FROM TIME TO DEPTH WITH CRS ATTRIBUTES

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keywords: *CRS attributes, workflow, multiple suppression, model building, depth migration*

ABSTRACT

We introduce a processing workflow for reflection seismic data that is entirely based on CRS stacking attributes. This workflow comprises the CRS stack, multiple attenuation, velocity model building, prestack data enhancement, trace interpolation, and data regularization. Like other methods its limitation is the underlying hyperbolic assumption. The CRS workflow provides an alternative processing path in case conventional CMP processing is unsatisfactory. Particularly for data with poor signal-to-noise ratio and low fold acquisition, the CRS workflow is advantageous. The data regularization feature and the ability of prestack data enhancement provides quality control in velocity model building and improves prestack depth migrated images.

INTRODUCTION

For data of very low signal-to-noise ratio (S/N) or acquisitions with very low fold, conventional CMP processing may not provide sufficient results and alternative processing sequences are considered to improve the images. The Common Reflection Surface (CRS) workflow represents such an alternative path for the processing of reflection seismic data from time to depth. Its key element is the CRS stack (e.g., Jäger et al., 2001) which provides zero offset stacked sections, coherency sections, and sections of the CRS attributes, also called kinematic wavefield attributes. These attributes form the foundation of the CRS workflow. It is a goal to establish a consistent CRS processing chain which is entirely based on the same assumptions, operators and apertures.

The CRS operator is a hyperbolic second-order approximation of the reflection traveltime surface which also considers neighboring CMPs. Owing to this fact, it stacks more traces than conventional CMP processing and therefore achieves a better S/N ratio. All coherent events along a hyperbolic path are fitted by this operator including reflections, multiples and diffractions. Multi-parameter stacking approaches were already investigated by, e.g., deBazelaire (1988) and Gelchinsky et al. (1999). A first attempt to establish a workflow based on CRS attributes was presented by Hertweck et al. (2007). It consists of the CRS stack (Jäger et al., 2001), the Normal Incidence Point (NIP) wave tomography (Duveneck, 2004), and a corresponding post- or prestack depth migration using the resulting tomographic models. The CRS operator may be utilized to generate prestack data of higher S/N ratio. Prestack migrations of these improved gathers lead to images of higher quality compared to conventional PreSTM or PreSDM. Moreover, CRS attributes determined during the stack procedure can be used for multiple attenuation.

Prestack data enhancement tools using CRS attributes for partial stacking were presented by Baykulov and Gajewski (2009); Hoecht et al. (2009) and first approaches to address multiples with CRS attributes were presented by Dümmong and Gajewski (2008). We combine these tools to an integrated workflow based on CRS attributes. The modules in the workflow positively interact with each other. Multiple suppression not only improves the imaging but also influences the NIP-wave tomography which assumes primary events. The prestack data enhancement module improves the prestack depth processing and the quality control of the velocity model building and it is also applied in the multiple suppression to reduce artifacts caused by adaptive filtering. In the next section, we first review the CRS method and then discuss

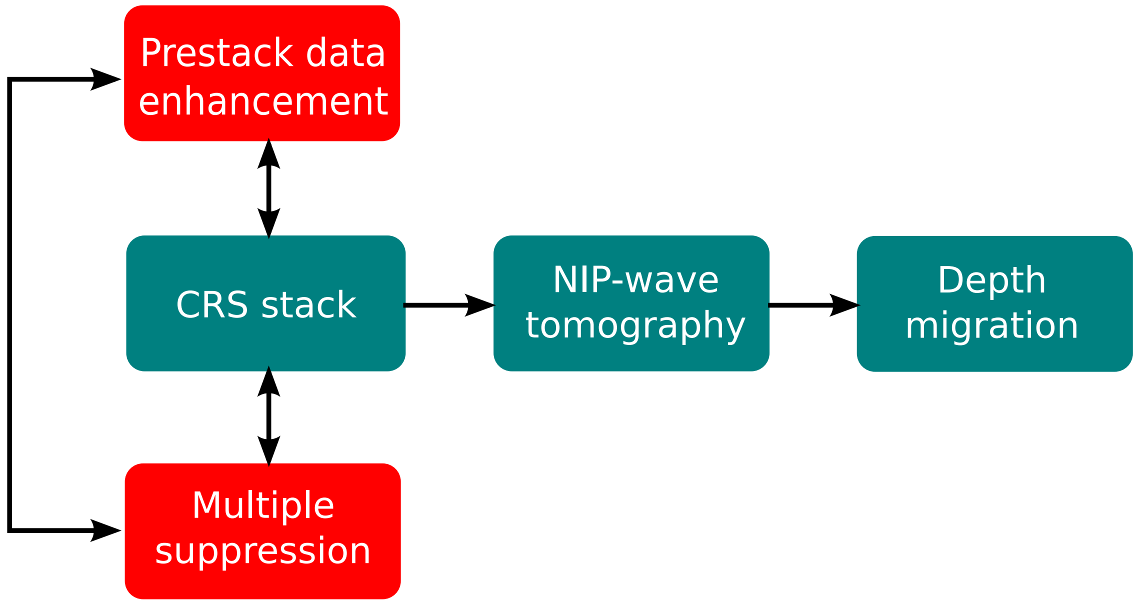


Figure 1: Sketch of the CRS workflow. All modules of the workflow depend on the CRS attributes, which are determined as a by product during the CRS stack.

multiple attenuation, prestack data enhancement, data regularization, and how these tools are incorporated into the workflow. Marine and land data examples illustrate the operation and performance of the workflow.

THE CRS WORKFLOW

The key element of the workflow (Figure 1) are the CRS attributes, which are obtained as a by product of the CRS stack. These attributes are fundamental to all other processing modules in the workflow. They are determined from the data in a multi-dimensional optimization procedure. The better the accuracy of the CRS attributes, the better the results of the following processing steps. Therefore, we briefly describe the CRS stack and the determination of the CRS attributes, as well as their physical interpretation.

Common Reflection Surface stack

The CRS stacking method is a multi-parameter stacking procedure (e.g., Mann, 2002), which automatically determines stacking attributes based on a semblance optimization for every zero offset sample of the data. Since these attributes vary with time for the same event, the CRS stack is free of NMO-stretch (Perroud and Tygel, 2004). Although the 3D CRS stack is available we restrict the description to the 2D case here. The corresponding hyperbolic second-order approximation of the traveltime is expressed by

$$t^2(x_m,h) = \left(t_0 + \frac{2\sin\beta_0}{v_0}\triangle x_m\right)^2 + \frac{2t_0\cos\beta_0}{v_0}\left(K_N \triangle x_m^2 + K_{NIP} h^2\right). \quad (1)$$

In this case, three stacking parameters control the operator. These are β_0 the angle of emergence of the zero offset (ZO) ray; K_N the curvature of the so-called normal wavefront; and K_{NIP} the curvature of the NIP wavefront at the registration surface. For the physical interpretation of the NIP and normal wave we refer to Hubral (1979) and Figure 2. In Equation 1 parameter t_0 is the time of the considered zero offset sample, v_0 is the near surface velocity, h is offset and Δx_m is the CMP displacement or CMP offset. For NIP-wave tomography the physical interpretation of CRS attributes is essential, see Duveneck (2004).

For stacking and time processing the physical interpretation of the parameters or attributes is not required. They can be considered as the coefficients of a hyperbolic surface which best fit the data. Equation (1) could be reformulated as $t = (t_0 + A\Delta x_m)^2 + B\Delta x_m^2 + Ch^2$ and no physical interpretation of the coefficients A, B, and C is necessary here. This also shows that in the time domain an erroneous v_0 in Equation

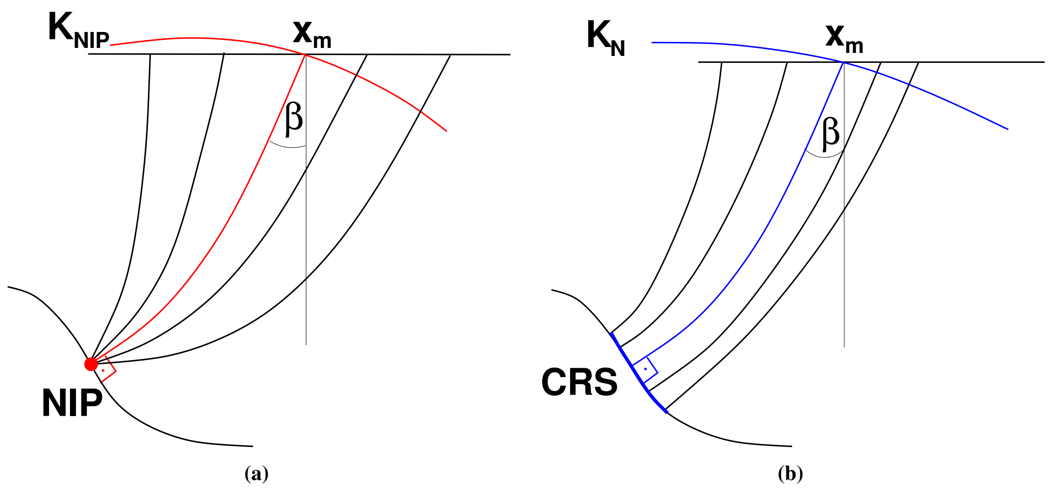


Figure 2: Physical interpretation of CRS attributes at midpoint location x_m. Angle of emergence β_0, point source at NIP with curvature K_{NIP} and exploding Common Reflection Surface (CRS) with curvature K_n at the registration surface.

1 has no influence on the processing. In the depth or model domain, e.g., for tomography the physical interpretation of the attributes as angle and curvatures is required and a wrong near surface velocity would lead to erroneous attributes and in turn to errors in the velocity model.

The lateral resolution in the CRS stack section is influenced by the choice of the apertures used in the CRS stack process. In the limit of $\Delta x_m = 0$ the CMP stack with the same lateral resolution is obtained. Physical intuition as well as many synthetic and field data examples have shown that the projected first Fresnel zone is a good choice for the CMP-offset Δx_m, (e.g., Müller, 1999; Mann, 2002). For this choice the lateral resolution is similar to the CMP stack but the signal-to-noise ratio is considerably improved.

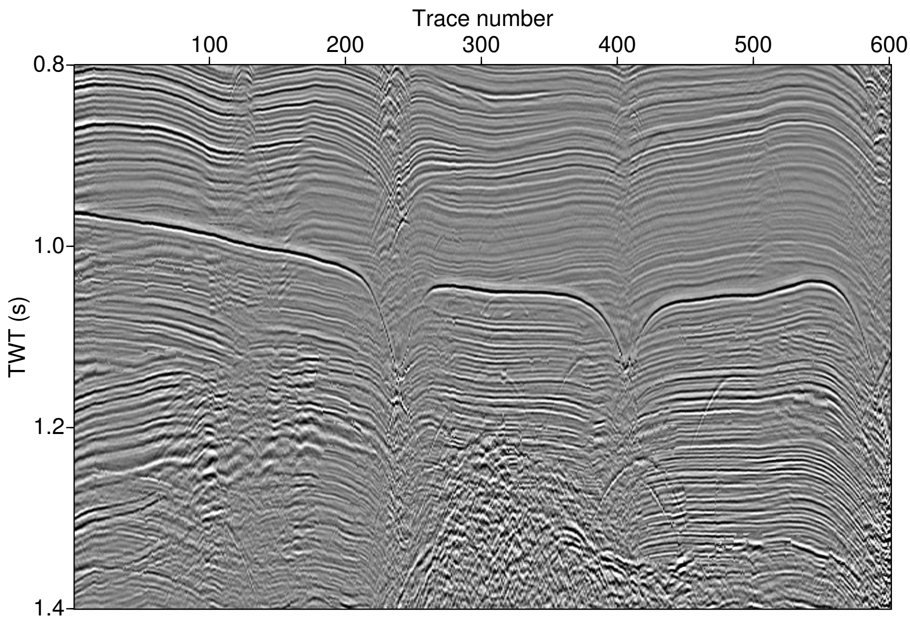
Let us now assume that the CRS attributes were properly estimated. In the following section, we describe how the attributes are utilized in multiple suppression.

Multiple suppression with CRS attributes

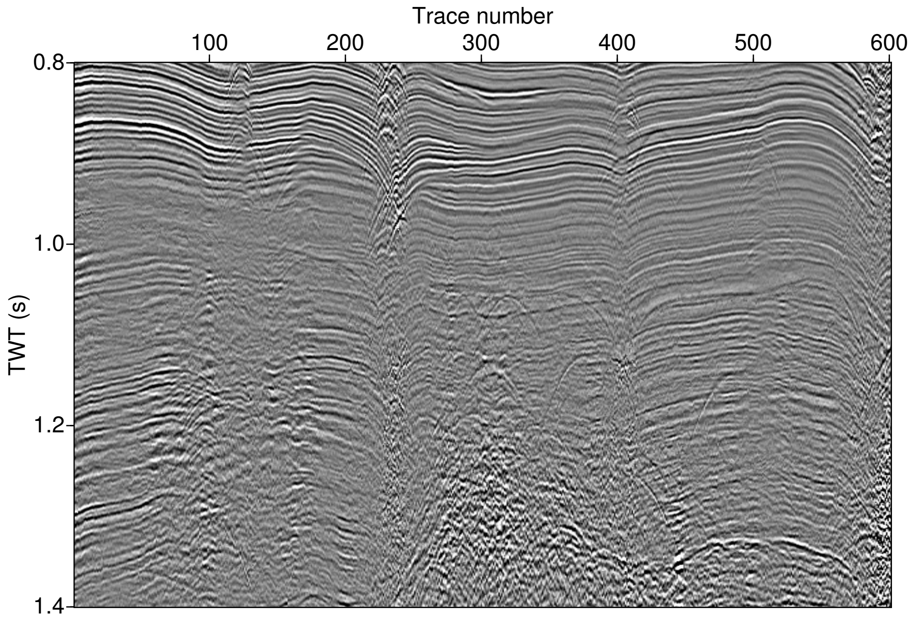
Multiple identification and attenuation is one of the most challenging tasks in the seismic data processing chain. An approach for the identification and removal of surface related multiples within the CRS workflow was introduced by Dümmong and Gajewski (2008). The multiples are predicted by auto-convolving every stacked trace (Kelamis and Verschuur, 1996). The basic idea is that the auto-convolution of a seismic trace predicts multiple reflections (Verschuur, 2006). The auto-convolution provides an estimate of the first order multiple. Convolving the first order multiple prediction with the poststack ZO trace gives the second order multiple. This process can be repeated until the desired order of multiples is reached. The convolution is performed with the high S/N CRS stack ZO traces and provides a direct prediction of the ZO traveltimes of the multiples.

This prediction is correct for 1D models. Inclined reflectors and heterogeneities lead to prediction errors. Therefore, a correction algorithm based on image comparison was implemented. The image comparison is based on a normalized 2D cross-correlation of the CRS stacked data with the predicted multiples, i.e., the section of auto-convolved ZO traces. The 2-D correlation between the two images is performed with different space and time shifts until the maximum of the cross correlation function is found. This process tries to match the predicted multiples in time and space to the original multiples in the stacked section. The time and lateral shift for the maximum of the cross-correlation specifies the correction for the predicted ZO multiple. The procedure can also be applied in a windowed fashion, i.e., only parts of the sections are correlated in order to account for different prediction errors in different parts of the section.

In the step described above we have identified the ZO times of the multiples. Since CRS attributes were determined for each ZO sample of the data we can use the CRS attributes of the predicted ZO sample

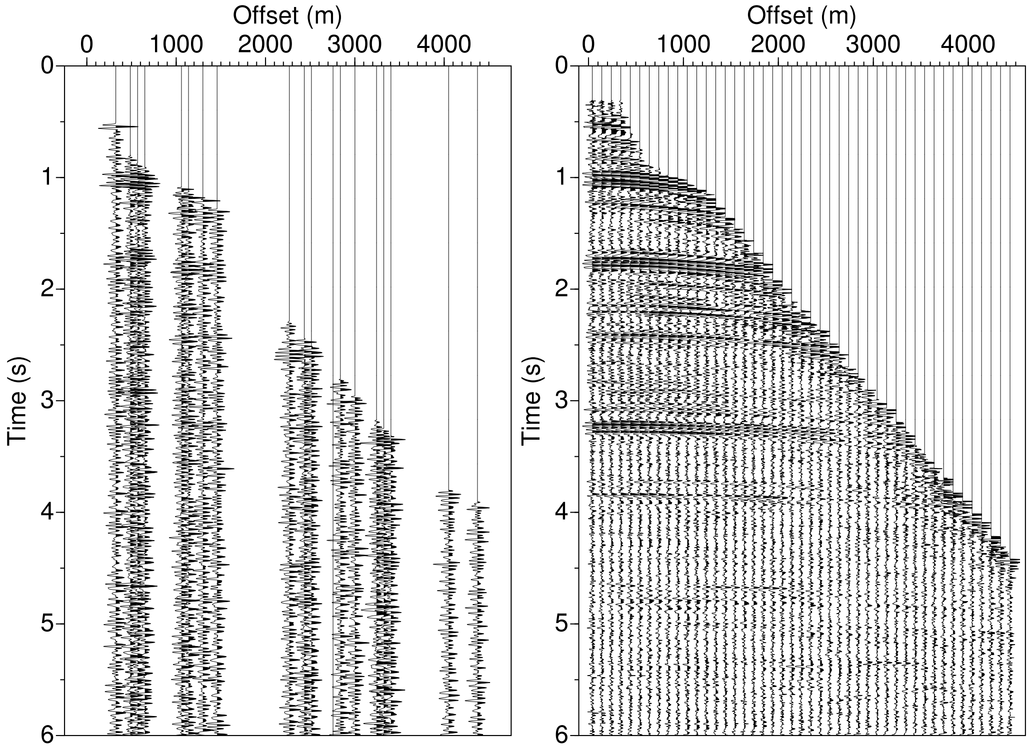


(a)



(b)

Figure 3: Marine data from the Maldives (a) before and (b) after CRS based multiple attenuation. Only small residuals of the multiple at about 1s TWT are left.



(a) **(b)**

Figure 4: Prestack data enhancement using partial CRS stacks of low fold CMP land data (a) with data gaps. The CRS supergather (b) shows a regular distribution of traces and an improved S/N ratio. Several events are clearly visible in (b) that are not obvious in (a).

to obtain the traveltime trajectory of the multiple. The coherency of this sample provides an indication how good the multiple was fitted by the CRS operator. To predict prestack seismograms of the multiples, we convolve this trajectory with the signal shape of the stacked trace. These seismograms are then adaptively subtracted from the prestack data. The last step may occasionally lead to a distortion of amplitudes, however, these effects can be healed by an application of the partial CRS stack method which is described below. This positive interaction of CRS attribute based modules demonstrate the benefit to combine them into an integrated workflow.

An example of this multiple attenuation process is shown in Figure 3. The data are from offshore the Maldives and are contaminated by surface related multiples. The CRS based multiple attenuation procedure worked well, although some residuals are still visible.

Data enhancement with partial CRS stacks

As the name *partial CRS stack* suggests only a part of the CRS stacking surface defined by its offset and midpoint apertures is used. The partial stack is performed in common offset bins for neighboring CMPs using the estimated CRS attributes. Apertures used for the partial stack, however, are usually smaller than those used for the CRS stack. No moveout correction is applied during the partial stack, .i.e., the moveout of the data is preserved by writing the stacked amplitude to a new trace with the same offset and time coordinates of the considered CMP location. Repeating this procedure for all desired offsets generates a new partially stacked CRS supergather. This gather has an improved S/N compared to the original gather since it is generated by stacking several neighboring traces. The application of partial stacks thus allows to improve prestack data quality. Since any location on the partial surface can be considered the method is also suitable for trace interpolation and data regularization. For implementation details and several applications to synthetic and field data we refer to, e.g., Baykulov and Gajewski (2009); Hoecht et al. (2009). An

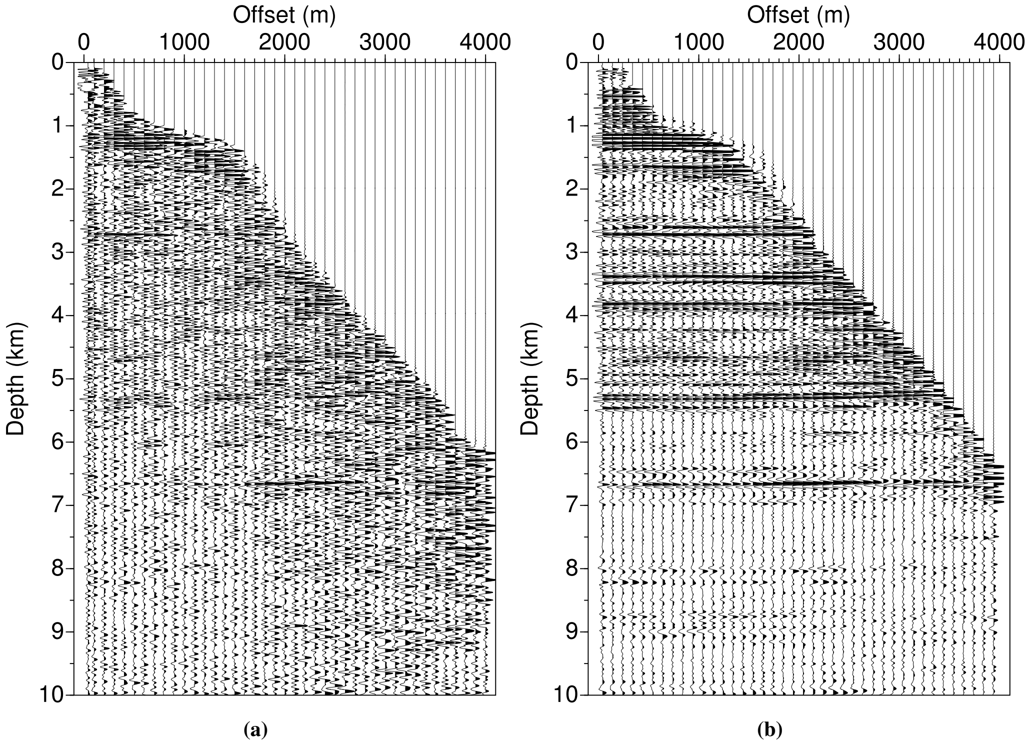


Figure 5: CIP gathers for low fold data from Northern Germany using (a) the original CMP data and (b) CRS supergathers. The gather in (b) facilitates velocity model quality control. For some events only the application of CRS supergathers makes QC at all possible.

application to low fold land data from Northern Germany is shown in Figure 4. The CRS supergather displays a regular distribution of traces of increased S/N compared to the original CMP gather. The offset aperture in the partial stack is 100 m.

Velocity model building

A velocity model is required for the use of CRS processed gathers in prestack depth imaging. For the velocity model building within the CRS workflow NIP wave tomography (Duveneck, 2004; Della Moretta et al., 2006) is used. Like all other modules in the workflow, NIP-wave tomography depends on CRS wavefield attributes. The parameters used for velocity model estimation are extracted from the CRS attribute sections, namely K_{NIP} and β_0. All parameters refer to NIP rays of a corresponding reflector element in depth. The CRS-based tomographic principle is based on the focusing criterion of the NIP-wave: For a velocity model consistent with the data, NIP-waves focus at the NIP for zero traveltime when propagated back into the subsurface (Duveneck, 2004), e.g., by ray tracing. In other words: At zero time the NIP-wave curvature K_{NIP} should go to infinity repectively the radius of curvature $R_{NIP} = 1/K_{NIP}$ should go to zero since the NIP-wave is emitted from a point source at the NIP. Picking of the attributes is facilitated in the poststack data domain with its higher S/N ratio. Each pick is characterized by the corresponding CRS attributes which were determined for each ZO sample independently. No link of the picks to a reflection is required. In this sense all picks are independent from each other and are individually processed in the tomographic procedure.

A single NIP ray needs to be traced for each pick. In the initial velocity model, CRS attributes are modeled by dynamic ray tracing. The inversion scheme then updates the underlying velocity distribution by acknowledging the tomographic principle for the data points extracted from the CRS stack. The algorithm iteratively determines the velocity model which is most consistent with the data (Della Moretta et al., 2006). The resulting model can then be used as a starting model for depth imaging processes. For complex subsurface structures, the model derived by NIP-wave tomography will most likely not be the final solution for the depth processing. It will, however, provide a suitable starting model for subsequent migration-based velocity analysis techniques.

In velocity model building sequences quality control (QC) is crucial. It is standard practice to consider Common Image Point (CIP) gathers derived from the prestack data volume. The S/N of CIPs can be improved by prestack data enhancement. In Figure 5, we show the benefits of partial CRS stacks on the QC for low fold land data from Northern Germany. In Figure 5 (a) a CIP gather obtained by employing the original CMP data as input in the prestack migration is presented whereas in Figure 5 (b) the same CIP obtained by employing CRS supergathers is shown. For both CIPs the same migration method and the same NIP-wave tomographic migration velocity model was used.

QC is considerably simplified for the CIP obtained from CRS supergathers. The events are flat. For this particular location the NIP-wave tomographic model is consistent with the data and no further velocity refinement is required. The CIP from CRS supergathers displays flat events at 8 km and below which are geologically feasible but are not visible in the CIP obtained from the original CMP data. The prestack data enhancement feature of the partial CRS stacking procedure helped to make these events visible and to perform quality control.

CONCLUSIONS AND OUTLOOK

Based on the hyperbolic reflection traveltime formula, we have presented a CRS stack based workflow from time to depth. The central tool is the CRS stack which also provides the wavefield attributes. These attributes are the backbone of all modules of the workflow. The current processing sequence comprises the CRS stack, velocity model building by NIP-wave tomography, multiple suppression, prestack data enhancement, trace interpolation, and data regularization. Depth processing can be performed with any migration tool using the NIP-wave tomographic model as a starting point. The presented workflow also provides an alternative processing path for situations where conventional CMP processing is unsatisfactory. It is particularly advantageous for data with poor S/N ratio or low fold acquisitions. Similar to many other tools in seismic data processing its range of applicability is limited by the hyperbolic assumption. With a careful choice of apertures the lateral resolution of the images generated by the CRS workflow are similar to CMP processing results. In many cases, the vertical resolution is superior to CMP processing due to the non-stretch NMO correction property of CRS. Moreover, since the S/N of the images is higher compared to CMP processing, spectral whitening and similar tools lead to better vertical resolution.

Future modules of the workflow will allow to separate reflections from diffractions, leading to a separate diffraction processing. This procedure will comprise poststack velocity analysis and the localization of small scale heterogeneities and diffracting features in the subsurfaces like faults, tips and edges. This will guide a model-adopted choice of CRS apertures which will further improve the lateral resolution of the CRS processing.

ACKNOWLEDGMENTS

We thank the Applied Geophysics Team, University of Hamburg, for helpful discussion, particularly to Sergius Dell and Claudia Vanelle. We also appreciate many contributions to the work flow by the Wave Inversion Technology (WIT) research teams in Karlsruhe, Germany, and Campinas, Brazil. This work was partially supported by the WIT consortium and the University of Hamburg. We are grateful to Thomas Lüdmann, University of Hamburg, and DGMK (via WEG) for providing the field data.

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