Joining quality factor estimation and redatuming operator to improve seismic resolution

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Abstract

The estimation of the quality factor is extremely important in the seismic processing. In subsequent step the Q factor is used in a inverse Q-filter to perform an improve in the high frequency content of the seismic signal possibiliting the obtention of better resolution in seismic data. In this work we will carry out the estimation of quality factors correcting the travel times of the rays within the layers. In previous works the time in the layers aren't precisely calculated due to simplification of the rays propagating. For this we will use the redatuming operator with the objective of correct the estimated travel times within the layers iteratively, thus allowing estimates to be made layer by layer of way more precisely. Time corrections are performed with a redatuming operator using models of interval velocities and RMs velocities. The feasibility of the methodology can be checked in two synthetic tests. The first data generated in a model with flat multilayers and the second data generated in a model of multilayer with the velocity varying laterally simulating a gas lens.

Introduction

Seismic waves propagate inside the earth and suffer attenuation effects due to the inelasticity and the heterogeneity of the medium (Ricker, 1953; Futterman, 1962; White, 1983; Kneib and Shapiro, 1995). Attenuation causes a loss of high-frequency energy with increasing traveltime and also time varying distortion of wavelet phase. Estimate and compensate the absorption of seismic waves is of fundamental importance because it allows improving the high-frequency (resolution) of seismic images, allowing a better interpretation of the effects of AVO and also to obtain information of lithology, saturation, permeability and pore pressure (Best et al., 1994).

Several methods for estimating the quality factor of the surface have been developed to performed the Q factor estimates of vertical seismic profiles (VSP) (Dasgupta and Clark, 1998; Hauge, 1981) and in crosswell data (Tonn, 1991). Most of these methods use the amplitude information of the received signal, this information generally inaccurate due to the noise interference, scattering and other geometric effects. Others methods are based on estimating the seismic absorption through the displacement of the centroid of frequency (Quan and Harris, 1997).

In this paper we use the analytical estimate of the Q factor developed by Zhang and Ulrych (2002) based on frequency variation. To estimate the Q factor with reasonable accuracy the correction for travel time in each layer is required and will be performed by seismic data redatuming.

Theory

In seismic data processing the inverse filtering of the Q factor is generally used to remove the effect of absorption (Hargreaves and Calvert (1991); Varela and Ulrych (1991)). Consider the absorption by the relationship between Q factor and the offset frequency peak

$$B(f,t) = B(f)e^{-\frac{\pi f t}{Q}}, \tag{1}$$

where f is the frequency and B the amplitude of the signal. The absorption which is subjected to the wave propagating in a medium increases with time and in terms of frequency the result is the translation of the high frequency bands for the lower bands.

Medium with a layer

Considering the propagation of a wave in a half-space with a Q-factor for t seconds, the amplitude spectrum of the received signal is defined by

$$B(f,t) = A(t)B(f)e^{-\frac{\pi f t}{Q}}, \tag{2}$$

where $A(t)$ is an amplitude factor independent of frequency and absorption f is frequency, t is time and Q is the quality factor. Considering that the amplitude spectrum of a source can be represented by a Ricker wavelet (Ricker, 1953) the frequency spectrum is then expressed by the equation

$$B(f) = \frac{2}{\pi}\frac{f^2}{f_m^2}e^{-\frac{f^2}{f_m^2}}, \tag{3}$$

where f_m is the dominant frequency, f_p is the peak frequency and can be determined by equating the derivative of the equation 2 with respect to frequency, to zero (Zhang and Ulrych, 2002). Then the f_p equation obtained is

$$f_p = f_m^2\left[\sqrt{\left(\frac{\pi t}{4Q}\right)^2 + \left(\frac{1}{f_m}\right)^2} - \frac{\pi t}{4Q}\right]. \tag{4}$$

The relationship between the quality factor and the peak frequency is defined by

$$Q = \frac{\pi t f_p f_m^2}{2\left(f_m^2 - f_p^2\right)}. \tag{5}$$

Considering the peak frequencies f_{p1} and f_{p2} at times t_1 and t_2 respectively (Zhang and Ulrych, 2002)

$$Q = \frac{\pi t_1 f_{p1} f_m^2}{2\left(f_m^2 - f_{p1}^2\right)} = \frac{\pi t_2 f_{p2} f_m^2}{2\left(f_m^2 - f_{p2}^2\right)}. \quad (6)$$

Thus, it was possible to derive the relation which gives the dominant frequency based on the frequency peaks of a reflection of the different points in time (different traces or offsets CDP)

$$f_m = \sqrt{\frac{f_{p1} f_{p2} \left(t_2 f_{p1} - t_1 f_{p2}\right)}{t_2 f_{p2} - t_1 f_{p1}}}. \quad (7)$$

Medium with multi layer

Considering first the case of a medium with two layers horizontal plane with quality factors Q_1 and Q_2 and transit times t_1 and t_2 in each layer, respectively. Zhang and Ulrych (2002), using the equation 2, obtained

$$B(f,t) = A(t)B(f)e^{-\frac{\pi f t_1}{Q_1}} e^{-\frac{\pi f t_2}{Q_2}}, \quad (8)$$

where $t = t_1 + t_2$. Then substituted to equation 2 on the left side of the previous equation and then eliminating the bases have replaced Q by equation 5, thus Q_2 can be estimated and defined by

$$Q_2 = \frac{\pi t_2 Q_1}{\alpha Q_1 - \pi t_1}, \quad (9)$$

where

$$\alpha = \frac{2 f_m^2 - 2 f_p^2}{f_p f_m^2}. \quad (10)$$

For a medium with multi layer the equation 2 of amplitude become

$$B(f,t) = A(t)B(f)exp\left(\sum_{i=1}^{N} \frac{\pi f \Delta t_i}{Q_i}\right), \quad (11)$$

Where Q_i and Δt_i are the quality factors and the travel time in layer i, respectively. In the same work Zhang and Ulrych (2002) considered that a given model with estimated velocity and the simplification of ray propagation of the wave field as straight rays according to Figure 2 and the calculated travel time of a particular offset as

$$\sum_{i=1}^{N} \Delta t_i = t_N, \quad (12)$$

where Δt_i is the travel time in each layer being determined by triangularization where t_N is the total time of reflection of a particular offset, $t_o(N)$ is the reflection time of zero offset in the layer N.

$$\Delta t_i = \frac{t_N}{t_o(N)}\left[t_o(i) - t_o(i-1)\right]. \quad (13)$$

The equation to obtain the Q_N then is defined by

$$Q_N = \frac{\pi \Delta t_N}{\alpha - \beta}, \quad (14)$$

Where α was previously defined and β is defined below by

$$\beta = \sum_{i=1}^{N-1} \frac{\pi \Delta t_i}{Q_i}, \quad (15)$$

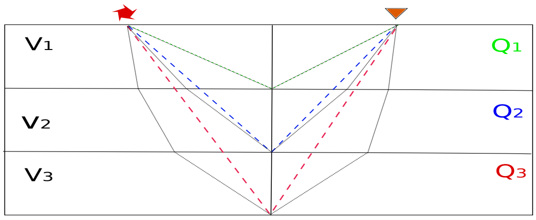

Figure 1: Esquematic propagation of right ray and Snell ray.

Considerations of Method

The method introduces a simplification about the trajectory of the wave field when considering the propagation in a straight line. We can perceive a difference between the time propagation of the signal obtained using Snell and by considering the straight beam. We can notice this difference observing the diagram in Figure 1 below, this error will certainly grow with increasing depth.

In a schematic representation for a model with three horizontal plane layers the travel time for each offset for the first Layer are identical, so we get always a good approximation of the first layer. For the second layer relationship would be

$$\Delta t_2^{'} = \frac{t_2}{t_o(2)}\left(t_o(2) - t_o(1)\right). \quad (16)$$

and

$$\Delta t_1^{'} = t_2 - \Delta t_2^{'} \quad (17)$$

that uses according to Figure 2 the rays propagating in the blue for second layer. For the third layer will have segments in red radius being defined by

$$\Delta t_3^{*} = \frac{t_3}{t_o(3)}\left(t_o(3) - t_o(2)\right) \quad (18)$$

where

$$\Delta t_2^{*} = \frac{t_3}{t_o(3)}\left(t_o(3) - t_o(1)\right) - \Delta t_3^{*} \quad (19)$$

and

$$\Delta t_1^{*} = t_3 - \Delta t_2^{*} - \Delta t_3^{*}. \quad (20)$$

Generalizing we can conclude that the equations for determining the segments ray-layers are

$$\begin{aligned} \Delta t_N^{*} &= \frac{t_N}{t_o(N)}\left(t_o(N) - t_o(N-1)\right) \\ \Delta t_{N-1}^{*} &= \frac{t_N}{t_o(N)}\left(t_o(N) - t_o(N-2)\right) - \Delta t_N^{*} \\ &\vdots \\ \Delta t_1^{*} &= t_N - \ldots\ldots - \Delta t_{N-1}^{*} - \Delta t_N^{*}. \end{aligned} \quad (21)$$

Correcting Travel Time Using Kirchhoff redatuming Operator

The redatuming operator is used to perform repositioning of the wave field acquisition system simulating acquisition at a another level iteratively correcting the travel time (Schneider (1978); Berryhill (1984); Pila et al. (2014); Oliveira et al. (2015)). The redatuming operator in the frequency domain is defined by

$$P(r_s,\omega) = \int_x \frac{\partial R}{\partial n}\sqrt{i\omega}P(r,\omega)\frac{e^{i\omega t}}{\sqrt{r}}dx, \quad (22)$$

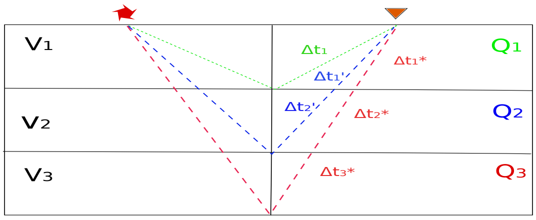

Figure 2: Esquematic propagation of right ray and the travel time in each layer.

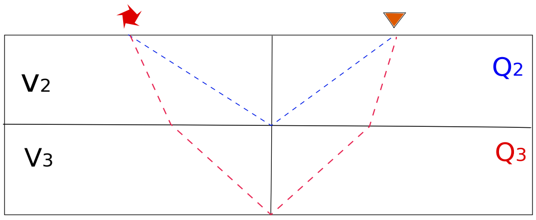

Figure 3: Esquematic propagation of right ray and Snell ray in redatumed model.

where $P(r,\omega)$ is the input field and $P(r_s,\omega)$ is the simulated field in the new level, ω is the frequency and r the distance vector between the position acquisition original and the output position at the new level. Thus performing the redatuming operator we can eliminate the layers one by one and we can thus use the time redatumed in the new layer associated with equation 5. Then schematically we have the following situation in Figure 3.

Numerical experiments

Model with Horizontal Plane Multilayer

In the numerical experiment we consider a horizontal plane model (Figure 4) consisting of 5 layers of velocities $v_1 = 1508\ m/s,\ v_2 = 2000\ m/s\ v_3 = 2132\ m/s,\ v_4 = 3015\ m/s$ and $v_5 = 3333\ m/s$. The exact attenuation factors used in each layer are $Q_1 = 80$, $Q_2 = 120$, $Q_3 = 160$ and $Q_4 = 200$. The seismic data was generated and organized in CDP families using the packet Seismic Unix (SU) and the CDP chosen was the 501 for analysis (Figure 5). The next step is to perform the redatuming recursively to calculate the travel times in each layer. Then we use the attenuated data together with new redatumed time to perform the estimating of the quality factor by using the equation 5.

The results showed a good estimate of the quality factors when were used the interval velocity and the RMS velocity in the redatuming operator. We can see this results with more details in the table 1.

We can also observe in the table 2 that the errors in the estimated values of quality factors (Q_1 and Q_2) are smaller in column of error 1 but are not very different from errors in column 2 and 3. In the last two values (Q_3 and Q_4) the relative errors of the values in column 2 are much larger than the errors of columns 3 and 4, thus we conclude that the estimated quality factors with time correction using redatumacao show better results. In the next experiment performed with the same seismica data we estimate the quality factor with a wrong velocity model of 10%. The tables 3 and 4 show the results in details of similar way of the first experiment.

In booth cases we can see in Figure 6 and 7 the estimated quality factor with Redatumed data and interval velocity (green point) or RMS velocity (black point) are near of the exact valuer (blue point), in contrast to the results obtained by Zhang and Ulrych (2002) in red, wich showed good results in the first two values but in the last two estimated results the values were completely different from the true (blue point).

Model with Lateral Velocity Variation

In the second synthetic numerical experiment we consider a model with lateral velocy variation consisting of 5 layers of velocitys $v_1 = 2000\ m/s,\ v_2 = 3162\ m/s,\ v_3 = 2236\ m/s,\ v_4 = 3015\ m/s$ and $v_5 = 3333\ m/s$ and the attenuation factors used in modelling in each layer were $Q_1 = 70$, $Q_2 = 120$, $Q_3 = 50$ and $Q_4 = 160$ (Figure 8). This model present an sinclinal simulating a gas lens and the seismic data were generated and organized in CDP families using the packet Seismic Unix (SU). The CDP chosen was the 300 for analysis (Figure 11). The next step is to perform the redatuming recursively to estimate the travel times in each layer. Then we use the attenuated data together with the new time redatumed in the same way like in early experiment to perform the estimating of the quality factor using the equation (5).

The quality factors estimated in table 5 were obtained considering too the interval velocity and RMS velocity of the layers.

We observe in the table 6 that the errors in the first two estimated values of quality factors (Q_1 and Q_2) are lower in column of error 1 in relationship the errors in column of error 2 and 3. In the last two values (Q_3 and Q_4) the relative errors in column of error 1 are larger than the errors of 2 and 3 allowing to conclude also that in general the quality factors estimated through the time correction of redatuming operator presents better results in this case. We reach too good results applied in the previous seismic data using a wrong velocity model of 10%. The table 7 show the result in details and in table 8 the relative errors. Evaluating the table also noted that in general the factors obtained with the correction time with redatuming had better estimates.

In booth cases we can see in Figure 9 and Figure 10 the estimated quality factor with Redatumed data and interval velocity (green point) or RMS velocity (black point) are near of the exact valuer (blue point), in contrast to the results obtained by the equation of Zhang and Ulrych (2002) in red, wich showed good results in the first two values but in the same way in the last two estimated results the values were completely different from the true (blue point).

The inverse Q-filtering result, was obtained using the Q-compensation filter (PROMAX software Q-filter to amplitude) with estimatives obtained utilizing interval velocity $Q_1 = 72.3$, $Q_2 = 119.51$, $Q_3 = 48.26$ and $Q_4 = 160.47$. We observe the improving of signal in the amplitude (see Figure 13) and in the resolution (see Figures 11 and 12) when the band of frequency was increased with a shift in the centroid of frequency of data (see Figures 14 and 15).

Table 1: In the first column the exact Q value, in second the value estimated with Zhang and Ulrych (2002), the third the estimative of quality factor with interval velocity and the fourth the estimative with RMS velocity.

	Exact	Zhang & Ulrych	Interval vel.	RMS vel.
Q_1	80	80.64	81.88	81.88
Q_2	120	121.03	125.97	125.97
Q_3	160	276.35	150.90	128.38
Q_4	200	533.66	169.03	186.45

Table 2: Relative error of quality factors: In the first column the relative error 1 of Zhang and Ulrych (2002), in second column the relative error with interval velocity and in third column the erros with RMS velocity.

	Relative error 1	Relative error 2	Relative error 3
Q_1	0.8%	2%	2%
Q_2	0.8%	5%	5%
Q_3	72%	5.6%	19.75%
Q_4	166%	15.5%	6.7%

Table 3: Q values estimated with error of 10% in the interval velocity and RMS velocity. In the first column the exact Q value, in second column the value estimated with Zhang and Ulrych (2002), the third column the estimative of quality factor with redatuming correction and interval velocity and in the fourth the estimative with redatuming correction and RMS velocity.

	Exact	Zhang & Ulrych	Interval vel.	RMS vel.
Q_1	80	80.64	81.88	81.88
Q_2	120	119.67	134.68	134.68
Q_3	160	277.56	131.52	160.77
Q_4	200	512.66	261.55	135.45

Table 4: Relative error of quality factors in a model with error of 10 % in velocities: in first column the errors of Zhang and Ulrych (2002), in second column the errors with interval velocity and in third column the erros with RMS velocity.

	Relative Error 1	Relative Error 2	Relative Error 3
Q_1	0.8%	2%	2%
Q_2	0.2%	12%	12%
Q_3	73%	17.8%	0.5%
Q_4	156%	30%	32%

Table 5: In the first colum the exact Q value, in second column the value estimated with Zhang and Ulrych (2002), the third column the estimative of quality factor with redatuming correction and interval velocity and the fourth column the estimative with redatuming correction and RMS velocity.

	Exact	Zhang & Ulrych	Interval vel.	RMS vel.
Q_1	70	74.50	72.02	72.02
Q_2	120	113.16	119.51	119.56
Q_3	50	105.60	48.26	60.15
Q_4	160	218.46	160.47	158.58

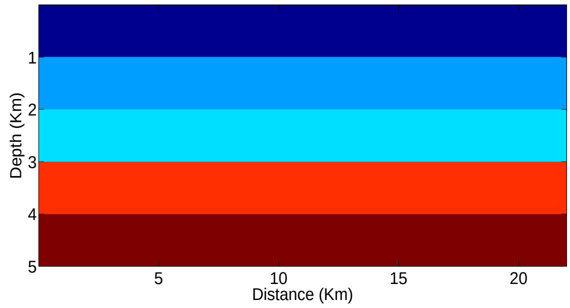

Figure 4: Velocity model with 5 horizontal layers.

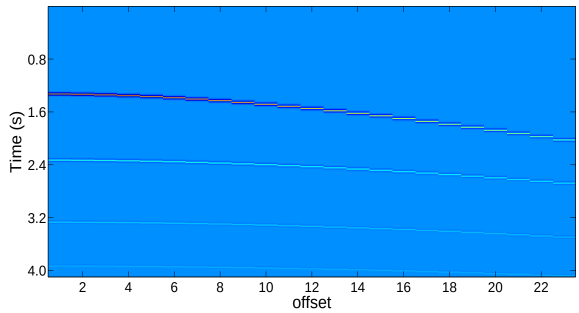

Figure 5: Seismic data CDP 501.

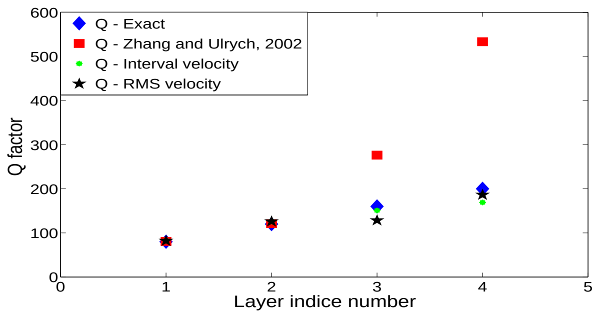

Figure 6: Estimation of quality factor Table 1. The Q factor estimated with redatumed data using the interval velocity and RMS velocity presents better results.

Table 6: Relative error of quality factors: in first column the relative error of the Zhang and Ulrych (2002), in second the relative error with interval velocity and in third column the relative error with RMS velocity.

	Relative Error 1	Relative Error 2	Relative Error 3
Q_1	6.5%	2%	2%
Q_2	5.8%	0.4%	0.4%
Q_3	110%	3.5%	20%
Q_4	36%	0.2%	0.8%

Table 7: Q values estimated with error of 10% in the interval velocity and RMS velocity. In the first column the exact Q value, in second column the value estimated with Zhang and Ulrych (2002), the third column the estimative of quality factor with redatuming correction and interval velocity and in the fourth column the estimative with redatuming correction and RMS velocity.

	Exact	Zhang and Ulrych	Interval vel.	RMS vel.
Q_1	70	74.50	72.02	72.02
Q_2	120	112.16	121.64	122.53
Q_3	50	104.61	70.13	66.42
Q_4	160	221.46	152.41	153.51

Table 8: Relative error of quality factors in a model with error of $10\ \%$ in velocities: in first colum relative error with Zhang and Ulrych (2002), in second column the relative error with interval velocity and in third column the relative error with RMS velocity.

	Relative Error 1	Relative Error 2	Relative Error 3
Q_1	6.5%	2%	2%
Q_2	6.5%	1.3%	2%
Q_3	108%	40%	33%
Q_4	38%	4.3%	4.0%

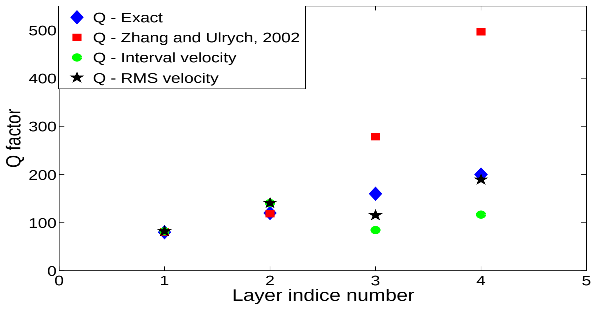

Figure 7: Estimation of quality factor Table 3. The Q factor estimated with redatumed data using the interval velocity and RMS velocity with error of 10% still presents better results.

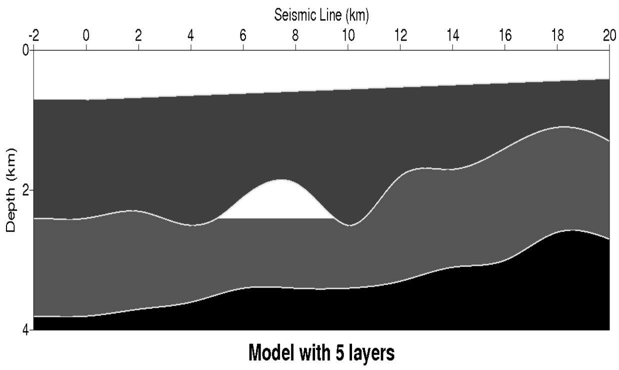

Figure 8: Model with lateral velocity variation.

Conclusions

The estimates of the quality factors are important for the subsequent filtering of the seismic data, making possible

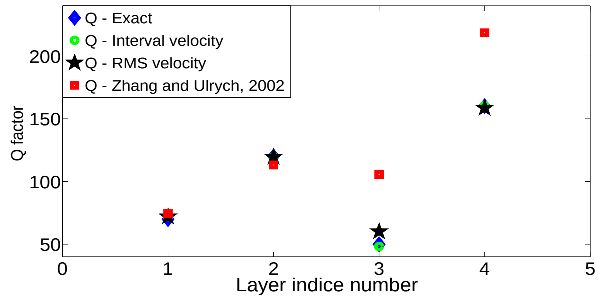

Figure 9: Estimation of quality factor Table 5. The Q factor estimated with redatumed data using the interval velocity and RMS velocity presents better results.

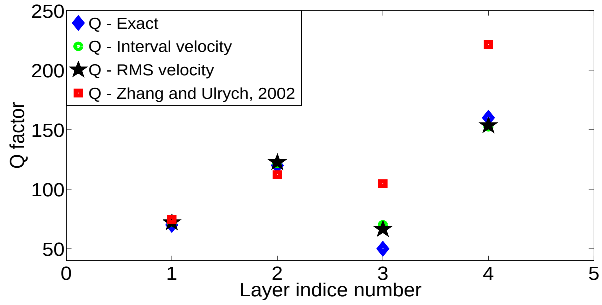

Figure 10: Estimation of quality factor Table 7. The Q factor estimated with redatumed data using the interval velocity and RMS velocity with error of 10% still presents better results.

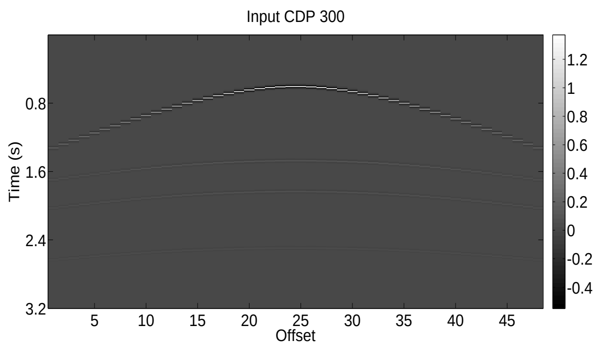

Figure 11: Input attenuated data.

obtain a seismic signal with better quality and resolution. This filter aims to compensate for the attenuation which the wave field is subject during propagation.

In this work the good estimation of quality factors is reached performing the travel time correction of the beams within the layers. This time information is extremely important for the realization of a estimated more precise of the quality factors. Thus we use the redatuming operator to correct the time propagation in models where the velocity values are approximate (RMS speed).

Performed two synthetic numerical experiments in which the first test consisted of a synthetic data attenuated organized in CDP's families generated from a model with horizontal plane layers. The results show that the

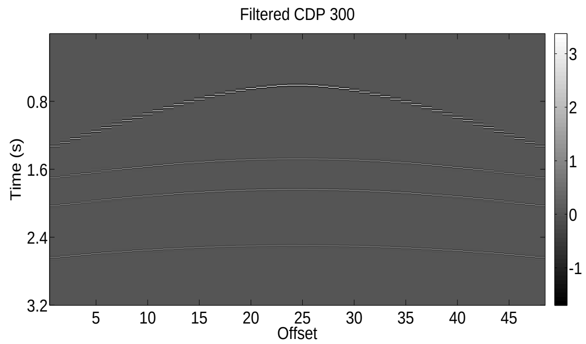

Figure 12: Filtered seismic data using the estimated quality factors. The filtered seismic data present a improved amplitude, possibiliting a better view of the last events.

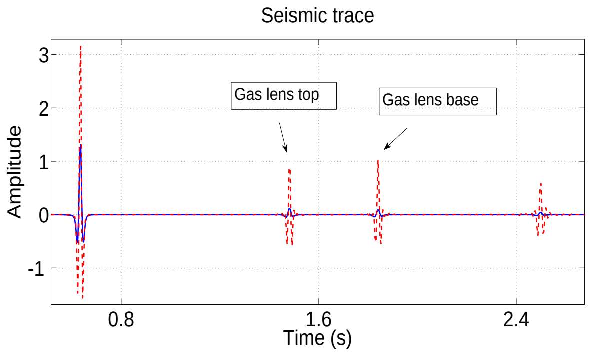

Figure 13: Input trace in blue line and in red line the filtered. The top and the base of the gas lens was substantially improved.

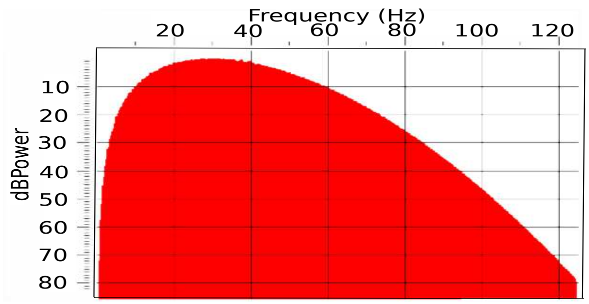

Figure 14: Distribution of frequency of input data.

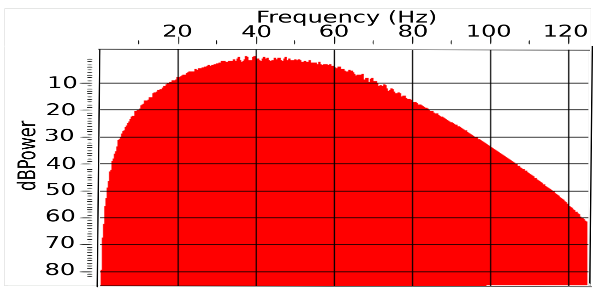

Figure 15: Distribution of frequency of filtered data.

redatuming operator satisfactorily correct the travel time and that the estimative of quality factors obtained are near of the exact value even in models with an error of the 10% in the velocity model.

In the second experiment the estimative was performed in a model with lateral variation of velocity, this model present a sinclinal simulating a gas lens and the quality factor in this case was recovered satisfactorily.

The methodology presented in this work used the redatuming operator interactively to correct the travel time making possible a better estimation of quality factor in pre-stack seismic data . Thus consequently was possible to reach a good filtering of data. The next step consist in estimate the quality factor in a real seismic data to perform the filtering in a pos-stack section.

Acknowledgments

This work has been partially supported by Federal University of Para (UFPA), the National Council of Scientific and Technological Development (CNPq), Brazil, as well as Petrobras, CAPES and INCT-GP.

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