Seismic attenuation (Q) estimation from VSP data and Q_P versus V_P/V_S

Chuandong (Richard) Xu and Robert R. Stewart, CREWES Project, Dept of Geology and Geophysics, University of Calgary

Summary

P- and S-wave attenuations are studied using vertical and horizontal vibrator sources and zero-offset VSP data from the Ross Lake heavy oilfield, Saskatchewan. We find that the S-wave shows a larger amplitude loss and phase change than the P-wave over the same depths. This suggests that we will need to pay attention to attenuation in matching the phase of PP and PS images. A new approach to spectral ratio method has been developed to calculate a robust continuous interval Q factor from zero-offset VSP data. We also establish an estimate quality indicator (QQI) curve to highlight where we can obtain a reasonable Q factor. Poor Q estimates may arise from casing-bond problems, multiple casing areas, or source inconsistencies.

The VSP-derived Q_P curve shows an inverse linear relationship with the VSP-derived V_P/V_S curve. Finally, the bulk value of Q_P, V_P/V_S and V_P are estimated for three major geological formations in this oilfield.

Introduction

The spectral ratio method is widely used to determine an attenuation or Q factor from VSP data (Tonn, 1991). By choosing any two VSP downhole geophones, the equation

$$\frac{\left|A(\omega)_{d_2}\right|}{\left|A(\omega)_{d_1}\right|} = e^{-\frac{|\omega|}{2Q}(t_2 - t_1)} \qquad (1)$$

(where t_1 and t_2 are the travel times from the source to geophones at depth d_1 and d_2, respectively) gives the interval Q factor of the formation between the depth d_1 and d_2, if the geophones are well coupled with the formation or wellbore, and the source is consistent. To estimate a relatively stable interval Q, a larger spacing is often required. Averaging the amplitude spectra over a few adjacent geophones is also commonly used. If we use every adjacent geophone, the calculated interval Q could possibly oscillate, or be negative. Therefore, choosing the proper spacing often becomes a case of trial and error.

In the following, we use a different approach of spectral ratio method to calculate Q values using each adjacent geophone, and discuss the conditions for estimating a reasonable Q.

The VSP data used in this paper are from Husky Energy Inc's Ross Lake heavy oilfield in south-western Saskatchewan. There were two types of source for the zero-offset VSP: a vertical mini-vibrator with 12 sec 8-180 Hz sweep and a horizontal vibrator with 12 sec 5-100 Hz sweep. As we are using largely vertical incidence geometries with these sources, we take the simple "P-source" terminology to represent the vertical-vibrator and "S-source" for the horizontal-vibrator. There are 130 3-component geophone levels ranging from 198 m to 1165 m at 7.5 m depth spacing. The VSP survey well has a normal sonic log and a low quality through-casing Dipole Sonic log (V_S).

Method

The zero-offset VSP gives an almost vertical incident ray-path for a horizontal-layer model. In such a layered model, the interval Q (Q_{int}) of each layer and the average Q (Q_{ave}) has a recursive relationship (Bale, et al., 2002):

$$\frac{T(n+1)}{Q_{ave}(n+1)} = \frac{T(n)}{Q_{ave}(n)} + \frac{T(n+1) - T(n)}{Q_{\text{int}}(n+1)} \qquad (2)$$

where n=1, 2,…, N-1 and $Q_{int}(1) = Q_{ave}(1)$.

The above equation shows that the Q_{int} depends on the relationship between $\frac{T(n)}{Q_{ave}(n)}$ and $\frac{T(n+1)}{Q_{ave}(n+1)}$:

- To make $Q_{int} > 0$, we must have $\frac{T(n+1)}{Q_{ave}(n+1)} > \frac{T(n)}{Q_{ave}(n)}$;
- If $\frac{T(n+1)}{Q_{ave}(n+1)} - \frac{T(n)}{Q_{ave}(n)}$ is very small, the Q_{int} calculation is instable.

Therefore, the ratio of the first arrival time and the estimated average Q factor, $\frac{T(n)}{Q_{ave}(n)}$, is acting as a quality indicator for Q-factor estimation (denoted as QQI).

The reference level (n=1) could be set at any depth. Here, we set the surface as the reference level. The spectral ratio between a down-hole recorded trace at a certain depth and the surface sweep is used to calculate the Q_{ave}. The advantage of this approach is that the surface sweep is relatively constant and designed to have a largely flat spectrum across a given band.

Q_P estimation

Both P- and S-source zero-offset VSPs are processed to get the downgoing P- and S-wavefields. For the P-source vertical-component data, after aligning the first arrival times, a 5-by-5 alpha-trimmed weighted median filter is used to separate the downgoing wavefield from the total wavefield. For the S-source horizontal-component data, a rotation from the x- and y-component to radial- and transverse-component by using the hodogram analysis is first needed to align energy in the source-receiver plane. The S-source radial component traces are then flattened at the first break time, and the same median filter as used for P-source data is applied to extract the downgoing shear wavefield. A few P- and S-wave traces at different depth are plotted in Figure 1. The S-wave shows a larger amplitude loss and phase change than the P-wave over the same depth range.

Figure 2 display the spectra of the defined surface sweep, a shallow station (220 m), and a deep station (1157 m) for both P-wave and S-wave. It shows that the S-wave amplitude decays faster than the P-wave, and has less high-frequency components (partially due to the lower band of the source sweep).

Using equation (2), the Q_{P_ave} and Q_{S_ave} curves are calculated and plotted against depth (Figure 3). It's noted that Q_{P_ave} and Q_{S_ave} have different trends.

The QQI curves for P- and S-wave are displayed in Figure 4. It is observed that the QQI_P from about 400 m to 1050 m is well behaved – steadily increasing with a slowly changing positive slope. When this curve has a negative slope i.e. 200 m to 400 m for QQI_P (blue line), the Q_{P_int} will be a negative value. A nearly vertical line (the kinks at 600 m and 800 m) would result in a very high Q_{P_int}. Smoothing can stabilize Q_{int} by sweeping out small kinks, but cannot change the general trend, which means we are unable to get a reasonable Q_P above 400 m in this case.

The QQI_P curve therefore suggests that a fairly reasonable interval Q_P can be estimated from 450 m to 1050 m in this well. A 30-sample boxcar smoother is applied on Q_{P_ave} to get the final Q_{P_int} .

The QQI_S curve (Figure 4, red) only increases in certain areas which can be used for a reliable estimation.

Q_P and V_P/V_S

In general, as depth increases, the rock becomes harder and more rigid, with both V_P and V_S increasing, V_P/V_S decreasing, and less attenuation (higher Q factor). The V_P/V_S is commonly used as a lithology indicator.

Since there is no V_S log in this well, the V_P/V_S curve is calculated from the zero-offset VSP by picking the first arrivals from P- and S-wave. Both P-velocities from log and from VSP are plotted to check the correlation between these two types of measurements (Figure 5, left plot).

Figure 5 displays the curves of interval Q_P derived from VSP (Q_{P_int30}), V_P from sonic log and V_S/V_P from VSP. Generally, these three curves are following the similar trend and tracking each other. Q_P shows almost a linear inverse proportional relation with V_P/V_S: higher V_P/V_S value (softer) corresponds to lower Q_P (more attenuation) and vice versa. This trend is more obvious in the crossplot of Q_P with V_P and V_S, respectively (Figure 6), and the crossplot of Q_P with V_P/V_S which gives $Q_P = -40.3924(V_P/V_S) + 144.1752$ by linear regression (Figure 7).

The following table has been obtained.

	Q_P	V_P/V_S	V_P (m/s)
400m - 610m (above Milk River)	~ 30	~ 2.8	~ 2200
610m - 870m (Milk River - K2WS)	~ 55	~ 2.3	~ 2700
870m - 1050m (K2WS - Mannvile)	~ 40	~ 2.7	~ 2500

Table 1: Q_P, V_P/V_S and V_P for major geological formations in Ross Lake.

Discussion

In Figure 4, the QQI_P curve shows a negative slope from 200 m to 400 m, which means that the amplitudes of high frequency components are increasing with depth. The possible reasons for this unphysical phenomenon might be poor coupling between the casing and cement or between the cement and formation. The double-casing interval is a formidable complication. In this case, the FIRST trustable Q_{P_ave} is likely about 40 at about 445 m depth.

As the VSP is acquired from the bottom of the well up, the surface condition at the source location may be changing as the vibrator continues to shake and enhance its frequency contents. This, of course, violates the assumption of a constant source. It would be useful to have a monitor geophone as the reference level.

The fact of V_P/V_S values in the 3-5 range at the near surface implies that the S-wavelength is 3-5 times shorter than the P-wave's for the same frequency. Given the same travel distance, there are more cycles of attenuation loss for the S-wave. Even in a medium with Q_P=Q_S, energy will eventually attenuate more for the S-wave, especially for high-frequency components. So, attenuation has a larger impact on the S-wave amplitude and phase.

Confidently estimating Q_S proved elusive in this dataset. Looking at Figure 4, we can pick some good points between 200 m to 750 m and get a partial set of Qs values. Below 750 m, it's hard to follow a positive slope. The narrow frequency band may be a partial culprit.

Conclusion

We use the spectral ratio method to calculate Q values. A reliable continuous interval Q_P curve from about 450 m to 1050 m in well 11-25 of Husky's Ross Lake oilfield has been estimated from a zero-offset VSP by this approach. Meanwhile, a quality indicator for Q factor estimation (QQI) has been established. This QQI curve reveals where the normal spectra ratio method gives us unstable Q values.

The VSP-derived Q_P curve demonstrates an inverse linear relationship with the VSP-derived V_P/V_S curve. Finally, the bulk value of Q_P, V_P/V_S and V_P are estimated for three major geological formations in this oilfield.

Acknowledgments

The authors would like to thank Husky Energy Inc. for providing the VSP data and well logs for this study.

References

Bale, R.A. and Stewart, R.R., 2002, The impact of attenuation on the resolution of multicomponent seismic data: CREWES Research Report, 14.

Tonn, R., 1991, The determination of seismic quality factor Q from VSP data: A comparison of different computational methods: Geophys. Prosp., 39, 1-27.

Xu, C. and Stewart R.R., 2001, Walkaway VSP Processing and Q estimation: Pikes Peak, Sask., CSEG Annual Conference, 2001.

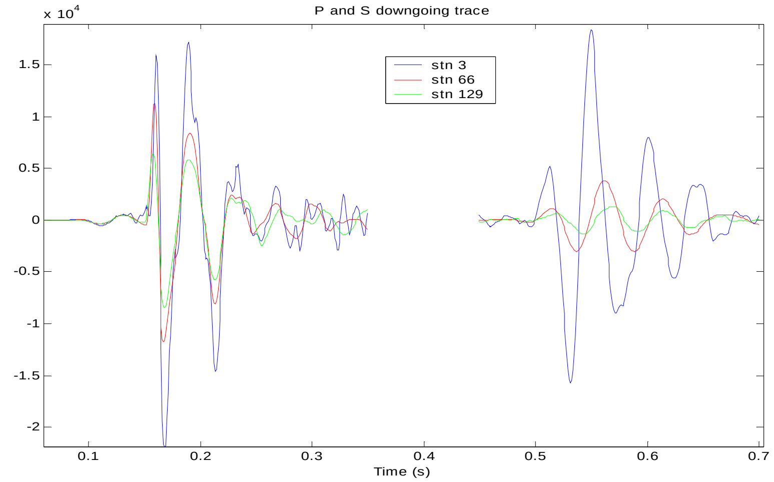

Figure 1: Traces of downgoing P- and S-waves at station #3 (214m depth, blue line), station #66 (685m depth, red line) and station #129 (1157.5m depth, green line).

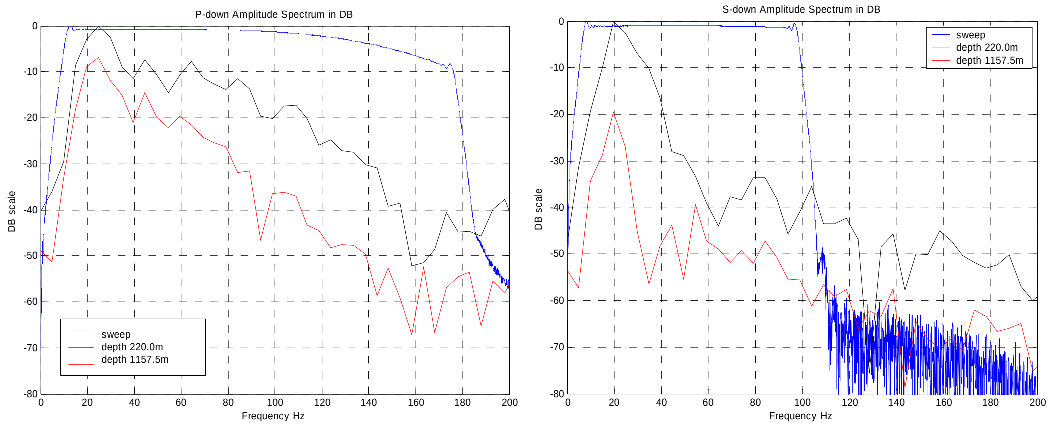

Figure 2: The amplitude spectrum of the sweep (blue line), station #4 (220m depth, black line) and station #129 (1157.5m depth, red line), for P-source (left) and S-source (right).

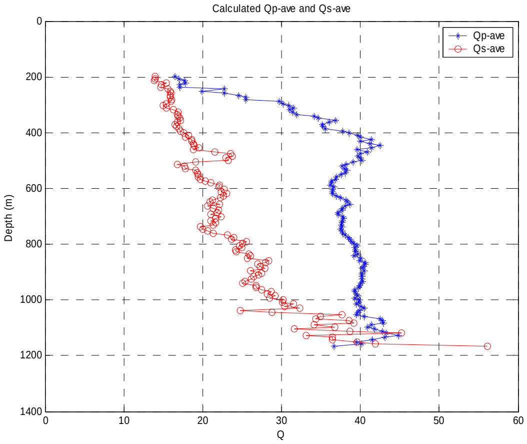

Figure 3: Average Q_P (blue) and average Q_S (red) curve.

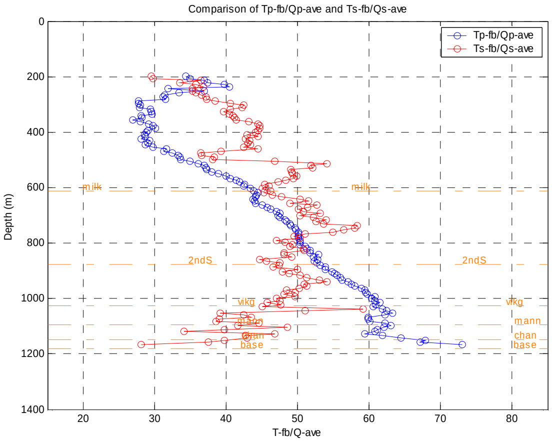

Figure 4: Q Quality Indicator (QQI) for Q_P (blue) and Q_S (red).

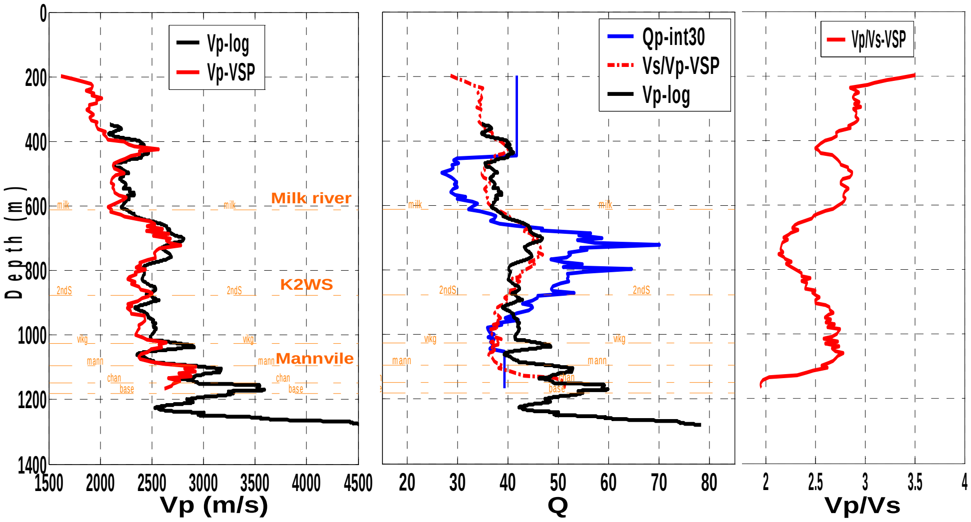

Figure 5: Left: V_P from VSP (red) generally less than V_P from log (black) shows the evidence of dispersion. Middle: smoothed interval Q_P (blue), VSP derived V_S/V_P (red, scaled) and V_P from sonic log (black, scaled).

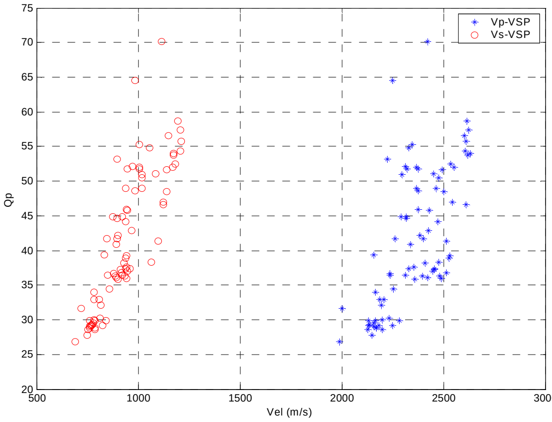

Figure 6: Q_P versus VSP derived V_P (blue) and V_S (red).

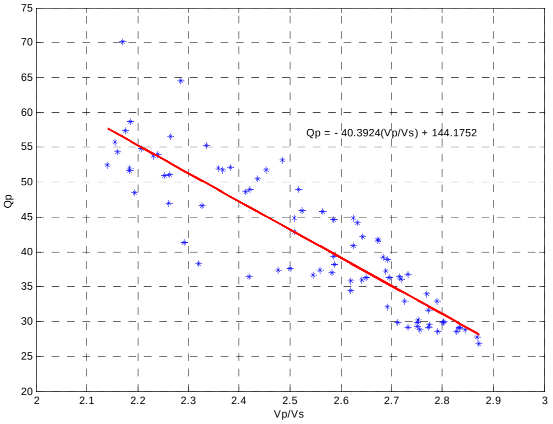

Figure 7: Q_P versus VSP derived V_P/V_S.