Redatuming's influence on well-to-seismic tie

Carlos E. A. Soares*[1], José J. S. de Figueiredo[1], Isadora A. S. de Macedo[1] and Francisco de S. Oliveira[2, 3], [1] CPGF-UFPA, [2] FAMET-UFPA, [3] PPGGRD-UFPA

This paper was prepared for presentation during the 17th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 16-19 August 2021.

Abstract

The quality of the data used in the well-to-seismic tie, as well as the method used to estimate the seismic wavelet are closely related to the high coherence of the traces obtained. The editions of the seismic data used in this work are related to the estimation and correction of the quality factor (Q-filtering) that are used to compensate for the dissipation of seismic energy during the propagation of waves in the subsurface. The methods used in this work to estimate the wavelet are two deconvolution mechanisms, the first called sparse-spike deconvolution and the second, homomorphic deconvolution, both determining the seismic wavelet in a deterministic way. This work has the objective of verifying the effect of corrections in the seismic data affecting the results of the well-to-seismic tie. The idea is to fix the corrections in the well data and the seismic wavelet estimation method and check the quality of the well-to-seismic tie based only on the correction of the seismic data. The results of the well tie in the Viking Graben data set showed that the editing in the seismic data generated good results, especially for homomorphic deconvolution, where the values were higher in the sections with the corrected seismic data.

Introduction

The quality of the data used in the well-to-seismic tie, as well as the method used to estimate the seismic wavelet are closely related to the high coherence of the traces obtained. The idea of this work is to use research already done with well-to-seismic tie and extend it to another type of analysis. Previous work has shown that corrections in well data and the method used to estimate the seismic wavelet are closely related to the quality of the well-to-seismic tie. We propose here to fix these analyzes already done with the well data and modify the quality of the seismic data and to verify the implication of this change in the correlation between the real and synthetic traces obtained with the well-to-seismic tie. Well-to-seismic tie consists of comparing information obtained from data from seismic acquisitions and well logging, to obtain more detailed information of the lithology of the area of interest. According to White et al. (2002), the well-to-seismic tie is a useful tool used to relate the seismic waveforms produced to the lithology, stratigraphy, and properties of subsurface rocks. According to Macedo et al. (2017), if the geology in the vicinity of the well is not excessively complex, the main factors that control the accuracy of the well-to-seismic tie are the quality of the seismic processing and the precise replication of the earth model from the well loggings.

The editions of the seismic data used in this work are related to the estimation and correction of the quality factor (Q-filtering) that are used to compensate the dissipation of seismic energy during the propagation of waves in the subsurface. Thus, this process aims to recover part of the energy dissipated by the inelastic attenuation, thus improving the resolution of the seismic signal. Oliveira et. al. (2016) found a way to improve the estimation of the Q factor from seismic reflection data with a methodology based on the Peak-Frequency-Shift (PFS) method developed by Zhang and Ulrych (2002) and the redatuming operator (Schneider, 1978; Berryhill, 1984; Pila et al., 2014; Oliveira et al., 2015). In summary, the processing of the methodology basically corresponds to the iterative use of redatuming to obtain the correct travel times to later estimate the quality factor with the PFS method. More detailed explanations of the PFS method and the redatuming method can be found in Oliveira et. al. (2016).

The methods used in this work to estimate the wavelet are two deconvolution mechanisms, the first called sparse-spike deconvolution (Macedo et. Al., 2020) and the second, homomorphic deconvolution (Macedo et. Al., 2020), both determining the seismic wavelet in a deterministic way. The sparse-spike deconvolution estimates the wavelet through the minimization of least squares with quadratic regularization of zero order and the homomorphic deconvolution performs a separation of the seismogram components in the cepstral domain by applying a linear filter to estimate the wavelet. Both deconvolutions are called non-classic because they do not use the premises used by classic deconvolutions.

The data used are real and belong to the Viking Graben data set, located north of the North Sea basin. We use the same seismic section with three different processes to identify the influence of these processes on the well-to-seismic tie operation. This work has the objective of verifying the effect of corrections in the seismic data affecting the results of the well-to-seismic tie. The idea is to fix the corrections in the borehole data and the seismic wavelet estimation method and check the quality of the well tie based only on the correction of the seismic data. The results of the well tie in the Viking Graben data set showed that the editing in the seismic data generated good results, especially for homomorphic deconvolution, where the values were higher in the sections with the corrected seismic data.

Method

Well-to-seismic tie

For the implementation of the well-to-seismic tie we use two types of geophysical data: the data from seismic surveys and the data obtained from the well loggings, both having their origin in the same region of interest. The two types of data have their differences, such as scale and axis of measures, however, resolving these differences, we can obtain a greater detail of the region of interest from the combination of these two types of data. The well loggings will serve to model the seismic trace obtained with the seismic survey. The seismic trace modeled from borehole data is called synthetic seismic trace, while the seismic survey trace is called real seismic trace. The well-to-seismic tie process basically involves comparing these two traces.

The good quality of the data used for the well-to-seismic tie process is of paramount importance for the success of the procedure. The main connecting element between the seismic reflections and the reflectivity's obtained by the well loggings is the wavelet, which represents a transient wave that starts from the seismic source and that travels and interacts with the environment. Thus, we must correctly identify these horizons and estimate the wavelet to later convert the seismic data into impedance. The measurement axes of seismic and borehole data differ since seismic data is collected in time and well data is collected in depth. Thus, we must have a time-depth relationship that connects these two data. This time information to obtain the time-depth relationship is usually provided through the so-called Vertical Seismic Profiling (VSP), which measures the time of arrival of a wave that leaves the surface and reaches a sensor inside the borehole. Generally, borehole data is converted from depth to time.

According to White and Simm (2014), the well tie procedure is divided into the following steps:

1) Editing the well loggings that will be used to generate the synthetic trace. The logs used are density and sonic (converted to compressional wave velocity), both logs can come with noises that must be removed for a possible improvement of the result.

2) Generation of the reflectivity profile from the well logs, generated by multiplying the values of both profiles at the same depth (impedance, $I = \rho v_p$). The reflectivity is calculated by:

$$r(i) = \frac{(\rho_{(i+1)}\, v_{(i+1)} - \rho_i\, v_i)}{(\rho_{(i+1)}\, v_{(i+1)} - \rho_i\, v_i)} \quad (1)$$

where i is the depth of the measurement.

3) Application of the time-depth relationship, which corresponds to a resampling of the reflectivity log (the reflectivity log is converted from depth to time) to be compared with the seismic data, since the well data are collected in greater detail than the seismic data.

4) Once the time-depth relationship is applied, $r(t)$ can be convolved with a seismic wavelet $w(t)$ to generate the synthetic seismic trace $s(t)$, according to:

$$s(t) = r(t) * w(t) \quad (2)$$

We have that $s(t)$ is the synthetic trace that will be compared with the real seismic trace. Thus, a good well-to-seismic tie will depend on the quality of the well logs, the estimated wavelet, and a good time-depth relationship.

Figure 1 shows the flowchart of the general methodology used in this work.

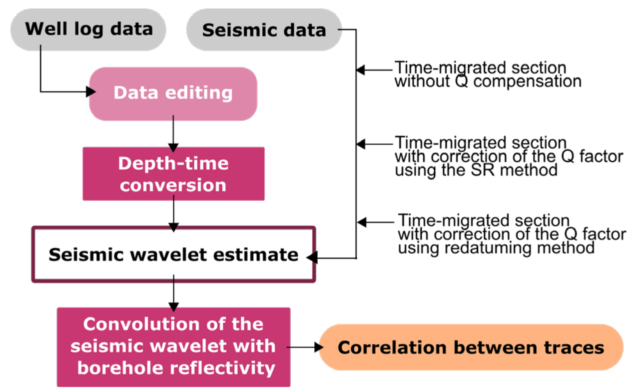

Figure 1 - *Flowchart that illustrates the steps to do well-to-seismic tie used in this work.*

Wavelet estimation methods

Deconvolution in time

The sparse-spike deconvolution corresponds to minimization by least squares using a zero-order quadratic regularize. When it aims to estimate reflectivity (spikes) from an observed signal, it is called sparse-spike deconvolution. It seeks to find the smallest number of spikes that best fit when being convolved with a certain wavelet. The function to be minimized is:

$$Jr = \|Wr - s\|^2 \quad (3)$$

where, Jr is the cost function to be minimized, Wr is the convolution matrix with the known wavelet and the reflectivity to be estimated, and s is the seismic signal. The minimization process occurs from the derivation in relation to the parameter to be minimized from the function and later equaling it to zero. As a result of the reflectivity given by:

$$r = \left(W^T W\right)^{-1} W^T s \quad (4)$$

When we have this type of inversion, we must guarantee that the inversion will be convergent (converge to a global minimum) and stable (small disturbances in the input cannot generate big changes in the result), one way to do this is using regularizes. Thus, when adding regularizes to the cost function, the parameter to be retrieved is forced to satisfy the links brought about by the regularizes. Thus, if we want to recover the wavelet, we must use a regularize that allows the characteristics of the wavelet to be recovered. Within the functionalities there are the regularization parameters that will indicate how strong the response will be to the regularize.

Equations 5 and 6 show 2 examples of regularizes. Thus, if we wanted to recover the reflectivity of the section, the most suitable would be to use the L1 standard regularize (equation 5) and if we wanted to recover a wavelet the indicated would be to use the L2 standard regularize (equation 6). Thus, the parameter to be recovered depends on the characteristics of the derivatives of the regularizes when added to the cost function.

$$+\alpha\sum_{i=1}^{M}\left|r_j\right| \tag{5}$$

$$+\alpha\sum_{i=1}^{M}\left(r_j\right)^2 \tag{6}$$

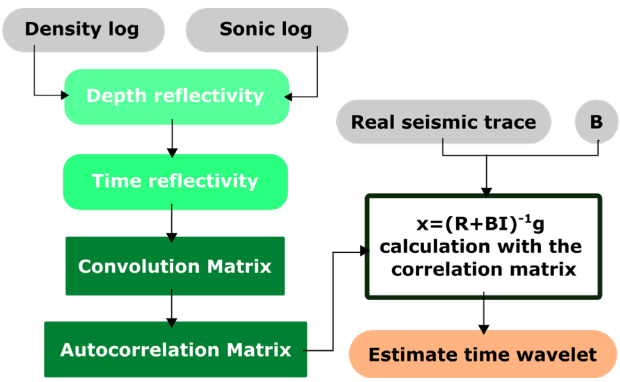

***Figure 2** - Flowchart of the deconvolution in time algorithm.*

Homomorphic deconvolution

Homomorphic deconvolution is a statistical filtering process for separating components of a signal in the cepstral domain. The cepstral domain corresponds to the domain that is arrived at when applying on a signal, the Fourier transform, the natural logarithm, and the inverse transform, respectively. In the cepstral domain, convolution corresponds to a sum.

The homomorphic deconvolution process can be described as follows for an example in which we want to estimate the wavelet:

1) Calculate the complex cepstrum of the real seismic trace, passing the signal from the temporal domain to the cepstral domain (Equation 7).

2) Calculate the complex spectral of the known component of the trace: in this case, the reflectivity obtained by the borehole data (Equation 8).

3) Isolate the component of interest in the cepstral domain: with the trace and reflectivity, we can obtain the wavelet by means of a simple subtraction (Equation 9).

4) Convert the component of interest from the cepstral domain to the time domain: convert the wavelet from the cepstral domain to the time domain by doing the inverse operations of those that were done to arrive at the cepstral domain (Equation 10).

$$x(n)\xrightarrow[FFT]{}X(w)\xrightarrow[Log]{}\hat{X}(w)\xrightarrow[iFFT]{}\hat{x}(n) \tag{7}$$

$$h(n)\xrightarrow[FFT]{}H(w)\xrightarrow[Log]{}\hat{H}(w)\xrightarrow[iFFT]{}\hat{h}(n) \tag{8}$$

$$\hat{x}(n)\approx\hat{w}(n)+\hat{h}(n) \tag{9}$$

$$\hat{w}(n)\xrightarrow[FFT]{}W(w)\xrightarrow[Log]{}\hat{W}(w)\xrightarrow[iFFT]{}\hat{w}(n) \tag{10}$$

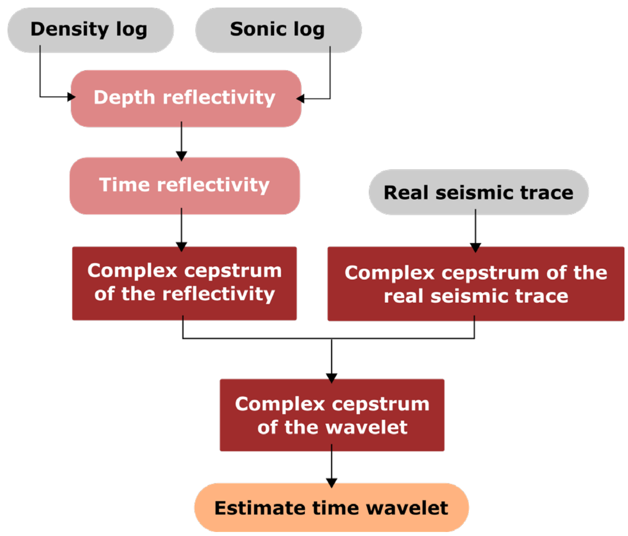

***Figure 3** - Flowchart of the homomorfic deconvolution algorithm.*

The quality factor, the peak frequency-shift method and redatuming operator

Zhang and Ulrych (2002) when applying the PFS method consider that the wave field propagation path is a straight-ray (SR). However, there is a difference between the signal propagation times obtained by Snell's Law and considering an SR. The error increases with depth. Thus, the estimation of the Q-factors depends on a good estimate of the propagation time of the wave field in each layer. The redatuming operation allows you to eliminate the layers one by one and use the redatuming time on the new layer.

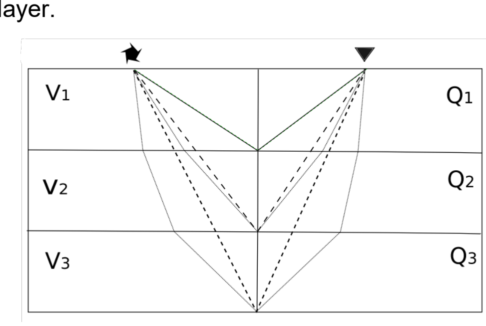

***Figure 4** - Schematic propagation of the SR (solid line) and Snell ray (dashed line). Source: From Oliveira et. al. (2016).*

The equations for determining the transit times of the ray segments in each layer are defined by:

$$\Delta t_{Nj}^{*} = \frac{t_{Nj}}{t_{oN}}\left(t_{oN} - t_{o(N-1)}\right),$$

$$\Delta t_{N-1j}^{*} = \frac{t_{Nj}}{t_{oN}}\left(t_{oN} - t_{o(N-2)}\right) - \Delta t_{Nj}^{*}, \quad (11)$$

$$\vdots$$

$$\Delta t_{1j}^{*} = t_{Nj} - \cdots - \Delta t_{(N-1)j}^{*} - \Delta t_{Nj}^{*},$$

where t_{oi} represents the travel times of vertical reflection and t_{ij} represents the corresponding SR approximations at interface i.

The redatuming is applied to the CMP families where the main events are identified and selected. The CMP family is redatumed to the next reference level corresponding to the event chosen previously. The redatuming operation can be performed using the root-mean-square velocity (rms velocity) or the layer interval speed above the event (Oliveira et al., 2015). The redatuming is performed iteratively for all chosen events. Briefly, the redatuming operation is carried out to reposition the seismic acquisition to a deeper level, displacing the seismic events. Thus, the first event can be eliminated making the second event the new first event, allowing the Q factor to be estimated more accurately.

$$Q_j = \frac{\pi t f_{pj} f_m^2}{2\left(f_m^2 - f_{pj}^2\right)}, \quad (12)$$

where f_{pj} is the peak frequency for each trace in the CMP family and f_m is the dominant frequency that can be determined from:

$$f_m = \sqrt{\frac{f_{p1} f_{p2}\left(t_2 f_{p1} - t_1 f_{p2}\right)}{t_2 f_{p2} - t_1 f_{p1}}}. \quad (13)$$

The final value of Q for a layer is then determined by the arithmetic mean of all Q_j in all displacements; i.e,

$$Q_N = \sum_{i=1}^{k} \frac{Q_{Ni}}{k}. \quad (14)$$

Results

The data set used in this work belongs to the so-called Vicking Graben, located to the north of the North Sea basin. More details on the area and on data acquisition can be found in Madiba and McMechan (2003) and Keys (1998). The data set used to perform the well-to-seismic tie consists of a 2D seismic line, with 2.142 common-midpoints (CMPs) with 6 s of data at a sampling rate of 4 ms and one borehole along the seismic section located in the CMP 808. The Figure 5 shows the information about the boreholes used in this study. A spike removal was performed on the data to obtain better results in the well-to-seismic tie.

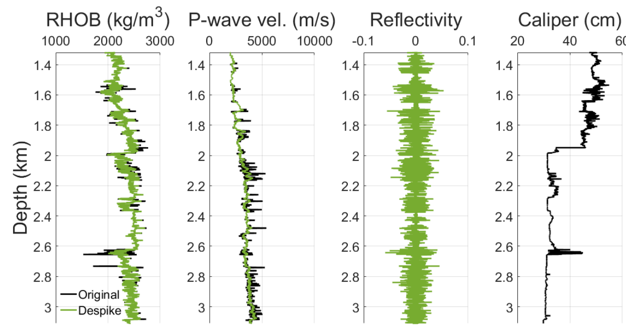

***Figure 5** - Log used to construct the synthetic seismogram. From left to right: density log, sonic log, reflectivity log and caliper log. The green lines are the output from the despiking process.*

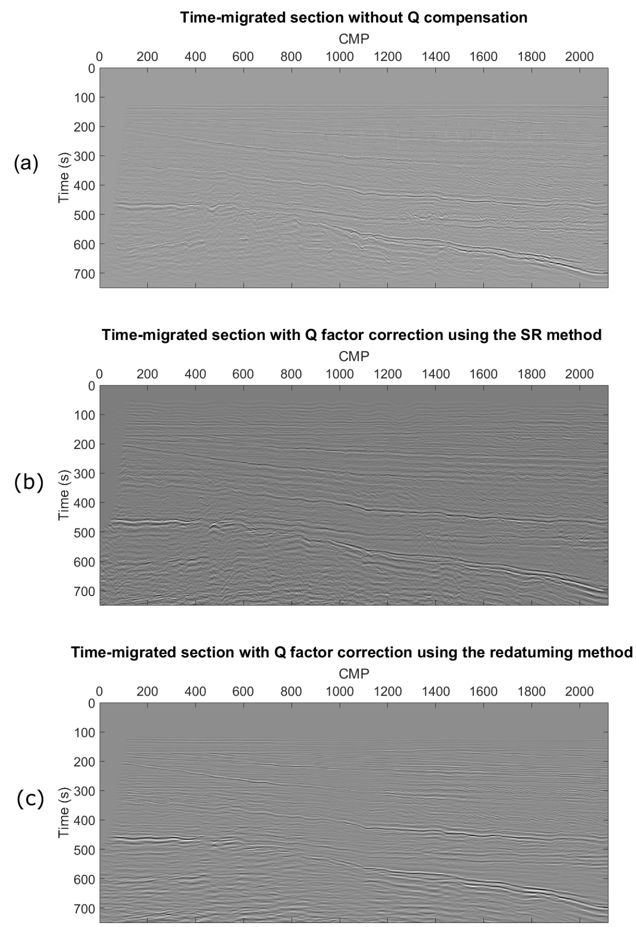

***Figure 6 –** (a) 2D seismic line corresponding to a time-migrated section without Q compensation. (b) 2D seismic line corresponding to a time-migrated section with correction of the Q factor using the SR method. (c) 2D seismic line corresponding to a time-migrated section with Q factor correction using the redatuming method.*

The 2D seismic line used in this study went through different processes regarding the estimation of the Q factor, to identify the influence of these processes in the well-to seismic tie operation. The first data corresponds to a time-migrated section without Q compensation (see Figure 6-a). The second data corresponds to time-migrated section with Q factor correction using SR method (see Figure 6-b). And the last data corresponds to time-migrated section with Q factor correction using the redatuming (see Figure 6-c).

The results of the sparse-spike and homomorphic deconvolutions are shown in table 1.

Table 1 *- Table with the results of the correlations obtained with the well tie for the different seismic data.*

2D seismic line	Sparse-spike Deconvolution	Homomorphic deconvolution
Without Q compensation	0.903367	0.741626
Correction of the Q factor using the SR	0.889253	0.825038
Q factor correction using the redatuming	0.889253	0.80478

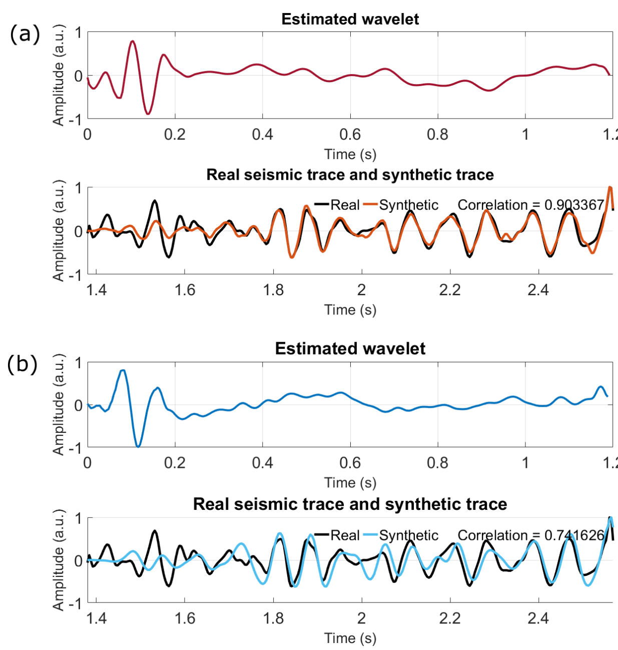

Figure 7 *- Wavelet estimated and the synthetic and real seismic traces on CMP 808 for time-migrated section without Q compensation. (a) Using sparse-spike deconvolution. (b) Using homomorphic deconvolution.*

For the estimation of the seismic wavelet by sparse-spike deconvolution, the least-squares minimization with zero-order quadratic regularization was used. The regularization parameter used was β = 0.01. For the estimation of the wavelet with homomorphic deconvolution, a linear filter was used in the complex cepstral domain, having as input parameters the complex cepstrum of the real seismic trace and the complex cepstrum of reflectivity obtained from the well logs after the application of the time-depth relationship. Although the formulations for the two types of deconvolution are totally different, their results are similar, as the estimated wavelets are similar.

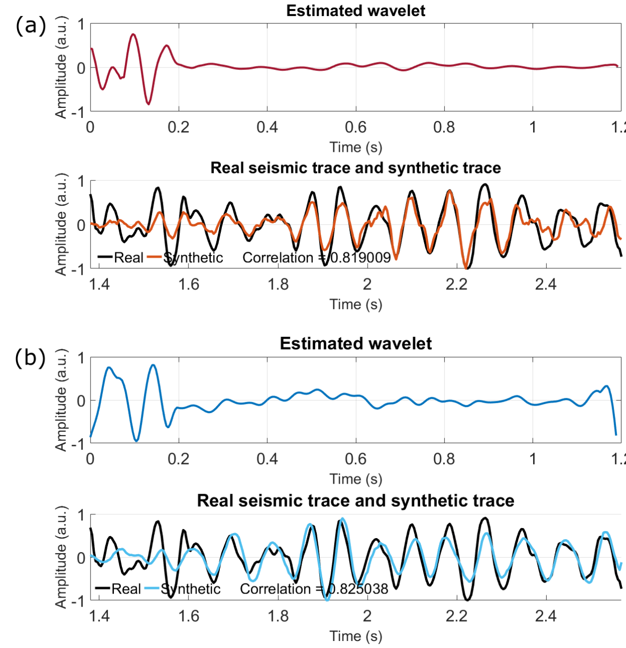

Figure 8 *- Wavelet estimated and the synthetic and real seismic traces on CMP 808 for time-migrated section with Q factor correction using SR method. (a) Using sparse-spike deconvolution. (b) Using homomorphic deconvolution.*

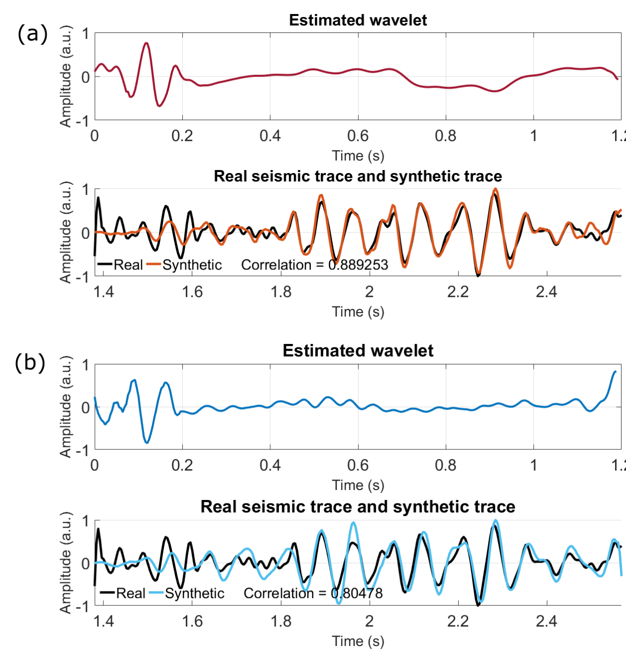

Figure 9 *- Wavelet estimated and the synthetic and real seismic traces on CMP 808 for time-migrated section with Q factor correction using the redatuming. (a) Using sparse-spike deconvolution. (b) Using homomorphic deconvolution.*

Macedo et. al. (2020), mention some advantages and disadvantages of both deconvolutions. For deconvolution in time, the choice of β can generate different results. Homomorphic deconvolution, on the other hand, requires transformations for different domains, but does not make use of any regularization parameters.

Figures 9 and 10 show the results of the deconvolutions for the time-migrated section without Q compensation, where the correlation of the real and synthetic traces, obtained with the deconvolution in time was shown to be superior to all other sections. However, the correlation for homomorphic deconvolution, obtained the lowest value.

Figures 11 and 12 showed the result of the deconvolutions for the time-migrated section with Q factor correction using SR method, which for the deconvolution in time provided a lower result compared to the time-migrated section without Q compensation. However, it obtained the best correlation for homomorphic deconvolution.

Figures 13 and 14 showed the results of the time-migrated section with Q factor correction using the redatuming method, which results were shown to be intermediate in relation to the two other sections for both deconvolution processes.

Thus, the homomorphic deconvolution performed better than the deconvolution in time for the sections with corrections in the Q factor. In addition, for the homomorphic deconvolution, the section that showed the best correlation was the time-migrated section with Q factor correction using SR method.

Conclusions

We propose to verify the way in which the editing of the seismic sections interferes with the well-to-seismic tie from two quality factor correction methodologies, which is an important process in compensating for the dissipation of seismic energy during the propagation of waves in the subsurface. Three seismic sections of the same area (Viking Graben), with quality factor corrections carried out in different ways, were analyzed: time-migrated section without Q compensation, time-migrated section with Q factor correction using SR method and time-migrated section with Q factor correction using the redatuming method. To verify the implications of the seismic sections edited in the well-to-seismic tie, we compared two mechanisms for estimating the seismic wavelet: the deconvolution intime and the homomorphic deconvolution. The results showed that both deconvolutions, for the different seismic data, obtained good correlation results.

In addition, the wavelet estimated with homomorphic deconvolution generated superior results in relation to the section without correction of the Q factor. As for the deconvolution in time, the results were slightly lower compared to the section without correction of the Q factor. The values for homomorphic deconvolution for the time-migrated section without Q compensation was 0.741626 and 0.825038 for the time-migrated section with Q factor correction using SR method.

For further studies, we will analysis other types of deconvolutions as well as the influence of wavelet size.

References

BERRYHILL, J. R. Wave-equation datuming before stack: *Geophysics*. 1984.

DE MACEDO, Isadora AS et al. Comparison between deterministic and statistical wavelet estimation methods through predictive deconvolution: Seismic to well tie example from the North Sea. *Journal of Applied Geophysics*, v. 136, p. 298-314, 2017.

DE MACEDO, Isadora AS et al. Estimation of the seismic wavelet through homomorphic deconvolution and well log data: application on well-to-seismic tie procedure. *Geophysical Prospecting*, v. 68, n. 4, p. 1328-1340, 2020.

DE MACEDO, Isadora AS; DE FIGUEIREDO, José Jadsom S. On the seismic wavelet estimative and reflectivity recovering based on linear inversion: Well-to-seismic tie on a real data set from Viking Graben, North Sea. *Geophysics*, v. 85, n. 5, p. D157-D165, 2020.

DE OLIVEIRA, Souza; DE FIGUEIREDO, Jose JS; FREITAS, Lucas. Redatuming operator analysis in homogeneous media. Acta Geophysica, v. 63, n. 2, p. 414-431, 2015.

MADIBA, Gislain B.; MCMECHAN, George A. Processing, inversion, and interpretation of a 2D seismic data set from the North Viking Graben, North Sea. Geophysics, v. 68, n. 3, p. 837-848, 2003.

OLIVEIRA, Francisco de S. et al. Estimation of quality factor based on peak frequency-shift method and redatuming operator: Application in real data set. *Geophysics*, v. 82, n. 1, p. N1-N12, 2017.

PILA, Matheus F. et al. True-amplitude single-stack redatuming. *Journal of Applied Geophysics*, v. 105, p. 95-111, 2014.

SCHNEIDER, W. Integral formulation for Kirchhoff migration. Geophysics, v. 43, p. 49-76, 1978.

SIMM, Rob; BACON, Mike; BACON, Michael. Seismic Amplitude: An interpreter's handbook. Cambridge University Press, 2014.

WHITE, Roy; SIMM, Rob; XU, Shiyu. Well tie, fluid substitution and AVO modelling: a North Sea example. *Geophysical Prospecting*, v. 46, n. 3, p. 323-346, 2002.

ZHANG, Changjun; ULRYCH, Tadeusz J. Estimation of quality factors from CMP records. *Geophysics*, v. 67, n. 5, p. 1542-1547, 2002.