Preconditioning of 2D land seismic data using a combination of MPFI and CRS methods

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Abstract

Multidimensional regularization and interpolation steps of seismic data are essential to many processes, such as migration, inversion and quantitative interpretation. The Common Reflection Surface (CRS) stack method can also be used to regularize and interpolate prestack seismic data. CRS-based reconstruction requires the determination or extraction of the kinematic wavefield attributes (CRS attributes) directly from the reflection multi-coverage data. Despite using global optimization to obtain more accurate CRS attributes, on onshore data due to its poor quality, irregular spatial sampling with gaps caused by missed shots and missing traces, these attributes can be related to artifacts or false events, which can corrupt the continuity of the reflection events. To overcome this problem, we propose a processing flow that involves the Matching Pursuit Fourier Interpolation (MPFI) method to reconstruct the prestack data before estimating the CRS attributes; that is, they are determined from the reconstructed data. We apply these two methods in a real vintage low-quality and low fold data from the onshore Tatucu Brazilian basin. The reconstructed data obtained by combining MPFI+CRS show significant improvements compared to the reconstructed data using the two algorithms separately. Prestack time migration images also offer an improved quality using the proposed processing flow.

Introduction

Seismic data reconstruction estimates missing traces, filling gaps between shots and improving the signal-to-noise ratio (SNR) of seismic records (Schonewille et al., 2009). Regularization and interpolation methods make datasets with a homogenized fold and regular distribution of azimuths (Hunt et al., 2010). Currently, several multidimensional methods for the reconstruction of seismic data are available. The popular methods are based on Fourier transform, such as Minimum Weighted Norm Interpolation (MWNI) (Liu and Sacchi, 2004), Projection Onto Convex Sets (POCS) (Abma and Kabir, 2006), Anti-Leakage Fourier Transform (ALFT) (Xu et al., 2005) and MPFI (Nguyen and Winnett, 2011). Trad (2014) pointed out that algorithms based on grid data, such as MWNI and POCS, are faster than those that adopt actual spatial coordinates, as MPFI and ALFT. However, the latter algorithms are simple to implement and have better results on severe noise-contaminated data.

Some authors as Hoecht et al. (2009); Baykulov and Gajewski (2009); Xie and Gajewski (2017); Garabito (2021) adopted the CRS stack operator for prestack data regularization and interpolation recently. The CRS stack method was introduced to estimate zero-offset (ZO) stacked sections (Jäger et al., 2001; Garabito et al., 2001). In general, CRS-based interpolation produces prestack data with high SNR and enhanced reflections. The CRS stack method is based on a second-order approximation of the reflection times and depends on kinematic wavefield attributes. Therefore, it incorporates an approximation of wave propagation in the data reconstruction, contrary to the Fourier-based methods, which are inherently signal processing tools. Hoecht et al. (2009) introduced two interpolation schemes, target-oriented and operator-oriented methods, using the finite offset (FO) CRS stack operator. Similarly, Baykulov and Gajewski (2009) proposed a 2D prestack data interpolation and enhancement algorithm called partial CRS stack, which uses the ZO CRS stacking operator. The algorithm was extended to 3D data by Xie and Gajewski (2017). Garabito (2021) introduces a new CRS-based method for interpolation and enhancement of prestack data by applying the migration and demigration operations using the CRS stacking operator.

A comparison of the CRS-based interpolation with the well-known MWNI method by applying to 2D land seismic data was presented in Garabito et al. (2017), in which the post-stack migrated image of the data by CRS-based interpolation is much better than the MWNI. Garabito et al. (2020) also present a comparison to the CRS-based interpolation with the MWNI and MPFI Fourier-based Interpolation methods. They showed that MPFI has better results than MWNI and, as expected, the CRS has the best result. In the works cited above, it was observed that the CRS-based interpolation method produces artifacts or false events that contaminate the reconstructed data and, consequently, the migrated images. This usually happens because of the poor quality of the land data (noisy), the coarse spatial sampling, and the gaps along the seismic line produced by the missed shots and traces can impair the accuracy and reliability of the CRS attributes, which define the stacking operator. The accuracy of the CRS attributes also depends on the optimization strategy used, and for this reason, a global optimization algorithm is commonly used to search for the optimal CRS attributes from prestack data.

In this work, to overcome the deficiencies of the CRS-based interpolation method, we propose a workflow for prestack data reconstruction combining with the MPFI interpolation method; that is, the CRS attributes will be determined from the prestack data reconstructed by the MPFI interpolation. The CRS attributes defined in this way can be used to interpolate and regularize the original prestack data or to apply denoising to the previously reconstructed data by the MPFI method. In this work, we present the application of these attributes to denoise the reconstructed prestack land seismic data of the Tacutu Brazilian basin. To demonstrate the efficiency of this combined approach, we will compare the reconstructed datasets obtained with the proposed processing flow and with the two interpolation methods applied separately.

Matching Pursuit Fourier Interpolation (MPFI)

The input data for MPFI is used with its real coordinates; that is, it does not need to be previously binned for a regular grid. The flexibility of MPFI to reconstruct the input data for any desired grid is a major attraction. Because MPFI uses Nonuniform DFT (NDFT) in each iteration, it becomes computationally expensive in multidimensional interpolation, a significant disadvantage about algorithms that use FFT, as the MWNI and POCS. Assuming that few Fourier components represent regularly sampled data, that is, sparse representation of data in the Fourier domain, the MPFI uses a greedy algorithm to solve one wavenumber per iteration, increasing flexibility for noise attenuation. For each frequency slice of the frequency-space (f-x) domain, they transform to frequency-wavenumber (f-k) domain, find the maximum energy Fourier coefficients, apply the matching pursuit estimated model, iteratively, and back to f-x domain.

First, the data is transformed from the time-space (t-x) domain to the f-x domain by the forward 1D FFT in the time dimension. The procedure to be performed by the MPFI algorithm can be described as follows:

1 Initialize all components of the Fourier optimal spectrum equal to zero.

2 Compute the Fourier spectrum of the input data using the forward NDFT.

3 Find the wavenumber corresponding to the highest energy coefficient and compute the Fourier coefficient corresponding to this wavenumber.

4 Update the input data by subtracting the contribution of the estimated optimally coefficient.

5 Repeat steps 2 to 4 until the residual input data to be less than a defined maximum error or until the algorithm reaches the maximum number of iterations.

An inverse NDFT of the Fourier optimal spectrum is applied to back to the f-x domain. After going through all the frequencies, the reconstructed data can be back to the t-x domain using the inverse 1D FFT in the time dimension. In general, MPFI and all Fourier-based reconstruction algorithms are applied on spatial windows to minimize the number of dips (wavenumber) that the algorithm needs to iteratively retrieved (Stanton and Sacchi, 2013).

CRS-based interpolation

The CRS stack method was introduced to simulate ZO stacked data from multi-coverage seismic data and, as by-products, three kinematic wavefield attributes sections can be applied in several seismic reflection problems. However, one of the most critical applications of the kinematic attributes and CRS stacking operator is in the interpolation and enhancement of prestack data as shown in Hoecht et al. (2009); Garabito (2018); Garabito et al. (2020). The kinematic wavefield attributes are the ZO central ray's emergence angle and the normal incidence point (NIP) wave and normal wave curvatures. Using these three kinematic attributes is determined by employing global optimization using as objective function the coherence measure (semblance) of the seismic signal in the prestack data. Once these kinematic attributes are known for a given time sample point in the ZO plane, the CRS stacking surface is constructed. To simulate a ZO stacked section with the CRS stack method, the amplitudes of the seismic traces are summed, and the result is placed at the evaluated point.

The reconstruction of prestack data based on the CRS stack method is applied in the time domain and in the midpoint-offset space. The interpolation and regularization algorithm introduced by Baykulov and Gajewski (2009) used the CRS operator locally and centred on the target trace located in the midpoint-offset space to sum the amplitudes of neighbouring traces and build the interpolated trace. Related to the target point, we can identify in the CRS stack surface the CMP traveltime curve, which corresponds to the central CMP curve of the entire CRS stack surface. This CMP travel time curve is necessary because it relates the partial CRS stacking surface to the ZO plane CRS attributes.

The CRS-based interpolation algorithm can be summarized as:

1 Determination of the three CRS attributes from prestack data.

2 For a target trace in the midpoint-offset space and a given time sample, define the partial CRS stack operator.

3 Sum of the amplitudes over the partial CRS stack operator and place the result to the point located in the center of the stacking operator.

4 Repeat the operation from step 3 for the entire target trace.

5 Repeating steps 2 to 4 for all traces with constant offset of the seismic line, a common-offset (CO) gather is interpolated and enhanced.

Applying the algorithm described above, we can reconstruct all the prestack datasets in CO gathers. Similarly, other seismic configurations gather, such as common-shot, can also be restored. Note that the partial CRS stack, the operator size or aperture can define the degree of enhancement of the reconstructed seismic signal.

MPFI interpolation + CRS denoising

As mentioned earlier, to overcome the limitations or errors of CRS-based interpolation, we propose combining MPFI and CRS-based interpolation methods. Because our final aim is to obtain the best reconstructed and enhanced prestack data, we will simultaneously determine the three CRS attributes by using a global optimization algorithm from interpolated and regularized prestack data with the MPFI method. We will use these attributes and the partial CRS stack operator for denoising the reconstructed data. Below are the main steps of the proposed workflow:

1. Apply the MPFI algorithm to interpolate and regularize the prestack input data.
2. Determination of the three CRS attributes from reconstructed prestack data by MPFI.
3. Denoising of the reconstructed prestack data by MPFI using the three CRS attributes and partial CRS stack operator.

Application in Tacutu land seismic data

The dataset is a seismic line 050-RL-090 of a land survey carried out in the Tacutu onshore basin, northern Brazil. The acquisition array is asymmetrical split-spread with minimum and maximum source-receiver offset of 150 and 2500 meters, respectively, each shot arrays with 96 receivers stations. The nominal intervals between sources and receivers are 200 and 50 meters, respectively. The recording time is 4 s with a sampling interval of 4 ms. This data has poor quality and a low nominal fold of 12 traces per CMP. The following processing flow was applied before interpolation and regularization process: 1) geometry; 2) trace editing; 3) field static corrections; 4) spherical divergence compensation; 5) coherent noise attenuation; 6) deconvolution; 7) velocity analysis, and 8) residual static correction. The data resulting from this pre-processing is called the original data. Figure 1(a) shows the common-shots gathers of three consecutive shots extracted from the original data, where the central shot is missing. The data quality is poor and has a low SNR, where reflection events are blurred and obscured by noise.

The MPFI reconstruction method was applied in shot-receiver coordinates. The choice of these reconstruction coordinates for the Fourier based interpolation is due to the low fold in the CMPs. The data were split into seven (7) spatial windows to ensure a better quality of Fourier interpolation algorithms. The total number of shots in each window and the number of shots missing in each window, between brackets, are 30(2), 23(1), 25(2), 27(5), 25(0), 26(3) and 30(3), respectively. Totalling 170 shots present, where it is desired to interpolate for a geometry with 186 shots. The data regularly sampled must have 101 receiver stations. Starting from 15489 live traces, on the parameters already defined, arrive at 18786 traces. The Fourier support used in the inversion consists of 512 coefficients in each spatial dimension for each spatial window. After reconstruction, all the parts were put together to form the reconstructed prestack data. Before using Fourier-based reconstruction, the NMO correction is applied to the data to minimize curvature in the offset axis coordinate (Trad, 2014). Figure 1(b) shows the reconstructed common-shot gathers using the MPFI method, where the missed traces and the central shot gather were interpolated. This result shows a significant improvement, where reflection events are partially visible.

We also apply the CRS-based interpolation to the same processed data. Initially, the three CRS attributes are extracted simultaneously from the prestack original data by using a global optimization as in Garabito et al. (2012). These attributes and the CRS stacking operator are used to regularize and interpolate the data using the partial CRS stack algorithm (Baykulov and Gajewski, 2009). As mentioned before, it is applied in the time domain and in the midpoint-offset coordinates. Note that CRS-based reconstruction does not require NMO correction and data windowing. Figure 1(c) shows the reconstructed common-shot gathers by the CRS-based interpolation. This result shows a significant improvement, where the reflection events appear surprisingly resolved and with strong amplitudes. The SNR also increases. However, we can also observe some noise in the reconstructed shot gathers, blurring the shallow events and as small linear events with different dips. The MPFI and CRS-based reconstruction algorithms interpolated the missed traces and shots, but as we observed, the MPFI offers lower quality results than the CRS-based interpolation and it has some noise and artifacts.

Coherent noise can also be generated in parts where data are missing and at the edges of the seismic line. Since the search for CRS attributes is based on an automatic prestack data coherence measure, some coherent noises can be included as events in the reconstructed data. We applied the search for CRS attributes to the reconstructed data by the MPFI method to avoid or mitigate these noises. We use the same global optimization algorithm to search for CRS attributes and the same processing parameters used for regularization and interpolation of the original input data by CRS to denoising the MPFI reconstructed data. We emphasize that in the MPFI+CRS method, the input data to search for CRS attributes is output from the MPFI reconstruction. These CRS attributes are used to denoise the MPFI reconstructed data, applying the partial CRS stack operator. Figure 1(d) shows the reconstructed shot gathers by the proposed workflow (MPFI+CRS) with a significant improvement in shallow events and mainly without the linear noise.

We applied Kirchhoff prestack time migration (PSTM) to evaluate the reconstruction quality of all datasets, using the same velocity model and migration parameters for a fair comparison. Figure 2(a) shows the original data PSTM image, which, in general, is noisy and has poor continuity of reflection events. The shallow part of the image shows an intense noise, interrupting shallow reflection events. The PSTM image obtained from the reconstructed data by MPFI (Fig. 2(b)), in general, also has low quality but slightly improves reflector continuity of the reflection events in the middle and deeper parts of the image. Figure 2(c) shows the PSTM image obtained from the reconstructed data by CRS-based interpolation in the original data. As expected, this result shows significant improvement, with dramatically increased SNR and improved continuity of reflection events, especially in the central and deeper parts. However, we can see that the shallow part has several problems and creates artifacts with strong amplitudes that interrupt the continuity of shallow reflections. Figure 2(d) shows the PSTM image obtained from the reconstructed data by MPFI+CRS proposed workflow. We can observe an improvement in the continuity of shallow reflectors. In general, Figure 2(d) is cleaner and has higher quality because the continuity of the reflectors has been improved even in the deepest parts, and migration noise artifacts are also attenuated.

Conclusions

We have successfully combined two well-known interpolation methods for prestack data reconstruction: the Fourier-based MPFI interpolation and the CRS-based interpolation.

We show that the independent application of each method does not produce satisfactory results. The MPFI method slightly improves the quality of the regularized data and also of the migrated image. CRS-based interpolation produces results with a high SNR and enhanced reflection events but creates false or noisy events that contaminate the prestack data and the migrated image, interrupting mainly the shallow reflections.

The application in real data from the Tacutu basin of the proposed approach, combining the two interpolation methods, provides high-quality results. The coherent false events were attenuated, and the artifacts caused in the migrated image have also been attenuated. We show that the proposed workflow is the best alternative for reprocessing old seismic data, mainly with low quality (noise), coarse spatial sampling, and low fold.

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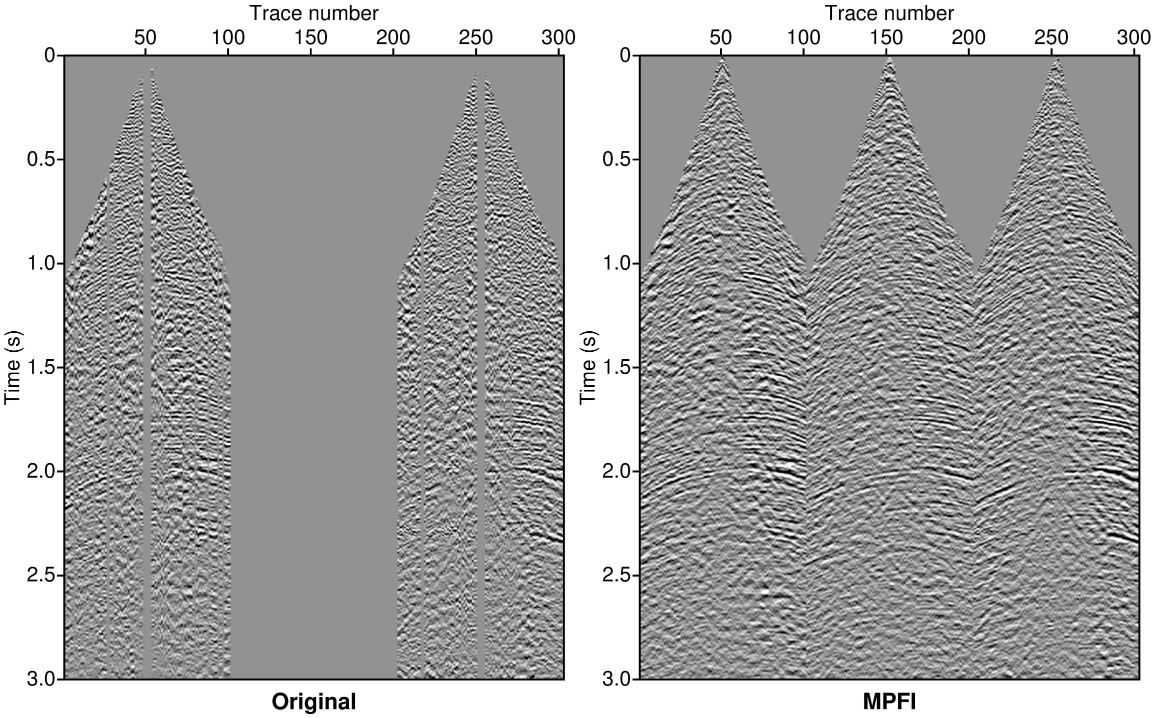
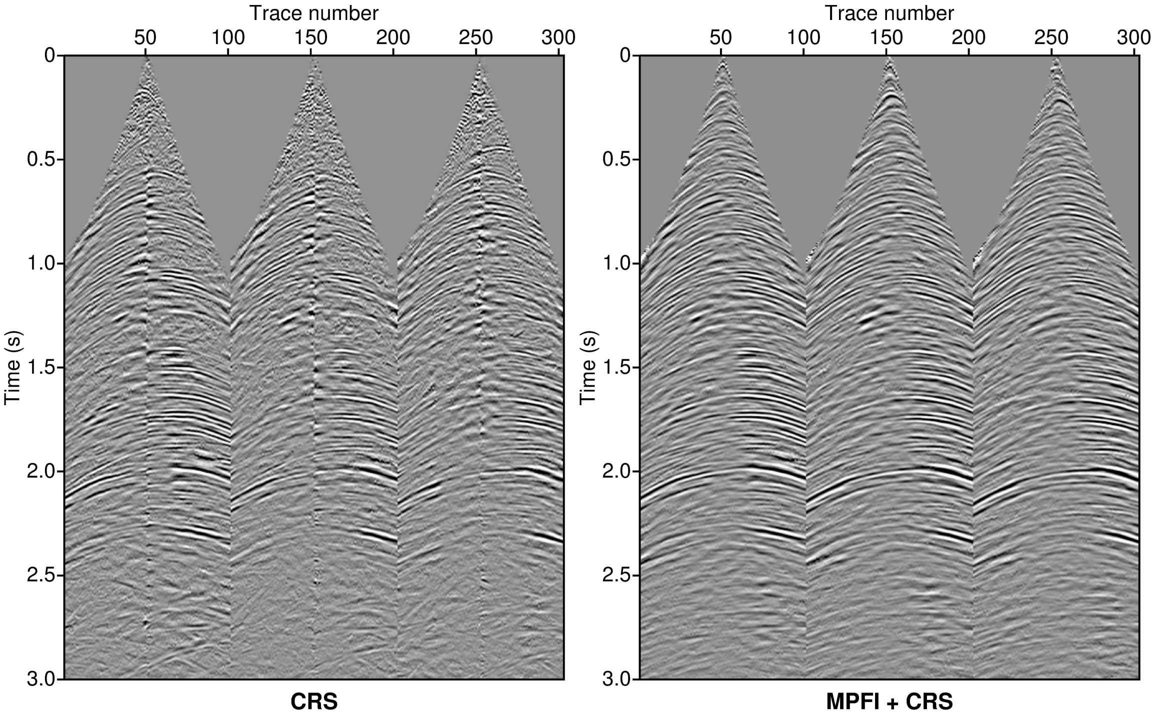


Original

(a)

MPFI

(b)



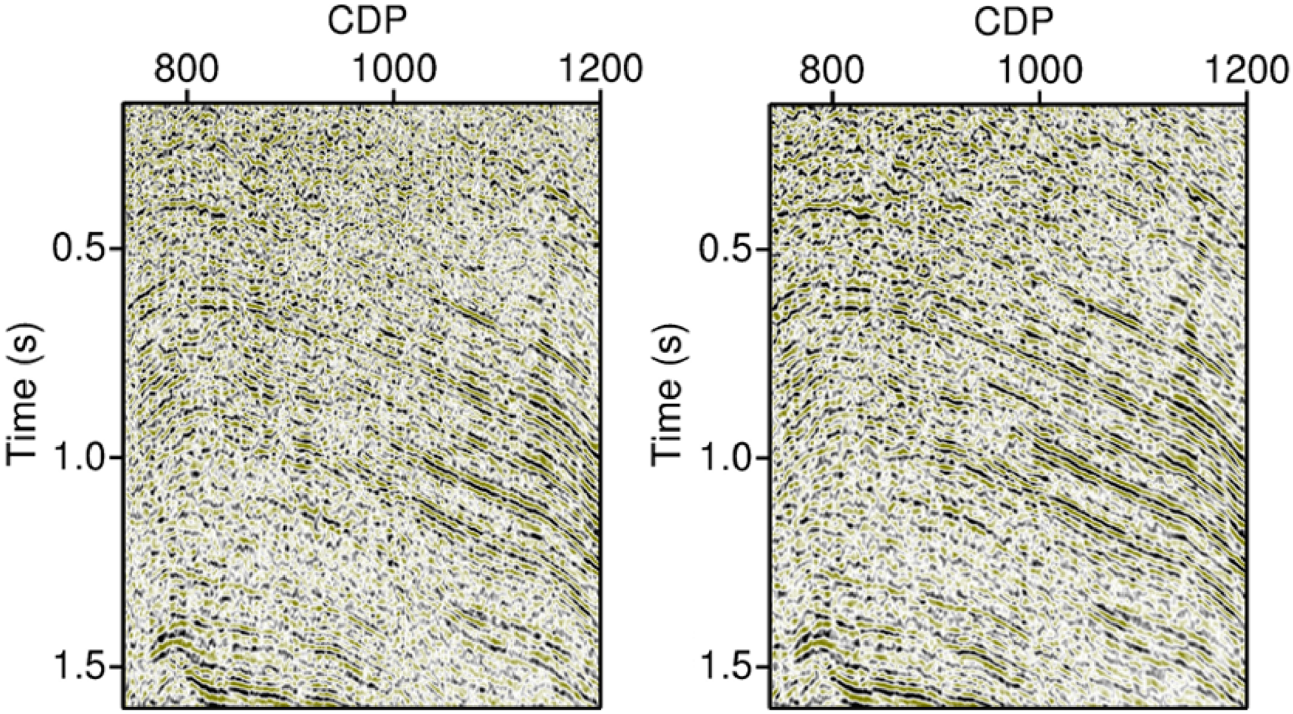
CRS

(c)

MPFI + CRS

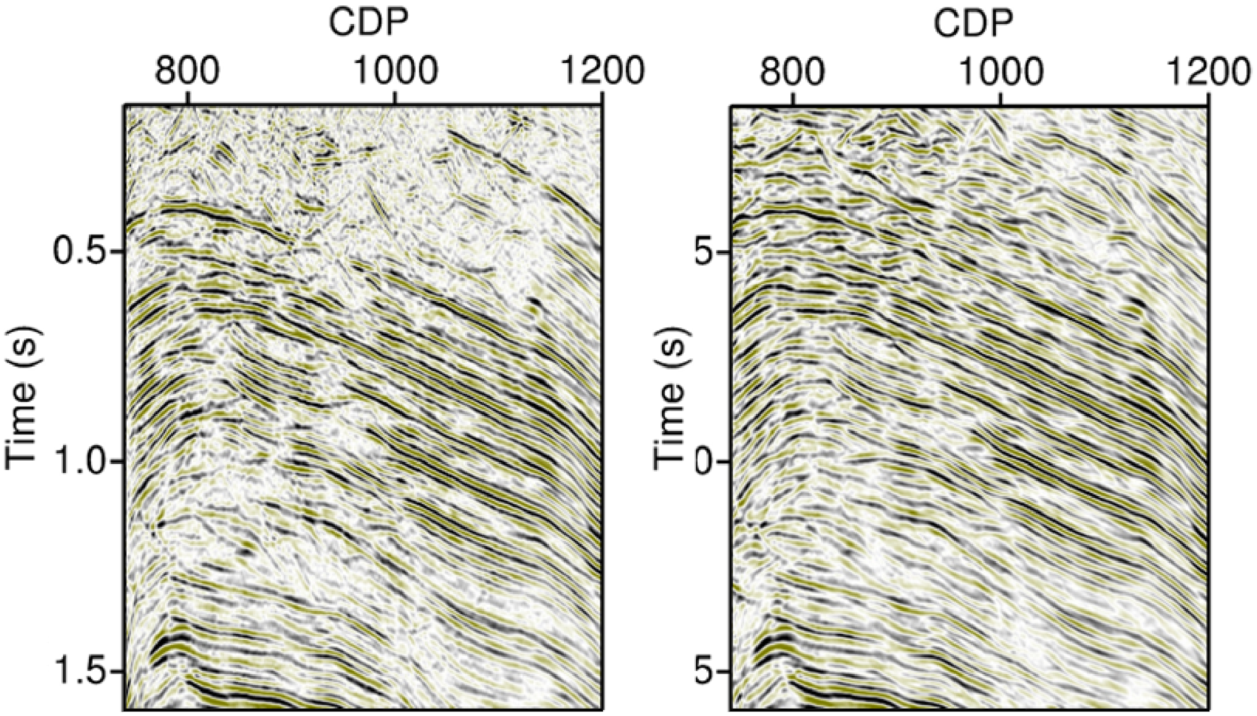
(d)

Figure 1: Common-shot gathers extracted from the original and reconstructed datasets of the Tacutu basin. a) original data, b) reconstructed data with MPFI method, c) reconstructed data with the CRS-based method using the kinematic attributes extracted from the original data and d) MPFI reconstructed data with CRS-based method using the kinematic attributes extracted from the reconstructed data with MPFI.



(a) Original

(b) MPFI



(c) CRS

(d) MPFI+CRS

Figure 2: PSTM images of the Tacutu basin obtained from: a) original data, b) reconstructed data with MPFI method, c) reconstructed data with the CRS-based method using the kinematic attributes extracted from the original data and d) MPFI reconstructed data with CRS-based method using the kinematic attributes extracted from the reconstructed data with MPFI.