Science Focus **Vol. 20 (2), 2015 pp. 12 - 19**
Faculty of Pure and Applies Sciences, LAUTECH, Ogbomoso, Printed in Nigeria

PETROPHYSICAL ANALYSIS OF SEISMIC ENERGY ATTENUATION IN RESERVOIR ROCKS

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Abstract
The phenomenon controlling the mechanism of intrinsic seismic attenuation, Q_{int}^{-1} in waves travelling in earth media is still poorly understood. To give insight to the mechanism – it's cause and effect, this paper used wave induced fluid flow in partially saturated porous rock as the candidate mechanism responsible for intrinsic attenuation (or absorption) in waves propagating in earth media. Using a hydrocarbon reservoir model containing fully water saturated patches surrounded by partially gas–saturated matrix, changes in compressional rock modulus is estimated at high and low frequency bands as a function of saturation at known irreducible water saturation. The study shows that (i) intrinsic attenuation is saturation dependent, (ii) fluid heterogeneity is a necessary condition for intrinsic attenuation, and (iii) intrinsic attenuation estimated at 0.4 irreducible water saturation (0.6 gas saturation) is higher than the intrinsic attenuation at 0.8 irreducible water saturation (0.2 gas saturation). Numerical wave simulations show that the rock-physics-based estimated attenuation is capable of causing amplitude reduction, waveform distortion, and prolonged traveltime in seismic waves travelling from a source to the receiver. Overall, the study links rock physics explanations for seismic attenuation to the waveform distortion and energy depletion commonly observed in exploration scale seismic data. The learning from this study provides insights into seismic amplitude anomaly commonly observed in seismic images of fluid saturated units.

***Key words**: seismic energy attenuation, anelasticity, partially saturated porous rock, seismic forward modeling, amplitude anomaly.*

Introduction

The total energy loss, Q_{Total} in a seismic wave after travelling froma source to the receiver can be decomposed into two forms: intrinsic energy loss, and extrinsic energy loss. The total energy loss, known as seismic attenuation, can be described by an additive law:$Q_{Total} = Q_{Scat} + Q_{Int}$. The mechanism of Q_{Scat}, the extrinsic energy lossis well known. The mechanism can be explained by energy partition at lithological boundaries, geometric spreading, thin layering effect, and wave scattering due to lithological heterogeneity (Menke, 1983; Tang and Burn, 1992; O' Doherty and Anstay, 1971: Sato and Fehler, 1998). The physics controlling the mechanism of intrinsic energy loss, Q_{Int} is not completely known. Several physical processes have been advanced to describe Q_{Int}. These mechanisms include wave induced fluid flow (White et al., 1975; pride et al 2004), Biot loss theory (1956a; 1956b), Squart flow (Mavko and Jibza, 1991), double porosity model (Pride and Berryman 2003,Pride et al., 2003). Although there is no single mechanism that can describe intrinsic attenuation in all geological environment, wave induced fluid flow is the widely accepted mechanism that accounts for intrinsic attenuation in partially saturated porous rocks, such as hydrocarbon reservoir. Hydrocarbon reservoirs usually have heterogeneous fluid composition (e.g., water, oil, and gas). When a compressional wave squeezes a reservoir material containing mesoscopic heterogeneity material, more compliant portions of the material (e.g., the patch) responds with a greater fluid pressure than the stiffer portions (the rock matrix). Subsequently, there is more fluid flow in the compliant portion than in the non-compliant portion of the rock. The differential fluid pressure generates significant energy loss in the seismic band. This energy loss is known as intrinsic seismic attenuation, or intrinsic energy loss.

In this paper, I used wave induced fluid flow (pride et al 2004) as the candidate mechanism to describe and account for intrinsic attenuation in porous rocks. The knowledge of seismic attenuation is important for interpreting seismic records after processing, planning seismic survey, and for enhancing the resolution and quality of seismic images.

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ISSN 1596-7026

Intrinsic energy loss, Q_{int} has become a field of extensive research in hydrocarbon industry due to its application in fluid unit interpretation (Raji and Adeoye, 2014) and reservoir management; Seismic signals reflected by oil and gas reservoirs usually exhibit abnormal amplitude reduction compared to the ones reflected by non-reservoir rocks. The abnormal amplitude reduction is attributed to the absorptive properties of the fluid saturating the pore spaces of the reservoir rocks. To account for this observation, Mathematical model describing the elastic behavior of the earth has been modified to account for the anelastic behavior of rocks and earth layers. The modified mathematical models include Standard Solid Linear Models (Zenar, 1948), Dispersive Wave Model (Futtermann, 1962) and Energy Dissipation Model (Lomnitz, 1957). More complicated models like Dvorkin et al (2003) and Pride et al(2004) relate seismic absorption to the material properties of the rock- such as porosity, permeability, saturation, and fluid content. Seismic attenuation can occur at difference frequency bands – seismic frequency, sonic frequency, and ultrasonic frequency band. At seismic frequency band, the difference between the low frequency and high frequency compressional modulus can be translated to seismic attenuation or seismic absorption using the mathematical model of Zener (1948). The petrophysical templates used for modeling rock modulus at low and high frequency bands are models of Gassmann, (1951), Mavko et al. (1995; 1998), andDvorkin and Mavko, 2006.

The focus of this paper is intrinsic attenuation, alsoknown as intrinsic seismic absorption, or intrinsic energy loss. In intrinsic absorption, part of the energy of the wave is irreversibly converted to heat and other form of energy. The energy conversion leads to amplitude diminution and phase dispersion. To model the amplitude diminution and phase dispersion as they relate to reservoir material properties and saturation conditions, I performed seismic forward modeling, perturbed the reservoir conditions (saturation levels and fluid type), and compute the absorption effect of reservoir saturation. The results show that provided two or more fluid are present in porous rocks, change in reservoir saturation can cause significant energy lossin seismic waves. On the other hand, this energy loss can be inverted from seismic records to describe the reservoir condition. The key assumption in this study is that if the results of the numerical models are similar to field observations, the rock material properties in the subsurface giving rise to the field observation is similar to the properties input to the numerical models. In the next sections, the paper (i) describes the link between modulus frequency dispersion and attenuation at partial saturation, (ii) the concept of irreducible water saturation and it roles in seismic attenuation, (iii) forward models seismic records to show the physical effects of attenuation on seismic waves. Finally, the paper discusses the results of the study and presents some conclusions. Throughout this paper, the words seismic attenuation and attenuation are used interchangeably. Also, intrinsic attenuation is used interchangeably with intrinsic energy loss.

2: Modulus – Frequency- Dispersion and Attenuation at Partial Saturation

In partially saturated rocks such as the one showed in **Figure 1**, visco-elastic effects and seismic attenuation may arise from the oscillatory fluid cross-flow between the fully saturated patches and the surrounding rock with partial gas saturation. The reaction of a rock with patchy saturation to loading due to elastic wave propagation depends on the frequency of the wave.

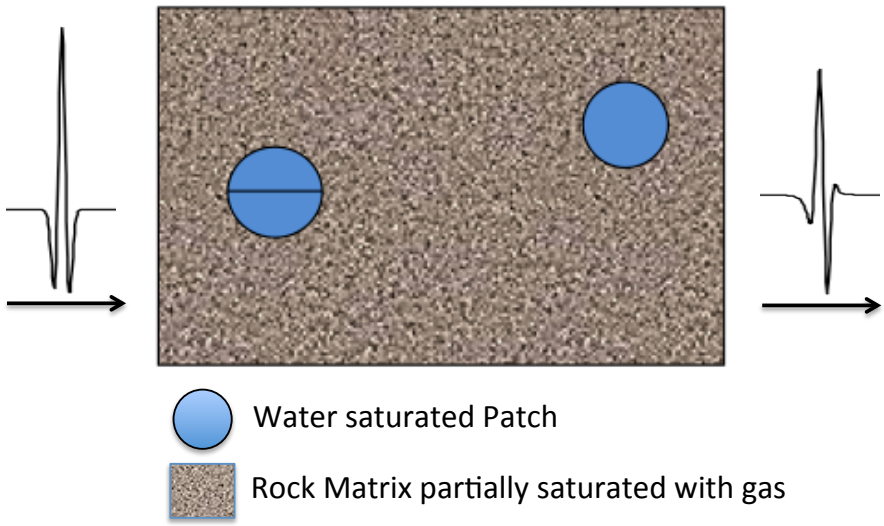


Figure 1: Schematic diagram of microscopic fully saturated patches in a partially saturated reservoir. Part of the energy of the wave has been lost to attenuation after travelling in the partially saturated rock.

If the frequency is low, loading will be slow. The oscillatory pore pressure between the fully liquid -saturated patches and the domain next to the patch will reach equilibrium. Then, the patch is "relaxed". If the frequency is high, loading will be high. The oscillatory fluid pressure between the fully liquid -saturated patch and the surrounding rock will not attain equilibrium. The patch is "unrelaxed'' (Dvorkin and Mavko, 2006). The elastic modulus of compressional waves (P-wave) in a partially saturated rock due to wave induced fluid flow changes with frequency. The difference between the compressional Moduli at high and low frequencies can be translated into inverse quality factor using Standard Solid Linear Model (Dvorkin*et al*., 2003). The compressional moduli of a partially saturated rock containing fully liquid saturated patches is estimated from the bulk moduli of a partially saturated rock (k_{sat0}) and the shear modulus of the dry frame (G_{Dry}) using Gasmann, (1951) model. At low frequency, the compressional (M_{sat0}) modulus is estimated as:

$$M_{sat0=}k_{sat0} + (\tfrac{4}{3})G_{Dry} \quad (1)$$

where $k_{sat0} = k_s \frac{\phi k_{Dry} - (1+\phi)k_f k_{Dry}/k_s + k_f}{(1+\phi)k_f + \phi k_s - k_f k_{Dry}/k_s}$ (2)

K_{Dry} and $K_s$are the shear modulus of dry frame and mineral phase respectively, and $\boldsymbol{\phi}$ is the porosity. $K_f$is the bulk modulus of the mixed fluid (water and gas).

The effective bulk modulus of the pore fluid mix (k_f) is estimated as the harmonic average of the modulus of water (k_w) having volumetric concentration, S_w and the modulus of the gas (k_G) with volumetric concentration, 1-S_w as:

$$\frac{1}{k_f} = \frac{sw}{k_w} + \frac{1-sw}{k_G} \quad (3)$$

At high frequency, the compressional modulus is calculated from the bulk and shear moduli.

$$\frac{1}{k_\infty + (\frac{4}{3})G_{Dry}} = \frac{1}{k_p + (\frac{4}{3})G_{Dry}} + \frac{1}{k_{sw=0} + (\frac{4}{3})G_{Dry}} \quad (4)$$

where the bulk modulus of the fully saturated patch(k_p) and dry patch$(k_{sw=0})$ are calculated as:

$k_p = k_s \frac{\phi k_{Dry} - (1+\phi)k_w k_{Dry}/k_s + k_w}{(1+\phi)k_w + \phi k_s - k_w k_{Dry}/k_s}$, and (5)

$k_{sw=0} = k_s \frac{\phi k_{Dry} - (1+\phi)k_G k_{Dry}/k_s + k_G}{(1+\phi)k_G + \phi k_s - k_G k_{Dry}/k_s}$ (6)

Similarly, the compressional modulus of saturated rock is, estimated from the dry frame(M_{Dry}) using V_P-fluid substitution equation of Mavko*et al*. (1995; 1998). Compressional modulus at low frequency is estimated as:

$$M_{sat0} = M_s \frac{\phi M_{Dry} - (1+\phi)k_f M_{Dry}/M_s + k_f}{(1+\phi)k_f + \phi M_s - k_f M_{Dry}/M_s}. \quad (7)$$

At high frequency, the effective compressional modulus of the rock is estimated as the harmonic average of the compressional modulus of the fully saturated patches (M_p) and dry patches ($M_{sw=0}$).

$$\frac{1}{M_{sat\infty}} = \frac{sw}{M_p} + \frac{1-sw}{M_{sw=0}} \quad (8)$$

where: $M_p = M_s \frac{\phi M_{Dry} - (1+\phi)k_w M_{Dry}/M_s + k_w}{(1+\phi)k_w + \phi M_s - k_w M_{Dry}/M_s}$, (9)

$M_{sw=0} = M_s \frac{\phi M_{Dry} - (1+\phi)k_G M_{Dry}/M_s + k_G}{(1+\phi)k_G + \phi M_s - k_G M_{Dry}/M_s}$. (10)

M_{dry} and M_s are the respective compressional modulus of the dry frame and the mineral phase. Then, the maximum inverse quality factor ($Q^{-1}_{\max}$) can be estimated from the compressional moduli at high and low frequencies using the standard linear model:

$$Q^{-1} = \frac{M_{sat_\infty} - M_{sato}}{2\sqrt{M_{sat0} M_{sat\infty}}}. \quad (11)$$

Where, $M_{sat\infty}$ and M_{sat0} are the respective compressional (P-wave) modulus of the rock at high frequency and low frequency, respectively. As shown in the results plotted in Figures 2a and 2b, the moduli changes as saturation changes.

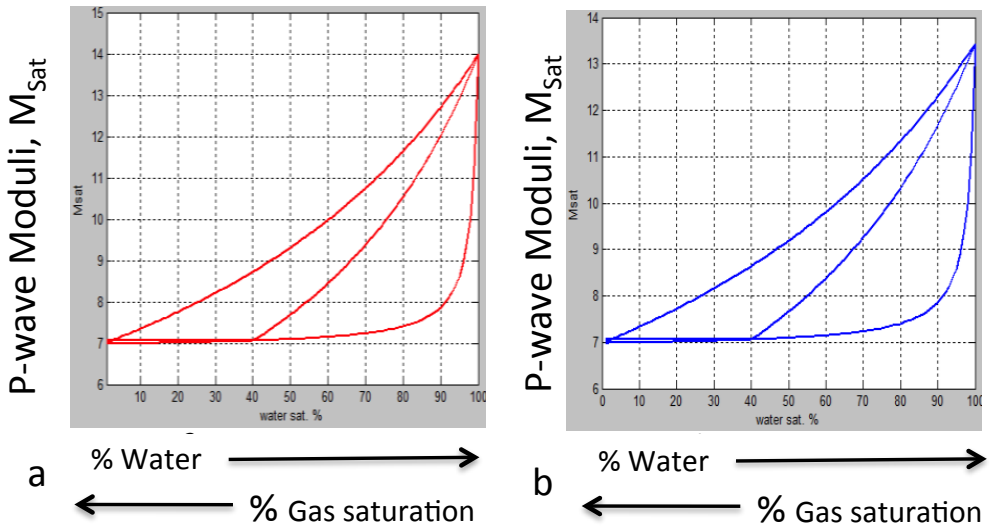


Figure 2: Compressional modulus at low frequency (M_{sat0}) and high frequency ($M_{sat\infty}$) versus saturation usingGassmann (1951) equation (2a), and Mavko et al. (1998) equation (2b). The curve line is low frequency modulus while the nearly straight line is high frequency modulus. The middle line is the modulus estimated at 40% (0.4) irreducible water saturation**.**

Irreducible Water Saturation, S_{Wr}

Real hydrocarbon reservoirs usually contain some quantities of water, no matter the level of hydrocarbon charge. This water is referred to as irreducible water saturation, sw_r. Given the volumetric concentration of the patch, $f_p = \frac{s_w - s_{wr}}{1 - s_{wr}}$, the bulk modulus of the pore fluid can be defined as shown in equations 12.

$$\frac{1}{k_{fr}} = \frac{sw_r}{k_w} + \frac{1 - sw_r}{k_G}. \tag{12}$$

when $s_w \leq s_{wr}$, the compressional modulus of the fluid is estimated from equation (3).But when$s_w > s_{wr}$, the bulk modulus of the partially saturated patch is estimated using Gassmann, (1951) formulation as:

$$\frac{f_p}{k_{satr\infty} + (\frac{4}{3})G_{Dry}} = \frac{f_p}{k_p + (\frac{4}{3})G_{Dry}} + \frac{f_p}{k_{sw=swr} + (\frac{4}{3})G_{Dry}}, \tag{13}$$

or from Vp-only fluid substitution equation (Mavko et al, 1995) as defined in equation 14.

$$\frac{1}{M_{satr\infty}} = \frac{f_p}{M_P} + \frac{1 - f_p}{M_{sw=swr}} \tag{14}$$

Alternatively, when$s_w \leq s_{wr}$, the moduli can be estimated from equation (8)
$M_{sw=swr}$and$k_{sw=swr}$ are defined as shown:

$$M_{sw=swr} = M_s \frac{\phi M_{Dry} - (1+\phi)k_{fr}M_{Dry}/M_s + k_{fr}}{(1+\phi)k_{fr} + \phi M_s - k_{fr}M_{Dry}/M_s},$$

$$k_{sw=swr} = k_s \frac{\phi k_{Dry} - (1+\phi)k_{fr}k_{Dry}/k_s + k_{fr}}{(1+\phi)k_{fr} + \phi k_s - k_{fr}k_{Dry}/k_s}.$$

Given a reservoir rock model with porosity, clay content, dry frame bulk modulus, and shear moduli of 0.27, 0.10, 2.64 GPa, and 3.2 Gpa, respectively, the dynamic changes in the rock elastic modulus with saturation are shown in figure 2. Figure 2a shows the estimated compressional moduli at low and high frequencies using the petrophysical model of Gassmann (1951) while figure 2b, show the estimated compressional moduli using Mavko et al. (1998) petrophysical model. The middle vertical line in the two plots is the estimated compressional modulus at 40% irreducible water saturation. The corresponding maximum inverse quality factor (or maximum attenuation), Q_{max}^{-1} estimated at 40% and 80% irreducible water saturations are shown in figure 3a and 3b respectively. An important observation about the effect of irreducible water saturation on $\mathbf{1/Q_{max}}$ is that the higher the irreducible water saturation, the lower the $\mathbf{1/Q_{max}}$.

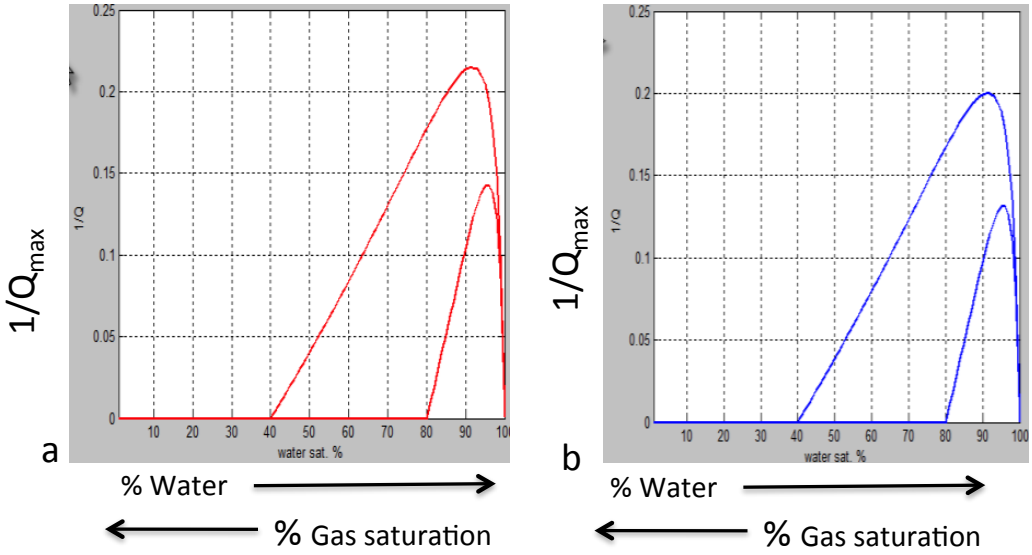


Figure 3: The maximum inverse quality factor ($1/Q_{max}$) versus irreducible water saturation, Swir at 40% and 80%, irreducible water saturation using Gassmann's equation (a) and Mavko et al. (1998) equation (b).

Seismogram Computation in Attenuating Earth Model

In this section, elastic earth model is compared with anelastic earth model. The effects of attenuation on wave propagation in anelastic earth meida are shown using synthetic seismograms. The geological model is made of three-layers consisting of a shale-sand-shale sequence. The two shale layers have the same elastic properties (i.e., v, ρ) but are different from the sand layer. For the elastic model, wave propagation in the three layers is described with velocity,v , and synthetic seismogram is computed using the reflectivity method of Muller (1985). The three-layered earth model and the synthetic seismogram are shown in Figure 4a and 4b, respectively. For the anelastic model, wave propagation is described with velocity, v and inverse quality factor Q^{-1}, or (attenuation). The causal absorption model of Futterman (1962) is incorporated into the reflectivity model of Muller (1985) as shown in equations 15 &16 to forward model P-wave propagation. Futterman (1962) model link absorption to velocity dispersion and the velocity dispersion is frequency dependent. The sand layer in the original model is replaced with a porous, partially saturated reservoir. The maximum inverse quality factor estimated from Figure 3a at 40% and 80% irreducible water saturation is used as the attenuation value to represent the effect of pore fluid in the resevoir. The motion of wave through this rock would caused oscillatory fluid cross-flow between the water saturated patches and the surrounding rock matrix with partial gas saturation; generate pore fluid pressure; and thus, leading to attenuation of the passing waves – amplitude reduction and waveform distortion.

$$V_{(f)} = v_{(f)} - i\sigma_{(f)}/2\pi f, \tag{15}$$

$$v_{(f)} = v[1 - (\pi Q_0)^{-1}\ln(f/f_c)]; \quad \sigma_{(f)} = \pi f/vQ_0. \tag{16}$$

In this equation, the Q_0 is obtained from Figure 3 as Q_{max}^{-1}. The seismograms computed for Q_{max}^{-1} of 0.22 (at 40% S_{wir}) and Q_{max}^{-1} of 0.15 (at 80% S_{wir}) are shown in Figure 4c and 4d, respectively. The physical effects of attenuation is shown on the reflections from the base of the reservoir in Figures 4c and 4d.

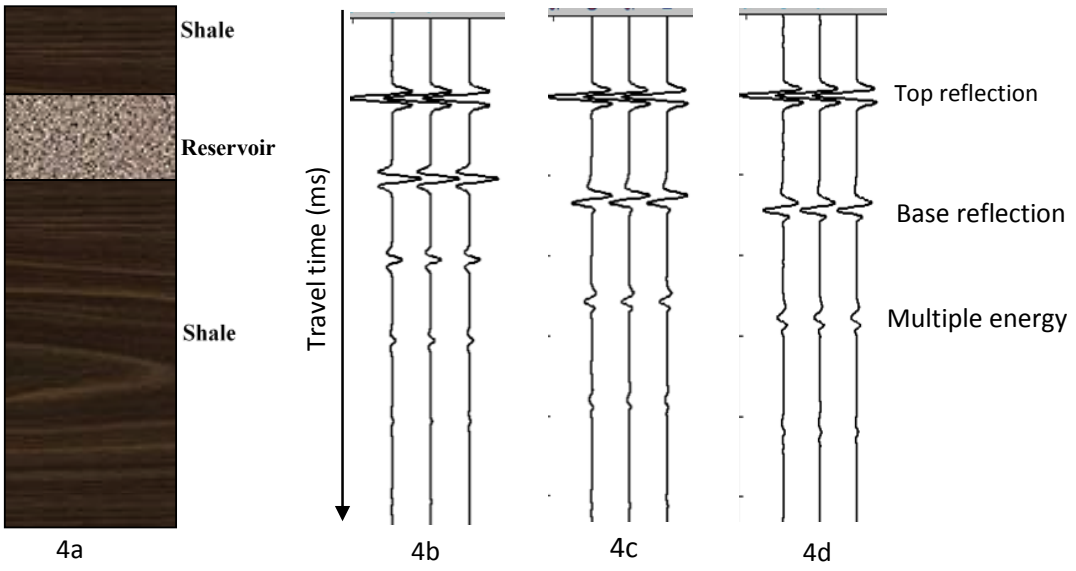


Figure 4: (a). Schematic diagram of a three layered earth model, (b) P wave reflection in elastic Earth model,(c) P wave reflection in anelastic (or attenuating) Earth model using Q value estimated at $0.4S_{Wr}$ saturation, (d) P-wave relection in anelastic Earth model using Q value estimated at 0.8 S_{Wr}.

Comparing the seismograms from elastic model (Fig. 4b) with those from anelastic model (Fig. 4c and 4d), the following are obvious: (i) the amplitude size of the seismic signal reflected from the base of the sand reservoir is smaller for the anelastic model than the elastic model. This is known as amplitude diminution: it is caused by energy absorption. (ii) The seismic events reflected at the base of the reservoir is delayed in the case of anelastic model compared to the elastic model: this is caused by frequency-velocity dispersion – velocity is frequency dependent. (iii) The events reflected at the base of the sand reservoir is distorted and phase-shifted in the case of anelastic model: this is due to phase dispersion. These three observations are the signatures of seismic attenuation or seismic absorption.

Amplitude diminution and phase dispersion cause poor image resolution. This explains why thin reservoir layers are often poorly resolved. Velocity dispersion causes delayed arrival – apparent time thickness. This effect accounts for seismic-well log mis-tie, and exaggeration (or overestimation) of reservoir thickness. The effects of seismic attenuation are usually corrected by a process known attenuation compensation. First, attenuation (Q^{-1}) is estimated in the seismogram and the Q^{-1} is use to undo the effect of attenuation through a backward propagation (e.g., see Raji and Rietbrock, 2013). Figure 5 shows field seismic record (a seismic trace from Gullfaks field) before and after attenuation compensation.

Discussion and Conclusion

In this paper, the phenomenon of seismic wave attenuation is discussed using numerical description of the physical mechanism, realistic geology models, well known rock physics formulations, and seismic forward modeling. The paper links the changes in fluid saturation to the elastic modulus of compressional waves at low and high frequencies, and to the rock inverse quality factor, Q_{max}^{-1} (maximum attenuation) using standard linear model (Zener, 1948). Further,the paper shows that seismic induced fluid flow between different regions of a rock can cause energy absorption in the passing waves.

The Detailed description of the mechanism of seismic absorption is necessary to (i) account for energy depletion in seismic waves propagating in earth media and (ii) for identifying fluid units in seismic interpretation. Results of the petro-physical model plotted in Figures 3 and 4 show that both the rock physics model of Gassmann (1951) and Mavko et al (1998) are acceptable for describing seismic attenuation in a reservoir rocks having two or more fluids. The values of Q_{max}^{-1} estimated from Gassmann (1951) and Mavko et al. (1998) at the same

irreducible water saturation are comparable. Estimated Q_{max}^{-1} at 40% irreducible water saturation (60% gas saturation) is higher than the estimated Q_{max}^{-1}at 80%irreducible water saturation (20% gas saturation). An important observation from the results is that fluid heterogeneity is a necessary condition for seismic attenuation: the higher the irreducible water saturation, the lower the attenuation, Q_{max}^{-1} (see Figures 3a & 3c).

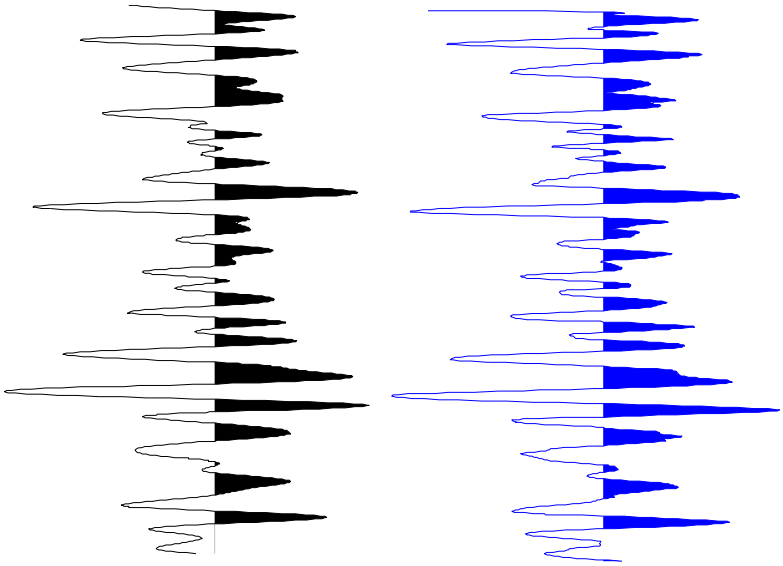


Figure 5: Field seismic trace before and after seismic attenuation compensation. Black is the trace before compensation, blue is the trace after attenuation compensation (Raji and Rietbrock, 2013).

The Q_{max}^{-1} estimated from the rock physics model is input to the reflectivity scheme to show how the pore fluid induced attenuation would affect the waveform and the energy of seismic waves propagating in such rock. The seismograms computed for the anelastic earth model showed the physical effects of attenuation on seismic waves. It shows that attenuation causes amplitude reduction, waveform distortion, and delayed arrival. These effects lead to poor seismic image resolution and time-thickness exaggeration. The multiples arrival shows that phase rotation is possible with longer traveltime in the attenuating media. Seismic modeling of wave attenuation is important for the design of attenuation compensation method, interpretation of fluid units, and reservoir characterisation.

Acknowledgement
This research is a part of doctoral studies undertaken at the department of Geophysics, University of Liverpool*, United Kingdom. The paper was written during my postdoctoral fellowship at the Department of Geophysics, Stanford University**, California, U.S.A., I wish to thanks Prof Andreas Rietbrock* and Prof. J. M. Harris** for the mentorship.

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