CRS-BEAM PSDM : KIRCHHOFF-BEAM PRESTACK DEPTH MIGRATION USING THE CRS OPERATOR

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ABSTRACT

Beam-migration methods efficiently extend the benefits of Kirchhoff migration and enhance its imaging accuracy, producing high fidelity images of complex geological structures. The common-reflection-surface (CRS) stack method produces zero-offset (ZO) sections from multi-coverage data with high signal-to-noise ratio and better continuity of reflection events, especially dipping structures. The CRS operator depends on three kinematic attributes determined from prestack data by automatic optimization procedures. These attributes have several applications: velocity model determination via tomography, determination of projected Fresnel zones, and time and depth migration. Following the concepts of beam-migration methods, we present one new depth migration procedure that combines Kirchhoff depth migration and the CRS stacking method, called CRS-beam PreSDM. The beam stack is based on CRS operators ability to collect paraxial contributions around a reference trace to be migrated. The present migration algorithm was tested on a synthetic 2D seismic dataset containing reflections of steep dip interfaces. The results obtained show improvements when compared to the conventional Kirchhoff migration. The algorithm was also applied to prestack migrate the real, low-fold, 2D land data of the seismic line 50-RL-90, acquired at the Tacutu basin, Brazil. The comparison of the two final results are very insightful in terms of resolution quality, thus leading to more accurate interpretations.

INTRODUCTION

Among all seismic processing techniques used to prospect for oil and gas, seismic migration produces more representative and interpretable images of the subsurface. Kirchhoff migration is one of the most popular seismic imaging methods, especially in 3D, due to its efficiency and flexibility in dealing with several kinds of datasets, including wavefield and non-wavefield volumes of data, such as common-offset data. The method is suitable to solve imaging problems in areas with smooth velocity variations and also provides good accurate results in areas with structurally complex geologic behavior. In media with strong lateral and vertical velocity variation, Kirchhoff migration loses part of its efficiency and accuracy, either in time or in the depth domain, mainly due to multipathing of the seismic energy and due to deformations of the wavefront form that takes places in such media.

As a viable alternative to Kirchhoff migration, beam type migration methods were introduced in the beginning of the 90s for the marine case. Among these beam algorithms, we cite the Kirchhoff-beam migration of Sun et al. (2000) and the Gaussian beam migration of Hill (2001). Subsequent works using this approach (Albertin et al., 2004; Gray, 2005) have confirmed the Gaussian Beam (GB) prestack depth migration as a robust method for imaging in depth, with precision comparable to wavefield extrapolation methods. The GB migration retains the main advantages of Kirchhoff migration and takes into account the multipathing energy by considering local slant stacks, decomposing the wavefield into source and receiver domains and extrapolating the wavefields into depth domain using ray-tracing algorithms.

For imaging in time domain, the CRS method simulates a ZO stacked section by means of summing prestack data along stacking curves calculated by a general hyperbolic traveltime approximation. This approximation depends on three kinematic attributes related to local properties of the reflectors (Jäger et al., 2001; Garabito et al., 2001; Mann, 2001). Since it is a data-driven method, the three kinematic attributes that define the CRS stacking curves or surfaces are determined from the prestack data by means of automatic optimization search processes based on coherency measures, i.e., semblance. The resulting ZO stacked sections presents an high quality in signal-to-noise ratio, and even in geologically complex areas the results are superior to conventional methods such as post-stack time migration and pre-stack time migration.

Following the beam migration approach, we present a new development of a prestack depth migration algorithm combining the Kirchhoff migration and the CRS stack method. This new migration algorithm, called CRS-beam PSDM, is similar to the modified Kirchhoff migration presented in Ferreira and Cruz (2005). In our approach, a relative traveltime stacking operator is defined with respect to the diffraction (Huygens) traveltime surface. A local stacking is then introduced using the relative operator, when the amplitudes are summed in a range defined by the projected Fresnel zone (PFZ) around one reference trace. These amplitudes are positioned in their true depth locations according to their dips contained in the input section. The CRS processing comes into play here via the determination of the PFZ and the relative stacking operator using the CRS-attributes. The CRS-beam migration approach was introduced for the first time in depth and time domains, respectively, in Garabito and Ferreira (2009) and Tassini et al., (2009).

In this work, by using a synthetic seismic data with high level random noise added which correspond to a layered model with curved and steep dip interfaces, we show the local character of the impulse response of the CRS-beam PSDM, showing its complete localization in space and in dip direction. Finally, the CRS-beam PSDM algorithm was applied to a real, 2D land seismic data acquired over the Tacutu basin, located in Northwestern Brazil, in Roraima state. The seismic line 50-RL-90 was acquired perpendicularly to the main fault that limits the basin in its Brazilian side. The dataset is noisy and low-fold, representing a challenge to the processing due to its quality. After the pre-processing steps, the data was prestack depth migrated using both Kirchhoff and CRS-beam algorithms.

MODIFIED KIRCHHOFF-TYPE MIGRATION

In terms of analytical mathematical operator, 2D Kirchhoff depth/time migration is represented by a weighted integration (summation) of amplitudes along the so-called diffraction stack (Huygens) traveltime surface (Schleicher et al., 1993):

$$I(M,t=0) = \int_A d\xi \, w(\xi,M) \, D \left[U(\xi,\tau_D(\xi,M))\right], \tag{1}$$

in which $I(M,t=0)$ denotes the stacked amplitude assigned to the diffraction point at M in depth migrated space and $U(\xi,t)$ denotes the seismic data recorded at the surface, while t is the time and ξ is the configuration parameter vector of the input data. For 2.5D media, operator D represents a half derivative applied to the data in order to restore the wavelet shape. Function $w(\xi,M)$ is the true-amplitude weight, designed to suppress as much as possible the geometrical spreading losses present in the recorded seismic amplitudes. In this work we shall consider only the kinematic migration, i.e. $w(\xi,M)=1$, since traveltime is the main issue considered in the present approach so far. The traveltime surface $\tau_D(\xi,M)$ (Huygens surface) is function of the depth coordinates of the diffraction point represented by M and of the parameterized coordinate vector, ξ, of the source-receiver pair, which varies within the migration aperture A.

Ferreira and Cruz (2005) presented a new approach for prestack depth migration through the modification of the Kirchhoff integral, including in the kernel of the migration operator the GB superposition integral. The kinematic version of the modified Kirchhoff integral, called in the referred work as KGB-PSDM, is given by:

$$I(M,t=0) = \int_A d\xi \, w(\xi,M) \int_{A^P} d\xi^P \sqrt{H_P(\xi^P)} D_L(\xi^P) \frac{\partial^2}{\partial t^2} U(\xi,\tau_D(\xi,\xi^P,M)) \tag{2}$$

The second integral in Eq. (2) represents the seismic data to be migrated. It is considered to be obtained by a superposition of GBs. The parameter ξ is the position of the reference trace to be migrated and ξ^P denotes the positions of the traces used in the stack that are in the vicinity of this reference trace. Function $\tau_D(\xi, \xi^P, M)$ denotes the relative traveltime (diffraction) surface along which it is performed the stacking of the paraxial amplitudes that contribute to the reference trace, which is a posteriori stacked along the Huygens curve, as it is normally accomplished in the migration process described by Eq. (1). Finally, $H_P(\xi^P)$ and $D_L(\xi^P)$ are factors belonging to the weight-function of the GB stacking procedure itself (e.g., see Ferreira and Cruz, 2005) and which are, respectively, the value of the PFZ at the relative position ξ^P and the Gaussian-decaying taper function – i.e., the imaginary part of the paraxial traveltime surface contributing to the weighting of the amplitudes of paraxial rays.

In fact, the inner integral in Eq. (2) is the GB superposition operator interpreted as an integral along the PFZ of each ξ, in which its weight-function is proportional to the PFZ factor $H_P(\xi^P)$. Migration operator considering Eq. (2) is the formal definition of the KGB depth migration in Ferreira and Cruz (2005) interpretation. They have presented several short papers with synthetic examples (e.g., see Ferreira and Cruz, 2005), where they compared the results with a finite-offset true-amplitude Kirchhoff migration. The results showed reduction of the number of artifacts present in the images, as well as a good S/N ratio. With these features and the extension represented by Eq. (2), the whole migration process can also be performed in the true amplitude sense.

In order to perform the stacking of the input traces in the given vicinity, let us analyse the same procedure from the CRS operator point of view. The CRS stacking method produces ZO stacked sections from multi-coverage data, based on a general hyperbolic traveltime approximation expressed as function of three kinematic attributes, as follows: the emergence angle of the zero-offset central ray, β_0, and the quantities K_N and K_{NIP} that are wavefront curvatures of the normal and normal-incident-point (NIP) waves, respectively, measured at the emergence point of the central ray. These thee kinematic attributes, also called CRS-attributes, are determined from the prestack data by means of automatic search processes using coherency analysis.

In this work, we employ the global optimization strategy to extract the CRS-attributes from prestack data (Garabito et al., 2006). These CRS-attributes are of great value for several applications, but in the present case we apply it to the determination of the PFZ and for the Kirchhoff beam prestack depth migration. With the PFZ radius determined through the three parameter triplet, the CRS operator is constrained to stack amplitudes around every midpoint coordinate inside the finite radius equivalent to radius of the PFZ. The stacked amplitudes along the CRS traveltime surface are finally migrated using the Huygens surface of the Kirchhoff migration. In other words, the paraxial contributions collected by the beam stack are colected using the CRS traveltime approximation.

NUMERICAL EXAMPLES

To test the efficiency and robustness of the CRS-beam PSDM algorithm we have generated a synthetic dataset using a ray tracing program for a layered model with lateral velocity variations, separated by smooth and steep dip interfaces (Figure 1). The velocities from the top to the base of the layers vary between 2000 m/s to 4500 m/s, respectively. The synthetic dataset consists of 140 common shot gathers with 120 traces each. The shot interval is 25 meters and the interval between traces is 50 meters. The near and far offsets are 25 meters and 3000 meters, respectively. The total recording time is 3 seconds, while the sampling interval is 4 milliseconds. To the data it was added a random noise with a signal-to-noise ratio equal to 3.

To examine the image of a single input trace provided by the CRS-beam PSDM approach, we generated the migration impulse response for one near-offset trace, where reflection events corresponding to steep dips are present. In Figure 2*a* it is shown the well-known Kirchhoff PSDM impulse response, where the input trace sweeps energy in all directions. This is what Gray et al. (2009) calls the basic "molecule" behavior of Kirchhoff migration. In the case of the CRS-beam algorithm, it also operates on a number of local regions within the input data and it images the Earth smearing traces from a region around the individual beam center location, constrained by a limited angular range and about a single initial direction. The beam center locations are centered at the region around the PFZ of the seismic experiment. Thus in Figure 2*b* the sweeping arms of the impulsive response now focus on a specific dip direction. This is the basic molecule behavior of the present CRS-beam migration approach. The local properties of the seismic reflector used to perform the beam stack were derived by the CRS-attributes.

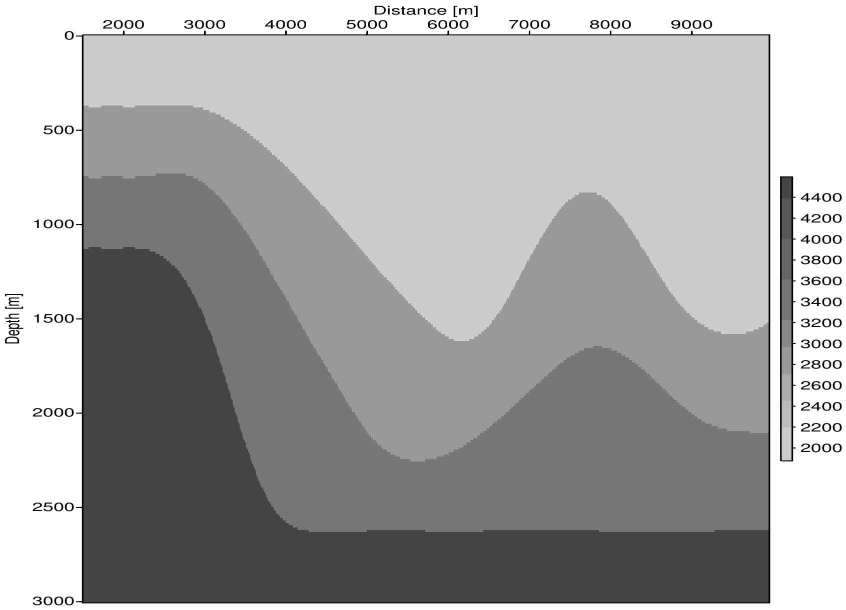


Figure 1: Synthetic velocity model.

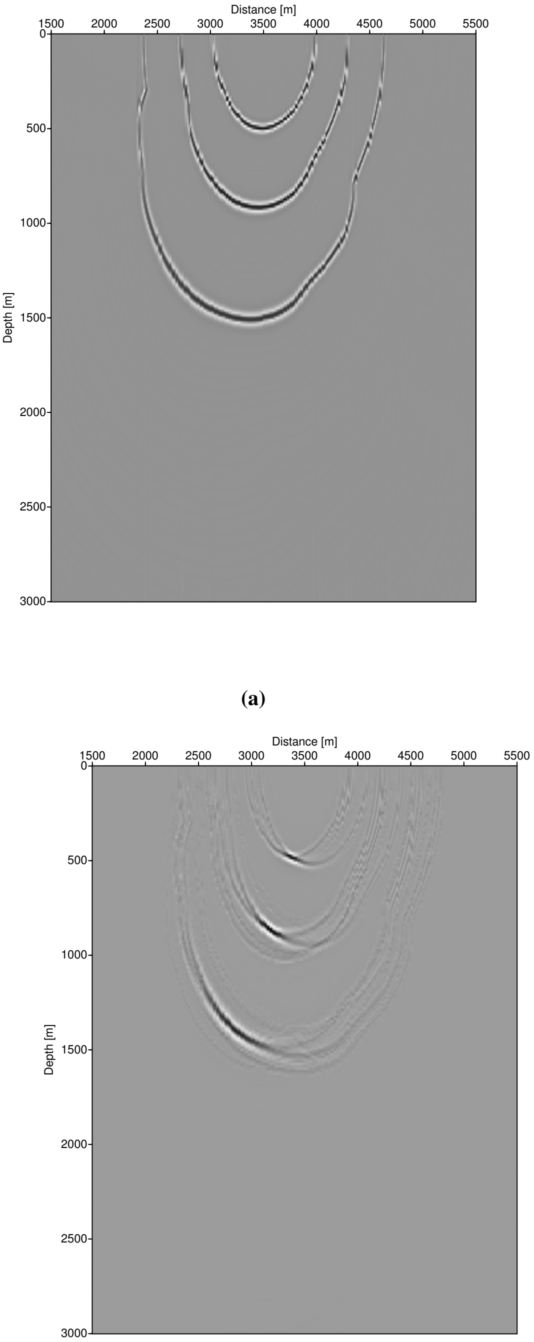
In Figures 3a and 3b the results of the Kirchhoff migration and of the CRS-beam PSDM migration are compared, respectively. Since the correct velocity model was used as input in both migration procedures, all reflectors were correctly positioned to their true positions in subsurface and all dips (smooth and steep) were properly imaged. The main difference between the two sections is in their resolution. The image obtained by the CRS-beam algorithm is much cleaner and lesser affected by artifacts than the one obtained by the Kirchhoff operator. In both procedures the tools for determining traveltime tables and filtering are the same, and the correct velocity model was previously smoothed.

Finally, as a way to investigate the sensitivity of both migration procedures towards errors present in the velocity models, in Figures 4a and 4b we have depicted common-image gathers (CIG's) along the half-offset dimension. Again the main difference is in the final resolution. But also it is clear that in the CRS-beam CIG's the moveout errors due velocity inaccuracies is much under control than in the Kirchhoff CIG's. This fact is in agreement with what Ferreira and Cruz (2005) have noticed.

REAL DATA EXAMPLE

The Tacutu basin is located along the border between the Cooperative Republic of the Guyanas and Brasil (Roraima state). According to Eiras and Kinoshita (1990), Tacutu is a Mesozoic sedimentary basin that developed as a intracontinental rift in the central cratonic area of the Guyana Shield. Its sedimentary framework is mainly composed of sedimentary and volcano-sedimentary rocks.

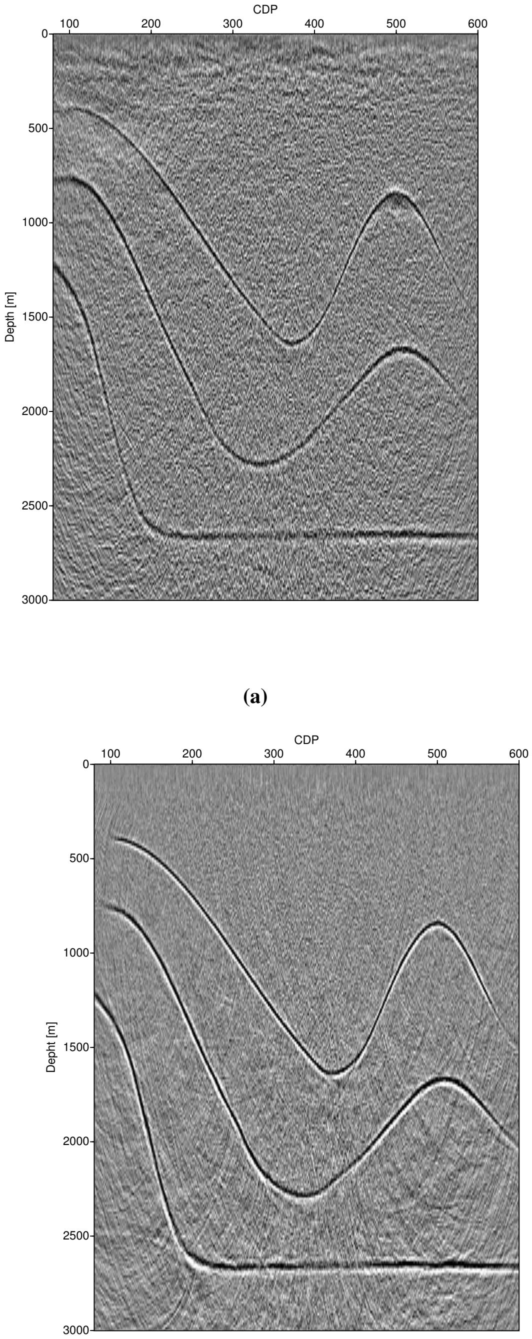
Despite the existence of a great volume of seismic and geological data in the area, the oil potential of the basin cannot be considered completely evaluated, since, in an exploratory sense, there are incomplete subsurface information and only a small number of exploration wells were drilled in the area. At the same time, the first drillings were not able to locate conventional reservoirs in the mapped geologic column (Eiras and Kinoshita, 1990). On the Brazilian side, circa 1948 Km of 2D reflection seismic data were acquired by Petróleo Brasileiro S. A. (PETROBRAS) between 1980 and 1986 in order to support further drilling, but in 1987 the exploratory activity came unexpectedly to an end. The acquired data were processed at the time with the classic CMP stacking method and later poststack time migrated. The interpretation of this processed data permitted the definition of the Tacutu graben and its tectonic evolution, but it is still believed that there are insufficient information towards a more accurate interpretation. This opens the door to, in



(a)

(b)

Figure 2: (a) Kirchhoff impulse response. (b) CRS-beam impulse response.



(a)

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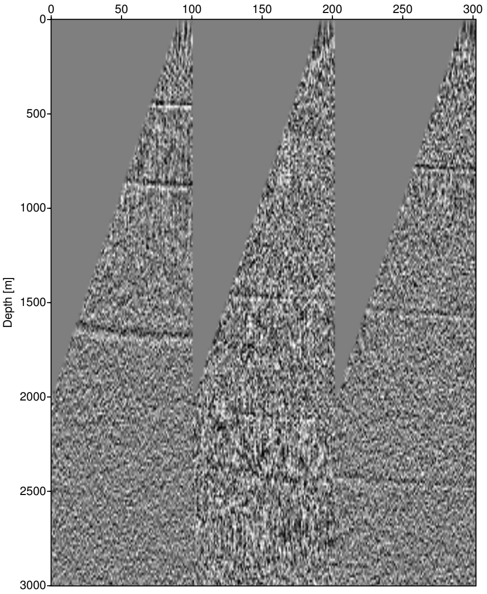
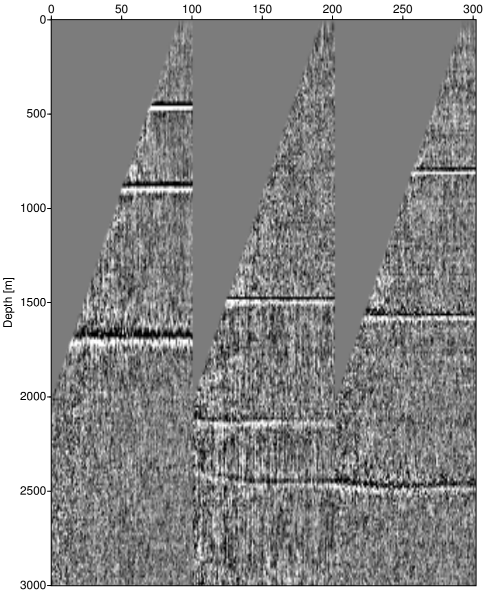
Figure 3: (a) Kirchhoff PSDM. (b) CRS-beam PSDM.



(a)



(b)

Figure 4: (a) Kirchhoff CIG's. (b) CRS-beam CIG's.

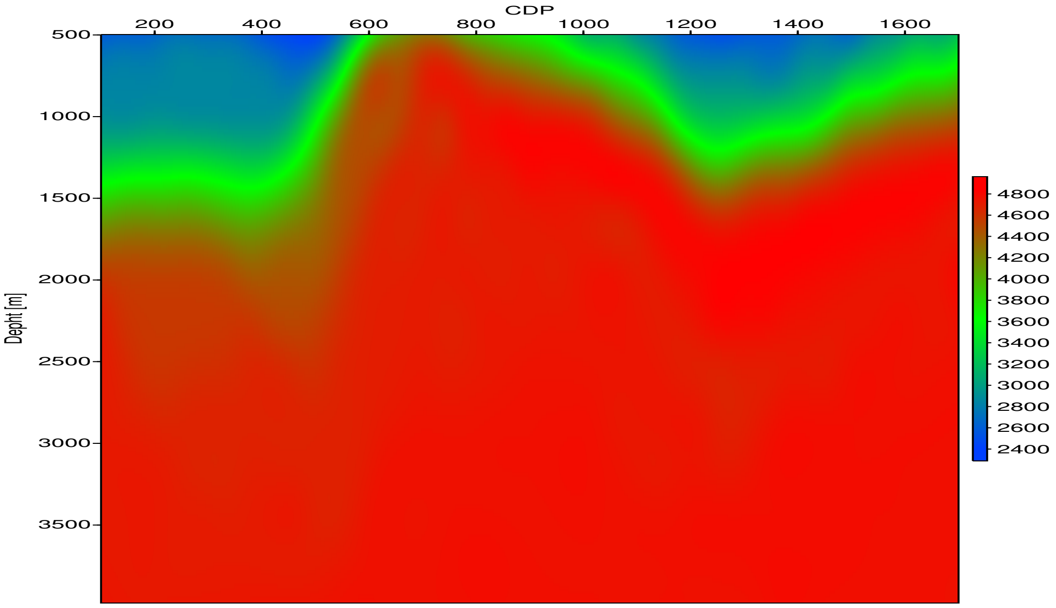


Figure 5: Velocity model Tacutu.

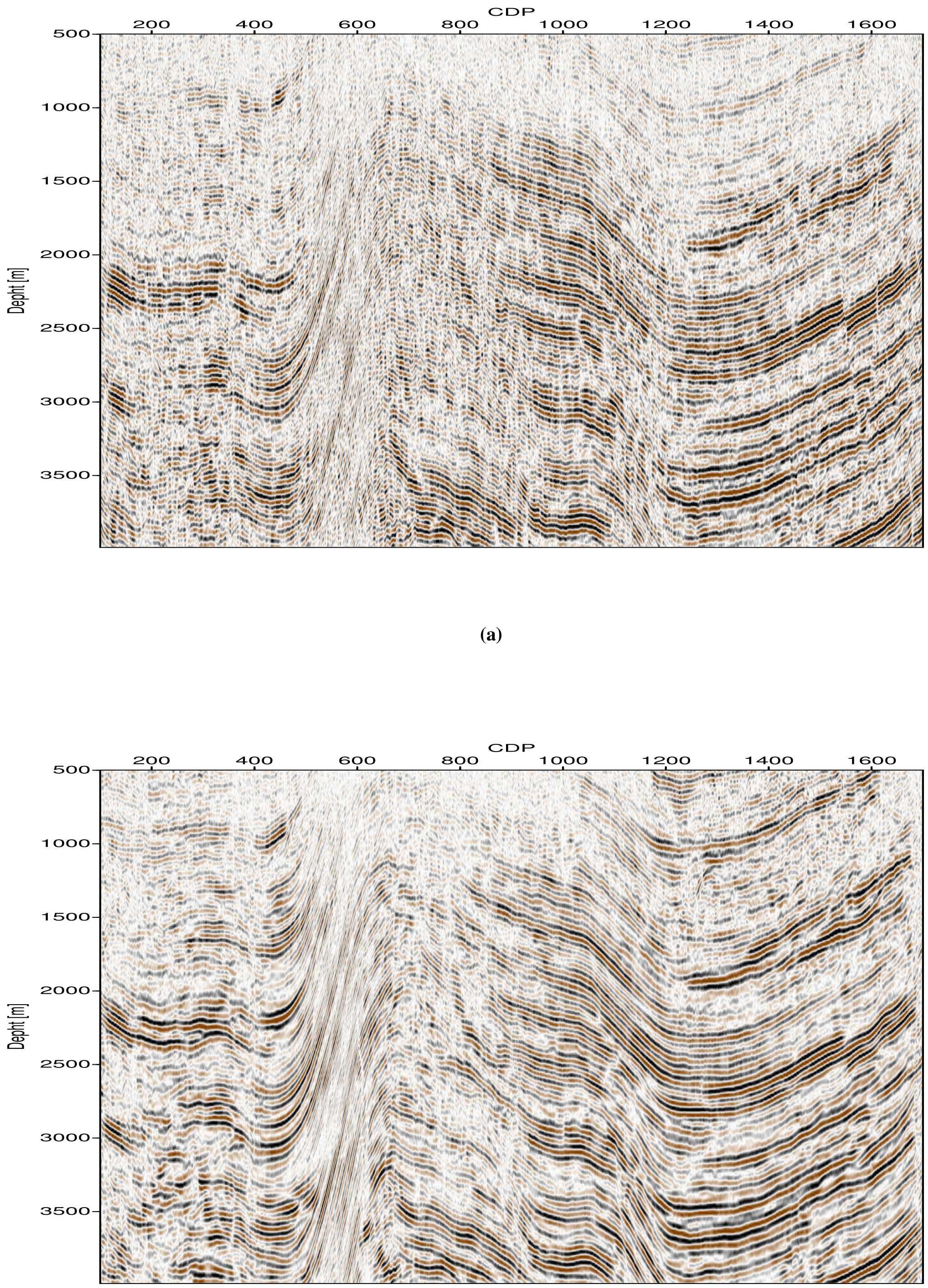
a first evaluation, the existence of untested exploratory plays. The reprocessing of the original data, with more sophisticated and/or unconventional processing techniques in order to obtain seismic images with better resolutions, is a key tool to reevaluate the area for future exploration activities. The effort worths the risk, since Tacutu still is an unexplored basin.

After the seismic surveying, wildcat wells 1-ST-1-RR and 1-TU-1-RR were drilled. The first well (1-ST-1-RR) was drilled over the profile of the seismic line 50-RL-90. This present line is the main object of interest of the present paper. It is composed of 179 common-shot gathers with a split-spread geometry and source interval of 200 meters. The number of receivers per shot is 96, with a receiver interval of 25 meters between consecutive geophones. The near and far offsets are 150 meters and 2500 meters, respectively. The total record time is 4 seconds with a sampling rate of 4 milliseconds. The CMP fold of seismic line 50-RL-90 is considered low, and together with the noisy quality of the data it is considered a limiting factor to data processing.

The pre-processing of the seismic line 50-RL-90 was carried out applying the conventional flow, i.e., since the trace edition until the residual statics. After, the CRS stacking method was applied to the data using the CRS stack algorithm based on the one-step global optimization strategy (Garabito et al., 2006). The same pre-processed data is input to the pre-stack depth migration applied in this work. The main results obtained from the CRS stack are a ZO stacked section, a coherence section and three sections corresponding to the CRS-attributes, namely: the emergence angle β_0 of the central ray and the two radii of curvature R_{NIP} and R_N, which correspond to the hypothetical NIP and Normal waves.

The velocity model for pre-stack depth migration was determined from the CRS-attributes, by means of applying the NIP-wave tomography developed by Duveneck (2004). Figure 5 shows the grided smoothed velocity model used in both depth migrations.

Finally, in Figures 6*a* and 6*b* are shown the results of the Kirchhoff and CRS-beam prestack depth migration, respectively. Besides the high level of lateral resolution reached by the CRS-beam migration procedure (Figure 6*b*), a first interpretation shows an enhancement of the fault trace on the right flank of the structure and a more evident continuity of reflectors on the left flank on the folded side at left.



(a)

(b)

Figure 6: Reflection seismic line 50-RL-90. Depth migrated results: (a) Kirchhoff PSDM. (b) CRS-beam PSDM.

CONCLUSIONS

We have developed a new procedure of prestack depth migration based on the Kirchhoff depth migration, on the superposition of GBs and on the CRS operator. We have tested the Kirchhoff and the CRS-beam migration approach on a 2D multi-coverage synthetic dataset with lateral velocity variation and steep dips. The results have shown the efficiency and robustness of the CRS-beam PSDM migration. The migrated images presented good quality and accuracy, even if the seismic data had a poor signal-to-noise ratio and steep dip reflectors.

This proposed migration approach may be applied to enhance the imaging of poor quality and low fold real data, both in depth domain and time domain. Future works using the present migration technique foresee the implementation of Gaussian taper functions and the preservation of amplitudes.

In a second example, both algorithms were applied to a 2D land seismic data acquired over the Tacutu basin, located Northwestern Brazil, in the Roraima state. The present data is a low-fold and noisy data, representing a challenge to seismic data processing. A preliminary interpretation of the final results of the line 50-RL-90 indicates an anticline structure strongly folded in its flanks. The main seismic facies identified in the processed section is of parallel undulated layers, indicating that folding took place after the deposition of the strata. Considering only the Kirchhoff migration result, it is possible to interpret two main faults on the right flank and some secondary faults on the left flank of the structure. After the CRS-beam PSDM procedure, two other secondary faults can be mapped ocurring, with some of them limiting and cross-cutting the anticline. It is also clearly seen that the traces of the planes of the faults occur subvertically in the section.

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