Design, acquisition and processing of three Permian Basin 3D VSP surveys to support the processing and interpretation of a large 3D/3C surface seismic survey

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Summary

Three 3D borehole seismic (VSP) surveys were designed and acquired in Andrews and Ector Counties, Texas in 2019 to provide data to support the processing and interpretation of a high-fold multicomponent 3C/3D survey. The three downhole receiver well locations were chosen in available wells in three distinct geological settings within the area covered by the surface seismic surveys. Large aperture 3-component (3C) borehole geophone arrays and both P-wave and S-wave vibrator sources were utilized, providing valuable time-depth and velocity information. In addition to the travel time information, high-resolution VSP reflection images were produced for the various wave types recorded (P-P, P-S and S-S) which gave useful insights into the signal properties of each.

Introduction

Three large scale 3D borehole seismic (VSP) surveys were acquired in the summer of 2019 in Andrews and Ector Counties, Texas. The surveys were designed to provide data in support of a large, extremely high fold 3D multicomponent surface seismic program. The locations of the VSP surveys represent distinct geological settings within the boundaries of the surface seismic program. VSP #1 was collected ~3 miles east of the Wolfcamp Central Basin Platform (CBP) slope margin. It was placed to better understand velocity modelling of carbonate materials shed from the CBP and interbedded with basinal carbonates and marine mud materials. The VSP #2 location was chosen to derive velocities from basinal features such as carbonate debris flow fan heterogeneities and turbidite flows. VSP #3 to the far north was acquired along strike with VSP #2, however, differing sedimentation is seen in well log data as well as differences in "Wolfberry" production along the same strike plane. It was collected to differentiate VSP #3 sedimentation from VSP #2, which seems to have more influence of sedimentation from the San Simone channel. Each VSP utilized large vertical aperture 3-component downhole geophone arrays covering over 11,500 ft. at a 50 ft. receiver interval. All three VSP surveys employed P-wave vibrator sources and two of the surveys included S-wave vibrator sources.

Processing and analysis of this comprehensive dataset provided detailed time-depth relationships and seismic-scale velocity information at each location. All three VSP surveys produced high resolution 3D reflection images around each borehole. Additionally, the VSP results offered insights into surface seismic signal processing and multiples observed in the surface seismic data. Processing of the new 3D/3C survey is still ongoing but initial comparisons of the P-wave images with the legacy surface seismic data are quite good and reveal stratigraphic information not previously seen.

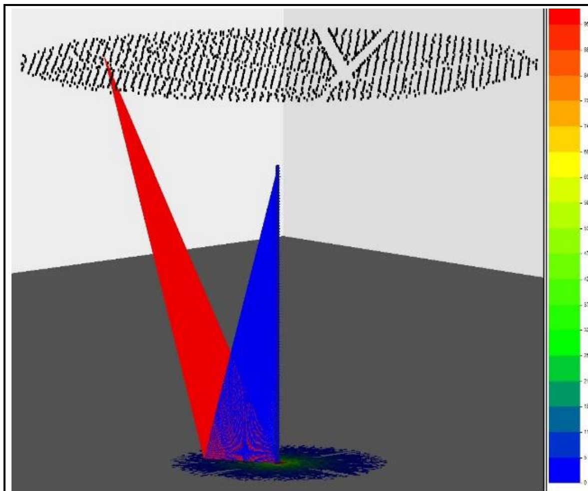

Figure 1: 3D VSP survey design for VSP #2 showing surface sources (black) and 3C borehole geophone array (blue). The estimated illumination at the deepest target depth at this location is shown along with the down-going direct rays (red) and up-going reflected rays (blue) for a single source.

Survey Design and Data Acquisition

Each of the three VSP surveys utilized an 80-level array of 3C GeoSpace DS-150 geophones spaced at 49.2 feet and moved three times in the wellbore to provide over 11,500 ft. of vertical aperture. P-wave source locations were spaced with a nominal 3D grid spacing of 495 ft. x 495 ft. out to a maximum offset from the well of ~12,000 ft. Figure 1 shows the estimated illumination for one of these VSP surveys along with the down- and up-going rays for a single source location. The P-wave sweep was the same as that used for the surface seismic program (2-90 Hz, 24 sec., low dwell) for direct comparison and far-field analysis. Each source location was acquired three times into each of the three tool settings.

Two of the VSP surveys also utilized S-wave vibrator sources, acquired along 2D spoke lines radiating away from each well. The S-wave source was swept in two orthogonal directions at each location and tool setting (2-48 Hz, 24 sec., linear). Figure 2 shows the source and receiver locations and estimated illumination for each of the three surveys and a description of the final acquisition parameters are shown in Table 1.

Data Processing

Processing of the VSP data was divided into three main stages in order to provide timely information to the client and the surface seismic processors. The first stage included the processing of the zero-offset source locations (ZVSP). By using the nearest source location we were assured of near-vertical energy ray paths and the strongest signal for evaluating the far-field source signature as it propagated down the well. ZVSP processing provides accurate time-to-depth profiles, detailed interval velocities at seismic scale and a reflectivity trace (aka corridor stack) that is high resolution and multiple free. This was done for both P-wave and S-wave sources and the results are shown in Figure 3. In addition, the spectrum of the source wavelet was analyzed at each geophone depth and an estimate of attenuation (Q) was made over the length of the array (Tonn, 1991). The orthogonal S-wave sources were also evaluated for any evidence of S-wave splitting occurring along the array (Alford, 1986).

	VSP #1	VSP #2	VSP #3
Top of array (MD)	135 ft.	637 ft.	57 ft
Bottom of array (MD)	11,700 ft.	12,300 ft.	11,720 ft.
Total array length	11,565 ft.	11,663 ft.	11,663 ft.
Geophone spacing	49.2 ft.	49.2 ft.	49.2 ft.
Geophone type	GeoSpace DS-150	GeoSpace DS-150	GeoSpace DS-150
# Source locations	1,573 (P) 0 (S)	2,178 (P) 168 x 2 (S)	737 (P) 121 x 2 (S)
Maximum source offset from well	11,993 ft.	12,362 ft.	11,964 ft.
Source grid spacing	495 ft. x 495 ft.	495 ft. x 495 ft.	495 ft. x 495 ft.
P-wave sweep	2-90 Hz 24 sec low dwell	2-90 Hz 24 sec low dwell	2-90 Hz 24 sec low dwell
S-wave sweep	N/A	2-48 Hz 24 sec linear	2-48 Hz 24 sec linear

Table 1: VSP acquisition parameters.

The second stage of this processing effort included the processing of all P-wave sources in order to create 3D P-wave images at each of the three locations. Initial signal processing of 3C borehole geophone data involves several steps of mathematical geophone component rotations in order to maximize either first arrivals or reflected arrivals. Because we are recording the direct arrival at depth we have the opportunity to use this source signature to deconvolve (or designature) the data to arrive at a stable zero-phase result. Any noise present is also addressed at this stage, though noise in the data was not a significant problem as the boreholes were quiet recording environments. The only significant noise present was the tube wave generated by the nearest source to the well. This is a trapped wave that is initiated by the surface wave from a nearby source and then propagates down the borehole at fluid velocity. It is typically easy to remove in processing. The main goal of the signal processing stage is to isolate and enhance the P-wave reflection energy recorded for each source location. To do that, each individual source and downhole receiver combination is dynamically rotated/tilted to maximize the P-wave reflection energy onto a single component. Then all the down-going energy is removed from the individual source records, including direct waves, near-surface reverberations, and mode conversions. From that point we then move into the imaging phase. For these surveys we utilized a receiver redatumming procedure to simulate an equivalent surface seismic geometry (Fuller et al, 2008) that was then followed by conventional surface-consistent applications (e.g. statics, amplitudes, deconvolution) and Kirchhoff pre-stack time migration. The same 41.25 ft. x 41.25 ft. processing grid used for the surface seismic processing was used for the VSPs to make project loading and interpretation easier. The comparison of the 3D VSP image for well #2 overlain on the coincident legacy surface seismic is shown in Figure 4.

The third stage of the project involved the signal processing and imaging of the mode-converted PS-waves. Signal processing was similar to that of the P-wave data but the goal was to now isolate and enhance the PSv-wave reflections for imaging. Initially the 3C geophone data are rotated into radial and transverse orientations but may be rotated later into more appropriate directions if any S-wave birefringence is detected. At this point in the processing no significant S-wave splitting is observed. Imaging of the PSv-wave reflections then followed a similar flow to the P-wave of upward continuation and pre-stack time migration.

Processing and imaging of all the S-wave sources, with the exception of the zero-offset locations, has not been performed at this time since it will not produce an image which can be directly compared to the surface seismic surveys. It will be useful however for future interpretation work in order to compare the PSv-wave reflectivity to the pure mode SS-wave reflectivity.

Results and Conclusions

The results to date from the processing and analysis of the three 3D VSP surveys are shown in Table 2 along with additional information available from this comprehensive borehole seismic dataset. This includes, but is not limited to, time/depth information, seismic scale interval velocity, attenuation/Q, multiple analysis, high-resolution reflectivity, anisotropy and S-wave birefringence. As the processing of the surface seismic survey proceeds the value of this information will be further assessed and presented.

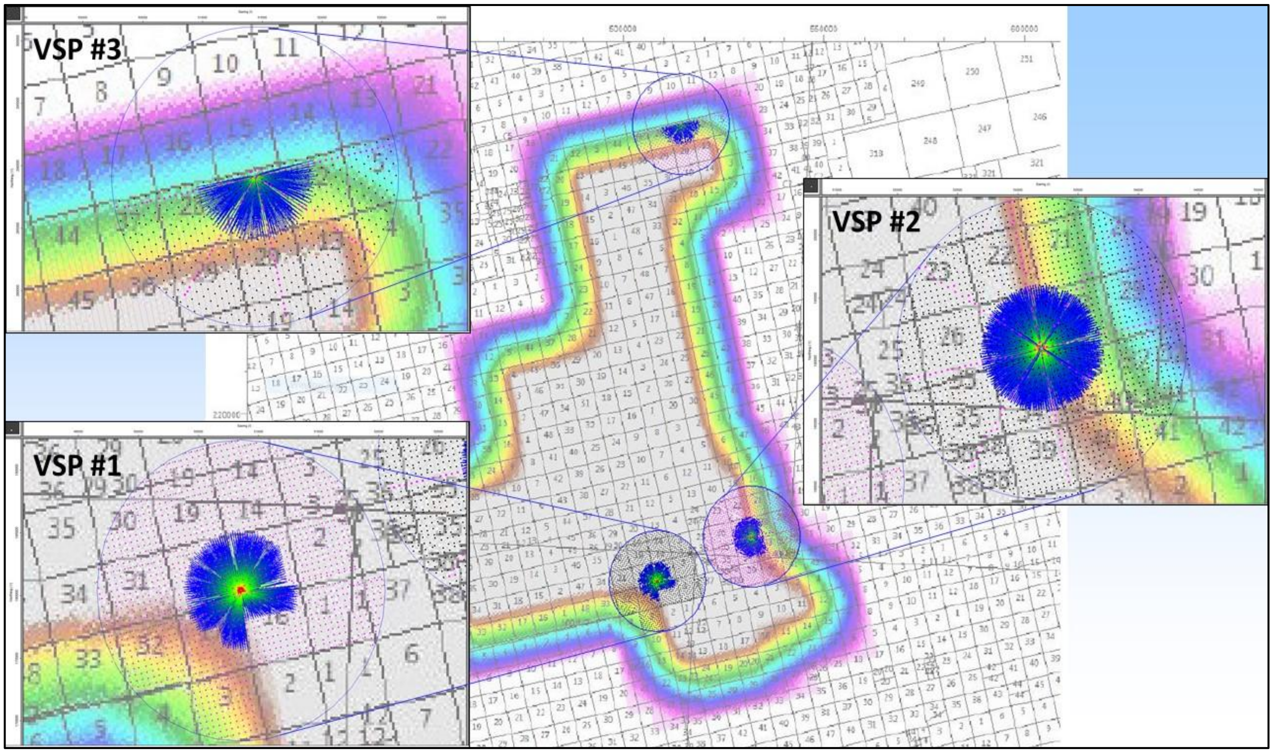

Figure 2: The locations of three 3D VSP surveys positioned within the larger 3D/3C surface seismic survey. Each location shows the estimated illumination at the deepest target depth along with the surface source locations. VSPs #2 and #3 recorded both P-wave and S-wave vibrator sources. VSP #3 was restricted to source locations south of the survey boundary.

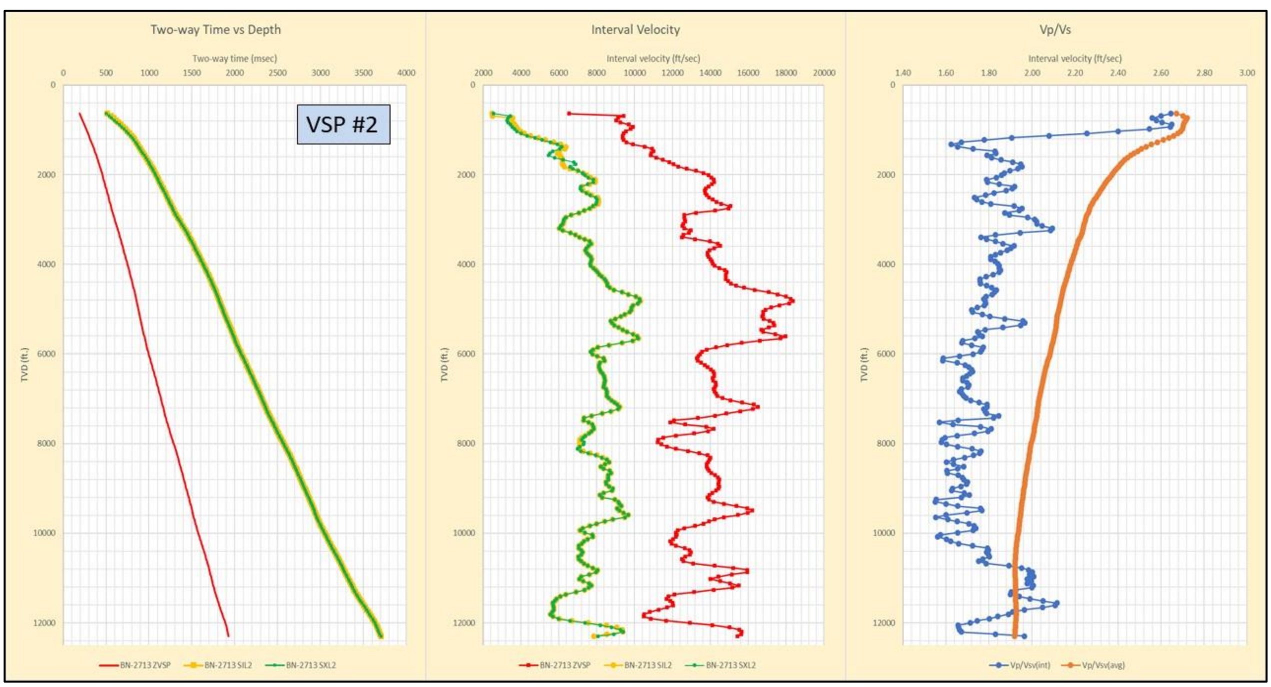

Figure 3: Time, depth and velocity information extracted from zero-offset VSPs at VSP #2 location. The left panel shows the two-way travel time versus depth for both the P-wave (red) and the two orthogonal (inline/xline) S-wave sources (yellow and green). The central panel shows the estimated vertical interval velocities derived from these travel times. Note that there is very little difference between the orthogonal S-wave velocities implying that there is little S-wave splitting at this location. The right panel shows the interval (blue) and average (orange) Vp/Vs values computed from the P-wave and inline S-wave velocities. This is very useful information for future mode-converted PSv-wave processing and interpretation.

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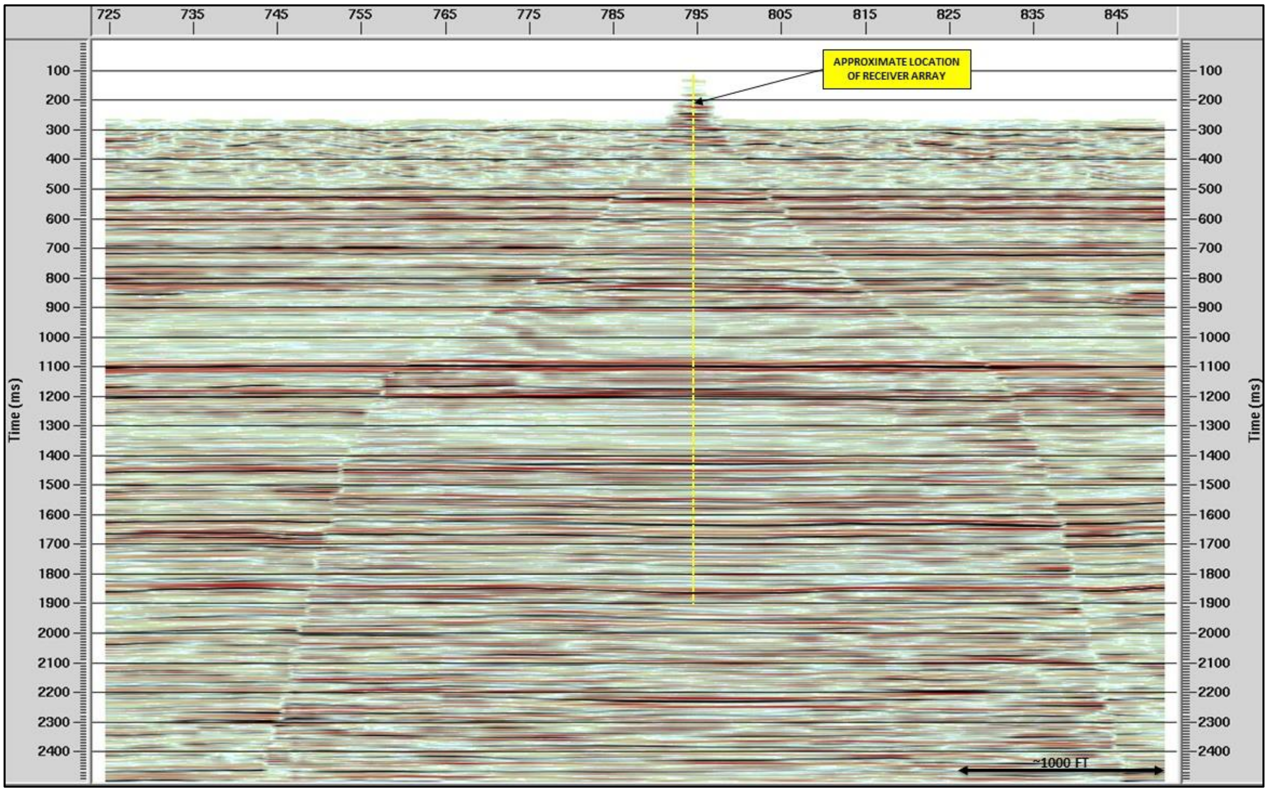

Figure 4: 3D P-wave reflection image for VSP #2 overlain on legacy 3D surface seismic survey. The approximate location of the total geophone array is shown in yellow. Differences in the start times are related to the final processing datum chosen for each project.

VSP Type (source)	*Data Obtained*	*Value for Surface Seismic Processing and Interpretation*
ZVSP (P or S)	Two-way time vs. depth function*	Accurate depth ties and interpretation at wells
ZVSP (P or S)	Interval velocity at seismic scale*	Detailed vertical velocity information to guide surface seismic processing and imaging
ZVSP (P or S)	Corridor stack*	Primary-only reflectivity and accurate depth registration; helps identify multiples
ZVSP (P or S)	Far-field source signature*	Measure of surface source characteristics for deconvolution and whitening
ZVSP (P or S)	Attenuation/Q profile*	Interval and Effective Q values for inverse Q application
ZVSP (P and S)	Vp/Vs ratio at seismic scale*	Vp/Vs profile for PS-wave processing and event registration
ZVSP (Sv/Sh)	S-wave birefringence estimate*	Direct measure of S-wave splitting at well location
2D and 3D VSP (P or S)	High-resolution 2D or 3D image*	High-resolution image for interpretation of subtle features not visible on surface 3D
2D and 3D VSP (P)	High-resolution PS-wave image*	High-resolution PS-wave images to calibrate PS-wave surface seismic images
2D and 3D VSP (P or S)	Source-consistent information (statics, amplitudes, decon)*	If locations are shared between VSP and surface programs the S-C values can be compared/used
2D and 3D VSP (P or S)	VTI estimates over length of borehole array	VTI information at well location to guide anisotropic imaging
2D and 3D VSP (P or S)	HTI estimates over length of borehole array	HTI information at well location to guide azimuthal processing
2D and 3D VSP (P or S)	Detailed images of down- and up-going wavefields including PS and SP mode conversions (offset sources)*	Complete picture of the entire seismic wavefield; also useful for detailed AVO analysis at well
2D and 3D VSP (P or S)	Wavefront arrival angle for source azimuths and offsets	Direct measure of arrival angles for accurate analysis of AVO curves
2D and 3D VSP (P or S)	Arrival times at depth for source azimuths and offsets	Direct measure of travel times for comparison to Kirchhoff PSDM travel-time tables

Table 2: Summary of all data available from the three VSP surveys acquired and its application to support the processing and interpretation of the 3D/3C surface seismic survey. Data marked with an asterisk (*) have been extracted at this time.