PRESTACK DATA ENHANCEMENT BY PARTIAL TIME MIGRATION: A SUBSALT CASE STUDY

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ABSTRACT

The imaging of salt bodies poses a significant challenge in seismic data processing. Reflection events from below the salt are usually very weak in amplitude due to the strong impedance contrast between the salt and the surrounding sediments. We suggest to apply a method that combines the robustness of time migration with the data enhancement properties of multi-parameter stacking. Due to the latter property, it is particularly well suited for subsalt imaging. The presented method is based on the generation of partially time-migrated gathers, i.e., prestack data in the common scatterpoint domain, that are used as input for a subsequent stacking procedure. The results are kinematically equivalent to conventional prestack time migration results, but lead to better image quality because of the inherent prestack data enhancement capability. The application to a complex synthetic data set as well as to a field data set demonstrates a considerable improvement, not only in the presence of faults and salt boundaries, but also in the subsalt region.

INTRODUCTION

The imaging of salt bodies is a challenging endeavour in seismic data processing. The data quality below the salt is usually fairly low due to the strong impedance contrast between the salt and the surrounding sediments as well as due to the irregularity of their surfaces.

In order to achieve a first image, time migration is applied to the data. Prestack time migration (PreSTM) is a classical tool for subsurface imaging because it is fast, robust and rather insensitive to velocity model errors. The conventional time migration operator is described by a double square root (DSR) equation (see, e.g., Yilmaz, 2001). This type of operator implies a straight ray approximation using constant velocities. Assuming that lateral velocity variations are moderate, RMS velocities provide a suitable model. However, these are not generally available. Instead, stacking velocities are considered as a starting model. Since these depend on the inclination of reflectors, they need to be updated during further processing.

In practice, time migration is carried out for common-offset data (e.g., Ferber, 1994), corresponding to a 'partial' migration, which is followed by inverse normal moveout analysis. Bancroft et al. (1998) expanded the method of migration from multiple offset to the equivalent offset by reformulating the DSR operator into a single square root equation. They also gave a theoretical explanation for the generated gathers, which they introduced as common scatterpoint (CSP) gathers. In both methods, the partially migrated common-offset gathers are focused in a procedure similar to normal moveout (NMO), i.e., by performing a stack over the offsets.

This process does, however, not address the low signal amplitudes in a subsalt setting. To overcome this problem, Baykulov and Gajewski (2009) have recently introduced a method for prestack data enhancement based on a multi-parameter (MP) stack, and successfully applied it to improve the image quality below a salt plug in a field data set. Furthermore, Dell et al. (2012) suggested that the performance of a multi-parameter stack on the CSP, i.e., partially time-migrated prestack data, combines the robustness of time migration with the enhancement potential of MP methods.

In this work, we apply the partial time migration as well as a subsequent multi-parameter stack to show that it leads to considerable improvement of the image quality compared to conventional time migration. This is particularly recognisable in the subsalt region of the chosen data set.

After a brief introduction of conventional PreSTM, we describe and discuss the prestack partial time migration with subsequent MP processing. We then apply both methods to the complex synthetic Sigsbee 2A data using RMS as well as stacking velocities. Furthermore, we investigate the performance of the method on a marine field data set. The results demonstrate the superiority of the new method, in particular in the subsalt region.

THEORY

Conventional prestack time migration

The classic time migration operator in 2D describes diffraction traveltimes by the DSR equation,

$$t_D(t_0, m, h) = \sqrt{\frac{t_0^2}{4} + \frac{(m-h)^2}{v^2}} + \sqrt{\frac{t_0^2}{4} + \frac{(m+h)^2}{v^2}} \quad , \tag{1}$$

where h is the half source-receiver distance, i.e., the half offset, m is the midpoint displacement with respect to the considered CMP position, t_0 is the zero-offset (ZO) two-way traveltime, and v is the migration velocity.

Figure 1(a) shows the principle of PreSTM. The time migration is first performed for each (half) offset h individually by summing all traces along the curve t_D for the according midpoint displacement. The summation result is assigned to $(m = 0, h, t_0)$. In a second step, the contributions for each (h, t_0) are summed into the apex of the operator for the ZO case, i.e., $(m = 0, h = 0, t_0)$.

Partial time migration

In order to preserve the moveout during the partial time migration, we parametrise the DSR operator with the apex of the diffraction traveltime instead of t_0 for each offset (Dell et al., 2012),

$$t_{apex} = \sqrt{t_0^2 + \frac{4h^2}{v^2}} \quad . \tag{2}$$

After substituting Equation (2) into Equation (1) and some simple algebra we obtain the partial time migration operator,

$$t_D(t_{apex}, m, h) = \sqrt{\frac{t_{apex}^2}{4} + \frac{m(m-2h)}{v^2}} + \sqrt{\frac{t_{apex}^2}{4} + \frac{m(m+2h)}{v^2}} \quad . \tag{3}$$

Note that both operators provide the same diffraction response. The difference lies only in the parametrisation. The advantage Equation (3) has over (1) is the preservation of the moveout in the data, which is demonstrated in Figure 1(b).

Multi-parameter stack of the CSP prestack data

In the techniques suggested by Ferber (1994) and Bancroft et al. (1998), these prestack traces are stacked along the (half) offsets by taking the moveout into account. Our method does not follow that approach. Instead, we generate new prestack traces for all midpoints, as pointed out by Figure 1(c). These constitute the prestack data in the CSP domain.

While Ferber (1994) and Bancroft et al. (1998) thus apply a single parameter stack over offsets, we suggest to apply a multi-parameter stack over offsets as well as midpoints. By doing so, we achieve the desired prestack data enhancement because the number of contributing traces is much higher than for the single parameter stack over h. Examples for such multi-parameter stacking operators are the common reflection surface stack (CRS, Müller, 1999), implicit CRS operator (i-CRS, Vanelle et al., 2010), multifocusing (MF,

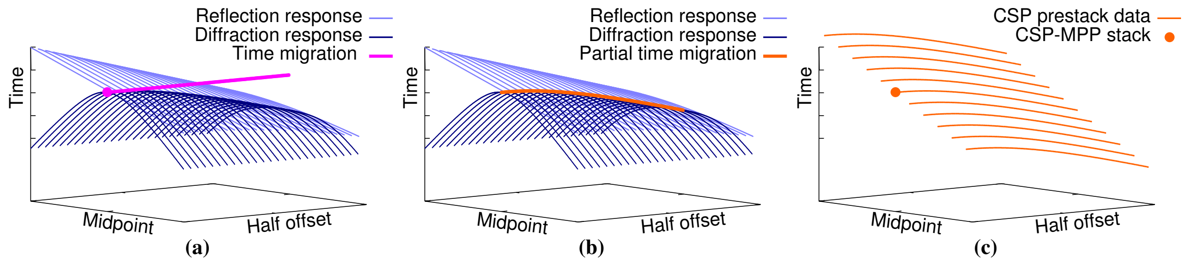

Figure 1: Comparison of (a) conventional prestack time migration, (b) partial time migration, (c) multi-parameter stacked CSP data.

Gelchinksy et al., 1999), and shifted hyperbola (de Bazelaire, 1988). The output of the MP stack is then, like for the time migration, assigned to the point (t_0, m, h), as shown in Figure 1(c).

If the same parameters, i.e., velocities and apertures, are applied, both conventional PreSTM and CSP-MP stack are kinematically equivalent. However, due to the data enhancement of the latter method, it results in a higher signal-to-noise level and thus better image quality.

In the following section, we compare both methods for the complex synthetic Sigsbee 2A data and a marine field data set.

SYNTHETIC DATA EXAMPLE

To verify our method, we have applied it to the complex synthetic acoustic Sigsbee 2A data set. The density is constant. The velocity model that contains a large irregularly-shaped salt body is shown in Figure 2. Random noise with a signal-to-noise ratio of eight was added to the data. Figure 3 shows the CMP stack of the data, in which we can recognise several weak events below the salt body.

In a first test, we used RMS velocities provided with the data set to perform conventional PreSTM as well as for the generation of the partially time-migrated CSP gathers. On the latter, we executed a multi-parameter stack of the CRS type (Mann, 2002) in order to obtain the final section. Figure 4 shows a conventional PreSTM section of the data with RMS velocities and Figure 5 shows the result of the MP-stacked partially time-migrated gathers. Note that we have used the same parameters, e.g. velocities and apertures, for both methods. We find that the overall image quality of the suggested method is better than that of the conventional PreSTM technique.

However, RMS velocities are usually not available for field data. Hence, we tested our method by using stacking velocities estimated from a CRS stack of the original data, and repeated the previously-described procedure with these velocities instead of the RMS velocities. Again, the same parameter sets were used. Figures 6 and 7 show the respective results. Again, we recognise the better image quality of the CSP-MP stack over the PreSTM result.

For a more detailed investigation of the properties of the two methods, we have chosen three regions with different structural features, as indicated by Figure 8. The first close-up in Figure 9 reveals that the CSP-MP stack leads to better continuity of reflections and higher resolution of faults and diffractions. Figure 10 shows the left part of the salt structure, a region with rugged topography. Again, we find considerably higher resolution in the CSP-MP image, not only at the top of salt but also and particularly at the bottom of the salt. Finally, in Figure 11, we recognise a considerable enhancement of the events below the salt.

FIELD DATA EXAMPLE

For a second and more realistic investigation, we have applied the method to a marine data set. The seismic data was acquired in the Levantine basin in the south-eastern Mediterranean Sea. The Levantine Basin has a complex seismic stratigraphy of the basinal succession. The deformation patterns of the intra-evaporitic sequences include folds and thrust faulting, which gives evidence for extensive salt tectonics and shortening during the depositional phase. Post-depositional gravity gliding caused salt rollers in the

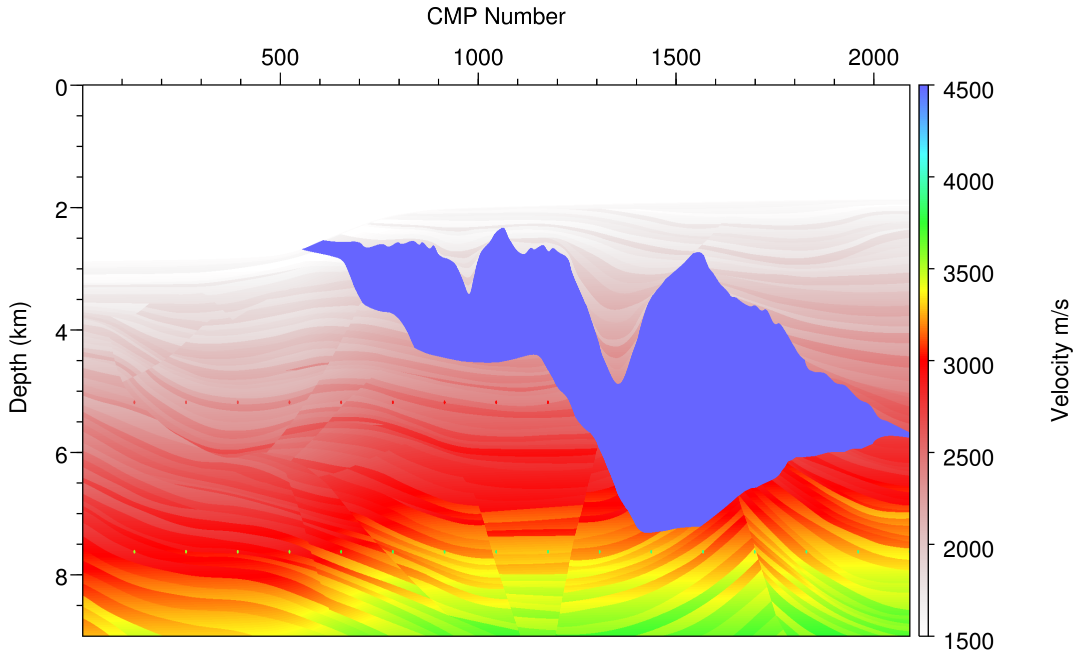

Figure 2: Velocity model for the Sigsbee 2A data, which contains a large irregularly-shaped salt body.

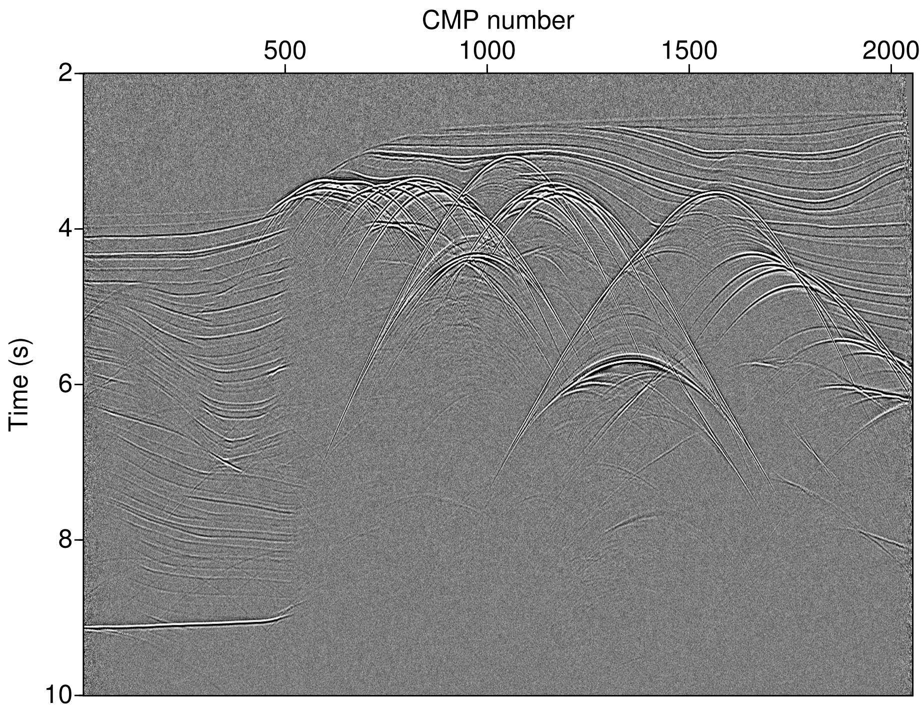

Figure 3: CMP-stacked section of the Sigsbee 2A data with random noise. Several weak events are present below the salt.

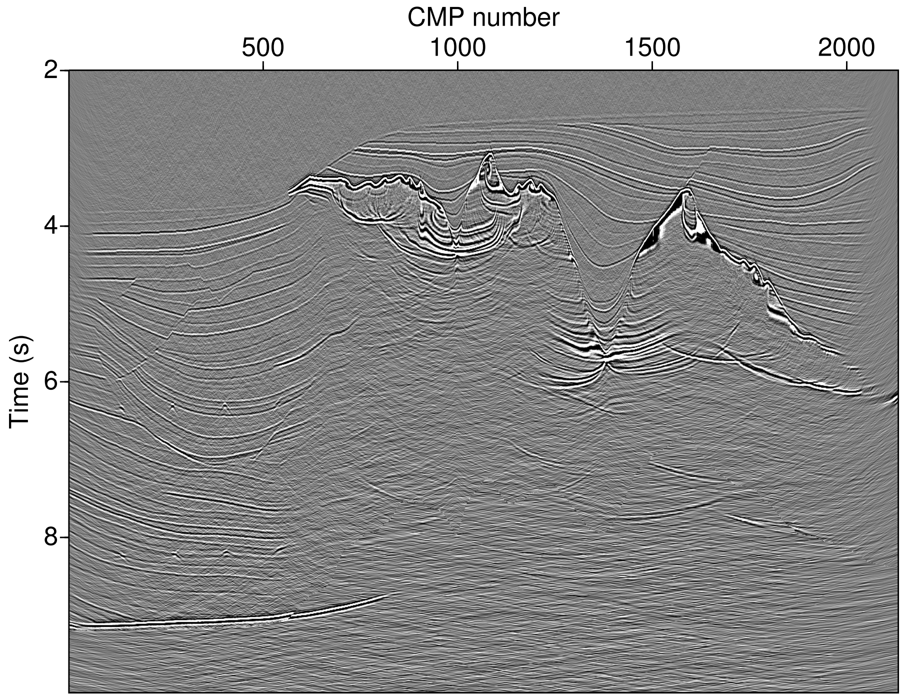

Figure 4: Prestack time-migrated section of the Sigsbee 2A data with random noise using RMS velocities provided with the data set.

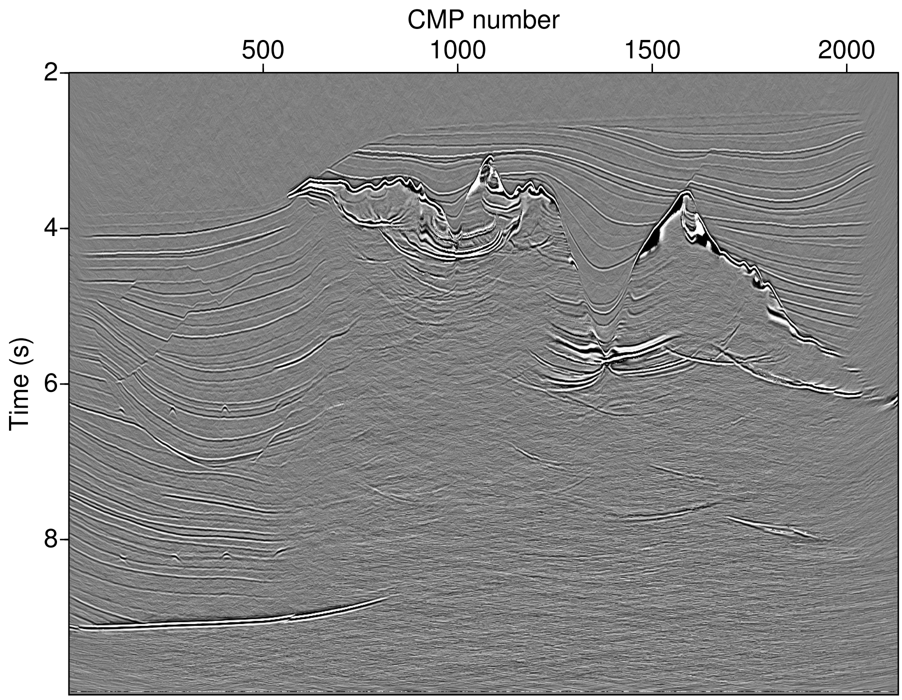

Figure 5: CSP-MP-stacked section of the Sigsbee 2A data with random noise using RMS velocities provided with the data set.

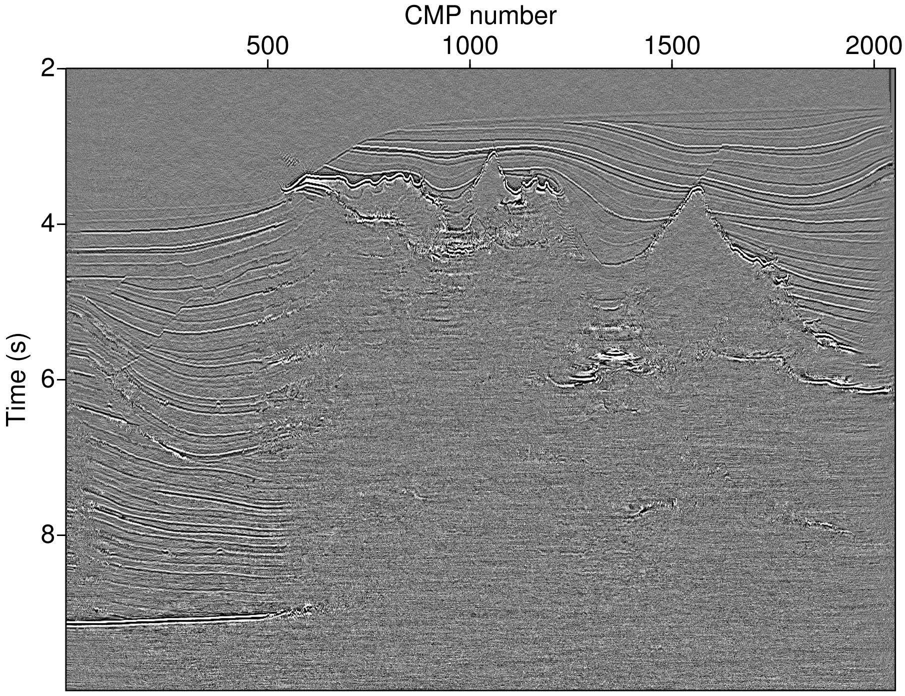

Figure 6: Prestack time-migrated section of the Sigsbee 2A data using stacking velocities determined from a CRS stack of the data.

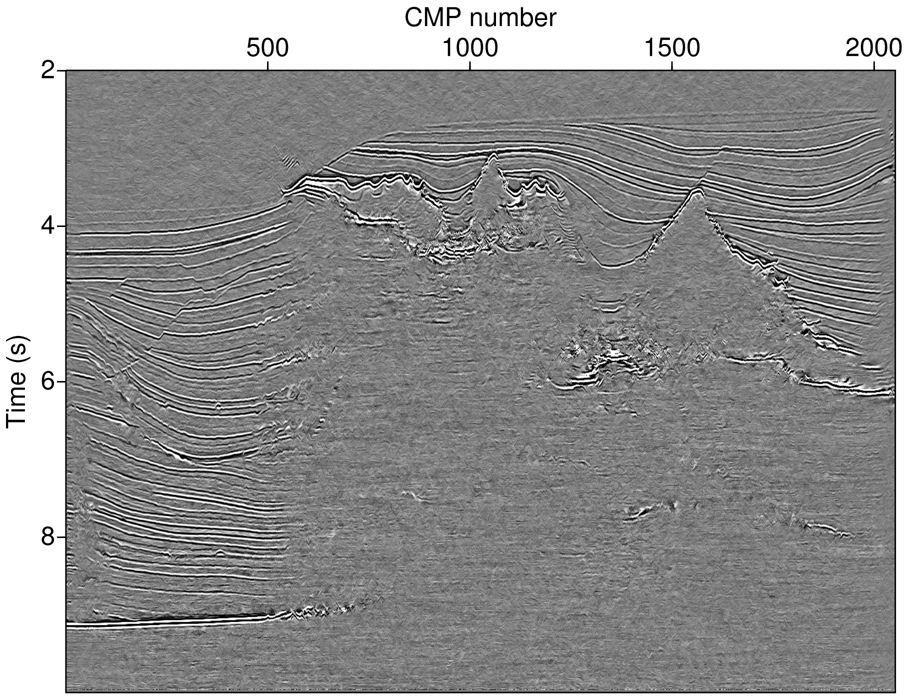

Figure 7: CSP-MP-stacked section of the Sigsbee 2A data using stacking velocities determined from a CRS stack of the data.

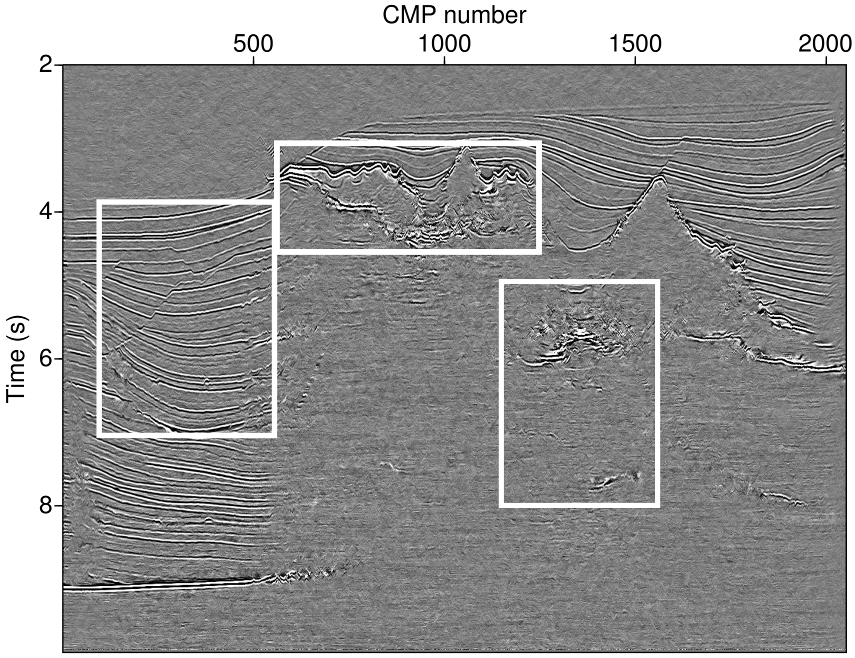

Figure 8: Sigsbee 2A: selection of regions with different structural features for a detailed investigation (see Figures 9, 10 and 11).

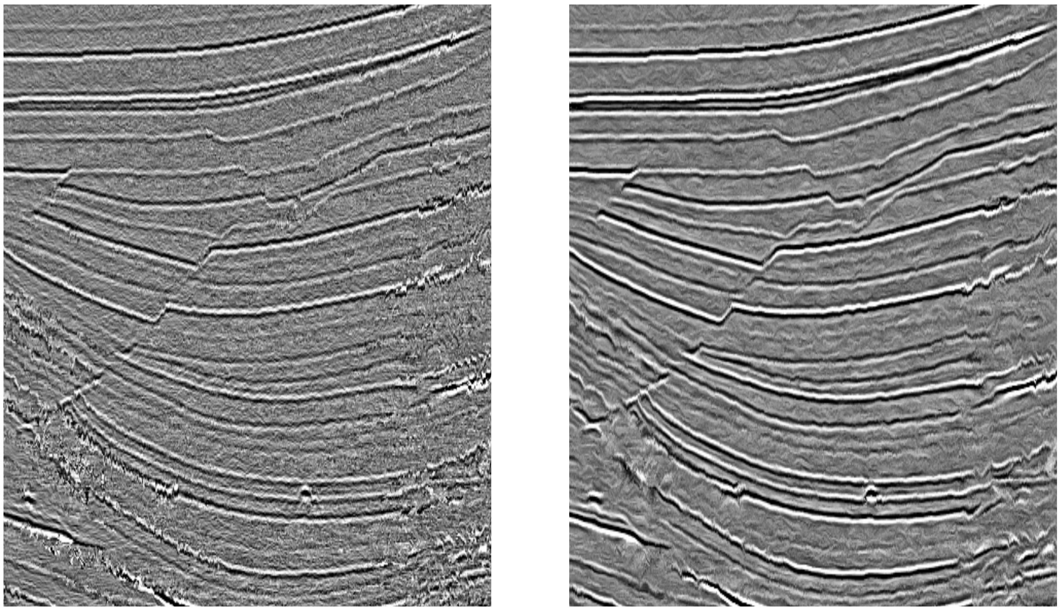

Figure 9: Close-up: layering and fractures in the Sigsbee 2A example. Left: PreSTM result; right: CSP-MP result. We observe higher resolution, better reflector continuity, and more clearly-defined faults and diffractions in the CSP-MP section. Furthermore, the CSP-MP section shows a higher signal-to-noise ratio.

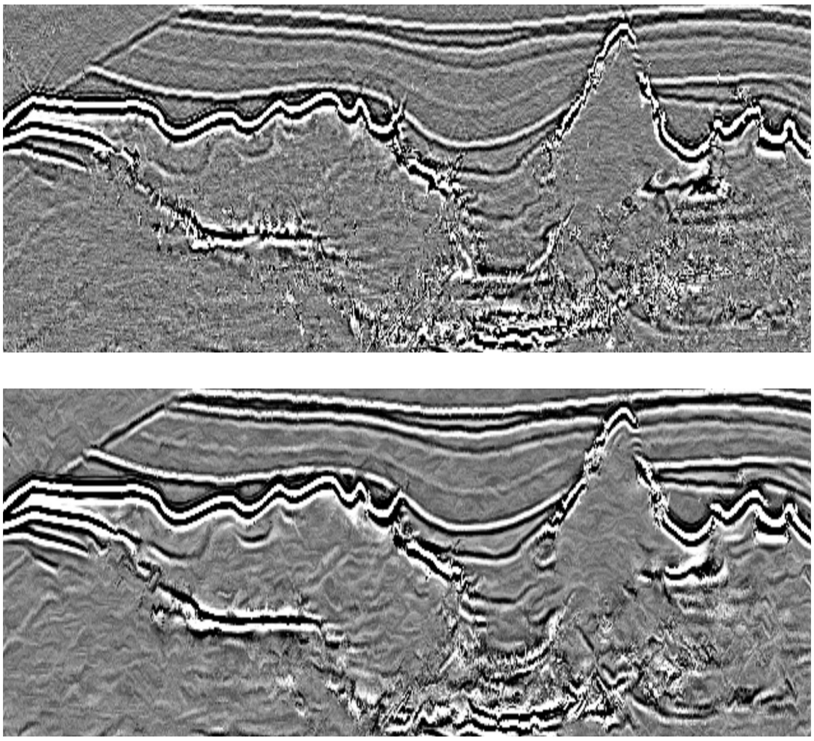

Figure 10: Close-up: top of salt in the Sigsbee 2A example. Top: PreSTM result; bottom: CSP-MP result. In addition to a better signal-to-noise level, we obtain higher resolution and a better definition not only of the top of the salt but also of its bottom.

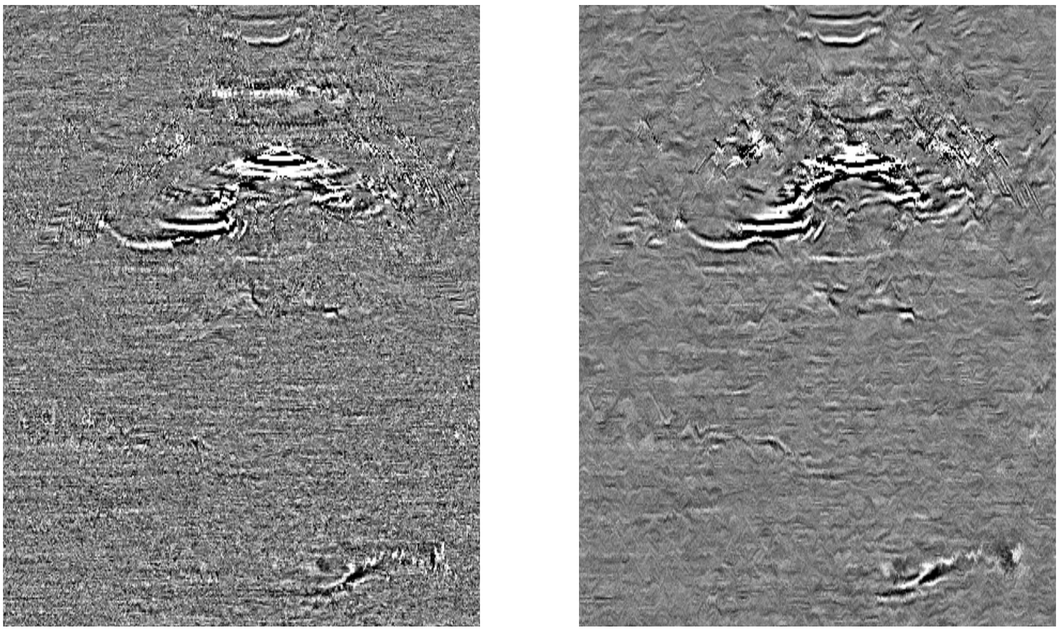

Figure 11: Close-up: sub-salt in the Sigsbee 2A example. Left: PreSTM result; right: CSP-MP result. We obtain a significant enhancement for the subsalt region in the CSP-MP section compared to the PreSTM section.

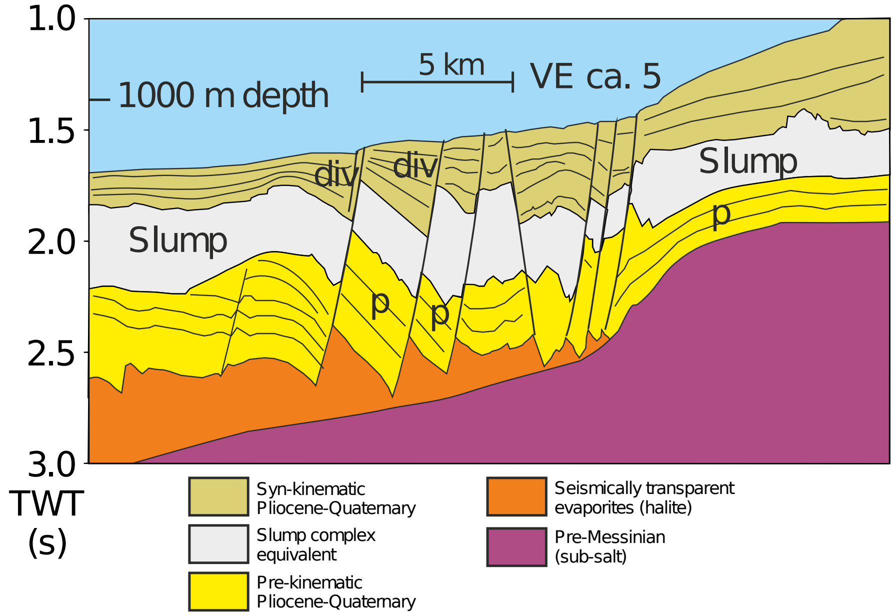

Figure 12: Geologic setting for the marine field data example (Netzeband et al., 2006).

extensional marginal domain, compressional folds, and faults within the Levantine basin (see Figure 12 and Netzeband et al., 2006).

A 2D acquisition with a shot spacing of 25 m and a receiver spacing of 12.5 m was performed. The minimum offset is 150 m, and the maximum offset is 7338 m. The record length is 8 s with 4 ms sample rate. We have chosen a subset of the data consisting of 2000 CMP gathers with a total line length of 15 km until 5 seconds for our investigation.

We applied stacking velocities estimated from a CRS stack of the original data, and repeated the previously-described procedure with these velocities to to compare the results of the conventional PreSTM and CSP-MP methods. Note that we have again used the same parameters, e.g. velocities and apertures, for both methods. Figure 13 shows the CMP stack of the original data. We can identify many diffractions caused by the salt rollers in the left part. Figure 14 and 15 show the PreSTM and CSP-MP results. As in the previous example, we recognise the better image quality of the CSP-MP stack compared to the PreSTM result.

A close-up on the salt rollers (see Figure 16 for the excerpted part) in Figure 17 reveals that the CSP-MP stack leads to better focused diffractions and better-defined salt flanks. Again, the subsalt region exhibits clearer events.

CONCLUSIONS AND OUTLOOK

In this work, we have combined a partial time migration method with prestack data enhancement for subsalt imaging. The method is based on the DSR equation parametrised in terms of the diffraction apex time. This operator is applied in a first step to generate new prestack gathers in the CSP domain. A subsequent multi-parameter stack is then applied to these data, which leads to a considerable enhancement of the data quality.

Application to the complex synthetic Sigsbee 2A example and field data shows that the CSP-MP results are superior to those obtained by conventional prestack time migration. They show a generally clearer definition of faults and better continuity of reflections. Furthermore, they lead to considerable improvement of the image quality not only at the bottom of salt, but also in subsalt regions.

In the future, we intend to no longer rely on classical stacking velocities as models for our method since these still depend on the reflector inclination. Currently, this dependency has to be eliminated by migration velocity analysis, an iterative procedure that requires repeated migration steps to update the model. In

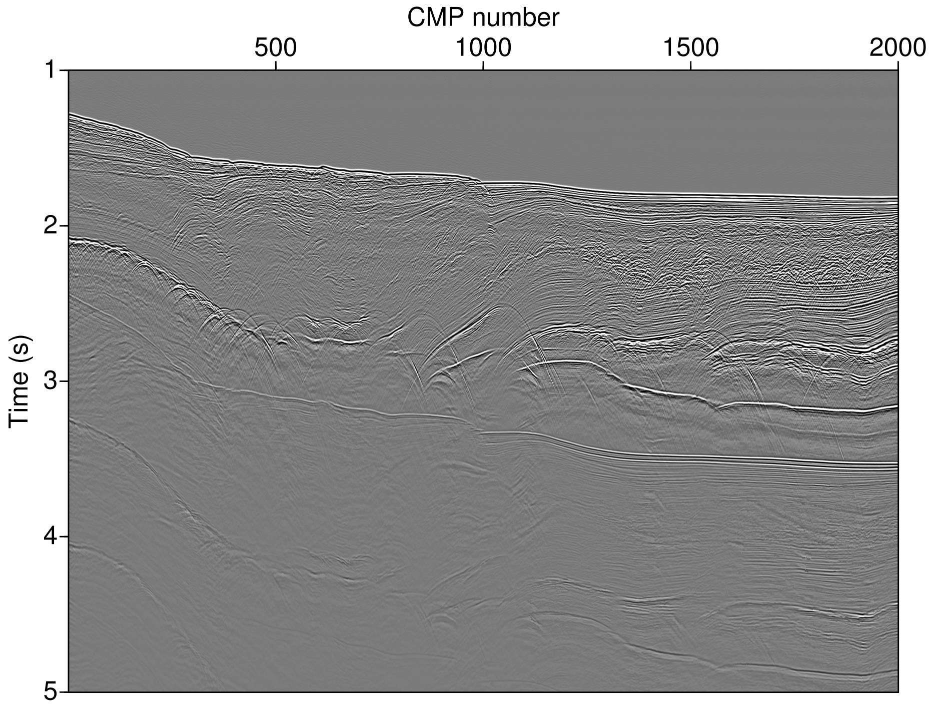

Figure 13: CMP-stacked section of the marine field data. The top of the salt is at 2.6 s at CMP 2000, the base of the salt at 3.2 s.

order to avoid this procedure, a new expression for migration velocities that are independent of the dip of a reflector has recently been introduced. Details can be found in Bobsin (2014) and Bobsin et al. (2014). We expect that employing these velocities will lead to yet another improvement of the migrated images.

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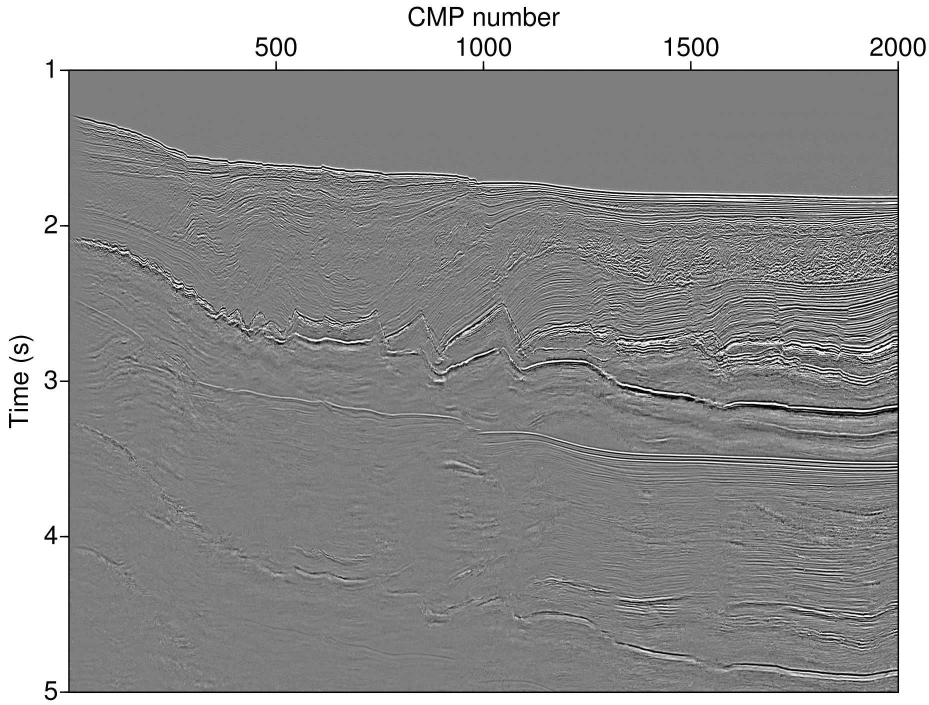

Figure 14: Prestack time-migrated section of the marine field data using stacking velocities determined from a CRS stack of the data.

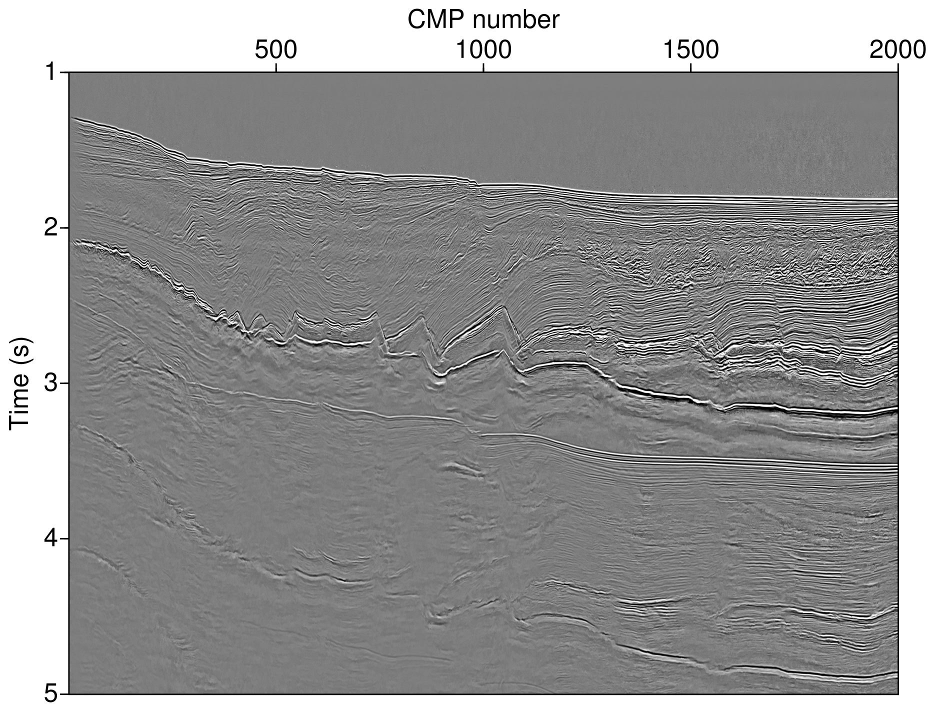

Figure 15: CSP-MP-stacked section of the field marine data using stacking velocities determined from a CRS stack of the data.

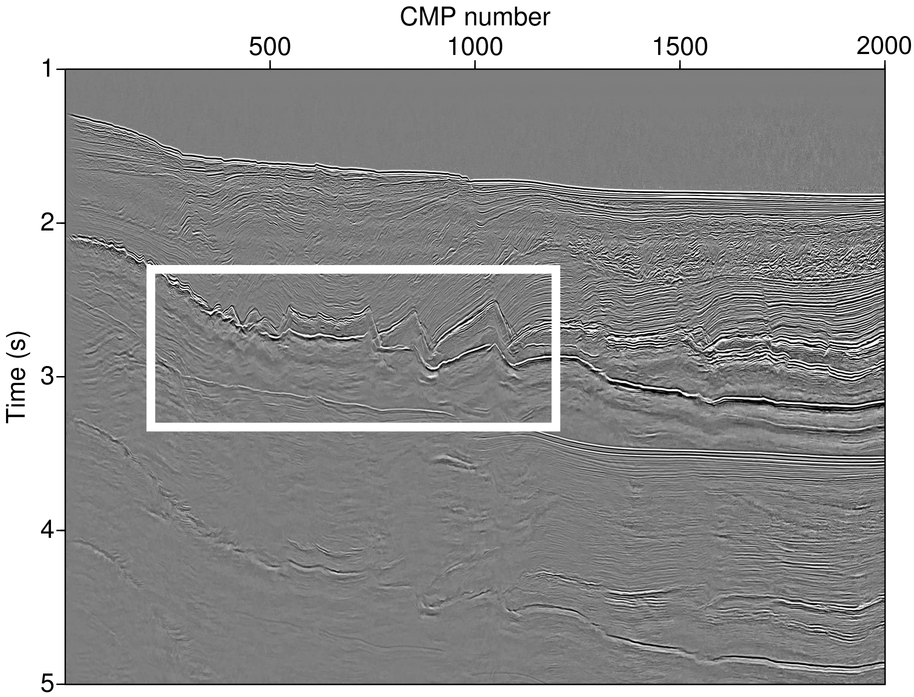

Figure 16: The selected region for a detailed comparison of the PreSTM and CSP-MP stack results for the marine field data set (see Figure 17).

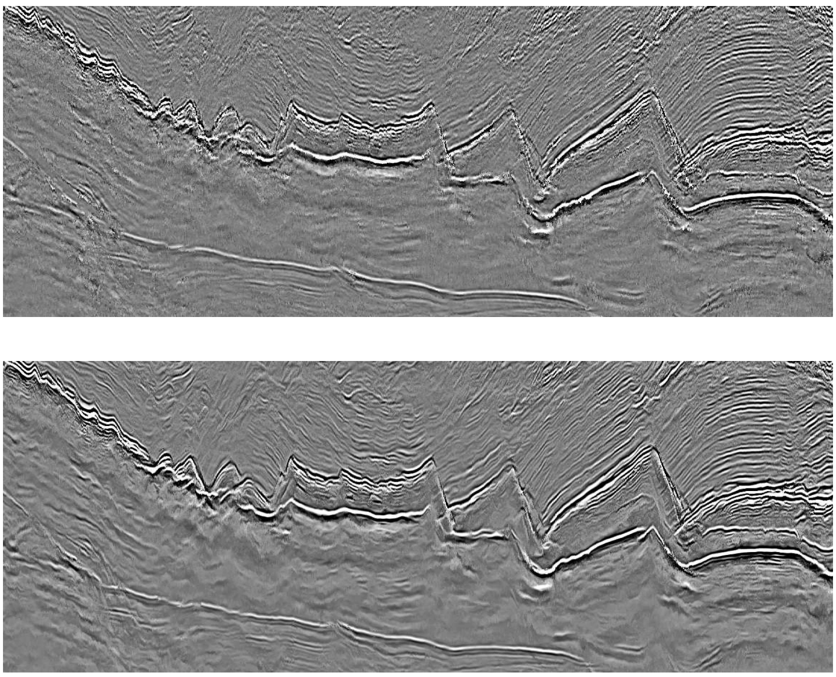

Figure 17: Close-up: salt rollers in the marine field data example. Top: PreSTM result; bottom: CSP-MP result. The CSP-MP section exhibits higher resolution, better-defined salt flanks, and more information at the bottom of the salt.

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