Attenuation estimation in crosswell data - an indicator of fracture density and permeability?

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We present an analysis of seismic attenuation using a crosswell seismic dataset gathered at a fractured rock test site. The aim of this study is to better understand the influence of fracture density and permeability on seismic attenuation which may eventually help us in evaluating the hydro-geological rock properties from measurements of seismic attenuation in field data. A new method has been developed to estimate the quality factor from a crosswell shot gather and used it to estimate the quality factor with depth. We show the effectiveness of the method for Q estimation in our crosswell data and present the Q values as a function of depth. The attenuation appears to be sensitive to the density of open fractures, with high attenuation in high fracture density areas. We show that the fracture density and permeability are statistically related to the observed attenuation and these parameters can reproduce the measured Q values with a rock physics model.
Introduction

Seismic attenuation is recognized as a potentially important quantity in reservoir characterization. Attenuation has been associated with fractures (MacBeth, 1999), petrophysical properties (Klimentos and McCann, 1990), and the general viscous motion of saturating fluid (Dvorkin and Nur, 1993). Payne et al. (2007) estimated permeability from seismic attenuation in a crosshole experiment and they observed higher attenuation over a depth interval where higher values of fracture permeability have been determined. Hence, in principle, we can relate the observed attenuation to a physical cause such as permeability or fracture density.

The focus of this study is to estimate average attenuation between two wells as a function of depth for a crosswell experiment and to determine whether attenuation correlates with fracture density and permeability information. First we show the derivation of an equation for $Q$ estimation in crosswell data and present the quality factor values as a function of depth. Then we demonstrate that the measured $Q$ values are related to independent fracture and permeability data using purely statistical methods as well as through rock physics modelling. It is hoped that this study may point the way to the further use of seismic attenuation as a fracture indicator.

Method

A number of computational methods for the determination of seismic quality factor $Q$ are available using either the amplitude or frequency content as input (e.g. Stainsby and Worthington, 1985). Reliable estimates of attenuation $Q$ from amplitude measurements require a good understanding of source radiation pattern and a highly repeatable source. Estimates of $Q$ based on frequency content in the first arrival seismic wavelet may provide a more stable estimate of $Q$.

Here we follow the method described by Zhang (2002), who presented an analytical method which uses the frequency information to estimate the quality factor $Q$ from individual CMP gathers. We extend and utilize this method to calculate a single $Q$ from a crosswell shot gather based on the following observations; 1) Quality factor can be estimated from the variation in peak frequency as a function of offset of a crosswell shot gather assuming the amplitude spectrum of the wavelet to be Ricker-like. 2) The medium is assumed to be isotropic and so each shot gather has a single $Q$ value which is independent of frequency.

Zhang (2002) shows the relationship between seismic quality factor $Q$ and the shift in peak frequency as,

$$Q = \frac{\pi f_p f_m^2}{2(f_m^2 - f_p^2)}$$

Where $f_m$ is the dominant frequency or peak frequency at offset zero, $f_p$ is the peak frequency, t is the time and $Q$ is the quality factor. We solve this equation to an equation with $f_p$ as a function of $f_m$ and $Q$.

$$f_p = \sqrt{f_m^2 + \frac{\pi^2 t^2 f_m^4}{16Q^2} + \frac{\pi^2 f_m^2}{4Q}}$$

The above equation gives the decrease in peak frequency with offset for a given dominant frequency and $Q$. In crosswell case, the peak frequency at horizontal arrival is taken as the dominant frequency, so that the variation in peak frequency at higher offsets can be calculated as a function of vertical source-receiver offset. Peak frequency variation for a set of possible $Q$ values can be calculated and matched with the observed peak frequencies and the best fitting peak frequency variation gives the average $Q$ value for that shot depth.

Hence, a generic equation for the peak frequency variation in crosswell case can be given as,
Where \( f_p \) is the peak frequency at a given offset, \( f_m \) is the frequency at offset = 0, \( x \) is the receiver spacing and \( h \) is the distance between the two wells, \( V \) is the seismic velocity, and \( Q \) is the seismic quality factor.

Fig.1a shows the illustration of a crosswell geometry with receiver spacing \( x \) and well separation \( h \) and fig.1b shows the application of the above equation for a crosswell experiment with \( h=25m \) and \( x=0.5m \). Obviously, the peak frequency decreases as the offset increases and it decreases abruptly for low \( Q \) values and decreases very little for very high \( Q \) values.

![Figure 1a](image1.png) Illustration of a crosswell geometry with receiver spacing \( x \) and well separation \( h \).

1b) Application of the equation for different \( Q \) values. Well separation is 25m, receiver spacing is 0.5m and dominant frequency is 2000Hz.

**Reskajeage Seismic Crosshole Experiment**

We use field data from an experiment that was carried out at a borehole test site in Reskajeage Quarry, Cornwall, UK (Herwanger, 2001). The seismic crosshole experiment was carried out between boreholes BH19 and BH20 using a 48-channel hydrophone string with a 0.5m receiver spacing and a sparker source with a central frequency of 2 kHz, fired at 1m depth intervals. The two vertical boreholes (BH19 and BH20) are 25 m apart, resulting in excellent aperture of the experiment.

The crosswell dataset is sorted into shot gathers and the first arrivals are picked manually. 53 shot gathers from 60m to 112m depth are used in this analysis. The method used in this study assumes the medium for a shot gather to be isotropic and calculates a single \( Q \) value for each shot gather. We therefore limit each shot gather to 10 traces from either side of the horizontal arrival for reliable \( Q \) estimation. This allows us to derive a crude estimate of \( Q \) as a function of depth. A typical shot gather in this study is shown in fig.2a. The application of the method used in this study for the estimation of quality factor from a shot gather is shown in fig. 2b.

![Figure 2a](image2.png) A typical shot gather from Reskajeage seismic crosshole experiment.

2b) The peak frequency variation with offset and the selection of best fitting \( Q \).

It is observed that the peak frequency of horizontal arrivals increases with depth. It may be due to the water-pressure in the borehole which influences the frequency content of the source-wavelet. It can also be greatly affected by the source coupling. Since the method used...
in this analysis calculates the quality factor from the curvature of the peak frequency variation, it is expected that it does not affect our quality factor estimation.

Results and Discussions

The Reskajeage test site was originally developed for a study of fluid flow in fractured rock. Reskajeage Quarry lies within the outcrop of the Mylor Slate Formation and it comprises a variable succession of medium-to-dark-grey slates with silty laminae, thinly bedded fine grained turbiditic sandstones, fine grained massive sandstones and structureless black mudstones (Jefferies et al. 2000). Evidence of the presence of abundant open fractures, in addition to many sealed predominantly quartz-cemented veins, has been obtained from fully orientated core and impression packing. Zones of intense fracturing are identified at around 80m and 105m depth. The density of open fractures as a function of depth for the boreholes BH20 and BH19 are plotted in fig. 3a and 3c. The highly fractured intervals correspond to hydraulically transmissive zones. The observed transmissivities as a function of depth for the boreholes BH20 and BH19 are plotted as a bar-chart in Fig. 3b and 3d, with each bar representing the transmissivity from one injection experiment. The estimated Q values are plotted as a function of depth in fig. 3e. The Q starts decreasing at around 74m depth and reaches a minimum value of 19 at 81m depth, then it increases and shows another interval of low Q at around 105m depth. Both the low Q intervals appear to correlate very well with the high fracture density and permeability intervals.

Figure 3a) Density of open fractures at BH20; 3b) Fluid Transmissivity at BH20; 3c) Density of open fractures at BH19; 3d) Fluid Transmissivity at BH19; 3e) Estimated Quality factor values. Fracture densities are derived from core inspection and impression packing. Transmissivity values are derived from double packer tests with 5m spacing in the shallow part of the boreholes (red) and 1m spacing in the deep part of the borehole (green). Fig. (a)-(d) are reprinted from Herwanger (2001) with author’s permission.

Figure 4a) Best-fit linear regression line using fracture density. 4b) Using Fluid Transmissivity. 4c) Using both fluid transmissivity and fracture density. 4d) Use of rock physics modelling.
Statistical regression analysis has been performed to investigate the correlation between the fracture and permeability data and the measured Q values. Fig. 4a shows the best fit linear regression line using the fracture density data and fig. 4b shows the best fit line using the permeability data. Both the parameters are used in fig. 4c to get the best fit. Further, the fracture density and permeability data have been used in Chapman (2002) rock physics model keeping all the other parameters fixed. The parameters used in the model are density= 2.7g/cc, Vp=5.2km/s, Vs=2.5km/s and kf=2.2MPa. The model reproduces the observed attenuation when suitable scale parameters are chosen for the fracture density and permeability. The model Q values and the measured Q values are plotted as a function of depth in fig. 4d. A statistical f test finds all the linear fits and the model Q values to be acceptable and hence we conclude that there is a statistical relationship between the measured Q values and the fracture and permeability data.

Conclusions

We have analyzed a crosswell dataset to measure attenuation as a function of depth. Our work is based on a method which relates the change in peak frequencies with offset of the first arrivals to Q values. The method appears stable, and we derive generally robust measurements. We see an apparent correlation between attenuation and independent measurements of fracture density and permeability. Statistical tests and rock physics modelling show that they are correlated. This fits with the theoretical expectation and highlights the important petrophysical information in attenuation measurements. This study may eventually help us in estimating the fracture and permeability information from the measurement of seismic attenuation in field data.

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References


MacBeth, C., 1999 Azimuthal variation in P-wave signatures due to fluid flow. Geophysics, 64, 1181-1192.


Stainsby S.D. and Worthington M. H., 1985, Q estimation from vertical seismic profile data and anomalous variations in the central North Sea, Geophysics, 50, 615.