Automatic tracking of reflection events in ZO volumes by means of CRS attributes

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Summary

We present an approach for the automatic tracking of reflection events in 3D zero-offset volumes. The method uses a subset of the kinematic wavefield attributes obtained from the 3D Common-Reflection-Surface stack technique to determine the spatial continuation of reflection events. The navigation based on triangulated trace locations is able to handle irregular geometries and gaps in the data. In this way, the input for all horizon based methods, for instance, layer-stripping velocity inversion, is obtained in an automated manner.

Introduction

The use of techniques applied to exactly defined stratigraphic sequences on stacked data, e. g., layer-based inversion methods, require the extraction of continuous reflection events and stacking parameters from the respective data volumes. If performed manually, this task is rather cumbersome and error-prone. Furthermore, in case of 3D data, an appropriate visualization of the data is difficult. Therefore, algorithms allowing an automatic tracking of events are desirable. We propose a technique that uses the stacking parameters (the so-called kinematic wavefield attributes) of the 3D common-reflection-surface (CRS) stack for the automatic tracking of reflection events in zero-offset (ZO) volumes. The method is suited for arbitrary acquisition geometries and automatically bypasses areas with insufficient information for reliable tracking.

The 3D CRS stack

The 3D CRS stack technology (e. g., Bergler, 2004) is a second-order generalized stacking velocity analysis tool parameterized in terms of kinematic wavefield attributes. For a planar measurement surface its hyperbolic stacking operator is given in midpoint/half-offset coordinates $(\mathbf{m},\mathbf{h})$ by

$$t^2_{hyp}(\mathbf{m},\mathbf{h}) = \left[t_0 + \frac{2}{v_0}\begin{pmatrix}\cos\alpha\,\sin\beta\\ \sin\alpha\,\sin\beta\end{pmatrix}\cdot\mathbf{m}\right]^2 + \frac{2t_0}{v_0}\mathbf{m}^{\mathrm{T}}\mathbf{TNT}^{\mathrm{T}}\mathbf{m} + \frac{2t_0}{v_0}\mathbf{h}^{\mathrm{T}}\mathbf{TMT}^{\mathrm{T}}\mathbf{h}, \qquad (1)$$

with ZO traveltime t_0 and near-surface velocity v_0. The symmetric 2×2 matrix $\mathbf{T}(\alpha,\beta)$ describes the transformation from local ray-centered Cartesian to global Cartesian coordinates, the quantities α, β, and the symmetric 2×2 matrices $\mathbf{N}$, and $\mathbf{M}$ denote the kinematic wavefield attributes. These eight attributes can be assigned a simple geometrical description: α and β are the emergence angles (azimuth and dip) of the ZO ray at the surface location $\mathbf{m}$, matrix $\mathbf{M}$ describes the curvature of a wavefront at the surface due to a point source at the normal-incidence point (NIP), matrix $\mathbf{N}$ is in the same way related to the wavefront of an exploding reflector experiment.
Implementations of the CRS stack automatically determine the eight attributes for each sample of the output volume by a coherence analysis similar to conventional stacking velocity analysis. Therefore, as result of CRS processing one obtains a CRS stacked ZO volume, eight attribute volumes, and a coherence volume.

Tracking in ZO volumes with the CRS operator

The CRS stacking operator (1) provides the curvature matrix $\mathbf{N}$ and the direction vector $\mathbf{w} = (\cos\alpha\sin\beta, \sin\alpha\sin\beta)^{\mathrm{T}}$ of the normal wave at the surface. These quantities are directly related to the local curvature and orientation of the reflection event at the respective location in the ZO stack volume. In this domain the complete CRS operator (1) for ZO (which is defined by the condition $\mathbf{h} = \mathbf{0}$) reduces to

$$t^2_{hyp}(\mathbf{m}) = \left(t_0 + \frac{2}{v_0}\mathbf{w}\cdot\mathbf{m}\right)^2 + \frac{2t_0}{v_0}\mathbf{m}^{\mathrm{T}}\mathbf{TNT}^{\mathrm{T}}\mathbf{m}. \qquad (2)$$

Thus, if a point A on an arbitrary event is considered and the corresponding wavefield attributes are known, equation (2) can be used to approximate the continuation to a point B of the event on a trace in the vicinity of A (Figure 1).
As the CRS stack is performed for each sample of the stacked ZO volume, the wavefield attributes and, thus, an approximation for the continuation is also known at each sample.

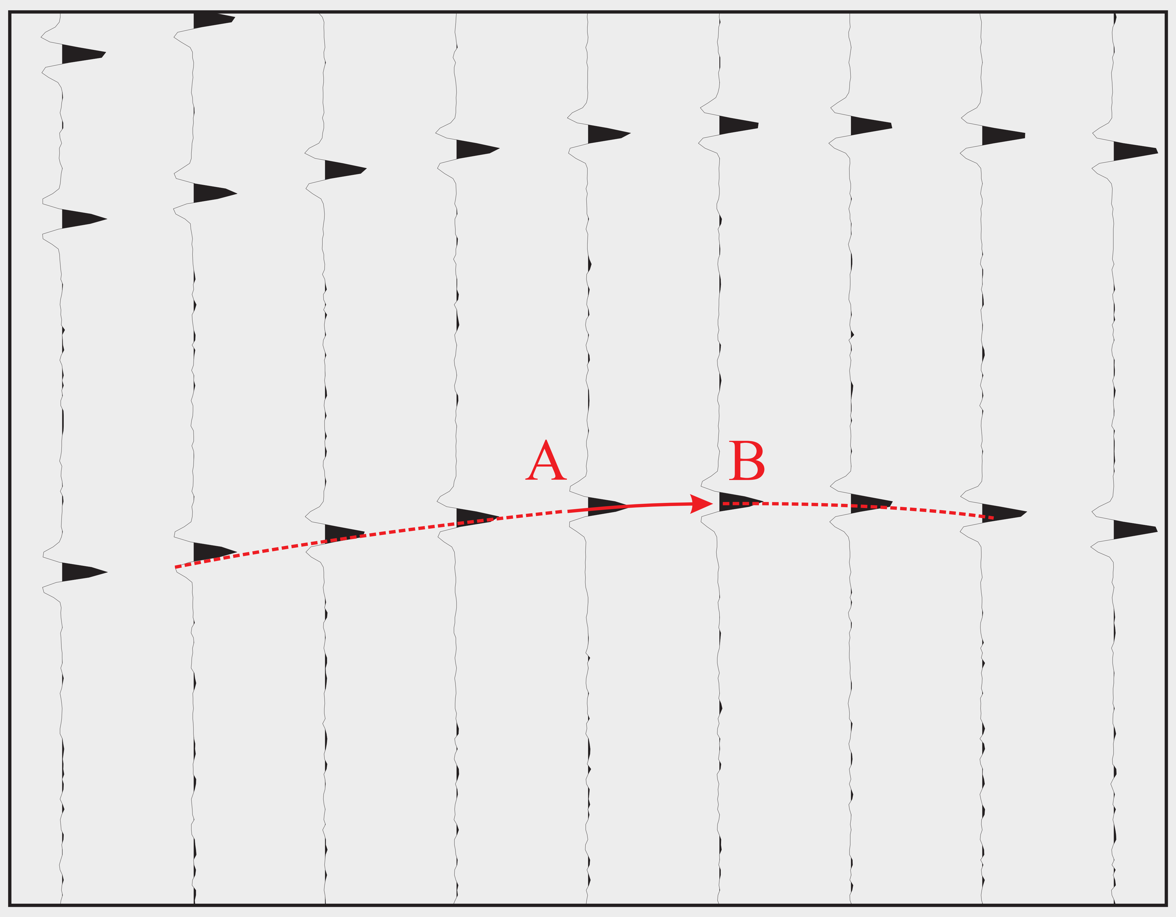

Figure 1: If a point A on the event is given the corresponding wavefield attributes together with the ZO representation (2) of the CRS operator yield an approximation for the spatial continuation B of the reflection.

Continuation criteria

A reflection event can be tracked automatically from a single seed point on the selected event. However, an implementation solely based on the calculation of the continuation is insufficient to perform a consistent tracking as it does not account for discontinuous events: the continuations can be evaluated but they are actually meaningless as they point to positions where the reflection event does not exist (Figure 2). Thus, additional criteria to validate the consistency of the continuations are required. A restriction to information that is available from the CRS technique provides:

Continuity of the kinematic wavefield attributes. Along the reflection events the wavefield attributes should vary smoothly. Thus, the attributes determined at point A should not substantially differ from the attributes on the continuation point B.

Continuity of the coherence values. Similar to the wavefield attributes the coherence value should vary smoothly from A to B.

Coherence threshold. The coherence values are highest on the reflection events. Therefore, a threshold for the minimal accepted coherence value indicates whether B is considered to lie on the reflection event.

Stack amplitude differences. Similar to the other quantities the stack amplitude is assumed to vary smoothly.

Other criteria, which are not related to the CRS technique, are, for instance, thresholds based on instantaneous quantities (e. g., instantaneous phase or frequency). Also, additional coherence criteria may be applied to the data.

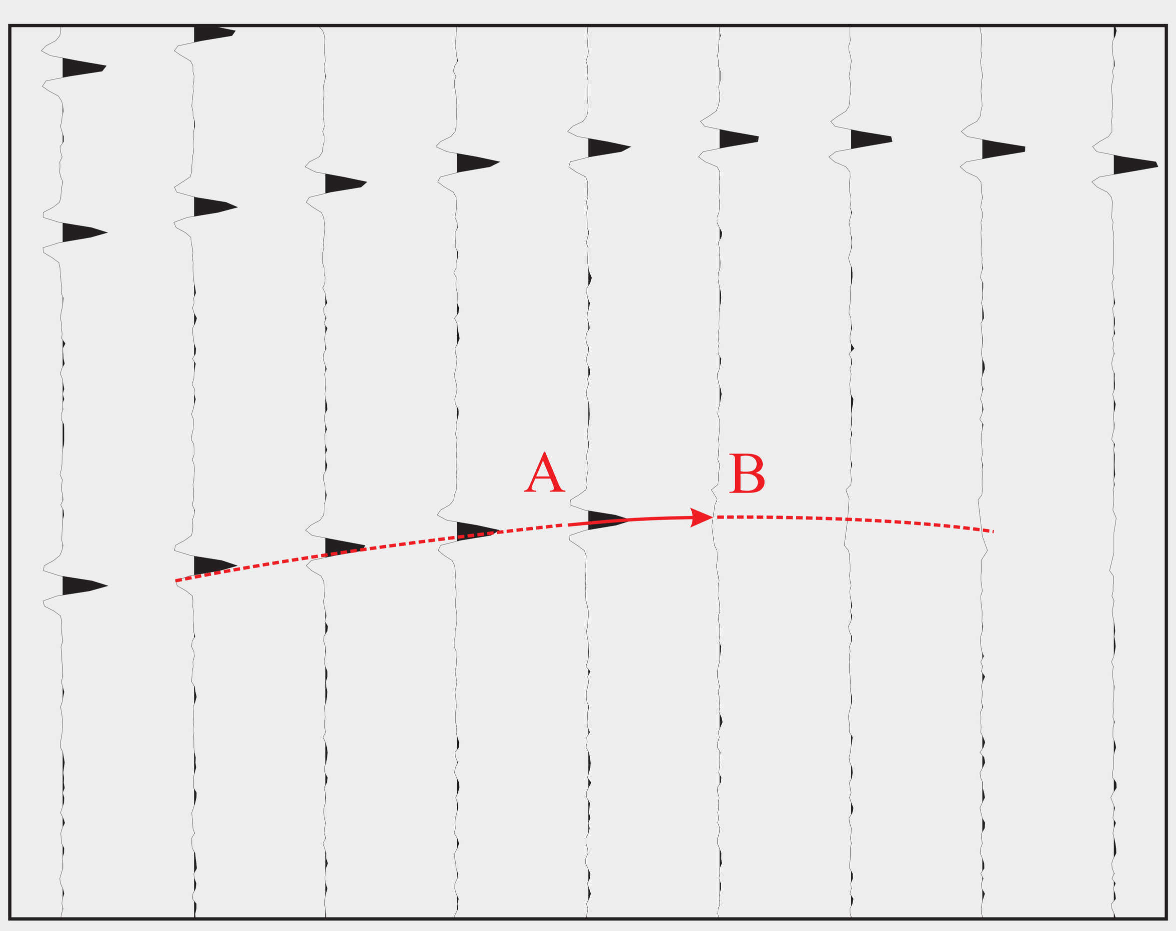

Figure 2: An event tracking solely based on kinematic wavefield attributes does not account for discontinuous reflection events. The continuation evaluated at point A leads to a location B where the reflection event does not exist.

In addition to the above mentioned validation criteria the evaluated continuation has to be refined. This is due to the fact that the attributes used for the calculation of the continuation are determined from data within a search aperture, i. e., they are obtained as best fit attributes from a number of traces. Therefore, the calculated continuation B will most likely not coincide with the true continuation B_T. However, as the spatial distance to the continuation is usually significantly smaller than the search aperture, it can be expected that B is at least located within the wavelet of the reflection event. As B_T is usually defined to be associated with the absolute maximum stack energy of the wavelet the refinement consists of the determination of this energy within a user-defined window centered around B.

Trace navigation

For 3D data the proper selection of the traces for the calculation of the continuation is essential as it defines the movement scheme and the regions in the data that are covered by the algorithm. In the following, it is assumed that the selected reflection events appear only once on each trace. If this is not the case the tracking has to be performed independently for each of the branches. Using this assumption the navigation in the ZO data volumes $(t,\mathbf{m})$ can be split into two independent routines, one which controls the movement along the time axis and one for the movement in the midpoint plane $\mathbf{m}$. The former movement defines the continuation. Therefore, it is given by the evaluation of the CRS operator (2) with the proper wavefield attributes and validation criteria. The movement in the $\mathbf{m}$ plane defines the traces along which the continuations are evaluated, i. e., it provides the input and the extrapolation direction for the tracking of the reflection events (Figure 3).
The movement scheme is realized by means of a recursive function that acts on the triangulated trace locations:

```
function track_event(central_trace){
  // Loop over neighbors except predecessor
  // and successfully validated neighbors
  loop(remaining_neighbouring_traces){
    // check current neighbor in loop (cnl)
    validate_continuation(cnl)
    // valid continuation found? activate
    if(cnl is valid) track_event(cnl)
    // else continue with loop
  }
  // no continuation? return to predecessor
  return
}
```

The process terminates automatically if the active trace does not have a predecessor, i. e., it coincides with the initial trace that started the navigation, and if this trace has validated all of its neighbors. It automatically keeps track of the movement path, i. e., it records where and when valid continuations are found, and is, thus, able to bypass regions of unreliable data.

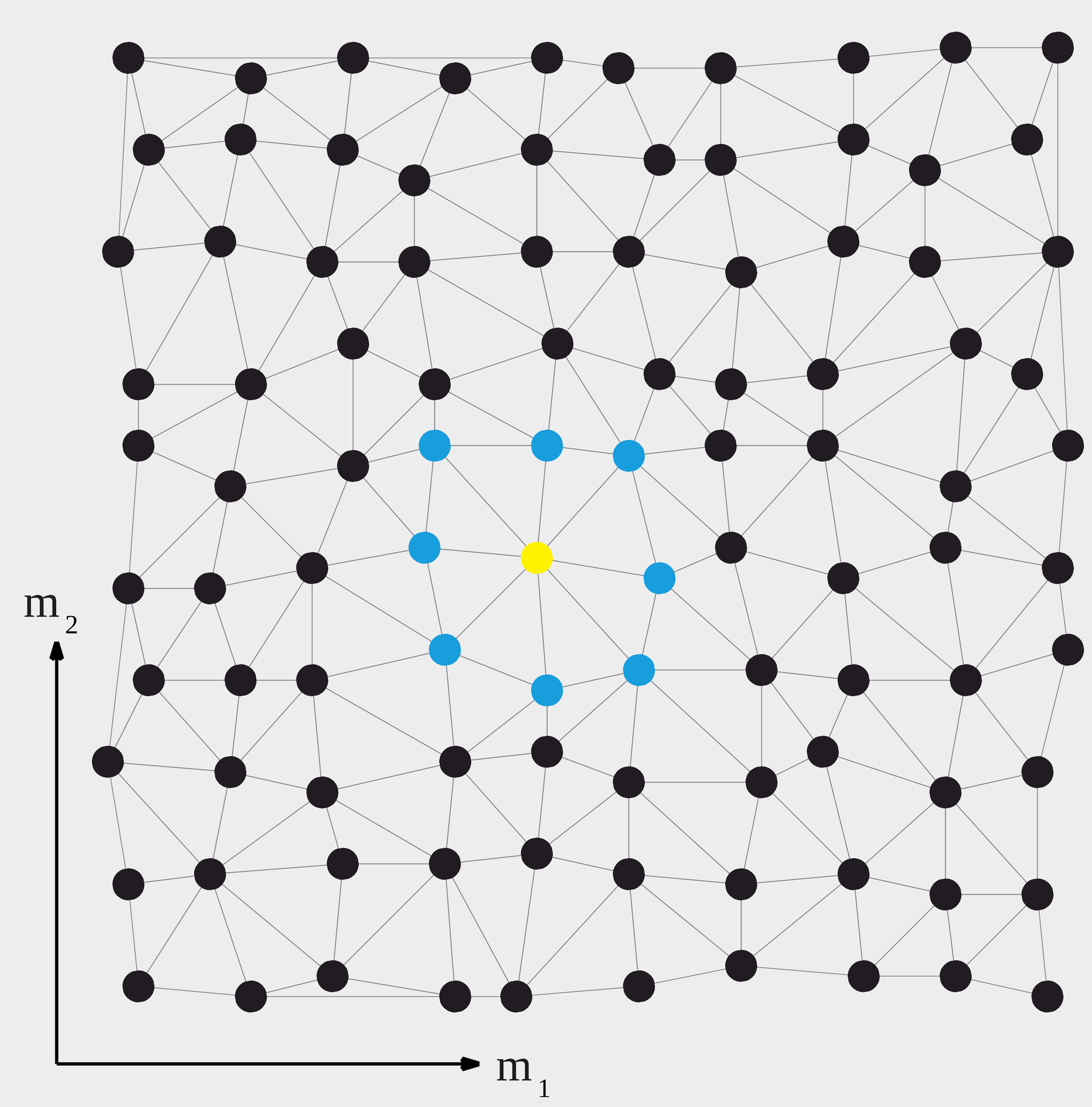

Figure 3: After Delaunay triangulation the nearest neighboring traces (depicted in blue) to an arbitrary central trace (yellow) are given by all the traces that share a triangle with it.

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Application to real data

The proposed technique has been applied to a real dataset with the aim to extract primary reflection events that serve as input for a layer-based inversion (Müller, 2007). The considered land dataset was provided within the scope of the project *High-resolution images of subsurface CO_2 storage sites in time and depth by the CRS methodology (CO_2CRS)* (Trappe et al., 2005).

Triangulation

The result of the first step, the Delaunay triangulation, is shown in Figure 4. As can be seen, the trace distribution is irregular in the midpoint plane. This is especially visible at the borders of the acquisition area where some traces are missing. In the center of the covered area, the distribution is, to a large extent, regular but regions of irregularity can also be observed.

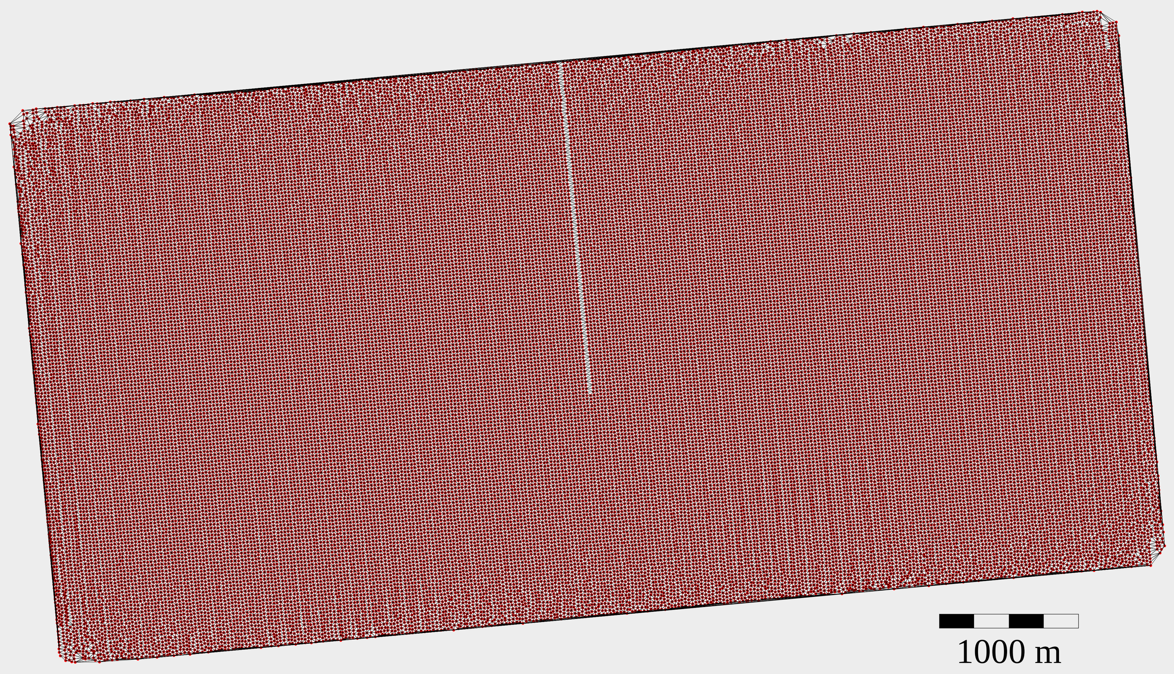

Figure 4: Delaunay triangulation (black lines) of the trace locations (red dots).

CRS stack and wavefield attributes

An inline section of the CRS-stacked volume is depicted in Figure 5. The most important attributes for the event tracking, i. e., dip and azimuth, are shown in Figure 6 and Figure 7 for the same inline section. The coherence values as depicted in Figure 8 serve as one of the previously introduced validation criteria for the tracking.

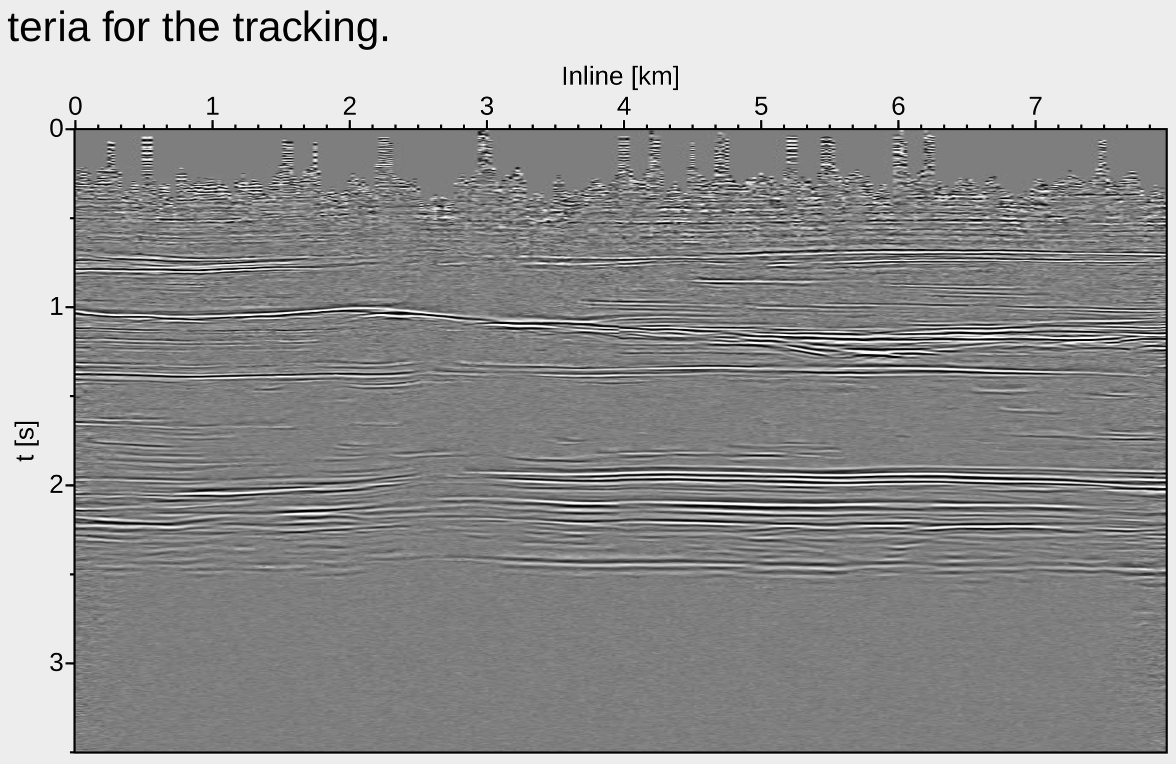

Figure 5: CRS stacked inline section related to the data example shown in Figure 11.

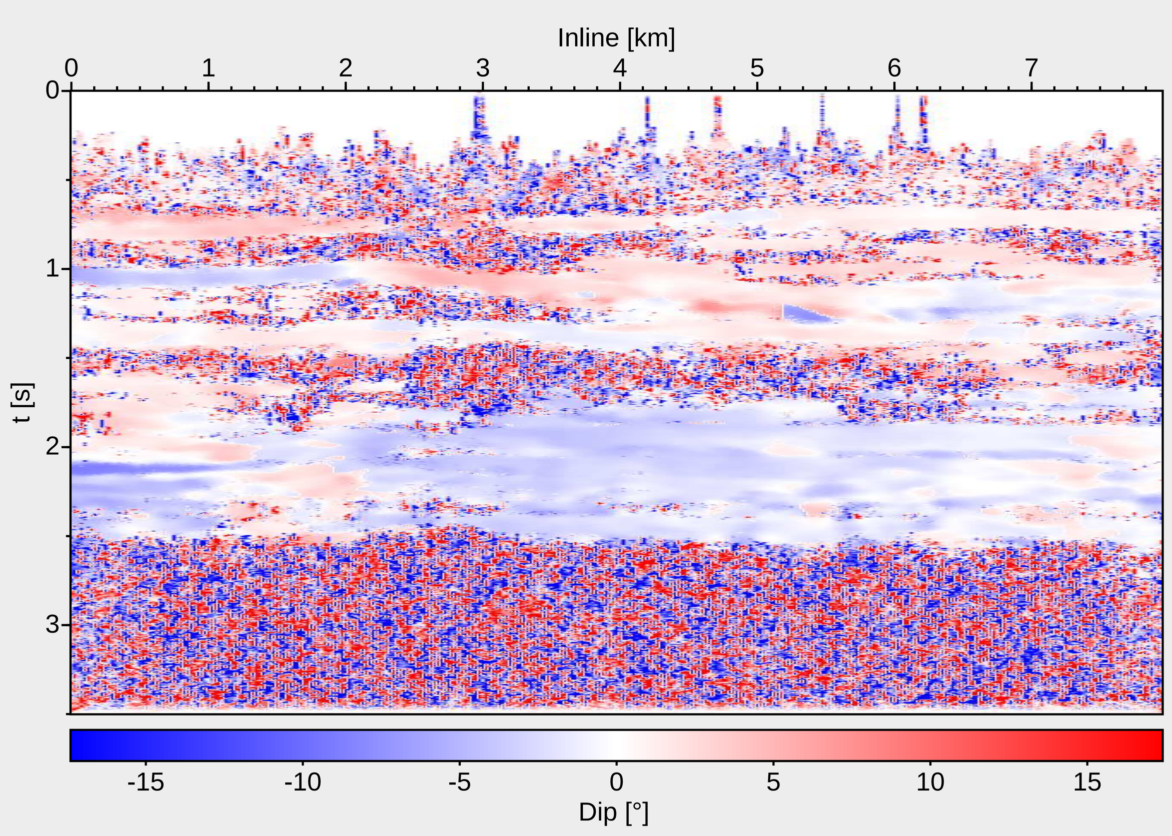

Figure 6: Dip section (β) corresponding to the CRS stack in Figure 5.

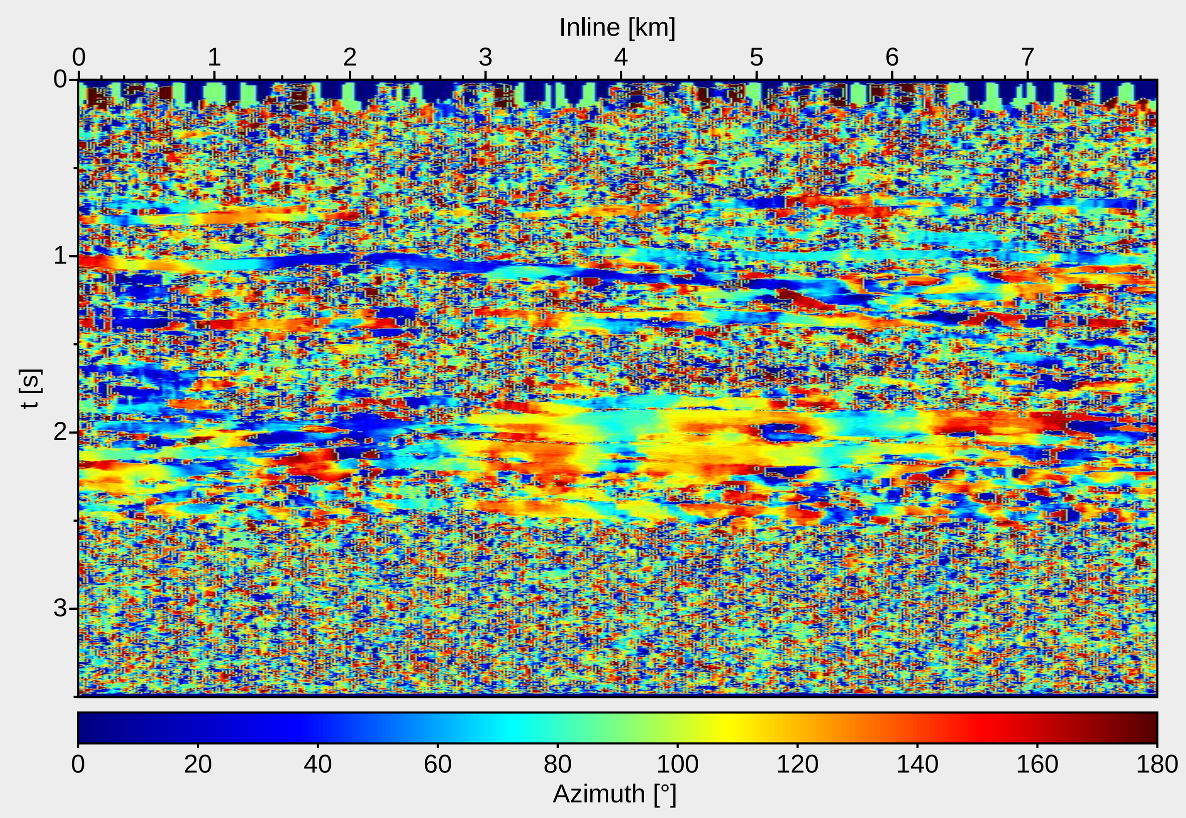

Figure 7: Azimuth section (α) corresponding to the CRS stack in Figure 5.

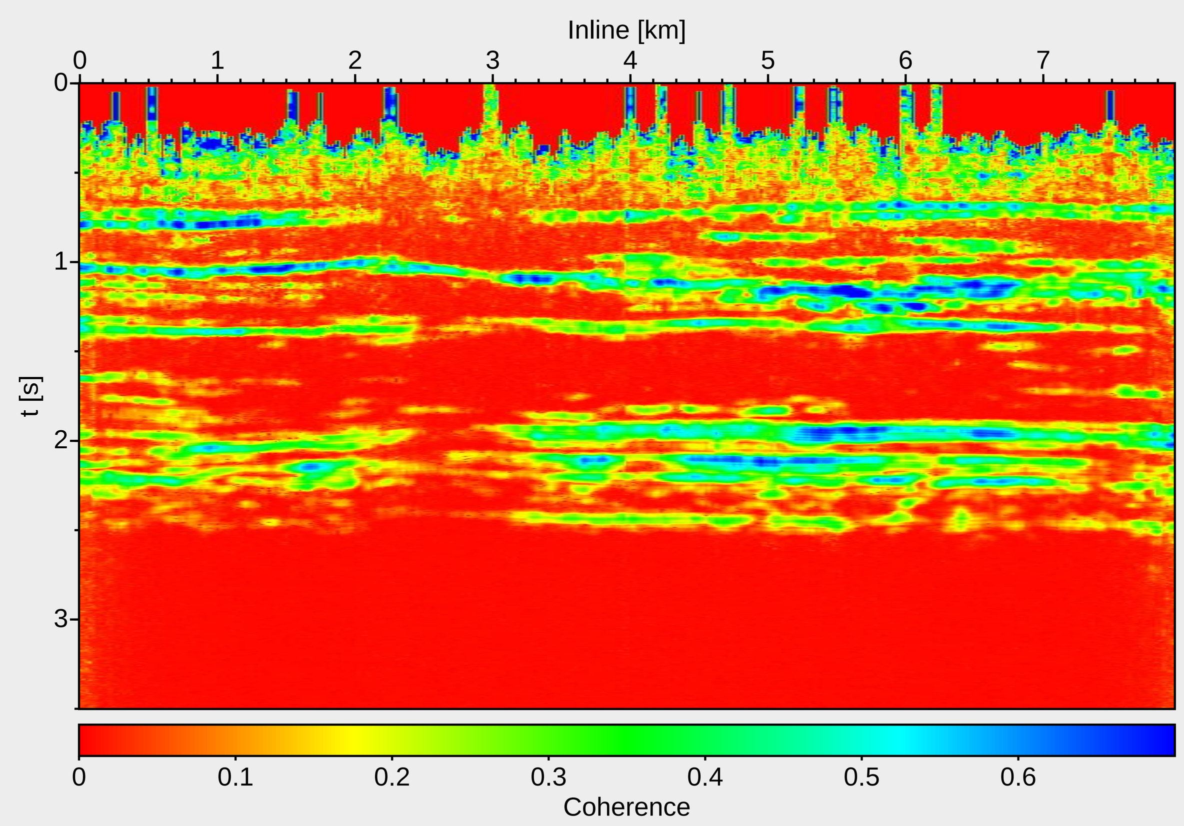

Figure 8: Coherence section corresponding to the CRS stack in Figure 5.

In addition, the curvatures of the normal waves can be used to determine the continuations of the reflection events. The inline component of this curvature is depicted in Figure 9. Due to the relatively dense trace spacing its influence on the tracking is minor for these data.

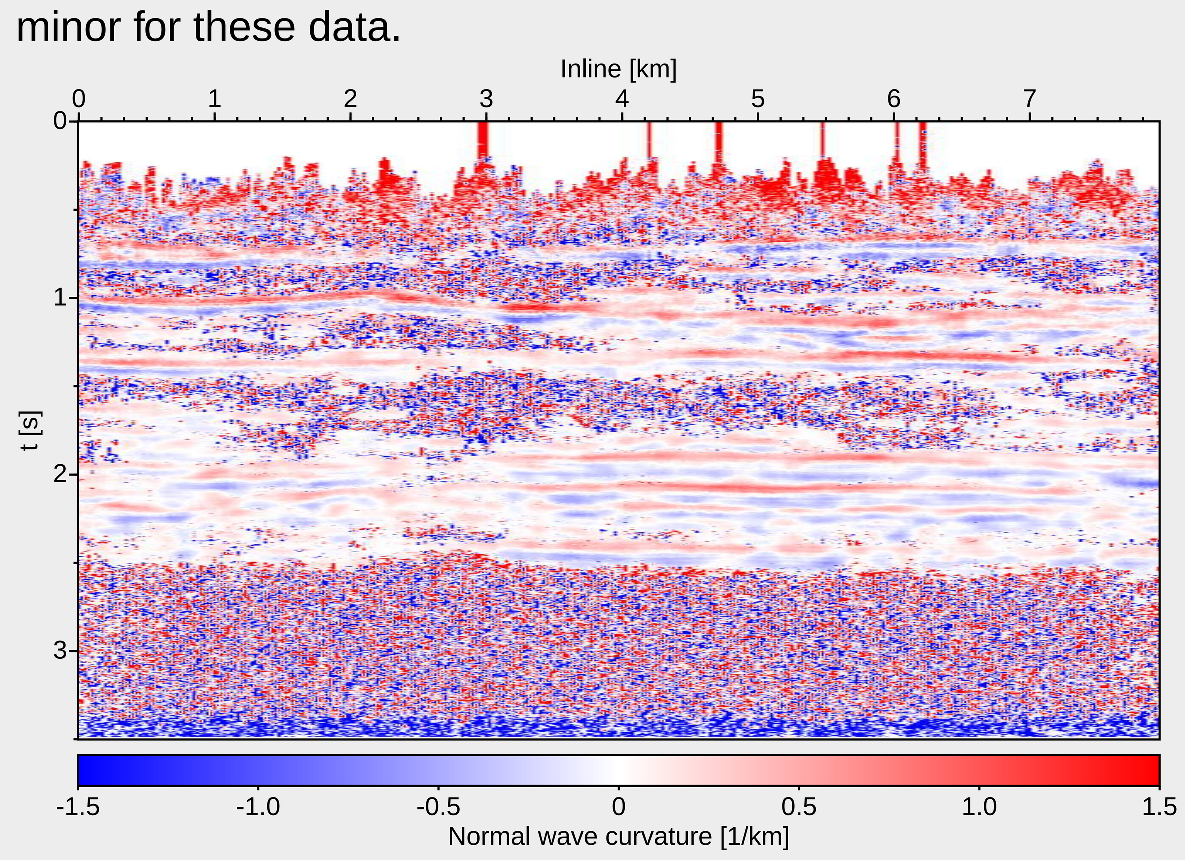

Figure 9: Inline component of the normal wave curvature (N_{00}) corresponding to the CRS stack in Figure 5.

Event tracking

The results of the event tracking are depicted in Figure 11: the tracked events are displayed together with an inline and a crossline section of the CRS stack. The figure shows the complete tracked events. These events almost cover the full measurement area but also contain some gaps.

As can bee seen in Figure 10 for a selected event, these gaps are due to low coherence values at their borders. The color coding represents the corresponding coherence values. It can also be observed that the stack amplitudes of the displayed inline and crossline sections strongly decrease within the area of the gap.

Both quantities, coherence and stack amplitude, enter into the validation criteria. Therefore, the algorithm is not able to track the event into these areas.

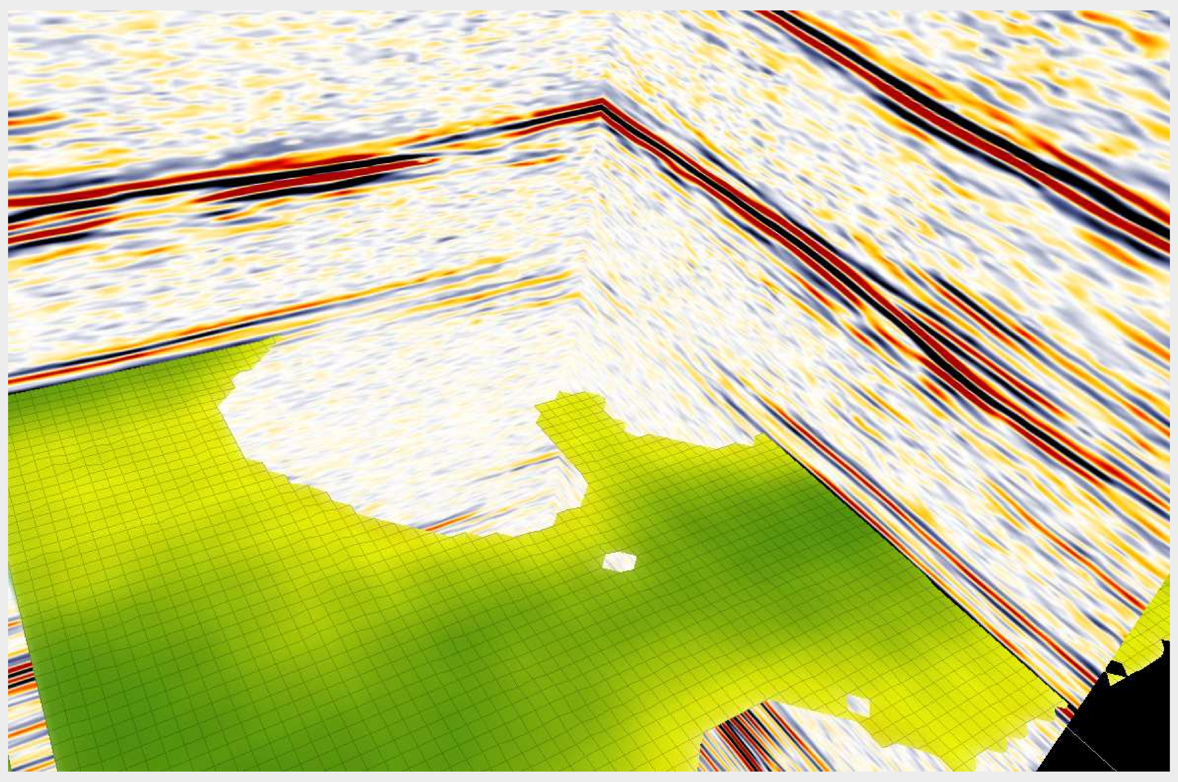

Figure 10: Detailed view of a gap in a tracked reflection event. The gaps are due to areas where no valid continuations were found. The color coding represents the coherence value. High coherence values are associated with darker colors.

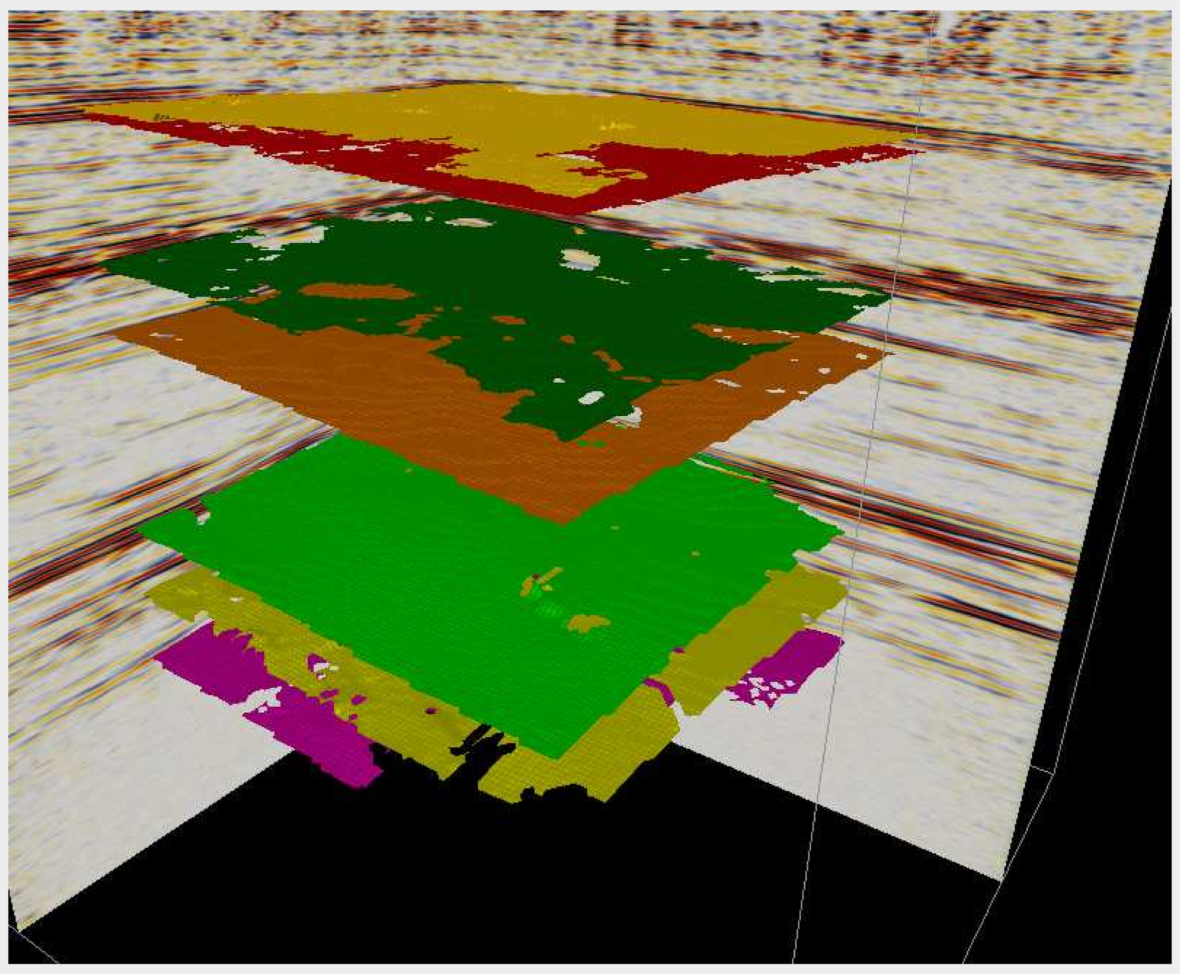

Figure 11: Seven reflection events automatically tracked in the CRS-stacked volume.

Conclusions

We presented a technique for the automatic tracking of reflection events in ZO volumes obtained with the 3D CRS stack method.

The method employs a subset of the kinematic wavefield attributes associated with the CRS-stacked volume for the calculation of the continuations of reflection events. Triangulated trace locations are used for the navigation between the traces. Due to this navigation which keeps track of the movement path and the additional validation criteria regions of invalidity are automatically bypassed by the method.

The method has been applied to a 3D land data set to extract reflection events for a layer-based inversion strategy. The results demonstrate the feasibility of the proposed approach.

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