# Multi-receiver quality factor from an array sonic log

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## Abstract

This work deals with the extraction of attenuation attributes from compressional waves picked up from an array sonic log acquired in a real well. To achieve this goal, an algorithm was developed based on spectral ratio analysis of recorded waves, which replaces the traditional artificial reference by a reference sample obtained from the well log. The main attenuation attribute considered was the quality factor Q. The results show values for Q factor in accordance with those related in the literature, as well in a good correlation with all petrophysical logs of the well, especially those physical properties related to fluid saturation, like oil-water contact recognition. A new approach for attenuation visualization is proposed based on a continuous map of quality factor as a function of depth and offset. The proposed method offers new independent and reliable information at very low additional costs, since it is derived from an already available data.

## Introduction

In the propagation of elastic waves in any material, there is dissipation of part of initial energy in the medium, pointed out by reduction in amplitudes of such waves as they propagate. From wave attenuation is possible to determine the attenuation coefficient of the medium and the quality factor Q, which is independent of elastic wave frequency. This, make the factor Q more suitable for the rock characterization. The quality factor Q depends, besides other variables, of the intensity of microfraturing, saturation, porosity and stress state. Low values of Q are, in general, associate with low strength rocks, while high values are more representative of hard rocks.

In this study, data were obtained through a full-wave array sonic log tool, in which elastic waves are recorded by eight different receivers. The distance between the source and first receiver is twelve feet (3,6576m) and two consecutive receivers are separated by half foot (0,1524m). The records of full-wave sonic tool allow the calculation of attenuation coefficient for compressional, shear and Stoneley waves (Mathieu & Toksöz, 1984; Goldberg et al., 1984a, Goldberg et al., 1984b). In this work the analyses were performed only for the compressional waves.

The most widely employed method for measuring attenuation of elastic waves in rocks is the spectral ratio method (Bourbié et al., 1987). This method is easy to implement, it is not very sensitive to signal/noise ratio and have been shown suitable for the data used in this work. The spectral ratio method, developed for analysis of waves recorded in laboratory, is based on a comparison between the waves obtained in a rock sample and in a same length sample of reference. Sample reference must be of a material with a negligible attenuation. For this reason normally is used to this purpose a sample of aluminum. To substitute this reference sample, in the well environment, we developed an analysis based on the method of spectral ratio, which uses no artificial benchmarks, but seeks to extract attenuation attributes directly from sonic log, using as reference a wave recorded in a specific interval of the well.

## Method

Based on the spectral ratio method, spectral analysis was performed directly from the data recorded in the sonic log in each receiver. Traces were analyzed for a given receiver at different depths. The wave that has higher amplitude in the first period is one that suffers the minor attenuation, constituting, this first period, the reference sample. This reference sample, together with the first period of a wave recorded in a different depth is the pair of samples required to analysis of the attributes of the attenuation, by the spectral ratio method, of the second depth. In this case the samples have the same length since source-receiver distance is fixed. The samples correspond to different depths, thus they have different attenuation coefficients in the range analyzed.

The methodology adopted in this work was applied to investigate the attributes of attenuation from a compressional wave recorded in a full-wave sonic logging in oil producing well. For each logged wave is selected the first wavelength since the first break. Then spectral amplitude and phase of those wavetrains are calculated using Fourier transform. Figure 1 shows selected portions of two waves (for analyzed and reference depths) and their amplitude and unwrapped phase spectra.

Originally trace samples were time spaced by 12 μs. We perform a resampling of these traces, setting then at 1μs of sampling. We also add 'zeros' before and after the first period of the waves, making the representation in the frequency domain more smooth and reliable.

In the range of frequencies used (tens of kHz) the attenuation coefficient varies linearly with frequency (Toksöz et al., 1979a; Toksöz & Johnston, 1981):

$$\alpha(f) = \gamma f \qquad (1)$$

The attenuation constant $\gamma$ (or logarithmic decrement) is related to Q factor by:

$$Q = \frac{\pi}{\gamma V} \qquad (2)$$

where V is the wave propagation velocity. The logarithm of the ratio between recorded wave amplitudes of a pair of receivers is given by:

$$\ln\left(\frac{A_1}{A_2}\right) = (\gamma_2 - \gamma_1)\, x\, f + \ln\left(\frac{G_1}{G_2}\right) \qquad (3)$$

where $G_1$ and $G_2$ represent geometric factors of the environment in which the waves propagate, x is the distance between source and receiver, and f is the frequency. The values of $G_1$ and $G_2$ do not interfere in the analysis of attenuation, because for determining the quality factor Q is necessary, according to the equations (1) and (2), only the angular coefficient of the line defined by equation (3). The term $(\gamma_2 - \gamma_1)$ is obtained directly from the graph of natural logarithm of the ratio of spectral amplitudes against frequency (Figure 2). Assuming minimum attenuation for reference sample ($\gamma_1 \approx 0$), and according the wave velocity from transit time, we calculate the quality factor, according to equation (2), for each depth and receiver.

## Results

In this work emphasis is placed on quantifying the P wave Q factor for several receivers (eight) of an array sonic log. It is proposed a new way for a unique and continuous visualization of Q factor as a function of depth and source-receiver distance.

In the selected range, we calculated the logarithm of the ratio of the amplitude spectra of the wave under consideration and the reference wave. From there, set a linear fitted function of natural logarithm of amplitude spectra ratio versus frequency, as shown in Figure 2, for a given depth and receiver.

According to equation (3) the slope of the fitted function corresponds to the product of the attenuation constant $\gamma$ and the sample length. The velocity between each pair of receivers was obtained by the ratio of distance by the difference between times of first break of these waves. Thus, we obtain multiple Q factor using equation (2) for each depth and receiver. The results are illustrated in Figure 3. Important is point out that the values of Q factor were normalized. It means that they are representative of the real values, but is necessary to know at least one real value of Q factor in the well to quantitatively estimate the other values. The real value for quality factor of a given depth may be achieved through lab measurement under in depth conditions, as described in Marques et al. (2009).

In the results showed in Figure 3 each vertical line represents a different receiver. Also, there are in these lines 180 different values, each one for a different depth level. Should be emphasized that these Q factor values represent averages for the analyzed depth interval, since they depends on the distance between the source and each receiver, although this representation facilitates the Q factor variation against depth. However, caution is needed in interpreting Figure 3, because although presented in two dimensions, depth and offset are in the same dimension.

Waveforms were analyzed for each foot in depth. Thus, despite close vertically, there is a relatively large space among vertical lines in Figure 3, doing visual interpretation some difficult. For a better visualization of the results, we used an approach to estimate Q factor values between the vertical lines of Figure 3, obtaining a map of the continuous variation of Q factor with offset and depth. As waveforms are not random due to the existence of a conditional regional factor, we used the *kriging* technique to estimate the Q factor in intervals between receivers, as this is a refined technique for spatial data interpolation. Figure 4 shows the krigged map for multi-receiver Q factor.

It is observed in Figure 4 the occurrence of depth intervals with low values for quality factor Q, indicated by the predominance of the blue color, but as the offset distance increases, the results show less definition. This occurs because the wave recorded in the receiver 8 suffers a more significant attenuation than that one recorded in the first receiver, due to the increasing distance from source.

Figure 5 presents a comparison between Q factors (first- and multi-receiver ones) and other geophysical logs recorded at the well in analysis. These geophysical logs indicate the presence of two zones with potential for oil reservoir: one that goes from 2101 m to 2111 m depth, and another that goes from 2124 m to 2141 m. Low values for quality factor are observed for those potentially producing hydrocarbon intervals, mainly in the first receiver, but also in general for all. Should be noted the persistent low values of quality factor for the shallowest depth interval, which coincides with the lowest Q factor in virtually all its thickness, for all receivers analyzed. This reinforces the interpretation of the other logs that indicate the occurrence of hydrocarbons in this depth interval. Such hydrocarbon occurrence is indicated by the Q factor extracted for the first receiver as well for all the others.

The deeper zone shows a probable lens of non-reservoir rock around the depth 2130 m. Again, Q factor values extracted from the first as well for almost all the others receivers suggest that above the lens there are hydrocarbons. In the reservoir interval below the shale lens, where the resistivity log suggests the occurrence of an oil-water contact roughly around 2136 m depth, it is not clear this fluid contact from Q values extracted from the first receiver only. But it is much clear when Q values from all receivers are analyzed. The depth interval from 2136 m to 2141m, which is interpreted as a full water saturated zone, is characterized as a high compressional Q values zone, as expected. In this way, seems to be very helpful see not only Q values for the first receiver, but the full spectrum of Q values for the eight receivers. One may observe that the Q factor changes not under linear dependence with the transit time log, so, both constitute independent and complementary sources of valuable information.

## Conclusions

Calculated attenuation attributes showed good correlation with other properties of the medium analyzed, as can be seen in Figure 5. The Q factor can be related to important petrophysical phenomena as fluid saturation, anisotropy and viscoelastic deformation, being this latter property of great importance for the study of mechanical behavior of evaporitic rocks, a phenomenon known as salt creep (Toksöz et al., 1979b). In the analyzed case is clearly identified a range of depths with low Q factor, which, together with analysis of other logs (Figure 5), indicate the presence of oil and an oil-water contact, especially as a contribution of the multi-receiver analysis. The map of continuous multi-receiver Q factor indicates a reduction in the variability of this attribute with increasing distance between source and receiver, what may be due to the averaging effect over the measurement of this property with the offset increasing. May be this phenomenon is also conditioned by the research scale. The full-wave sonic log also records other types of wave, in addition to compressional. It is recommended proceed with further analysis of the attributes of shear waves attenuation and look for potential correlations between P and S quality factor ratio and fluid saturation, as reported in literature.

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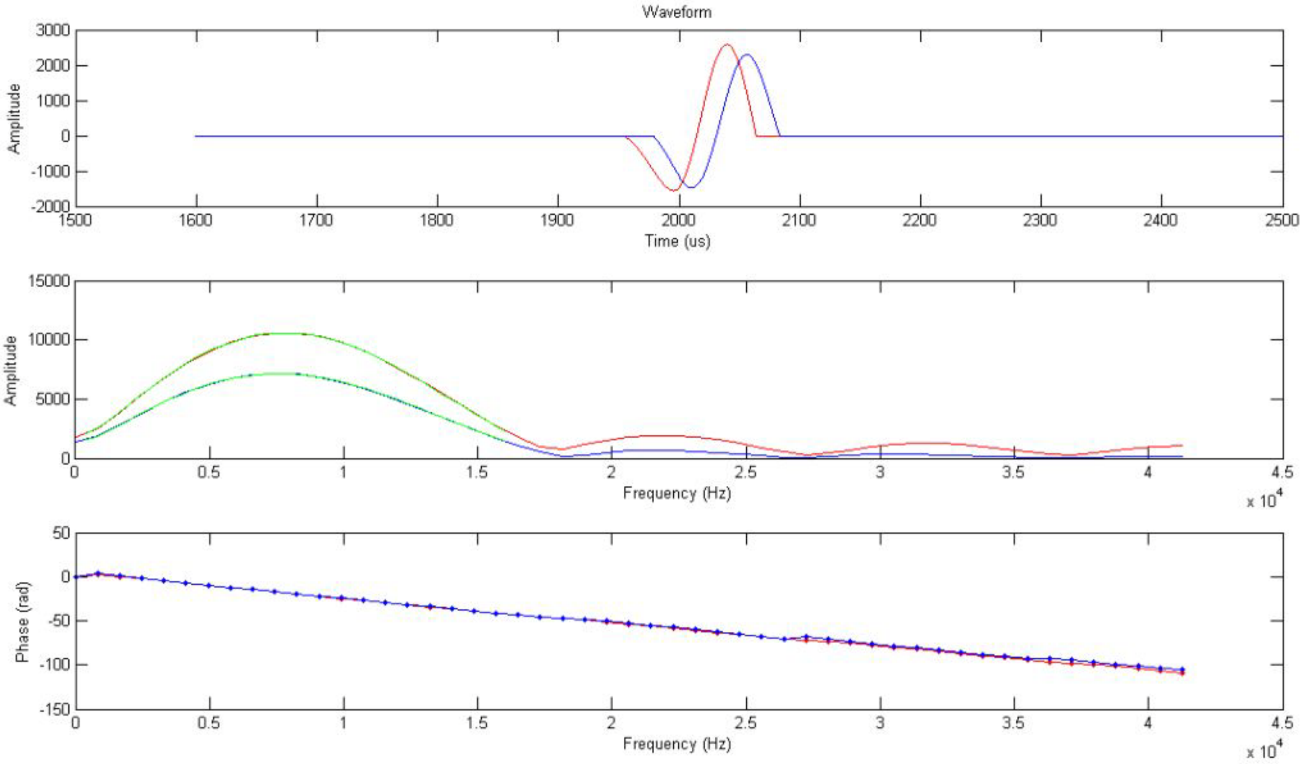

**Figure 1** – Waveform first period and its spectra of amplitude and unwrapped phase for depths of analysis (blue curve) and reference (red curve).

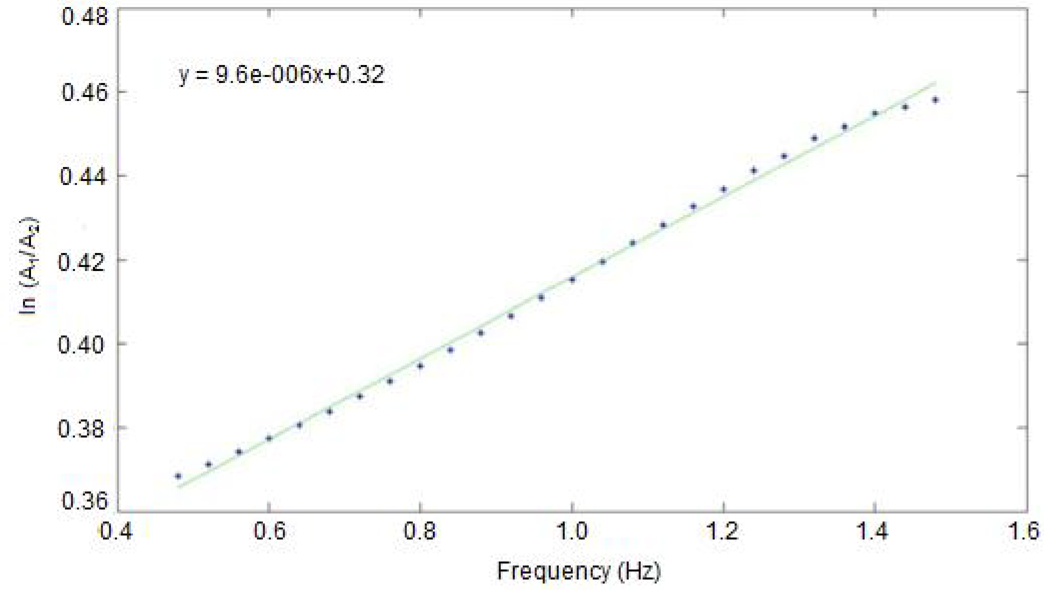

**Figure 2** – Linear fit in the graph of natural logarithm of the ratio of amplitudes versus frequency for extraction of the attenuation coefficient.

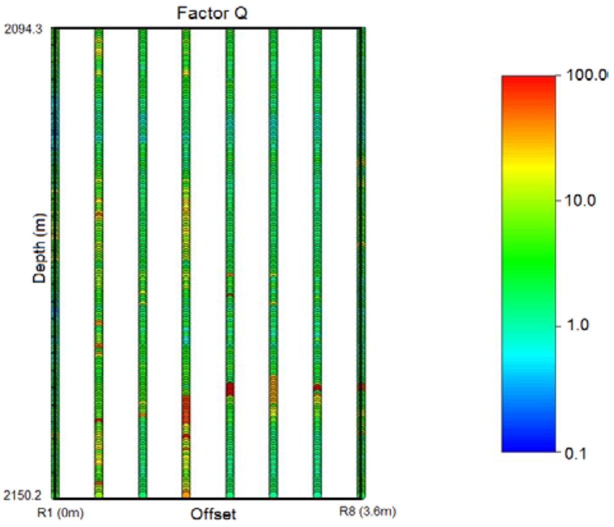

**Figure 3** – Multi-receiver P wave Q factor, in a logarithmic scale, for an 8 receiver array sonic log.

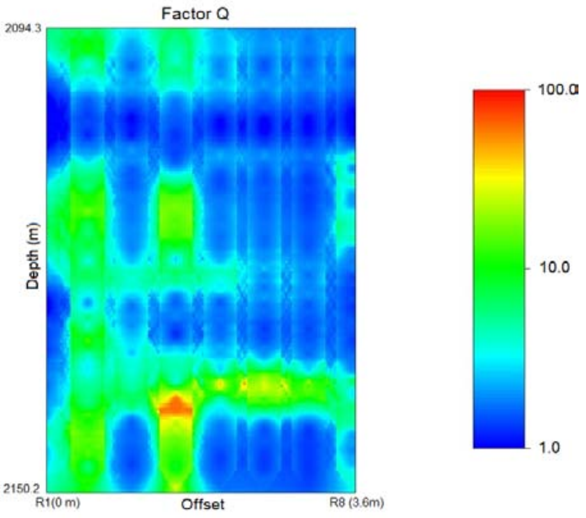

**Figure 4** – Krigged map of multi-receiver compressional Q factor for the analyzed well.

**Figure 5** – Comparison between gama ray, resistivity, density and sonic logs and Q factor.

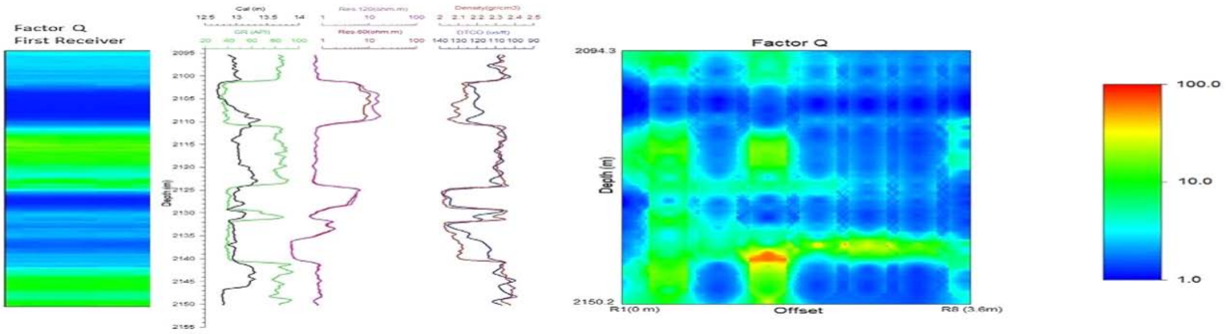

**Figure 5** – Comparison among first-receiver Q factor, gamma ray, resistivity, density and sonic logs and multi-receiver Q factor.