VSP processing and analysis at the Ross Lake heavy oilfield, Saskatchewan

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ABSTRACT

In June 2003, the CREWES Project, Husky Energy Inc., and Schlumberger Canada conducted a multi-offset VSP survey at Ross Lake oilfield, Saskatchewan. This paper describes the processing of two of the data sets with source offsets of 53m and 400m. The processing results have a frequency bandwidth from 10Hz to 90Hz. The corridor stack (from 53m offset) ties the offset section (from 400m) nicely as well as the synthetic seismogram generated from wireline log data. Q values for both P wave and shear wave were also estimated through the spectral ratio method. We have confidence in extracted Q*p* values from 28 to 51 over the interval of 450m to 1000m and Q*s* values from 6 to 22 over the interval of 200 to 800m.

INTRODUCTION

The Ross Lake heavy oilfield (operated by Husky Energy Inc.) is located in southwestern Saskatchewan (Figure 1). The producing reservoir is a Cretaceous channel sand in the Dimmock Creek member of the Cantuar formation of the Mannville Group. The produced oil is about 13° API.

FIG. 1. Location of Ross Lake oilfield, Saskatchewan (from Xu and Stewart, 2003)

In June 2003, the CREWES Project, Husky Energy Inc., and Schlumberger Canada conducted a multi-offset VSP survey in well 11-25-13-17W3. The zero-offset VSP survey used both vertical and horizontal vibrators as sources, but the vertical vibrator only was used for offset VSP surveys. All the surveys were conducted with a downhole five-level, three-component receiver. Two VSP surveys, offset 53.67 meters and 399.12

meters were processed. The acquisition parameters of the processed surveys are shown in Table 1.

Table 1. Acquisition parameters of selected Ross Lake VSP surveys.

Survey Type	**Zero-offset VSP**	**Far-offset VSP**
Offset	53.67 m	399.12 m
Source Elevation	856.1 m	867.7 m
Source Azimuth	16.3o true north	337.2 o true north
Source Type	Litton 315 P-vibe: sweep = 8 - 180 Hz, 12sec linear sweep IVI S-MINI-vibe: Sweep = 5 - 100 Hz, 12sec linear sweep	Litton 315 P-vibe: sweep = 8 - 180 Hz 12sec linear sweep
Top & Bottom Level	197.5m -1165m	197.5m -1165m
Number of Levels	130	130
Receiver Spacing	7.5m	7.5m
Seismic reference datum	KB=871.6 M	

DATA PROCESSING

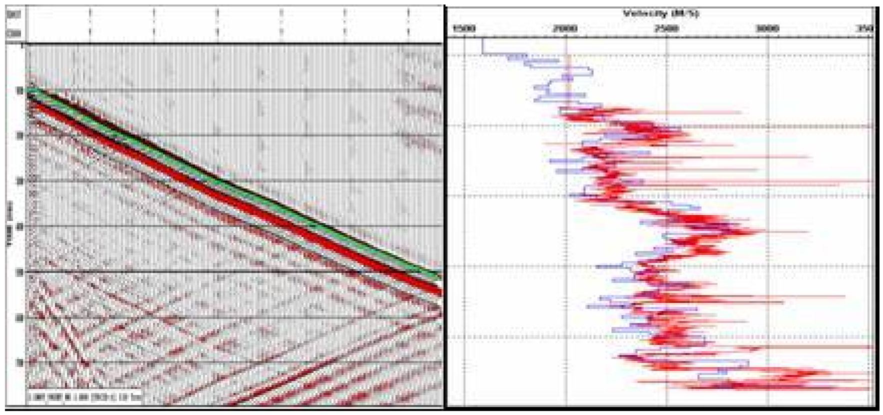
The flows used for processing the zero-offset and offset VSP data are shown in Table 2.

Table 2. Processing flow for zero-offset (a) and offset VSP data (b).

(a)	(b)
1. **geometry**	1. **geometry**
2. **first arrival picking**	2. **first arrival picking**
3. **amplitude recovery**	3. **hodogram analysis**
4. **wavefield separation**	4. **amplitude recovery**
5. **deconvolution**	5. **wavefield separation**
6. **corridor stack**	6. **deconvolution**
	7. **VSP-CDP transform**

Processing zero-offset VSP data

First, traveltime inversion for velocity was conducted based on first arrival picking. The resultant velocities are used for NMO processing and sonic log calibration. The sonic log and velocity estimated from the VSP are similar, with the sonic values usually somewhat higher (Figure 2).

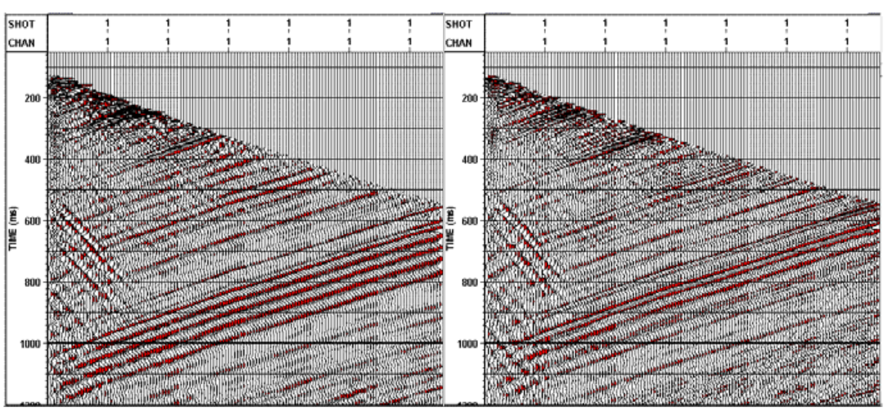


(a) (b)

FIG. 2. First arrival picking (a) and the velocity inversion result (blue line). The red line represents velocity from the sonic log.

A mean scale gain function was calculated in a 200ms window around the first arrival time and then applied to entire traces to balance the amplitude between traces. Exponential gain was also used for amplitude recovery.

The upgoing and downgoing waves were separated by a 13-trace median filter. First PP data were aligned by the first arrival time and the downgoing waves were extracted by median filter. The upgoing waves were then estimated by subtracted downgoing wave from the whole wavefield.

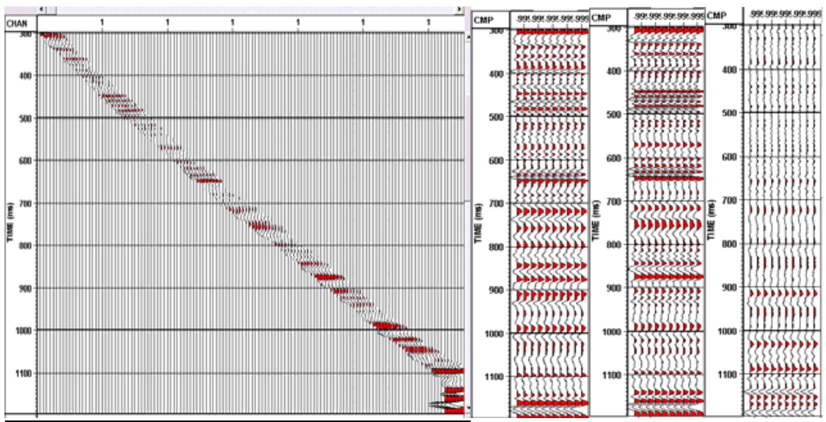


(a) (b)

FIG. 3. Upgoing wave before (a) and after (b) deconvolution.

To attenuate multiples and enhance the resolution of VSP data, a deterministic waveshaping deconvolution operator was designed from downgoing waves and applied to upgoing waves. After deconvolution, multiples were greatly attenuated and the resolution was similarly improved. The comparison between the upgoing wavefield before and after deconvolution is shown in Figure 3.

Before stack, a 50ms corridor mute was applied to the data to remove multiples and other noises. By comparing the stack with and without corridor mute, we see that the corridor stack has higher resolution (Figure 4). Subtracting corridor stack from non-corridor stack, multiples can be estimated (Figure 4).

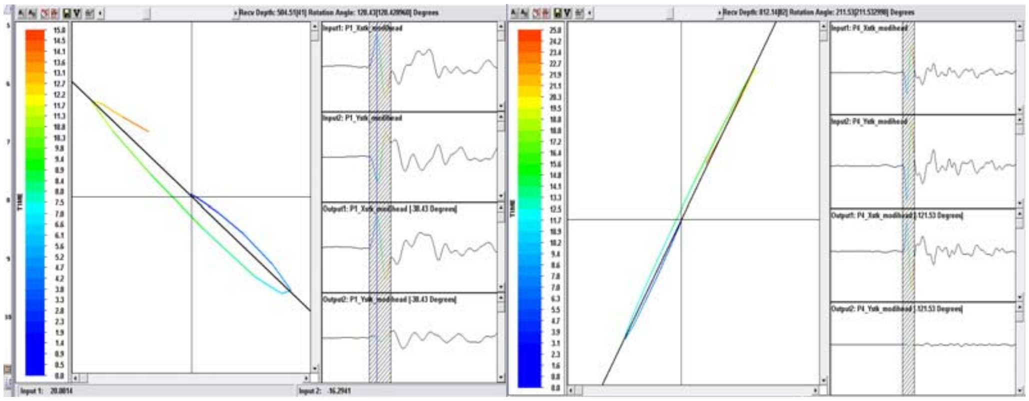


(a) (b (c) (d)

FIG. 4. Corridor mute (a) and the stack trace (duplicated 10 times) with (b) and without corridor mute (c). The right side (d) is the result of subtracting corridor stack from non-corridor stack.

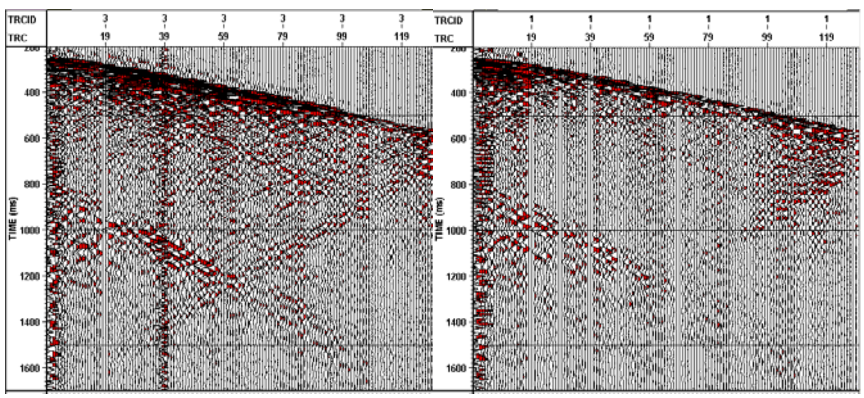
Processing offset VSP data

In the following section, only the techniques different from the zero-offset VSP processing flow will be discussed. One of the differences is that the wave polarization must be determined for the offset VSP. Hodogram analysis can be adopted to determine the polarization of the various wave modes. During the processing, an analysis window of one wavelength along the first arrival is used and hodogram is produced at each depth level. Figure 5 displays the hodogram and the comparison between the horizontal channel data before and after rotation at depth level 504m. There is no distinct amplitude difference between the x and y data on raw data, while most energy is redistributed to Hmax (the horizontal channel in source-receiver plane) after data rotation. A polarity reversal is found on the trace at the depth level 812m (Figure 5), and it is corrected after hodogram analysis and data rotation. Random orientation can also be found from Figure 6: little coherent signal can be seen on the raw x and y data. After data rotation, most of the P and SV energy was redistributed to Hmax. Both the downgoing and upgoing waves become clearer after data rotation. There is very little P energy on Hmin (the horizontal channel orthogonal to source-receiver plane), But some SH wave exists on Hmin (Figure 7). It is thought to be created by imperfect verticality of the source or horizontal heterogeneity of near surface structure.



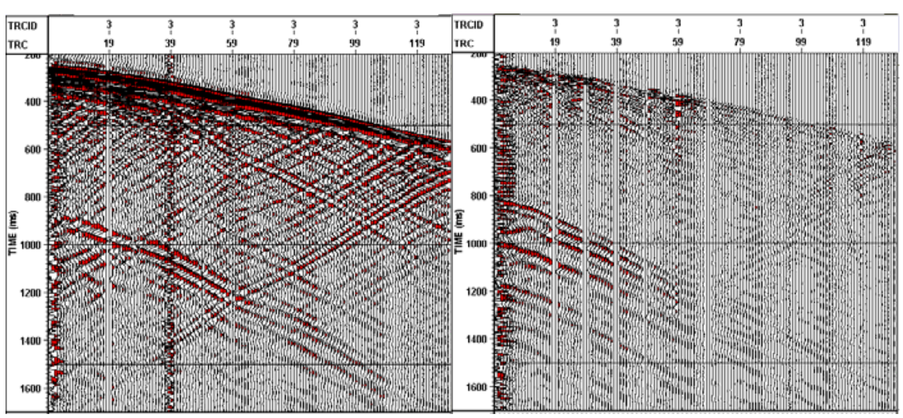
(a) (b)

FIG. 5. Hodogram analysis of horizontal channels at depth 504m (a) and depth 812m (b).



(a) (b)

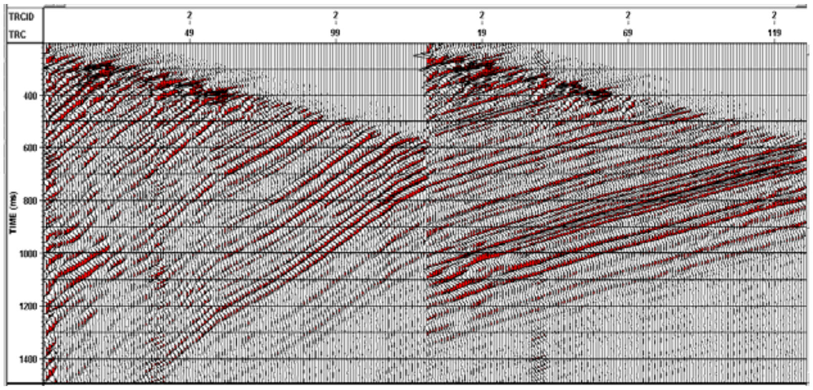
FIG. 6. X channel (a) and Y channel (b) record before rotation (offset=399.1m).



(a) (b)

FIG. 7. Hmax (a) and Hmin (b) from X Y channel rotation (offset=399.1m).

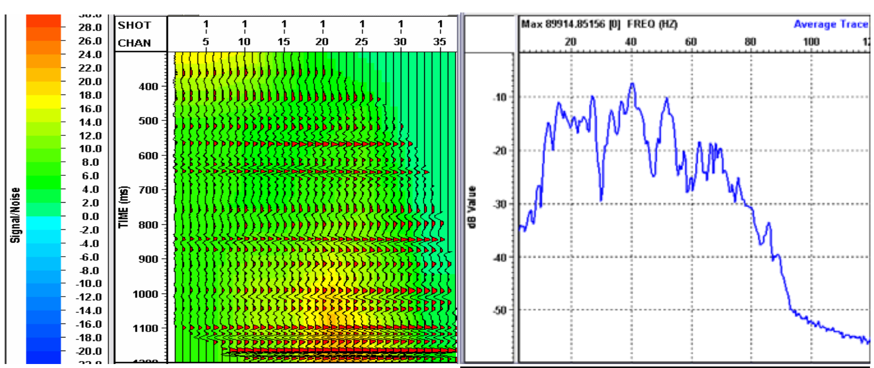
To unravel the upgoing P waves and upgoing SV waves, the upgoing wavefield should be first separated from both channel Z and Hmax. By time-variant rotating the two data sets, the upgoing P and upgoing SV wave will be separated from each other as shown in Figure 8.



(a) (b)

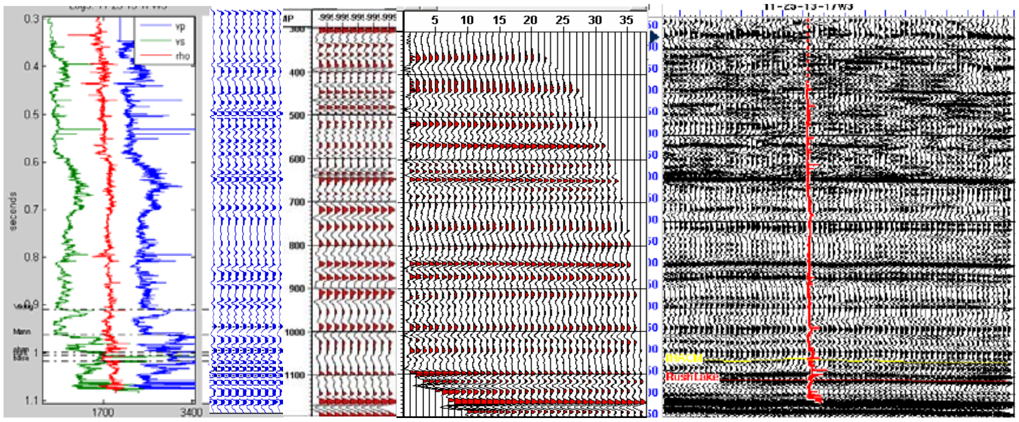
FIG. 8. Upgoing PS (a) and PP (b) wave from upgoing waves of Z & Hmax after time-variant rotation (offset=399.1m).

Most of the rest of the processing resembles that of the zero-offset case. Because of the far offset, there will be a large moveout left if only statics shift are applied to the data, especially for shallow part. When both NMO and static shifts were applied to the data, the reflections were flattened. Finally the VSP-CDP transform was introduced to map the time-depth domain data into the offset-time domain similar to surface seismic images (Figure 9). The average signal-to-noise ratio of VSP-CDP mapping result is about 15. Its frequency bandwidth is 10HZ to 90HZ. A synthetic seismogram generated from the well log ties the VSP processing results very well. A good correlation is also found for the VSP results and an intersecting surface seismic section (Figure10). The surface seismic section is extracted from a 3-D volume as described by Xu and Stewart (2003).



(a) (b)

FIG. 9. VSP-CDP mapping of upgoing P wave (a) and its amplitude spectrum (b).



(a) (b) (c) (d) (e)

FIG. 10. Velocities from sonic log (a), synthetic seismogram (b), repeated 10 times, corridor stack of zero offset (c), VSP-CDP mapping result of offset VSP (d), and (e) surface seismic data with the sonic log spliced into it at the well location (from Xu and Stewart, 2003).

ATTENUATION ANALYSIS

The spectral ratio method (Hauge, 1981; Toksöz and Johnson, 1981) is widely used for Q value estimation from VSP data. Supposing first arrival wavelets, $g_1(t)$ and $g_2(t)$ are recorded at depths Z_1 and Z_2. The amplitude spectra, $G_1(f)$ and $G_2(f)$ of these two geophone responses are plotted as a function of frequency. In such case

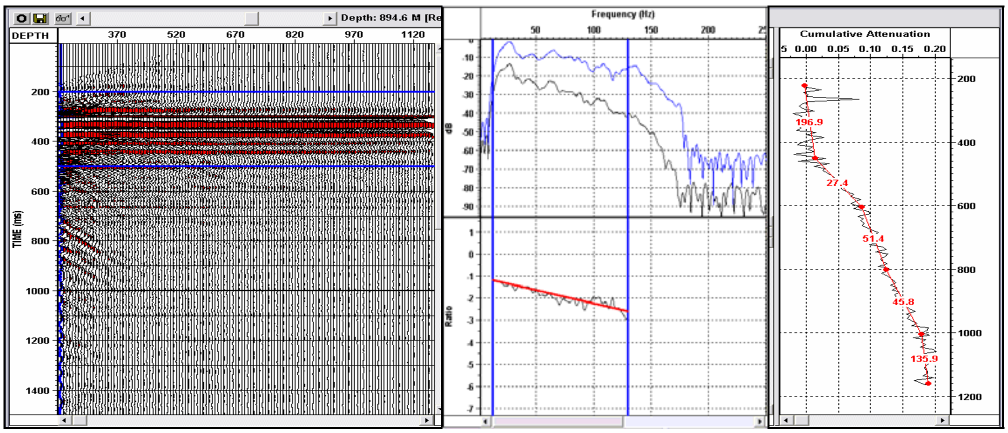
$$G_2(f) = kG_1(f)e^{-Af}, \tag{1}$$

Where f is frequency and k is a frequency independent factor that accounts for amplitude effects such as spherical divergence, variations in recording gain, and changes in source and receiver coupling. The exponent, A, is the cumulative seismic wave attenuation between depths Z1 and Z2, and it is also assumed to be independent of frequency. This equation can be rewritten as

$$\ln\left[\frac{G_2(f)}{G_1(f)}\right] = -Af + \ln(K). \tag{2}$$

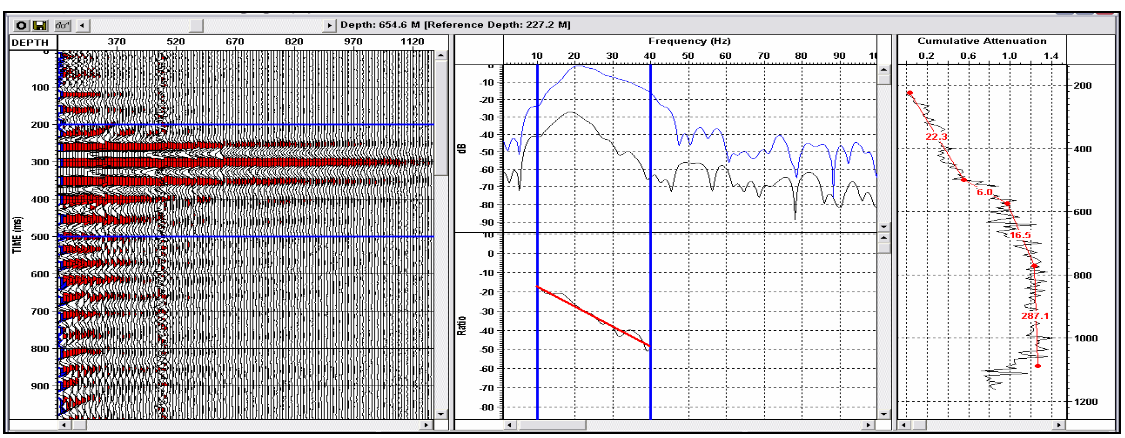
The left side of this equation is the spectral ratio of the two VSP responses recorded at Z_1 and Z_2. The cumulative attenuation value is determined by the slope of the best straight line fit to this spectral ratio trend.

Both vertical vibrator and horizontal vibrator were used for Ross Lake zero-offset VSP survey. To estimate the Q values, first downgoing P waves and shear waves were extracted from vertical vibrator records and horizontal vibrator records separately. Because the first three receiver level records are too noisy, so the fourth level at depth 224m was chosen as reference trace. The amplitude spectra for all the levels were calculated using a 300ms window. Considering the signal to noise ratio, frequency bands from 12HZ to 130 HZ for P wave and 10HZ to 40 HZ for shear wave were chosen to build the cumulative attenuation curves for Q value estimation (Figure 11 and Figure 12). By fitting the cumulative attenuation curve with linear segments (Figure 11 and Figure 12) the attenuation-depth structures were determined and the estimated P wave and shear wave Q vales are shown in Table 3.



(a) (b) (c)

FIG. 11. Qp estimation from downgoing P wave from P source zero-offset VSP survey (a: downgoing P wave; b: amplitude spectra and calculated ratio; c: cumulative attenuation and picked Qp value).



(a) (b) (c)

FIG. 12. Qs estimation from downgoing S wave from S source zero-offset VSP survey (a: downgoing S wave; b: amplitude spectra and calculated ratio; c: cumulative attenuation and picked Qs value).

The shear waves appear to be more attenuated than the P waves. The overall trend is attenuation decreasing with depth for both P wave and shear wave. When comparing the estimated Q value with the result of Xu and Stewart (2005), the Q values of the P wave over depth 400m-1000m are similar, although Xu and Stewart (2005) used a surface sweep signal as reference. While the average Q*p* estimated over an interval of 200m to 1200m is 67 and Q*s* is 23 by Haase and Stewart (2004), it appears a little higher than the values estimated in this paper.

Table 3. Estimated Q values for P wave and shear wave. The values estimated in this paper are given as (a), (b) represent Xu and Stewart's values (2005), (c) are the average Q values of Haase and Stewart (2004).

	Depth	***Qp***			***Qs***	
		(a)	(b)	(c)	(a)	*(c)*
Above RIBSTNG	200-450m	197	--		22	
RIBSTNG –MILKRV	450-600m	28	30		6	
MILKRV -1WSPK	600-800m	51	55	67	17	23
1WSPK-VIK	800-1000m	46	40		287	
VIK- MASFLDSH	1000-1165m	136	--			

CONCLUSIONS

Zero-offset and offset VSP data from the Ross Lake heavy oilfield, Saskatchewan are discussed in this paper. The processed results have high signal-to-noise ratio, with an overall value of about 15. The frequency bandwidth of PP wave VSP-CDP mapping is 10Hz to 90Hz. The results of the zero-offset VSP processing and offset VSP processing result correlate nicely and also tie the synthetic seismogram and surface seismic image convincingly. The Q values for P wave and shear wave are also estimated from the zero-offset VSP survey. The results indicate higher attenuations for the shear waves than the P waves.

FUTURE WORK

1. Process the converted waves for the offset VSP;

2. Process other offset VSP surveys and walkaway VSP survey at Ross Lake;

3. Compensate for attenuation using estimated Q models.

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REFERENCES

Haase, A. B., and Stewart, R. R., 2004, Attenuation Estimates from VSP and Log Data: 74th Ann. Internat. Mtg., SEG Exp. Abstr.

Hauge, P. S., 1981, Measurements of attenuation from vertical seismic profiles, Geophysics, **46**, 1548-1558.

Toksöz, M. N., and Johnson, D. H., 1981, Seismic Wave Attenuation, Society of Exploration Geophysicists.

Xu, C., and Stewart R.R, 2003, Ross Lake 3C-3D Seismic Survey and VSP, Saskatchewan: A preliminary interpretation, 15: CREWES Research Report, **15**,

Xu, C., and Stewart R.R, 2005, Interval Q estimation and a quality indicator-QQI, 17: CREWES Research Report, **17**.