A seismic reflection imaging workflow based on the Common-Reflection-Surface (CRS) stack: theoretical background and case study

Thomas Hertweck, Christoph Jäger, Jürgen Mann, Eric Duveneck, and Zeno Heilmann, Geophysical Institute, University of Karlsruhe, Germany*

Summary

In recent years, many case studies have demonstrated that the Common-Reflection-Surface (CRS) stack produces reliable stack sections with an excellent signal-to-noise ratio. In addition, an entire set of physically interpretable stacking parameters, so-called kinematic wavefield or CRS attributes, is determined. These attributes can be applied in further processing in such a way that a complete and consistent seismic reflection imaging workflow can be established which leads from the preprocessed multicoverage data in the time domain to migrated sections in the depth domain. The basic steps of this CRS-stack-based seismic reflection imaging workflow are the CRS stack itself, the determination of a smooth macrovelocity model by means of CRS attributes, and limited-aperture pre- and poststack Kirchhoff-type depth migration where the aperture is possibly optimized by means of the determined attributes. Our workflow approach has been applied to a recently acquired seismic dataset and revealed superior results compared to standard processing based on NMO/DMO/stack with a subsequent time migration and depth conversion.

Introduction

It is well known that processing of seismic reflection data aims at obtaining the best possible image, either in time or in depth. Especially in regions with complex geological structure or for data with low signal-to-noise (S/N) ratio, this is a difficult task that usually requires extensive human interaction. One possible alternative is to automatically extract as much information as possible directly from the measured data. The ongoing increase in available computing power makes such so-called data-driven approaches (e. g., Hubral, 1999) feasible, which, thus, have increasingly gained in relevance in recent years. One of these methods is the Common-Reflection-Surface (CRS) stack (e. g., Müller, 1999; Jäger et al., 2001; Mann, 2002). As is shown below, the CRS stack provides a simulated zero-offset (ZO) section of very high S/N ratio and is therefore a superior substitute for the conventional NMO/DMO/stack approach (e. g., Yilmaz, 2001). Besides the improved ZO simulation, there is an additional benefit that is obtained with the CRS stack: instead of the usual stacking velocity, the process yields an entire set of so-called kinematic wavefield (or CRS) attributes. This additional information is very useful in further processing. Firstly, the attributes can be utilized in the determination of a velocity model: an attribute-based tomographic inversion has recently been introduced by Duveneck and Hubral (2002), see also Duveneck (2004). It yields a smooth macrovelocity model well suited for ray-based depth imaging. In contrast to conventional inversion methods, this tomographic approach used here does not assume continuous reflection events in the data and requires only minimum picking effort. Secondly, properties like, e. g., the geometrical spreading factor (Vieth, 2001) or the projected Fresnel zone (Mann, 2002) can be estimated by means of the kinematic wavefield attributes, they can be utilized for static corrections (Koglin and Ewig, 2003), or they help to distinguish between reflection and diffraction events (Mann, 2002). Finally, they can be used in combination with the determined velocity model and the simulated ZO section in a subsequent Kirchhoff migration process to determine an optimal migration aperture.

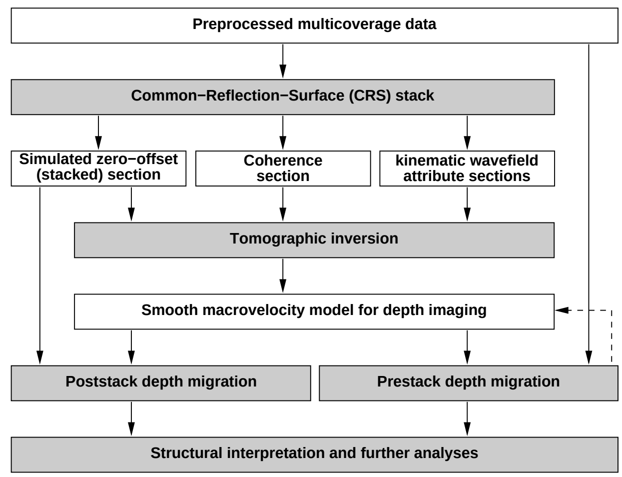
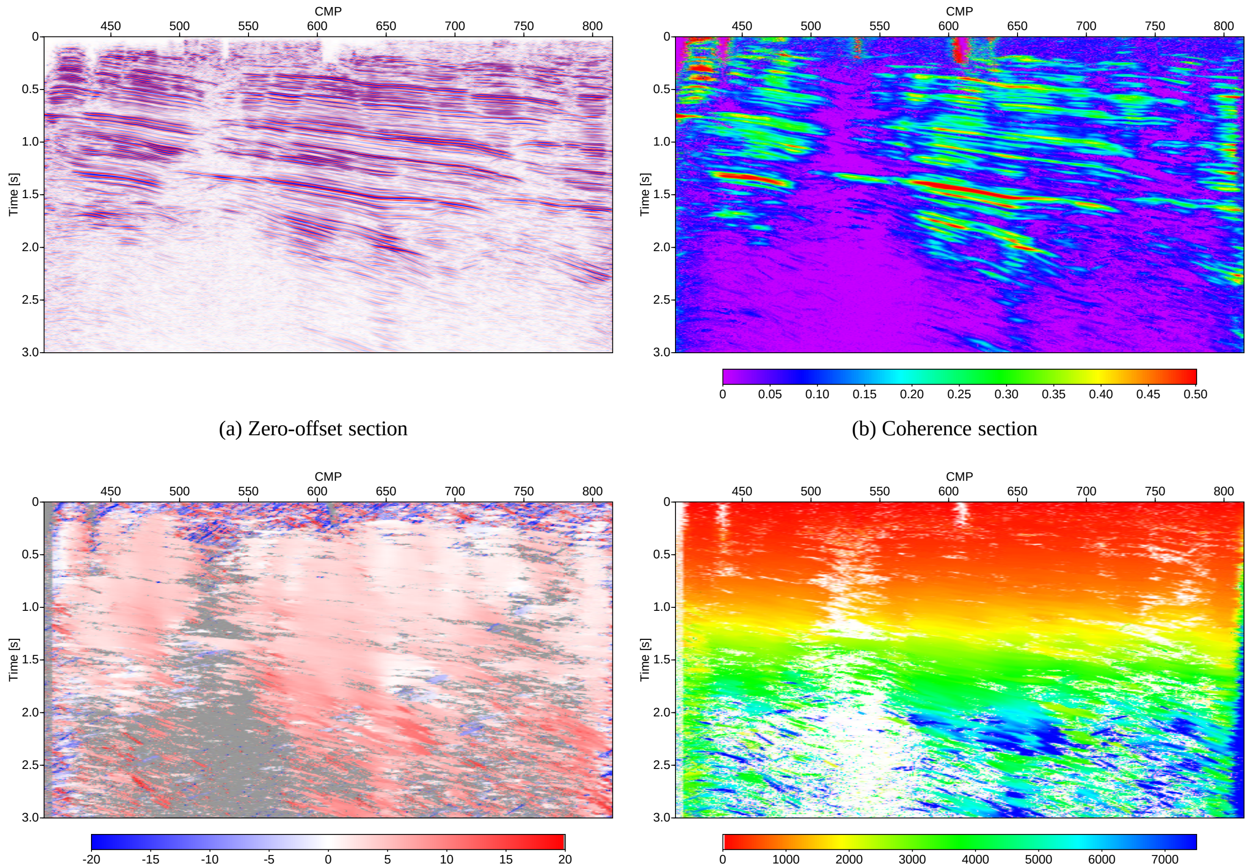


Fig. 1: A seismic reflection imaging workflow based on the CRS stack.

By combining the above-mentioned methods, i. e., the CRS stack, the determination of a macrovelocity model by means of an attribute-based tomographic inversion, and a limited-aperture pre- and/or poststack Kirchhoff-type depth migration, we gain an entire CRS-stack-based seismic imaging workflow with flexible processing strategies (Figure 1). This workflow will be evaluated in detail in the following sections by means of a real data example.

The seismic data used for the following case study was acquired in the close vicinity of Karlsruhe, Germany, along two almost parallel lines ($\approx$ 12 km length each) with a line separation of $\approx$ 2.5 km. About 240 geophone groups were laid out with a group spacing of 50 m (fixed spread). Three vibrators made up the seismic source, the source spacing was 50 m, and a time sampling interval of 2 ms was used. The acquisition was performed with the intention to obtain a structural image of the subsurface relevant for a projected geothermal power plant. The latter will be based on two boreholes reaching a depth of $\approx$ 2.5 km, where a strongly fractured horizon of hot-water-saturated lacustrine limestone is located. As the achievable production rate de-



(a) Zero-offset section

(b) Coherence section

(c) Angle section, α [°]

(d) R_{NIP} section, R_{NIP} [m]

Fig. 2: Results of CRS processing: a) simulated ZO section, b) coherence section, a measure how well the CRS operator fits to the data, c) emergence angle α of the ZO ray at the surface, d) radius of curvature R_{NIP} of the NIP wavefront observed at the surface. Gray (c) and white (d) color, respectively, denote regions with low coherence that were masked out for displaying purpose.

pends on the degree of fracturing of the target horizon and the number of faults in the target area, a detailed knowledge of the subsurface structure is essential.

After preprocessing was carried out for the field data in this case study, the contractor applied a standard imaging sequence, consisting of NMO/DMO/stack, finite-differences (FD) time migration, and a time-to-depth conversion using macrovelocity models based on stacking velocity sections. As an alternative we applied the CRS-stack-based seismic imaging workflow, see Figure 1 (Hertweck et al., 2003; Mann et al., 2003). Starting point was the preprocessed multicoverage seismic reflection data.

CRS stack. The simulation of stacked ZO sections is routinely applied to enhance the S/N ratio and reduce the amount of seismic data for further processing. A conventional approach to achieve this goal is the application of NMO and DMO corrections to the multicoverage dataset followed by a subsequent stack along the offset axis, usually denoted as NMO/DMO/stack (e. g., Yilmaz, 2001). The CRS stack (e. g., Müller, 1999; Jäger et al., 2001; Mann, 2002) is a powerful alternative to this conventional approach that can be seen as a generalized multi-dimensional high-density stacking-velocity analysis tool. It produces a ZO section in a purely data-driven way. In addition, the CRS method provides a number of kinematic wavefield attributes associated with each ZO sample. In the 2D case, the CRS stack fits entire stacking surfaces to the events rather than only stacking trajectories, as is done in conventional ZO simulation methods. Thus, far more traces contribute to each simulated ZO sample which explains the high S/N ratio even for data of poor quality. To determine the attributes of the CRS operator fitting best an actual reflection event, a coherence analysis is performed in the multicoverage data along test stacking operators parameterized by different sets of kinematic wavefield attributes. The best fitting operator yields the highest coherence. This analysis is repeated for each ZO sample to be simulated, irrespective of whether there is an actual reflection event. In case of conflicting dip situations, also local coherence maxima have to be considered. Based on such coherence analyses, the entire CRS approach can be applied in a noninteractive way and without the need for any a priori knowledge of a macrovelocity model.

Within the course of this project, the CRS stack method was complemented by an algorithm smoothing the obtained CRS attributes in an event-consistent way. Afterwards, the smoothed attributes were used for a final optimization and stacking iteration, resulting in a significant enhancement of event continuity. The final stack is restricted to the projected first Fresnel zone calculated from the obtained CRS attributes. The ZO section simulated by means of the CRS stack along with the coherence section and two (of three) attribute sections are shown in Figure 2 for one seismic line. The angle section shows the emergence angle α of the ZO ray, measured with respect to the top-surface normal, whereas the R_{NIP} section depicts the radius of the so-called normal-incidence-point (NIP) wavefront as observed at the emergence point of the ZO ray. The NIP wave is the hypothetical wave that would be obtained by placing a point source at the reflection point of the ZO ray, i. e., at the NIP, see Hubral (1983) for details.

Tomographic inversion. In order to obtain a depth image from the time-domain pre- and/or poststack data, a macrovelocity model needs to be estimated, which is one of the crucial steps in data processing. Fortunately, such a model can be obtained directly from the CRS stack results: the attributes R_{NIP} and α related to the NIP wave at a given ZO location describe the approximate multi-offset reflection response of a common-reflection point (CRP) in the subsurface. Therefore, the NIP wave focuses at zero traveltime at the NIP if propagated into the subsurface in a correct model. This principle can be utilized in an inversion that uses the above-mentioned attributes picked in the CRS-stacked section to obtain a laterally inhomogeneous velocity model. The CRS-stack-based velocity determination approach is realized as a tomographic inversion (Duveneck, 2004), in which the misfit between picked and forward-modeled attributes is iteratively minimized in the least-squares sense. The velocity model is defined by B-splines, i. e., a smooth model without discontinuities is used which is well suited for ray-tracing applications.

In this case study, about 1000 ZO samples were picked for each profile to achieve an appropriate resolution and reliability, and the respective attribute values were extracted from the auxiliary CRS sections. Picking was performed automatically based on the coherence associated with the ZO samples. The picked data were verified, using several criteria in order to discriminate outliers and attributes related to multiples, before the tomographic inversion process was applied. The determined velocity model for the seismic line under consideration is displayed in Figure 3.

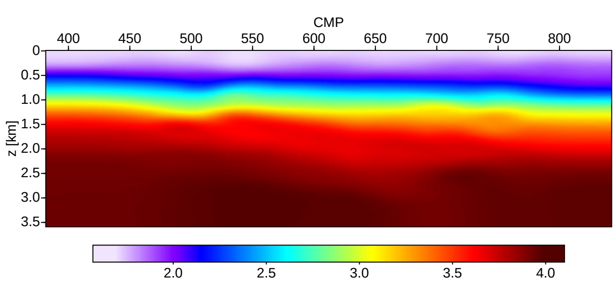


Fig. 3: Smooth macrovelocity model for depth imaging obtained by the tomographic inversion based on CRS attributes.

Depth migration. A Kirchhoff poststack depth migration (PostSDM) was performed using the CRS-stacked section (Figure 2(a)) and the determined macrovelocity model (Figure 3). The result is shown in Figure 4(a). In addition, a Kirchhoff prestack depth migration (PreSDM) was carried out, also using the inverted macrovelocity model, where offsets up to 3 km were considered, see Figure 4(b). The necessary traveltime tables were calculated by means of an FD eikonal solver. The resulting depth-migrated prestack data were firstly muted to avoid excessive pulse stretch for shallow reflectors and then stacked in offset direction. Some common-image gathers (CIGs) are displayed in Figure 4(c), where the muting can directly be seen. As most of the events in the CIGs are flat, we can state that the estimated macrovelocity model is kinematically consistent with the data. Note that no velocity model refinement was applied after the PreSDM. The post- as well as the prestack depth migration results show many structural details; in particular, many faults, vertical offsets of reflectors, deflection of reflectors, changes of reflector characteristics across faults, and fracturing are directly observable in the sections. Although the PreSDM seems to provide a higher resolution and more details, there are also regions, especially in the deeper part, where some structures are better resolved in the PostSDM. Consequently, the poststack depth-migrated result provides complementary information and both migrated sections were used for a structural interpretation. A preliminary interpretation is shown in Figure 4(d)—it was performed to determine structure and faulting and is only a small fraction of what may be accomplished by a quantitative interpretation of, e. g., reflector characteristics.

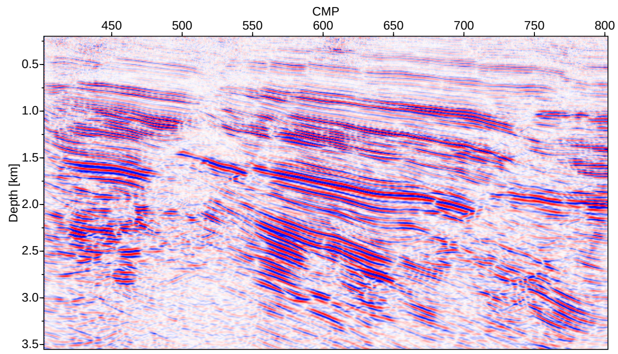
From the interpreter's point of view (HotRock EWK Offenbach/Pfalz GmbH), the CRS-stack-based imaging results have some major advantages compared to standard processing results (not shown here): in general, reflectors are imaged much better (or imaged at all), where lateral variations in reflector characteristics can easily be observed. In addition, faults may be traced form near-surface up to a depth of about 3 km.

Conclusions

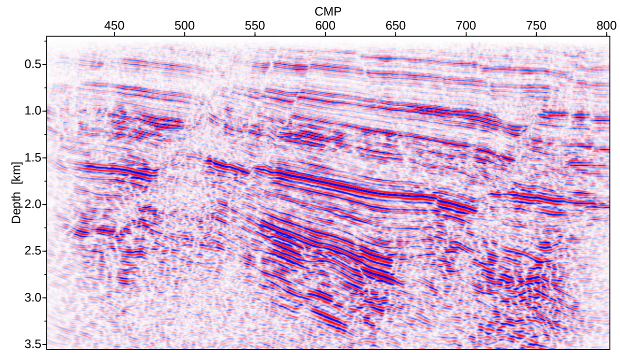
The great potential of a seismic imaging approach based on kinematic wavefield attributes obtained by the CRS stack was demonstrated in a recent exploration project. Due to the fact that a standard processing sequence was carried out in parallel, the reliability and high quality of the results of the applied CRS-stack-based seismic imaging workflow could be proven. With the obtained results, a very good basis for the geological interpretation and a successful drilling is available. The target area and the existing faults and fractures were imaged clearly and the high grade of tectonic displacement necessary to ensure a sufficiently large production rate for the projected geothermal power plant was verified.

Acknowledgments

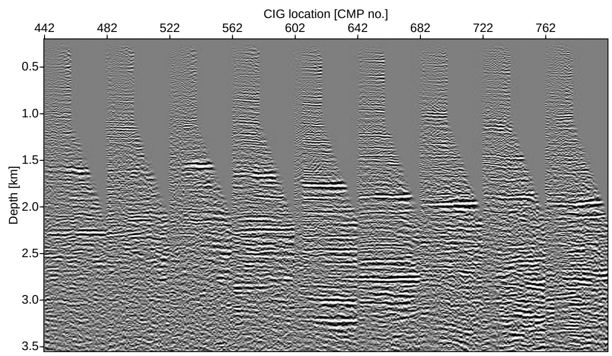
This work was kindly supported by HotRock EWK Offenbach/Pfalz GmbH, Karlsruhe, Germany, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany, and the sponsors of the Wave Inversion Technology (WIT) Consortium, Karlsruhe, Germany. The authors also like



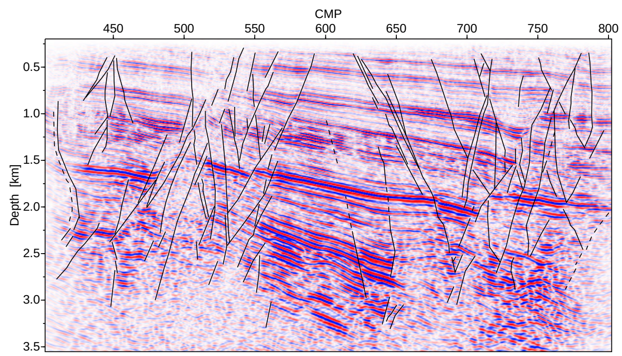
(a) PostSDM



(b) PreSDM



(c) CIGs



(d) Interpretation

Fig. 4: a) Poststack depth migration result using the CRS-stacked section (Fig. 2(a)) and the estimated macrovelocity model (Fig. 3), b) prestack depth migration result using the estimated macrovelocity model (Fig. 3), c) some common-image gathers extracted from the prestack depth migration result before stacking over all offsets, d) preliminary structural interpretation of the depth migration results [image courtesy of HotRock EWK Offenbach/Pfalz GmbH].

to thank Deutsche Montan Technologie (DMT) GmbH, Essen, Germany, for the collaboration during the entire project.

References

Duveneck, E. (2004). Velocity model estimation with data-derived wavefront attributes. *Geophysics*, 69:265–274.

Duveneck, E. and Hubral, P. (2002). Tomographic velocity model inversion using kinematic wavefield attributes. In *Expanded Abstracts*. 72nd Ann. Internat. Mtg., Soc. Expl. Geophys. Session IT 2.3.

Hertweck, T., Jäger, C., Mann, J., and Duveneck, E. (2003). An integrated data-driven approach to seismic reflection imaging. In *Extended Abstracts*. 65th Conference & Exhibition, Europ. Assoc. Geosci. Eng. Session P004.

Hubral, P. (1983). Computing true amplitude reflections in a laterally inhomogeneous earth. *Geophysics*, 48(8):1051–1062.

Hubral, P., editor (1999). *Macro-model independent seismic reflection imaging*, volume 42(3,4). J. Appl. Geophys.

Jäger, R., Mann, J., Höcht, G., and Hubral, P. (2001). Common-Reflection-Surface stack: Image and attributes. *Geophysics*, 66:97–109.

Koglin, I. and Ewig, E. (2003). Residual static correction by means of CRS attributes. In *Expanded Abstracts*. 73rd Annual Internat. Mtg., Soc. Expl. Geophys. Session SP 1.4.

Mann, J. (2002). *Extensions and Applications of the Common-Reflection-Surface Stack Method*. Logos Verlag, Berlin.

Mann, J., Duveneck, E., Hertweck, T., and Jäger, C. (2003). A seismic reflection imaging workflow based on the Common-Reflection-Surface stack. *J. Seis. Expl.*, 12:283–295.

Müller, T. (1999). *The Common Reflection Surface Stack Method – Seismic imaging without explicit knowledge of the velocity model*. Der Andere Verlag, Bad Iburg.

Vieth, K.-U. (2001). *Kinematic wavefield attributes in seismic imaging*. PhD thesis, University of Karlsruhe, Germany. http://www.ubka.uni-karlsruhe.de/vvv/2001/physik/2/2.pdf.

Yilmaz, Ö. (2001). *Seismic Data Analysis*. Soc. Expl. Geophys., Tulsa.