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Walkaway Vertical Seismic Profiling (WVSP) Modeling and Imaging Study along Faulted Coal Seams over a High Velocity Limestone Model: A Synthetic Study

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Abstract: The problem of collecting reflection data from the layers below a high velocity layer (HVL) and imaging those layers accurately is solved using walkaway vertical seismic profiling (WVSP) technique. The procedure is shown on a dataset from a model of highly faulted, thin-bedded coal layers separated by a high velocity layer of limestone. By locating the receivers above, in, and below the HVL, the reflections are expected to be recorded locally in situ in the borehole below the HVL before they travel back to the surface as in the case of surface seismic. The imaging results obtained from the model (or synthetic) WVSP data lead to the conclusion that promising results may be obtained via the acquisition of field WVSP data such that the layers below the HVL are well-imaged. Analysis of the test results showed that the layers below the HVL can be imaged accurately and robustly when the receivers are situated below the HVL only, while the strong images below the HVL tend to fade away and lose their strength when the receivers are moved above the HVL. However, both these cases of the receiver location geometry are needed to obtain images that are vertically and horizontally stable. When a full instrumentation of the borehole is provided, good images as far as 500 m away from the VSP borehole are obtained from the layers with various dips and faults that are nearly 800 m in depth from the surface. Two cases of velocities (4000 m/s and 5000 m/s) are tested for the high velocity limestone layer. Both cases showed good images below the HVL. Unfortunately, some pulled-up effects are seen in the images right below the HVL where the layers that are immediately below the HVL are imaged above their correct locations, the pulled-up effects are corrected in the deeper sections below the HVL however. Comparison of a depth converted corridor stack from the zero offset VSP data and the depth migrated image show good agreement.

Keywords: Walkaway VSP (WVSP), FDM, RTM, high velocity layer (HVL), coal layers

1. Introduction

Vertical seismic profiling (VSP) method is a seismic technique which is never meant to be a replacement for surface seismic. Having said that, however, it differs from surface seismic considerably in recording geometry since the receivers are placed at depth in a borehole as opposed to on the surface. The same seismic sources can be used in both techniques. Since seismic events are recorded in the well, subsurface geology or the vertical discontinuities inside the earth can be observed in great detail in VSP. Because the geophone depths are known exactly, the depths of the reflectors can be determined precisely along the borehole till the total depth (TD) as published in geophysical literature by many scientists (Balch and Lee, 1984; Galperin, 1985; Hardage, 1985; Toksöz, 1985; Wyatt, 1987; Yilmaz, 1987). Having the receivers in the borehole results in a number of other advantages, as well as some disadvantages. Since there is less or no cultural or environmental noise interference at depths the borehole provides quieter environment for the receivers, thus the recorded signal quality or signal to noise ratio (S/N) is usually higher and the signal bandwidth is expected to be wider in VSP than surface seismic (Steward, 2001). A good borehole coupling of the probes to the well is needed for appropriate VSP recording. Also, the negative effects of weathered zone or near the surface can be minimized on the seismic signal on the receiver side because the reflected signals are recorded at depth before reaching the surface. Because the source signal can be recorded along the borehole, further analysis on the signal can be performed to extract earth properties from it (Čınar, 1989; Karshi, 1995; Yilmaz, 2015). Subsurface imaging of the VSP reflections can be done in 2D as well as 3D (when the VSP survey is 3D) using migration algorithms suitable for those VSP geometries (Wyatt, 1987; Hofland 1990; Jaramillo 1993; Jaramillo et al.,1993; Hornby et al., 2006; Burch et al., 2010). Reflector mapping can also be done using VSP data to CDP domain mapping (VSPCDP Mapping;
The advantage of the flexibility of locating the receivers in various depths in a VSP survey is made use of in this investigation. Since it is known that recording the reflections coming from the layers below a high velocity layer (HVL) is difficult in surface seismic, we use the approach of placing the receivers below the HVL and recording the reflections in situ before they travel back to the surface. If the reflections are generated there below the HVL they can be recorded in situ near to where they originate. The problem and the proposed approach to the solution are explained schematically in Figure 1, where it is expected that the receivers below the HVL should record the reflections and diffractions there before they hit the HVL from the bottom side.

The WVSP technique is commonly used in oil exploration with promising results for near and subsalt imaging (Ray et al., 2005; Hornby et al., 2006; Burch et al., 2010). The VSP technique is also applied on land surveys for different purposes as, for instance, in coal exploration as shown in (Bubshait et al., 2009, Bubshait, 2010; Cankurtaranlar et al., 2012; Charlotte et al., 2014;), also in reservoir properties analysis (Xu et al., 2003; Johnston, 2010) or in subsurface imaging using one or multicomponent VSP data (Erdemir, 1997; Xu et al., 2003). In addition, the reader is referred to some WVSP and crossborehole (x-hole) imaging results from computer modeling and physical modeling studies (Balch and Chang, 1991; Balch et al., 1991, 1994; Jaramillo et al., 1993).

The efficacy of the WVSP technique for the HVL problem is studied on a model with many challenges for seismic imaging in this paper. A two-dimensional (2D) computer modeling study is performed to produce a finite difference modelling (FDM) dataset from a model of highly faulted and thin-bedded coal layers with a high velocity layer of limestone (HVL) between them. Our model includes vertically and horizontally varying velocities \(V(x, z)\) but the velocities are constant within the layers.

Figure 1. Conceptual schematic of a typical WVSP configuration. WVSP is expected to record seismic reflections below a high velocity layer (HVL) or zone (HVZ) because the receivers are located below it in the VSP borehole.
The FDM data generated from the model were processed and depth imaged for different source receiver combinations. Promising results were obtained in the images in terms of identifying, seeing and imaging the layers above and below the HVL and detecting the faults near and far away from the borehole as well as other layering structures ranging from flat to vertical dips.

The aim of this study can be summarized as to show how to build a realistic and complicated geophysical model from a geological subsurface model and stratigraphic information, and to use the model to produce synthetic seismic data set using the FDM technique for a WVSP survey on it. Also to show and emphasize that the WVSP technique can be used and applied to accurately image subsurface layers with different dips and thicknesses and the faults along the layers in the presence of a high velocity limestone layer (HVL) between the coal layers.

2. Model building
A realistic geological earth model was selected for use in our modeling rather than a superficial one. A compact subsurface layered geophysical model, that is built based on the geological model and stratigraphic column and two dimensional (2D) seismic lines by Saatçilar et al. (2014), has been used to calculate the WVSP synthetic data. It was noted in their paper that the geological model had been constructed from the wells drilled along a 2D line, there are coal layers in the area and a high velocity limestone layer between them, and the layers are disrupted by many faults. The depth of the limestone is about 750 m from the surface. Also from the near surface down to about 650 m depth the area is covered with low velocity volcanic tuff-like materials as indicated in the stratigraphic column. The geological model and the stratigraphic column, originally given by Saatçilar et al. (2014, Figures 2 and 7) are screen captured and shown in Figure 2 for informational and reference purposes.

The picture of their model was first scanned, imported and digitized in a computer. An extra layer is added to the original model at the bottom at 1150 m depth for quality control (QC) purpose. Because we did not have access to their original model in digital form and the scales were not very clear in the paper published, the scale of the geological model is approximated. The model size was set to 3500 m wide (x) and 1250 m deep (z).

Geological names of the layers of the model are figured out after matching the stratigraphic column (Toprak, 2009) to the model at the borehole location. The geophysical properties (densities and P-wave velocities) of the layers needed for the modeling are found in the literature (Mavko et al. 2009; GPG Notes, 2021) and assigned to our model to create the geophysical model as shown in Figure 3. The names shown on the model have special meanings in the stratigraphic column. The KP1, KM2, KM3 are the coal layers and the HVL is limestone with a velocity of 4000 m/s. The borehole location was chosen strategically to challenge the WVSP for imaging various problem structures including a vertical displacement, dipping layers, faults and the layers below an HVL. The topography is ignored by adding an extra layer of low velocity (1000 m/s) at the top to create a flat surface for the modeling. The faults indicated by the dashed yellow lines on the model in Figure 3 are copied from the original model.

![Figure 2](image)

**Figure 2.** Shown are the reference information used in the geophysical model construction; (a) the geological crosssection (modified from Saatçilar et al. (2014, Figure 7), (b) the stratigraphic column after (Toprak (2009), Saatçilar et al. (2014, Figure 2). Because the original model had poor resolution, some information is retyped and shown in parenthesis in (a).
3. Synthetic data generation by finite difference modeling (FDM) technique

The WVSP data is generated using an acoustic finite difference modeling (FDM) code from the Seismic Unix (SU) package (Stockwell et al. 2008) where the FDM means that the wave equation is solved and the wave-propagation is done using a finite difference mathematical approach to the wave equation (please see the reference for the FDM algorithm and the solution used in the code). The surface multiples were suppressed in the modeling. The dominant frequency of the data is set to 40 Hz with an 80 Hz maximum frequency that is the bandwidth of the wavelet. A larger bandwidth could also be chosen but thinking that the earth is a filter itself and only a limited bandwidth of signal can be propagated into the medium, a choice of 40 Hz dominant frequency seemed reasonable for our imaging work. Also it was reported by Cankurtaranlar et al. (2012, Figure 3) that the field VSP data had center frequencies 40–50 Hz range which is in-line with our choice of the frequency bandwidth. The source spacing was 50 m and receiver interval was 5.0 m in the modeling. The sources were placed at the surface with 10 m source depth (two grids). The receiver borehole was straight and vertical at 2075 m in x-location. Closest source offset to borehole head was 25 m. The borehole total depth (TD) was 1250 m spanning across all of the model depth range. There are 67 sources and 251 receivers total. The data sampling rate is resampled to 2.0 ms for processing from a finer modeling sampling rate. The record length was 4.0 s. The source type chosen was pressure type with a Ricker wavelet. The receivers were Omni type of pressure sensors (or hydrophone equivalent) as no directionality was of interest at this point. The density model was ignored for simplicity by setting a constant value for the all layers.

The source waveform used in the synthetic data generation is shown in Figure 4a and the synthetic near offset shot gather from the WVSP data set is plotted in Figure 4b, where the downgoing waves and the upgoing reflections are indicated by the green and orange arrows, and the first-break times are shown by blue arrow. Although strong first-breaks are observed below the limestone layer (which is about 800 m) shown by a red arrow, the reflections from the layers below the HVL seem very weak. The picked first-break traveltimes are shown in gray color curve.

A spectral analysis was done on the ZVSP data. The amplitude and F-X spectra are shown in Figure 5; where (a) is amplitude spectra from individual traces (every 10th trace) in blue color and (b) is from all traces combined in red color, (c) shows the combined F-X spectra and (d) from individual traces. The dominant frequency (40 Hz) is shown by the arrows in all figures. Some low frequency noise is detected on the amplitude spectrum below 3 Hz which is interpreted as numerical noise created by the modeling code. The noise was removed by a low-cut filtering. The amplitude decay as a function of trace (or depth) is clearly observed in (d). Using the amplitude decay as a function of distance one can study the attenuation along the borehole as a function of depth, as indicated in Çınar (1989) and Karslı (1995). No further analysis on the amplitudes was performed in this study.

Various snapshots were created to understand and examine wave-field propagation in our model from different sources at different surface locations. Snapshots
Figure 4. Shown are (a) source wavelet used in the modeling, (b) near zero-offset VSP shot gather with 25 m source offset from the well head. Downgoing waves, reflections (or upgoing waves) and first-break times are indicated by green, orange and blue arrows respectively. Red arrow shows the strong first-breaks below HVL. The two figures indicate what is sent into the modeling medium from the source and what is recorded at the receivers. First arriving downgoing waves are used in first-break travelt ime picking and shown in gray color curve.

Figure 5. Amplitude spectra from the synthetic zero-offset shot gather; (a) from individual traces (10th trace) are plotted, (b) averaged spectrum for the whole shot gather. F-X spectra plots of the same shot gather are shown as (c) the averaged spectra and (d) from individual traces. Amplitude accumulation at the dominant frequency (40 Hz) is shown by the arrow.
from a source (S) near the well are created at 100 ms time steps, and presented in Figure 6 with the model superimposed in the background. In panels (a) through (h) are shown how the wave field propagates in the model and how the reflections are created at the layer boundaries.

Some of the seismic events in panel (h) are identified with letters and shown in Figure 7, where the events (a) are reflections from the layer above the HVL and (b) from the limestone, the diffractions from the fault corners far away from the borehole are identified as (c) and (d) on both sides of the borehole, and the downgoing first-arrival is indicated as (e).

Some selected shot gathers are plotted in Figures 8a and 8b with 500 m shot distance between them. The ZVSP is indicated by arrow, where in (a) the raw gathers (also called total waves) and in (b) the upgoing waves obtained after wave-field separation are shown. F-k wave-field separation was applied to all gathers to obtain the upgoing waves followed by a band-pass filter to remove residual noise on the gathers. Notice that at the zero-offset source location the data behave more linearly in which the downgoing waves and the reflections or upgoing waves are more distinct. The linearity gets lost as the source offset increases and the first-arrivals seem to travel more horizontally. Since the model depth is short compared to source-offsets severe refractions (shown by an orange arrow in Figure 8a) are observed on the data, after 1000 m source offset the refracted events become more visible.

4. Analysis of the zero-offset VSP (ZVSP) gather
A special attention was paid to the zero-offset VSP (ZVSP) gather, as is usually done in field VSP surveys. The ZVSP
A corridor stack (CS) is built from the upgoing waves of the ZVSP gather. Details on how to build a CS are not discussed here. A CS is represented usually on a time axis, and it can be considered as a representation of the reflections of the ZVSP gather in two-way surface seismic reflection time for flat layers so that it can be directly matched and tied to surface reflections that are also in two way time at the VSP borehole. The CS may also be used to tie surface reflections to depth along the VSP well. It may also be used to distinguish true reflections from multiples on surface seismic data if strong multiples are present, and it is especially a useful and effective approach along the borehole depth till TD.

The ZVSP reflections aligned at the two-way reflection time and the corresponding CS are shown together in Figure 9, where (a) is the aligned reflections with the mute gate line (blue), and (b) and (c) are the corridor stack displayed in both image and wiggle displays using 8 traces.

The depth converted CS is shown in Figure 10 together with the wireline P-wave log derived from the geological model (the velocity model in this case). The strong reflections match the HVL, or limestone, at 800 m depth correct location.

5. Data processing of the synthetic WVSP shot gathers before migration
The processing steps and the quality control of the WVSP data followed here are done according to the outline presented in an earlier paper published in the MTA bulletin by Erdemir (2021). Basic processing steps to be mentioned here include; data view and displays, first-break time picking, upgoing wave field separation, muting, band-pass time domain filtering, receiver gather sorting, and further picking and muting in the receiver gather domain, refraction analysis and refraction time picking and muting for removal of refracted waves and interference. The velocity control, based on traveltime analysis, is performed premigration such that the first-arrival traveltimes calculated using the velocity file match the data. The quality-control steps are not shown here in detail due to space limitations. The gathers are processed and viewed in shot and receiver gather domains interchangeably and interactively for optimum processing results. There were severe refractions and low velocity near surface layer effects on the data: removing the refractions without sacrificing signals was a time consuming task.
6. Prestack depth migration of the WVSP upgoing data
The imaging is done using a reverse time migration (RTM) algorithm (Hofland, 1990, Schneider et al., 1992). The algorithm uses second order time and fourth order space solutions to the wave equation. The forward traveltimes are calculated using ray-tracing, and the data is back propagated in time using finite differencing method (FDM), and the imaging is done at the time where the forward and backward traveltimes coincide. How the forward traveltimes from source S propagate in the model is shown in Figure 11 together with the velocity model plotted in the background where the traveltimes are shown as iso-time contours in the figure.

The RTM algorithm can take source and receiver locations independently in any variation of space and depth coordinates (x, z) which is an important feature for borehole seismic imaging since the receiver and source geometries may vary significantly. The algorithm was also applied to multimode imaging of various WVSP data sets, for instance to synthetic data (Jaramillo, 1993); to field data (Erdemir, 1997); to a physical model of crosstheorehole data for P-P, P-S, S-P and S-S mode imaging (Balch et al., 1991,
Figure 9. (a) Synthetic ZVSP reflections aligned at the two-way reflection time, (b) and (c) are the corridor-stack shown in image and wiggle forms respectively. Vertical axis is in two-way reflection time.

Figure 10. Shown are in (a) the P-velocity log, (b) CS as a single trace, and in (c) and (d) the CS is repeated eight times. The CS is depth converted using the interval velocities. A good match is seen between the interval velocity and the CS plots. The reflections from the HVL are very strongly seen at 800 m (green arrow).
Erdemir, 1992); and to a 3D physical model data (Balch et al., 1991, Chang H 1991) as well as to a field crosshole data set (Karazincir, 1995). Details of the algorithm can be obtained from Hofland (1990), Chang (1991) and Erdemir (1992).

6.1 Imaging results
The migration is performed on the upgoing waves. As each shot gather is migrated separately, 67 migrated sections are obtained after migrating all shots. The migrated sections are later summed to obtain stacked images. Considering that the WVSP data character may vary considerably as the source offsets increase, stacked images are constructed in four offset ranges so as to analyze the images in different offset combinations or groups, as follows; a near offset group (0–300 m), a mid-offset group (0–600 m), a mid-far offset group (0–1000 m), and a far-offset group (0–1500 m). It was noticed that each offset group produced a slightly different result. The stacked images show more dominant and higher amplitudes around the borehole and create unevenly distributed amplitudes in the images as more offsets are included in the stacking of the images. A simple sum is applied in producing our stacked images.

The ZVSP shot data is migrated first, and its imaging result is shown in Figure 12, where in (a) the migrated section and in (b) its comparison with the model are shown. A significant amount of information is obtained from this single shot migration. The layer boundaries are at their correct locations, and the layer at 1150 m depth (z) below the HVL (limestone) is imaged well and surprisingly strongly. Some seismic events are also recognized at 1500 m and 2700 m in x and 600 m to 850 m in z ranges, but it would be difficult at this point to make sense of those reflections if the model were not known. No incidence angle limitation was applied during the migration. The single trace at the well location in this image may be compared to the depth converted CS. The HVL is seen as a strong image at 750 m depth at the borehole location, and indicated by the arrow.

6.2. Images from the near offsets group
After examining the ZVSP image, migrations from offsets of 0–300 m are summed together to build a near offset group image and shown in Figure 13, where in (a) the image alone and in (b) the image with the model are displayed. A considerable amount of subsurface information is obtained in these short offsets as seen in the figure. The source interval distance is 100 m and only seven shots are used in the stacked image. The vertical changes in the subsurface are clearly seen along the borehole. The right dipping layer at 500 m is clearly imaged, and the first coal layer KP1 and the HVL (limestone) are well imaged. The layers immediately below the limestone can be recognized but are weak in amplitude. The image of the bottom layer at 1150 m is resolved with high amplitudes and on the accurate location in depth. However, its lateral extension is shorter than the HVL. This is thought to be because the HVL does limit the seismic rays hitting the layers below itself due to high refractions and unfortunately shadows them.

Seismic events at 1500 m and 2700 m in x-direction match fault corners as seen in Figure 13b. It is especially interesting to mention that even in these short offsets some faults which are 600 m away from the borehole, beyond the maximum source distance of 300 m, can still be imaged. The upper layer at 500 m depth created reflections far away from the borehole on the right side of the well, and even though some of them have vertical displacement they seem
to be robustly imaged. Some sections of the layer at 500 m depth are imaged in parts on the right-hand side of the borehole because the layer dips away from the borehole.

6.3. Images from mid-offsets group
A stacked image from the mid-offsets group of 0–600 m is created and shown in Figure 14 as in (a) the image alone and in (b) with the model. This image displays obvious enhancement of signal-to-noise ratio (S/N) through the power of summing more offsets, with more continuous and clear images above and below the HVL. The three coal layers are imaged well; one above and two below the HVL. The layers below the HVL are clearly seen about 1000 m depth, and their horizontal extent is nearly 500 m on the left (updipping) side, and about 300 m on the right (downdipping) side as seen in Figure 14b. Some low frequency migration artifacts exist in the image which is explained as that some of the far offset gathers still contain undesired leftover events with high amplitudes after processing, and they created some swinging artifacts in the images (shown by orange arrow in Figure 14a) during the migration. The faults to the left (1500 m) and right (2700 m) of the borehole in x are distinctly imaged now as seen in Figure 14b.

6.4. Images from far-offsets group
Shot gather images from offsets of 0–1000 m are summed to create a far offsets group image, shown in Figure 15, where in (a) the image alone and in (b) the image with the model are displayed. The image is seen laterally extended from the borehole up to nearly 500 m. The layers below the HVL are imaged well and they look strong. Figure 15b shows that the layers immediately below the HVL are also imaged but are raised in depth slightly. It can be said that the interference from the HVL shows up as a pull-up effect in the image there. The bottom layer at 1150 m is imaged

Figure 12. Image from depth migration of the ZVSP reflections; (a) the migrated image, (b) the image is overlaid on the model. The layers are seen migrated to their correct locations. The HVL is indicated by the arrow.
at its correct location indicating that the interference effect of the HVL is eliminated after some distance at this depth.

The last stacked image shows promise in that the challenging areas for imaging can be mapped successfully using the WVSP method. It may be recalled that problem areas were 1) the vertical layer and the small faults away from the well at depths around 500 m, 2) the thin coal layers above and below the HVL (limestone), 3) the bottom layer at 1150 m depth, 4) the fault corners away from the well and beyond the effective imaging zone. These are all seem imaged in Figure 15 without ambiguity.

6.5. Effect of source interval distance on the image
The stacked images shown so far are based on a 100 m source interval. Some circular migration artifacts or migration noise (shown by an orange arrow in Figure 15a) are seen in all images. In order to see if they can be suppressed, the source interval was reduced to 50 m and another stacked image is created from the new data set. The new stacked image is shown in Figure 16, alone in (a) and with the model in (b). The migration artifacts seem suppressed considerably at the new source interval. In the 50 m case however the data volume is doubled in size and the processing efforts are increased considerably. Another test was done using a 25 m source interval, but not much improvement was obtained in the image quality over the 50 m case.

The input data was further processed to remove the right dipping noise strongly seen on the left side of the borehole, the final image from the reprocessing is shown in Figure 16c where the noise seems to be eliminated and the image below HVL is clearer.

7. Interpretation of the images and remarks
The P-velocity log, depth converted CS and the stacked image are combined and presented side by side in Figure 17 as (a), (b), and (c), respectively. The CS is merged with the stacked image at the borehole location, a good match between the two is obtained as seen in (c) in the
7.1. Effect of receiver location on the image

Two cases are tested for receiver location; in the first the receivers are placed above the HVL, in the second below the HVL. For each case a new stacked image is created. The near offsets are used in the tests for the stacked image. The results showed distinct differences between the two cases. When the receivers were above the HVL only, the layers below the HVL are not imaged well, especially the bottom layer at 1150 m is not imaged at all. When the receivers were put below the HVL only, the layers below the HVL are imaged well but with a short and limited lateral distance of the imaging zone. The results from the tests are shown in Figure 18, where the images are shown from the receivers when above the HVL in (a) and when below the HVL in (b), respectively. The green box shows the location of the receiver group in the borehole included in the imaging. The stacked image for the receivers located over the complete depth range in the borehole was given in Figure 13 already.

7.2. Interpretation of some of the features seen in the images

Some of the features seen in the WVSP images especially show the effectiveness of the technique for unexpectedly imaging and locating particular subsurface structures. Some selected features are indicated in circles in Figure 19a. The events were initially considered as artifacts or migration noise in the images because they are considerably away (about 600 m) from the borehole and they have no physical connectivity to the images seen in the vicinity of the borehole. When the model layer boundaries (black lines in the figure) are overlaid on the stacked image, they did match the displacements caused by the faults at their...
correct locations. A possible explanation for those events is shown by arrows in Figure 19b, where the downtraveling wave hits the fault faces (or corners) and diffracted around them and are recorded by the receivers in the borehole. Similar explanations can be postulated for the images seen at shallower layers at 500 m. On the right side of the borehole vertical discontinuities, nearly 600 to 700 m away from the borehole, are imaged well.

8. Results, conclusion and discussion

It is shown in this investigation that the WVSP technique is a useful approach to obtaining seismic images below a high velocity layer (HVL). Good images are obtained above and below the fast velocity limestone layer. The thin-bedded coal layers are imaged very clearly above the HVL and are acceptably visible below the HVL. However, the layers immediately below the HVL seemed pulled up slightly in the images, which is explained as an interference effect caused by the high velocity contrast between the HVL and the layers below it. It is interesting to note that the image of the layer about 200 m below the HVL is focused well at its correct position showing that the wave propagation frees itself from the HVL effect at this depth. This phenomena is witnessed in both cases of limestone velocities of 4000 m/s and 5000 m/s as seen in the stacked images in Figures 16 and 20 (Appendix A), respectively.

The image quality below the HVL increased sharply when the receivers were also placed below the HVL, however the images below the HVL got considerably weaker or disappeared when the receivers were placed above the HVL only. Based on the results from receiver location tests it is concluded that the reflections coming...
Figure 16. Stacked image from offsets of 0–1000 m. The source interval distance is 50 m. The image quality is increased considerably over the image from the 100 m source interval case; (a) is the image alone, (b) plotted with the model, (c) the image in (a) is displayed after further processing. The white looking artifact seen on the left side of the borehole is suppressed, yielding a clearer image.
Figure 17. The stacked image is compared to the depth converted CS; where (a) shows the interval velocity or the model, (b) the CS in wiggle form, and (c) the CS is overlaid on the image at the well location.

Figure 18. Stacked images from the receiver location tests; (a) the stacked image when the receivers are above the HVL, (b) the image when they are below the HVL. The layers below the HVL are not imaged in (a) yet they clearly seen in (b). The dashed boxes show location of the receiver array included in the image. Near offsets are used in the tests, the combined image is shown in Figure 13.
from the layers below the HVL are severely masked by
the HVL causing amplitude reduction by absorbing their
energy or preventing them from reaching the receivers
above the HVL. The situation is similar to a salt dome
or any other structure case which can create a high
velocity (or impedance) contrast between itself and the
neighboring layers.

The modeling data has 40 Hz dominant and 80 Hz
maximum frequency. It has been shown that the thin-
bedded coal layers of about 30 m thickness are detected
and imaged correctly at this frequency. If higher frequency
data had been obtained, sharper images may have been
created.

No incidence angle limitation was set in the migration
algorithm, some source distance related noise or artifacts
were encountered in the images from the data set with
source spacing of 100 m. The artifacts are eliminated greatly
when the source interval is reduced to 50 m improving the
image quality distinctively. However, reducing the source
interval distance increased the data acquisition efforts and
doubling the size of the data.

Shorter offsets produced stacked images well and
correctly focused around the borehole. It is seen that even
in these short source offset cases, some structures with
high dips and locations far away from the borehole can
still be imaged unexpectedly well (as seen about 300 m
depth) showing that the WVSP is a well suited technique
to observe the vertical discontinuities along and around
the instrumented borehole. The data from the large offsets,
0–1000 m and greater, helped in yielding strong images
of the subsurface structures that are located about 500 m
away from the borehole and on both sides of it. Sources

![Figure 19](image-url)

Figure 19. (a) Circled sections show that subsurface features (or faults) far away from the VSP borehole (even
beyond the farthest source offsets) can be imaged. The model layers (black lines) are drawn on the image for
explanation, and (b) the green arrow indicates conceptually how the seismic events from the fault corners get
recorded in the borehole.
with offsets farther than 1000 m did not contribute much to the stacked images for our model which has layers limited to 1150 m depth. Including those longer offsets in the sum introduced artifacts of low frequency noise in the stacked images, causing a decrease in the resolution in the images near the borehole. This is believed to be an effect of the refracted waves traveling horizontally towards the borehole from the far sources or the residual downgoing wave-field not completely removed during the processing of the data prior to migration.

In summary, it can be said that this WVSP modeling and imaging study has produced positive and promising results indicating that the method has great potential in an application where the objective is to record reflections from the layers below a high velocity layer (HVL) as long as the receivers are located below the HVL. The statement made here is however no guarantee that the method will work in every situation so test recordings are strongly recommended prior to the commencement of any survey in the field.

Disclaimer

It should be emphasized that the modeling study performed here is not to judge, discuss or compare its findings and results to any previous work done by the owner of the geological model(s). The geological model was selected only because it had been already published in the literature (by Saatçilar (2014)) and it was a realistic model with interesting and challenging features for use in the WVSP modeling work.

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Appendix A

Seismic image from a higher velocity layer of limestone

In order to see the effect of higher velocity value in the HVL (limestone) in the images of the layers below the HVL, the velocity value of limestone was increased to 5000 m/s from 4000 m/s, and another FD forward model data was generated. The FDM data were processed and migrated, and the stacked images were created in the same way as applied to the earlier data. The image from the higher velocity model is shown in Figure 20 as (a) the stacked image alone and (b) with the model. The fast layer and the coal layers above it are imaged well, and the thin layers right below the HVL are also imaged but they seem again they are pulled up, even slightly more than the lower velocity case. The pull-up effect may be reasoned from high velocity effect as in the salt dome case. The bottom layer seems to be imaged fine at its correct location.

Figure 20. Stacked image when the HVL (limestone) is modeled with a higher velocity of 5000 m/s; (a) is the image alone, (b) the image with the model. The bottom layer at 1150 m is still imaged strongly at this higher velocity as well. The layers immediately below the HVL are imaged but they seem to be pulled up slightly higher than their correct locations.