SV-P and S-S imaging at a CO₂ storage site in the Illinois Basin using vertical seismic profiling data

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Running head: **Direct-S waves in VSP data**

ABSTRACT

Only compressional (P) waves are typically used to illuminate the geology of land-based carbon dioxide (CO₂) storage sites because the costs associated with horizontal-force vibrators needed to emit shear (S) waves deters the use of that mode. However, S-waves are highly sensitive to fractures and provide clues to the porosity and permeability of the reservoir and seal. Shear wave energy may also be produced by vertical-force vibrators, and the resulting up-going direct-S waves may be recorded either as reflected S-S modes or as converted SV-P modes. These two data components can contribute information not available in P-wave components. In particular, the SV-P mode makes converted-wave analysis possible when working with seismic data generated by vertical vibrators and recorded with only vertical geophones.

In this paper, we present a method for extracting S-waves emitted by vertical-force vibrators. This is a low-cost opportunity for full seismic wavefield analysis that enhances understanding of geologic reservoirs. We illustrate S-wave seismic imaging with a vertical seismic profiling dataset acquired at a CO₂ storage site in Decatur, Illinois. We discuss a data processing flow that segregates direct-S modes. We compare SV-P and S-S images

generated by a vertical vibrator source with P-P, P-SV, and P-SH images – the typical images made with vertical-vibrator sources. All images appear consistent and complement each other, indicating the method presented here allows the use of S-waves in CO₂ storage site screening without requiring horizontal geophones.

INTRODUCTION

Seismic exploration mostly exploits compressional waves, which are denoted as P-waves. These waves can be generated relatively easily by explosive sources or vertical-displacement vibrators and recorded by vertical geophones. P-waves arrive first at a receiver station which facilitates their identification, propagate through both solid and fluid environments, and usually have a high signal-to-noise ratio. Analysis of P-wave reflection times allows structural shapes of geologic bodies buried deep underground to be defined. Also P-wave amplitudes reveal petrophysical properties of rocks and aid the identification of oil and gas reservoirs.

Another type of elastic wave that constitutes a seismic wavefield is a shear wave (or S-wave). Some S-waves are converted from P-waves at interfaces that separate rock layers with different bulk densities and/or seismic wave velocities. Shear waves are highly sensitive to geological heterogeneities (MacLeod et al., 1999; DeAngelo et al., 2003; Stewart et al., 2003), and application of S-wave reflection seismology extends capabilities for subsurface exploration. To analyze S-waves, one needs to use horizontal geophones and common practice is to deploy three mutually orthogonal geophones that collect three-component (3C) seismic data. Such 3C data acquisition may be performed on the surface, or receiver stations may be deployed in a well as in vertical seismic profiling (VSP) (Hardage, 2000). Another option is crosswell seismic profiling (Antonelli et al., 2004) which requires both receivers and sources to be located in a well.

Direct shear waves can be produced by special horizontal-force sources such as horizontal vibrators. Registration of direct-P and two direct-S waves, which are polarized inline and crossline, by three-component receiver stations results in nine-component (9C) seismic data.

Each component of 9C data provides exclusive pieces of information and exposes details not available in other components (Hardage et al., 2003). Nine-component seismic data appear to be a powerful tool for seismic exploration; however, 9C data acquisition is difficult and expensive technology and therefore only occasionally used in the industry.

Hardage and Wagner (2014) discussed field tests that demonstrated how vertical displacement vibrators (vertical vibrators) emitted significant amounts of direct shear waves. Downgoing direct-S wavefields (radial and transverse) produced by a vertical vibrator were shown to be equivalent to downgoing direct-S modes produced by a horizontal vibrator. Moreover, direct-S modes produced by a vertical vibrator provided wider bandwidth data because vertical vibrators can be operated to produce a wider range of frequency sweeps than can horizontal vibrators. Tests for a wide range of surface geological conditions show that direct-S waves produced by a vertical vibrator have radiation amplitudes that exceed the radiation amplitudes of direct-P waves. Thus, to get access to shear wave benefits, one may use vertical vibrators that are widely available wherever seismic reflection seismology is practiced.

Direct-S waves, as well as other elastic waves, reflect and convert at seismic interfaces. Reflected direct-S waves are recorded by horizontal geophones as an S-S mode, as are P-SV modes converted from P-waves. Converted direct-S waves, in turn, are recorded by vertical geophones as an SV-P mode and co-exist in vertical geophone data with reflected P-waves. P-SV and SV-P wavefields are equivalent unless geology has significant lateral variability, which means that all the information and capabilities provided by P-SV modes are available when SV-P data are recorded by vertical geophones. It should be noted that ray paths of P-SV and SV-P modes differ. A P-SV conversion point is located closer to the receiver whereas a SV-P conversion point is located closer to the source (Hardage et al., 2014).

Although, P-SV and SV-P raypaths for a particular source-receiver pair illuminate different points on an interface, when all reflection points are assembled into images, a P-SV image is the same as a SV-P image in simple-layer geology.

To be interpreted, direct-S modes must first be segregated from their companion modes. The SV-P mode needs to be separated from the P-P mode, and the SV-SV mode must be separated from the P-SV mode. Hardage et al. (2014) separated SV-P and P-P reflections recorded in VSP data by applying an additional inclination-angle rotation to data that had been rotated to get maximum power of direct-P arrivals. Li and Hardage (2015) developed a more appropriate rotation approach and performed time-variant receiver rotation for VSP data acquired across a Marcellus Shale prospect. They compared the SV-P image with a surface-based P-SV profile and demonstrated that these two modes were equivalent.

In this work, we test SV-P and S-S imaging on a VSP data set collected across a CO₂ storage site in the Illinois Basin in the US. First, we describe the geological setting in which the VSP data were acquired. Then we extract five different modes from the VSP data and construct a seismic image for each of them. We compare SV-P and SV-SV images with the more widely used P-P, P-SV, and P-SH images. In this notation, we use SV and SH to denote the orientation of horizontal geophones, not to refer to distinct S modes. An SV geophone is oriented in the vertical plane passing through a source station and a receiver station; whereas, an SH geophone is oriented perpendicular to this vertical plane. If preferred, one could use the terms “radial” or “SR” instead of SV and the terms “transverse” or “ST” instead of SH. We demonstrate that all these images are consistent and that they confirm and complement each other.

DECATUR PROJECT AND GEOLOGICAL BACKGROUND

The VSP data we work with were collected as a part of the Illinois Basin – Decatur Project (IBDP) located at Decatur, Illinois. This is a carbon capture and storage (CCS) project funded by the US Department of Energy – National Energy Technology Laboratory and managed by the Midwest Geological Sequestration Consortium (MGSC). The project is an integrated industrial CCS system, which includes a source of CO₂, gas transportation infrastructure, and injection and monitor wells (Finley et al., 2013).

At the IBDP, approximately about one million tonnes of CO₂ was injected into the Mt. Simon Sandstone, a porous, brine-filled sandstone reservoir, over a three-year period starting in November 2011. The Cambrian Mt. Simon Sandstone is a regional blanket sandstone that underlies large parts of Midwest United States and is the primary saline reservoir for carbon sequestration in the Illinois Basin region (Leetaru and McBride, 2009). At the project site, the Mt. Simon has a thickness of 1640 ft (500 m) with an average interval porosity of 0.2 and a permeability of 185 md. The sandstone reservoir is capped by the Eau Claire Shale that has a thickness of 495 ft (151 m). The Eau Claire is composed of black marine shale and silty mudstone at its base and low-permeability siltstones and carbonates in the upper part (Finley et al., 2013). Below the Mt. Simon Sandstone is a thin Pre-Mt. Simon Sandstone unit with poor reservoir properties. The sedimentary rocks lie unconformably on granitic or rhyolitic Precambrian basement rocks (Leetaru et al., 2014).

VSP DATA ACQUISITION

Time-lapse 3D VSP was used to monitor CO₂ plume development. The acquisition system consisted of 31 multicomponent geophones that were permanently installed in an observation well located 196 ft (60 m) west of the CO₂ injection well. An array of 29 sensors was deployed

over a depth interval from 2045 to 3445 ft (623 to 1050 m), with a spacing of 50 ft (15.24 m). Also, two geophones were located in the near subsurface. Three-component seismic data were recorded with trace lengths of 5 s at a 2-ms sample rate.

Each source station consisted of two vertical displacement vibrators which utilized a linear sweep beginning at 8 Hz and ending at 120 Hz. Each time-lapse 3D survey involved more than 500 source stations. The 3D VSP survey design is outlined in Figure 1.

In this work, we focus on the baseline survey that was conducted before CO₂ injection. At this stage, rock properties were not altered by the CO₂ plume which facilitated velocity model building. We processed the 3D VSP data along only one source line extending from west to east (noted by blue outlines in Figure 1). A string of 14 sources was located west of the well at offsets of 265–2646 ft (81–807 m), and 13 source stations were located east of the well with an offset range of 248–3442 ft (74–1049 m).

SV-P AND SV-SV MODE SEPARATION

In this section we address the problem of P-P and SV-P mode separation. All of the following also applies to the separation of P-SV and SV-SV modes.

Arrivals of reflected P-P waves and converted SV-P waves are recorded by the same geophone. Because of their different propagation velocities, P-P events and SV-P events corresponding to the same reflection boundaries reside at different times in vertical-geophone data. P-P waves arrive earlier and there are time windows in the gathers in which only P-P waves are recorded. However, with increasing recording time, more SV-P waves arrive and two different types of events interfere (P-P and SV-P). Thereby, to provide optimal imaging and robust interpretation, P-P and SV-P waves must be segregated into separate wavefields.

Event separation can be performed by distinguishing between P-P and SV-P ray paths. P-P and SV-P waves arrive at VSP receiver stations at different angles. Therefore, optimal rotation of geophones, done so that there is maximum reflected energy of each desired mode, provides the opportunity to enhance one type of events and weaken the other type (Hardage et al., 2014; Li and Hardage, 2015). However, such optimal geophone rotation may occur deficient and desired events may still be contaminated by interfering modes. In this case, events must be separated using slope contrast based on the concept that SV-P waves emerge at a larger angle and SV-P events appear less sloped in trace gathers.

The more pronounced that the slope contrast is between two interfering modes, the more accurately the two modes can be separated. The magnitude of the slope contrast between two upgoing reflections is determined by VSP acquisition geometry and the location of a target in VSP image space. As source offset decreases, SV-P and P-P ray paths become closer to vertical and the difference in their slope contrast vanishes. The same effect is observed with increasing distance between VSP receivers and a target.

Thus, the success of the P-P and SV-P separation depends on VSP acquisition geometry, and the mode separation accuracy varies from survey to survey. Far-offset sources and larger vertical dimensions of VSP receiver arrays favor more accurate mode separation.

We conducted ray tracing modeling, to investigate how direct-S waves propagate through our area of study and to predict reflection events recorded by the VSP source-receiver geometry that was implemented. Propagation velocities for P- and S-waves were preliminary obtained by travel time tomography using checkshot and 3D VSP direct arrival times.

In this work, the target of interest were the Eau Claire Shale and the Mt. Simon Sandstone, which are positioned in the depth interval between 5050 ft and 7050 ft. Figure 2

displays modeled events of P-P (shown in blue) and SV-P (shown in red) reflected waves corresponding to the top and the bottom of the interval of interest. The events were calculated for a source offset of 2172 ft, which would be in the middle of the source line shown in Figure 1.

Note that P-P and SV-P reflection events have almost identical slopes. This is caused by the small difference in approach angles for reflected rays. The contrast in emergence angles did not exceed 9 degrees for the reflector at 5050 ft or 5 degrees for the reflector at 7050 ft (Figure 3). This minor slope difference complicates accurate separation of P-P and SV-P energies. However, P-P and SV-P reflections from the storage reservoir originate at different times which does assist in separating the wavefields. Because the Eau Claire Shale and the Mt. Simon Sandstone overlay basement rocks and these basement rocks have minor internal reflectivity, we expect the time window between 900 ms and 1300 ms will be dominated by reflected SV-P events from the reservoir target and have no P-P intra-basement reflections.

In contrast, P-P events from the reservoir occur in the time interval of 650 ms to 800 ms and are definitely mixed with SV-P events from shallower interfaces. We tested event separation and observed that due to the slight slope contrast between P-P and SV-P reflections in this target window, each wave mode had a significant degree of distorted amplitudes. Because our goal was to investigate SV-P wave performance, we decided to limit mode separation to the common practice of optimal geophone orientation. P-P reflection events were processed knowing that they were mixed with SV-P events just as has been done in conventional VSP processing workflows for decades.

The processing workflow that we used to process SV-P and SV-SV modes, as well as other wave modes, is discussed in the following section.

VSP DATA PROCESSING

The VSP data were processed shot-by-shot. The processing started with frequency filtering. All three data components were contaminated by industrial background noise of 60 Hz. We applied a notch filter to eliminate this interference. This filtering was followed by first-break picking on the Z-component. Using the first breaks, we rotated the two horizontal geophones so that one of them had a maximum energy for P-wave arrivals and was oriented toward the source (Hmax-component). The other horizontal data component was orthogonal to the “source-borehole” plane (Hmin-component). Because of S-wave splitting (Hardage et al., 2011), the Hmin-component contains what will be called P-SH waves. This terminology does not mean that P converts to SH. We use the term to indicate only which horizontal geophone records converted S-data.

To get downgoing P- and S-wave signatures, we performed simultaneous rotation of Z- and Hmax-data in the vertical plane. One of the geophones was aligned toward the source and contained maximum downgoing P-wave energy. The other geophone was orthogonal and contained maximum downgoing S-wave energy. These downgoing wavefields were segregated by median filtering. An example of downgoing P and S wavefields produced at one of the offset stations is shown at Figure 4.

Next, we used an f-k filter to extract upgoing wavefields from Z-, Hmax-, and Hmin components. We then applied time-variant rotation of upgoing Z- and Hmax-data to enhance upgoing wavefields for P-P, P-SV, SV-P, and SV-SV modes. In this procedure, each geophone is rotated to a different approach angle depending on arrival time. We simulated the approach angles of each mode by ray tracing and calculated time-angle relations at each receiver station. This time-variant rotation provided four different upgoing fields. The

P-SH upgoing wavefield was optimized by the orientation of horizontal geophones in the first receiver rotation step. The ray tracing also provided path lengths for each mode, which were used for geometrical spreading compensation.

Seismic waves lose energy as they pass through a rock sequence. This attenuation is determined by the length of a ray path and varies from source to source. In addition, wave excitation conditions can vary from source station to source station when a survey is carried out at an industrial facility. For instance, some vibrators may be located on soft ground, and some vibrators may be located on strengthened roads. To reduce the influence of these factors on wavefield illumination strength, we normalized upgoing wavefields. For each source and each data mode we calculated reflection events corresponding to depth levels of 3300 ft and 5300-ft (the interval not affected by CO₂ injection) and balanced all traces based on the RMS value of reflections limited to these events.

The final step of the preprocessing was to deconvolve a source signature from each trace to create zero-phase data and to weaken multiples generated at hard reflection interfaces. We used the downgoing P wavefield generated at each source station to design an operator for deconvolution of upgoing P-P, P-SV, and P-SH wavefields associated with that source station. Similarly, downgoing S-wave signatures were used to deconvolve upgoing SV-P and SV-SV wavefields. Processed upgoing wavefields for each data component generated at this source station are presented in Figures 5 through 7.

IMAGING RESULTS

We used common-reflection-angle migration (Koren and Ravve, 2011), to obtain seismic images in the depth domain for all modes. This imaging is Kirchhoff migration in which the integration operator is defined by a scattering angle and the dip angle of a reflection

boundary. Every source was migrated separately and after that each single-source image was subjected to post-migration processing.

To reduce imaging noise in the final image, we muted areas not illuminated by reflected waves for every single-source image. The muting geometry was defined by ray tracing. The next step was to eliminate static shifts caused by near-surface features and inaccuracies in the migration velocity models. To achieve this, for every single-source image we interpreted a horizon corresponding to basement of the Eau Claire Limestone, a strong reflector at a depth of 5215 ft, and shifted all images vertically to put this horizon at the proper depth level.

Stacking of single-source images and normalization for stacking-fold variations produced seismic images for each data component (Figures 8-13). In these figures, the seismic images were tied to the corresponding sonic-based synthetics.

Figures 8 and 9 present seismic images obtained for the P-P and SV-SV modes. These images confirm the assumption of horizontal reflection boundaries at the site. Strong reflectivity in the interval between 4800 ft and 5500 ft is caused by sharp boundaries between the Eau Claire Shale and its embedded limestone layers, and the underlying Mt. Simon Sandstone. Another high reflectivity zone occurs between 6500 ft and 7100 ft, where the Lower Mt. Simon contains a few silty zones and arkose intervals. These two strong reflectivity intervals are separated by Mt. Simon sandstones which have consistent seismic properties and do not produce strong reflections. The SV-SV image looks valuable, although is slightly distorted by imaging artifacts. For example, note a migration smile at an offset of 800 ft (east side, indicated by yellow arrow) and a depth of about 6000 ft. Note that the SV-SV image indicates a number of reflector dislocations in the Mt. Simon Sandstone interval

(shown as blue dash lines). Some of these dislocations are also detected by the P-P image. For instance, features at an offset of 600 ft (west side) are consistently indicated by SV-SV and P-P images. However, most of the dislocations depicted in the SV-SV image are not evident in the P-P image. This principle that S images are more sensitive to subtle faults than an P images is well documented in Hardage et al. (2011). Because we are operating with a single 2D profile, we do not yet undertake to interpret these features as real faults. However, the SV-SV image motivates us to study the reservoir interval in detail with a full 3D VSP data volume.

Figures 10 and 11 display P-SV and SV-P images, and Figure 12 shows a side-to-side comparison of these two images on the west side of the profile. The SV-P image appears to be consistent with the P-SV image. This image similarity confirms that the SV-P mode was separated from the accompanying P-P modes with reasonable accuracy. The SV-P and P-SV images display the same reflection boundaries; however, the SV-P image extends twice the distance from the VSP well and looks more robust than the P-SV image. The SV-P image also exhibits flat horizons that correspond to the geological model of the site. The P-SV image, in turn, looks to be corrupted by migration noise and some reflection boundaries look curved.

The P-SH image (Figure 13) also displays horizontal bedding. However dynamic properties of the reflectors do not correlate with the synthetic seismogram made from well log data.

Shear-waves can provide significant increase of seismic imaging resolution, even despite the fact that S-wave data often have reduced frequency bandwidth in comparison with P-wave data. The reason is that the lower propagating velocity of S-waves compared with

P-waves causes S-waves to have shorter wavelengths than P-waves. Spatial resolution is controlled by the illuminating wavelengths, not by the illuminating frequencies.

To evaluate spatial resolution increase associated with shear-wave using at the Decatur project, we compare wavenumber spectrums of each S-wave image (both direct and converted) with wavenumber spectrum of the P-P image (Figure 14). All shear-wave modes contribute higher wavenumbers which means that S-waves have shorter wavelengths and higher imaging resolution. Wherein, the SV-P and SV-SV images reveal more pronounced resolution enhancement.

TIME-LAPSE ANALYSIS

An injected CO₂ plume propagating through a storage reservoir changes the seismic properties of reservoir rocks. The common practice for CO₂ monitoring is to conduct a seismic survey before CO₂ injection (baseline survey) and then repeat the seismic acquisition at selected time intervals (monitor surveys). Comparison of monitor and baseline seismic surveys provides information about CO₂ volume changes. Couëslan et al. (2013) used vertical-geophone data acquired at the Decatur storage site and performed time-lapse 3D VSP analysis. They observed growth of CO₂ plume with time and reported its north-west orientation from the injection well (Figure 1).

The monitor seismic survey we used for our time-lapse analysis was acquired after injection of about one million tonnes of CO₂. The injection interval was at the base of the Mt. Simon Sandstone. Some of the permanently deployed receiver stations were not working properly for this time-delayed VSP, and we had to reduce the number of receiver stations used for data processing to 23. This reduced receiver array covered a depth interval from 2045 to 3145 ft. To get the monitor image we followed the processing sequence described

earlier in this paper. In order to have the same source-receiver geometry, the number of receiver stations in the baseline data set was accordingly truncated to 23, and the data were reprocessed.

Before comparing the monitor and baseline seismic images, the monitor image was subjected to matching filtering (Rickett and Lumley, 2001) to eliminate amplitude differences in the intervals not affected by CO₂. The matching filter focused on a depth interval from 5100 to 5500 ft which constitutes the gas storage seal.

Figure 15 displays time-lapse difference between the monitor and the baseline surveys for P-P and SV-P seismic modes. The injection interval is denoted by a blue dash at the base of the Mt. Simon. The difference seismic images do not reveal any strongly pronounced saturated interval. With the exception of the bright spot at a depth of 6600 ft and offset of 400 ft (P-P difference image), the amplitudes appear consistent over the entire Mt. Simon Sandstone.

The single 2D seismic line selected for testing of direct-S wave imaging does not allow a full understanding of the CO₂ volume distribution. The seismic profile just touches the edge of the plume, as reported by Couëslan et al. (2013), in which gas saturation is moderate. In addition, the relatively small amount of sources involved does not allow adequate elimination of processing and time-lapse noises under which the time-lapse signal is buried. We plan to construct full 3D VSP images for each seismic mode to overcome these issues.

CONCLUSIONS

We were able to construct seismic images for SV-P and SV-SV modes extracted from the VSP data acquired at the Decatur CO₂ storage site. We dealt with a relatively short vertical array of 3C receivers, and the zone of interest was deep. This meant ray paths were close to

vertical and exhibited minor contrasts between reflection events that needed to be separated. Specifically it was difficult to separate SV-P and P-P on the rotated geophones that captured upgoing P, and SV-SV and P-SV on the rotated geophones that recorded upgoing SV. In spite of this, we obtained seismic images that appeared to be interpretable. The SV-P and P-SV images were equivalent, which they should be in flat, consistent layering. Longer vertical arrays of 3C geophones and greater source offsets should allow effective separation of SV-P and SV-SV modes from VSP data acquired across numerous geologic settings.

Our next step is construction of full 3D VSP images for direct-P and direct-S waves using the processing workflow we describe. The 3D VSP seismic imaging should resolve some of the uncertainty regarding the reservoir properties that are observed in our 2D seismic profile analysis. In particular, 3D VSP image should confirm or refute the assumption concerning faulting/fracturing in the Mt. Simon Sandstone. Also, we expect to get robust time-lapse analysis which allows improved location of the CO₂ plume.

Results of this work motivate us to develop processing techniques for SV-P and SV-SV modes generated by vertical vibrators and recorded in both borehole and surface seismic data. Application of these S-wave modes provides expanded opportunities for subsurface characterization. The SV-SV mode contributes subsurface characteristics that may not be available from other seismic modes. The SV-P mode allows S-wave information to be generated when working with conventional surface-based P-P recording equipment: vertical-force vibrators and vertical receivers. Direct-S wave analysis appears to be quite helpful for CO₂ storage site management. Our research shows a low-cost option for acquiring direct-S data that can contribute to deeper understanding of a reservoir, its seal, and CO₂ plume tracing.

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LIST OF FIGURES

1 3D VSP survey design. VSP well is shown by green circle. Sources involved in the baseline survey are shown by white squares. Sources involved in the post-injection survey are shown by black dots. Blue outlines indicate profile used for direct-S wave imaging testing.

2 Modeled events corresponding to the top and the bottom of the interval of interest for (a) P-P and SV-P modes, which are recorded by a vertical geophone, and (b) P-SV and SV-SV modes, which are recorded by a radial geophone. Blue lines indicate P-P and P-SV events. Red lines indicate SV-P and SV-SV events.

3 Ray-tracing results for the reflector at 5050 ft (left) and the reflector at 7050 ft. Red lines represent SV-P waves, blue lines represent P-P waves. Numbers in white ellipses indicate contrasts in emergence angles. The greyscale background mirrors the velocity model.

4 P (a) and SV (b) downgoing wavefields generated by a source station at offset of 2172 ft from the VSP well.

5 P-P (a) and SV-P (b) upgoing wavefields generated by a source station at offset of 2172 ft after data processing.

6 P-SV (a) and SV-SV (b) upgoing waveform recorded by a source station at offset of 2172 ft after data processing.

7 P-SH upgoing wavefield generated by a source station at offset of 2172 ft after data processing. "P-SH" does not mean that P converts to SH. We use this term to indicate only which horizontal geophone records converted SV data.

8 P-P image obtained by collecting all single-source seismic imaging and tied to the sonic-based synthetics. Blue dash lines indicate potential subtle faults.

9 SV-SV image obtained by collecting all single-source seismic imaging and tied to the sonic-based synthetics. Blue dash lines indicate potential subtle faults. The yellow arrow shows a smiley migration artifact.

10 P-SV image obtained by collecting all single-source seismic imaging and tied to the sonic-based synthetics.

11 SV-P image obtained by collecting all single-source seismic imaging and tied to the sonic-based synthetics.

12 SV-P image from the west side of the acquisition line tied to the corresponding P-SV image.

13 P-SH image obtained by collecting all single-source seismic imaging and tied to the sonic-based synthetics.

14 Comparisons between wavenumber spectrums of P-P image and (a) P-SV image, (b) P-SH image, (c) SV-P image, and (d) SV-SV image. Direct and converted shear waves (blue lines) contribute higher wavenumbers which means shorter wavelengths and higher imaging resolution.

15 Differences between the monitor and the baseline surveys for the P-P (a) and SV-P (b) seismic modes. These data extend west from the injection well at the zero offset. The blue dash at a depth of 7000 ft indicates the injection interval.

Figure 1: 3D VSP survey design. VSP well is shown by green circle. Sources involved in the baseline survey are shown by white squares. Sources involved in the post-injection survey are shown by black dots. Blue outlines indicate profile used for direct-S wave imaging testing.

Klokov and Hardage –

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Klokov and Hardage –

Figure 3: Ray-tracing results for the reflector at 5050 ft (left) and the reflector at 7050 ft. Red lines represent SV-P waves, blue lines represent P-P waves. Numbers in white ellipses indicate contrasts in emergence angles. The greyscale background mirrors the velocity model.

Klokov and Hardage –

Figure 4: P (a) and SV (b) downgoing wavefields generated by a source station at offset of 2172 ft from the VSP well.

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Figure 5: P-P (a) and SV-P (b) upgoing wavefields generated by a source station at offset of 2172 ft after data processing.

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Figure 6: P-SV (a) and SV-SV (b) upgoing waveform recorded by a source station at offset of 2172 ft after data processing.
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Figure 7: P-SH upgoing wavefield generated by a source station at offset of 2172 ft after data processing. "P-SH" does not mean that P converts to SH. We use this term to indicate only which horizontal geophone records converted SV data.

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Figure 8: P-P image obtained by collecting all single-source seismic imaging and tied to the sonic-based synthetics. Blue dash lines indicate potential subtle faults.
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Figure 9: SV-SV image obtained by collecting all single-source seismic imaging and tied to the sonic-based synthetics. Blue dash lines indicate potential subtle faults. The yellow arrow shows a smiley migration artifact.

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Figure 10: P-SV image obtained by collecting all single-source seismic imaging and tied to the sonic-based synthetics.

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Figure 11: SV-P image obtained by collecting all single-source seismic imaging and tied to the sonic-based synthetics.
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Figure 12: SV-P image from the west side of the acquisition line tied to the corresponding P-SV image.

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Figure 13: P-SH image obtained by collecting all single-source seismic imaging and tied to the sonic-based synthetics.

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Figure 14: Comparisons between wavenumber spectrums of P-P image and (a) P-SV image, (b) P-SH image, (c) SV-P image, and (d) SV-SV image. Direct and converted shear waves (blue lines) contribute higher wavenumbers which means shorter wavelengths and higher imaging resolution.

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a

b

Figure 15: Differences between the monitor and the baseline surveys for the P-P (a) and SV-P (b) seismic modes. These data extend west from the injection well at the zero offset. The blue dash at a depth of 7000 ft indicates the injection interval.

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Graphical Abstract

Vertical-force vibrator

P-P

P-SV

SV-P

SV-SV

Seismic images