Vp/Vs characterization of a shale gas basin, northeast British Columbia, Canada
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Summary

A large 3D/3C seismic survey will be acquired in northeast British Columbia (NEBC) in 2012. In order to assist in the design of this survey, a high resolution multicomponent 2D line was acquired to give information about shear wave properties particularly for the near-surface. Shear (SH) and compressional (P) sources and 3-component geophones were used in this acquisition. Knowledge about the velocity-depth structure of the near-surface and feasibility of acquiring multicomponent data were the main drivers for this acquisition. Also, it is important to know the structure of the near-surface for the investigation and integration with deeper data. As a result, Vp/Vs analysis was carried out for both the shallow and deep formations. The analysis targeted both the near surface study and deeper horizon registration for PP and PS reflection data.

From the shallow P-wave data, one refractor was detected and the presence of a glacial channel was confirmed at the east end of the line. The depth of this refractor ranges from 140 m to ~230 m in the channel. The average velocity for the first layer is 1950 m/s and for the second layer is 2800 m/s. From the S-wave data a different model was determined, with two refractors detected to the west end of the line and one refractor to the east of the line. The depth of the first refractor is ~70 m and the second ~140 m; to the east the refractor detected is at ~180 m. The S-velocity for the first layer is 350 m/s to 420 m/s, and 650 m/s to 800 m/s for the second layer to the west and 1400 m/s for the third layer. Finally static corrections for the reflection analysis were computed. For SH-wave data the static corrections range from -150 ms to -250 ms and for the P-wave data, values range from 10 ms to -15 ms.

Vp/Vs analysis was performed for the near-surface structure with the values of velocities obtained from the shallow analysis and also through PP-PS registration for deeper structures. Good agreement was observed when comparing these results to Vp/Vs values from well log data. Values of Vp/Vs ranged from 5 in the near-surface to 2.2 in deeper formations.

Introduction

Example shot records from the project are shown in Figure 1 for P- and S- wave data. The P-wave data has good quality for first arrivals as well as for the reflection events. The quality of SH-wave data is more irregular with only a few shots showing clear events. The example gather shows good SH reflections between 500 ms and 2200 ms.

Shear and compressional data have been used for near-surface characterization in order to calculate static corrections for PP and PS reflection surveys (Al Dulaijan, 2008; Martin, 2002; Parry and Lawton, 1993). Static corrections are used in the processing of reflection seismic data to remove the effects of variable low velocities in the shallow weathered layer and the effects of elevation. The problem caused by statics is more severe in areas with glacial sediments due to their irregular thicknesses, which is the case in a large part of western Canada (Lawton, 1990) and also in NEBC.
The relationship of P-wave to S-wave velocity is very important to interpreting lithologic information from the formations of interest in the study area. Consequently, an objective of this project was Vp/Vs analysis for the near-surface and for deeper structures and validate this result with well log data.

Another objective of this study was to obtain accurate near-surface depth and velocities. A 2D multicomponent seismic line was processed and interpreted. It comprised 220 shots. Vertical source (P) and SH sources were used in this acquisition. The shear vibrator polarization was transverse to the line azimuth so, initially rotation of the original data was performed to transform it into the radial and transverse components; the field orientation of the H1 component of the geophones was zero degrees (magnetic north). After rotation of the data, the first break arrivals were picked and these values were exported for analysis of the near-surface depth and velocity structure. From this information, static corrections were calculated.

**Method**

The plus-minus time analysis method (Hagedoorn, 1959; Dufour, 1996) was used for both depth and velocity determination and compared with a generalized linear inversion (GLI) method. The basis of the plus-minus time analysis method lies in the traveltime reciprocity: The traveltime from source to receiver is the same as from receiver to source if they are interchanged. The plus-times are used to give the traveltime from the surface to the refractor while the refractor velocity is estimated from the minus times.

**Vp/Vs analysis**

One way to obtain Vp/Vs is from velocity analysis performed during processing of each section mode; the weakness of this method is the difficulty in precisely and accurately determining the subsurface velocities from surface seismic data (Tatham, and McCormack, 1991). For this reason, the ratio is usually determined from time measurements alone. Once the structural interpretation and reflection correlation of the data have been performed, Vp/Vs can be calculated using the interval time measurements of the fully processed stacked section. For shear data, Vp/Vs can be obtained from ts/tp, or the ratio of the correlated time intervals. This process is referred as registration.

For converted waves, P- and S-wave velocity ratio (Vp/Vs) can also be calculated from the P-wave (PP) time and converted wave (PS) time extracted from stacked sections, if reflections from the same interface can be identified on PP and PS data sets. The following relationship is used to register the PP and PS data.

\[
\frac{V_p}{V_s} = \frac{2\Delta T_{PS} - \Delta T_{PP}}{\Delta T_{PP}}
\]

where \(\Delta T_{PS}\) is the converted-wave time difference between two chosen events and \(\Delta T_{PP}\) is the P-wave reflection time difference between the same two events.

Figure 2 shows the stratigraphic column of the area. The shales of interest are the Muskwa, Otter Park and Evie Formations.
Vp/Vs characterization

S-wave data analysis

The results for velocities and depths deduced from the analysis of the S-wave data are shown in Figure 4. The S-wave structure is more complex than the P-wave structure, with three layers being detected at the west end of the line, and only two layers at the east end of the line, including the channel identified in the P-wave data.

FIG. 4. Cross-section obtained from analysis of SH first arrival data.

A comparison of the plus-minus results with the generalized linear inversion method (Hampson and Russell, 1984) was made (GLI by Sensor Geophysical). In this method, three layer models were assumed for both P-wave data and SH-wave data (Figures 5 and 6). For the P-wave data, a velocity of 1000 m/s was assumed for the first layer, and an average velocity of 1950 m/s for the second layer and an average velocity of 2900 m/s for the third layer were obtained. The depth for the first layer varies from 1 m to 10 m and for the second varies from 140 m to 210 m. For the SH-wave data, a velocity of 350 m/s was assumed for the first layer, a velocity from 500 to 900 m/s was determined for the second layer and an average of 1400 m/s was obtained for the third layer. The depth for the first layer was found to vary from 50 m to 90 m and for the second layer from 180 m to 210 m.

Comparing figures 5 and 6 with the results from refraction analysis, they have good agreement in terms of velocities. However, the depth profile shows some differences. The depth of the basal refractor is similar in both methods but there are some differences in the general model. The P-wave data assumed three layers but the first layer is very thin and is not present at the east end on the line; this is similar to the result of the refraction study where only two layers were considered. For the SH model, three layers were interpreted for the GLI method; the deeper refractor is similar in both methods. The difference is that for the GLI method, the three layers are present for the entire profile whereas for the refraction analysis in this study, there are three layers to the west and only two layers to the east. The GLI method forces three layers to be continuous along the profile whereas the plus-minus method gives the flexibility of changing analysis windows depending on data changes and allows more significant lateral changes in the velocity-depth model.

FIG. 5. Results from the GLI method. a) P-wave velocity profile. b) P-wave depth profile.

Static corrections, assuming vertical rays, were calculated for the P-wave and SH-wave near-surface models and the results are shown in Figure 7. The datum used was 600 m
and the velocity of the deepest refractor was used as the replacement velocity. Higher static corrections were calculated to the east end of the line due to a thicker first layer which has lower velocity. The datum static corrections vary from -150 ms to -250 ms for SH data and about -15 ms to 10 ms for P-wave data. The elevation along this line ranges from 515 m to 526 m above the sea level.

The processing sequence for the reflection data involved the usual steps including geometry assignment, data edition, noise attenuation, FK filtering to remove surface generated noise, deconvolution, CDP mean stack and FD time migration. Some special processes were applied including the T-F adaptive noise suppression, offset consistent gain control and TV spectral whitening. For the stack, a +100 ms bulk shift was applied on the PP and PS data and +300 ms bulk shift to the SS data.

The migrated images were used to undertake PP-PS registration, assisted by the shallow Vp/Vs analysis from the near-surface analysis. Well log control was added into the process to detect the variations in Vp/Vs at well location that was extrapolated to the entire seismic line. The result of this process is shown in Figure 8. Interval Vp/Vs values from the seismic analysis matches closely the results from analysis of well-log data (shown on Figure 8).

**Discussion and conclusions**

- Both depth sections, from compressional and shear data, show a channel that was also mapped from an airborne electromagnetic (EM) survey acquired in the area.
- The final model produced from the SH data shows three layers in the west end of the line and two layers to the east end of the profile. The model obtained from the P-wave data shows only two layers. The difference in model between the two wave modes is due to higher sensibility of shear waves to changes in velocities.
- High Vp/Vs values for the first layer were obtained, reaching values up to 6. For shallow layers, values of 3 to 4 are expected. This high value is due to high P-wave velocity relative to the low SH-wave velocity in the area. At greater depth, Vp/Vs values generally are closer to 2. The results are comparable to the values obtained from well log data located in the same area.
- The Vp/Vs for the shale gas zone of interest located at 1400 ms is lower compared to non-reservoir shale. The presence of flat cracks affects Vp/Vs, decreasing its value with increase in porosity. If the pores are spherical, Vp/Vs is constant in a gas saturated medium. The presence of gas also decreases Vp/Vs because Vp decreases but Vs remains relatively unchanged.
- The receiver static corrections for the S-wave data gave significantly higher values than the static corrections times for the P-wave data as expected due to lower velocity of the SH-waves. The ratio varies from 10 to 16 (S to P static correction ratio).
- The main reflectors were interpreted in both PP and PS sections and interpretation of these sections enables event registration that generates interval Vp/Vs. This ratio was obtained with the information of interval times between the horizons of interest and matched closely the results from analysis of well log data.

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