CRS-stack-based seismic imaging for land data – a case study from Saudi Arabia

Zeno Heilmann, Jürgen Mann, Ingo Koglin*
Geophysical Institute, University of Karlsruhe

Summary

In this case study we are giving attention to the seismic processing of a challenging land data set from the Arabian Peninsula. It suffers from rough top-surface topography, a strongly varying weathering layer, and complex near-surface geology. Particularly for land data, the increased computational expense required by the generalized high-density velocity analysis preceding the Common-Reflection-Surface stack process often proves to be worthwhile. In order to define optimal spatial stacking operators, we determine for every sample of the zero-offset section an entire set of physically interpretable stacking parameters. These so-called kinematic wavefield attributes can be applied to solve various dynamic and kinematic stacking, modeling, and inversion problems. By this means, a very flexible CRS-stack-based seismic reflection imaging workflow can be established. The main steps of this workflow are, besides the stack itself, residual static correction, determination of a macrovelocity model via tomographic inversion, and Kirchhoff depth migration. The presented extension of this imaging workflow supports arbitrary top-surface topography. Both, stack and stack-based residual static correction are applied to the original prestack data without the need of any elevation statics. Finally, a redatuming procedure relates the stacked zero-offset section, the kinematic wavefield attribute sections, and the quality control sections to a chosen planar measurement level.

	Parameter	Value
Shots and receivers	Number of shots	1279
	Shot interval	30 m
	Number of receivers	1279
	Receiver interval	30 m
Midpoints	Number of CMP bins	2840
	Maximum CMP fold	120
	Offset range	–3602 . . . 3607 m
Recording parameters	Recording time	2 s
	Sampling interval	4 ms
	Frequency content	5 - 65 Hz
	Mean frequency	30 Hz

Table 1: *Acquisition geometry and recording parameters.*

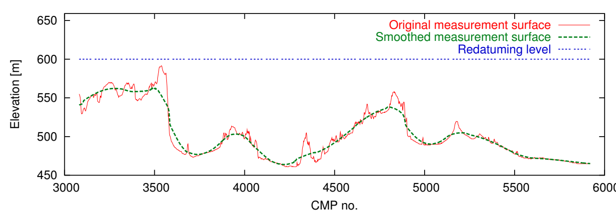

Fig. 1: *Comparison between original and smoothed measurement surface. The horizontal redatuming level at $z = 600$ m is also displayed.*

Introduction

Due to the tremendous increase in available computing power, so-called data-driven imaging approaches (see, e. g., Hubral, 1999) have become feasible today—even for 3D processing. The Common-Reflection-Surface (CRS) stack (see, e. g., Mann, 2002) is one of these promising methods. Besides an improved zero-offset (ZO) simulation, its decisive advantage over conventional methods is that we obtain for every ZO sample an entire set of physically interpretable stacking parameters as a by-product of the stacking process. These so-called CRS attributes can be applied both, to improve the stack itself and to support subsequent processing steps such as residual static correction (RSC), macrovelocity model determination and Kirchhoff depth migration. In the following, this will be demonstrated by means of a dataset acquired in Saudi Arabia along a crooked 2D line of about 45 km length. Details on the acquisition geometry and recording parameters are compiled in Table 1.
The data suffers from complex near-surface geology and rugged topography (see Figure 1). Even though the latter can be directly addressed by the CRS stack process, the complex near-surface geology caused by sand dunes, carbonate outcrops, *wadis*, and *sabkahs*[1] made static correction absolutely necessary. Therefore, we used preprocessed data where the influence of the complex near-surface geology—particularly of the strongly varying weathering layer—had been largely removed by means of refraction statics.
To restore the original source and receiver elevations we applied inverse elevation statics with the constant replacement velocity $v_0 = 3.5$ km/s, which is the average refractor velocity. The main purpose for restoring the original geometry is to minimize the systematic error that was introduced to the prestack data by assuming every ray to emerge vertically. As a consequence, the physical meaning of the attributes extracted from the prestack data is preserved as far as possible.

CRS stack for topography

In recent years, two different CRS stacking operators that consider the top-surface topography have been developed at Karlsruhe University. Chira et al. (2001) and Heilmann (2003) assumed a smoothly curved measurement surface for which the elevation of all source and receiver points contributing to

[1] low-lying saline flats

a single stacking process can be approximated by a parabola. This approach is attractive from the computational point of view as a pragmatic attribute search strategy can be applied using three one-parameter searches to determine the optimal stacking operator. However, small elevation statics are still required in order to extrapolate the original data to the chosen smoothly curved measurement surface.
Zhang (2003) presented a very general stacking operator that directly considers the true elevation of every source and receiver. This approach demands far more computational effort, as at least two of the three attributes have to be searched for simultaneously due to the higher complexity of the stacking operator. On the other hand, no elevation statics are required and the elevations of the emergence points of the simulated ZO rays can be chosen—within certain limits—arbitrarily. A similar approach based on the methology of *Multifocusing* was presented in Gurevich et al. (2001).
To minimize the computational effort, we combine both methods of topography handling mentioned above to a cascaded processing strategy: we start with the more convenient but less accurate description for smooth topography to obtain an initial stack result and initial attribute sections. In a second step we use the more accurate description for arbitrary topography to refine these results in a local optimization process. In this way, most of the specific disadvantages of these approaches can be compensated without loosing their individual benefits. A subsequent CRS-based residual static correction (Koglin, 2005) further optimizes the stack results. A flowchart of this pragmatic strategy is depicted in Figure 2.

In the case of complex near-surface conditions which lead to a strongly variable data quality along the line, event-consistent smoothing of the initial attributes was helpful to remove fluctuations and outliers. The latter are mainly caused by the limitations of the utilized parameter search strategy. The smoothing algorithm is based on the combined application of mean and median filters within volumes aligned with reflection events (see, e. g., Hertweck et al., 2005).

We implemented a redatuming procedure that relates the obtained results to a fictitious horizontal measurement surface close to the smoothly curved reference level (see Figure 1). Due to the fact that the emergence angle of every simulated zero-offset ray is known, it is easy to extrapolate them to a constant reference level—especially, if the redatuming velocity v_r between the smoothly curved reference level and the planar redatuming level is chosen to equal the above mentioned replacement velocity v_0. In this case no refraction has to be considered when crossing the smoothly curved reference level.

Residual static correction

For CRS-based residual static correction, the cross-correlations are performed within so-called CRS supergathers, consisting of all moveout corrected prestack traces within the spatial stacking aperture, instead of being confined to individual CMP, common-shot, or common-receiver gathers. The moveout correction makes use of the previously obtained attributes and considers the true source and receiver elevations. Thus, elevation static correction can be omitted that may introduce non surface-consistent errors of the same scale as the searched-for residual statics. Due to the spatial extent of the employed stacking operator, a supergather contains many neighboring CMP gathers. For each considered supergather, corresponding to a particular zero-offset location, the moveout correction will, in general, be different. Since each prestack trace is included in many different supergathers it contributes to far more cross-correlations than in methods using individual gathers, only. The cross-correlations of the stacked pilot trace and the moveout corrected prestack traces are summed up for each shot and receiver location. This summation is performed for all supergathers contained in the specified target zone. The searched-for residual time shifts are then expected to be associated with the maxima in the cross-correlation stacks and are used to correct the prestack traces. For the next iteration of residual static correction the entire attribute search and stacking process is repeated, now using the corrected prestack data set. The stack result after residual static correction is depicted in Figure 4. Comparing this result with the stack before RSC (3), it can be observed that besides a strongly improved resolution and event continuity also the small scale undulation of shallow reflection events is mostly removed. Although the gap around CMP no. 5000 has not been closed completely, it has been considerably reduced by applying the residual static correction.

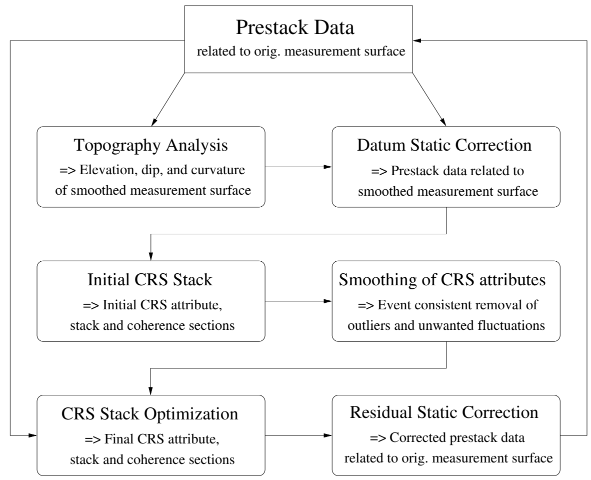

Fig. 2: *Cascaded processing scheme to handle topography in CRS stack and residual static correction.*

Tomographic inversion

The tomographic inversion method employed in this case study makes use of the kinematic information extracted by the CRS stack: two of them are related to the hypothetical normal-incidence-point wave at a given zero-offset location (see Hubral, 1983) and can be used to describe the approximate multi-offset reflection response of a common reflection point in the subsurface. Therefore, this wave focuses at zero traveltime at the normal-incidence-point if propagated into the subsurface in a correct model. This principle was utilized in an inversion by Duveneck (2004) to obtain a smooth but laterally inhomogeneous velocity model. Since picking is

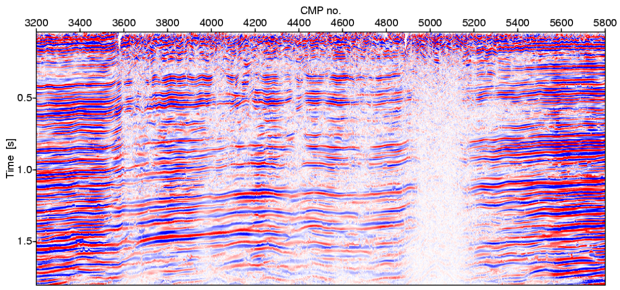

Fig. 3: *CRS stack section*

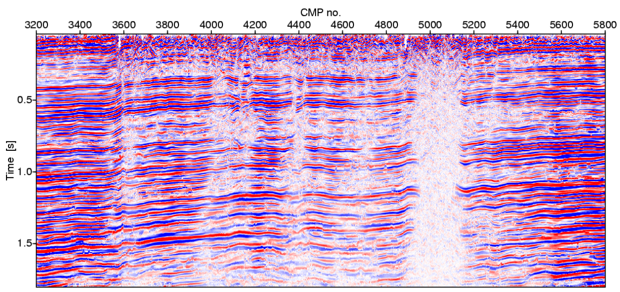

Fig. 4: *CRS stack section after residual static correction*

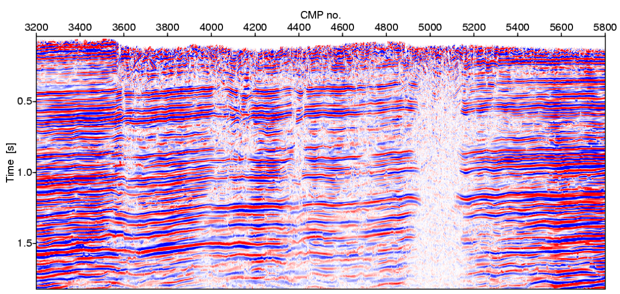

Fig. 5: *CRS stack section after residual static correction and redatuming, related to a fictitious horizontal measurement surface at $z = 600$ m. Note the reduced acquisition footprint around CMP no. 3600 compared to Figure 4.*

performed in the simulated ZO section, the effort related to this process is considerably reduced compared to other tomography methods that demand picking in the prestack data. Afterwards, the misfit between picked and forward-modeled attributes is iteratively minimized in the least-squares sense. To obtain the forward-modeled attributes dynamic ray-tracing is used. As the redatuming procedure provides stack and attribute sections related to a planar reference level the real topography can be neglected.

In this case study, about 4000 zero-offset samples together with the associated attribute values were picked. Automatic picking was performed using a module based on the coherence associated with the zero-offset samples. The picked data was checked using several criteria, in order to discriminate outliers and attributes related to multiples, before the tomographic inversion process was applied. The obtained macrovelocity

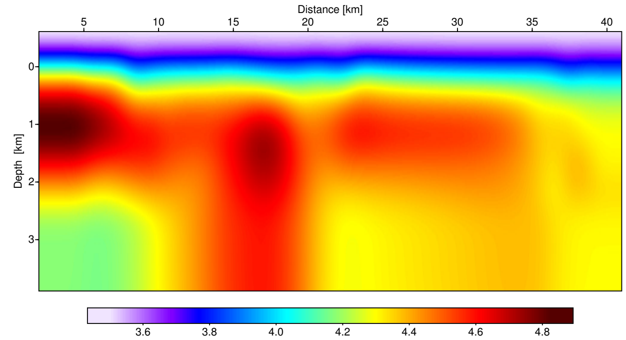

Fig. 6: Macrovelocity model [km/s] obtained by CRS-attribute-based tomographic inversion.

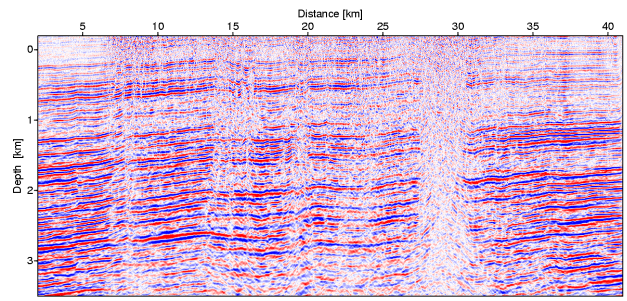

Fig. 7: Prestack depth migration result.

model is defined by 231 B-spline nodes. It is displayed in Figure 6.

Depth migration

A Kirchhoff prestack depth migration for topography (Jäger et al., 2003; Hertweck, 2004) was applied. We used the prestack data after residual static correction together with the macrovelocity model obtained by the tomographic inversion (Figure 6). The necessary kinematic Green's function tables were calculated by means of an eikonal solver. The resulting depth-migrated prestack data was firstly muted to avoid excessive pulse stretch for shallow reflectors and then stacked in offset direction in order to obtain the depth-migrated image displayed in Figure 7. Some common-image gathers are displayed in Figure 8, where the muting can directly be seen. As most of the events in the common-image gathers 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 prestack depth migration. As a complementary or alternative step of the CRS-stack-based imaging workflow, poststack depth migration was performed. Input for the poststack depth migration were the final stack section after redatuming (Figure 5) and the macrovelocity model derived from the attributes (Figure 6). The result is depicted in Figure 9. The poststack depth migration result as well as the prestack depth migration result show many structural details; in particular, faults, vertical offsets of reflectors, deflection of reflectors, changes of reflector characteristics across faults, and fracturing are directly observable in the sections. Although the prestack

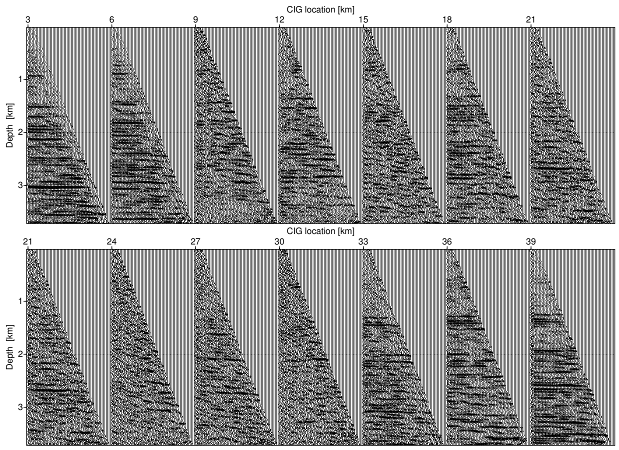

Fig. 8: Some common-image gathers extracted from the prestack depth migration result before stacking over all offsets.

depth migration 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 poststack depth migration. Consequently, the poststack depth migration result provides complementary information and both migrated sections can be used for a structural interpretation.

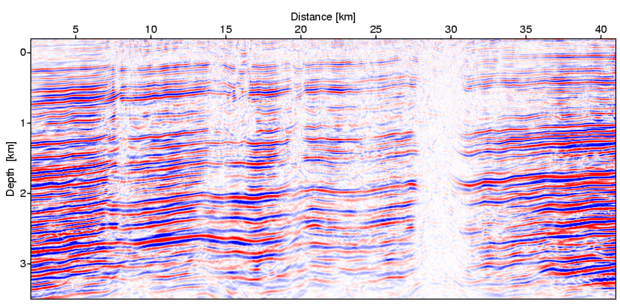

Fig. 9: Poststack depth migration result.

Conclusions

We presented a recent extension of CRS-stack-based time-to-depth imaging for complex near-surface conditions and rugged top-surface topography. The practical application was demonstrated by means of a data set from the Arabian Peninsula. Besides the CRS stack itself subsequent processing steps, i. e, redatuming, residual static correction, tomographic inversion and depth migration, were applied that directly benefit from the stack results.

The data-driven CRS stack approach was shown to be particularly suitable for land data processing as the three-parameter traveltime approximation allows for a large stacking aperture in midpoint and offset direction. The large fold results in an enhanced signal-to-noise ratio and event continuity of the stack section and furthermore in a more reliable and stable residual static correction. By directly considering the original source and receiver elevations during stack and residual static correction another very important advantage of CRS processing is maintained, i. e., the physical meaning of the extracted stacking parameters. To provide standardized results for interpretation and further processing a redatuming procedure utilizes the extracted emergence angle to extrapolate the CRS results from the floating datum to a horizontal reference level. In this way, the top-surface topography handling is fully integrated into a consistent time-to-depth imaging workflow.

Acknowledgment

This work was kindly supported by the sponsors of the Wave Inversion Technology (WIT) Consortium, Karlsruhe, Germany. We gratefully acknowledge the permission of Saudi Aramco to use and present their data. TEEC kindly provided the preprocessed data with refraction statics applied.

References

Chira, P., Tygel, M., Zhang, Y., and Hubral, P. (2001). Analytic CRS stack formula for a 2D curved measurement surface and finite-offset reflections. *Journal of Seismic Exploration*, 10(1-3):245–262.

Duveneck, E. (2004). Velocity model estimation with data-derived wavefront attributes. *Geophysics*, 69(1):265–274.

Gurevich, B., Keydar, S., and Landa, E. (2001). Multifocusing imaging over an irregular topography. *Geophysics*, 67(2):639–643.

Heilmann, Z. (2003). Extensions of the Common-Reflection-Surface Stack considering the surface topography and the near-surface velocity gradient. In *Ext. Abstr., 8th International Congress, Soc. Bras. Geofísica (SBGf), Rio de Janeiro*.

Hertweck, T. (2004). *True-amplitude Kirchhoff migration: analytical and geometrical considerations*. Logos Verlag, Berlin.

Hertweck, T., Mann, J., and Klüver, T. (2005). Event-consistent smoothing in the context of the CRS stack method. *J. Seis. Expl.*, 14(2-3):197–215.

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, C., Hertweck, T., and Spinner, M. (2003). True-amplitude Kirchhoff migration from topography. In *Ext. Abstr.*, Session MIG 2.1. 73rd Ann. Internat. Mtg., Soc. Expl. Geophys.

Koglin, I. (2005). *Estimation of Residual Static Time Shifts by means of the CRS-based Residual Static Correction Approach*. Logos Verlag, Berlin.

Mann, J. (2002). *Extensions and applications of the Common-Reflection-Surface stack method*. Logos Verlag, Berlin.

Zhang, Y. (2003). *Common-Reflection-Surface Stack and the Handling of Top Surface Topography*. Logos Verlag, Berlin.