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The use of seismic attenuation to indicate saturation in hydrocarbon reservoirs: Theoretical study and modelling approach

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ABSTRACT

Theoretical rock physics modelling and synthetic time lapse seismic data are used to explore the use of attenuation to indicate saturation in hydrocarbon reservoirs. Given the time variant changes in saturation and the properties of the reservoir rock, the patchy saturation mechanism and the theory of modulus-frequency-dispersion are applied to formulate a theoretical curve that describes the dynamic effect of saturation on seismic attenuation. Attenuation is measured in time lapse synthetic seismic records and the theoretical curve is used to estimate the approximate saturation that gave rise to the Seismogram-derived Attenuation (SdA). Results show that SdA can be used to indicate the changes in reservoir saturation if a relationship between SdA and saturation is known. The saturation values predicted by the theoretical model are consistent with the saturation values inverted from SdA. This study also shows that seismic attenuation depends on porosity, mineral content of the rock, and the property of the saturating fluid(s). For the case study, at a saturation of 0.7, a 10% reduction in porosity caused a 5.9% rise in attenuation; and a 10% reduction in the bulk modulus of the saturating fluids caused an 11% reduction in attenuation.

Keywords: attenuation, reservoir saturation, synthetic seismograms, rock physics, anelasticity

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INTRODUCTION

Attenuation is the phenomenon that is responsible for energy dissipation in waves as they travel in rocks. The associated physical process causes amplitude diminution, phase dispersion, and waveform distortion in seismic waves. Attenuation is a combination of energy absorption and energy redistribution. The level of attenuation a wave experiences depends on the degree of anelasticity and the scale of inhomgeneity in the rock it passes through. Attenuation is sensitive to the presence of fluids, degree of saturation, porosity, pressure, and the mineral content of the rock. Despite the compelling evidence from laboratory and theoretical studies [1, 2, 3] that increase in saturation (up to a critical saturation level) will cause increase in seismic attenuation, predicting saturation from SdA is still a difficult endeavour.

The observed changes in amplitude and frequency content of seismic signals recorded from a reservoir rock as its saturation changes make it theoretically plausible to use attenuation measured in seismic data (Seismogram derived Attenuation, SdA) to monitor saturation in hydrocarbon reservoirs. However, a relation between SdA and saturation is still unknown. The patchy saturation model is commonly used to explain the physical phenomenon that causes seismic attenuation in waves travelling in an isotropic porous medium saturated with two or more fluids. The phenomenon is explained by the movement of fluids with low compressibility (e.g., water) in and out of spaces accommodating a more compressible fluid (e.g., gas) due to the changes in pressure created by the passage of seismic waves. The process causes attenuation because a part of the energy of the passing wave is irreversibly converted to heat during the movement of fluid in and out of confined rock pore structure. The patchy saturation model plausibly describes the volumetric disposition of fluids having different compressibilities [1], and it is suitable for describing the mechanism of attenuation in reservoir rock which usually contain two or more saturants (e.g., water, oil or gas). The theory of modulus-frequency-dispersion typically describes the dynamic effect of saturation on attenuation in a porous isotropic rock containing two or more fluids [4]. The model has been applied to the study of attenuation in real hydrocarbon reservoirs [5 & 6]. A detailed knowledge of attenuation is beneficial to seismic data processing and pore fluid discrimination. The low frequency shadow associating with attenuation has been exploited to identify hydrocarbon bearing layers [7 & 8]. A combination of P- and S-waves attenuation has been applied to discriminate gas sand from oil sand, and oil sand from water sand [9 & 10].

The increase in reservoir saturation with time can be observed in time lapse saturation logs. Saturation values obtained from well logs can be combined with the elastic moduli of the rock using [11]equation and the standard linear solid model [1], to create the attenuation-saturation character curve for the rock under investigation. This is plausible because changes in reservoir saturation will affect the amplitude, frequency content, and travel time of a wave travelling through the reservoir. Therefore, the effects of changes in saturation should be measurable in seismic waveforms in terms of attenuation. Amplitude diminution and frequency down-shift in waves are foot prints of seismic wave attenuation and they have been used to measure attenuation in seismic records [e.g., 12 &13]. This study adopts the patchy saturation mechanism and applied the theory of modulus-frequency dispersion to show the effect of change in saturation on the attenuation of seismic waves. Theoretical curve formulated from rock elastic moduli is used to invert the saturation that gave rise to seismic attenuation. Further to this, the study shows that other material properties of rock (porosity, fliud compressibility or bulk modulus of fluid, mineral composition) affect wave attenuation in rocks. The assumptions in the study are as follows: (i) saturation is the sole cause of the attenuation measured in seismic data, (ii) the theoretical curve from the modulus-frequency-dispersion describes the approximate relation between attenuation and saturation for the rock model under study.

THEORY AND METHOD

Patchy saturation model is known to be the principal process responsible for attenuation and dispersion in seismic waves at frequencies similar to those used in seismic exploration [14]. I adopt the patchy saturation mechanism, and applied the theory of modulus-frequency-dispersion to observe the dynamic effect of saturation on attenuation. A modelled reservoir rock used for this study consists of two parts: the patches, and the background rock matrix. The Patches are fully saturated with water, while the rock matrix is partially saturated with gas. The properties of the reservoir rock and their numeric values are detailed in the appendix. The effect of pore fluid changes on the elastic moduli of the rock is estimated using the rock properties that can be obtained from well log data and laboratory measurements, and related by rock physics formulation [11]. The maximum attenuation (Q_{max}^{-1}) is related to the rock moduli-versus- frequency using the Krammer-Kronig relation and the standard linear model [1] as:

$$Q_{max}^{-1} = (M_\infty - M_0)/2\sqrt{M_\infty M_0}, \qquad 1$$

where M_∞ is the high frequency compressional moduli, M_0 is the low frequency compressional moduli. Q_{max}^{-1} is also known as the maximum inverse quality factor. At low frequency, the effective pore fluid is the mixture of water and gas at pore scale. The bulk modulus of the fluid (K_F) is the harmonic average of the moduli of water and gas [15]. The bulk modulus of the partially saturated rock (K_F) is estimated using the formulation of [11] while the compressional modulus of the partially saturated rock is estimated as:

$$M_0 = K_0 + \frac{4}{3}G_{DRY}, \qquad 2$$

$$K_0 = K_s \frac{\emptyset K_{DRY} - (1+\emptyset)K_F K_{DRY}/K_S + K_F}{(1-\emptyset)K_F + \emptyset K_S - K_F K_{DRY}/K_S}, \qquad 3$$

$$\frac{1}{K_F} = \frac{S_W}{K_W} + \frac{1-S_W}{K_G}, \qquad 4$$

At high frequency, fluid distribution in the rock is assumed to be at a patch-scale. The concept of effective pore fluid is no more applicable. The bulk moduli of the fully water-saturated patch (K_P) and the partially gas-saturated region ($K_{SW=0}$) are estimated individually using [11]. The compressional modulus of the entire rock at high frequency is estimated as the harmonic average of the water and gas saturated regions of the rock. Assuming shear modulus is the same for the water saturated and gas saturated regions, compressional modulus of the entire rock is calculated in term of the bulk and shear modulus[16] as:

$$\frac{1}{M_{SAT\infty}} = \frac{S_W}{K_P+\frac{4}{3}G_{DRY}} + \frac{1-S_W}{K_{SW=O}+\frac{4}{3}G_{DRY}}, \qquad 5$$

where S_W is the volume of water in the patch and $1 - s_w$ is the volume of gas in the background rock matrix.

$$K_P = K_s \frac{\emptyset K_{DRY}-(1+\emptyset)K_W K_{DRY}/K_S+K_W}{(1-\emptyset)K_W+\emptyset K_S-K_W K_{DRY}/K_S}, \qquad 6$$

$$K_{SW=O} = K_s \frac{\emptyset K_{DRY}-(1+\emptyset)K_G K_{DRY}/K_S+K_G}{(1-\emptyset)K_G+\emptyset K_S-K_G K_{DRY}/K_S}. \qquad 7$$

Equation 1 applies porosity (θ), saturation (s_w , $1 - s_w$), the bulk modulus of fluid (K_F), bulk modulus of gas (K_G), bulk modulus of water (K_W), the elastic modulus of the dry rock (K_{Dry}, G_{Dry}), and the bulk moduli of the minerals (K_s) to provide analytical solution for the effective elastic moduli of a water-gas-saturated isotropic rock. The black curve in figure 1 shows the dynamic effect of saturation on attenuation for the modelled reservoir rock. [17] simulated plane wave propagation in a patchy saturated rock model containing water with gas inclusion. They showed that the dynamic effects of saturation on the attenuation of seismic waves propagating in a patchy saturated rock can be explained by a curve similar to the one shown in figure 1. The curve (Fig. 1) is used in this study to surmise a first order approximate relation between seismogram derived attenuation (SdA) and saturation. The black curve in figure 1 is hereafter known as the theoretical curve. Because: hydrocarbon reservoirs are rarely fully saturated, and attenuation increases with saturation in the partial saturation range, I consider the partial saturation part of the curve. The blue circles in figure 1 are the values of attenuation and saturation selected for the time lapse seismic study. The values of attenuation and saturation represented by the blue circles are listed in table 1.

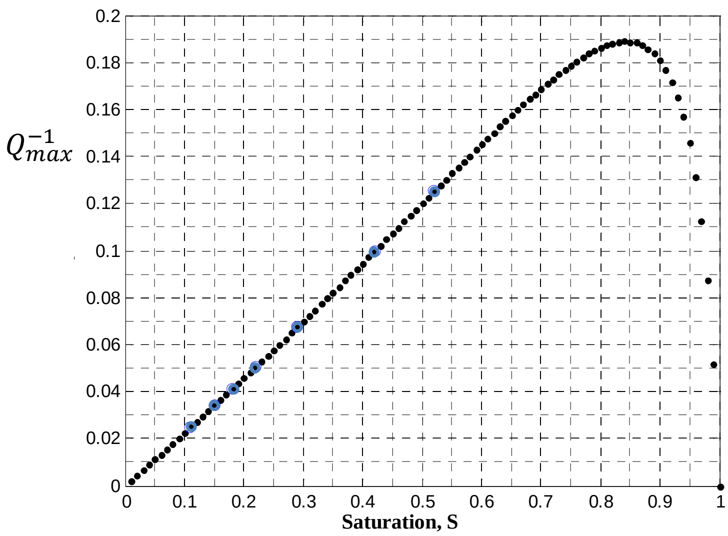

Fig. 1: Attenuation (Q_{max}^{-1}) plotted as function of saturation, using the theoretical model of Mavko et al. (1998). The blue points are the attenuation values selected for the time lapse study.

Table 1: Saturation and the corresponding attenuation extracted from the theoretical curve (blue circles) in Fig. 1

saturation	0.11	0.15	0.18	0.22	0.29	0.42	0.52
Q_{max}^{-1}	0.025	0.034	0.041	0.051	0.067	0.100	0.125

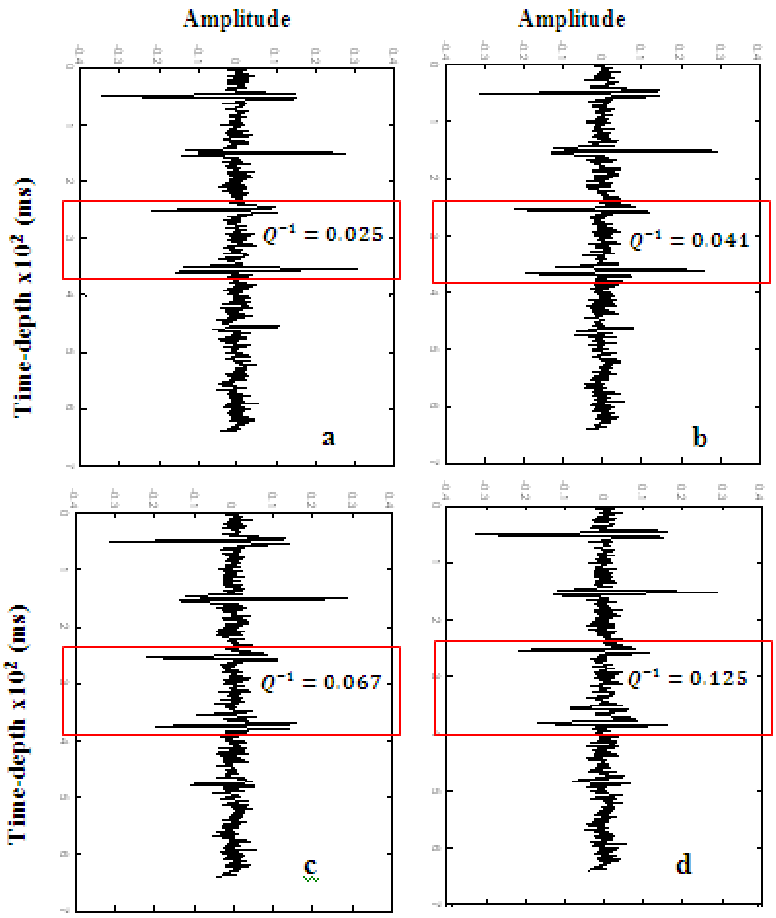

Fig. 2: Time lapse seismic data showing increased amplitude diminution, waveform distortion and time-thickness in the reservoir section (red box) due to the time-variant increase in reservoir saturation. Q^{-1} is the value of the attenuation in the reservoir.

Seven (7) synthetic seismograms were computed to represent the time lapse field seismic data recorded over a period of seven years in the same vicinity of the modelled reservoir rock. The field seismic model consists of five layers. The Q_{max}^{-1} in table 1 is assigned to the fourth layer of each of the time lapse seismograms to model high attenuation due to the reservoir saturation, while a Q^{-1} value of 0.005 is used to model low attenuation (due to the absence of fluid) in the other layers. A MATLAB programme is developed to generate attenuated seismic traces for the Earth seismic model, by incorporating the causal absorption model [18] into the plane wave reflection algorithm [19]. The programme can generate attenuated P-P, P-S, S-P, S-S events, their multiples and random noise. The programme is suitable for generating realistic seismograms for absorptive/attenuating Earth models. Random noise is about 10% of the maximum primary signal amplitude. To avoid ambiguity, the synthetic time-lapse seismograms are hereafter known as field seismograms. Four of the seven time-lapse field seismograms are shown in figure 2. The physical effects of increased attenuation on the field seismograms (Fig. 2) include increased amplitude diminution, wavelet distortion and phase delay, especially in the signals corresponding to the base of the reservoir. The red box in each seismogram captures the signals corresponding to the top and the base of the reservoir interval. The continuous decrease in the signal amplitude that corresponds to the base of the reservoir indicates increased attenuation due to increased fluid saturation. Increased reservoir thickness in the time-lapse field seismograms is the effect of phase delay due to velocity dispersion that usually characterise attenuation. Attenuation is estimated in the time lapse seismic data using the SFVQM algorithm [20]. The attenuation measured in the reservoir interval (Q_a^{-1}) of the seven time-lapse seismic records are 0.027, 0.037, 0.043, 0.056, 0.061, 0.081 and 0.105 respectively. Saturation is predicted for each of the attenuation measured in the time lapse seismograms by using the theoretical curve shown in figure 1. A plot of the SdA with the corresponding saturation is shown in the red colour in figure 3. The saturation equivalence of the seismogram derived attenuation, SdA (red circles in Fig. 3) can be obtained by tracing each red point to the abscissa. The attenuation estimates for the highest input saturation (indicated by the red arrows) in figure 3 significantly differ from the input model (the blue circles indicated by the blue arrows). This is because: (i) the effects of seismic noise is very high - the amplitude of the signal corresponding to the base of the reservoir has been drastically reduced by attenuation and the noise is now about the size of the desired seismic signal (see figure 2d); (ii) the attenuation measuring algorithm is less reliable for predicting attenuation when the Q^{-1} model ≥ 0.10. The influence of the two factors mentioned in (i) and (ii) caused significant error in the saturation predicted from the attenuation measured in the field seismograms. To reduce the uncertainty in saturation estimates due to the effect of seismic noise, the seismic data can be treated for noise by a frequency-neutral algorithm such that the process of de-noising does not affect the frequency profile of the primary signals. In this case, the effect of noise on attenuation measurement is reduced by measuring attenuation in noise free synthetic seismograms in addition to the one measured in the field seismograms. Synthetic noise-free seismograms are generated for each of the time lapse seismic data using the MATLAB programme described earlier. Attenuation estimates in the reservoir section of the noise-free synthetic seismograms (Q_b^{-1}) are 0.023, 0.033, 0.040, 0.053, 0.069, 0.105 and 0.151, respectively. To reduce the uncertainties in saturation estimates due to the effect of noise on attenuation measurement, saturation is predicted from the mean attenuation (Q_m^{-1}). Mean attenuation is computed as the average of Q_a^{-1} and Q_b^{-1}. The plot of Q_m^{-1} and the corresponding saturation is shown in figure 4.

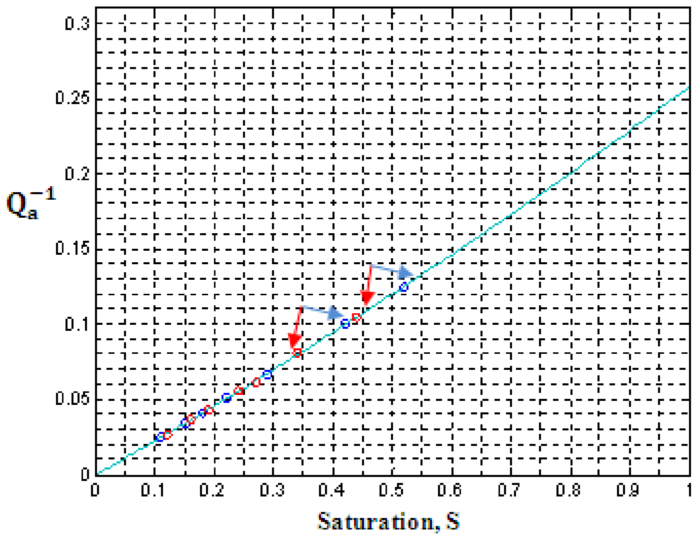

Fig. 3: Seismogram-derived attenuation plotted with saturation (red circles). Saturation is inverted from the SdA using the theoretical curve. The blue circles are the plots of attenuation and saturation from the theoretical curve in figure 1.

The saturation values inverted from the SdA after correcting for the effect of noise ($\boldsymbol{S_{QS}}$) (red circles in Fig. 4) and the saturation predicted by the theoretical model $\boldsymbol{S_{QM}}$ (the circles plots in Fig. 4) are compared in table 2. Results show that correcting the effects of noise on attenuation measurement shows significant improvement in the saturation estimates: the saturation values predicted from SdA after reducing the effect of noise are more consistent with the saturation computed using the theoretical model.

Table 2: Saturation values predicted for the seismic derived attenuation (S_{QS}) and the theoretical rock physics model (S_{QM})

S_{QM}	0.11	0.15	0.18	0.22	0.29	0.42	0.52
S_{QS}	0.11	0.15	0.18	0.23	0.30	0.39	0.54

Effects of Other Reservoir Parameters on Seismic Attenuation

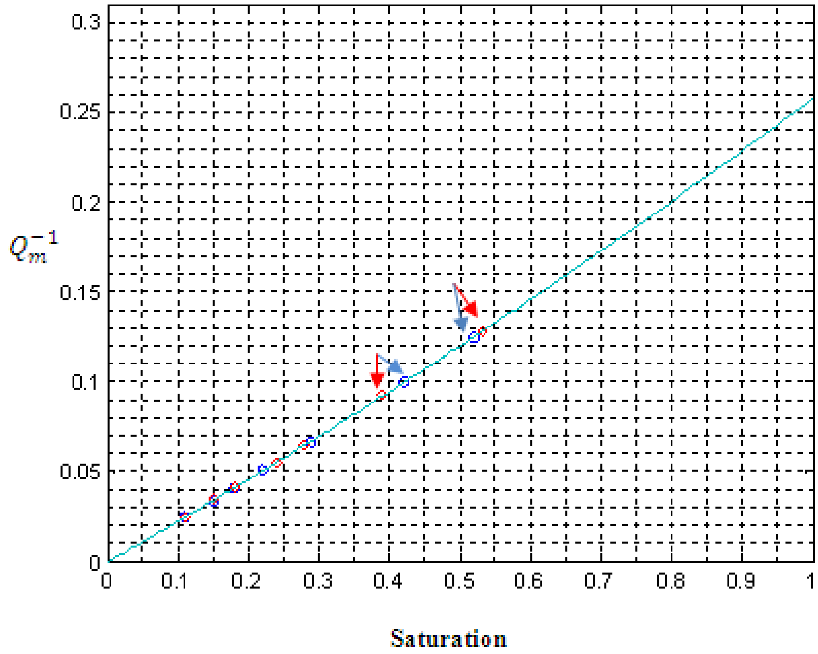

Fig. 4: A plot of SdA versus saturation after correcting the effect of noise on attenuation (red plots). Saturation is inverted from the SdA using the theoretical curve. The blue circles are the plot of attenuation and saturation from figure 1.

i. Porosity, Bulkmoduli of Fluid and Mineral Composition

Apart from saturation, attenuation depends on other properties of rock and fluid. These factors include porosity and mineral composition of the rock [21, 22]; the compressibility and viscosity of the fluid [23, 3]; and temperature [24, 25]. To study the influence of other material properties of rock on attenuation, I kept saturation constant and perturb the porosity, the bulk modulus of the fluids, and the mineral composition of the rock, one after the other, by 10%, in contrast to the values used to compute the curve in figure 1. Figure 5 shows the effects of these parameters on attenuation as predicted by the theoretical model. In contrast to the black curve (reproduced from figure 1), the green curve shows the effects of 10% reduction in porosity; the blue plot is the effect of altering the mineral composition-reducing the quartz composition by 10%, and increasing clay composition by 10%; and the red plot shows the effects of reducing the modulus of the fluid by 10%. The results plotted in figure 5 show that: the change in mineral composition has the least effects on attenuation - the blue curve almost completely overlay the theoretical (black) curve. At 0.17 attenuation (Q_{max}^{-1}) and 70% saturation (shown in black horizontal and vertical lines), a 10% reduction in porosity increased attenuation by a 5.9%, while a 10% reduction in the fluid moduli caused an 11% decrease in attenuation.

ii. Scattering Effects and Tuning Thickness

The assumption that the attenuation measured in waves is the sole contribution of saturation is not is not always valid. Attenuation measured from seismic data is a combination of the intrinsic and scattering attenuation. The relationship can be defined [26] as:

$$1/Q = 1/Q_i + 1/Q_e. \quad (8)$$

Where $1/Q_i$ is the intrinsic attenuation, and $1/Q_e$ is the scattering attenuation. Scattering attenuation and tuning effects caused by thin layers can influence the magnitude of attenuation measured in seismic data. When the thickness of an attenuating layer (h) is less than a quarter of the dominant wavelength ($\lambda/4$), the layer is referred to as a thin layer. The scattering attenuation caused by a thin poroelastic layer can be estimated suing the model [27] as:

$$Q_{sct}^{-1} = S\frac{kh}{1+k^2h^2}, \quad 9$$

where $S = \langle\epsilon^2\rangle$. ϵ is the correlation function for the fluctuation of the impedance, k is the wave number and h is the thickness of the layer.

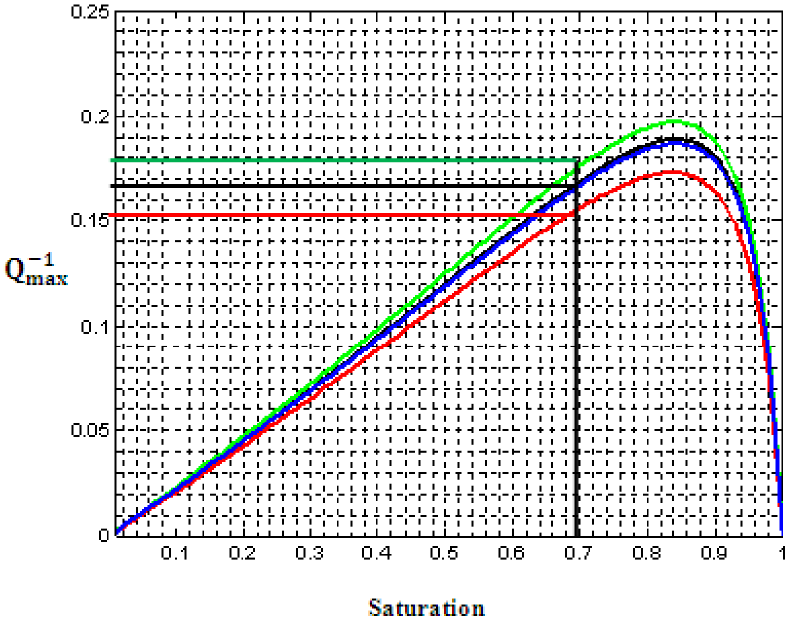

Fig: 5: Attenuation estimate versus saturation – Showing the effects of other material parameters of reservoir on attenuation. For examples, at 70% saturation (the black vertical line), the attenuation value of 0.17 changes to 0.15 and ≈0.18 due to the 10% change in the fluid bulk modulus and porosity respectively. The green plot is when the porosity is reduced by 10%, the red plot is when the fluid bulk modulus is reduced by 10%, while the blue plot is when the mineral composition (clay and quartz) is altered by 10%. Please note that the blue curve is overlaying the black curve. The black curve is from figure 1.

The model can be used to estimate the scattering attenuation due to thin layer. In order to quantify the sole attenuation induced by saturation, the attenuation due to scattering should be deducted from the attenuation measured in the seismic records. The resultant attenuation should then be used to predict saturation as described in earlier section. In seismograms recorded from thin layers, the arrival times of the incident and transmitted signals are close, and thus make it difficult to reliably compute the signal spectra required for attenuation measurement.

RESULTS AND DISCUSSION

Theoretical rock physics model and perturbational forward modeling is applied to study the possibility of using attenuation to indicate saturation in reservoir rocks. Results show that the time variant changes in saturation can be observed in attenuation measured in seismograms recorded at the reservoir interval. The relationship observed in the theoretical curve is used to describe the saturation dependence of seismic attenuation for the modelled reservoir rock. Attenuation measured in seismic records is input to the theoretical curve to invert the saturation equivalence for the SdA. The higher the attenuation measured in seismic records, the higher the saturation inverted from SdA using the theoretical curve. The results show that the time variant saturation increase in reservoir rocks can cause increased seismic wave attenuation that is measureable in time lapse seismic data, and that attenuation can be used to monitor saturation in reservoirs. If the actual relationship between seismogram derived attenuation and saturation is known, attenuation can be used to a first order approximation, to predict hydrocarbon saturation in reservoirs.

Aside saturation, attenuation depends on some material properties of rocks. These properties affect the magnitude of attenuation estimates using rock physics theoretical model and the saturation predicted from the curve. For the case study, a 10% reduction in porosity caused a 5.9% rise in attenuation, while a 10% reduction in the bulk modulus of the saturating fluids caused an 11% drop in attenuation. These changes have corresponding effects on the saturation predicted from the seismic-derived-attenuation, SdA using the theoretical curve. One important observation from the study is that an x degree of saturation can cause different magnitude of attenuation in different rocks due to the variation in the material properties and condition of the rock. Depth of burial, effects of overburden materials, and temperature may cause variation in porosity and mineral composition of reservoirs found at different depths, it is possible that reservoir rocks found in the same area but at different depths can have different attenuation, even if they have similar saturation. It also follows that different attenuation values may be measured in seismic data recorded from two reservoir rocks having similar material properties and saturation, but different thicknesses. It is therefore important to note that every attenuation–saturation case should be treated individually based on the properties and condition of the rocks. Separate theoretical curves should be computed for different rocks, and the theoretical curve should be used to invert saturation for the attenuation measured in seismic data, after removing the contribution of scattering attenuation.

CONCLUSION

Porosity, saturation, mineral composition, and fluid compressibility are important rock properties that play significant roles in the process of attenuation of seismic waves. The effect of these rock properties on attenuation is studied using a what-if pertubational forward modelling technique. Results show that: saturation can be inverted from seismic attenuation using a theoretical curve base on rock-fluid elastic modulus theory. In addition to saturation, porosity, mineral composition, and fluid modulus influence the degree of attenuation a wave experience in a rock.

APPENDIX
The Definitions and Numerical Values of the Properties of the Model Rock

Bulk modulus of water, Kw = 2.64 GPa
Bulk modulus of gas, Kg = 0.08 GPa
Porosity, θ = 0.3
Proportion of clay in the rock, $fclay$ = 0.05
Proportion of Quartz in the rock, $fquartz$ = 0.95
Bulk modulus of clay, K_{clay} = 1.45
Bulk modulus of K_{quartz} = 37.9
Bulk modulus of the minerals, Ks = $(fclay * K_{clay})$ + $(f_{quartz}*K_{quartz})$
Bulk modulus of the dry rock, Kdry = 2.6 GPa
Shear modulus of the dry rock, Gdry = 3.2 GPa
Compressional modulus of the dry rock, Mdry = Kdry+4/3*Gdry

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