Analysis of the West Castle seismic surveys

Part I. Near surface characterization using a high-resolution 3C seismic survey

Gabriela M. Suarez and Robert R. Stewart

ABSTRACT

Seismic surveys were acquired in the early fall of 2006 in the West Castle Area of Southwestern Alberta. The 2D vertical-component 10 km crooked line and a 3C 2D high resolution survey were processed with the objective of obtaining new information about the subsurface structures and the near-surface layers of this geologically complex area. The 3C high resolution survey showed two near-surface layers of velocities in the range of 700-2700 m/s. The final processed image of the 2D crooked line allowed the interpretation of some of the major geological structures of the areas such as the Lewis thrust. Results also suggested that improvement in the acquisition and processing are required. Pre-stack depth migration and special crooked line processing techniques are possible options to attain a better subsurface image.

INTRODUCTION

The West Castle River area of southwestern Alberta (Figure 1) was host to a group of seismic surveys conducted in the early fall of 2006 by the University of Calgary, the CREWES Project, and Kinetex Inc. These seismic surveys included a 10 km multicomponent seismic line and a simultaneously recorded ARAM line with vertical element geophones (Figure 2). In addition, high-resolution 3C seismic surveys, employing a hammer seismic source, were acquired. A set of shallow, borehole seismic surveys with a downhole 3C geophone and hydrophone cable were also undertaken (Stewart et al., 2006).

The area, in the front range of the Rocky Mountains, is highly structural and prospective for hydrocarbons (Figure 3). Gas exploration in this area was abandoned in the 1970's when few wells were drilled with success. Since then; relatively little has been reported concerning the subsurface. Our intent was to conduct an integrated study that will provide useful information of this area. Included is processing of the subsurface seismic data, interpretation of these images and integration of the seismic information with well logs. In addition to new knowledge about the area, this information will be useful for future geophysical efforts in optimizing the acquisition parameters for better seismic images.

Included in this study are the results of the near-surface characterization using the high resolution 3-C seismic surveys (Part I) and the processing of the 10 km vertical component seismic line recorded with the ARAM system (Part II). The final parameters used in the processing of this data set will be used as a future reference for subsequent data, which justifies the extensive testing that has been undertaken to find the best parameters that will compensate for the acquisition and for the subsurface effects.

FIG. 1. Map showing the location of Pincher Creek, which is close to the area where the seismic surveys were done.

FIG. 2. Photograph, looking south, of the West Castle River area of southern Alberta with the seismic line (shot in August-September 2006) annotated (from Stewart et al., 2006).

Location of the Area of Study

The West Castle River valley is located in a mountainous district of southwestern Alberta, south of the Crowsnest Pass, immediately east of the Continental Divide .The area is confined on the west by the British Columbia-Alberta boundary around townships 4-5, range 3-4, west of 5^{th} meridian. The study area is located 2 kilometers north of the Castle Mountain ski resort on road 93 (Figure 1).

FIG. 3. Geologic cross-section from the south-west to north-east across the Lewis and Gardner Thrusts in the West Castle area (from Norris, 1993).

Previous geophysical investigations of the study area

During the 1940s the first geophysical surveys (gravity and seismic) were undertaken in western Canada, leading to the discovery of the Jumping Pound, Sarcee and Pincher Creek gas field (Link, 1949; Bally et. al., 1966). During the 1950s extensive regional seismic surveys were undertaken, culminating in discovery of the Waterton, Wildcat Hills and West Jumping Pound.

Fox (1959), Shaw (1963), Keating (1966) and others published regional sections that were based on seismic information and contributed greatly to a better understanding of regional structure and problems related to mountain building. However, there is still room for additional geophysical documentation relating to the geology of the Rockies and Foothills of Alberta and southeastern British Columbia.

Most of the geophysical exploration in this area has been accomplished by Shell Canada Limited. Some of this seismic information is presented by Bally et al (1966) and detailed interpretations are presented by Richards (1959) and Blundum (1956). Kerber (1991) used information from three wildcat wells along North Kootenay Pass (Shell North Kootenay Pass D-58-H/G-82-07 and Shell North Kootenay Pass 4-23-3-5W5) and to the east of it (Shell Waterton Home 7-3-6-3W5), as well as a migrated seismic section that extends west of the Alberta-British Columbia border at North Kootenay Pass to east of the Coleman fault.

Several other wells exist in the area as a result of hydrocarbon exploration, but the closest ones to the West Castle River area are Shell Waterton Home 7-3-6-3W5 and Shell West Castle 5-7-4-3W5.

The latest information acquired in this area was done during fall of 2006 by the University of Calgary, CREWES, and Kinetex Inc, including two 10 km 2D seismic lines, a high-resolution 3C seismic surveys and a set of shallow, borehole seismic surveys with a downhole 3C geophone and hydrophone cable (Stewart et al., 2006).

Structure and stratigraphy of the survey area

The southern region of the survey area is situated on the hanging wall of the Lewis Thrust, within the middle Proterozoic sediments of the Helikian Purcell Supergroup. Grey and green argillites of the Lower Siyeh and Grinnell formations outcrop on the valley floor, which are traversed by the West Castle River (Figure 3). The West Castle River crosses the Lewis Thrust, which is underlain by Jurassic and Cretaceous sediments of the Fernie, Kootenai, Crowsnest, Blackstone, Cardium, Wapiabi and Belly River formations (Stewart et al., 2006).

PART I. NEAR SURFACE CHARACTERIZATION USING THE HIGH-RESOLUTION 3-C SEISMIC SURVEY

More and more attention has been paid to the applications of converted-wave exploration in assessing oil and gas reservoirs. Due to complexities in acquisition, statics, data processing and interpretation, the technology has taken some time to mature.

Complementing P-wave exploration, the information extracted from converted shear waves can enhance the reliability and precision of lithologic and reservoir prediction. Although multi-wave exploration has been undertaken in many countries for over 10 years, converted-wave data are still challenged to meet the demand of lithologic and reservoir predictions due to the difficulties with the acquisition, processing and interpretation (Zhiwen et al., 2004).

Expectations for S-wave reflection quality are usually high because combined P- and S-wave section interpretations are often applied to subtle exploration problems. Anomalously large S-wave statics represent a challenge because they severely degrade reflection continuity on the stacked section if not given special care. The anomalous reflection delay times result from the sensitivity of S-wave velocity to near-surface, rock-matrix properties, whereas P-waves are primarily sensitive to more laterally constant properties due to saturating fluids in the near-surface rocks. Obtaining a good S-wave statics solution is, then, a key processing step to good S-wave reflection quality (Anno, 1987).

A significant challenge faced converted wave exploration is the near-surface static corrections required for the P-S wave, which are more complicated than for the P-wave. Since fluids generally have less impact on P-S waves than simple P-waves and P-S waves have lower near-surface velocities and a thicker low-velocity layer, the near surface static correction for P-S wave is often much higher than for P-wave and changes dramatically (Zhiwen et al., 2004).

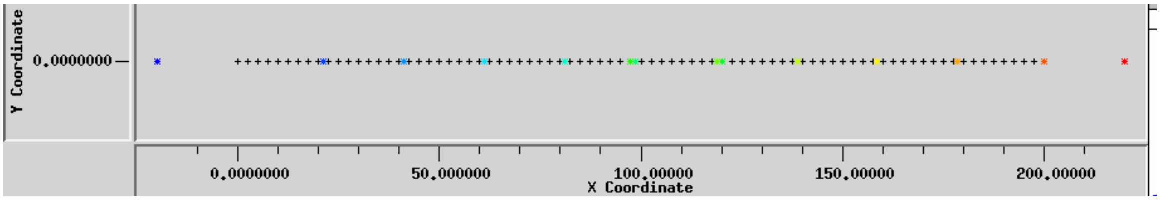
The West Castle River area of southern Alberta was host to a group of seismic surveys conducted in the early fall of 2006 including a high-resolution 3-C seismic survey. This data set is used to provide useful information of the very shallow strata, specially a near surface model that could be use as a refraction static model in the processing of multicomponent surface seismic data of the area. This is an important point to consider in Alberta, where the weathering statics problems are very severe due to the irregular thickness of glacial sediments.

The correction of this effect will improve the resolution and continuity of the reflections, especially for the shear wave data. This first part of the study involved the generation of near surface models from the P-wave component and from the radial component data through the analysis of the first arrivals, using the ProMAX processing software, as well as GLI3D to generate the near surface models. Also to properly identify the first shear arrival in the radial component, polarization analyses were done.

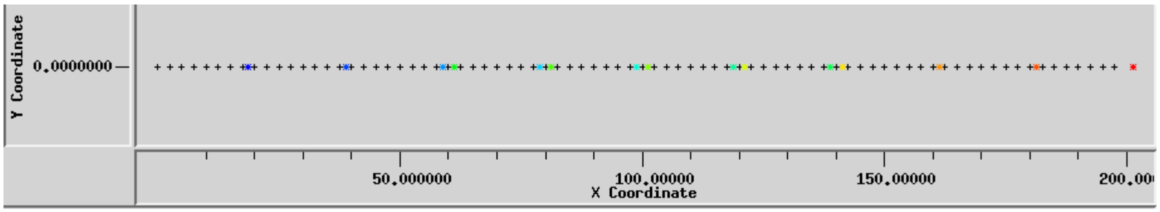
Acquisition parameters of the high-resolution 3-C survey

The high-resolution multicomponent survey employed a hammer source and multicomponent geophones. The source consisted of a 12 lb. sledgehammer with handle trigger. The receivers were 10 Hz VectorSeis 3-C “nail”-type geophones that were being recorded at a 1 ms sampling rate by a Geometrics Geode recording system, with four boxes giving 96 channels and 30 stations live.

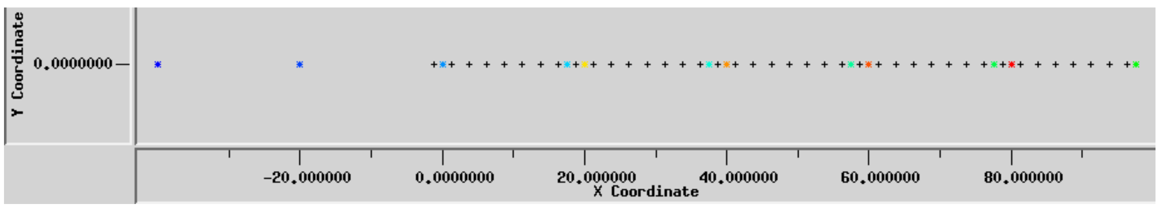
The acquisition was undertaken in 4 different areas along highway 93, by 2 different groups, which worked one in the morning and one in the afternoon for every half of the spread. The spread was divided in two fix spread of 100 m each, with receiver intervals of 2.5 m. Several shots for the same source point were done to enhance the signal to noise ratio. In total around 12 shots were recorded for every one of the areas with 40 traces each.



(a) Area 1 Acquisition geometry



(b) Area 3 Acquisition geometry



(c) Area 4 Acquisition geometry

FIG. 6. 2D acquisition geometries for the lines: (a) Area 1, (b) Area 3 and (c) Area 4.

For Areas # 1 and # 4 500 ms were recorded, while for areas # 2 and # 3 150 ms of data were recorded. However, because the availability of equipment was limited for Area # 2 we will not analyze it.

Examples of some of the shots showing the three orthogonal components for areas 1, 3 and 4 can be seen in Figures 4, 5 and 6. The data in these figures was trace-equalized and scale using a 500 ms sliding window for areas 1 and 4 and a 50 ms window for area 3, with the purpose of assisting in the picking of the first arrivals. The vertical data contain the best data, as expected. However, through the analysis of the data we notice that the source was not a pure P-wave source. There are several reasons for this including the radiation patterns of a vertical impact on a half-space and the hammer used as the source might not hit exactly with a 90-degree angle to the horizontal.

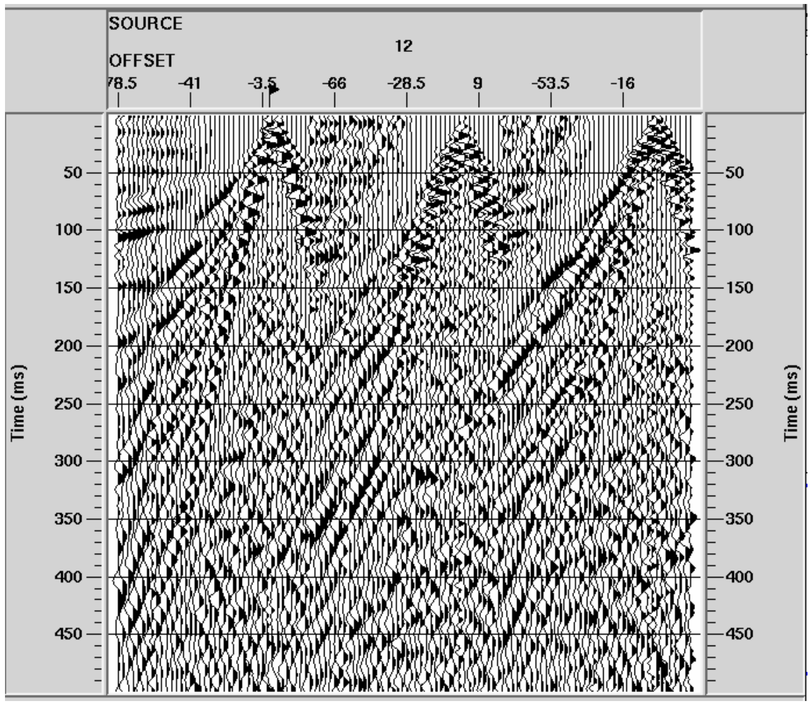


FIG. 4. Three-component shot gather for Area 1: vertical component (left), transverse component (middle) and radial component (right).

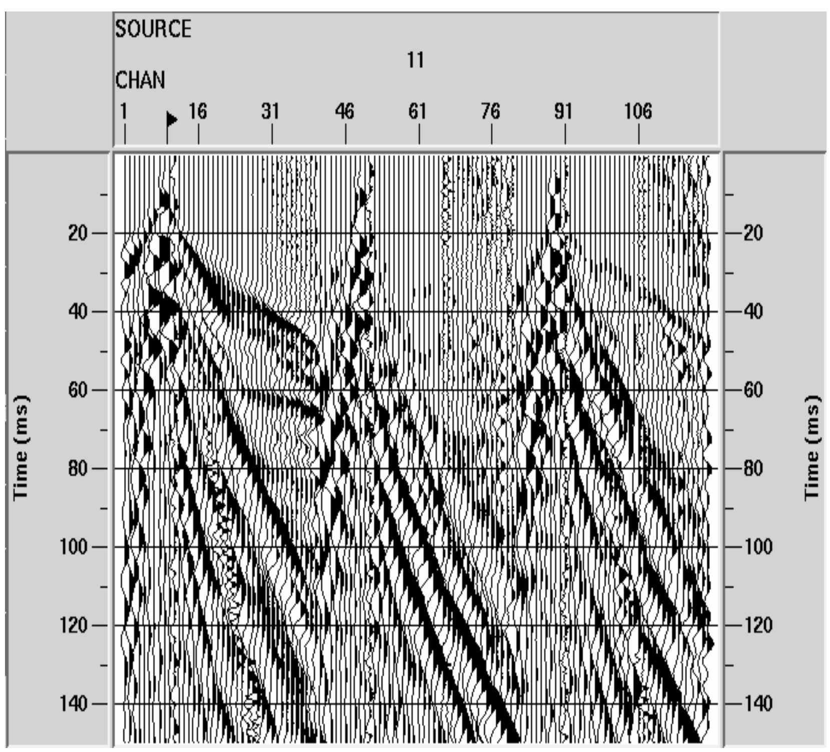


FIG. 5. Three-component shot gather for Area 3: vertical component (left), transverse component (middle) and radial component (right).

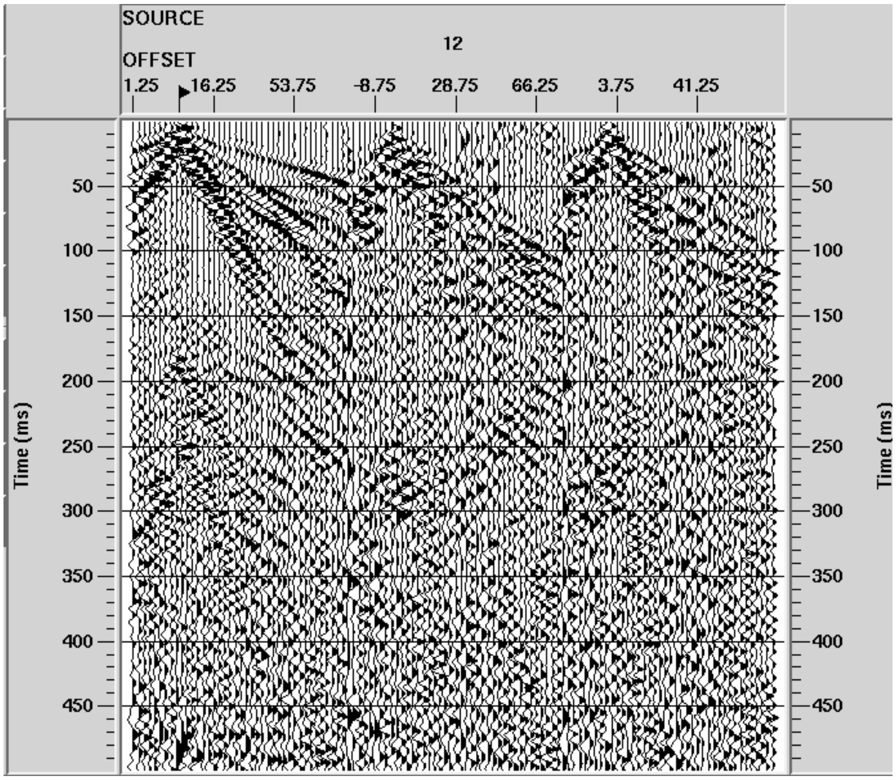


FIG. 6. Three-component shot gather for Area 4: vertical component (left), transverse component (middle) and radial component (right).

Near-surface velocity structure

Refraction analysis of the twelve records for each area was undertaken to calculate and compare the near surface P- and S-wave velocity and depth profiles. In Figure 5 we can see an example of a vertical component shot gather where the first arrivals are observed across all traces, whereas the radial component does not show the refracted arrivals as clearly as in the vertical component.

The 100 m offset range for these surveys was a limitation, which is one of the reasons why we used the hand pick method to determine the first arrivals and not a more analytical method such as trace correlation. The quality of the first breaks is going to affect the results of the refraction modelling, so consistency in the first arrivals picking from shot to shot should be kept.

As we mention earlier, the refracted shear arrivals for the radial component could not be easily identified. To corroborate our observations three quality control techniques were used to validate the shear wave arrivals picked by hand. The first method was comparing the data for the three components; the second method was applying a linear moveout correction using the velocity for the first arrival vertical component previously identified; and the third method was using hodograms to determine the polarization of the event that we thought represented a shear wave refraction.

With the first technique we were trying to compare the three components to identify unique events for the radial component, compare them with the ones in the transverse component and see if they correspond to some kind of surface waves that should only be seen in the transverse channel. Another characteristic is that the event identified as a shear-wave refraction would show several layers with lower velocities than the P-wave refractions.

The second technique consisted of correcting the radial component shot gather with a linear velocity equal to the velocity of the first arrival of the P-wave, so 3 different corrections that correspond to the three different velocities of each area were done. Velocities of 1810, 2700 and 2420 m/s were used as the input velocity for the Linear Moveout module of ProMAX.

The third technique was generating hodograms. A hodogram is a graphical display of particle trajectory, often projected into a plane as a crossplot over a chosen time window of two orthogonal components of seismic data (Winterstein, 1990); it is one of the polarization methods that allow a visual estimation of the polarization. To create the hodograms we used the hodogram analysis module of the seismic processing package ProMAX.

In Figure 7, we can see some of the hodograms created for shot 10 receiver 8 of area 1. We can notice how the energy in the horizontal versus vertical component plot has a larger component in the horizontal axis than in the vertical. This same observation can be done in the inline versus cross-line component graph where the energy has a larger component in the radial than in the transverse, showing some ellipticity as well. The same comments can be applied to the examples hodograms for area 3 and 4 (Figure 7). The extra plot in Figure 7 is to illustrate how a hodogram appears in areas where groundroll is present.

The next step in obtaining the near surface model is to use the traveltimes observed from the P-wave refractions and shear refractions. As it was previously explained the method used in our study is an inversion method called Generalized Linear Inversion Method or GLI, which was implemented using the Hampson and Russell Software called GLI3D.

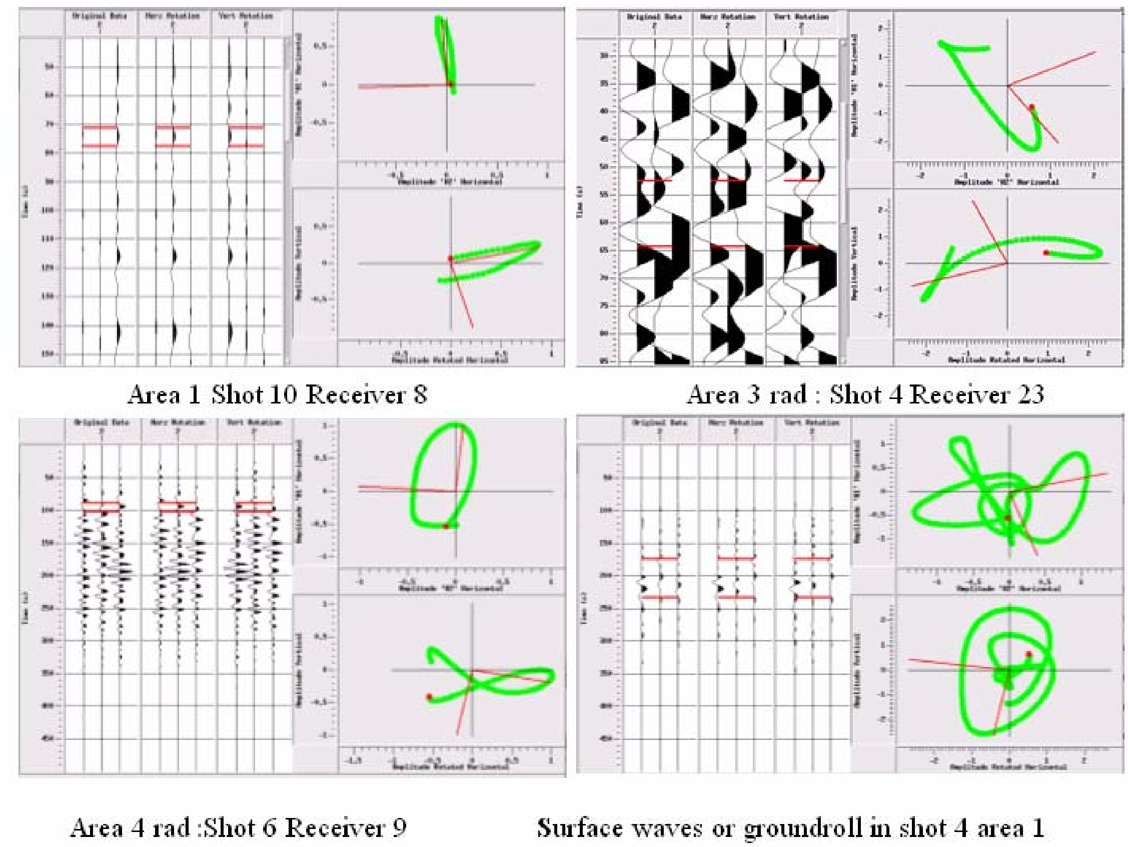


FIG. 7. Example of hodograms for some receivers of areas 1, 3 and 4

The resulting near-surface models for areas 1, 3 and 4 are presented in Tables 1, 2 and 3. The velocities and layer thicknesses for P-wave and S-wave data are presented respectively. A determination of the S velocity in the surface layer was not obtainable from the radial component records, some of the possible reasons could be the contamination of the near-offset data by P-wave energy or shear refracted arrivals not correctly identified.

The data from Tables 1 to 3 shows clearly that the velocities for P-waves and S-waves are very different, having Vp/Vs ratios between 2.8 (area 3), 3 (area 4) and 3.5 (area 1). We can not make any assumption of the water table location until we have information to compare with, for example, VSP data processed from the area; however it is believed that the first shallow layer in this area has a thickness of around 7 m, which is reflected in our results. The velocity values between 1800 and 2700 m/s could indicate the location of the water table considering the fact that its velocity should be around 1700 m/s for this area.

The differences in the near-surface P-wave and S-wave velocity structure have a significant impact on weathering static corrections. Some magnitudes of static corrections were calculated using as replacement velocity a value of 1800 m/s, which might not be the correct value for this area but at least will give an idea of the necessary static corrections. These corrections were between 10 and 15 ms for the P-wave and between 20 and 50 ms for the S-waves.

Table 1. Resulting near surface model for Area 1.

Layer	P		S		Vp/Vs
	Velocity (m/s)	Thickness (m)	Velocity (m/s)	Thickness (m)	
1	640 ± 20	8	Not determined	5	-
2	1820 ± 30	-	520 ± 20	-	≈ 3.5

Table 2. Resulting near surface model for Area 3.

Layer	P		S		Vp/Vs
	Velocity (m/s)	Thickness (m)	Velocity (m/s)	Thickness (m)	
1	1600 ± 20	6	Not determined	4.8	-
2	2700 ± 30	-	980 ± 20	-	≈ 2.8

Table 3. Resulting near surface model for Area 4.

Layer	P		S		Vp/Vs
	Velocity (m/s)	Thickness (m)	Velocity (m/s)	Thickness (m)	
1	2420 ± 20	6	800 ± 10	3.8	≈ 3

Discussion and Limitations

A main challenge in multicomponent seismic processing is accurate estimation of static values, velocities and thickness of the near surface layers.

Picking the shear refractions represented a real challenge and even though alternative techniques were employed to help in its identification, there is still a high level of uncertainty on its identification. Another limitation was the short range of offset recorded and the inconsistency of the source from shot to shot point due to the use of the hammer and different persons every time.

The issues surrounding first break analysis served to give us a first insight of the near surface structure of the West Castle River Area. Our final results were valuable for the refraction static solution of the 10 km seismic line, as they improved the continuity of some of the reflectors in this highly structural zone.

CONCLUSIONS

We used refraction seismic analysis on short 3C receiver spreads to determine shallow P- and S-wave velocity structures.

The analysis of first arrivals is a suitable tool to compute these corrections because it gives velocity information at every shotpoint. This is an advantage which other methods for the determination of near-surface velocities do not offer.

This first approach to the near surface structure of the West Castle area showed a 2-layer model with P-wave velocities of 640 to 2700 m/s and 500 to 900 m/s for the S-wave velocities. The resultant V_P/V_S values were between 2.8 and 3.5, which corroborates some of the results presented in the literature where unconsolidated sediments V_P/V_S is from to 2 up to 8. According to our results, the water table location could be at 8 m with velocities between 1800 to 2700 m/s.

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