

QUALITY FACTOR (Q) ESTIMATES, SEISMIC ATTENUATION AND AVO ANALYSIS

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ABSTRACT

A means to improved Q estimates through the simulation of a stable and physically realizable wavelet using unit impulse function and band pass Butterworth filter is presented in this paper. In comparison with Ricker wavelet commonly use in synthetic experiment for Q measurement, this wavelet is more stable - minimizes spectral interference and thus gives better estimates of rock quality factor from both noise-free and noisy synthetic VSP data. The paper also examines the influence of frequency bandwidth on the unit spike wavelet and noted that "misappropriation" of frequency can lead to exaggeration or underestimation of attenuation especially in shallow targets where stratigraphic filtering is minimal. The study also demonstrates how attenuation may influence AVO curve as well as its gradient - intercept plot and the interpretation arising there from. It therefore recommends that data processing and analysis for AVO anomalies should include attenuation compensation to improve the reliability of AVO results and further mitigate the risks of dry wells.

INTRODUCTION

Seismic wave propagating through earth materials lose part of its energy due to transmission and reflection at rock contacts, scattering, spherical divergence and the viscoelastic properties of the rock. This energy loss is usually exhibited in the form of amplitude diminish, wavelet distortion and delayed arrival as the high frequency content of the wave is preferentially affected. This phenomenon known as attenuation is classified into two types: intrinsic and extrinsic attenuation. The rock properties and conditions along the wave travel path is the key factor responsible for intrinsic attenuation. Extrinsic attenuation is the results of stratigraphic filtering and scattering arising from Earth's inhomogeneity. Attenuation has become a field of extensive investigations due to its link to rock material parameters such as porosity and saturation (Raji and Rietbrock, 2010b). A detailed knowledge of attenuation structure is also an important prerequisite for the design of inverse Q - filter. Spectral Ratio and Frequency Shift methods are the most popular techniques developed for the estimation of quality factor, Q of earth materials (Hobbs, 1999; Tai *et al*, 2006). Spectral interference, choice of reference event, reflection and transmission losses affect the accuracy of Q estimates from Spectra Ratio method (Zhang and Ulrych, 2002). Frequency shift method measures pulse broadening (an exclusive finger print of intrinsic attenuation) in the frequency domain. The method is not affected by far field geometry, transmission and reflection losses (Quan and Harris, 1997).

The real seismic signal is generally unknown. Because the spectrum of Ricker wavelet is close to those observe in seismic data, most mathematical models for the study of attenuation including O'Neil and Hill (1979); Cerveny and Frangie (1982); Tarif and Bourbie (1987); Zhang and Ulrych (2002) assumed the spectrum of Ricker wavelet as the incident and transmitted spectrum. Frequency shift technique computes Fourier transform in the window containing desired seismic event and estimate Q from changes in centroid/peak/dominant frequency. In reality, the target wavelet due to attenuation is no longer the same as the (initial) Ricker wavelet having undergone several changes - peak frequency shifts

lower frequency, increase in time-width, amplitude bandwidth becoming narrow (Fig.1). Amplitude-versus-offset (AVO) being seismic lithology and pore-fluid indicator has been extensively used by oil and gas industries in the last few decades. Nonetheless, problems do still exist. Some wells drilled on AVO anomaly were found to be either dry or contain sub-commercial volumes of hydrocarbon. The success or otherwise of AVO in identifying hydrocarbon – rich lithology depends on the factor playing leading role in the change in the reflection coefficients with offset. The factors affecting reflectivity with offset include poor S/N, tuning, anisotropy, complex structure and stratigraphy and near surface effects.

This paper presents a mean to improved Q estimates from frequency shift method by introducing Ormsby-like wavelet as the (initial and target) spectrum of the propagating seismic wavelet. The second object of this paper is to show how attenuation may affect AVO anomaly. The consequent effect of this is to show how attenuation affect AVO and to recommend or otherwise, that correction for attenuation effect should form part of the routine in AVO processing in order to further mitigate the risk dry wells.

MATERIALS AND METHOD

Forward modeling

The anelastic behavior of the earth is mimicked in a three-layer earth model by incorporating the Aki and Eringen (1962) causal absorption model into the reflectivity method of Muller (1985). P-P and P-SV wave reflection is computed at the top and base of attenuating zone using a forward model (MATLAB code designed by Raji and Andreas (2010a)). Each event is “gated” and the spectrum of the wavelet is computed using short-time Fourier transform (STFT). This is followed by measurement of time-variant parameters of the wavelet spectrum. The Quality factor, Q is estimated as:

$$Q = \frac{\eta t \sigma_a}{f c_{aS} - f c_{aR}} \dots \dots \dots (1)$$

is the travel time difference between the incident and reflected events, σ_a is the average spectrum variance of incident, aS and reflected, aR wave. $\eta = \sqrt{\sigma_a}$. fc is the centroid frequency. The variance and centroid frequency defined by (Quan and Harris, 1997) are presented in equations 2 and 3.

$$\sigma_{aS}^2 = \frac{\int_0^\infty (f - f c_{aS})^2 / s(f) df}{\int_0^\infty s(f) df} ; \quad \sigma_{aR}^2 = \frac{\int_0^\infty (f - f c_{aR})^2 / R(f) df}{\int_0^\infty R(f) df} \dots \dots \dots (2)$$

$$f c = \frac{\int_0^\infty f / a(f) / df}{\int_0^\infty a(f) / df} \dots \dots \dots (3)$$

The centroid frequency defined in (3) uses Ricker wavelet spectrum as the incident and transmitted seismic events and Q is estimated using (1). On the other hand, an Ormsby-wavelet, simulated using a unit impulse function and a band-pass Butterworth filter is used to represent the seismic signal spectrum and to replace the Ricker wavelet spectrum). estimate fc and Q using the same algorithm described

lower frequency, increase in time-width, amplitude bandwidth becoming narrow (Fig.1). Amplitude-versus-offset (AVO) being seismic lithology and pore-fluid indicator has been extensively used by oil and gas industries in the last few decades. Nonetheless, problems do still exist. Some wells drilled on AVO anomaly were found to be either dry or contain sub-commercial volumes of hydrocarbon. The success or otherwise of AVO in identifying hydrocarbon – rich lithology depends on the factor playing leading role in the change in the reflection coefficients with offset. The factors affecting reflectivity with offset include poor S/N, tuning, anisotropy, complex structure and stratigraphy and near surface effects.

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MATERIALS AND METHOD

Forward modeling

The anelastic behavior of the earth is mimicked in a three layer earth model by incorporating the Futterman (1962) causal absorption model into the reflectivity method of Muller (1985). P-P and P-SV wave reflection is computed at the top and base of attenuating zone using a forward model (ATLAB code designed by Raji and Andreas (2010a). Each event is “gated” and the spectrum of the wavelet is computed using short-time Fourier transform (STFT). This is followed by measurement of time-variant parameters of the wavelet spectrum. The Quality factor, Q is estimated as:

$$Q = \frac{\eta t \sigma_a}{fc_{aS} - fc_{aR}} \dots \dots \dots (1)$$

is the travel time difference between the incident and reflected events, σ_a is the average spectrum variance of incident, aS and reflected, aR wave. $\eta = \sqrt{\sigma_a}$. fc is the centroid frequency. The variance and centroid frequency defined by (Quan and Harris, 1997) are presented in equations 2 and 3.

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$$fc = \frac{\int_0^\infty f / a(f) df}{\int_0^\infty a(f) df} \dots \dots \dots (3)$$

The centroid frequency defined in (3) uses Ricker wavelet spectrum as the incident and transmitted seismic events and Q is estimated using (1). On the other hand, an Ormsby-wavelet, simulated using a unit impulse function and a band-pass Butterworth filter (is used to represent the seismic signal spectrum and to replace the Ricker wavelet spectrum). estimate fc and Q using the same algorithm described

above. The amplitude spectrum of this wavelet is similar to the Ormsby wavelet. Ormsby wavelet was introduced by Ormsby, an aerospace Engineer. The frequency spectrum of Ricker and Ormsby wavelet is presented in figures 2a and 2b. Distinctive characteristics of the spectra of wavelets generated from band-pass filter are that they are physically stable within the flat top and undergo minimum changes with travel time. The filter

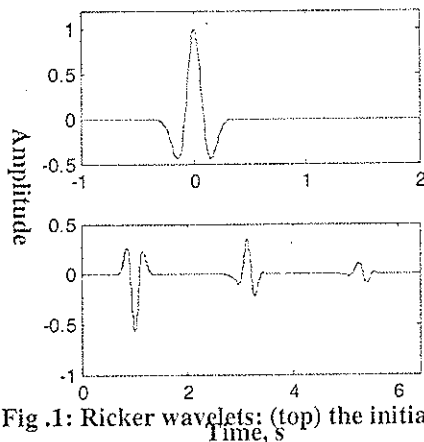


Fig.1: Ricker wavelets: (top) the initial wavelet, (bottom) target wavelet at different propagation time in a medium.

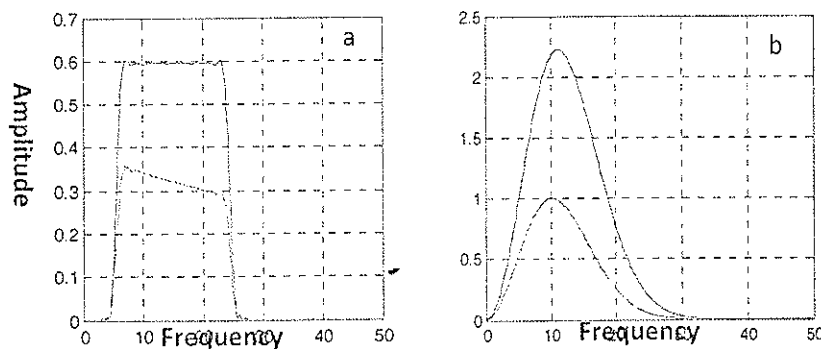


Fig. 2a: (Left) Amplitude spectrum of Ormsby wavelet- Blue is incident and red is reflected wavelet
Fig. 2b: (Right) Amplitude spectrum of Ricker wavelet- blue is incident and red is reflected wavelet

function is designed for both positive and negative frequencies. To ensure that filter output is real and reduce computation time, post-nyquist frequency, $H(-f)$ is defined as $H(-f) = H(f)^*$.

Synthetic data test for Q estimation

The model defined above computes P and SV plane wave reflections at the top and base of a 0.5s (P-wave time) thick attenuating layer of P and S wave velocities of 4000m/s and 2500m/s respectively. The attenuating zone lies in a background Q of 500. The overlying and underlying layers share the same acoustic (ρ, v_p, v_s) parameters. The input Q values for the attenuating layer ranges from 10 to 100. The various P-wave quality factors computed at the base of the attenuating layer using both Ricker and Ormsby wavelets are presented in table 1.

A further test of the two wavelets with 20% noise corrupted synthetic data from an attenuating medium of quality factor of 50 is used to compute the attenuation profile presented in figure 3. To determine the optimum frequency for the source wavelet at a given depth of the attenuating layer, we set various frequency bandwidths for the Ormsby wavelet and estimate attenuation as presented in table 2.

Table1: Q estimates using the two wavelets

Model Q	10	20	30	50	100
Q Est. Ricker	6.1	16.5	29.1	52.9	111.6
QEst.Ormsby	7.9	19.7	30.2	48.4	101.3

Table2: Attenuation measured using three different frequency bandwidths

Model attenuation	Bandwidth 5-20	Bandwidth 5-25	Bandwidth 5-40
0.500	0.047	0.051	
0.033	0.024	0.033	0.074
0.020	0.019	0.021	0.047
0.010	0.006	0.010	0.027
			0.013

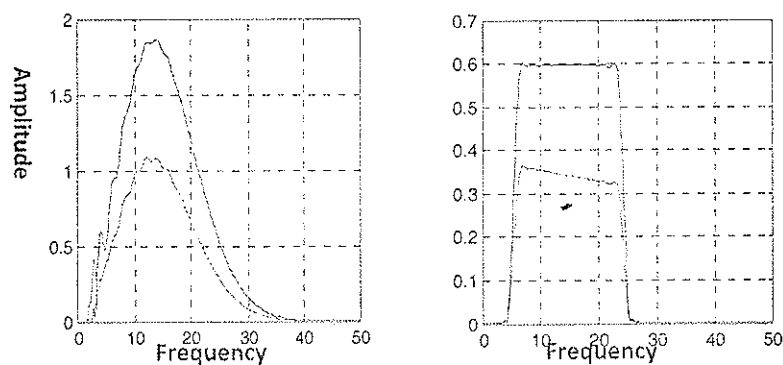


Fig. 3: (Left) Amplitude spectrum of Ricker wavelet from 25% noise corrupted signal - incident (blue) and reflected (red). (Right) Amplitude spectrum of Ormsby wavelet from 25% noise corrupted signal- incident (blue) and reflected (red)

Attenuation effects on AVO

Variation in the magnitude of reflection coefficients as a function of the offset (or angle of incidence) is determined with and without consideration for attenuation. The Geology under investigation is partially gas- saturated sand (here called gas sand A) encased by two isotropic homogeneous half spaces. The layer parameters for the top and basal shale half spaces are 2.4g/cm^3 , 500m/s and 180m/s for the density, P- and S-waves velocities respectively. The density, P-wave velocity and S-wave velocity of the gas - sand are respectively 2.14g/cm^3 , 400m/s and 270m/s . Angular reflection co-efficient with attenuation is computed at the top of the

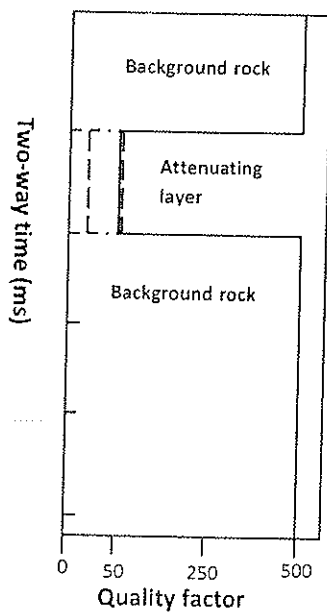


Fig.4: quality factor profile for a three layered earth model. Black line is the actual Q. Red line is Q estimate in noisy data using Ormsby wavelet while blue line is the Q estimate using Ricker wavelet. (Fig. not drawn to scale)

gas sand using a mathematical approximation of the well known Knott-Zeopritz equation. This approximation defined by Wiggins (1983) is defined in equation 4 for compressional (P) wave angle based reflection coefficients.

$$R_{PP}(\theta) = R_{PP}(0) + B \sin^2(\theta) \dots \dots \dots (4)$$

$$B = R_{PP}(0) - 2R_{SS}(0) \dots \dots \dots (5)$$

$$R_{PP}(0) = (Z_{P2} - Z_{P1}) / (Z_{P2} + Z_{P1}) \dots \dots \dots (6)$$

$$R_{SS}(0) = (Z_{S2} - Z_{S1}) / (Z_{S2} + Z_{S1}) \dots \dots \dots (7)$$

Where Z is the impedance, a product of density and velocity squared (ρv^2). P and S denote compressional wave and Shear wave respectively, subscripts 1 and 2 respectively represents the top and lower layer. The lower half space layer is a gas sand- shale mix. The thickness of the lower half space is L and the proportion of gas - sand in lower half space layer is x (see fig. 5) and Q equals 10. The P-wave and S-wave impedance (Z_P and Z_S) of the lower half space is the Hill (1963) average of the lower shale and gas sand defined in (8). The impedance of the upper half space is exclusively that of the upper shale. AVO without attenuation is computed starting from (8) through to (4). AVO with attenuation is computed following the same pattern but with the gas sand impedance reduced due to the presence of attenuation as defined in equation 9.

$$Z = \frac{x}{Z_{GS}} + \frac{L-x}{Z_{SS}} \dots \dots \dots (8)$$

$$Z_{GS}^{Q^{-1}} = Z_{GS}(1 - 2Q^{-1}) \dots\dots\dots (9)$$

Superscript Q^{-1} represents attenuation while subscripts GS and SS respectively represent gas sand and shale. AVO curves for gas sand A are presented in figure 6. Gas sand A is replaced with gas - sand B (having different layer parameters and higher attenuation). Following the same procedures described by equations 4 to 9, reflectivities with offset for gas - sand B are also computed. The AVO gradient-intercept plots for gas sands A and B are presented in figures 7a and b respectively, a superimposition of gradient - intercept plots for gas-sands A and B on the AVO class chart anomaly of Rutherford and Williamson (1989) is presented as figure 8. Details of AVO gradient - intercept analysis is not covered in this literature. Interested reader is referred to Castagnal *et al.* (1998) for the details.

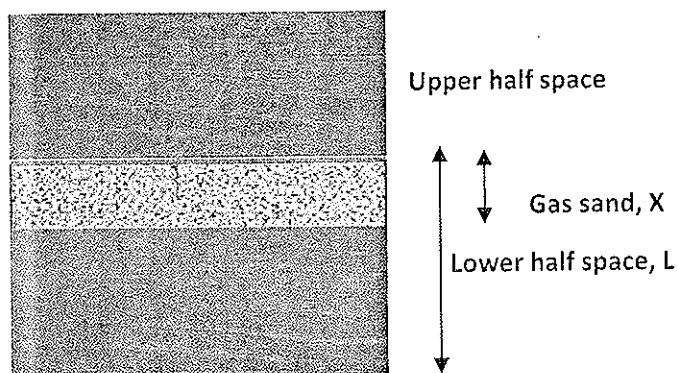


Fig.5: A gas sand model encased by two shale half - spaces.

DISCUSSION

The Frequency shift method proposed for quality Q , factor measurement extracts attenuation parameter from differences in spectra content of the incident and transmitted seismic signals. The spectra of the initial (incident) and target (transmitted) signals are commonly assumed to be Ricker-like. In seismic wave propagation, the target wavelet undergoes several changes - pulse broadening, phase shift and amplitude narrowing due to attenuation (Q^{-1}). This wavelet therefore becomes different from the incident/initial signal spectrum. 25% noise introduced to the data influenced the centroid frequency estimated from the spectrum of the Ricker wavelet, causing it to over-predict attenuation significantly as shown in figure 4. Frequency test on the Ormsby source wavelet showed that synthetic experiment can provide useful information like optimum frequency when the level/ depth of attenuation is known (e.g. from well logs). This information is essential in survey planning and acquisition design.

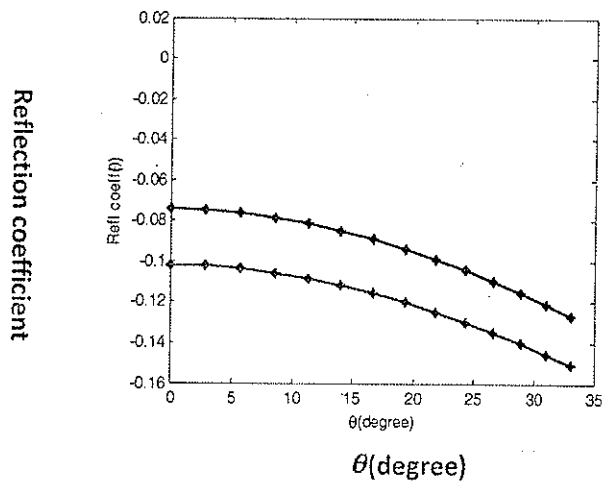


Fig.6: AVO curves for gas sand A: AVO without attenuation (black), AVO with attenuation (red)

Magnitude of reflection coefficient generally increases with offset (i.e. increased angle of incidence). The magnitude is generally higher in the AVO without attenuation compared to AVO with attenuation. This implies that attenuation reduces AVO curves.

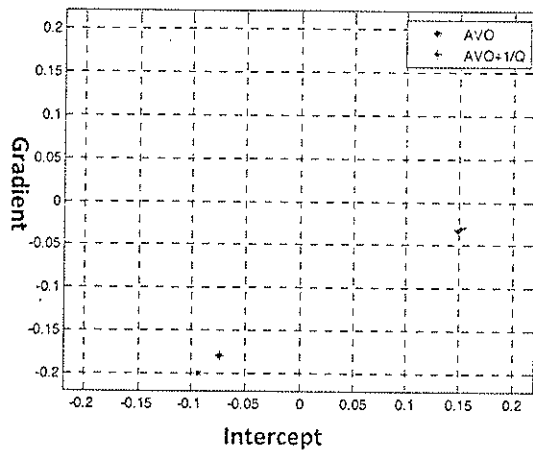


Fig.7a: AVO gradient – intercept analysis (gas sand A). Black star is AVO without attenuation while red star is AVO with attenuation.

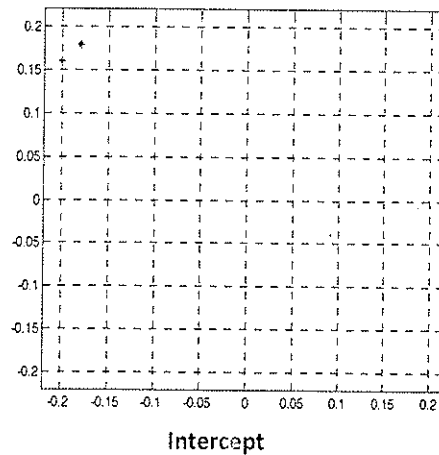


Fig.7b: AVO gradient – intercept analysis (gas sand B). Blue star is AVO without attenuation while red star is AVO with attenuation.

As shown in figure 8, AVO gradient- intercept analysis with and without attenuation plot at different points in the Rutherford -Williams gas – sand class chart for both gas – sands A and B. In exceptional cases, as shown by plots from gas sand B, attenuation can cause class change. Effects of attenuation on AVO could cause gas to be mistaking for oil and oil to be mistaken for water.

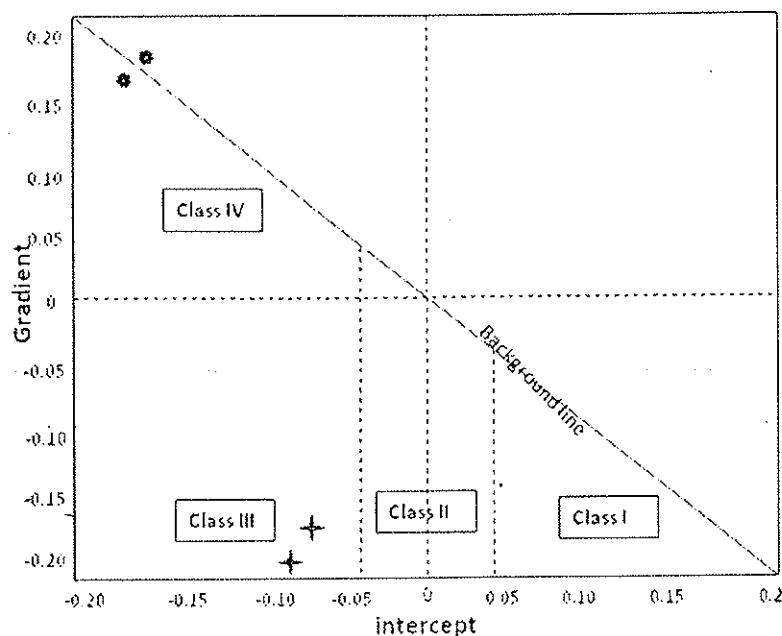


Fig.8: AVO gradient- intercepts plots superimposed on the Rutherford and Williams Gas sand class anomaly (1989). Stars represent gas sand A while circles represent gas sand B. Red is AVO with attenuation while black is AVO without attenuation.

CONCLUSION

A careful selection of wavelets spectra that will undergo changes only due to the propagation seismic attributes of the rock, less affected by spectra interference and the presence of noise can improve the reliability of any attenuation model that is based on frequency shift technique. During propagation, high frequency components are more attenuated than low frequency components. "Over use" of frequency can exaggerate attenuation effects. This paper introduces Ormsby wavelet to the frequency shift method of Q measurement. Ormsby wavelet improves the performance of the Frequency Shift Method, leading to robust estimates of Q in both pure and noisy seismic data compared to Ricker wavelet commonly use in synthetic experiments for Q computation. It also demonstrates how attenuation may affect reflectivity with offset, AVO curves and AVO gradient-intercept plots and the interpretation arising there from. It may be concluded that AVO anomaly is not completely reliable without proper attenuation compensation and abundant well control. Attenuation compensation should therefore form part of the routine in data processing in a search for hydrocarbon bearing rocks using AVO anomaly.

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