Seismic Attenuation (Q) Estimation from VSP Data

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Abstract

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.

Our VSP-derived Qp curve shows an inverse linear relationship with the VSP-derived Vp/Vs curve. Finally, the bulk value of Qp, Vp/Vs and Vp are estimated for three main 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). For two receivers at depths d1 and d2:

$$\frac{|A(\omega)_{d2}|}{|A(\omega)_{d1}|} = e^{-\frac{|\omega|}{2Q}(\frac{d_2}{v_2}-\frac{d_1}{v_1})} \quad (1)$$

where A( ) is the amplitude spectrum at different depth, =2 f is the frequency, v1 and v2 are the average velocities from surface to depth d1 and d2, respectively. Expressed in time, equation (1) becomes:

$$\frac{|A(\omega)_{d2}|}{|A(\omega)_{d1}|} = e^{-\frac{|\omega|}{2Q}(t_2-t_1)} \quad (2)$$

where t1 and t2 are the travel time from source to geophones at depth d1 and d2.

By choosing any two VSP downhole geophones, equation (2) gives the interval Q factor between them, if the geophones are well coupled with the fomation or wellbore and the source is consistent. To determine a relarively stable interval Q, a larger spacing is often selected. Averaging the amplitude spectra of a few adjacent geophones first is also commonly used. If we use every adjacent geophone, the calculated interval Q can oscillate, or even be negative. Therefore, choosing the proper spacing often becomes a case of trial and error.

In the following, we use a different approach 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 198m to 1165m. The VSP survey well has a normal sonic log and a low quality through-casing Dipole Sonic (VS) log.

Data preperation

The data used for the Q calculation are the zero-offset downgoing wavefield traces. 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 hologram 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 (Figure 1), and the same median filter is applied as for P-source data to extract the downgoing shear wavefield (Figure 2).

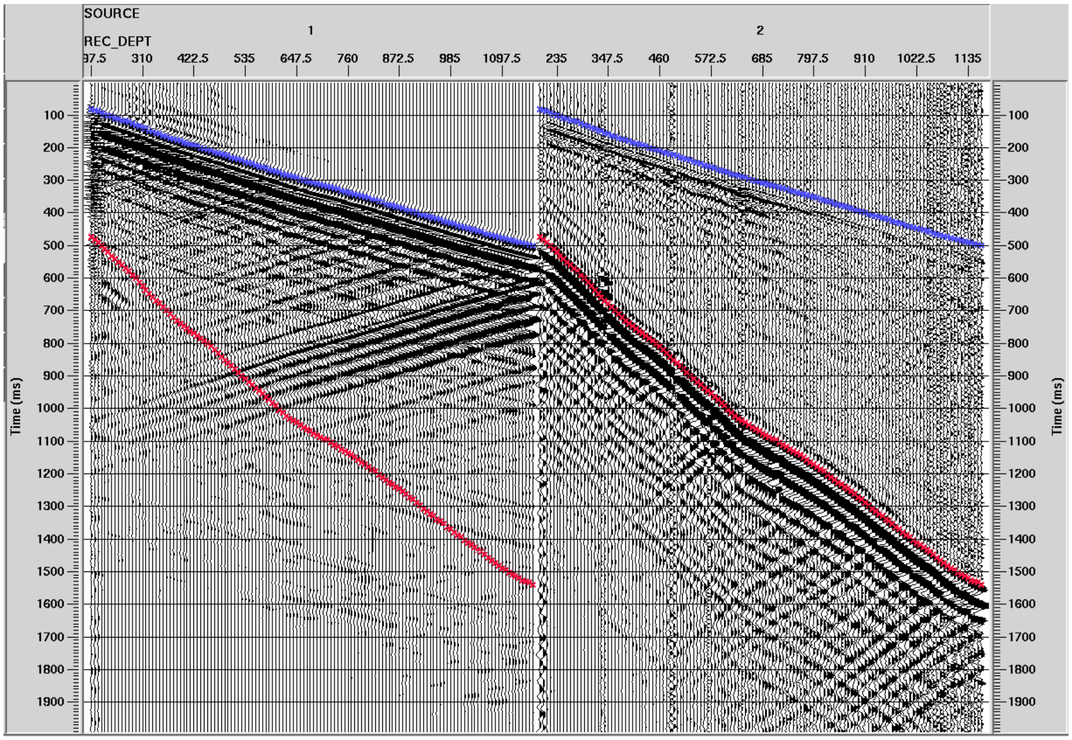

Figure 1. P-source vertical (left) and S-source radial (right) components traces with P-wave first breaks (blue) and S-wave first breaks (red). AGC is applied for display.

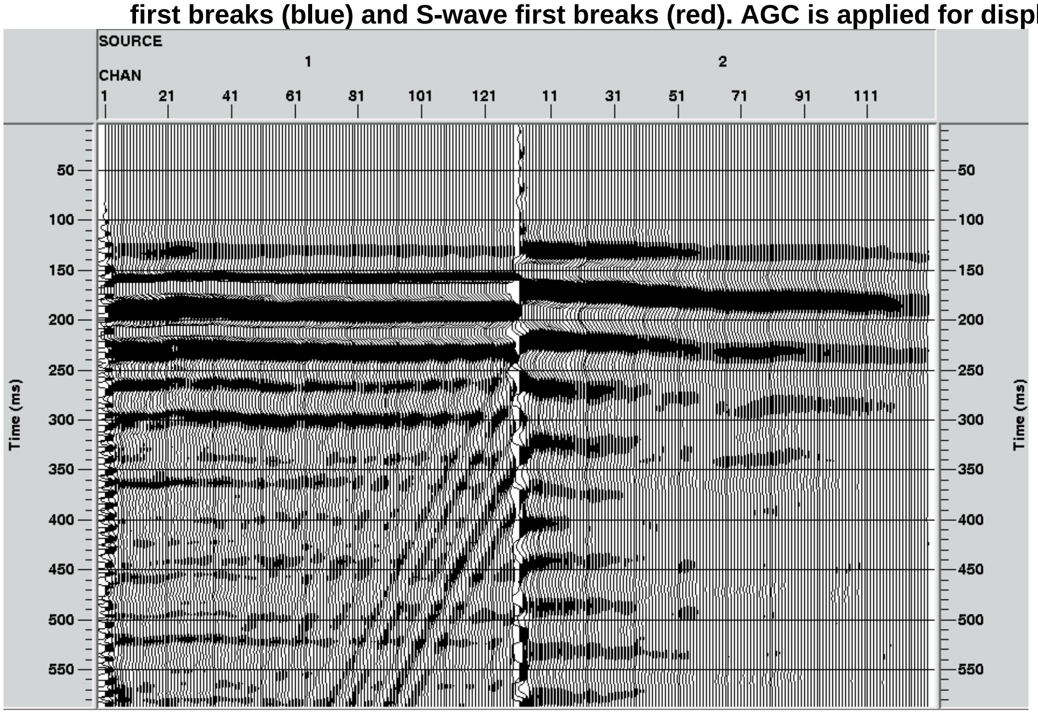

Figure 2. Aligned downgoing P wavefield from P-source (left) and downgoing S wavefield from S-source (right), displayed using a single scalar.

We observe in Figure 2 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). The P-wave has little phase change. Meanwhile, the S-wave shows some changes (also in Figure 3).

In the near surface, we find the VP/VS values in the 3-5 range, which means for the same frequency, the S wavelength is 3-5 times shorter than P-wave's. Given the same travel distance, there are more cycles of attenuation loss for the S wave. Even In a medium with QP=QS, energy will eventually attenuate more for the S-wave, especially for high-frequency components. So, attenuation can have a larger impact on the S-wave amplitude and phase.

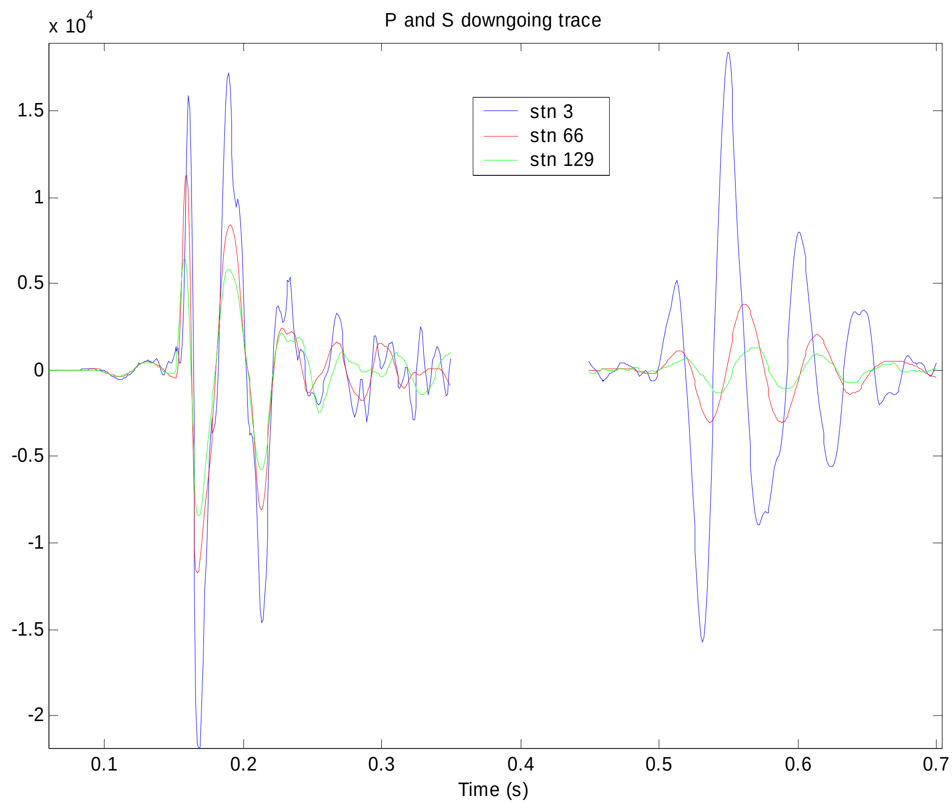

Figure 3. Traces of downgoing P and S waves at station #3 (214m depth, blue line), station #66 (685m depth, red line) and station #129 (1157.5m depth, green line).

<u>Qp estimation</u>

The spectral ratio method of various levels is often used to estimate a Q factor (Xu, et al., 2001). Here, we set the surface as the reference level. The spectral ratio between any trace and the surface sweep is used to calculate a Qave instead of Qint. The benefit of this approach is that the surface sweep is relatively constant and designed to have a largely flat spectrum across a given band. Figure 4 displays the spectra of the defined surface sweep, a shallow station (220m) and a deep station (1157m) for both P-wave and S-wave.

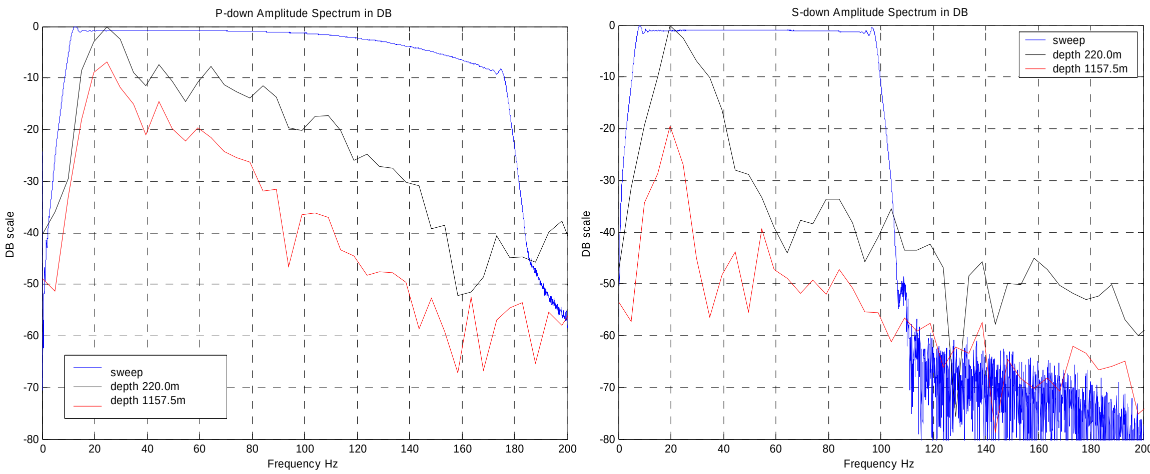

Figure 4. The amplitude spectrum of the sweep (blue line), station #4 (220m depth, black line) and station #129 (1157.5m depth, red line), for P-source (left) and S-source (right).

In this way, Qp_ave and Qs_ave curve for the whole interval are calculated and plotted against depth (Figure 5). It's noted that Qp_ave and Qs_ave have different trends.

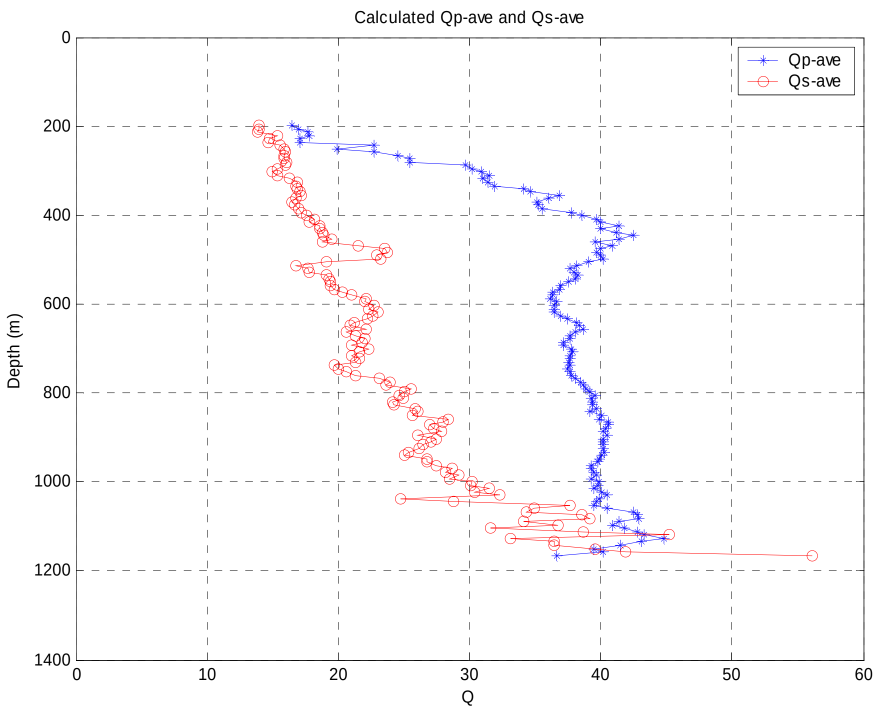

Figure 5. Average QP (blue) and average QS (red) curve.

To calculate Qint in a layered model (Bale, et al., 2002), we use:

$$\frac{T(n+1)}{Q_{ave}(n+1)} = \frac{T(n)}{Q_{ave}(n)} + \frac{T(n+1)-T(n)}{Q_{\text{int}}(n+1)}$$, n=1, 2,…, N-1 (3)

where we set Qint(1) = Qave(1).

From equation (3), Qint depends on the relationship between $\frac{T(n)}{Q_{ave}(n)}$ and $\frac{T(n+1)}{Q_{ave}(n+1)}$. To make Qint >0, we must have:

$$\frac{T(n+1)}{Q_{ave}(n+1)} > \frac{T(n)}{Q_{ave}(n)} \qquad (4)$$

If $\frac{T(n+1)}{Q_{ave}(n+1)} - \frac{T(n)}{Q_{ave}(n)}$ is very small, the Qint calculation is instable.

So, 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 QQI curves for P- and S-wave are displayed in Figure 6.

The QQI_P curve from about 400m to 1050m is well behaved – steadily increasing with a slowly changing positive slope. If the curve has a negative slope i.e. 200m to 400m for QQI_P (blue line), the Qp_int will be a negative value. A nearly vertical line (the kinks at 600m and 800m) would result in a very high Qp_int. Smoothing can improve Qint by sweeping out small kinks, but can't change the trend, which means we can NOT get a reasonable Qp above 400m in this case.

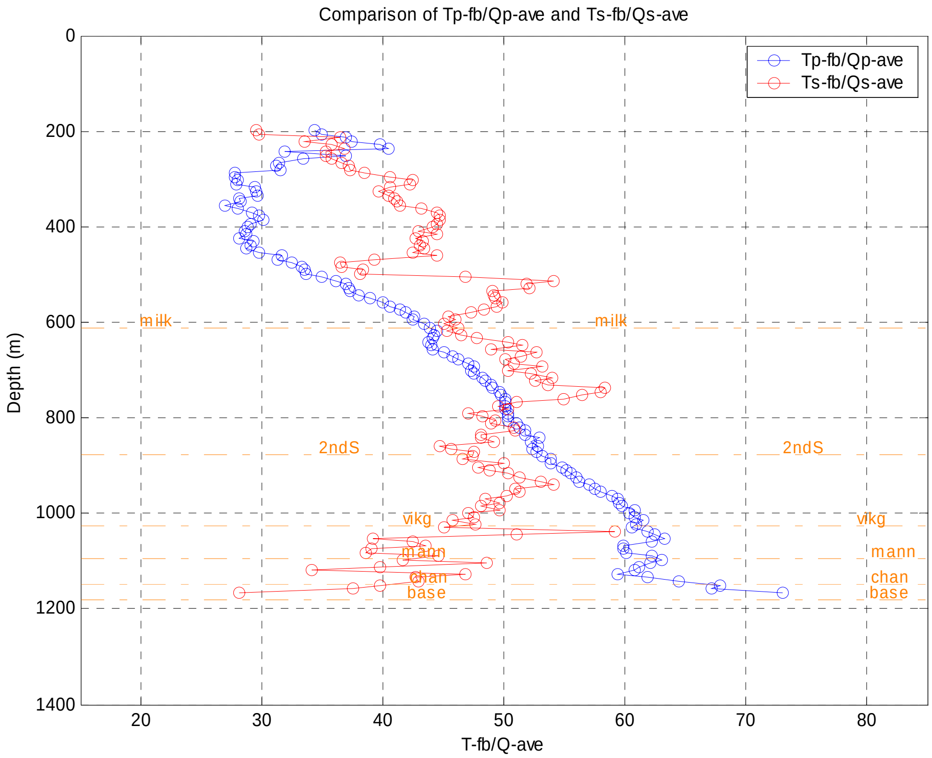

Figure 6. Q Quality Indicator (QQI) for QP (blue) and QS (red), with formation tops.

So, this calculation suggests that a fairly reasonable interval QP can be estimated from 450m to 1050m. To avoid an oscillatory Qint,, different sizes of boxcar smoothers are tried to smooth Qave. Figure 7 shows the results with 10, 20 and 30 samples smoothing, Qint10 (black line), Qint20 (red line) and Qint30 (blue line) curve.

The QQI_S curve (Figure 6) only increases in certain areas which can be used for reliable estimation.

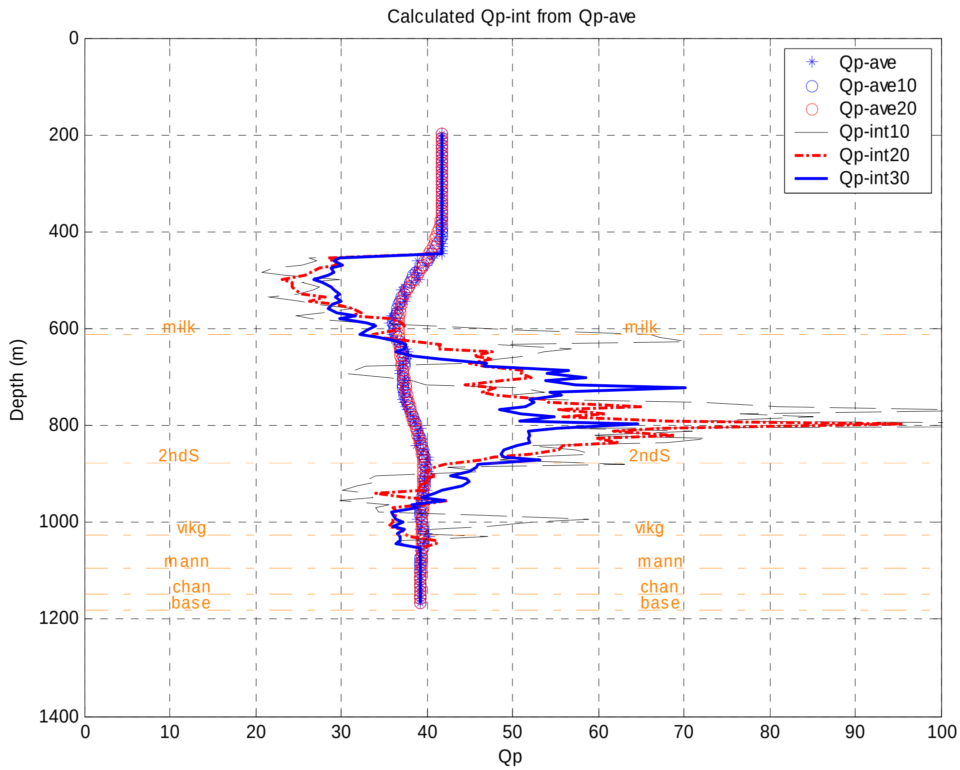

Figure 7. Average Qp with 10, 20 and 30 samples smoothing, and derived interval Qp.

<u>Qp and Vp/Vs</u>

In genaral, as going deeper, the rock (formation) becomes more harder and rigid, with both Vp and Vs increasing, Vp/Vs decreasing, and the waves attenuate less (higher Q factor). Vp/Vs is commonly used as a lithology indicator.

Since there is no Vs log in this well, the zero-offset VSP is used to get the Vp and Vs curves by picking the first arrivals from P- and S-wave. P-velocity from log and from VSP are plotted to check the correlation between these two types of measurements (Figure 8, left plot).

Figure 8 displays the interval Qp derived from VSP (QP_int30), Vp from sonic log and Vs/Vp from VSP. Generally, the three curves are following the similiar trend and tracking each other. QP shows almost a linear inverse propotional relation with Vp/Vs : higher Vp/Vs (softer) corresponds to lower Qp (more attenuation) and vice versa. It's more obvious in the crossplot of Qp with Vp and Vs, respectively, and the crossplot of Qp with Vp/Vs which gives us Qp = -40.3924(Vp/Vs) + 144.1752 by linear regression (Figure 9).

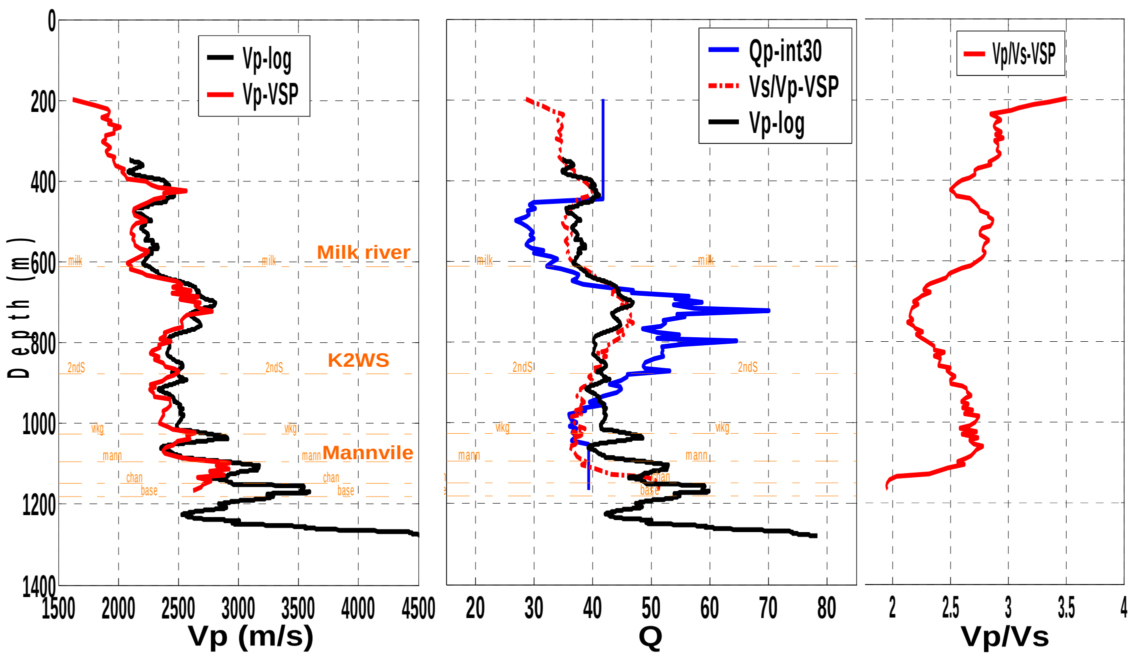

Figure 8. Left: Vp from VSP (red) is generally less than Vp from log (black) shows the eveidence of dispersion.
Middle: smoothed interval QP (blue), VSP derived VS/VP (red, scaled) and VP from sonic log (black).

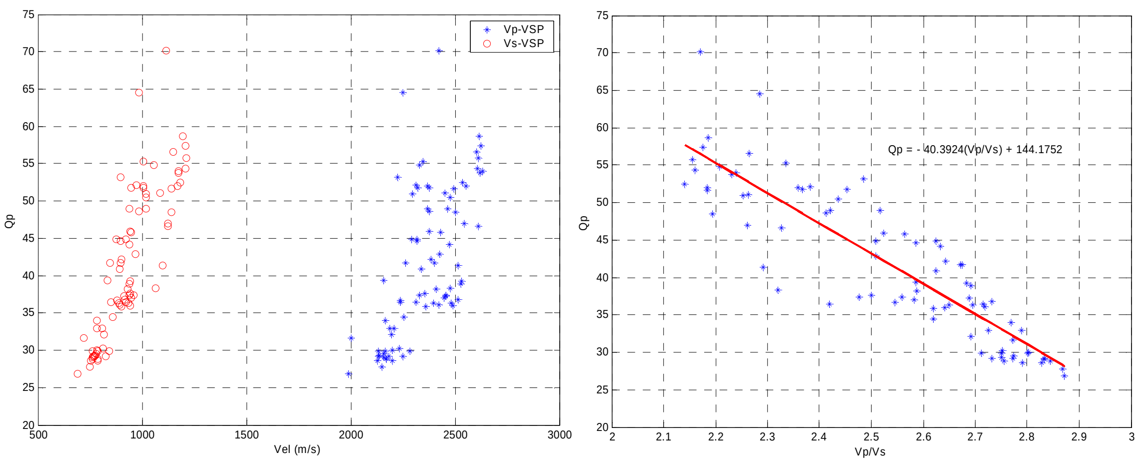

Figure 9. Left: Qp with VSP derived Vp (blue) and Vs (red).
Right: Qp shows an inverse proportional relation with VSP derived Vp/Vs.

The following table has been obtained.

Table 1. QP, VP/VS and VP for main geological formations in Ross Lake.

	QP	VP/VS	VP (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

Discussion

In Figure 6, the QQI_P curve shows a negative slope from 200m to 400m, which means that the amplitudes of high frequency components are increasing with depth. The possible reasons for this unphysical phenomen might be poor coupling between the casing and cement or between the cement and formation. The double-casing interval is a formidable complication. Therefore in this case, the FIRST trustable Qave is about 40 at about 445m depth. The Qave ~ 18 at about 200m may not be reliable.

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.

Confidently estimating Qs proved elusive in this data set. Looking at Figure 6, we can pick some good points between 200m to 750m and get a partial set of Qs. values. Below 750m, 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 Qp curve from about 450m to 1050m in well 11-25 of Husky's Ross Lake oilfield has been derived 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 Qp curve demonstrates an inverse linear relationship with the VSP-derived Vp/Vs curve. Finally, the bulk value of Qp, Vp/Vs and Vp are estimated for three main geological formations in this oilfield.

Acknowledgement

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