ENHANCEMENT OF STACKED SECTIONS USING ZO CRS PARAMETERS

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ABSTRACT

Multiparametric stacking techniques, such as the common-reflection-surface (CRS) (in its conventional, non-hyperbolic and implicit forms) and Multifocusing (MF), are inherently affected by random and coherent noise, conflicting dips and diffraction attenuation. Reasons for such difficulties include, among others: (a) acquisition problems, such as environment noise and equipment failures and (b) processing problems, such as parameter estimation strategies and limitations of traveltime approximations.

To correct those problems, we propose a spreading-type algorithm that is applied to a CRS stacked volume. The CRS method provides, in addition to a stacked volume, a set of CRS parameters defined at each sample of that volume. For our purposes, such parameters are used to define the CRS diffraction traveltime surface along which the sample will undergo the spreading. More specifically, by means of the proposed algorithm, each sample in the CRS stacked volume will be spread out to its neighboring points in the volume along the CRS diffraction traveltime surface that pertains to that sample. As a result of the spreading, and also taking into account suitable apertures, significant noise reductions is attained.

The proposed method was applied to synthetic (Sigsbee2b-nfs) and real (Jequitinhonha) datasets with promising results in terms of better signal-to-noise ratio, event enhancement and conflicting-dip corrections.

INTRODUCTION

Images provided by stacked data are obtained robustly and inexpensively, being amenable to first interpretations useful for further processing steps. Stacked volumes, which generally represent an approximation of a (simulated) zero-offset (ZO) acquisition, can be constructed through several methods. The simpler and most widespread of such methods is the common-midpoint (CMP) method (Mayne, 1962) in which normal moveout (NMO), as well as its extension of dip moveout (DMO) (Hale, 1984) is employed. In the CMP method, a single common midpoint (CMP) gather is considered to construct a stacked trace. That method adjusts seismic reflection events by hyperbolas depending on a single parameter, the NMO velocity. NMO/DMO stacking is a simple and robust procedure, being part of most processing sequences used in practice. Nevertheless, the dependence on a single parameter, as well as the restriction to CMP gathers, may impose significant limitations to the use of CMP method, for example in situations of low coverage and/or poor signal-to-noise ratio (S/N).

Such drawbacks of the CMP method have been overcome by so-called multiparameter stacking techniques, which are able to, by means of more general moveouts that depend on more parameters (multiparametric moveouts), stack the data on supergathers that are free from the restrictions imposed by the CMP configuration. Typical examples of multiparametric traveltime techniques are the common reflection surface (CRS) and multifocusing (MF). A main advantage of such methods is their ability to exploit the full redundancy contained in the seismic dataset (Jäger et al., 2001; Berkovitch et al., 2008). Moreover, the additional parameters provided by the the multiparametric traveltimes are also useful for further imaging procedures.

In spite of the advantages provided by multiparametric stacking techniques as compared to the CMP method, some tradeoffs have also to be recognized. The estimation costs involved in the multiparametric stacking method are higher than the corresponding situation of a single parameter estimation involved in the CMP method. In both situations, the estimation is carried out by coherence (semblance) analysis directly performed on the multicoverage data set. Moreover, special care needs to be taken with respect to the apertures employed, especially in the midpoint direction. Such apertures control the lateral resolution of the image: for example, too large apertures tend decrease the high-frequency content of the stacked image, with the result of filling gaps and hiding faults. The role of apertures in the CRS stacking method has been recently addressed in Faccipieri et al. (2015).

Despite of the full redundancy made use by multiparametric stacked methods, their resulting stacked volumes are not immune to complications related with noise. That noise may be produced due to acquisition (environmental noise, traffic, equipment failure, etc.) and also processing (parameter estimations, traveltime accuracy limitations, noise alignment (the so-called worms) and conflicting dips).

In order to reduce the noise on stacked data produced by multiparametric techniques, we propose a re-stacking algorithm that, within a given stacked volume, is able to further enhance coherent events and further attenuate non-coherent events. As explained below, the re-stacking algorithm is carried out by a spreading operator constructed using CRS parameters already available in the input stacked volume.

The proposed method can be very effective to enhance reflections or diffractions, whenever one considers stacked volumes of enhanced reflections (so-called reflection-only or R-volumes) or enhanced diffractions (so-called diffraction-only of D-volumes) extracted from the prestack data. Algorithms designed to separate stacked reflections and diffraction volumes, and, hence, to obtain R- and D-volumes, are based on a careful aperture control of CRS (see, e.g., Asgedom et al., 2013; Faccipieri et al., 2015) or MF (see, e.g., Berkovitch et al., 2009). At each point of such volumes, the CRS parameters are assumed available. Here, the new denoising technique has been applied to illustrative synthetic and real datasets. The examples confirmed the expected properties of event enhancement, pulse shape recovery and noise attenuation both in reflection and diffraction situations.

FORMULATION

In the following, the input of the proposed technique are stacked volumes of reflections only (R-volumes) and diffractions only (D-volumes), as extracted from a given prestack volume.

The CRS traveltime is defined in the prestack data, with traces specified as $(\mathbf{m}, \mathbf{h})$, in which $\mathbf{m} = (m_1, m_2)^T$ and $\mathbf{h} = (h_1, h_2)^T$ represent midpoint and half-offset coordinates, respectively. As usual practice, we assume that the application of the stacking traveltime produces a data volume that well approximates the one obtained if the subsurface were illuminated by a ZO acquisition.

The CRS traveltime in the prestack domain is given by

$$t_R(\mathbf{m}, \mathbf{h}; \mathbf{m}_0, t_0) = \sqrt{(t_0 + \mathbf{a}^T \Delta\mathbf{m})^2 + \Delta\mathbf{m}^T \mathbf{B} \Delta\mathbf{m} + \mathbf{h}^T \mathbf{C} \mathbf{h}}, \tag{1}$$

where $(\mathbf{m}_0, t_0)$ represents the central point at which the CRS stack is performed, $\Delta\mathbf{m} = \mathbf{m} - \mathbf{m}_0$ and $\mathbf{a} = \mathbf{a}_0(\mathbf{m}_0, t_0)$ (2×1 vector), $\mathbf{B} = \mathbf{B}(\mathbf{m}_0, t_0)$ and $\mathbf{C} = \mathbf{C}(\mathbf{m}_0, t_0)$ (2×2 symmetric matrices) are the CRS parameters. Here, $\mathbf{m}_0$ and t_0 refers to the midpoint (trace) position and the traveltime (time sample) at the corresponding ZO (stacked) volume.

Following Faccipieri et al. (2013), stacked data in which reflections are enhanced and diffractions are attenuated, referred here as R-volumes, are obtained using the CRS stacking operator (1) with Projected Fresnel Zone (PFZ) apertures. For reflections, such apertures are typically small. Points in an R-volume are denoted $R_* = R(\mathbf{m}_0, t_0)$. In the same way, stacked data in which diffractions are enhanced and reflections attenuated, referred here as D-volumes, are obtained using the CRS stacking operator (1) in which $\mathbf{B} = \mathbf{C}$, namely

$$t_D(\mathbf{m}, \mathbf{h}; \mathbf{m}_0, t_0) = \sqrt{(t_0 + \mathbf{a}^T \Delta\mathbf{m})^2 + \Delta\mathbf{m}^T \mathbf{C} \Delta\mathbf{m} + \mathbf{h}^T \mathbf{C} \mathbf{h}}, \tag{2}$$

also with PFZ apertures, which are typically large for diffraction events. Points in a D-volume are denoted $D_* = -\partial_{t_0} D(\mathbf{m}_0, t_0)$, where ∂_{t_0} is the partial derivative with respect to time. For a better understanding on the relationships between reflection and diffraction traveltimes, also in the framework of stacking and time migration, the reader is referred to Gelius and Tygel (2015).

ENHANCEMENT OF R- AND D-VOLUMES

In the following, we introduce an enhancement procedure applied to the R- and D-volumes to improve its quality (noise reduction, sharpness and continuities of events, etc.). The approach is very similar to a Kirchhoff migration, being performed by simple data spreading: For each data sample (together with its CRS parameters) in the considered data volume, the procedure consists of spreading the data along the reflection (R-volume) or diffraction (D-volume) traveltime operator that pertains to that sample. The spreading is carried out on a suitable (PFZ) weighted by the inverse of number of samples within that aperture. The procedure is performed for all samples in the whole data volume.

To explain why that simple procedure works, we describe its resulting amplitude on any given point, $(\mathbf{m}_0, t_0)$, of the output (ZO stacked) volume. Setting $\mathbf{h} = 0$ in Equations (1) and (2), the reflection and diffraction traveltimes in the ZO domain can be written in the simple form

$$t^U_{ZO}(\mathbf{m}; \mathbf{m}_0, t_0) = \sqrt{(t_0 + \mathbf{a}^T \Delta\mathbf{m})^2 + \Delta\mathbf{m}^T \mathbf{K}^U \Delta\mathbf{m}}, \tag{3}$$

where $U = R_*$ or $U = D_*$ to refer to reflection or diffraction. In this way, we have

$$\mathbf{K}^U = \begin{cases} \mathbf{B} & \text{(for reflection)} \\ \mathbf{C} & \text{(for diffraction)} \end{cases} . \tag{4}$$

The resulting amplitude, $U_s(\mathbf{m}, t)$, from our spreading scheme can be written in the form of a weighted sum

$$U_s(\mathbf{m}, t) = \sum_k \left(\sum_{i=-I_0}^{I_0} \sum_{j=-J_0}^{J_0} W^U_{ijk}\, U(\mathbf{m}_{ij}, t_k) \right) . \tag{5}$$

Here, the summation runs over midpoints and traveltimes

$$\mathbf{m}_{ij} = (m_{01} + i\Delta m_1, m_{02} + j\Delta m_2), \quad t_k = t_0 + k\Delta t\ , \tag{6}$$

in which $\mathbf{m}_0 = (m_{01}, m_{02})$ denotes the reference midpoint, Δm_1 and Δm_2 represent the midpoint trace-sampling rates along axes of the given Cartesian coordinates at the acquisition surface and Δt is the time sampling. Moreover, I_0 and J_0 are the number of traces to the left and to the right of the reference trace, $\mathbf{m}_0$ in the respective horizontal directions. Such traces are the ones used for the spreading operation, comprising the rectangle centered at $\mathbf{m}_0$ and sides $2I_0\Delta m_1$ and $2J_0\Delta m_2$ in the two horizontal directions. The summation on the time samples (k index) run over all time samples on each trace.

The quantity W^U_{ijk} in Equation (5) represents weight function and is given by

$$W^U_{ijk} = W^U(\mathbf{m}_{ij}, t_k; \mathbf{m}_0, t_0) = \frac{1}{4I_0J_0}\delta[t_0 - t^U_{ijk}]\ , \tag{7}$$

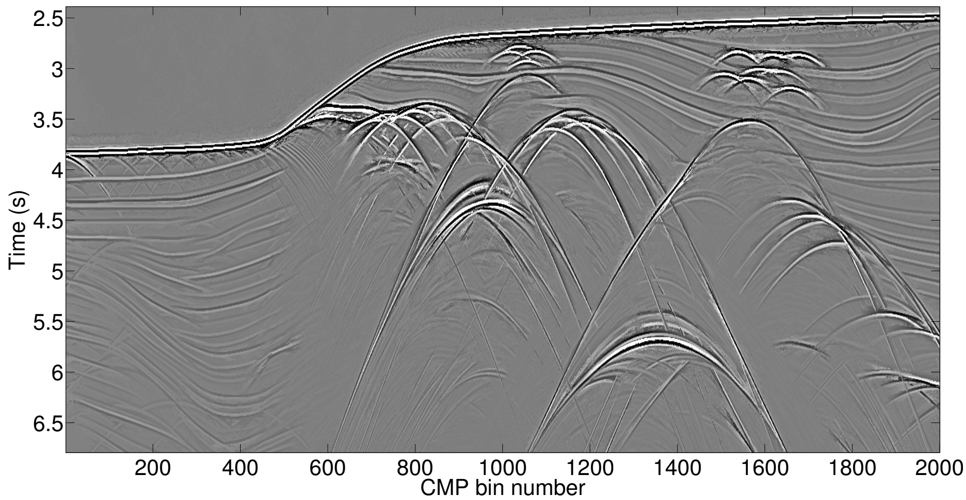
in which $\delta(.)$ is Kronecker delta function. More specifically,

$$\delta[t - t^U_{ijk}] = \begin{cases} 1, & \text{if} \quad t^U_{ijk} = t_0 \\ \\ 0, & \text{if} \quad t^U_{ijk} \neq t_0\ . \end{cases} \tag{8}$$

In Equation (8), the quantity t^U_{ijk} represent the spreading traveltime. The spreading traveltime is given by

$$\begin{aligned} t^U_{ijk} &= t^U_{ZO}(\mathbf{m_0}; \mathbf{m}_{ij}, t_k) \\ &= \sqrt{\left(t_k + \mathbf{a}^T_{ijk}\Delta\mathbf{m}_{ij}\right)^2 + \Delta\mathbf{m}^T_{ij}\mathbf{K}^U_{ijk}\Delta\mathbf{m}_{ij}}\ , \end{aligned} \tag{9}$$

in which $\Delta\mathbf{m}_{ij} = \mathbf{m}_0 - \mathbf{m}_{ij}$ is the trace displacement. Equation (9) can be interpreted as a ZO CRS traveltime defined for the trace location and traveltime $(\mathbf{m}_{ij}, t_k)$, taken as reference, and evaluated at the output trace location, $\mathbf{m}_0$. Note that $\mathbf{a}^T_{ijk} = \mathbf{a}^T(\mathbf{m}_{ij}, t_k)$, $\mathbf{K}^U_{ijk} = \mathbf{B}(\mathbf{m}_{ij}, t_k)$ or $\mathbf{K}^U_{ijk} = \mathbf{C}(\mathbf{m}_{ij}, t_k)$ for the reflection or diffraction situations, respectively.



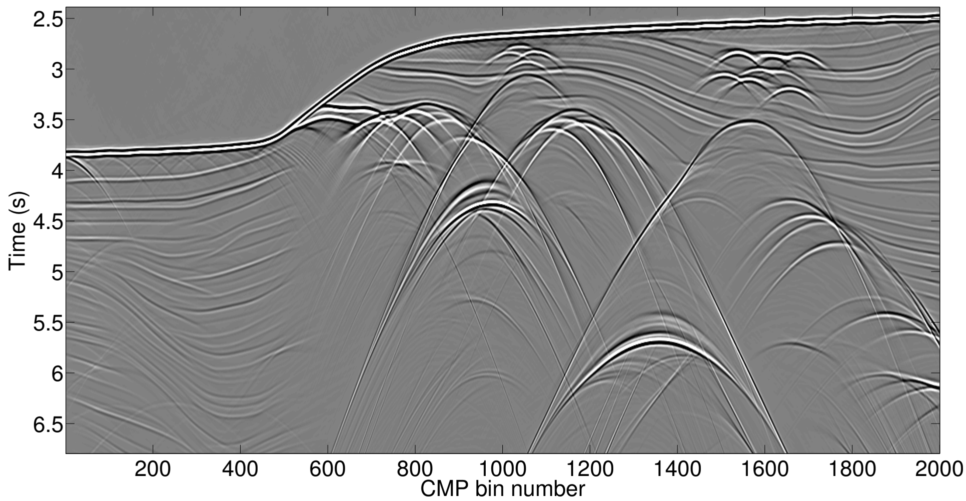


Figure 1: Sigsbee2b dataset: Top: Stacked section obtained with CRS method using global estimation of parameters. Bottom: Reflection-enhanced section obtained with the new method. Note the difference in noise levels and the reduction of problems related to conflicting dips.

Note that, due to time discretization, the computation of t^U_{ijk} requires interpolation between neighboring time samples. From the above description, we readily infer that

(a) The output amplitude $U_s(\mathbf{m}, t)$ will peak whenever $(\mathbf{m}_0, t_0)$ sits on a reflection or diffraction event. The reason is that the amplitudes of several neighboring points (in principle, $4I_0J_0$ of them) along the traveltime of that event will be accumulated. Such amplitudes are given by $U(\mathbf{m}_{ij}, t_k)$ with $t^U_{ijk} = t_0$ (after due interpolation).

(b) Away from a reflection or diffraction event, the procedure tends to attenuate the resulting amplitude by destructive interference.

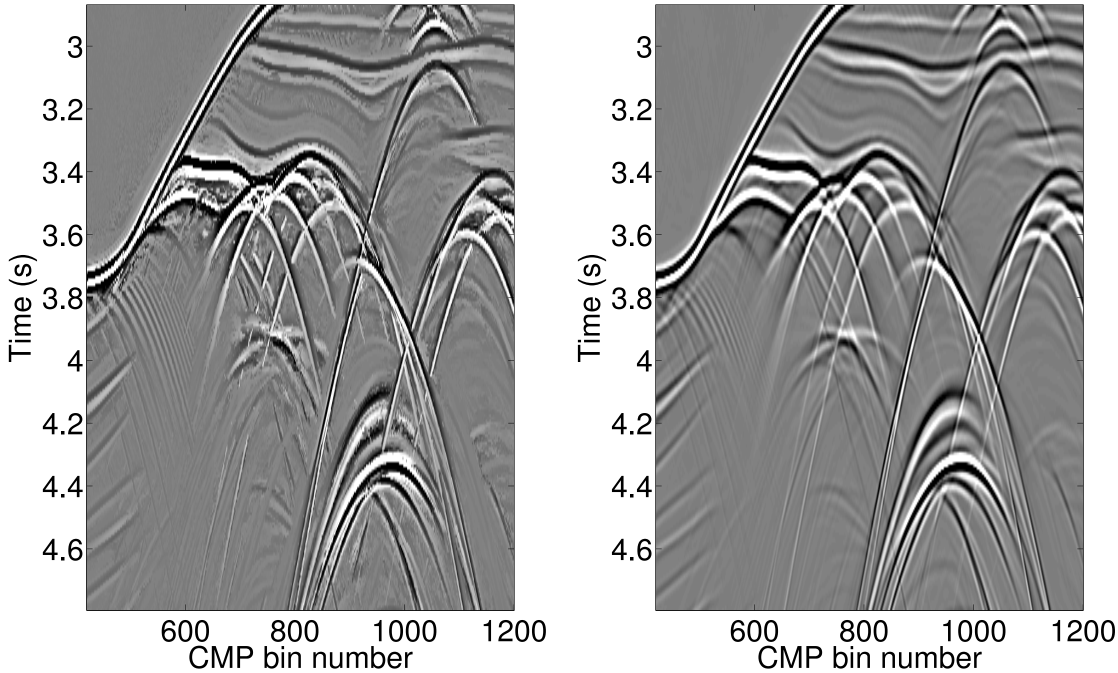


Figure 2: Sigsbee2b dataset: Detail of the stacked section presented on Figure 1 for the CRS method (left) and the proposed method (right).

(c) The procedure automatically takes care of conflicting dips. That is because different events at the same point will be accessed by all traveltimes that pertain to it.

RESULTS

The proposed method has been applied to 2D synthetic and real datasets, all sections being constructed with the same CRS parameters and proper apertures. The CRS parameters have been estimated following the algorithm described in Faccipieri et al. (2015) and Faccipieri et al. (2013). That algorithm performs bi-parametric estimations considering the diffraction traveltime (depending on the parameters $\mathbf{a}$ and $\mathbf{C}$ only. This, in turn, is followed by a single parameter search of the third parameter, $\mathbf{B}$. Note that, in the present situation, the three parameters are scalars, and, as such, denoted by a, B and C, respectively.

Our first example uses the the Sigsbee2a dataset (Pfaffenholz et al., 2002). Figure 1 shows a comparison between the stacked sections obtained using the conventional CRS method with the proposed method for reflections-only data. In both sections, the same CRS parameters have been used. The stacking and spreading apertures are: (i) Midpoint: 1100 ft from zero to 2.6 s, increasing linearly until 2700 ft at 7.5 s and constant until the maximum time sample, 9 s. (ii) Half-offset: 700 ft constant. Observe that high-frequency noise was attenuated and regions with conflicting-dip reflections were corrected. Figure 2 shows the comparison in more detail over a zoomed small region.

The second example is a 2D real marine dataset, acquired in Jequitinhonha basin (offshore Brazil), that has 4 ms time sampling, 12.5 m between Common Midpoint (CMP) gathers, 25 m between hydrophones with minimum and maximum offsets of 150 m and 3125 m, respectively. Figure 3 shows a comparison between the stacked sections obtained under conventional CRS method and by the proposed method applied to a reflections-only stacked section. Once more, a global estimation of CRS parameters has been used and in both sections the stacking and spreading apertures are: (i) Midpoint: 30 m from zero to 1.3 s, increasing linearly until 150 m at 3.5 s and constant until the maximum time sample, 6 s. (ii) Half-offset: 650 m

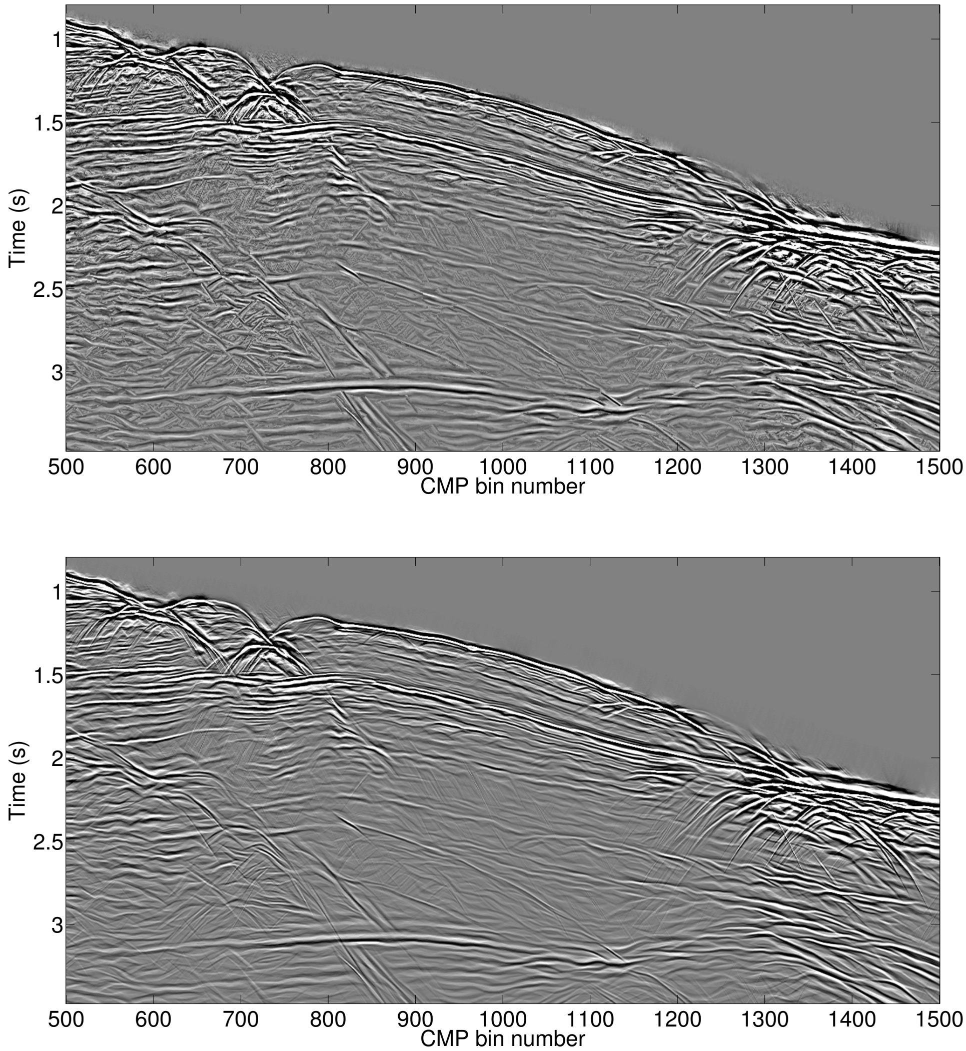


Figure 3: Jequitinhonha dataset: Top: Stacked section obtained with CRS method using global estimation of parameters. Bottom: Reflection enhanced section obtained with the proposed method. Note that there is no change in the events present on the original sections, only the noise levels and problems related to conflicting dips were corrected.

from 0 to 1.3 s, increasing linearly until 1050 m at 3.5 s and constant until the final time, 6.0 s. We see that high-frequency noise has been attenuated, especially where diffractions were present and close to the multiples. Also, in regions with conflicting dips, the proposed method was able to enhance the reflections and provide better continuity to them.

We also tested the enhancement and recovering of diffractions using the proposed algorithm. The method was applied to a diffractions-only stacked section obtained following Faccipieri et al. (2013). That section is shown in Figure 4 (top). We observe that some residual reflections are still present in the section combined with high-frequency noise. Figure 4 (bottom) shows the same section obtained using the proposed method. It is possible to observe that most of the noise and the residual reflections were attenuated leading to a clearer section. Some preliminary migrated images of the sections presented in Figures 4 (top) and 3 (top) can be found in Figure 6. We can observe that the presence of migration artifacts (migration smiles) are attenuated after the application of the new method.

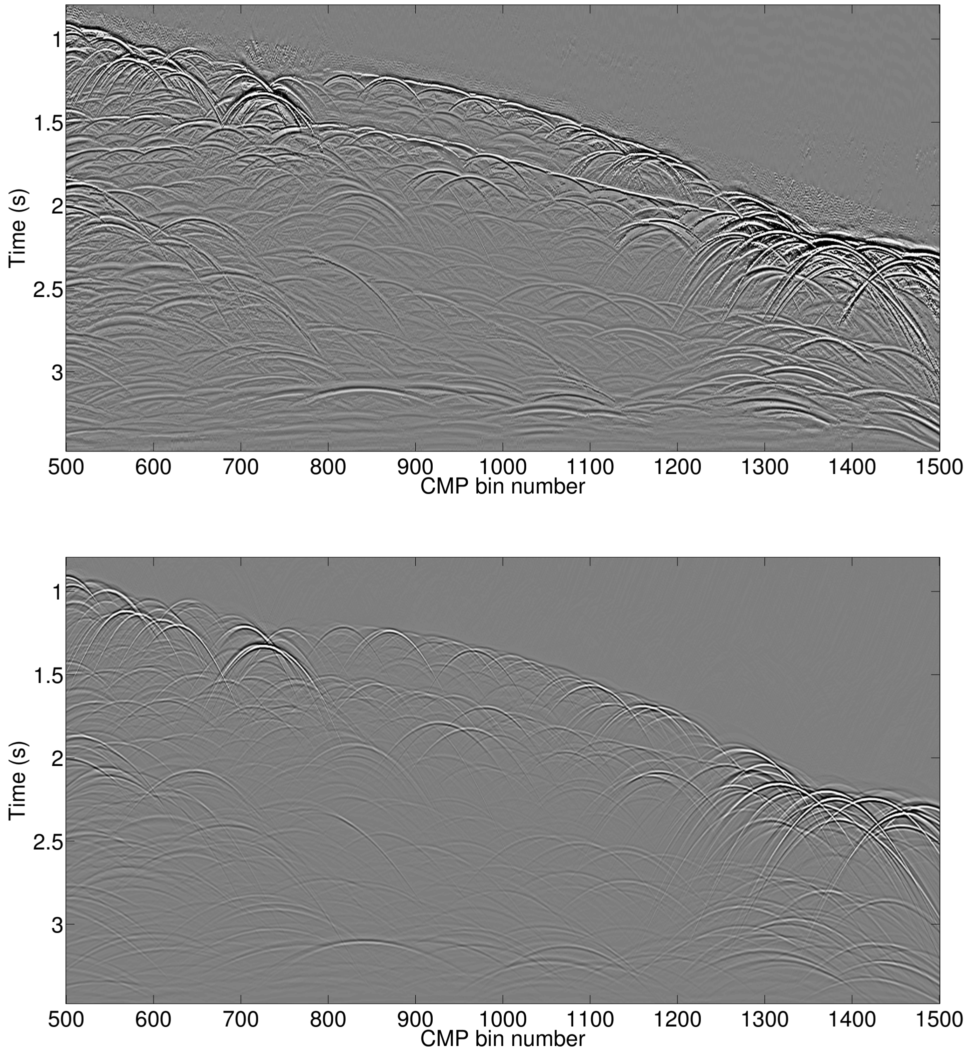


Figure 4: Jequitinhonha dataset: Top: Stacked section obtained with CRS method for diffractions using global estimation of parameters. Bottom: Diffraction enhanced section obtained with the proposed method. Note that there is no change on the events present on the original sections, only the noise levels and problems related to conflicting dips were corrected.

CONCLUSIONS

We presented a Kirchhoff time-migration approach to improve the quality of stacked sections obtained by the CRS method. The approach is based on re-stacking the data under the use of a suitable spreading operator that depends on the CRS parameters already available from the initial stack. The proposed method was applied to synthetic (Sigsbee2b-nfs) and real (Jequitinhonha) datasets with good results in terms of better signal-to-noise ratio, event enhancement and conflicting-dip corrections.

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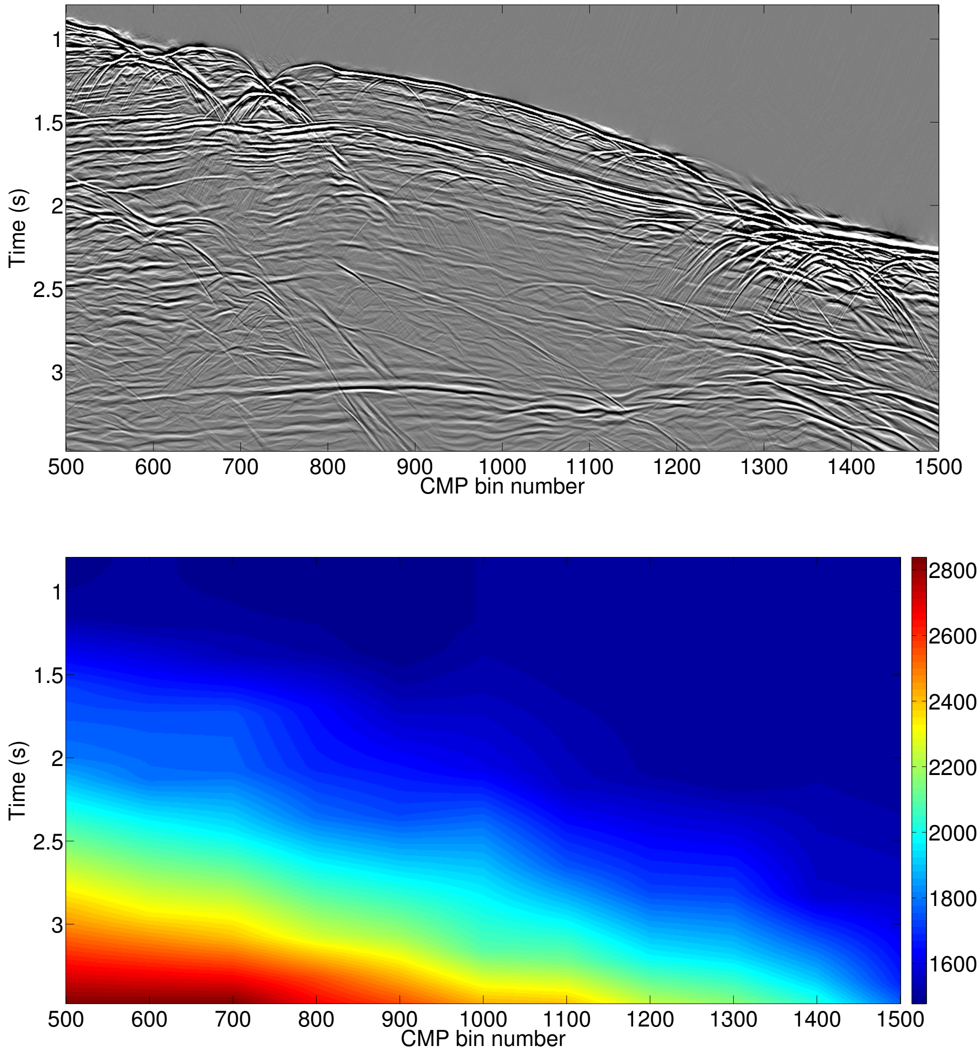

Figure 5: Jequitinhonha dataset: Top: Combined stacked section obtained adding together the reflection and diffraction sections obtained with the proposed method. Bottom: Migration velocity model, in m/s, obtained with conventional velocity analysis.

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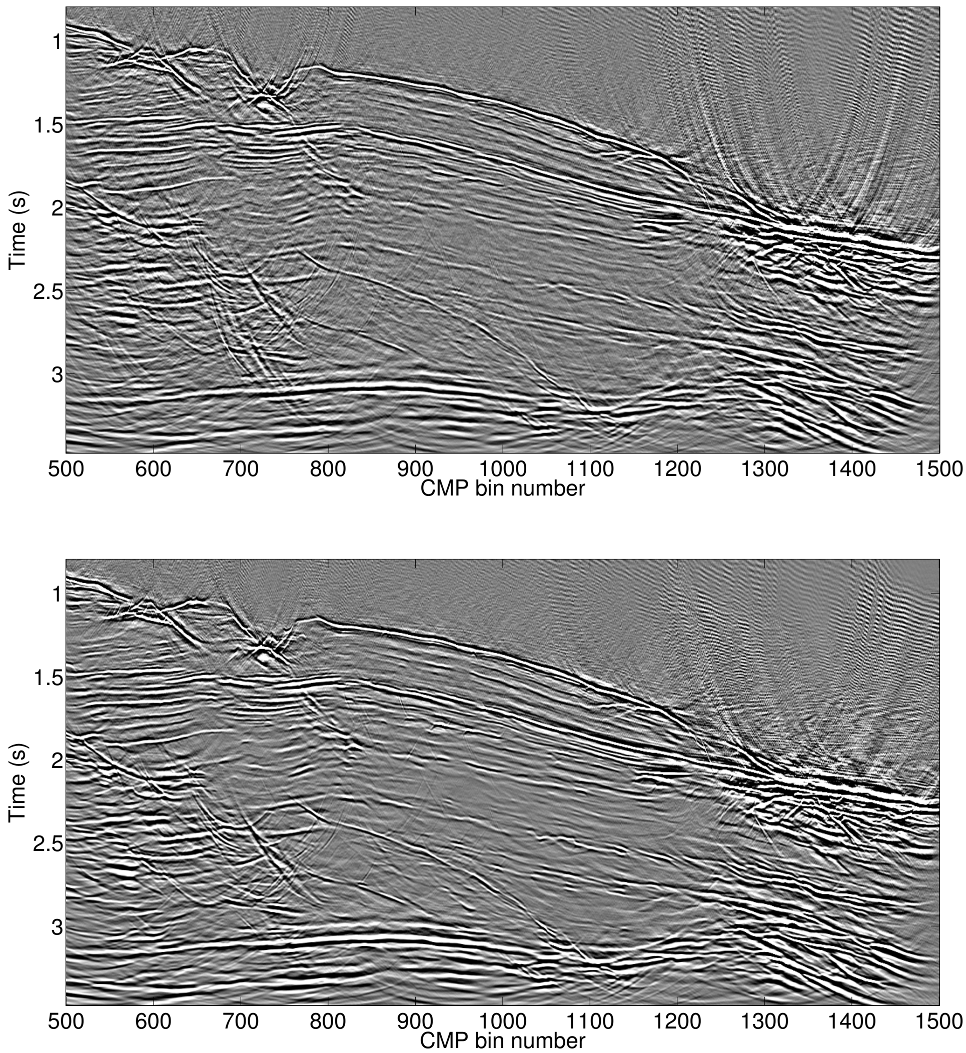

Figure 6: Jequitinhonha dataset: Top: Poststack time-migrated image obtained from CRS stacked sections of the top Figure 3 using the migration velocity model of the bottom Figure 5. Bottom: Same poststack time migration with the combined stacked sections of top Figure 5.

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