Estimating seismic attenuation (Qp & Qs) from rock properties

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ABSTRACT

As one of the basic attributes of seismic waves propagating in the earth, attenuation (or Q) has important values in the acquisition, processing, and interpretation of seismic data. The relationship between seismic attenuation and rock properties is investigated in this paper using VSP data and well logs from the Ross Lake heavy oilfield, Saskatchewan. The results reveal that Q values of P- and S-waves correlate to P modulus, Vp/Vs, effective porosity, and shale volume. The equations for Q estimation using these four rock properties were then derived using multiple parameter least-square regression method. The results show better prediction quality of *Qp* (R^2=0.65) than *Qs* (R^2=0.48).

INTRODUCTION

Energy absorption is a fundamental feature associated with the propagation of seismic waves in all real materials, and as a result, the shape of transient waveforms will evolve with propagation distance or time (Kjartansson, 1979). Numerous physical mechanisms have been proposed to interpret the attenuation including frictional dissipation due to relative motions at grain boundaries and across crack surfaces (Walsh, 1966); dissipation in a fully saturated rock because of the relative motion of the frame with respect to fluid inclusions (Biot, 1956a, b); inter-crack fluid flow (also known as “squirt” flow) (Mavko and Nur, 1975); and partial saturation effects such as gas-pocket squeezing (White, 1975). Nonlinear friction is commonly assumed to be the dominant attenuation mechanisms, especially in crustal rocks (Johnston et al., 1979). In real materials, we expect that multiple mechanisms of attenuation are present, each having its own characteristic frequency and magnitude (FIG 1).

As one of the basic seismic attributes of waves propagating in the earth, understanding the causes of attenuation as well as the relationship between the attenuation of seismic data and rock properties is important in the acquisition, processing, and interpretation of seismic data. Using attenuation measured on rock samples and well logs, a number of authors (e.g., Klimentos and McCann, 1990; Best et al., 1994; Koesoemadinata and McMechan, 2001) examined the relationship between lab measured attenuation and rock properties for sandstones. Since each of the multiple mechanisms of attenuation have their own characteristic frequency and magnitude, understanding the relationship between attenuation estimated directly from seismic wave and rock properties may be of more importance in seismic exploration. The VSP is particularly valuable in the study of seismic attenuation because reliable seismic attenuation can be measured due to the special geometry of a VSP survey.

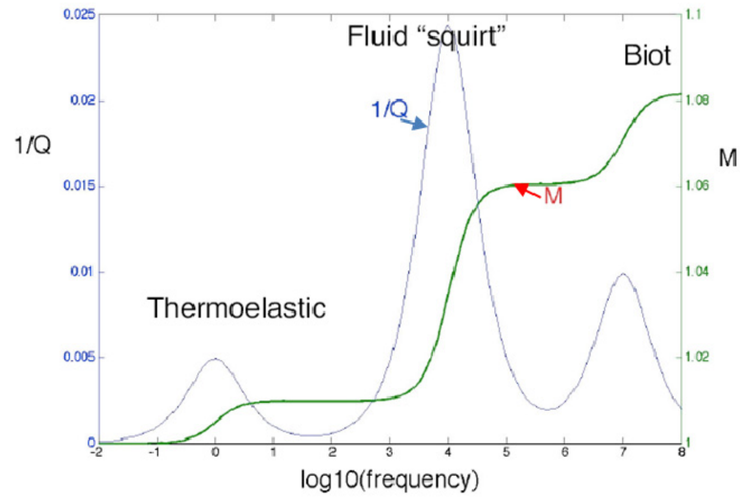

FIG 1. Superposition of multiple attenuation mechanisms (from Mavko, 2006). In real materials, multiple mechanisms of attenuation are present, each having its own characteristic frequency and magnitude (Mavko, 2006). The modulus M (green line) tends to increase with frequency in most rocks. The highest attenuation (the attenuation is plotted as blue line) tends to be in frequency range where M is increasing most rapidly. Three mechanisms of attenuation, thermoelastic, squirt flow, and Biot's relative motion of the frame with respect to fluid inclusions, are labeled at their corresponding characteristic frequencies.

Previous study

Utilizing the benefit of VSP geometry, the relationship between seismic attenuation (*Q*) and rock properties was studied in shale and sandstone using well logs and VSP data from well 11-25-13-17W3 at the Ross Lake heavy oilfield, Saskatchewan (Zhang and Stewart, 2007; 2008). In this study, attenuation characteristics of seismic data are expected to provide information helpful to seismic processing, seismic interpretation, and reservoir characterization. Seismic attenuation was derived from zero-offset VSP data. The rock properties were calculated from well logs. Since the attenuation derived from VSP data is in seismic frequency range, it is of more value in seismic exploration. The study results revealed that interval *Q* values from VSP data for the P wave and shear wave correlate interestingly with petrophysical variables. *Q* values increase with P- and S-velocities and decrease with Vp/Vs and porosity. Shaly sandstone shows more attenuation than pure shale and sandstone.

ESTIMATING *Q* VALUES FROM ROCK PROPERTIES

Since there are correlations between the *Q* values and the rock properties, an empirical equation can be used to approximately calculate *Q* values from rock properties. Assuming a linear relationship between the *Q* values and the rock properties in the studied well, each single rock property is used to predict the *Q* value using least-square regression method (Appendix). The purpose is to see which rock property is the most relevant for *Q* estimation. FIG 2 shows the fit between the actual *Q* values and predicted *Q* values from Vp, Vs, P modulus, shear modulus, Vp/Vs, shale volume, effective porosity, and density. *Qp* correlates more with velocities and

Vp/Vs, while the *Qs* is influenced more by Vp/Vs and shale volume. Then least-square regression for multiple rock properties is also implemented. The results indicate that moduli are better than velocities for *Qp* prediction, while velocities are a little better for *Qs* prediction. To test the sensitivity of each rock property on the prediction accuracy, one rock property is excluded from the calculation each time. The results are shown as FIG 3 for both *Qp* and *Qs*. The prediction using all the testing rock properties is also displayed (the far right-end bar) for comparison. Compared with estimating *Q* value with one rock property, multiple rock properties yield better results (higher R^2 value). No exclusion of one rock property has much influence on the result for *Qp*. Relatively, density and shear moduli have the least influence. The *Qs* values seem to be affected more by shale volume and porosity.

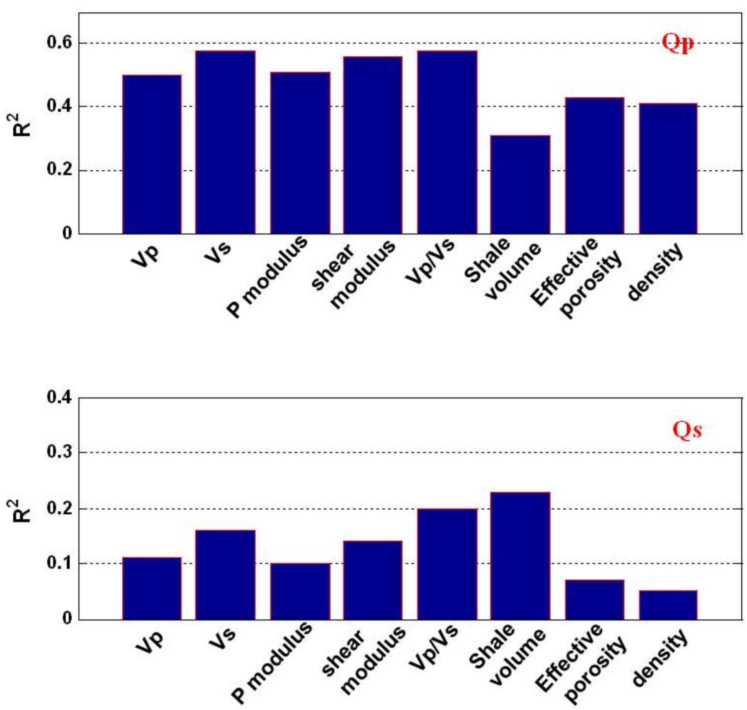

FIG 2. Correlation between real Q values and the Q value from single rock property values. The prediction of Q value is from linear regression equation including only one rock property. The higher R^2 value indicates higher correlation.

Based on this analysis, P modulus, Vp/Vs, effective porosity, and shale volume are chosen to build empirical equation for *Q* prediction using multiple parameter least-square regression method (**Appendix**). The equations for *Qp* and *Qs* are:

$$\boldsymbol{Qp = 1.95 * M - 13.63 * \frac{Vp}{Vs} + 37 * \emptyset + 21 * Vsh + 28.6}$$

$$\boldsymbol{Qs = 66.4 * M - 13.38 * \frac{Vp}{Vs} + 285 * \emptyset + 101 * Vsh - 210} \quad (1)$$

where M is P wave modulus, unit: GPa; ϕ is effective porosity; Vsh is shale volume. The comparison between the real and predicted Q values using equation (1) is shown as FIG 4. It shows better prediction quality of Qp (R^2=0.65) than Qs (R^2=0.48).

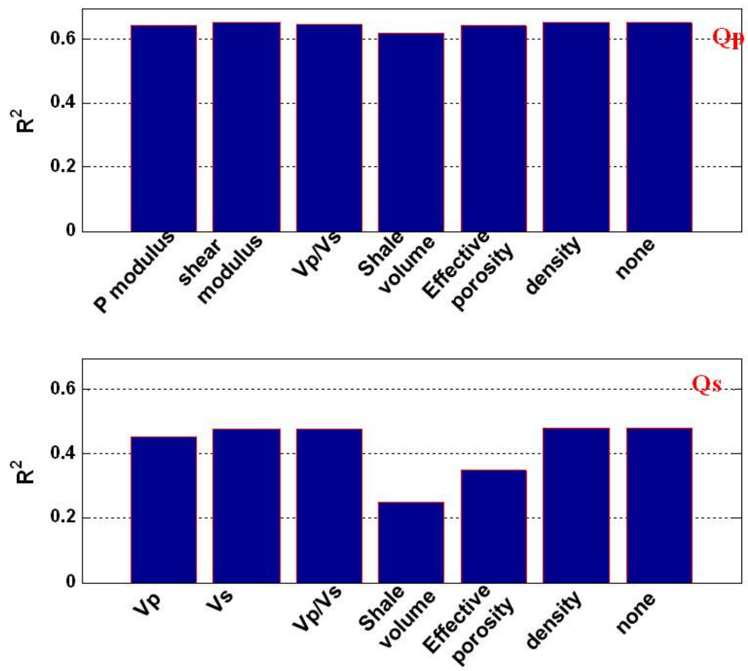

FIG 3. The influence of a single rock property value on prediction accuracy of Q value from rock properties. The prediction of Q value is from linear regression equation including all the rock properties listed at the bottom of each plot, except for the one right below the bar plot. "None" in the figure indicates that all the previous six values are used for linear regression calculation.

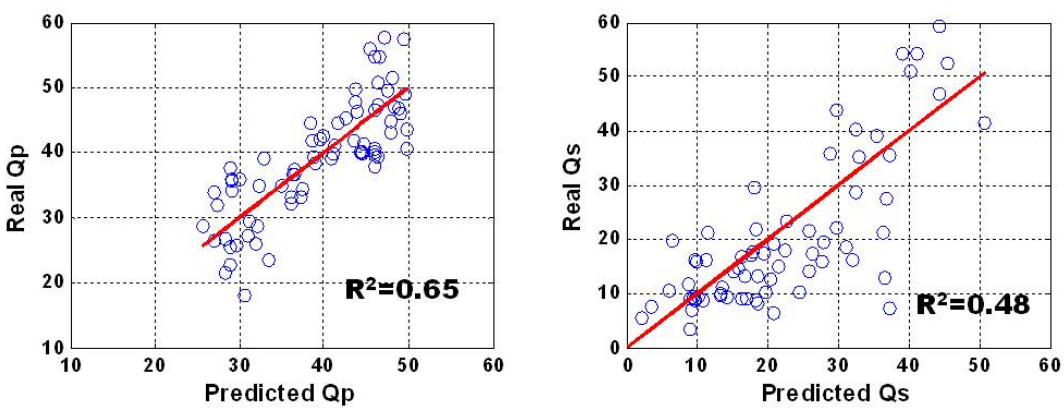

FIG 4. Comparison between real and predicted *Qp* and *Qs* values using equation (1).

CONCLUSIONS

In this report, the relationship between seismic attenuation and rock properties was quantitatively investigated using the VSP data and well logs at Ross Lake heavy oilfield, Saskatchewan. The results reveal that Q values of P- and S-wave relate more to P modulus, Vp/Vs, effective porosity, and shale volume in the study area. The equations for Q estimation using these four rock properties were then derived using multiple parameter least-square regression method. The results show multiple rock properties have better prediction quality than a single rock property.

ACKNOWLEDGEMENTS

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APPENDIX: LINEAR LEAST-SQUARE REGRESSION METHOD FOR EMPIRICAL RELATIONSHIP BETWEEN Q VALUES AND ROCK PROPERTIES

Supposing the relationship between Q values and rock properties are linear, and it can be written as:

$$\begin{aligned} a_1 * x_{11} + a_2 * x_{12} + \cdots + a_m * x_{1m} + Q_0 &= Q_1 \\ a_1 * x_{21} + a_2 * x_{22} + \cdots + a_m * x_{2m} + Q_0 &= Q_2 \\ &\cdots \\ a_1 * x_{n1} + a_2 * x_{n2} + \cdots + a_m * x_{nm} + Q_0 &= Q_n \end{aligned} \tag{2}$$

where a_1, a_2, …, a_m are the unknown coefficients; and x_{kl} is the l^{th} rock properties at measurement depth k, $k=1, 2, \ldots, n$ is the measurement depth, $l=1, 2, \ldots, m$ is the rock properties used for Q prediction, Q_0 is a unknown constant, and Q_1, Q_2, …, Q_n are the Q values measured at each depth. Equation (2) can be rewritten as,

$$XA = Q \tag{3}$$

where

- $X = \begin{bmatrix} x_{11} & \cdots & x_{1m} & 1 \\ x_{21} & \cdots & x_{2m} & 1 \\ & \cdots & & \\ x_{n1} & \cdots & x_{nm} & 1 \end{bmatrix}$;
- $A=(a_1, a_2, \ldots, a_n, Q_0)'$;
- $Q=(Q_1, Q_2, \ldots, Q_n)'$;

If n is greater than the number of unknowns, then the system of equations is over-determined, and the coefficients can be solved using the least square solution of the equations. The least squares solution to the problem is a vector A, which estimates the unknown vector of coefficients. The normal equations are given by

$$(X^T X)A = X^T Q \tag{4}$$

where X^T is the transpose of the design matrix X. Solving for A,

$$A = (X^T X)^{-1} X^T Q \tag{5}$$