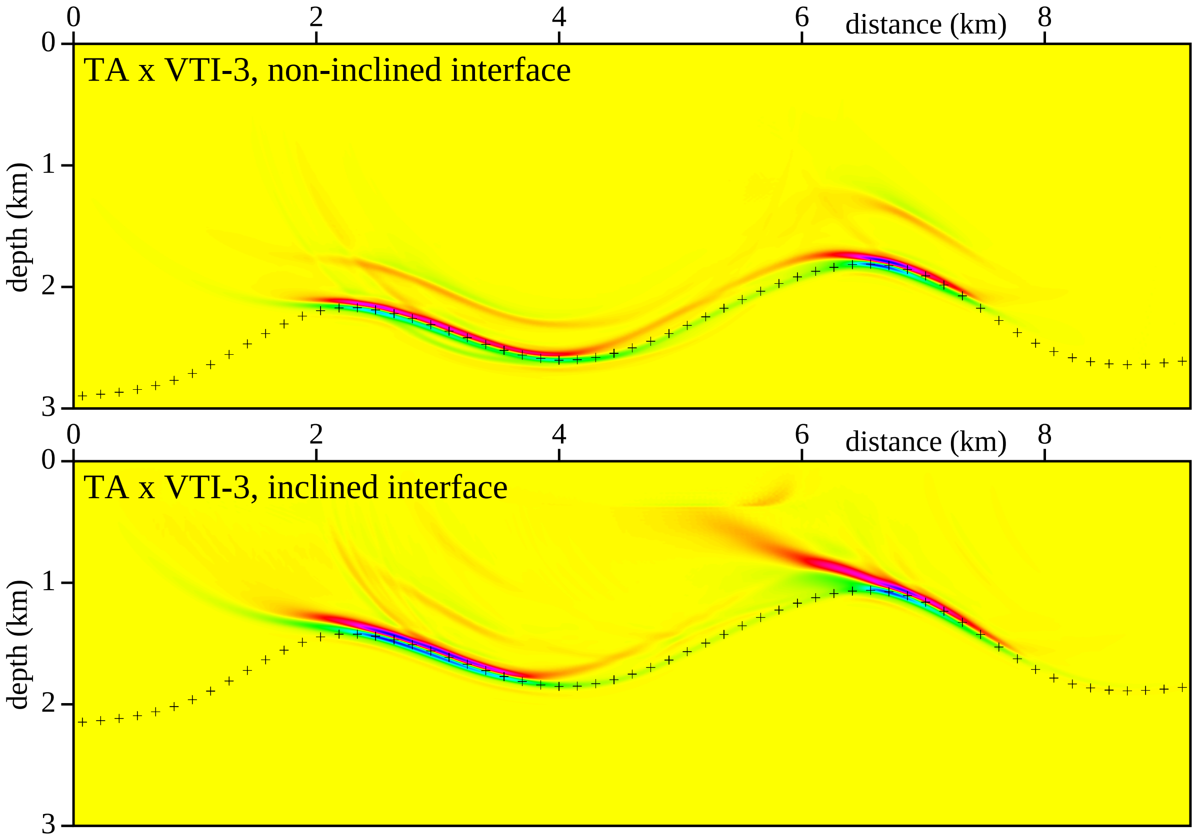

Figure 11. Stacked migrated sections when the triclinic anisotropy is used for the recorded wave field and the transversely isotropic medium with a vertical symmetry axis (VTI-3) is used for the migration. The crosses denote the interface in the velocity model used to compute the recorded wave field. Compare to Figure 8.

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