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DETERMINATION OF AN OPTIMAL PROCESSING FLOW FOR THE SUPPRESSION OF FREE-SURFACE MULTIPLES IN REAL 2D MARINE DATA

Andrei Gomes de Oliveira[1] and Ellen de Nazaré Souza Gomes[1,2]

ABSTRACT. The presence of multiple reflections is common in marine surveys due to the air-water interface. Multiples have significant energy and can mask deep reflectors, leading to the misinterpretation of seismic cross-sections. In this study, surface-related multiple elimination (SRME), predictive deconvolution in the $\tau - p$ domain and Radon and $f - k$ filtering are used to eliminate surface multiples in real 2D marine data. These methods are applied in different combinations, and the results are analyzed with the aim of determining an optimal seismic processing flow for the removal of surface multiples.

Keywords: surface multiples attenuation, SRME, Radon filtering, predictive deconvolution in the $\tau - p$ domain, $f - k$ filtering.

RESUMO. No levantamento marinho é comum a presença de reflexões múltiplas devido à interface ar-água. Essas reflexões múltiplas possuem energia considerável e podem mascarar reflexões primárias (refletores) levando a erros de interpretação da seção sísmica. Neste trabalho é determinado um fluxo ótimo de processamento sísmico para atenuação de múltiplas de superfície. Os métodos de eliminação de múltiplas de superfície (SRME), deconvolução preditiva no domínio $\tau - p$ e as filtragens Radon e $f - k$ são aplicados a um dado marinho real 2D em diferentes combinações. Os resultados são analisados com objetivo de determinar um fluxo de processamento sísmico ótimo para atenuação de múltiplas de superfície.

Palavras-chave: atenuação de múltiplas de superfície, SRME, filtragem Radon, deconvolução preditiva no domínio $\tau - p$, filtragem $f - k$.

[1]Universidade Federal do Pará, Programa de Pós-Graduação em Geofísica, Rua Augusto Correa 01, Campus Básico, Guamá, CP 8608, 66075-110 Belém, PA, Brazil. Phone: +55(91) 3201-7692; Fax: +55(91) 3201-7693 E-mail: andrei.jval@gmail.com; cpgf@ufpa.br

[2]National Institute for Petroleum Geophysics (INCT-GP), Brazil – E-mail: ellensgufpa@gmail.com

INTRODUCTION

One of the factors that affects the quality of seismic images is multiple reflections. These multiples are generated by reflections that, when reaching the surface, are reflected back to the subsurface. They are of a periodic nature and are generally of lower amplitude than primary reflections (Verschuur, 2006). Among the several types of multiples, those generated at the air-water interface (surface multiples) are high-energy and can mask deeper reflectors, potentially causing misinterpretation of the data. There are several techniques that aim to remove surface multiples (Riley & Claerbout, 1976; Tatham et al., 1983; Berkhout, 1984; Tatham, 1989; Verschuur et al., 1989), including Radon filtering and surface-related multiple elimination (SRME) (Verschuur et al., 1989, 1992).

This study aims to determine an optimal flow of seismic processing for the attenuation of surface multiples in real 2D marine data. Previous studies (Zhenwu et al., 2009a; 2009b) have used a combination of only SRME and Radon filtering to attenuate multiples. Four different attenuation methods are applied: $f-k$ filtering (Zhou & Greenhalgh, 1994; Houston, 1998; Lokshtanov & Helle, 1992), parabolic Radon filtering (Oliveira et al., 2007; Abbad et al., 2011), predictive deconvolution in the $\tau-p$ domain (Yilmaz, 2001) and SRME (Berkhout & Verschuur, 1997; Verschuur et al., 1992). These methods are used separately and in different combinations, and the results are analyzed. All seismic processing is conducted in Promax[1].

ATTENUATION OF MULTIPLES: METHODS

The methods for the attenuation of multiples can be classified in several ways (Weglein, 1999; Xiao et al., 2003). This study uses the classification proposed by Verschuur (2006), which divides the methods into two broad categories: those based in the differences in the spatial behavior of the primary and multiple reflections and those based on the frequency and predictability of the multiples.

Methods based on differences in the spatial behavior of primary and multiple reflections

These methods take advantage of the fact that multiple reflections travel along different paths in the subsurface than the primary reflections, and thus they are affected by different velocities and/or reflecting structures (Verschuur, 2006). In these methods, data one domain to another, in which multiple and primary are in distinct regions. In the transformed domain, filtering techniques are applied to attenuate the multiples, and the filtered data are mapped back to the original domain. Information regarding the velocity model of the medium is needed *a priori*. Examples include $f-k$ and Radon filtering.

$f-k$ filtering

Filtering reduces unwanted linear noise (ground-roll, guided waves, etc.) in seismic data, and $f-k$ filtering is based on the dip of linear events (Embree et al., 1963). The recorded seismic data (P, the pressure field) are mapped from the time domain into the frequency-wavenumber domain through 2D Fourier transform.

In the transformed domain, linear events of different slopes are mapped into different regions. A filter is designed to attenuate (or enhance) the events in a particular region, and inverse mapping of the filtered data is done through the inverse 2D Fourier transform.

In this study, the pressure field is applied to $f-k$ filtering, with the goal of attenuating surface multiples. Because hyperbolic events (primary and multiple reflections) are mapped in the same region of the $f-k$ domain (the cone near the frequency axis), the filter must be applied to the residual data after the normal moveout (NMO) correction, using a velocity model of the primary or multiple reflections or an intermediate value between these velocities (Yilmaz, 2001). Thus, primary and multiple reflections are mapped in different regions in the $f-k$ domain.

Used in this work was a function for the prediction of multiple surface (Multiple Prediction, an intrinsic function of Promax), which predicts the multiple and generates its velocity model. The NMO correction is then applied to the seismic data using the velocity model of the multiples, and the residual data are mapped into the $f-k$ domain. In this transformed domain, the primary and multiples events occur in different regions; the multiples are parallel to the frequency axis. A filter is applied to attenuate the energy of the multiples, and the filtered pressure field is mapped back to the original domain. Then, the inverse NMO correction is applied. Figure 1 shows a scheme of how $f-k$ filtering is applied to the data and Figure 2 shows the processing flow.

One of the problems $f-k$ filtering can cause distortions in the filtered signal, which is mainly due to the frequency range of the $f-k$ filter overlapping signal that must be preserved. A possible solution for this problem was presented by Duncan & Beresford (1994), who proposed implementing an adaptive slowness $f-k$ filter, which reduces the distortion and increases the attenuation of the filter. An adaptive filter is not used in here.

[1] Promax: seismic processing package from the company LandMark.

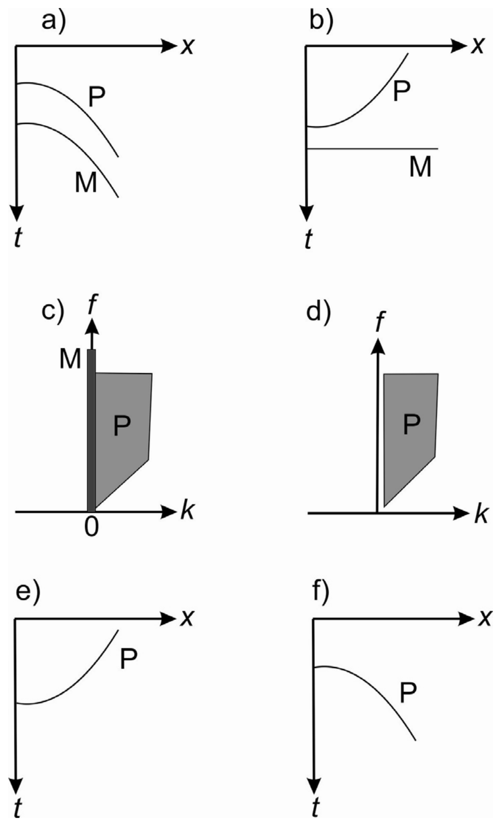

Figure 1 – Scheme applying $f-k$ filtering. a) In the family CDP, primary and multiple present hyperbolic moveout; b) After application NMO correction using the multiple velocities table, multiple events are horizontalized and the primaries are over-corrected; c) The data are mapped to the $f-k$ domain, there are multiple situated parallel to the frequency axis and the primaries in the region comprised by the cone in gray; d) After application of the filter in the region near de axis of frequencies, the residual data consist of primary reflections; e) The residual data are mapped back to the TX field; f) After applying the inverse NMO, using the multiple velocities table, the resulting data are attenuated of the multiples.

Radon filtering

Similarly to the $f-k$ filtering, in Radon filtering, the data are mapped from the acquisition domain (time) into a new domain, the Radon domain, through the Radon transform. In this transformed domain, undesirable events are removed by filtering.

Radon-transformed seismic data appear along a curve and are summed in the Radon domain. According to the curve used for summing the seismic data, Radon transforms are linear, hyperbolic or parabolic (Yilmaz, 2001).

Parabolic Radon filtering is applied in this study.

Parabolic Radon transform

The use of the parabolic Radon transform for the separation of primaries and multiples was introduced by Hampson (1986). Initially, the data are arranged in common midpoint (CMP) gathers and the NMO effect is corrected through the equation

$$t_n = \sqrt{t^2 - \frac{4x^2}{v_n^2}}\,, \tag{1}$$

where t_n is the time after the NMO correction and v_n is the velocity used in the NMO correction. The residual data from the NMO correction are now approximately parabolic and of the form

$$t = \tau + qx^2\,, \tag{2}$$

where τ is the zero offset time and q is the parameter defining the parabolic curvature (Hampson, 1986). In the parabolic Radon transform, the residual data from the NMO correction are summed along the parabola (Yilmaz, 2001).

$$S(q,\tau) = \sum_k P(x, t = \tau + qx^2)\,, \tag{3}$$

where S represents the sum of the points on the parabola in the Radon domain.

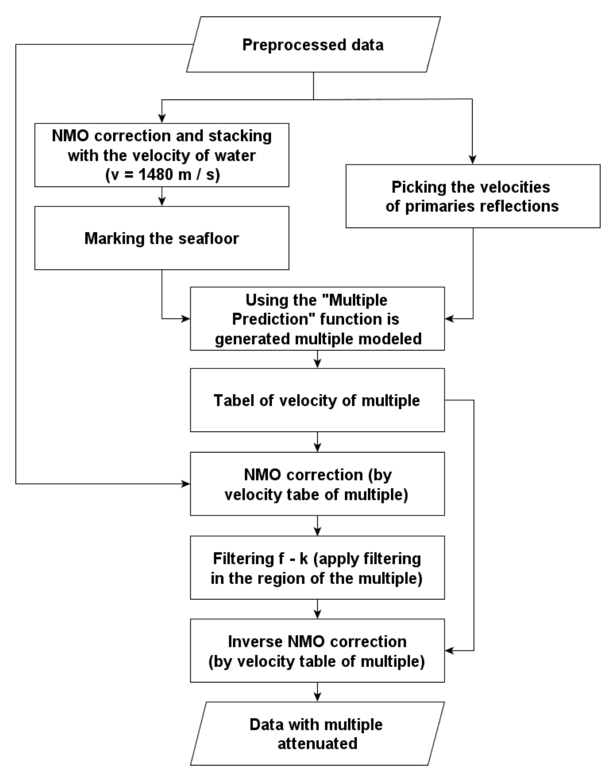

Figure 2 – Flow charts for the attenuation of surface multiples: $f-k$ filtering.

In this study, the first step of Radon filtering consists of NMO correction to the pressure field using the primary reflection velocities. Then, the parabolic Radon transform is applied to the residual data. With these events mapped into different regions, filtering is applied to remove multiples. The filtered data are mapped back to the acquisition domain, inverse NMO correction is applied, and the final product is the data with attenuated multiples (Fig. 3).

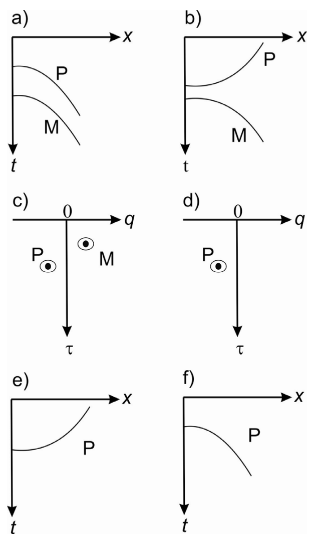

Figure 3 – Scheme of applying Radon filtering. a) In the family CDP, primary and multiple present hyperbolic moveout in the field of acquisition, TX. b) After application NMO correction using a velocity function that is in between the primary and multiple velocities, so that the primary reflections are over-corrected and the multiple reflections are under-corrections. c) After applying Radon transform, the primary reflections are mapped into the negative wave numbers plane and the multiples reflections mapped onto the positive wave numbers plane. d) After application of the filter that was to model multiple reflections and subtract of the original data, obtained residual data. e) After application inverse Radon transform, obtained the data in the T-X acquisition domain. f) After applying the inverse NMO, using a velocity function that is in between the primary and multiple velocities, the resulting data are attenuated of the multiples.

The successful application of Radon filtering is linked to the degree of separability of the primary and multiple reflections in the Radon domain, in addition to the inverse transformation of these events into the original domain.

Factors such as limitations in the data collection and problems due to data discretization lead to the loss of resolution and generate artifacts that result from the inverse Radon transform. Therefore, a least-squares estimate of the inverse Radon transform is sought (Yilmaz, 2001) to minimize the losses in resolution.

In this study, parabolic Radon filtering is applied to attenuate free-surface multiples, as shown in flow in Figure 4.

Methods based on the frequency and predictability of the multiples

These methods assume that primaries and multiples have an inherent relationship and that multiple reflections are repetitive events. Based on statistical assumptions, the multiples are modeled and subtracted from the original data (Verschuur, 2006). Predictive deconvolution in the $\tau - p$ domain and SRME are examples of the application of these methods.

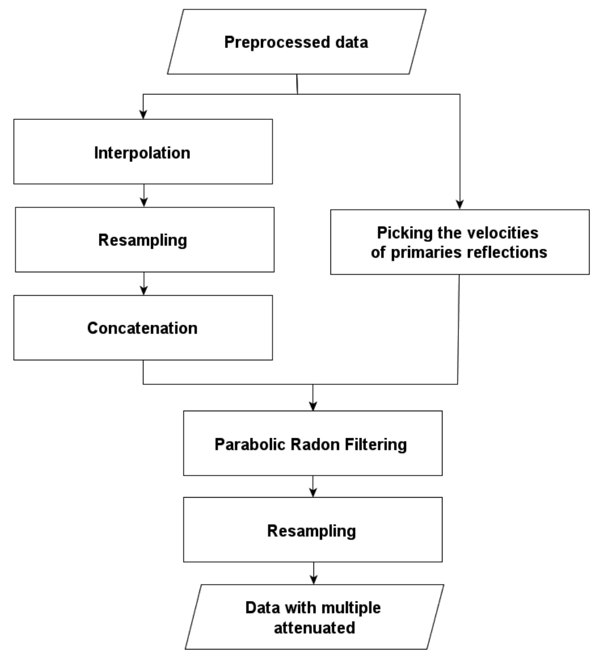

Figure 4 – Flow charts for the attenuation of surface multiples: parabolic Radon filtering.

Predictive deconvolution in the $\tau - p$ domain

For the application of deconvolution, seismic data are mapped from the acquisition domain (time) to the $\tau - p$ domain, where the data are decomposed into plane waves. A linear moveout (LMO) correction is initially applied to the data, $P(x, t)$, through the coordinate transformation defined by (Claerbout, 1978):

$$\tau = t - px \,, \tag{4}$$

where p is the ray parameter, t is the two-way travel time, x is the offset and τ is the time of intersection of $p = 0$. The data are then summed along the offset axis according to the relationship

$$S(p, \tau) = \sum_x P(x, \tau + px) \,, \tag{5}$$

where $S(p, \tau)$ represents the plane wave with the ray parameter p and $P(x, \tau + px)$ is the residual data after the LMO correction. The data are then summed along oblique paths.

After applying the LMO correction to the seismic data for a range of p values and applying the results from Eq. (5), the data in the $\tau - p$ domain are obtained.

Alam & Austin (1981) and Treitel et al. (1982) presented the first studies using predictive deconvolution in the $\tau - p$ domain for the attenuation of multiples. In this transformed domain, the time between the multiples is the same along the sum of each oblique path. The predictive deconvolution operator can be determined from the correlation of each p trace (Yilmaz, 2001).

Yilmaz (2001) shows that the attenuation of multiples through predictive deconvolution applied to data in the $\tau - p$ domain has a better result compared to the attenuation of multiples through predictive deconvolution applied to the same data in the time domain.

In predictive deconvolution, multiples are predicted in the time, based on the primary reflection that is in the time t. The value α is called the prediction lag. The predictive deconvolution parameters, prediction lag α and operator length n are obtained from the autocorrelation of the seismic traces in the CMP gather in the $\tau - p$ domain. Both parameters are specified from the trace corresponding to the smallest p value. The operator length n is kept constant, while the prediction lag is adjusted based on the p value in every gather in the $\tau - p$ domain (Alam & Austin, 1981) by

$$\alpha(p) = \alpha(0)\sqrt{1 - p^2 v^2}\,, \tag{6}$$

where $\alpha(0)$ is the prediction lag for $p = 0$ and v is the velocity of the primary reflection whose multiples are the target for attenuation. As p increases in the trace gather, the prediction lag decreases (Yilmaz, 2001).

The Figure 5 shows a scheme of how the predictive deconvolution in the $\tau - p$ domain is applied to the data, and the seismic processing workflow is shown in Figure 6.

Surface-Related Multiple Elimination (SRME)

In the SRME method, the multiples are modeled from the convolution of the recorded seismic data; thus, there is no need for *a priori* information about the subsurface medium, and these modeled multiples are subsequently subtracted from the original seismic data.

Considering a source-receiver pair for the 2D case, a multiple in the frequency domain is modeled by (Veshuur, 2006)

$$\begin{aligned} M_1(x_r, x_s, f) &= \\ -\sum X_0(x_r, x_k, f)\, a P(x_k, x_s, f)\,, \end{aligned} \tag{7}$$

where X_0 is the earths impulse response free of surface multiples and containing primary and internal multiple reflections, $P(f)$ is the total recorded field, x_s is the source location, x_r is the receiver location and x_k is the lateral coordinate over which the data are summed (Fig. 7). The sum along x_k means that all possible combinations of paths are considered. Only one event in X_0 and one event in P are considered. The minus sign in Eq. (7) represents the reflection at the interface.

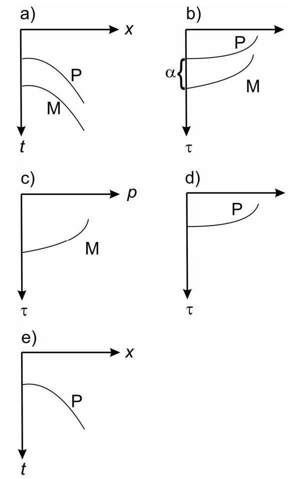

Figure 5 – Scheme of application predictive deconvolution in the $\tau - p$ domain. a) Initially, the data are organized in families CMP in the field of acquisition. b) The data are mapped to the $\tau - p$ domain, this new domain, the prediction lag, a, of the multiples reflections is determined. c) Using the predictive deconvolution in the $\tau - p$ domain are multiples predicted and subtracted from the original data. d) In the residual data have primaries reflections. e) The residual data are mapped from $\tau - p$ domain to acquisition domain.

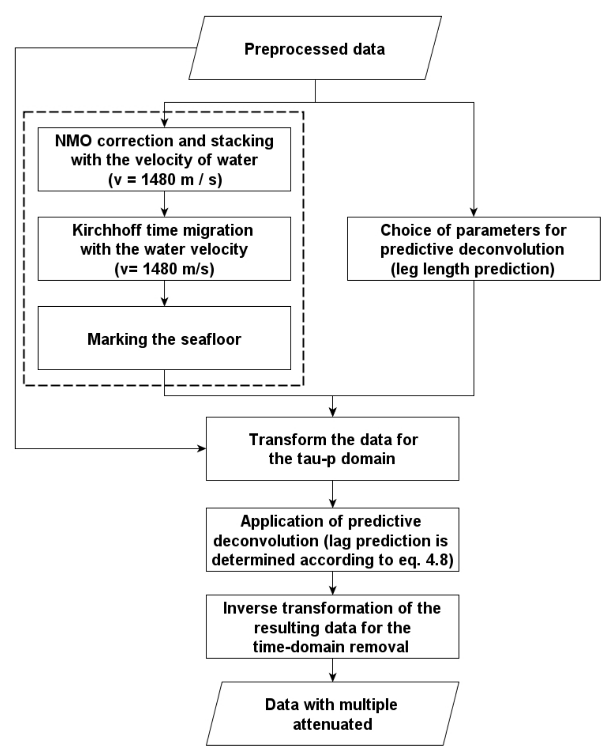

Figure 6 – Flow charts for the attenuation of surface multiples: predictive deconvolution in the $\tau - p$ domain.

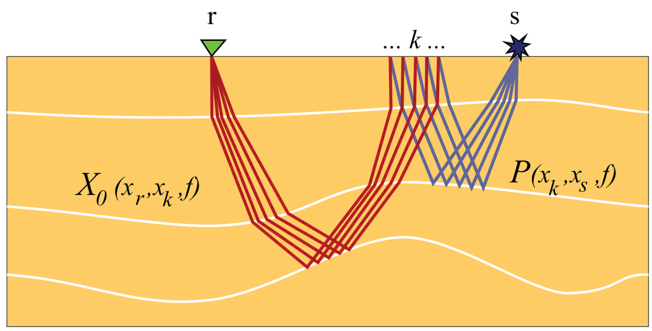

Figure 7 – Diagram of how a first-order multiple for the 2D data are constructed. The multiple is a combination of a shot gather of the P data and a receiver gather of the primary impulse response X_0. These gathers are convolved and summed, generating the modeled multiple. Only one reflection from each wave field is shown (Verschuur, 2006).

This process is repeated for all source-receiver combinations, and the first-order multiple can be written as a matrix (Berkhout, 1982):

$$\mathbf{M}_1 = -\mathbf{X}_0\mathbf{P}\,, \tag{8}$$

The matrix notation of the seismic data in Eq. (8) is explained in Figure 8. Eq. (7) represents an element in the matrix of the predicted surface multiples $\mathbf{M}_1$ that are calculated by the combination of a row from matrix $\mathbf{X}_0$ with a column from matrix $\mathbf{P}$.

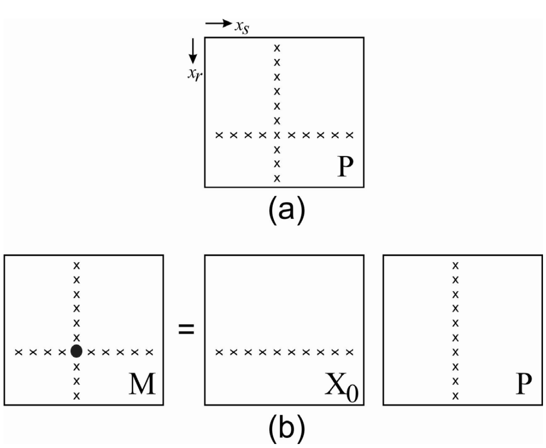

Figure 8 – a) Seismic data $P(x_r, x_s, f)$ in the frequency domain, organized in the matrix form $\mathbf{P}$. Each column has a monochromatic common shot gather, and each row has a common receiver gather. The intersection between a row and a column gives the seismic response of a source-receiver combination for a given frequency. b) The predicted multiple can be written with a matrix $\mathbf{M}$. Each component of the matrix $\mathbf{M}$ is obtained from the combination of a row from matrix $\mathbf{X}_0$ and a column from matrix $\mathbf{P}$ (Verschuur, 2006).

The implicit relationship between the data with and without surface multiples, according to the Feedback Diagram (Berkhout, 1999) (Fig. 9) is given by:

$$\mathbf{P}(f) = S(f)\mathbf{X}_0(f) - \mathbf{X}_0(f)\mathbf{P}(f)\,, \tag{9}$$

where $S(f)$ describes the source properties. The seismic field without surface multiples, $\mathbf{P}_0$, is defined by:

$$\mathbf{P}_0 = \mathbf{X}_0 S(f)\,. \tag{10}$$

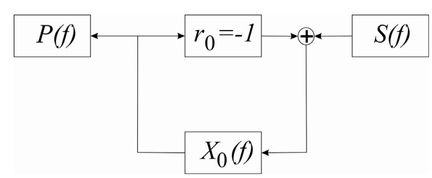

Figure 9 – Generation of the surface multiple represented in a feedback diagram (Verschuur, 2006).

Eq. (09) can be rewritten as:

$$\mathbf{P}(f) = \mathbf{P}_0(f) - \mathbf{X}_0(f)\mathbf{P}(f)\,, \tag{11}$$

with the inverse of the source signature by the operator $A(f)$ given by

$$A(f) = S(f)^{-1}\,. \tag{12}$$

The relationship between the data with and without surface multiples can be writen as

$$\mathbf{P} = \mathbf{P}_0 + A(f)\mathbf{P}_0\mathbf{P}\,. \tag{13}$$

Eq. (13) can be expanded in a series, and the field free of surface multiples is explicitly written as:

$$\mathbf{P}_0 = \mathbf{P} - A(f)\mathbf{P}^2 + A^2(f)\mathbf{P}^3 - A^3(f)\mathbf{P}^4 + K\,. \tag{14}$$

For the determination of the field, the powers of the matrix of the recorded data $(\mathbf{P})$ and the powers of the inverse of the source signature, $A(f)$, $A^2(f)$, $A^3(f)$, K, must be calculated. In practice, however, the source signature is unknown. Several strategies based on the suppression of multiples have been presented to estimate the operator $A(f)$ (Verschuur et al., 1992; Carvalho & Weglein, 1994; van Borselen et al., 1996; Ikelle et al., 1997). In these studies, the estimation of the operator $A(f)$ is non-linear, which is an undesirable characteristic in the inversion process (Verschuur, 2006). An alternative implementation is proposed by Berkhout and Verschuur (1997), who begin with Eq. (13). According to this equation, to determine the field free of surface multiples, it is necessary to know $\mathbf{P}_0$. Considering that there exists an approximation of $\mathbf{P}_0$, a first approximation is given by

$$\mathbf{P}_0^{(0)} = \mathbf{P}\,. \tag{15}$$

For the i-th iteration, the operator $A(f)$ is estimated by the minimization of:

$$E\left\{|\mathbf{P} - A^i \mathbf{P}_0^{i-1}\mathbf{P}|^2\right\}, \tag{16}$$

for $i = 1, 2, 3, K, N$ (N is the number of iterations). $E\{\}$ is the average of all frequencies within the bandwidth of the seismic data (Verschuur, 1991). The field free of surface multiples is updated at each iteration using the equation

$$\mathbf{P}_0^i = \mathbf{P} - A^i \mathbf{P}_0^{i-1}\mathbf{P}\,. \tag{17}$$

The advantage of the formulation presented in Berkhout and Verschuur (1997) (Eqs. (15) through (17)) compared to other strategies for the estimation of $A(f)$ is that this operator is estimated through linear optimization.

At each iteration, the field free of surface multiples is updated. The estimate of the parameter $A(f)$ is a sensitive point of the SRME method because the data containing attenuated multiples depend on the subtraction of the original data and the modeled multiples weighted by $A(f)$. For this subtraction to produce satisfactory results, the amplitude of the modeled multiples and the multiples in the recorded data must match, otherwise the subtraction will generate what is called a "scar" (remnants of the modeled multiple or the multiple in the original data).

In this study, SRME is applied to real data (Fig. 10). According to this figure, even if the SRME does not require the velocity model of the medium *a priori* because the real data used are in the *end-on* format, it is necessary to transform the data into the *split spread* format. This was done using the velocity model for primary reflections. The value of $A(f)$ is estimated iteratively. Figure 11 shows the scheme as the attenuation is performed by applying the SRME.

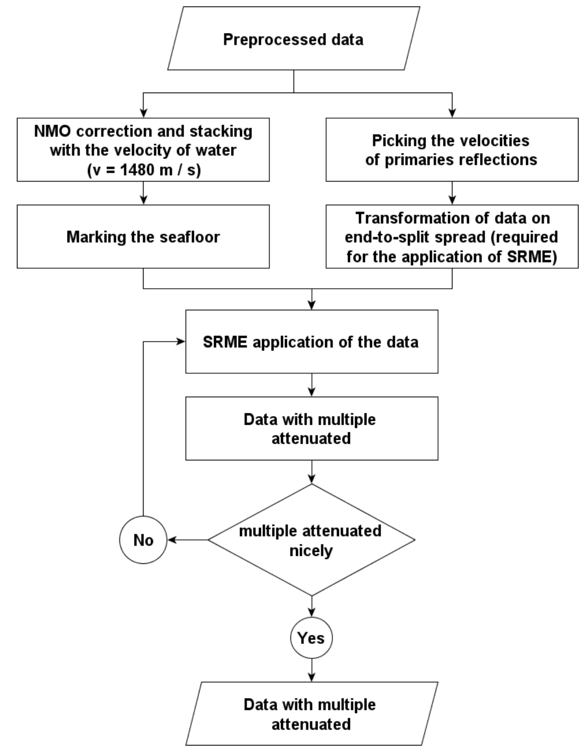

Figure 10 – Flow charts for the attenuation of surface multiples: SRME.

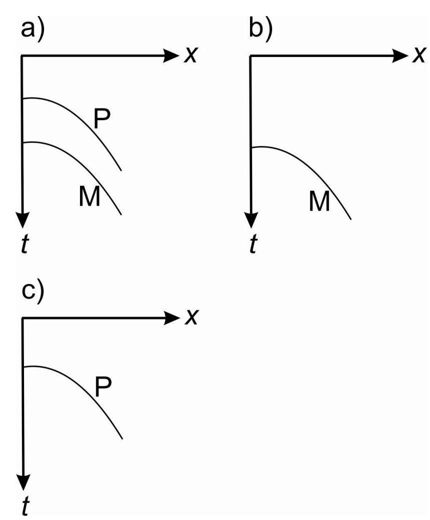

Figure 11 – Scheme of application SRME. a) Initially, the data are organized in families CMP in the field of acquisition. b) By the convolution original data with itself the multiple are modeled. c) The multiple modeled are subtracted from the original data and the residual data consist of primary reflections.

THE REAL DATA

The actual data were collected along a 2D marine line in the Jequitinhonha Basin, near the south coast of the state of Bahia in Brazil and between the sedimentary basins of Almada and Cumuruxatiba. The Jequitinhonha Basin is a terrestrial-marine basin, with most of it offshore; only 500 km^2 of its total area of 10,000 km^2 is terrestrial. In the continental shelf region, the bathymetry ranges from 50 m to 3000 m (Mohriak, 2003). This area has a complex geology and has experienced many topographic changes due to geological events (rifting, tectonics, etc.) that occurred over a long period during the opening of the Atlantic Ocean.

Survey acquisition geometry

The seismic acquisition involved the use of a marine streamer cable (*Mariner Tower Streamer*). The data were acquired in 1985 in a dip profile in the continental self break region and the line is referred to as line 0214-0266. The survey covers 39,425 m, and the acquisition geometry is shown in Table 1.

Table 1 – Acquisition geometry of line 0214-0266.

Parameters of the acquisition geometry	Values
Number of sources	1577
Number of receptors	120
Interval between receptors	25 m
Minimum distance	150 m
Maximum distance	3125 m
Interval between sources	25 m
Aproximate depth of receivers	$\cong$10.5 m
Aproximate depth of sources	9 m
Sampling interval	0,004 ms
Total record time	7000 ms

The Figure 12 show the raw data organized with a minimum offset of 150 m. The shallowest part (where the water layer ranges from 34 to 74 m thickness) shows several types of multiples. In the deepest part (where the water layer ranges from 75 to 1,830 m) the free-surface multiples are easily identifiable beginning at 1000 ms (see Fig. 12). In these figures, the first-order multiples are indicated by a red arrow and the second-order multiples are indicated by blue arrows.

The preprocessing of the data consisted of incorporating the survey geometry and trace editing. To attenuate the surface multiples, $f-k$ filtering, Radon filtering, predictive deconvolution in the $\tau - p$ domain and SRME methods were applied. A complete discussion of all possible combinations of these four methods is given in Oliveira (2011). This study shows only the combinations (flows in Figs. 13 and 14) that generated the best results.

The results were analyzed using two CMP gathers (1620 and 2820), as shown in Figure 10 by the solid orange lines. The best result is shown in a minimum-offset seismic section.

RESULTS

In CMP gather 1620 (Fig. 15), surface multiples appear at approximately 1710 ms (indicated by a red arrow). In Figure 15, the edited data (Fig. 15a) are compared with data that have had various methods applied: $f-k$ filtering (Fig. 15b), predictive deconvolution in the $\tau - p$ domain (Fig. 15c), parabolic Radon filtering (Fig. 15d), SRME (Fig. 15e), SRME and predictive deconvolution in the $\tau - p$ domain followed by parabolic Radon filtering (Fig. 15f), and SRME and predictive deconvolution in the $\tau - p$ domain followed by parabolic Radon filtering and $f-k$ filtering (Fig. 15g). This comparison demonstrates that:

- With the application of $f-k$ filtering, multiple reflections are attenuated (Fig. 15b), however the primary reflections are also attenuated, mainly at large offsets. Starting at time 2500 ms and at large offsets, artifacts are present (the signal amplitude increases, which differs from the unfiltered signal).
- The application of the predictive deconvolution in the $\tau - p$ domain attenuates a portion of the multiple reflections (Fig. 15c), especially at small offsets.
- By applying parabolic Radon filtering, the multiples are strongly attenuated at small offsets and parts of the primary reflections are lost at small offsets and for shallow events. This loss is due to stretching, which is muted due to the NMO correction applied before parabolic Radon filtering (Fig. 15d).
- As a result of the SRME method (Fig. 15e), multiples are attenuated, although the attenuation is small for large offsets. There is no loss of the primary reflection for large offsets and shallow events.
- With the combination of SRME and predictive deconvolution in the $\tau - p$ domain, followed by parabolic Radon filtering, the multiple is almost entirely attenuated. There is, however, a loss of amplitude of the shallowest primaries (Fig. 15f). This result is better than those obtained by the separate application of SRME, predictive deconvolution in the $\tau - p$ domain and parabolic Radon filtering, as well as combinations of only two of these methods.
- The application of the combination of SRME and predictive deconvolution in the $\tau - p$ domain, followed by parabolic Radon filtering and $f-k$ filtering, almost entirely attenuates the multiple. However, there is also loss of amplitude of the shallower primaries, mainly at large offsets (Fig. 15g).

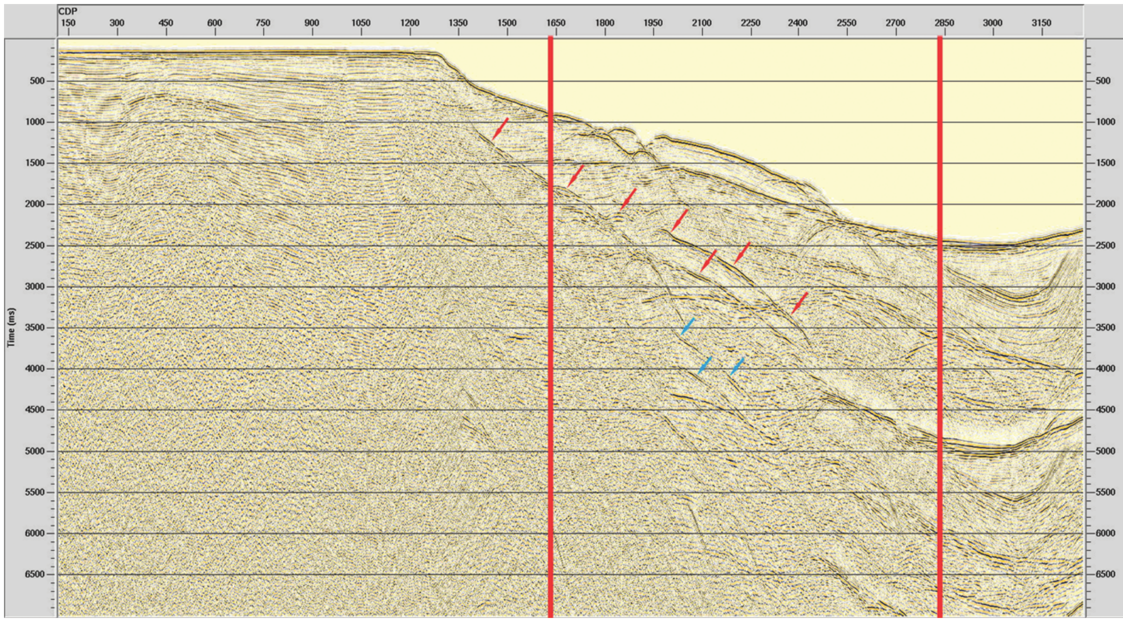

Figure 12 – Raw seismic section organized by minimum offset (150 m) with gain (automatic gain control, AGC). The red and blue arrows indicate first- and second-order surface multiples, respectively. The solid orange lines represent the CMP gathers chosen for the analysis.

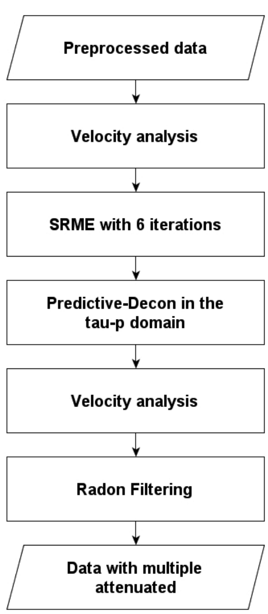

Figure 13 – The combinations of methods that provide the best results: SRME and predictive deconvolution in the $\tau - p$ domain followed by parabolic Radon filtering.

The results for the CMP 2820 gather, which is in the deepest part of the survey, are shown in Figure 16, surface multiples appear at approximately 4800 ms (indicated by a red arrow). The edited data are shown in Figure 16a. In this gather, the surface multiples are clearer (between 2300 and 5600 ms) than in the previous CMP gather.

- The result from only $f - k$ filtering attenuates part of the multiple, but the deepest primary reflections are also attenuated (Fig. 16b), unlike the result for CMP gather 1620.

- According to the results in Figure 16c, there is no attenuation of the surface multiple after the application of predictive deconvolution in the $\tau - p$ domain, unlike the result from the previous CMP gather.

- The application of parabolic Radon filtering (Fig. 16d) results in the attenuation of the multiple. However, the amplitude of the primary reflections is also decreased. This loss is greater at large offsets and for shallower events, and it is due to the stretching that is muted due to the NMO correction applied before the Radon filtering.

- With SRME, the multiple is attenuated. However, this attenuation is small at large offsets (Fig. 16e).

- The combination SRME and predictive deconvolution in the $\tau - p$ domain followed by parabolic Radon filtering (Fig. 16f) and the combination of SRME and predictive deconvolution in the $\tau - p$ domain followed by parabolic Radon filtering and $f - k$ filtering (Fig. 16g) show that the best results are obtained from the combination that excludes $f - k$ filtering.

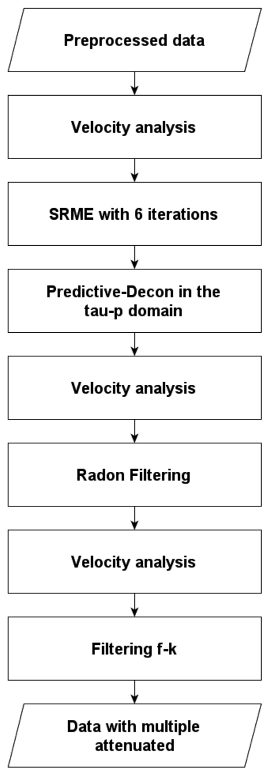

Figure 14 – The combinations of methods that provide the best results: SRME and predictive deconvolution in the $\tau - p$ domain followed by parabolic Radon filtering and $f - k$ filtering.

According to these comparisons, the best results are obtained from the combination of SRME and predictive deconvolution in the $\tau - p$ domain followed by Radon filtering. All possible combinations of these four methods were tested and their results were analyzed in Oliveira (2011).

The best result, organized by minimum offset, is shown in Figure 17. Compared to Figure 12, where the data are only edited, there is significant attenuation of the surface multiple at the deepest part of the basin. In the shallowest part, no improvement is observed, which is thought to be due to the different types of multiples that are present in this region due to the shallow water depths.

CONCLUSIONS

This study presents an analysis of the methods of attenuating surface multiples in real 2D marine data from the Jequitinhonha Basin. The data were acquired in the continental shelf break region, and they are characterized by the presence of strong surface multiples. The methods were applied separately and in different combinations, and an optimal flow for the attenuation of surface multiples was determined. Based on the results, it is concluded that:

- When applying methods that are based in the moveout difference between primaries and multiples, the subsurface velocity model for the real data is difficult to estimate. In this sense, the methods that are based on the frequency and predictability of the multiple perform better.
- The results of methods applied in a transformed domain are affected by problems arising from mapping (finite data, data discretization, etc.; Yilmaz, 2001).
- SRME is an effective technique (especially when combined with other techniques) for attenuating surface multiples, however this method is based on the subtraction of the data recorded from the modeled multiple weighted by $A(f)$ (the inverse of the source signature), which is usually unknown. Therefore, $A(f)$ must be estimated. Incorrect values lead to modeled multiples that, when subtracted from the data, leave remnants in it (scarring). In this study, an iterative method proposed by Berkhout & Verschuur (1997) was used to minimize the problem.
- The application of the individual methods of $f - k$ filtering, predictive deconvolution in the $\tau - p$ domain, SRME and parabolic Radon filtering produce results that are generally unsatisfactory. In the order of least to most effective, these methods are the following: $f - k$ filtering, parabolic Radon transform, SRME and predictive deconvolution in the $\tau - p$ domain. Combined methods produce better results than the application of any of these methods individually. The best result is obtained from the combination of SRME and predictive deconvolution in the $\tau - p$ domain followed by parabolic Radon filtering applied to the deepest part of the data.

No satisfactory results were obtained for the shallowest part of the data, which is thought to be due to complex multiples in the shallowest part of the data that caused by the combination of different types of multiples.

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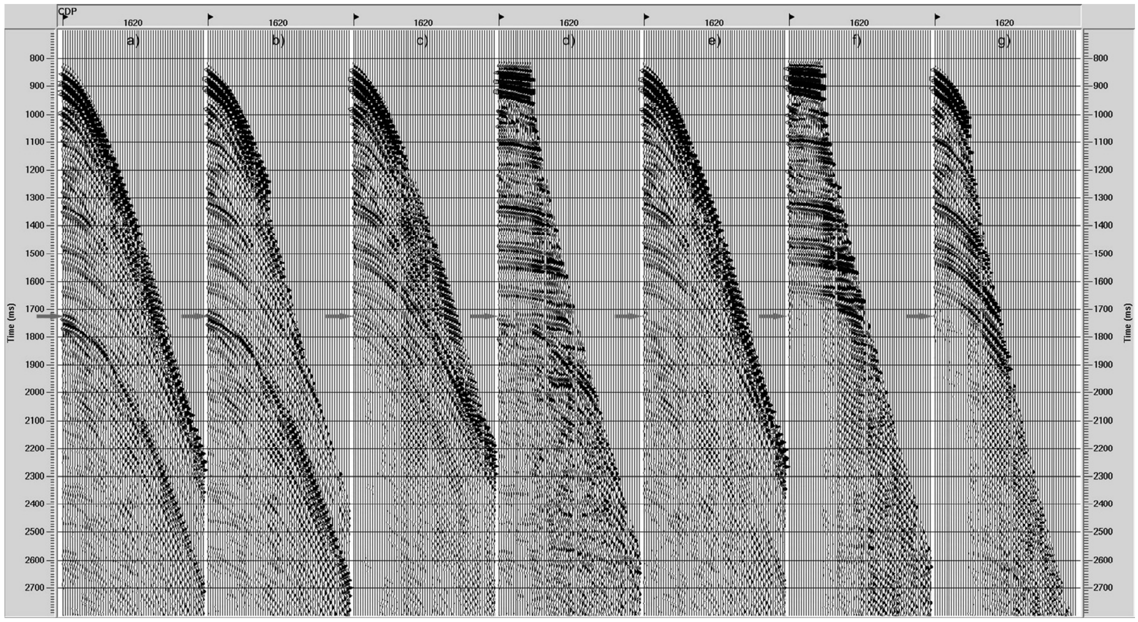

Figure 15 – CMP gather 1620 with no gain. The surface multiples start to appear at approximately 1710 ms. The onset of the multiple is indicated by the arrow. The data shown are a) edited only, b) the result of $f-k$ filtering, c) the result of the application of predictive deconvolution in the $\tau-p$ domain, d) the result of Radon filtering, e) the result of the application of SRME, and f) the results of the application of a combination of methods: SRME and predictive deconvolution in the $\tau-p$ domain followed by parabolic Radon filtering and g) SRME and predictive deconvolution in the domain followed by parabolic Radon filtering and $f-k$ filtering.

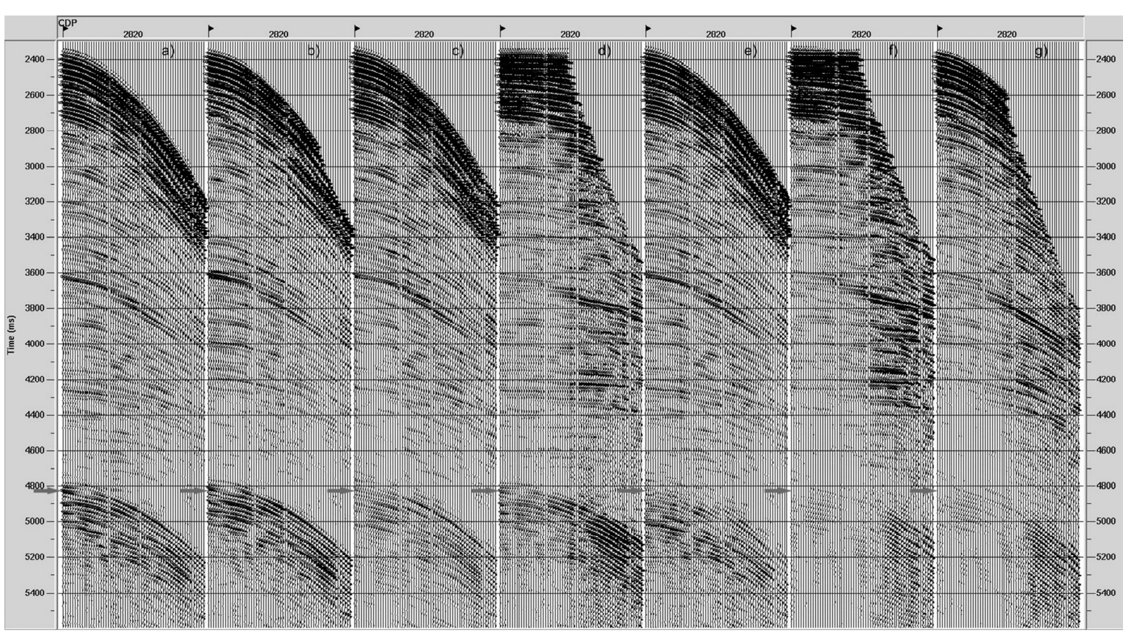

Figure 16 – CMP gather 2820 with no gain. The surface multiples are easily identified between 4500 and 5000 ms. The onset of the multiple is indicated by the arrow. The data shown are a) edited only, b) the result of $f-k$ filtering, c) the result of the application of predictive deconvolution in the $\tau-p$ domain, d) the result of parabolic Radon filtering, e) the result of the application of SRME, and f) the results of the application of a combination of methods: SRME and predictive deconvolution in the $\tau-p$ domain followed by parabolic Radon filtering and g) SRME and predictive deconvolution in the $\tau-p$ domain followed by parabolic Radon filtering and $f-k$ filtering.

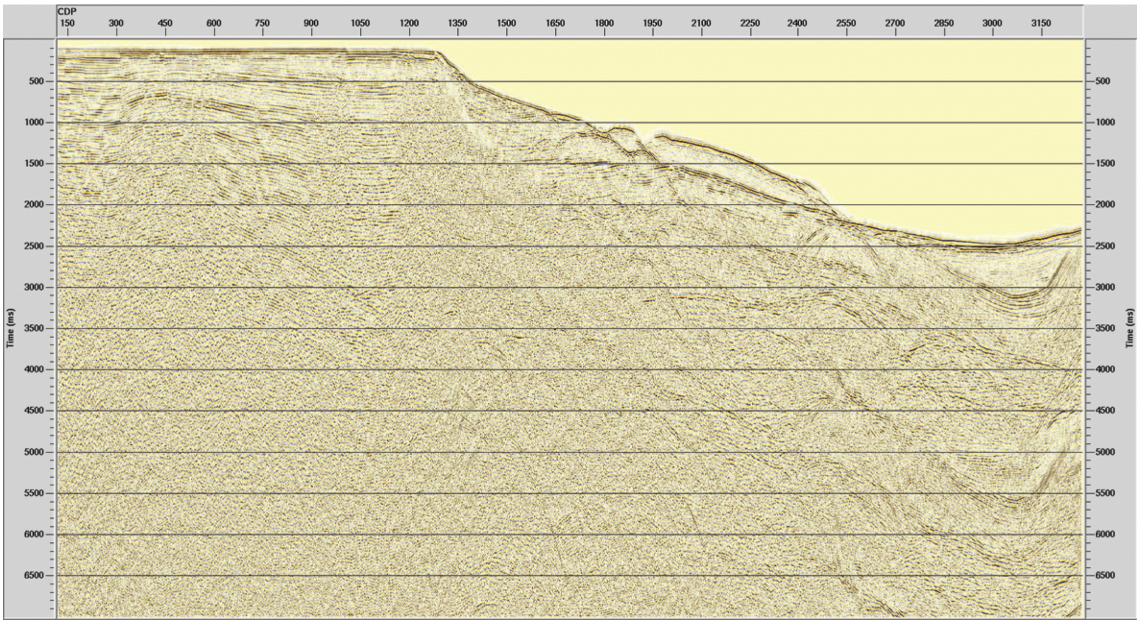

Figure 17 – Data organized by minimum offset (150 m) with gain (AGC), after the application of SRME and predictive deconvolution in the $\tau - p$ domain followed by parabolic Radon filtering.

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NOTES ABOUT THE AUTHORS

Andrei Gomes de Oliveira. Graduated in Mathematics from Universidade do Estado do Pará-UEPA (1997). Specialization GNTI by FGV (2004). MSc. in Geophysics by Federal University of Pará-UFPA (2011), with emphasis on Seismic Methods, working mainly on the theme: seismic processing. CIO Project UFPA/FADESP/Petrobras/FINEP (1988-1997). CIO UNIFAP/AP (1997). CIO, CEA/AP (1998-2001). Researcher IEPA/AP (2000-2001). Teacher UNIFAP (1998-2001). CIO OSETPP/PA (2002-2003). Teacher FIBRA (2004, 2006, 2012), FACI (2005), FAP (2006). Participation in projects: INCT-GP, FINEP and CNPq.

Ellen de Nazaré Souza Gomes. Graduated in Science with specialization in Mathematics from the Universidade do Amazonas (1990), MSc. in Mathematics (1999) and PhD. in Geophysics (2003) from the University Federal do Pará-UFPA. Associate Professor I UFPA working at the College and the Graduate Program in Geophysics. Part of INCT-GP. Has experience in the area of geophysics, with emphasis on Seismic Methods, acting mainly the following topics: Seismic Processing, Numerical Modeling and Inversion.