Common-Reflection-Surface stack for OBS and VSP geometries and multi-component seismic reflection data

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Summary

The 2D Common-Offset Common-Reflection-Surface (2D CO CRS) stack has so far mainly been applied to single-component seismic data acquired along one straight line, e. g., conventional marine streamer surveys or land surveys with virtually flat measurement surfaces. A new hyperbolic traveltime formula for the 2D CO CRS stack that takes arbitrary top-surface topography into account is presented. This formula can then be used to derive stacking operators that are in principle able to handle a vertical seismic profile (VSP) acquisition geometry as well as reverse VSP and cross-well seismics. Moreover, the application of the 2D CO CRS stack to ocean bottom seismics (OBS) is discussed and successfully tested with a complex synthetic OBS data example. We also introduce an approach that allows to generate separate stacks of compressional and transversal waves from multi-component seismic reflection data. Based on the traveltime approximation for finite offset, the polarization is analyzed during the search for the optimum orientation and curvature of the CRS stacking operator. We apply this approach to a simple synthetic data set and obtain stacked sections and kinematic wavefield attribute sections separately for PP and PS reflection events. All concepts introduced here for the 2D case can be directly transferred to the more general 3D case.

Introduction

The CRS stack is a fully-automated, data-driven stacking method, i. e., a knowledge of a macro-velocity model is not required except from near-surface velocities at the sources and receivers. The 2D stacking operator describes a surface rather than a curve and depends on so-called kinematic wavefield attributes. The attributes that yield the stacking operator that fits best an actual event in the prestack data is determined by means of coherence analysis. This stacking method was originally developed to stack data acquired along a straight line on a planar measurement surface into a zero-offset (ZO) section (2D ZO CRS stack) (Höcht, 1998; Mann et al., 1999; Müller, 1999) and, thus, is an alternative to conventional stacking tools such as the common-midpoint (CMP) stack and the normal-moveout(NMO)/dip-moveout(DMO)/stack. Besides high-quality stack sections with high signal-to-noise ratios, the CRS stack provides sections of the determined wavefield attributes which are useful for further analyses, e. g., estimation of projected Fresnel zones and geometrical spreading factors, tomographic and Dix-type velocity model determination, etc.

Zhang et al. (2001) extended the CRS stack for finite-offset (FO), i. e., the prestack data are stacked into a FO gather, e. g., into a CO gather (2D common-offset (CO) CRS stack, Bergler, 2001). In this case, the moveout surfaces are described by five kinematic wavefield attributes rather than by three in the ZO case. Both authors considered only planar measurement surfaces. Bergler (2001) showed that the 2D CO CRS stacking operator can be used to describe traveltimes of PS converted waves by choosing a P-wave velocity at the sources and a S-wave velocity at the receivers. Moreover, Bergler et al. (2002) discussed the application of the 2D CO CRS stack to data that were acquired with two components (vertical and horizontal). However, in this approach the CRS stack was performed with both components separately and the distinction between PP and PS reflection events was achieved after the CRS stack. The objective of this paper is to show that the 2D CO CRS stack is able to distinguish between both wave types during the CRS stack to obtain a PP and a PS CO CRS stack section and five kinematic wavefield attribute sections for each of the both wave types.

Zhang (2003) derived the most general moveout formula used in the CRS stack to handle

- 3D data acquisition on a measurement surface
- arbitrary top-surface topography, source and receiver elevations are explicitely considered
- velocity gradients in the vicinity of the sources and receivers.

Zhang (2003) used this formula in order to derive stacking operators for the 2D ZO CRS stack in the presence of arbitrary topography and for the 2D CO CRS stack for planar measurement surfaces. We use this general moveout formula to present a 2D CO CRS stacking operator which is able to consider arbitrary top-surface topography as well as arbitrary acquisition geometries. For the sake of simplicity, we will neglect velocity gradients and restrict ourselves to hyperbolic traveltime formulas as they turned out to often approximate the reflections events in the prestack data better than their parabolic counterparts obtained from paraxial ray theory.

Arbitrary topography

The traveltime formula for the 2D CO CRS stack for arbitrary topography and acquisition geometries can directly be derived from the general moveout formula given in Zhang (2003) by setting

- the azimuth angles at the sources and receivers equal zero, i. e., $\theta_S = 0$ and $\theta_G = 0$,
- all the variables associated with the y-direction equal zero,
- and the gradients of the near surface velocity equal zero, i. e., $\nabla v(S) = 0$ and $\nabla v(G) = 0$.

The first two items are due to the fact that we consider 2D data acquisition along a straight line. Putting these assumptions into the general traveltime equation yields the searched-for hyperbolic traveltime formula:

$$
\begin{aligned}
&T^2(\Delta x_S, \Delta x_G, \Delta z_S, \Delta z_G) = \\
&\left(t_0 + \frac{\sin\beta_G}{v_G}\Delta x_G - \frac{\sin\beta_S}{v_S}\Delta x_S + \frac{\cos\beta_G}{v_G}\Delta z_G - \frac{\cos\beta_S}{v_S}\Delta z_S\right)^2 \\
&+ t_0 D B^{-1}\left(\Delta x_G - \Delta z_G \tan\beta_G\right)^2 \\
&+ t_0 A B^{-1}\left(\Delta x_S - \Delta z_S \tan\beta_S\right)^2 \\
&- 2t_0 B^{-1}\left(\Delta x_G - \Delta z_G \tan\beta_G\right)\left(\Delta x_S - \Delta z_S \tan\beta_S\right) .
\end{aligned}
\tag{1}
$$

A, B, and D are three elements of the 2D surface-to-surface ray propagator matrix in a global coordinate system. t_0 denotes the traveltime along the central ray, v_S and v_G are the near-surface velocities at the source and receiver, β_S and β_G are the emergence angles of the central ray at source and receiver, respectively. Δx_S and Δx_G denote the horizontal displacement between sources and receivers of central and paraxial ray. Δz_S and Δz_G are the corresponding vertical displacements.

Ocean bottom seismics

Figure 1a shows a simple sketch of a typical 2D OBS acquisition geometry with receivers on the ocean bottom and sources some meters below the water surface.

In the following, we assume a virtually horizontal ocean bottom without significant topography and a constant source depth. This implies $\Delta z_S = \Delta z_G \equiv 0$, see also Figure 1a. Inserting these conditions into Equation (1), the OBS stacking operator can be written as

$$
\begin{aligned}
T^2(\Delta x_S, \Delta x_G) = &\left(t_0 + \frac{\sin\beta_G}{v_G}\Delta x_G - \frac{\sin\beta_S}{v_S}\Delta x_S\right)^2 \\
&+ t_0 D B^{-1}\Delta x_G^2 \\
&+ t_0 A B^{-1}\Delta x_S^2 \\
&- t_0 2B^{-1}\Delta x_G \Delta x_S .
\end{aligned}
\tag{2}
$$

If there is significant topography present at the ocean bottom, it is possible to use Equation (1) to take the topography into account. This does not affect the simplifying assumption $\Delta z_S \equiv 0$. Note that Equation (2) coincides with the original 2D CO CRS stacking operator (Bergler, 2001; Zhang et al., 2001) developed to stack data acquired along one straight line on a planar measurement surface (e. g., land seismics or conventional marine data acquisition). Zhang et al. (2001) and Bergler (2001) related the elements A, B, C, and D of the propagator matrix to three wavefront curvatures K_1, K_2, and K_3, where K_1 is defined as the wavefront curvature of an emerging wave at the receiver in a common-shot (CS) experiment, while K_2 and K_3 are the wavefront curvatures at the source and receiver, respectively, in a (hypothetical) common-midpoint (CMP) experiment. In terms of wavefront curvatures, Equation (2) reads

$$
\begin{aligned}
T^2(\Delta x_S, \Delta x_G) = &\left[t_0 + \frac{\sin\beta_G}{v_G}\Delta x_G - \frac{\sin\beta_S}{v_S}\Delta x_S\right]^2 \\
&+ 2t_0 \left[\Delta x_S (K_1 - K_3)\frac{\cos^2\beta_G}{v_G}\Delta x_G\right. \\
&+ \frac{1}{2}\Delta x_S\left((K_1 - K_3)\frac{\cos^2\beta_G}{v_G} - K_2\frac{\cos^2\beta_S}{v_S}\right)\Delta x_S \\
&\left.+ \frac{1}{2}\Delta x_G K_1 \frac{\cos^2\beta_G}{v_G}\Delta x_G\right] .
\end{aligned}
\tag{3}
$$

A detailed discussion and application of this stacking operator in the framework of the 2D CO CRS stack can be found in Bergler (2001).

Vertical seismic profiling

Equation (1) can be used to derive stacking operators applicable to VSP data. A typical 2D VSP acquisition geometry is characterized by receivers placed in a borehole while the sources are located along a straight line on the top-surface intersecting the borehole (Figure 1b). VSP is also possible in marine environments. In this case, the sources are located some meters below the water surface. Let us assume a vertical borehole and that all sources are disposed at the same level, i. e., in the same water depth or on a measurement surface on land without topography: the vertical displacements between the sources Δz_S and the horizontal displacements between the receivers Δx_G vanish, i. e., $\Delta z_S = \Delta x_G \equiv 0$. Thus, for such VSP geometries, Equation (1) simplifies to

$$
\begin{aligned}
T^2(\Delta x_S, \Delta z_G) = &\left(t_0 - \frac{\sin\beta_S}{v_S}\Delta x_S + \frac{\cos\beta_G}{v_G}\Delta z_G\right)^2 \\
&+ t_0 D B^{-1}\tan\beta_G^2 \Delta z_G^2 \\
&+ t_0 A B^{-1}\Delta x_S^2 \\
&+ t_0 2B^{-1}\tan\beta_G \Delta z_G \Delta x_S .
\end{aligned}
\tag{4}
$$

In principle, this operator has the same structure as the original 2D CO CRS stacking operator and simplifies in different subsets of the prestack data volume where the stacking surface reduces to a stacking curve. Thus, similar pragmatic search strategies as proposed by Bergler (2001) can be applied.

Furthermore, stacking operators for so-called reverse VSP and cross-well acquisition geometries can easily be derived by means of Equation (1). In the former case, the sources are placed downhole while the receivers are deployed at the surface. Thus, $\Delta x_S = \Delta z_G \equiv 0$, assuming a vertical borehole and a flat measurement surface. Cross-well acquisition means that both, sources and receivers, are placed downhole in neighboring boreholes. In this case, $\Delta x_S = \Delta x_G \equiv 0$, again assuming vertical boreholes.

Including polarization information

In the following, we discuss the application of the stacking operator (3) to multi-component seismic reflection data to

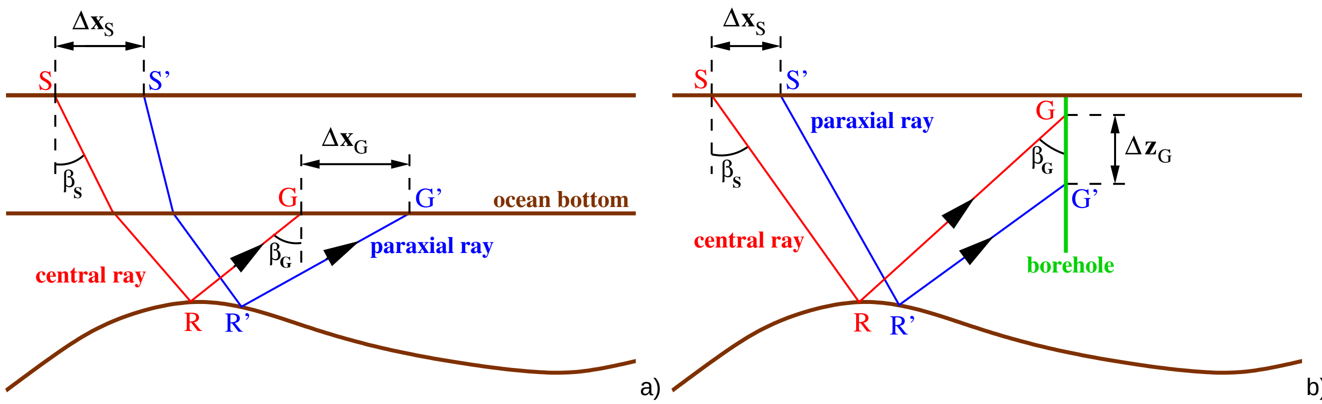

Figure 1: An arbitrarily chosen central ray and a paraxial ray in the close vicinity of the central ray for a) a 2D OBS and b) a 2D VSP acquisition geometry.

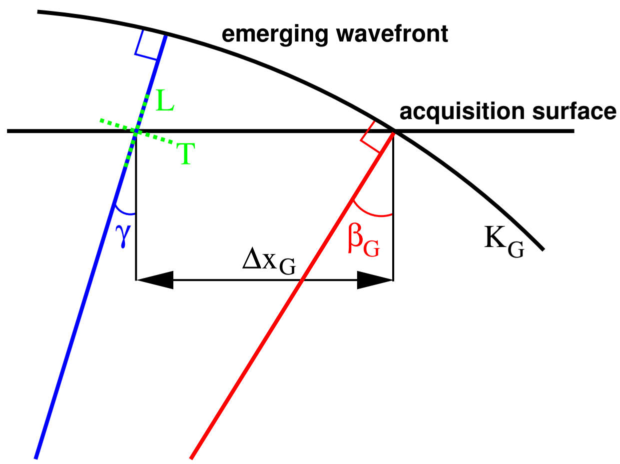

Figure 2: Definition of emergence angles for central (red) and paraxial (blue) ray. The expected transversal (T) and longitudinal (L) polarization directions are indicated in green.

generate separate PP and PS images of the subsurface. Assuming an isotropic layer below the receiver line, the polarization directions of P and S waves emerging at the receivers are directly related to the propagation direction of the emerging wavefront (which might be hypothetical). For the receiver associated with the central ray, this direction is given by the wavefield attribute β_G. However, for any other trace within the stacking aperture, this direction will, in general, be different. Thus, it has to be extrapolated from the (known) attributes associated with the central ray. In the second-order approximation inherent to the CRS stack approach, we can assume the radius of curvature $R_G = 1/K_G$ of the emerging wavefront at the receiver to be constant within the stacking aperture. Thus, the emergence angle γ of a paraxial ray can be extrapolated by (modified after Höcht et al., 1999)

$$\sin\gamma = \mathrm{sgn}(R_G)\,\frac{R_G \sin\beta_G + \Delta x_G}{\sqrt{R_G^2 + 2R_G\Delta x_G \sin\beta_G + \Delta x_G^2}}\,, \qquad (5)$$

where Δx_G is the horizontal displacement between the receiver of the central ray and the receiver of the considered paraxial ray (see Figure 2). Note that K_G depends on the considered source/receiver configuration. It is given by a linear combination of the two curvatures K_1 and K_3 defined at the receiver (Bergler, 2001)

$$K_G = K_1\left(1 + \frac{1}{l}\right) - \frac{K_3}{l}\,, \qquad (6)$$

where l is a real number and describes an arbitrary measurement configuration: $\Delta x_G = l\,\Delta x_S$. Equation (5) does not consider the free surface or the effect of the seafloor in OBS data. Appropriate corrections are required in such situations.

Implementation strategy

For a given set of the five wavefield attributes, R_G and γ can always be calculated (the singularity of Equation (5) for the common-receiver gather, $R_G = \Delta x_G = 0$, is removable). The angle γ allows to extract the longitudinal and transversal components from the multi-component data for the coherence analysis as well as the stack. From a practical point of view, a simultaneous search for all five parameters is quite time consuming. Therefore, the global optimization problem is often decomposed into several (global) optimization steps performed with subsets of the entire prestack data, optionally followed by a local optimization with the full, spatial operator. For the CO CRS stack, Bergler (2001) implemented such a search strategy which starts with a two-parameter search in the CMP gather. However, the need to determine R_G and γ during the stack requires a different search strategy:

- Search for β_G and K_1 in the CS gather. In this case $K_G = K_1$ such that γ is always well defined. This yields separate CS-stacked CO sections for PP and PS waves.

- Two successive one-parameter searches (or alternatively one two-parameter search) in the simulated CO sections. This yields the second angle β_S and a combination of K_1, K_2, and K_3. Polarization does not have to be considered, as the PP and PS events are already separated in the simulated CO sections.

- A final one-parameter search in the CMP gather for a combination of K_2 and K_3. This search is performed in the multi-component data. Thus, polarization has to be considered with $K_G = K_3$.

- Stack along the full spatial operator (3) in the full prestack data set. For each contributing trace, K_G is given by Equation (6). This yields the final CRS-stacked CO sections for PP and PS reflections.

Synthetic data examples

We show two synthetic data examples to test different new approaches introduced in this paper. The first one demonstrates the ability to handle OBS acquisition geometries by means of the CO CRS stack, the second example considers the aspects of multi-component data processing.

The complex OBS model is depicted in Figure 3a, the velocities are given in m/s. The horizontal reflector at a depth of 1 km represents the ocean bottom on which the receivers are located. Shot spacing is 25 m, receiver spacing 50 m. The modeled prestack data contain the primary PP reflections with a zero-phase Ricker wavelet, peak frequency 30 Hz, and a sampling interval of 4 ms. Figure 3b displays the CO section for half-offset $h = -500$ m extracted from the prestack data. We added random noise to create an even more realistic data set. The CO CRS stack section (Figure 3d) for half-offset $h = -500$ m shows a dramatically increased signal-to-noise ratio compared with the CO section from the prestack data. All reflectors are clearly visible. Furthermore, we obtain five kinematic wavefield attribute sections for the simulated half-offset as an additional output. As an example, Figure 3c shows the section for the determined emergence angles β_G which have well-defined, reasonable values along the reflection events.

To evaluate our approach to generate PP and PS sections from multi-component data, the proposed strategy was applied to a very simple synthetic 2D land data set. The model (not shown) consists of a single horizontal reflector at a depth of 2 km. P-wave velocity v_P is 2 km/s, S-wave velocity v_S is $v_P/\sqrt{3}$. Shot spacing is 25 m, receiver spacing 50 m. The modeled multi-component prestack data contain the primary PP and PS reflections with a zero-phase Ricker wavelet, peak frequency 30 Hz, and a sampling interval of 4 ms. Free-surface effects have not been modeled. Figure 4 shows the horizontal and vertical components for half-offset $h = 500$ m. Both events are present on both components. Figure 5 shows a subset of the CO sections obtained after the CO CRS stack together with the associated coherence sections as well as the β_S-sections for PP and PS events. A clear separation between both wave types is achieved and the signal-to-noise ratio is dramatically increased. Note that the resulting CO sections represent the longitudinal or transversal component of the data with respect to the determined stacking operator, i. e., the direction of particle displacement will, in general, vary from event to event as well as along the events.

Conclusions and outlook

We presented a new hyperbolic 2D CO CRS stacking operator to handle arbitrary top-surface topography and acquisition geometries. We observed that this formula reduces to the original one for an OBS acquisition geometry if there is no significant topography present at the ocean bottom. Moreover, the formula was specialized for VSP acquisition geometries with vertical boreholes. Stacking operators for reverse VSP as well as for cross-well seismics can also be derived. The application of the operator was successfully demonstrated with a complex synthetic OBS data set. The obtained CO CRS stack section showed a dramatically increased signal-to-noise ratio which indicates that the stacking operator fits well the reflection events in the prestack data. Moreover, we obtained five CO sections for the determined kinematic wavefield attributes which show well-defined and reasonable values along the reflection events.

We have also presented a new approach to handle multi-component data by means of the 2D CO CRS stack. This approach is able to distinguish between PP and PS reflections by combining operator shape and orientation with polarization information. It provides stacked sections and kinematic wavefield attribute sections separately for both wave types. An application to a simple synthetic land data set demonstrated that the approach is able to detect, clearly separate, and locally parameterize PP and PS events during the stack.

The proposed approach can also be applied to other multi-component acquisition schemes like land seismic data or OBS data with varying surface/seafloor elevation or VSP data. In these cases, different CRS stacking operators are required to approximate the reflection traveltimes, but the handling of polarization information remains the same. Tests with more realistic models for land and OBS geometries as well as the extension to the general 3D case are currently in progress.

Acknowledgments

We would like to thank the sponsors of the Wave Inversion Technology (WIT) Consortium for their support.

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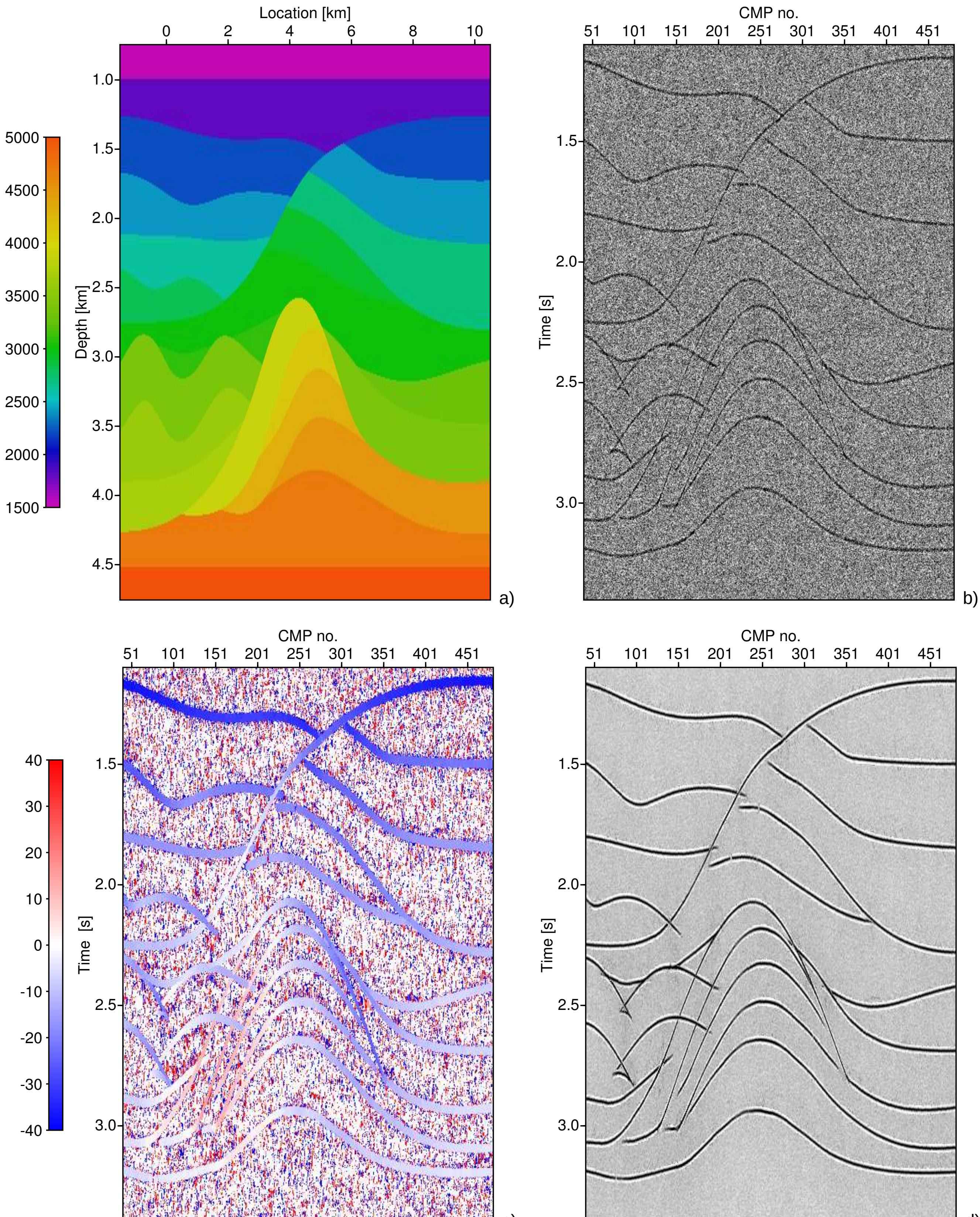

Figure 3: Synthetic OBS data example: a) Subsurface model. The velocities are given in m/s, the horizontal reflector at a depth of 1 km represents the ocean bottom. b) CO section for half-offset $h = -500$ m extracted from the prestack data. c) β_G-section [°] and d) stacked section obtained from the CO CRS stack for half-offset $h = -500$ m.

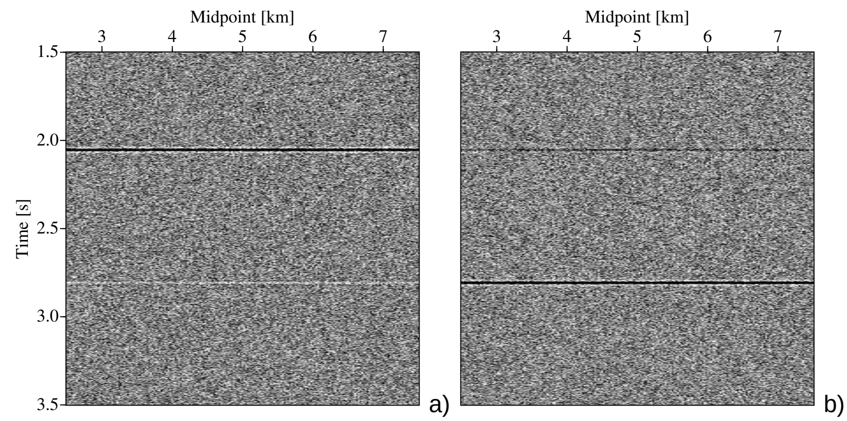

Figure 4: CO sections for half-offset $h = 500$ m extracted from the synthetic prestack land data: a) vertical and b) horizontal component. Both events can be observed on both components, the upper event is the PP reflection, the lower the PS reflection.

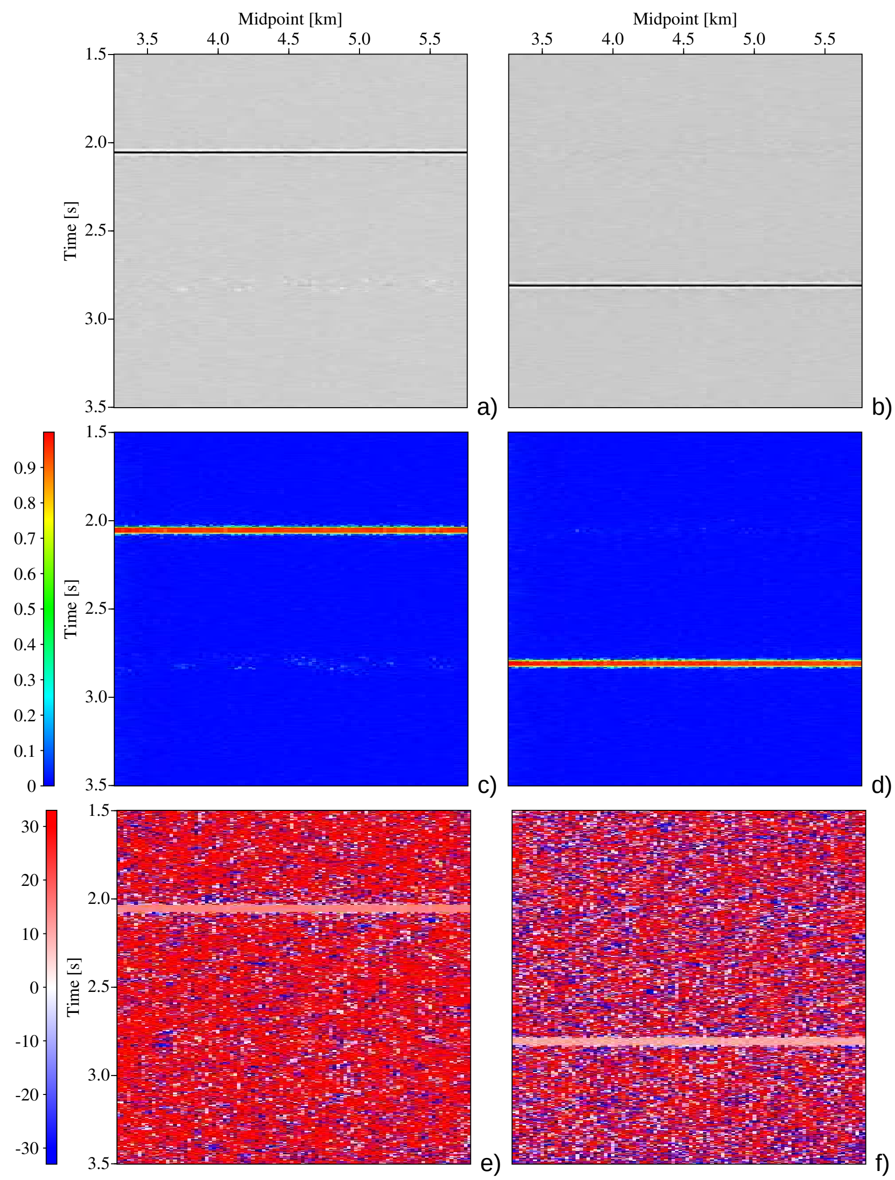

Figure 5: Results of the CO CRS stack for PP (left) and PS (right) reflection events simulated for half-offset $h = 500$ m: a) and b) stacked sections. c) and d) coherence sections. e) and f) β_S-sections [°].