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 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 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 d_1 and d_2:

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

where A(ω) is the amplitude spectrum at different depth, $\omega=2\pi f$ is the frequency, v_1 and v_2 are the average velocities from surface to depth d_1 and d_2, respectively. Expressed in time, equation (1) becomes:

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

where t_1 and t_2 are the travel time from source to geophones at depth d_1 and d_2.

By choosing any two VSP downhole geophones, equation (2) gives the interval Q factor between them, if the geophones are well coupled with the formation or wellbore and the source is consistent. To determine a relatively 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 (V_S) 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).

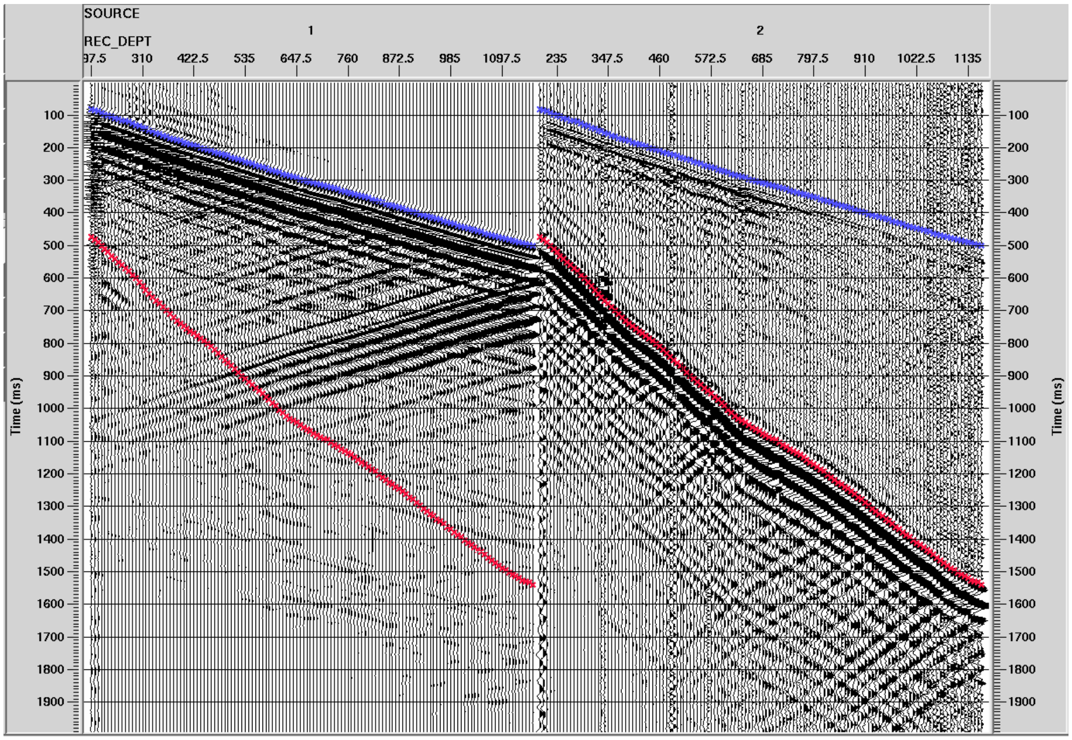

FIG. 1. P-source vertical (left) and S-source radial (right) components traces with P-wave first breaks (blue) and S-wave first breaks (red). AGC is applied for display.

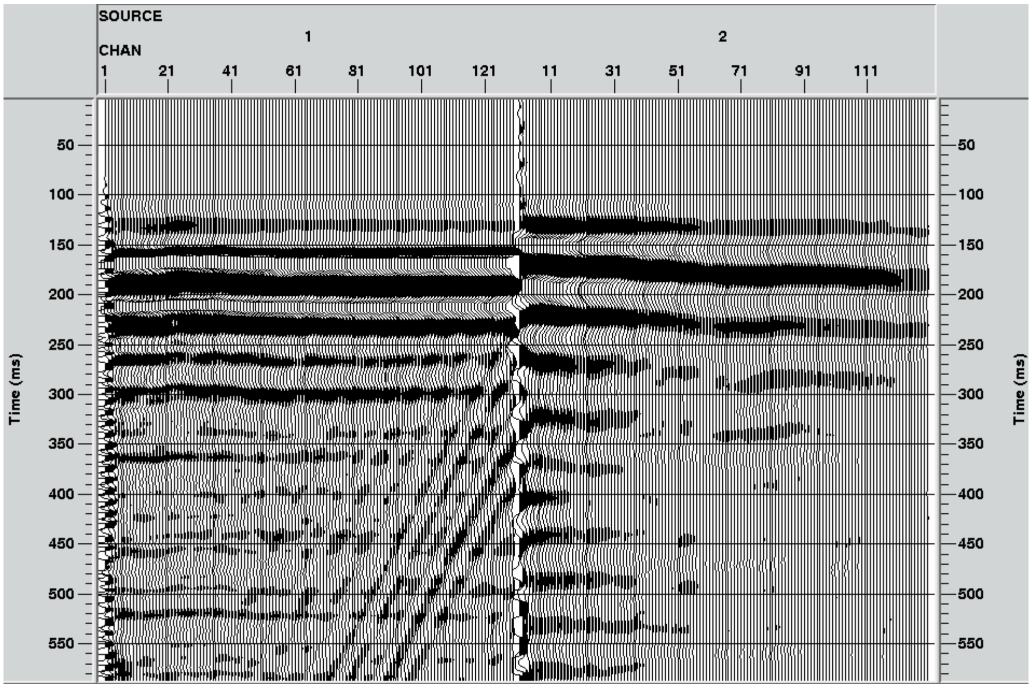

FIG. 2. Aligned downgoing P wavefield from P-source (left) and downgoing S wavefield from S-source (right), displayed using a single scalar.

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 V_P/V_S 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 $Q_P=Q_S$, 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.

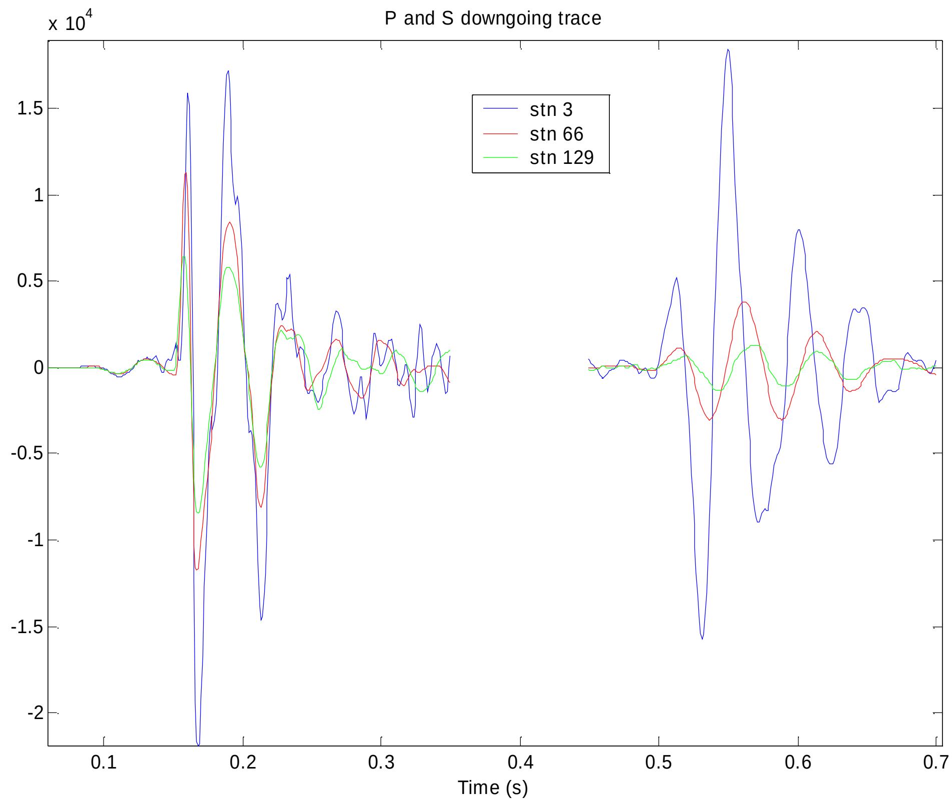

FIG. 3. Traces of downgoing P and S waves at station #3 (214m depth, blue line), station #66 (685m depth, red line) and station #129 (1157.5m depth, green line).

Q_p estimation

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 Q_{ave} instead of Q_{int}. 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.

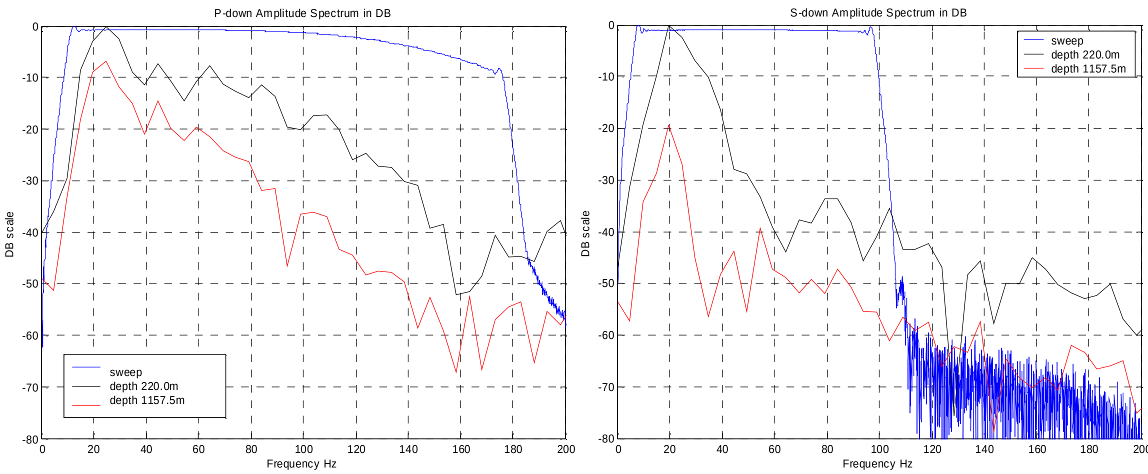

FIG. 4. The amplitude spectrum of the sweep (blue line), station #4 (220m depth, black line) and station #129 (1157.5m depth, red line), for P-source (left) and S-source (right).

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

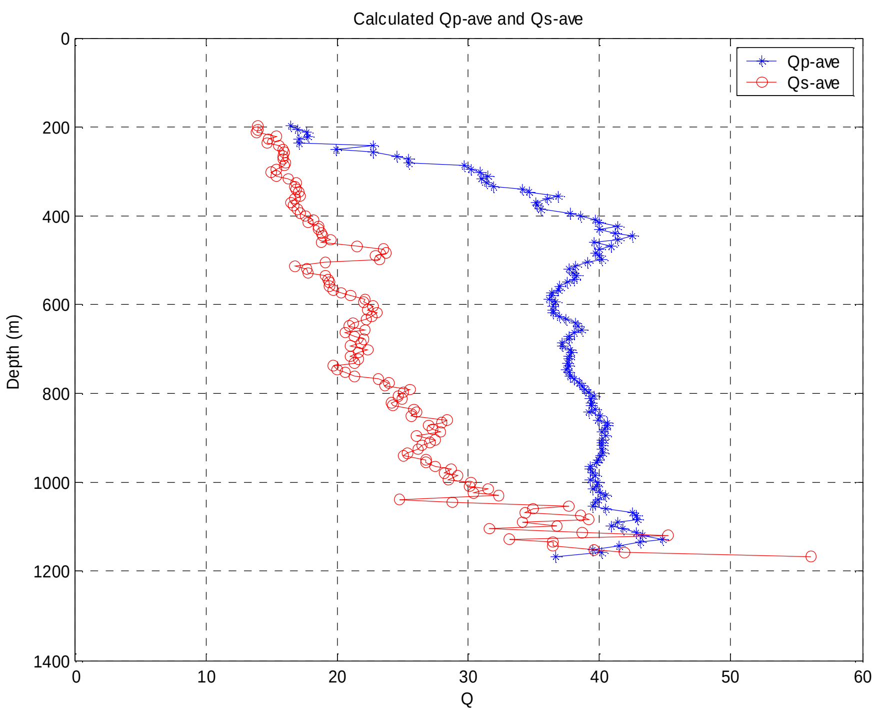

FIG. 5. Average Q_P (blue) and average Q_S (red) curve.

To calculate Q_{int} in a layered model (Bale, et al., 2002), we use:

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

where we set $Q_{int}(1) = Q_{ave}(1)$.

From equation (3), 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:

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

If $\frac{T(n+1)}{Q_{ave}(n+1)} - \frac{T(n)}{Q_{ave}(n)}$ is very small, the Q_{int} 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 Q_{p_int} will be a negative value. A nearly vertical line (the kinks at 600m and 800m) would result in a very high Q_{p_int}. Smoothing can improve Q_{int} by sweeping out small kinks, but can't change the trend, which means we can NOT get a reasonable Q_p above 400m in this case.

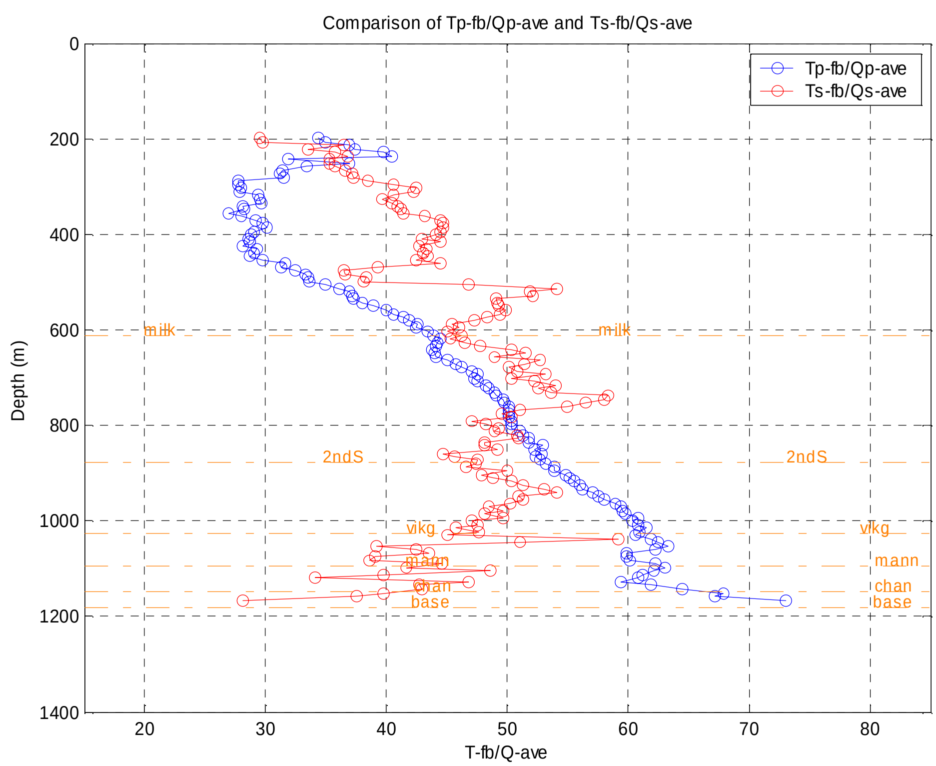

FIG. 6. *Q* Quality Indicator (QQI) for Q_P (blue) and Q_S (red), with formation tops.

So, this calculation suggests that a fairly reasonable interval Q_P can be estimated from 450m to 1050m. To avoid an oscillatory Q_{int},, different sizes of boxcar smoothers are tried to smooth Q_{ave}. Figure 7 shows the results with 10, 20 and 30 samples smoothing, $Q_{int}10$ (black line), $Q_{int}20$ (red line) and $Q_{int}30$ (blue line) curve.

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

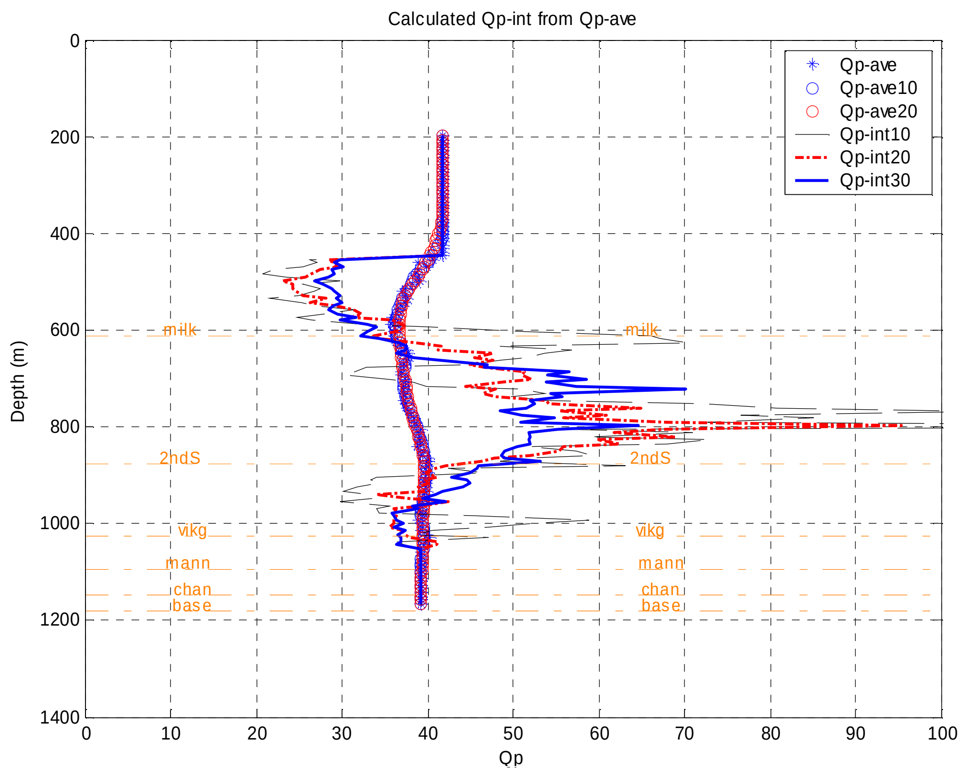

FIG. 7. Average Q_p with 10, 20 and 30 samples smoothing, and derived interval Q_p .

Q_p and V_p/V_s

In general, as going deeper, the rock (formation) becomes more harder and rigid, with both V_p and V_s increasing, V_p/V_s decreasing, and the waves attenuate less (higher Q factor). V_p/V_s 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 V_p and V_s 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 Q_p derived from VSP ($Q_{P\_int}30$), V_p from sonic log and V_s/V_p from VSP. Generally, the 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 (softer) corresponds to lower Q_p (more attenuation) and vice versa. It's more obvious in the crossplot of Q_p with V_p and V_s, respectively, and the crossplot of Q_p with V_p/V_s which gives us Q_p = -40.3924(V_p/V_s) + 144.1752 by linear regression (Figure 9).

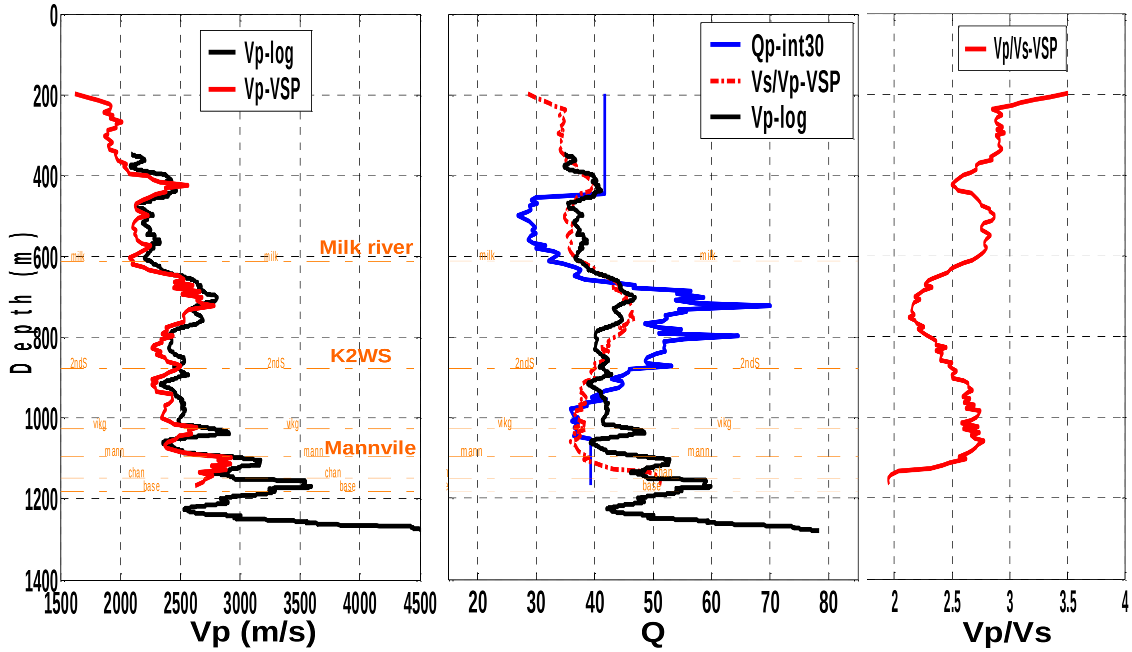

FIG. 8. Left: Vp from VSP (red) is generally less than Vp from log (black) shows the eveidence of dispersion. Middle: smoothed interval Q_P (blue), VSP derived V_S/V_P (red, scaled) and V_P from sonic log (black).

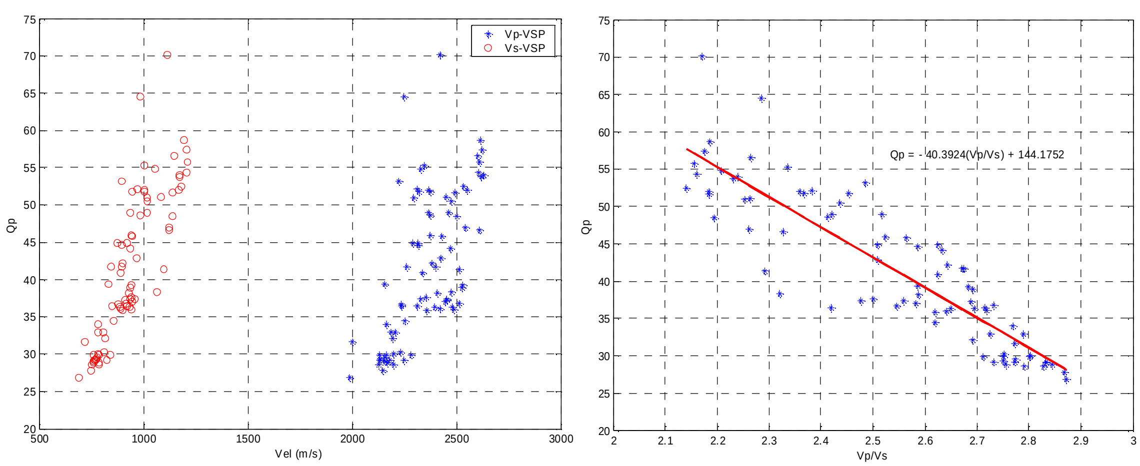

FIG 9. Left: Q_p with VSP derived V_p (blue) and V_s (red). Right: Q_p shows an inverse proportional relation with VSP derived V_p/V_s.

The following table has been obtained.

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

	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

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 phenomenon 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 Q_{ave} is about 40 at about 445m depth. The Q_{ave} ~ 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 Q_s 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 Q_s. 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 Q_p 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 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 main geological formations in this oilfield.

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