Simultaneous accelerometer and optical fibre multi-azimuth walk-away VSP experiment, Newell County, Alberta, Canada

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Summary

CREWES conducted a high-resolution multi-azimuth walk-away three-component vertical seismic profile (VSP) survey at the Containment and Monitoring Institutes Field Research Station (CaMI.FRS) in September 2018. This data is primarily intended for use in full-waveform inversion (FWI) and modelling studies. The FRS has three wells, referred to here (from SW to NE) as the geophysics, injection and geochemistry wells. The 2018 VSP had thirteen source lines, four acquired with a 10 m Vibe Point (VP) spacing and the remainder acquired with a 60 m VP spacing. The source was an Inova Univib running a linear 1-150 Hz sweep with two sweeps per VP. In addition to existing permanent 3C geophones and optical fibre, a string of Inova 3C VectorSeis accelerometers was deployed in the geophysics well for this survey from surface to bottom hole. The accelerometer data are currently undergoing zero-offset and far-offset VSP processing. First-break picks sorted by offset and azimuth confirm the presence of very weak HTI anisotropy at the FRS, as observed on a single offset semi-circular walk-around VSP recorded in the injection well in 2015.

Source Overview

Figure 1 shows Vibe Points (VP) as red dots for thirteen source lines. Twelve source lines are centered on the geophysics well (Observation well 2) and are separated by counter-clockwise fifteen-degree rotations. Four of the source lines (lines 1,4,7 and 10), were acquired at a 10 m VP spacing and the others were acquired at 60 m spacing. The minimum source offset from the geophysics well was 6 m, and the maximum was 480 m. Note the gaps in VP coverage due to required offsets from high-pressure hydrocarbon pipelines (red lines). Source line 13 is high-lighted by blue dots representing surface 3C receiver locations for instrument testing. Some VP within 60 m of the well were dropped due to well lease infrastructure. Planned VP locations in the NE quadrant inside the 60 m ring on source line 1 were rotated clockwise to source line 12, and from source line 4 counter-clockwise to source line 5. The sweep used was a 1-150 Hz linear sweep over 16 s with 0.2 s half-cosine tapers and a 3 s listen time. Acquisition was conducted using an Inova Geophysical Univib, with two sweeps per VP.

Receiver Overview

The Cami.FRS has a permanent buried 5 km optical fibre loop in place. The loop runs 1) down and back up the

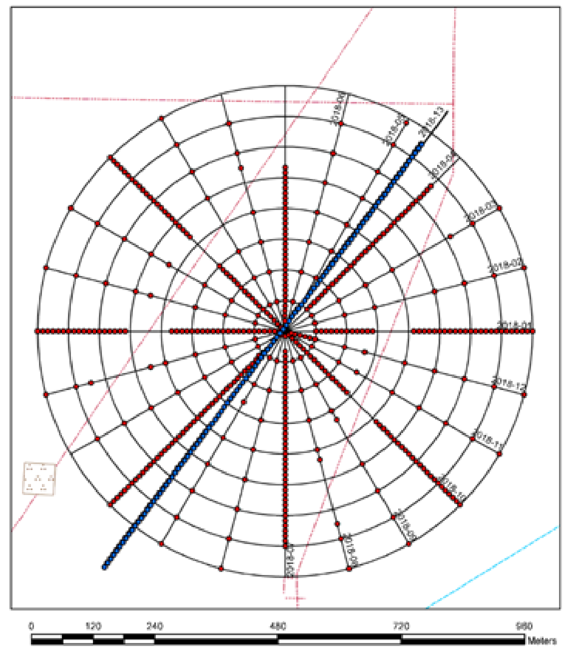

Figure 1: Survey map. Black rings are 60 m interval circles centred on the geophysics well. Red dots are Vibe points, Blue dots are surface receiver locations, red lines are hydrocarbon pipelines. North is up.

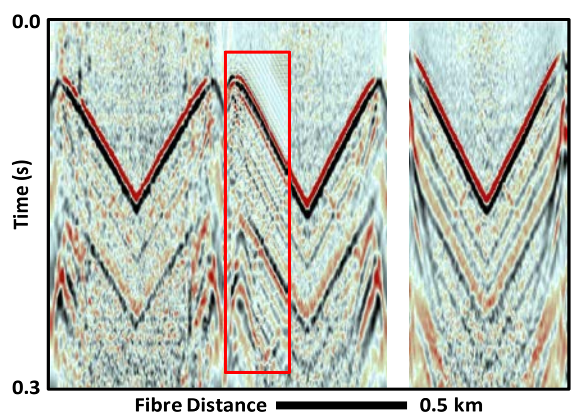

Figure 2: Fibre data for VP 5143 (60 m from geophysics well) with the accelerometer vertical component inset (red box) for helical fibre in the geophysics well (left), straight fibre in the geophysics well (center), and straight fiber in the geochemistry well(right).

geophysics well with straight fibre, 2) down and back up the geophysics well with experimental helically wound fibre, 3) down and back up the geochemistry well with straight fiber, 4) to the south end of an approximately 1 km long and 1 m deep horizontal trench with straight fiber, 5) the length of the trench with helical fiber, and 6) back along the trench to the geophysics well as straight fibre. The trenched fibre is located parallel to source line 13. All VPs in this walk-away VSP were recorded on this fibre loop with a Fotech Solutions interrogator.

High Definition Seismic Corporation (HDSC) deployed a string of Inova 3C VectorSeis accelerometers in the geophysics well at 1 m spacing, from the surface to 324 m depth, recorded on an Inova Scorpion system. The 1 m spacing was achieved by interleaving separate 2 m cables. Unfortunately, one of the two deepest cables failed during deployment. Time and budget did not allow the string to be removed from the well for trouble shooting. Inclination data from the VectorSeis show that rather than being entirely vertical, the well is inclined by up to nine degrees at the deepest receiver location at an unknown azimuth. Projecting measured receiver depth to true vertical depth using the measured inclinations gives us a 0.3 m vertical and 5.6 m horizontal error for the deepest receiver.

Figure 2 shows an example of a two vertical fold optical fibre source gather for VP5143, which is located 60 m from the geophysics well. The corresponding vertical component accelerometer data is inset (red box). In both cases, the data have a 100 ms window AGC for display, but no other processing. In general, the accelerometer data retains more high -frequencies than the fibre data. Note that the fibre loop gives us the opportunity to create three VSP dataset with four-fold source gathers for the same source effort as a single 3C accelerometer VSP dataset with two-fold source gathers.

This paper focuses on initial zero-offset and far-offset VSP processing results for VPs on source lines 1 through 12 recorded on the VectorSeis accelerometers in the geophysics well, as well as looking for evidence of HTI anisotropy in the direct arrival times recorded in the borehole.

Additional Work

Other recent experiments that have been proposed and/or conducted at the CaMI.FRS are detailed by Innanen (2019a), Innanen (2019b) and Spackman (2019)

Zero-offset VSP Processing and Synthetic Seismograms

Zero-offset VSP processing was conducted for VP 1149, which is about 6 m from the geophysics well. In this case, the down-going P wave-field (P-down) was extracted from the raw vertical component data (V-raw) by flattening on first-break picks and median filtering. The up-going P wave-field (P-up) was extracted by subtracting P-down from V-raw, and finally was deconvolved using P-down. Figure 3 shows first-break based top mute and inside corridor mute after conversion to two-way travel time, the outside corridor stack (red traces, repeated 10 times) compares well with a P-P synthetic seismogram (blue traces) calculated using the CREWES Syngram software package using well logs acquired in the geophysics well. The reservoir of interest for CO_2 injection program is the Basal Belly River sandstone at a depth of 296 m.

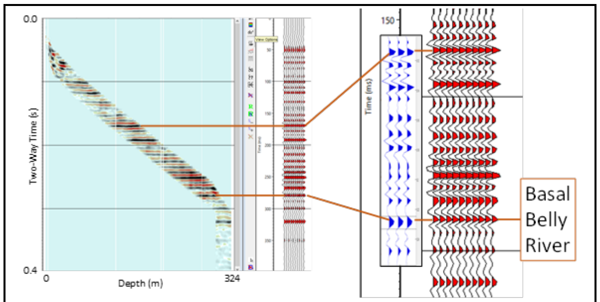

Figure 3: Zero offset VSP corridor stack after deconvolution with down-going P-wavefield compared to P-P synthetic.

Source Statics and Anisotropy

We know from a previous 3C-3D survey acquired in 2014 (Isaac and Lawton, 2014) that source statics at the FRS can vary by up to 15 ms across the survey area.

A walk-around VSP conducted at the FRS in 2015 with a semi-circular source line at 400 m radius centred on the injection well resulted in observed travel time variations on the order of 3 ms for a single receiver at 383.5 m depth (Hall et al., 2015). The fast direction roughly coincides with source line 13 of the 2018 survey (SW-NE; blue line; Figure 1, this report). The fit to an azimuthal travel-time variation model led to an interpretation of weak HTI anisotropy caused by fracturing due to the regional stress field. No source statics were applied to these data prior to modelling.

Azimuthal plots of first-break pick times from the 2018 survey displayed in constant source-receiver offset panels show sinusoidal patterns as observed for the 2015 survey. However, the amplitudes of the sinusoids are greatly reduced when source statics from the 2014 3C-3D survey are applied. Similarly, if we position first-break times at their associated VP locations for fixed receiver depths, interpolate and contour (Figure 4 and Figure 5), we expect non-circular contour lines if anisotropy is present (Figure 4). Application of interpolated source statics from the 2014 survey makes the contour lines more circular (Figure 5). HTI anisotropy, while likely present, may be even weaker than previously thought. Contour lines for deeper receivers also become more circular with application of source statics, but the contours are not necessarily centred on the well location (not shown). This may be due to a slight well deviation from vertical with depth. It will be interesting to see if this effect correlates with azimuths recorded on future dip logs.

Far-offset VSP Processing

Far offset VSP processing has thus far followed examples shown by Hinds et al., (1996) and in the Schlumberger Vista far-offset VSP tutorial. The first step in far offset processing is first-break picking, which was performed on the Vertical (V) component for all VPs and used as a guide for the time window used for component rotations.

A polarity reversal that is observed on the V component for all VP other than the zero-offset (VP 1149), consistently moves to greater depths with increasing source-receiver offset. The reversal is a multi-trace switch from down-going first motion (trough) at depth to up-going (peak) on shallower traces. It is unlikely that first motion on the shallow receivers is a direct-arrival. We believe it to be due to a mix of interfering wave-types. Polarity reversals due to horizontal receiver orientation in the borehole are also observed on the H1 and H2 components.

Component rotations from H1 and H2 to Hmax and Hmin (horizontal rotation angle theta; Figure 14), and from V and Hmax to V' and Hmax' (vertical rotation angle phi; Figure 15) were calculated by the Vista module VSPRPol. This module uses a method described by Grechka and Mateeva (2007) to calculate rotation angles using a least-squares minimization algorithm. Initial first-break picking on V transitioned from peak to trough with depth, however, in testing, a horizontal line of picks at the average direct arrival time worked just as well as a guide for VSPRPol for this data (not shown). In addition, polarity reversals observed on Hmin, Hmax and Hmax' are unaffected by reversing polarities on H1 and H2 prior to calling VSPRPol. First-breaks were re-picked on the Hmax' component after one round of manual polarity reversal picking, where we chose to pick polarities so first motion is represented by a trough (red) on Hmax'. All V' traces have been polarity reversed so the polarity of the up-going P wave-field matches the V component.

Rotation angles theta and phi are preserved in the trace headers and were imported into Matlab® in order to plot source-receiver offset panels against source-receiver azimuth and receiver depth. Theta shows good consistency with increasing receiver depth, although it starts to spread out a bit more at the farthest offset (480 m) which correlates with noisier data at depth. It also exhibits wrapping, which

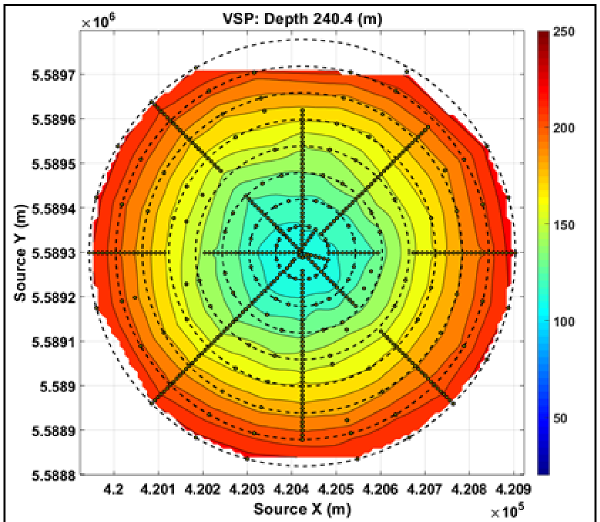

Figure 4: Contour map of interpolated first break picks positioned at VP locations for receiver at 240 m depth. Non-circular contours may indicate the presence of anisotropy. Black dashed lines are 60 m interval circles centred on the geophysics well.

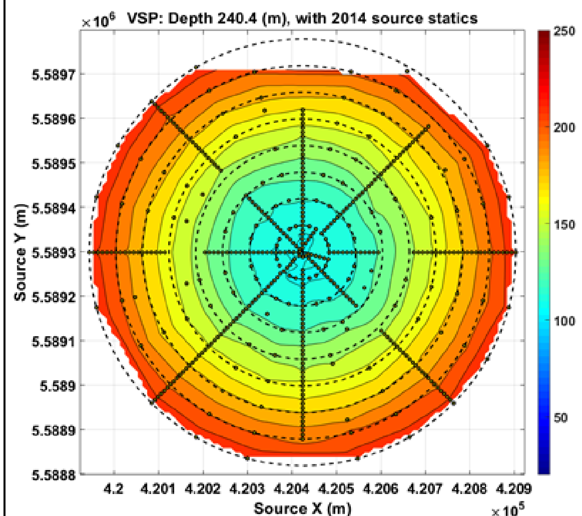

Figure 5: Contour map of interpolated first break picks positioned at VP locations for receiver at 240 m depth after application of 2014 3C-3D source statics. Black dashed lines are 60 m interval circles centred on the geophysics well.

appears to correlate with observed polarity reversals in Hmax and Hmin. Rotation angle phi exhibits a turn-over that becomes wider and moves to greater depths with increasing source-receiver offset. This appears to correlate with the position of the polarity reversal observed on the vertical component. This is related to refracted or turning ray first arrivals at the shallow geophones in the well.

Multi-azimuth walk-away VSP field experiment

Like the zero-offset VSP processing, the down-going P wave-field was extracted from Hmax' by flattening on the first-break picks, but a f-k filter was used instead of a median filter. P-down was then removed from V and Hmax' by subtraction to give us P-up which was then deconvolved using P-down to give us V (decon'd P-up) and Hmax' (decon'd P-up) (left panels; Figure 6 and Figure 7). Ray-tracing using a 1D model constructed from the zero-offset VSP interval velocity curve gives us time-variant rotation angles, which are used for our final component rotation to Z''up, mostly containing up-going P wavefield and Hmax''up which mostly contains the up-going Sv wavefield (right panels; Figure 6 and Figure 7). The velocity curve was constructed using every 10th trace, as the Dix equation is unstable for small differences in travel-time. These figures have AGC applied for display, which makes it difficult to compare true amplitudes from panel to panel.

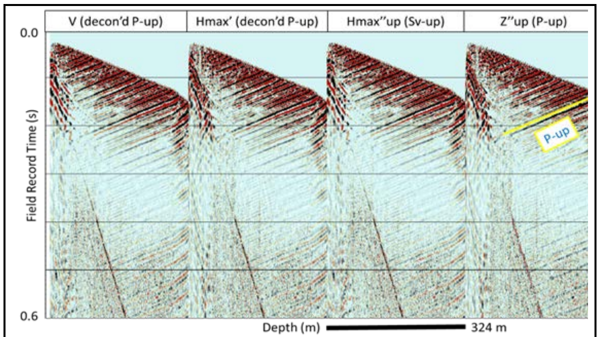

Figure 6: Time variant rotations to separate upgoing P and upgoing Sv. V and Hmax' were rotated to Hmax''up and Z'' up.

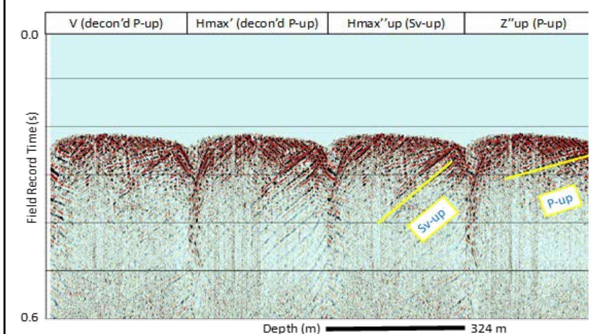

Figure 7: Time variant rotations to separate upgoing P and upgoing Sv. V and Hmax' were rotated to Hmax''up and Z'' up.

Discussion and Future Work

CREWES acquired a multi-azimuth walk-away VSP at the Containment and Monitoring Institutes Field Research Site (FRS) in Newell County Alberta in September of 2018. Downhole accelerometer data from the geophysics well on the site have been processed to a zero-offset corridor stack which compares well to a P-P synthetic calculated from well logs recorded in the same well. In preparation for future full waveform inversion work, receiver components of far-offset VSP data have been rotated from 1) H1 and H2 (field orientation) to Hmax and Hmin (rotation angle theta), and then V and Hmax to V' and Hmax' (rotation angle phi), where theta and phi were calculated rather than hand-picked from Hodograms. Theta shows good consistency with increasing receiver depth, while phi shows a turn-over point that appears to track a phase change between up and down-going first motion observed on the vertical component.

First-breaks were initially picked on V, and then re-picked on Hmax'. Analysis of the first-break picks shows that there may be very weak HTI anisotropy present on site, although this finding becomes less convincing after application of source statics from a 3C-3D survey that was conducted in 2014.

The down-going P- wavefield was extracted from the Hmax' component and used to remove down-going P from V and Hmax', which were then deconvolved using the down-going P. Ray-tracing was conducted through a 1D velocity model constructed from the zero-offset velocity curve, and the angles of the rays impinging on receivers in the borehole were used for a further time-variant component rotation from Vup and Hmax'up to Hmax''up and Z''up, where up-going Sv is concentrated on Hmax''up and the up-going P is concentrated on the Z''up component. These results will be the input to future inversions. Z''up has been VSP-CDP transformed and stacked for all source points. However, the results show clear signs of statics problems and are not shown here.

Future work includes:1) additional processing flow parameter testing and quality control, 2) better well ties and interpretation including comparison to the 2014 3C-3D, 3) use of first-break picks to create a full 3D anisotropic (isotropic?) depth model, 4) completion of far-offset P-P and P-S VSP processing including pre-stack depth migration, 5) comparison to fibre and geophone data from this and other surveys at the FRS and, of course, 6) inversion for physical properties of the Earth.

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