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3C Deghosting for Refraction Time-lapse Monitoring

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Summary

Refraction time-lapse monitoring provides affordable areal measurements of reservoir changes using waves that travel from sources along a fast layer underlying the reservoir. When the waves exit the fast layer, they travel through the reservoir and propagate to the receivers, with corresponding arrival times depending on the state of the reservoir. For thermal EOR (Enhanced Oil Recovery), changes in the reservoir can be observed and interpreted from changes in these arrival times.

Buried receivers benefit onshore seismic acquisition, in part because statics problems are less severe and because some decoupling from surface waves can be expected. Unfortunately, the statics problem is often just replaced by another problem – surface ghosting with strong near-surface effects. For refraction data, which is lower fold, ghost removal can be even more important than for conventional seismic data.

At Peace River in Alberta, Canada, we carry out deghosting using a 3C wave field separation technique and show that the method significantly improves the time shift measurements. We then demonstrate its use in a processing workflow by generating an interpretable areal time-shift maps for a new refraction time-lapse data set recorded in 2010/2011.

Introduction

In June to August of 2009, as part of an extensive investigation into methods for seismic monitoring at Peace River, Shell acquired four P-wave refraction data sets to monitor heavy oil thermal EOR at Peace River Pad 32 (Hansteen et al., 2010). Since then, three vintages with improved acquisition have been acquired in 2010 (two) and 2011 (one) and new processing technology has been deployed. While the original study of Hansteen et al. (2010) used only the vertical component signal we have found that using data from all components of 3C geophones allows the removal of receiver-side near-surface effects thus allowing the extraction of more reliable reservoir time lapse information.

We present here a new method to perform receiver-side deghosting and assess its impact on the reservoir monitoring results. Our method uses data recorded on buried multi-component (3C) receiver arrays to isolate the primary or up-going wave field. In doing so it removes any additive time-shift noise caused by time-variant changes in the near-surface layer above the receivers. This noise is present in the removed down-going or ghost wave field.

Refraction Seismic monitoring

Refraction seismic monitoring acquires head waves travelling on a high velocity formation below the reservoir. As the waves exit the reservoir and are recorded on overlying geophones, changes in reservoir velocity between seismic vintages are measured as first arrival time shifts. For Pad 32 at Peace River, seven P-wave refraction surveys have been acquired, all of which were recorded using the same 12 m buried 3C geophone array and using a mixture of repeated (in PVC-cased holes in 2009) and re-drilled shot holes (2010/,11). The geometry and preliminary results are described in (Hansteen et al., 2010) and a summary, for all surveys, of acquisition dates, number of shot points and recorded channels is provided in Table 1. There are some notable differences between the first 4 and the last 3 acquisitions including season-consistent acquisition, PVC cased shot holes(2009) versus re-drilled shot holes (2010, 11) and the recording of all available (782) 3C stations for (2010, 11) surveys as opposed to only 483 acquired in 2009 to save on channel costs. The last improvement was made after the importance of the horizontal channels for deghosting purposes was realized.

Survey Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Survey date	May 31 2009	June 25 2009	July 3 2009	Aug 28 2009	Dec 16 2010	Dec 17 2010	Dec 12 2011
NB of shots	205 (same hole)	204 (same hole)	207 (same hole)	200 (same hole)	205 (redrilled)	205 (same hole)	205 (redrilled)
NB of live 3C phones	483	483	483	483	782	782	782
Pump noise attenuation	No (just bandpass)	No (just bandpass)	No (just bandpass)	No (just bandpass)	Yes, linear radon	Yes, linear radon	Yes, linear radon
Operational change	start of steam cycle	plateau	plateau	plateau	shutin	shutin	shutin after pressureup

Table 1: *Summary of refraction time-lapse acquisitions on our study area. Major operational changes as well as changes in acquisition and processing are listed.*

The basic processing steps used were:

1. Vector fidelity QC and orientation analysis
2. Pump noise attenuation: Linear radon production (pump) noise attenuation on last 3 surveys.
3. Up-down separation.
4. Surface consistent deconvolution
5. 3D static corrections, applied identically to all vintages.
6. Computation of matching operators and redatuming as per Hansteen & Wills (2009).
7. Time shift time lapse analysis on first arrivals

Step 1 showed that more than 20% of stations suffered some form of 3C vector fidelity issue, such as dead, improperly gained or mislabelled channels. Once these issues were resolved, horizontal geophone orientations were obtained through first break polarization analysis and these showed that no significant changes between acquisitions took place. This confirms that the phones were properly cemented and did not move over time and which is critical to time-lapse analysis.

3C Deghosting Method

The importance of handling ghosts at Peace River can be demonstrated with a downhole DAS fiber optic recording of refractions. This recording was made at Peace River Pad 19, which is within 5 km of our study area (Pad 32). Both acquisitions record the same type of refracted arrival, but in our study area it is done using a shallow buried 3C array as opposed to a vertical array at the Pad 19 site. The result of recording one shot into a well with an offset of 2 km is shown in Figure 1. In addition to a first arrival refraction with good S/N, we see a high amplitude ghost reflection. As the receiver moves from deep (right) to shallow (left), the ghost delay becomes smaller until, very near the surface, the wavelets add together. Such interference from the ghost can cause strong near-surface variations in the measured time shifts, which is undesirable.

The receiver-side deghosting method for P-wave refractions recorded on buried 3C geophones has been adapted from a similar S-wave method (De Meersman, 2011 and 2012). Figure 2 (Left) shows a refraction as it propagates from below a line of buried 3C receivers towards the receivers and then the earth's surface. After reflecting at the surface the wave propagates back down into the earth and passes the buried receivers a second time. The first or up-going arrival is typically referred to as the primary whereas the second, down-going arrival is known as the (receiver-side) ghost. The figure shows the wave fronts and rays for both wave fields. Arrows representing the particle motion indicate the direction and polarity of the recorded signal. In Figure 2 (Right) these polarization vectors are displayed in relation to a 2C receiver recording coordinate system. The 3C field data have been rotated from an inline-crossline-vertical frame into a ray-centered radial-transverse-vertical frame. No P-wave energy is present on the transverse component so that it can be ignored, resulting in the 2C radial-vertical coordinate system used here. The figure clearly shows that polarizations associated to both arrivals are oblique to the recording directions. Simply put; both the vertical and radial recordings contain a mixture of up-going and down-going energy. If P and G represent the primary and ghost wave fields and θ represents the ray or propagation angle of the refracted wave we can obtain expressions for the data recorded on the vertical (V) and radial (R) components and invert for the primary and ghost fields. Assuming a coordinate system where the vertical axis points down and the radial direction pointing towards the source we get:

$$\begin{bmatrix}\mathbf{P}\\ \mathbf{G}\end{bmatrix} = \frac{-1}{\sin(2\theta)}\begin{bmatrix}\sin(\theta) & -\cos(\theta)\\ \sin(\theta) & \cos(\theta)\end{bmatrix}\begin{bmatrix}\mathbf{V}\\ \mathbf{R}\end{bmatrix} \qquad (1)$$

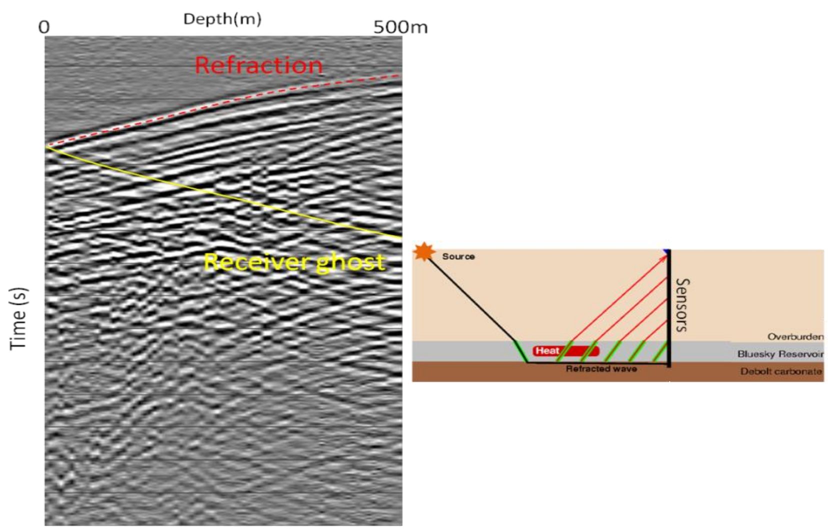

Figure 1: Downhole DAS refraction data recorded at Peace River Pad 19. The right part of the seismogram shows deep receivers which, due to the geometry, have early refraction arrivals. The left part shows shallow stations and the convergence with the strong ghost arrival. Other upgoing and downgoing arrivals measure refraction phases involving shear waves and various multiples. This downhole record justifies the need for ghost removal from the analogous surface refraction data set and which is the main topic of this paper.

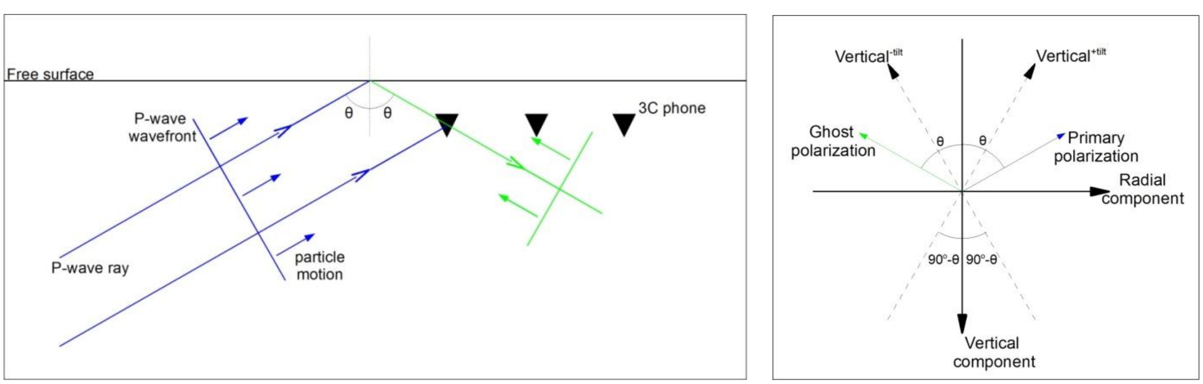

Figure 2 Left: P-wave refraction (blue) and its ghost (green) as they are recorded on a buried 3C receiver array. Right: Projections of the polarization vectors of primary (blue) and ghost (green) P-wave refraction energy with respect to a vertical-radial coordinate system and as a function of ray angle theta. Polarization vectors represent the recorded data.

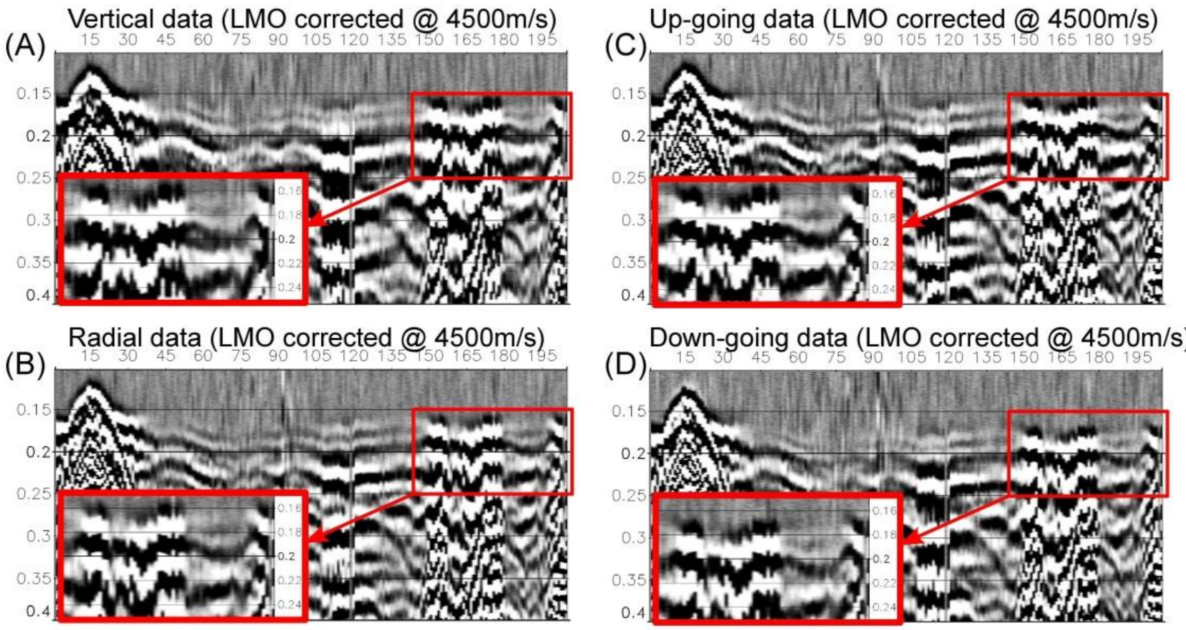

Figure 3: Illustration of our up-down separation procedure on a single receiver gather. (a) Input vertical first breaks, (b) input radial first breaks, (c) computed up-going (primary) wave field, (d) computed down-going (ghost) wave field. The ghost is delayed by approximately 10ms with respect to the primary (170ms versus 160ms as seen on insets). The original vertical and radial data contain a mixture of primary and ghost energy.

The primary wave field is estimated by projecting the data onto the direction indicated as the Vertical+tilt in figure (left) whereas the down-going is obtained from projecting the recorded data onto the Vertical-tilt direction. Note that these projections are of opposite polarity relative to the vertical component and must be reversed to facilitate interpretation. Figure 3 shows data from a single receiver acquired during the last survey and after a linear moveout correction using a 4500m/s velocity and 350 ms bulk shift to approximately flatten the first arrival at 150 ms. Figure 3A shows the raw vertical component, Figure 3B the radial component, Figure 3C the up-going and 3D the down-going wave field. The arrival time delay between up-going and down-going wave fields is approximately 10 ms. A ray angle $\theta=30^{o}$ was used in the separation. It was determined through a grid search and chosen because it minimized the amount of energy prior to the first down-going arrival.

Result and Interpretation

In the four 2009 vintages, strong time-lapse timeshifts due to near surface ghosting were present and diagnostics showed that they were receiver-consistent. While it is likely that shot-side ghosts were present, we speculate that they were mitigated in the time-lapse matching procedure that was required to remove strong dynamite wavelet effects and are, in fact, less serious for the present refraction method because the imaging procedure requires a source stack over a wide geographical area after redatumming. The effect of deghosting is illustrated in Figure 4 which compares reservoir time shifts calculated from the upgoing and downgoing wave fields together with their differences. The difference map represents pure near-surface effects. The primary feature on the difference map is the blue inverted L-shaped feature, which is present as a noise on the downgoing map and is mostly removed from the upgoing data. This feature was present in preliminary studies of the data and was difficult to reconcile with reservoir models – it is now understood to be an artefact caused by near-surface changes. Note that the time lapse signal associated to the near-surface (speedup) is roughly equivalent in magnitude but opposite in sign to that of the reservoir (slowdown). If no deghosting is applied we would be unable to separate both time lapse signals, thus compromising interpretation.

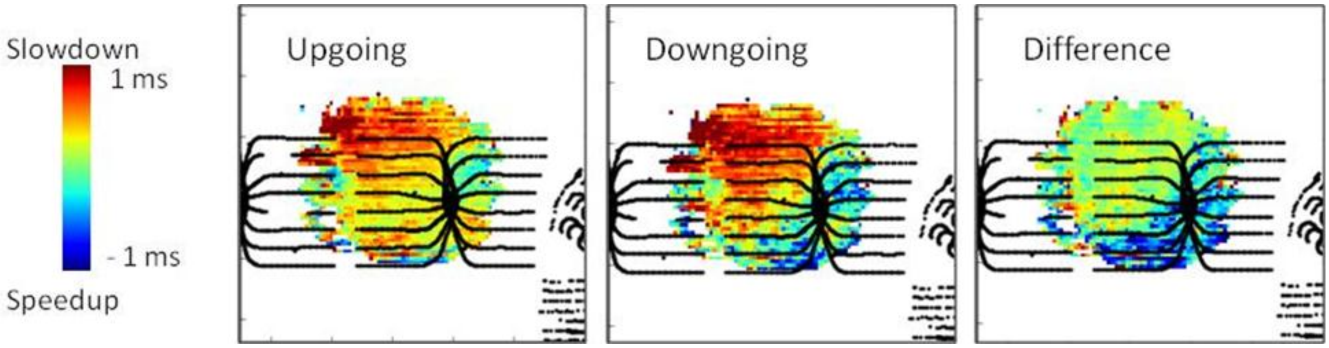

Figure 4: Maps of time shifts calculated using the upgoing and downgoing wave fields from the August versus June vintages. The difference map shows strong near-surface artefacts (blue) that are present on the downgoing data as noise but absent in the deghosted upgoing data.

For the 2010,11 vintages of the up-going wave field we obtain Figure 5 and which compares time shifts obtained through two types of stack with those obtained after imaging (Hansteen and Wills, 2009). A conventional refraction exit-point stack (middle) shows more noise than an exit point sum (left) (made by extracting prestack timeshifts followed by binning and averaging). The image map shows features similar to the stack with the addition of significantly better resolution as evidenced by features that track well paths. Note also that the measured timeshifts are well under a millisecond. The patterns have a consistent and plausible interpretation as remnants of foamy oil in regions surrounding the wells; a strong pressure-up between the vintages essentially erased traces of the foamy oil and so slowdowns were present in the baseline but not in the monitor, leading to observed time-lapse speedups.

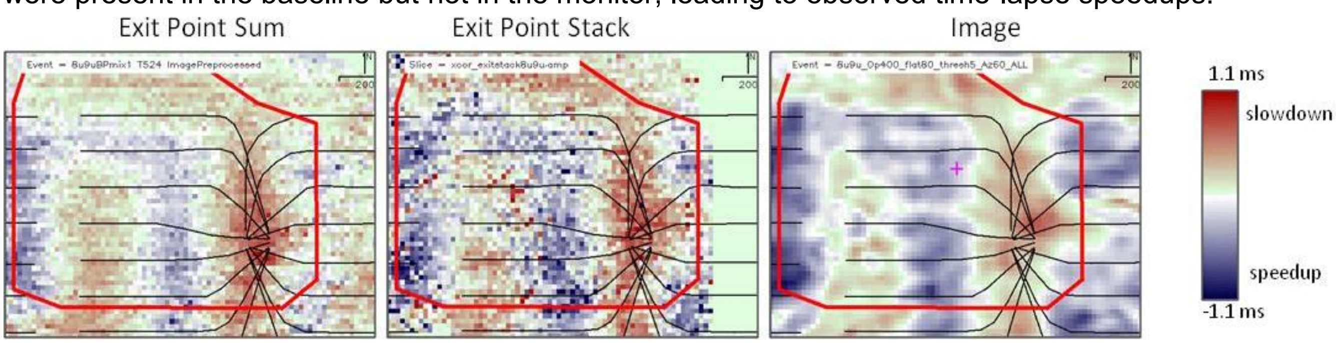

Figure 5: Time shift Maps after final processing. Left: exit point sum, created by extracting prestack timeshifts and averaging at exit points. Middle: Timeshift extracted on a stacked data set. Right: Time shift map after imaging. The red polygon indicates the extent of the receiver array.

Conclusions

Receiver-side deghosting is an important step in refraction time-lapse monitoring and is accomplished by the 3C method described here. The full workflow leads to an image with a plausible interpretation and may enable a significant reduction in costs of acquiring time-lapse areal land seismic data.

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Thank you for submitting an abstract to GeoConvention 2013: Integration.