

# Reflectivity Guided $Q$ Analysis for Reservoir Description

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## SUMMARY

In reservoir description, seismic attenuation,  $Q$ , may be defined at all layers which exhibit acoustic impedance discontinuities. The proposed reflectivity guided  $Q$  analysis (RGQA) is based on the idea that  $Q$  values can be computed from the peak frequency variation of a seismic wavelet. RGQA first estimates peak frequencies at a CMP location, then correlates the peak frequency with sparsely distributed reflectivities and, finally, computes a  $Q$  curve from the peak frequencies at the locations of reflectivities. The peak frequency is estimated from the prestack CMP gather using peak frequency variation with offset analysis (PFVO), which is similar to AVO analysis to reduce the effects of stacking on the waveform. The estimated  $Q$  section, which has the same layer boundaries as those defined by the reflectivity, may be easily interpreted as an aid in reservoir description.

## INTRODUCTION

There are mainly three categories of techniques to investigate seismic attenuation properties for hydrocarbon reservoir description. They are iso-frequency analysis (Castagna et al., 2003), direct  $Q$  estimation (Spencer et al., 1982; Taner and Treitel, 2003; Dvorkin and Mavko, 2006; Parra et al., 2006) and attenuation tomography (Quan and Harris, 1997; Pratt et al., 2003). In seismic exploration, seismic data carries information of the interface of rock layers along the propagating wavepath. Generally we deduce layer information from interface information. Acoustic impedance and AVO inversion are two instances of this strategy to delineate rock properties. Attenuation is an intrinsic rock property, i.e., attenuation must be associated with other layer properties for meaningful interpretation. The layer boundaries defined by the reflectivity correspond with the layer boundaries of changes in the attenuation. The technique presented here uses the peak frequency variation at layer boundaries to estimate the attenuation properties of layers.

## THEORY

The following four points outline the theory behind the technique that we have named reflectivity-guided  $Q$  analysis, or RGQA in abbreviated form:

1. We assume a frequency-independent  $Q$  which is the only parameter required to fully describe the attenuation properties of a layer.  $Q$  is related to lithology, porosity, pore fluid, saturation etc.. Together with other available geological and geophysical information,  $Q$  provides one more attribute for reservoir characterization. Like velocity,  $Q$  is an interval property, which

can be derived from the reflections occurring at layer boundaries.

2. A  $Q$  curve can be estimated from the frequency variation of a zero-offset trace, which describes a vertically traveling seismic wavelet. Its time-variant spectrum describes the attenuation property of the medium. Frequency variations can be simply described by the peak frequency shift.

Assuming the peak frequencies of a wavelet at time  $t_1$  and  $t_2$  are  $f_{p1}$  and  $f_{p2}$  respectively, if the amplitude spectrum of the seismic wavelet is similar to that of a Ricker wavelet, the inverse  $Q$  value can be calculated using (from equation 12 of Zhang and Ulrych (2002))

$$\frac{1}{Q} = \frac{2(f_{p1}^2 - f_{p2}^2)}{\pi(t_2 - t_1)f_{p2}f_{p1}^2}. \quad (1)$$

3. The zero-offset trace is not naturally available. Seismic stacking sums up traces in a CMP gather to reduce noise and improve overall data quality. However, stacking distorts the frequency variation pattern caused by seismic attenuation. The seismic wavelet at a CMP location in a stacked seismic section is different from that which is observed on a vertical-incidence trace.
4. Required peak frequencies of seismic wavelets at zero-offset can be estimated by means of modeling the frequency variation along offset in a CMP gather. We call this technique, PFVO analysis.

Figure 1 shows the flow diagram of the RGQA algorithm. Attenuation analysis is implemented on a prestack CMP gather and requires sparsely distributed reflectivities for interface selection.

Layer interface information can be obtained from acoustic impedance inversion or sparse reflectivity inversion (Oldenburg et al., 1983; Ulrych and Sacchi, 2005). Nowadays, piece-wise constant acoustic impedance information is generally available for reservoir description (Latimer et al., 2000). RGQA employs post-stack acoustic information to help the extraction of attenuation information from prestack data.

If a medium is absorptive, the high frequencies of seismic waves traveling in this medium will be attenuated. Consequently, in a CMP gather, attenuation properties can be quantitatively determined from the frequency variation along offset.

There are two main issues in  $Q$  estimation from the frequency variation with offset: one is how to determine the peak frequency at each time sample; another is how to determine  $Q$  from the peak frequency variation. For the first issue, one general and, hopefully, reliable way is to use spectral decomposition, i.e. to perform time frequency analysis on each trace and, from instantaneous amplitude spectra, to determine a peak frequency. Concerning the second issue, we try to fit the peak

## Reflectivity Guided $Q$ Analysis

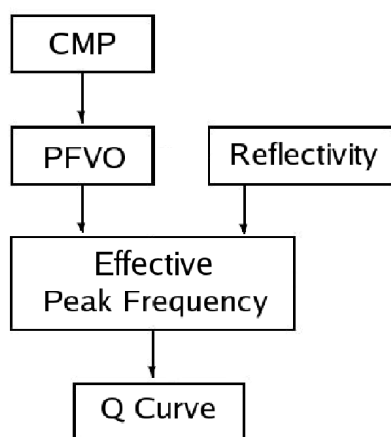


Figure 1: flow diagram of Reflection guided  $Q$  Analysis.

frequencies of an event at different times by a formula like the equation introduced in Zhang and Ulrych (2002) depending on the shape of the amplitude spectrum of a seismic wavelet.

Seismic peak frequencies at a zero offset can be estimated from prestack CMP gathers using peak frequency variation along offset (PFVO) analysis. This multichannel analysis makes the estimation algorithm more robust to random noise and to crossing events in a CMP gather. PFVO analysis follows a similar implementation procedure as AVO. It fits the peak frequency along offset with a straight line. PFVO operates on a CMP gather without NMO, because NMO stretch at far offsets distorts the spectrum of reflections. For a Ricker spectrum, the peak frequency varies with time (Zhang and Ulrych, 2002)

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

where  $f_m$  is the peak frequency of a wavelet at its initial state ( $time = 0$ ) and  $f_p$  is the peak frequency after travel time  $t$ . It can be observed from this equation that if the peak frequency at time  $t - \Delta t$  is  $f_{p0}$  after a time interval  $\Delta t$ , the peak frequency is

$$f_p = f_{p0} \left[ \sqrt{\left(\frac{f_{p0} \pi \Delta t}{4Q}\right)^2 + 1} - \frac{f_{p0} \pi \Delta t}{4Q} \right]. \quad (3)$$

In equation (3), the term  $\frac{f_{p0} \pi \Delta t}{4Q}$  is almost always less than 1 for small  $\Delta t$  and weak attenuation (large  $Q$ ). In a further step, we expand the square root via a Taylor series and keep only the first term, we obtain

$$f_p = P_f - G_f \Delta t, \quad (4)$$

where  $P_f = f_{p0}$ ,  $G_f = \frac{\pi f_{p0} f_m}{8Q}$  and  $\Delta t$  is the NMO shift at an offset for an event starting from two-way traveltimes  $t_0$  at zero offset.  $\Delta t$  is a function of  $t_0$ , RMS velocity and offset, i.e.

$$\Delta t = t(t_0, v_{rms}, offset). \quad (5)$$

Equation 4 shows that for a seismic wavelet with a Ricker like amplitude spectrum, the peak frequency decays almost linearly with arrival time in absorptive media. If peak frequencies at different offsets are picked, based on Equation 4, the peak frequencies along offset can be linearly fitted. The intercept,  $P_f$ , of the linear fit is the peak frequency at a zero offset, while the gradient,  $G_f$ , is related to seismic attenuation.

The technique is implemented mainly in six steps as outlined below:

1. build a CMP super-gather to suppress the effects of random noise. This is equivalent to an AVO super gather. The CMP gather used for  $Q$  estimation requires to be free of NMO stretch. Consequently, if NMO is applied when forming a CMP super-gather, inverse NMO needs to be applied afterwards.
2. do time-frequency analysis on each trace using the continuous wavelet transform or the short window Fourier transform.
3. compute instantaneous amplitude envelopes using the Hilbert transform.
4. search for the maximum amplitude among frequencies at interface locations. The peak frequency is the frequency corresponding to the maximum amplitude.
5. fit peak frequencies with offset (the traveltime at an offset) linearly using  $L_1$  norm to get  $P_f$  and  $G_f$ , and edit  $P_f$  by removing the values corresponding to negative or very small  $G_f$ 's.
6. calculate  $Q$  from the effective  $P_f$  values.

Theoretically, peak frequencies at two offset locations can fully define the trend of peak frequency variation of a reflection. By using multichannel information along offset, the algorithm is robust to random noise and the effects of cross events. Forming super-gathers, spectral decomposition and  $L_1$  linear fitting are the main parts of the whole PFVO computation.

## EXAMPLES

Figure 2(a) shows a synthetic CMP gather. From the CMP gather,  $P_f$  and  $G_f$  are extracted, and  $P_f$  and  $G_f/P_f$  which are displayed in Figure 2(b) and Figure 2(c) respectively. The reason to display  $G_f/P_f$  instead of  $G_f$  is that the value of  $G_f/P_f$  lies in a relatively narrow range.  $G_f/P_f$  is called relative gradient. The low frequency caused by tuning events at  $time = .6s$  is excluded from the calculation because it does not decay with offset. The estimated  $Q$  curve is shown in Figure 2(d).

The method is also tested on a real 2D dataset. The calculated peak frequencies at each CMP location are shown in Figure 3 and the estimated attenuation section is shown in Figure 4. The attenuation section displays the values of  $1/Q$ . The inverse of  $Q$  is used since it lies in the range of (0,1) and is ideal for the display purpose. The blue background indicates small inverse  $Q$  values, which means less absorption than the red areas.



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