VERTICAL SEISMIC PROFILING (VSP) SURVEYS TO DETECT OLD MINE WORKS

at the Sterling Mining Company
Carroll Hollow Mine,
Jefferson County, Ohio

MSHA Contract # J53R1011

Submitted by

Lawrence M. Gochioco, P.G.
LM Gochioco & Associates Inc.

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SUMMARY

Two vertical seismic profiling (VSP) survey projects were conducted at the Sterling Mining Company (SMC) property to detect the old abandoned Sterling Mine works, which closed in 1962. The first survey was conducted on May 24, 2005 in an open hole filled with water. The hole location was supposed to be within 80 ft of the projected old mine works boundary. A total of six far-offset VSP data were collected. However, the processed data did not provide conclusive evidence that clearly showed anomalous signals that could be interpreted to be associated with the detection of old mine workings. After the surface seismic survey program was completed and verified by drilling and hole-to-hole tomography surveys, it became apparent that the VSP Hole #1 was not within the proposed 80-ft distance to the old mine works. Instead, the boundary of the old mine works was found to be about 300 ft further south.

As a result, MSHA requested a second VSP survey be conducted in which the location of old mine works had already been verified by drilling. Fortunately, SMC drilled a pair of holes in the summer of 2005, located about 1800 ft northeast from the first VSP site. The pair of holes were only 100 ft apart. One hole encountered solid coal while the other encountered old works. Thus, the second VSP program was conducted at this new site on March 13, 2006, in which a total of seven source offset data sets were collected.

After processing, the two VSP data sets with 50-ft and 150-ft source offsets collected over known old mine works showed some disturbances in the seismic signal at the estimated two-way arrival time of approximately 37.5 ms. As was illustrated in schematic diagrams, mine voids would likely cause some type of disturbance to the seismic signal. The signal disturbance was more pronounced in the 50-ft than the 150-ft source offset locations because the source was much closer to the receiver array. Despite what may appear to be an apparent successful project to demonstrate the VSP technique, the investigator feels the project was a “limited or partial” success as the raw data had below average signal-to-noise ratio. Attenuating the dominant downgoing and upgoing tubewaves were a major challenge in processing.

INTRODUCTION

On April 26, 2005, LM Gochioco & Associates (LMG&A) Inc. was awarded a contract by the Mine Safety and Health Administration (MSHA), U.S. Department of Labor, to conduct field testing and demonstration of three geophysical methods that could be used to detect air- or water-filled old mine workings or voids. The award included conducting three geophysical methods; namely, vertical seismic profiling (VSP), surface seismic reflection (SSR), and inseam seismic (ISS), at the Sterling Mining Company (SMC) Carroll Hollow Mine. This report covers the survey results of the VSP program.

Prior to data acquisition, a kick-off meeting was held at MSHA’s Pittsburgh Research Center on May 11 in which representatives from District 3 (Pat Betoney) and 5 (Terry Sheffield) were also present because mines selected for this study were located in their district. The kick-off meeting provided useful background information on the respective roles of the contractor and the MSHA supervising team.

The following day (May 12), the team went to the SMC office in Salineville, OH, and met Tim Miller, geologist, who was our contact person in this geophysical investigation study. Miller provided detailed information about their company's concurrent mining activities, geologic conditions, and concerns about the nearby flooded old mine works (old Sterling Mine) located northeast of their reserve. Thereafter, we explored the surface sites where the proposed locations of the SSR survey lines and VSP hole would be located. It was decided then to place the VSP hole near the two proposed northern surface seismic lines as this particular old mine works was of major concern to the company.

Under MSHA's contract, the company was required to conduct a VSP survey in one hole and gather a total of four far-offset VSPs. After the field data acquisition program was completed, the company conducted VSP surveys in two open holes and acquired a total of eleven far-offset and five near-offset VSPs.

GEOLOGIC CONDITIONS

The overburden thickness at the Carroll Hollow Mine ranges from 200 to 350 feet. The surface is mostly gentle rolling hills with open fields and wooded areas. The mine is located in Fox Township, Carroll County, OH. The Mahoning coal (7A) seam is the lowest Conemaugh Age seam in the Pennsylvanian Formation in Ohio. The seam occurs in ~10 square mile area pods which can reach a maximum thickness of 45 inches, usually in the center of the pod. The coal is frequently channeled out on the edges and at times through the center. The coal is also slumped into by the overlying shale along the channel margins. The immediate overburden is the black shale grading upward by gray shale and sandstone.

In this mine, the average seam thickness is 34", but the mining height is about 42". The abandoned mine had the same mining height and is water-filled with up to 30 feet of head above the seam elevation. Hydrological testing was based on borehole drilling. The mine dips to the southeast where the pressure head reached up to 65 feet. The immediate roof has bone coal with 7 foot of shale, coarsening up to 5 feet of sandyshale which is then topped by 15 feet of sandstone.

Figure 1 shows the relative locations of the active mine works of Carroll Hollow Mine, located on the southwest portion of the map. The flooded abandoned old mine works are shown in dark gray, located to the northeast section of the map. Separating these two mines is a solid blue band with an arrowhead on top that snaked across the reserve block on a north-south trend. This solid blue band corresponds to hole-to-hole tomography surveys conducted by Gecoh Exploration, a company based in Lexington, KY. SMC contracted Gecoh Exploration to perform the surveys in the early 1990s to image seam continuity, thin coal areas, and to detect mine voids.

The map also showed washout areas in the reserve in which a major paleochannel system had eroded the seam completely. Based on results from surface drilling, underground observations, and hole-to-hole tomography surveys, the paleochannel system had a northward trend, which could explain why the old mine works ended abruptly.

ABANDONED OLD STERLING MINE (closed in 1962)

The coal company did extensive research work in gathering historical information about the abandoned mine. The Mahoning coal at the old Sterling Mine was mined from 1890 to 1962 from a portal along State Route 39 (approximately 5 miles away from the study area). The J. M. Hirst and Company was a long time operator. The mine ran submains every 500 ft from which individual rooms were mined and the coal was hand-loaded. Individual rooms usually measured 200 ft long and 24 ft wide. On the western edge of their reserve, some rooms in the south were cut short because of poor roof conditions, thin coal, and washouts. These adverse mining conditions indicated the presence of a nearby paleochannel system.

Ever since the mine was closed in 1962, water had been accumulating in the empty chambers, and had built to a hydrostatic head of up to 65 ft. above the seam elevation in 2005. Miller's interpretation after reviewing the old Sterling Mine maps appeared to be a simple "cut and paste" job and its accuracy was in question. As a result, SMC conducted a series of hole-to-hole seismic tomography surveys in the 1990s to better image the thin coal areas and old mine works. The survey results indicated that errors in the accuracy of the old map could increase as we head further north. The large northern-most room is of most concern as there were distinct gaps and the lack of pillars in the drawing. However, an outline of the room's western tip was shown and the gap appeared to be linear. Was the absence of pillars the result of poor data transfer from one map to another? Could it be that a simple cut-and-paste method was used, and that this process could have accidentally omitted some pillars or entries? Was the old map also accidentally rotated during the process? To address these critical issues, the placement of two surface seismic lines and the first VSP hole were initailly planned.

VERTICAL SEISMIC PROFILING

Most of the land seismic surveys conducted is predominantly 2D and 3D surface seismic reflection method. Even though this technique is robust, the quality of data is largely dependent on near-surface conditions in which the data were collected. Shallow unconsolidated materials, commonly called the weathering layer, can result in poor source-to-receiver coupling, resulting in the recording of lower frequency data. Moreover, the surface seismic reflection method has inherent resolution limitations because the seismic wavelet must propagate greater distances through the weathered layer, resulting in higher attenuation rates of the higher frequencies.

Since the depths and thicknesses of coal seams are usually known before hand, it is important that the reflection associated with the coal seam is correctly identified in the seismic section to avoid misinterpretations. Without sonic and density logs to generate synthetic seismograms for correlation with the surface seismic data, VSP surveys are usually conducted to fill the gap.

VSP has some advantages over the surface seismic reflection method in that the receiver is lowered in the borehole beneath the weathering layer. As a result, VSP data sets tend to have a broader frequency spectrum. The recorded VSP wavefield data also provide better insight into the fundamental properties of reflection and transmission of seismic wavelets in the subsurface near the borehole because the receiver records both the downgoing and upgoing seismic waves. In cases where surface access is extremely limited to conducting surface seismic surveys, the VSP method can fill in some gap.

Figure 2 shows a schematic diagram of a typical oilfield VSP survey. A wall-locking geophone tool or hydrophone string is lowered down the borehole to certain assigned depths. The wall-locking mechanism engages and locks the geophone rigidly against the wall of the borehole to provide good receiver coupling. This process is repeated every time for all the pre-determined acquisition depths. The wireline and recording trucks are used to operate the geophone system and the Vibroseis is used as the seismic source. The schematic diagram shows the travel paths of various waveforms. As described, downgoing multiples (1), direct arrivals (2), upgoing reflection (3), and the upgoing multiples (4) are recorded simultaneously. There are other types of waveforms that are not illustrated in this figure, but are also recorded. The seismic waveform that is most useful is the upgoing reflected waves (3). **Figure 3** shows an example of a typical VSP data collected from the petroleum industry to highlight the various recorded waveforms.

Let us concentrate or focus on the schematic diagram presented in **Figure 4** that highlights reflections only from the coal seam horizon. Assume a fixed offset distance from the borehole in which source (S1) is located. At different receiver depth intervals (only four are shown in this case), reflection points from the coal seam could be mapped. As the receiver is raised to its shallowest level, the recorded coal seam reflection is farthest from the borehole. By collecting data from multiple depth levels, we can record a continuous subsurface profile of reflections away from the borehole, defined as the “coverage area”, and indicated in the figure. Now, let us take the case where a second source position (S2) is selected, but is located farther away from the borehole. Calculated raypaths of seismic energy corresponding to the four different receiver depth levels are shown (in red). Notice that as the source is moved farther away, the VSP method is able to record seismic reflections farther away from the borehole. If the coal seam is uniformly thick across over this interval, then we should expect to record continuous upgoing reflections from the coal seam horizon and over the entire depth interval. (Note: Straight raypaths are only assumed for illustration purposes. In reality, the raypaths will have some curvature according to Snell’s Law).

If a borehole is located near a suspected mine void whose exact location is unknown, then the VSP method can be used to profile the coal seam horizon. By selecting different source offset locations and distances, we can collect a radial pattern of VSP data away from the borehole. If a mine void is located inside this coverage area, then there is a good probability that it could be detected. The second half of **Figure 4** shows a break or gap in the upgoing reflected waves could indicate the presence of mine voids or a washout.

Figure 5 shows a sample raw VSP data collected in the Central Appalachia coal basin in 1990 (Gochioco, 1998). The published case study was conducted as part of an comprehensive exploration program that included surface seismic to map seam continuity and washout areas. The data set has good signal-to-noise ratio as evident by the clean first break information from time, t = 0 second. The receiver depth interval ranged from 130 to 37 m. Consol Energy had to drill a larger 6-inch diameter corehole so that the wall-locking geophone tool could be lowered down the hole. Most of the coal exploration coreholes measured only between 2.0 and 2.5 inches in diameter. The seismic source was the 8-gauge seisgun. *(Footnote: Consol invested $110,000.+ in 1988 to acquire the wall-locking borehole geophone system that included a 1500-ft steel wireline cable. An electric motor drives the cable reel that had a built-in depth counter and pressure gauge. The system was later bolted and housed inside a 4x4 van.)*

Conducting VSP surveys require the lowering of either a wall-locking geophone tool or a hydrophone string down an open cased or uncased hole starting at the deepest level. A seismic source is initiated on the surface and VSP data is then recorded. Thereafter, the receiver is raised to shallower preset depth levels and the source is initiated again. The process is repeated until the shallowest depth level is reached and data recorded. The VSP method is widely used in petroleum exploration and production (Galperin, 1974; Wuenschel, 1976; Hardage, 1983; Oristaglio, 1985, Hinds, 1996, Ray et. al, 2003, Ray et. al., 2005, and Van Gestel, 2002), but has seen limited application in the coal industry (Greenhalgh and Suprajitno, 1985; and Gochioco, 1998).

DATA ACQUISITION in VSP Hole #1

SMC drilled the first proposed VSP hole, Kantz05-7. Unfortunately, the survey crew later discovered that the hole location was 150 ft north from the projected old mine works instead of the proposed 80-ft distance. The company later redrilled a second hole 75 ft further south and closer to the projected old works. The new VSP hole was named Kantz05-7A (see **Figure 6**). Drilling went an extra 100 ft below the coal seam elevation to provide more subsurface coverage and data collection.

Tim Miller provided hand-drawn geologic cross sections of Kantz05-7 and Kantz05-13, as shown in **Figure 7**. The geologic cross section of Kantz05-7 and Kantz05-7A are identical as they were only 75 ft apart and had the same surface elevation. The cross section shows the depth to the top of the coal seam is 261 ft. Drillhole Kantz05-13 is located about 330 ft southwest of the VSP hole #1 (Kantz05-7A), and lies near the end of the surface seismic Line 2B.

After weeks of preparation, the first VSP survey was conducted on May 24, 2005. Geophex Ltd. was contracted by LMG&A Inc. to acquire the VSP data. Given the small diameter corehole, a 24-channel hydrophone string at 5-ft center was used as the receiver. The Geometrics Geode seismograph was used to record the data and a spring-activated mechanical impact device was used as the seismic source.

Table 1 shows the surface coordinates of the VSP hole #1, Kantz05-7A, with respect to the near- and far-offset source locations, based on the Ohio North State Plane coordinate system.

	Easting (ft)	Northing (ft)	Elevation (ft)	Offset Distance to K-7A
Hole Kantz05-7A	2416656.8353	339195.7215	1282.85	
S-1	2417008.1840	339222.2000	1243.51	352.4
S-2	2416675.1535	339554.6125	1253.64	359.4
S-3	2416907.7615	339000.0076	1247.40	318.2

S-4	2416677.2273	338852.6127	1295.05	343.7
S-5	2416358.8788	338985.6380	1259.56	364.6
Walkaway #1	2416618.3120	339006.6740	1289.40	192.9
Walkaway #2	2416610.0680	338954.9480	1295.14	245.3
Walkaway #3	2416607.0480	338900.5110	1300.14	299.4
S-6	2416604.6250	338853.4420	1305.54	346.2

TABLE 1. Surface coordinates of the VSP hole#1 and respective source offset locations.

DATA PROCESSING

The generalized VSP data processing workflow is shown below.

1. Assign geometry information
2. Spectrum analysis and filter testing
3. First break picks
4. Apply front-end mute to first break
5. FK analysis of wavefields
6. Attenuate downgoing and upgoing tubewaves via FK-Filter
7. FK analysis of wavefields
8. Separate the downgoing and upgoing wavefields via FK-Filter
9. From Step 8, bulk shift the downgoing waves horizontally to the 10-millisecond mark.
10. Filter testing of downgoing waves and apply filter appropriately
11. Extrapolate a deconvolution filter from the downgoing waves.
12. From Step 8, bulk shift the upgoing waves into two-way travel times to direct correlation to surface seismic reflection data.
13. Filter testing of upgoing waves and apply filter appropriately
14. Apply the deconvolution operator extracted from the downgoing waves
15. Apply corridor-mute
16. Stack the upgoing waves to generate a VSP seismogram

INTERPRETATION of VSP #1 data

The first indication in which good VSP data had been collected is examining how clean the first breaks are of each seismic trace. The "first break" is associated with the geophone or hydrophone recording the first direct seismic arrival from the surface seismic source and the time interval before it is relatively quiet. Thus, VSP data sets with easy-to-pick first breaks usually indicate a data set with good signal-to-noise ratio. Good examples of raw VSP data with clean first braeks as applied to petroleum and coal exploration are presented in **Figures 3 and 5**.

Since a lot of VSP data sets had been collected in this project and their respective results are almost similar, only a select number of data sets will be presented and discussed in this report. However, all the raw far-offset VSP data sets will be included to show the complexity in gathering good VSP data at this site and the difficulty in processing them because of the poor signal-to-noise ratio.

Figures 8 to 13 show the raw VSP data sets collected from the six far-offset source positions relative to hole Kantz05-7A. The offsets ranged in distance from 320 to 360 ft away from the VSP hole. Unfortunately, all six VSP data sets do not have clean first breaks and are contaminated by the dominant multiple downgoing and upgoing tubewaves. The "red" line shown on top of each raw data is the estimated slope (i.e. velocity) of tubewaves.

What are tubewaves? Tubewaves are associated with seismic energy that propagates up and down the water column in the hole. Since hydrophones were used as receivers, the hole had to be filled with water in order for the hydrophones to work. Recording of tubewaves is therefore expected in such a setup. Tubewaves can bounce back and forth from the top of the water column and hole bottom, and undergo several cycles before it attenuates to a magnitude below background noise level. Usually, the problem of tubewaves can be removed (or attenuated) in data processing because the tubewave velocity in this hole was measured to have an average velocity of 4,250 ft/s. If the upgoing P-wave reflections have velocities greater than 8,000 ft/s and the raw data have good signal-to-noise ratio, then wavefield separation is possible without the likelihood of introducing artifacts into the data set.

Out of the six far-offset VSP data sets, data from source location S-2 was the best because the "first break" is easier to interpret than the other five. Thus, it was selected to demonstrate the key steps in processsing and interpreting VSP data. **Figure 14** shows an expanded scale of the raw data collected from source location S-2. The dominant seismic event in the data is evidently the tubewaves, bouncing up and down the VSP hole in multiple wavetrains. Wavefield separation was accomplished by applying the FK-filter.

What does the FK mean in FK-filter? The "F" is defined as "frequency" (inverse of time, 1/time), and the "K" is the "wavenumber" (1/λ, where λ is the wavelength). Since seismic data are usually displayed in the Distance-Time domain, an inversion process can be applied to the data via the Fourier Transform, and converted into the FK-domain for analysis. Studying data sets in different domains is a common Mathematical process. For example, the location of the point in three-dimensional (3D) space can be described by the X, Y, Z coordinate system or by the R, θ, φ spherical coordinate system.

After applying the FK-filter to attenuate all the upgoing waves, the downgoing waves are highlighted as shown in **Figure 15**. Likewise, attenuating all the downgoing waves and upgoing tubewaves in the data would result in a section that shows only upgoing reflected waves as shown in **Figure 16**. The final step in processing all VSP data sets is to tranform the data into two-way time and apply a corridor-mute stack in order to generate a VSP seismogram. The VSP seismogram in turn could be used to correlate with the surface seismic data (Gochioco, 1998). **Figure 17** shows the final processed VSP data from the S-2 source location. The display on the right-side of **Figure 17** is the one that we hope to see any indication of detected old mine works. However, the data is so weak and incoherent between 40 and 100 milliseconds that interpretation cannot be done objectively.

Months later after the surface seismic data had been processed and interpreted, it became apparent that the size of the old mine works was smaller in scale and the boundary distance moved furtehr south to about 250. The findings were subsequently confirmed by post-seismic drilling and hole-to-hole tomography surveys, as shown in **Figure 18**. Therefore, all the VSP data collected from Kantz05-7A will not contain any useful data associated with the detection of old mine works. Thus, MSHA requested LMG&A Inc. to conduct another VSP survey in holes that have confirmed old mine works.

DATA ACQUISITION in VSP Hole #2

In the summer of 2005, SMC drilled a pair of two closely-spaced holes to the northeast of Hole Kantz05-7A (see **Figure 19**). The first hole, Kantz05-8, was drilled near the edge of suspected old mine works to a total depth of 170 ft. The coal seam was found at depths of between 149.5 and 153 ft. The actual seam thickness was 34" with a 3-ft top shale and another 17 ft of sandy shale above it. The second hole, Kantz05-9, was drilled about 100 ft away and encountered fractured roof from 147 to 149 ft. A free-fall drop occurred between 149 to 153 ft (old works). Thereafter, water level quickly rose to 135 ft (or 14 ft above the seam elevation), confirming old mine works. A hand-drawn geologic cross section was provided by Tim Miller, and his interpretation of the subsurface is presented in **Figure 20**.

Figure 21 is a larger scale map of **Figure 19**, highlighting the locations of drillholes Kantz05-8 and Kantz05-9. Results of the hole-to-hole tomography surveys are also presented and showed a good correlation with the known location and width of the old mine works. Thus, Kantz05-8 was selected to be VSP Hole #2.

Given the small diameter hole, LMG&A Inc. rented a 12-channel hydrophone string at 1-m interval and conducted the VSP survey using the same seismic recording system (Geometrics Geode) as the first contractor. The 12-gauge seisgun was used as the seismic source. The second VSP survey was finally conducted on March 13, 2006. The receiver depths ranged between 183 and 55 ft from the surface. A total of seven source offset VSP data sets were collected. Four source offset positions at 50-, 100-, 150-, and 200ft distances southeast to the VSP hole #2 and over old mine works were conducted. Likewise, three source offset positions at 50-, 100, and 150-ft distances northwest to the VSP hole #2 and over solid coal were conducted. The seven source positions are shown on the map of **Figure 21** as 50-A, 100-A, 150-A, 200-A, 50-B, 100-B, and 150-B.

INTERPRETATION of VSP #2 data

Figures 22, 23, and **24** are the raw VSP data collected in the northwest direction and over solid coal. First breaks are already difficult to interpret in **Figure 22**, despite the fact that the source was only located 50 ft away. As expected, first breaks in VSP data from the 100- and 150-ft source offsets positions showed a deterioration in quality. The time interval between time, t = 0 s, and the first break tubewave noise or energy were being recorded. That means that tubewaves were bouncing up and down for extended periods of time after each shot. Therefore, first break picks from all three data sets would be questionable and very subjective.

Figures 25, 26, 27, and 28 are the raw VSP data collected in the southeast direction, towards the old mine works with respective source offset distances of 50-, 100-, 150-, and 200-ft. Again, we experienced the same problems as the former setup. First breaks are barely interpretable with the 50-ft offset while the other three data sets are extremely difficult. The multiple asymmetric downgoing and upgoing tubewaves indicate the subsurface to be highly-fractured. In addition, the shallow hole permitted the tubewave energy to have a short cycle time. For example, the water column in this VSP hole was about 130 ft (TD = 183 ft, and water level at 53 ft). Using an average water velocity of 4,237 ft/s, it would take only 30.6 ms for the tubewave energy to propagate over the entire water column in one direction. All seven data sets seem to show a dramatic amplitude and phase change in the seismic signal at an approximate depth of between 127 and 130 ft, indicating a fracture. The geologic cross section of **Figure 20** shows this to be the boundary between sandstone and the sandy shale roof. Such fractures would also become secondary sources of tubewaves.

Since the two near-offset (50-ft) VSPs showed decent first break information, let us look at them closely. The top and bottom red lines shown in **Figure 29** are interpreted to be the respective first break and tubewave velocities of the VSP data from the northeast (NE) direction. By simply calculating the slopes of each line, the correponding velocities were found to be about 9,000 ft/s and 4,320 ft/s. Likewise, the corresponding velocities of the first break and tubewaves from the VSP data with a 50-ft source offset from the southeast (SE) direction were found to be approximately 7,000 ft/s and 4,154 ft/s (see **Figure 30**). Using these two pairs of values, the average velocities were then calculated to be 8,000 ft/s (rock) and 4,237 ft/s (tubewaves).

A bandpass filter and automatic gain control (AGC) were applied to **Figure 29**, and the result is shown in **Figure 31**. Since the raw seismic data were recorded in Time–Distance domain, the data can be transformed into the FK-domain via a Fourier Transform. Analyses of **Figure 31** in the FK-domain would result in FK-plot shown in **Figure 32**. The seismic energy envelopes located on the left- and right-hand sides of the display correspond to the dominant upgoing and downgoing waves respectively. In most VSP data with accepatable signal-to-noise ratio, the seismic energy envelope of the downgoing waves should always be several magnitudes stronger than the upgoing waves before any wavefield separation. However, the upgoing and downgoing wave energy envelopes are nearly identical in magnitude because the upgoing tubewaves are as robust as the downgoing ones, suggesting that it would be very difficult to extract any weak upgoing reflection events.

After applying an FK-filter to attenuate all the downgoing waves, the resultant VSP data is presented in **Figure 33**. Evidently, the upgoing tubewaves are still dominant with very little evidence of any good upgoing reflected waves to interpret. Another FK analyses was applied on **Figure 33**, to attenuate the upgoing tubewaves and the resultant display is presented in **Figure 34,** highlighting the remaining upgoing energy envelope. It is clear that there is too much data over the entire record time, suggesting that residual upgoing tubewave energy mixed with any weak reflected energy as their velocity contrast was considered small. The filtered upgoing reflected data is then converted into two-way travel time by simply doubling the first break information of each trace (see **Figure 35**). In other words, if the nearest trace and farthest race first breaks were 16 and 38 ms, then converting the data into two-way travel time is done simply by bulk shifting or applying a time delay of 16 and 38 ms, respectively, which would eventually result in the nearest and farthest traces having new break times of 32 and 76 ms.

The same processing steps that were applied to the VSP data set having a source offet of 50-ft in the NW direction were later applied to the 50-ft and 150-ft source offset locations over the old mine works. To minimize redundancy, short brief descriptions of the following figures are described.

- Figure 36 – VSP data with 50-ft SE source offset after bandpass filter and AGC were applied.
- Figure 37 – FK analyses plot of Figure 36 showing the power distribution and dominance of the upgoing and downgoing tubewaves.
- Figure 38 - Figure 36 after attenuating all the downgoing waves.
- Figure 39 - FK analyses plot of Figure 38 showing only the upgoing waves.
- Figure 40 - Figure 38 after attenuating upgoing tubewaves to enhance upgoing reflected events and transforming the data into two-way travel time.
- Figure 41 – VSP data with 150-ft SE source offset after bandpass filter and AGC were applied.
- Figure 42 – FK analyses plot of Figure 41 showing the power distribution and dominance of the upgoing and downgoing tubewaves.
- Figure 43 - Figure 41 after attenuating all the downgoing waves.
- Figure 44 - FK analyses plot of Figure 43 showing only the upgoing waves.
- Figure 45 - Figure 43 after attenuating upgoing tubewaves to enhance upgoing reflected events and transforming the data into two-way travel time.

From VSP Hole #2, Kantz05-8, we know that the depth of the coal seam was about 150 ft beneath the surface. Using the calculated average (rock) velocity of 8,000 ft/s, the coal seam reflection is expected to have a two-way arrival time of approximately 37.5 ms. Examining the processed VSP data sets of **Figures 40 and 45**, it is apparent there are disturbances in the both data sets at about 37.5 ms, as indicated by the red arrows. The disturbance is more pronounced in **Figure 40** than in **Figure 45**, indicating that the seismic energy beam from the 50-ft SE source offset might be focusing on a larger surface area with more voids than from the 150-ft SE source offset data. However, I believe the data sets still contain some residual tubewave noise as their respective velocity contrasts was not large enough to cleanly separate them.

Processing results of the VSP data sets with the 100-ft and 200-ft source offset locations were extremely difficult and not presented in detail in this report because picking first breaks were less objective and residual tubewaves were still noticeable in the final processed data.

VERIFICATION

Evidently, there was no need for verification in the surveys conducted in VSP Hole #1 as the drillhole was not within the planned 80-ft distance. On the other hand, the location of old mine works at the VSP Hole #2 site was already confirmed by drilling and hole-to-hole tomography surveys. Thus, a verification drilling program was not needed.

CONCLUSIONS

Despite what may appear to be a "partial" success in some surveys conducted in VSP Hole #2, I would be cautious with such a conclusion as I believe the data sets did not have good enough signal-to-noise ratio to objectively build my confidence level. As was illustrated in Figure 4 however, the effects of mine voids on the seismic signal was predicted to cause some type of disturbance. The signal disturbance was more pronounced in the 50-ft than the 150-ft source offset locations. The fact that we could detect a disturbance with just the 50-ft source offset indicates that the old mine works boundary is even closer to VSP Hole #2 than previously thought, as was shown in the geologic cross section in Figure 20. Thus, the mine boundary is estimated to be within 15 to 20 ft of Katnz05-8 instead of the mid-point at 50 ft. This interpretation is supported by Figure 21 in which the hole-to-hole tomography survey results showed the old mine boundary to be much closer to Kantz05-8.

The dominance of downgoing and upgoing tubewaves contaminated the data sets, making it difficult to pick first breaks. Processing all the data required more guesstimates than necessary, thus lowering some objectivity in processing.

To minimize the problem of recording tubewaves in VSP surveys, using a wall-locking geophone system is recommended. Employing such a system would require a 6-inch hole which is uncommon in coal exploration drilling. Secondly, the hardware needed to operate such a system is very expensive to acquire and deploy, as was explained in page 6. To my knowledge, such a system for mineral exploration is not available in rental pools. A company will have to incur a major capital expense to acquire such a capability, which will likely result in much higher project costs. The wall-locking geophone tool would still record tubewave energy but at lesser amplitudes as it is less sensitive to tubewaves than the hydrophone.

Lawrence M. Gochioco, PG

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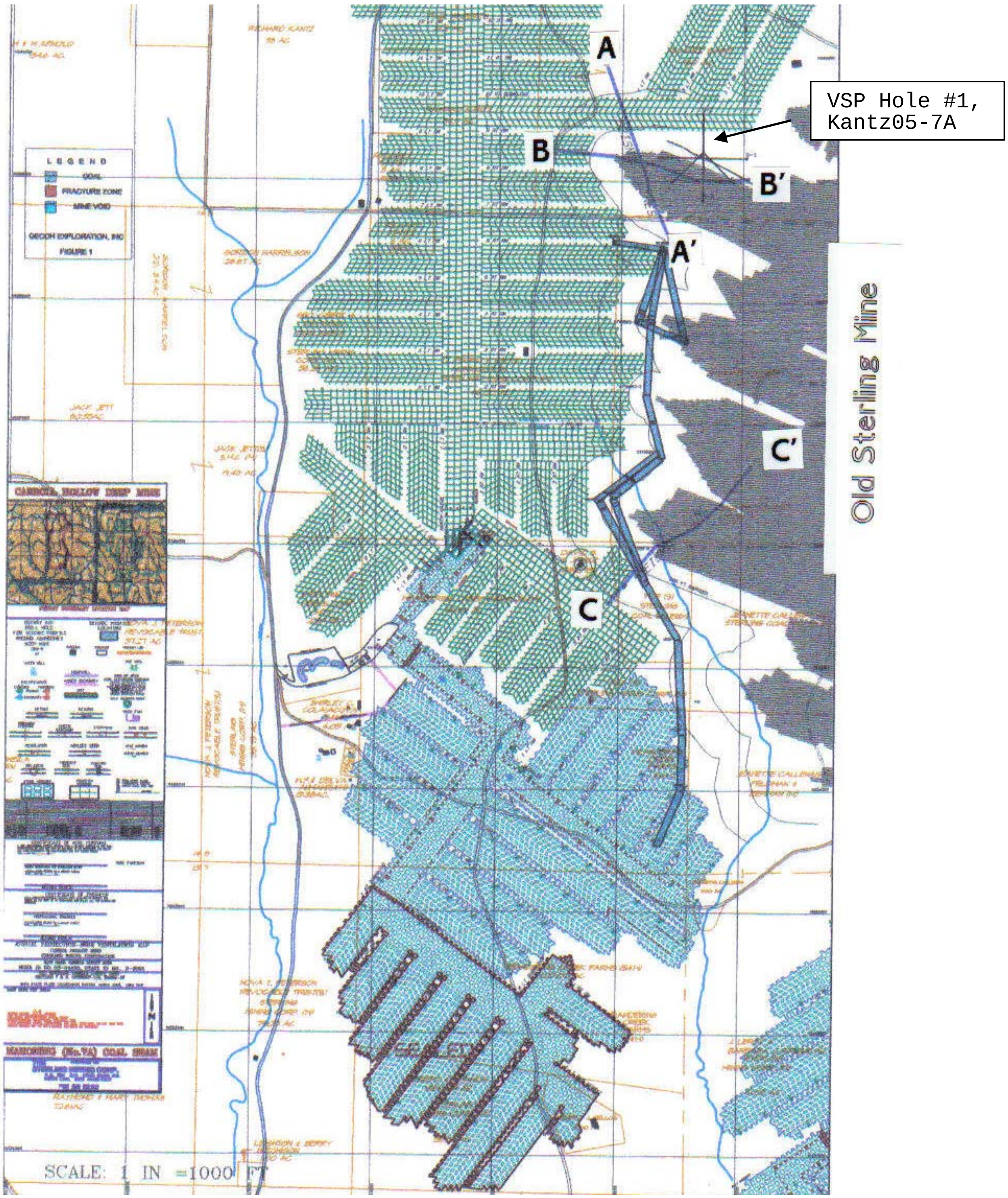

Figure 1. Map of study area showing the locations of the VSP hole #1 with respect to the three surface seismic lines. The old Sterling Mine works, shaded dark gray) are located on the northeast section of the map.

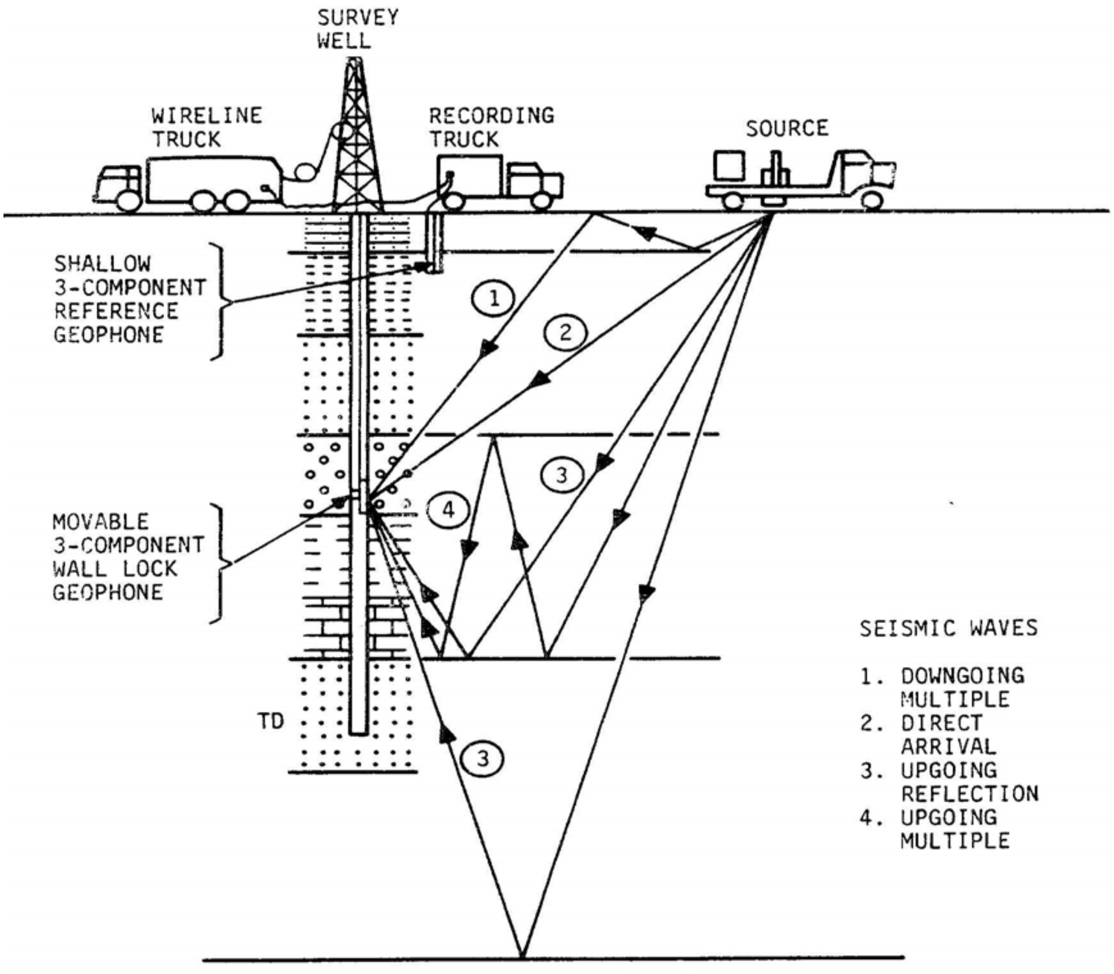

Figure 2. Schematic diagram shows the hardware resources needed to conduct an oilfield VSP survey. Raypaths of some different types of seismic data are highlighted.

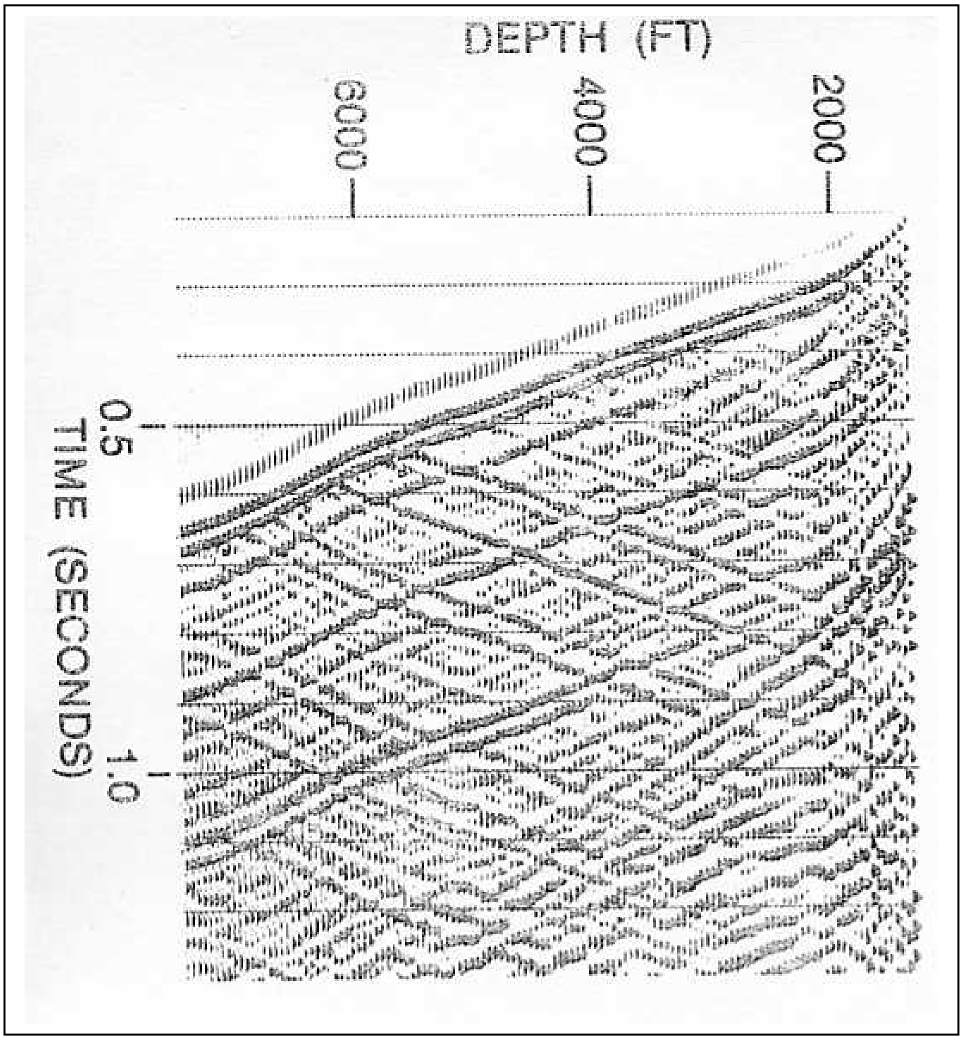

Figure 3. Sample VSP data applied to oil and gas exploration. The horizontal depth scale displayed on top of the figure indicates the receiver depth interval that ranged from 1500 to 7800 ft beneath the surface. The vertical scale is time.

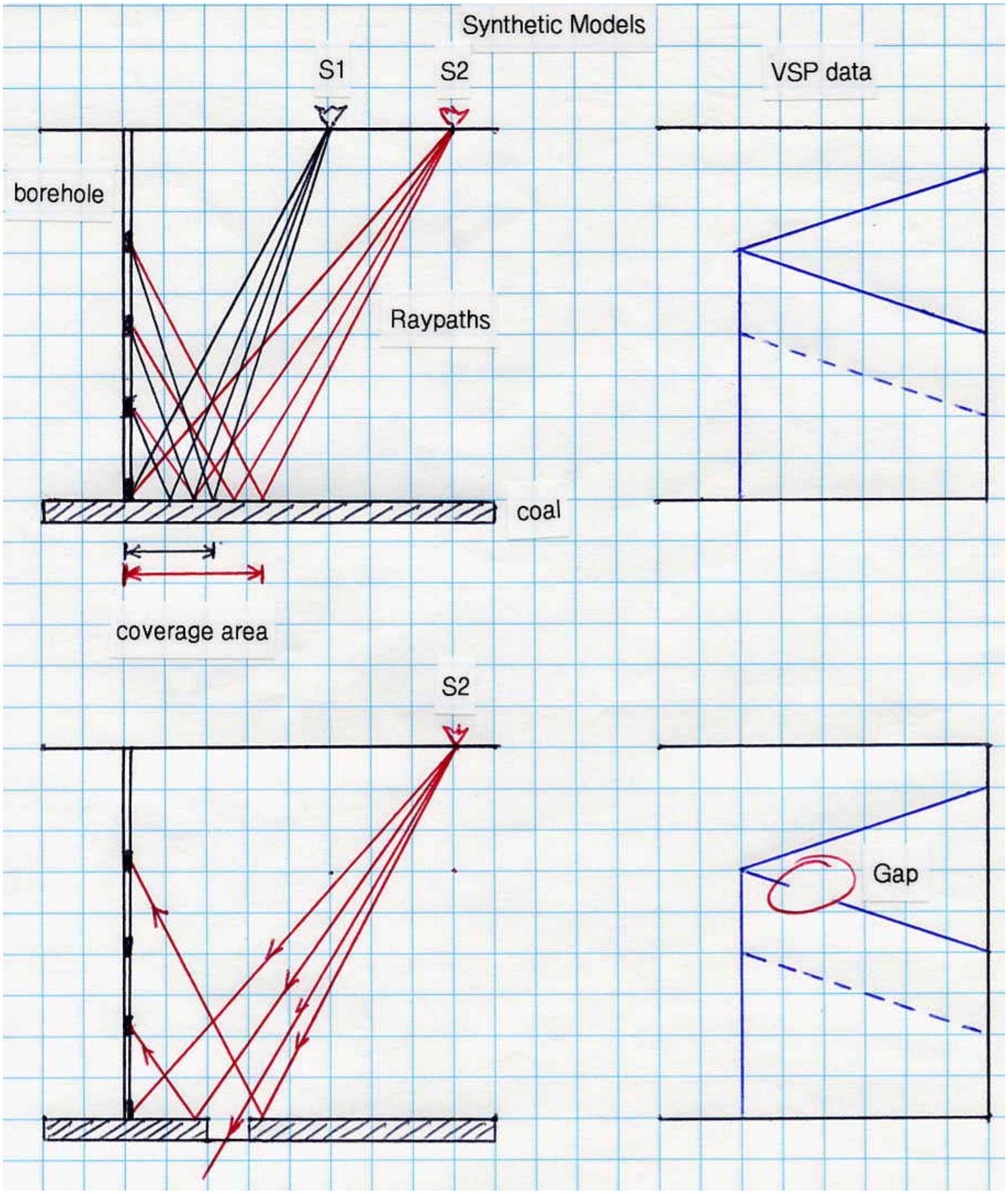

Figure 4. Schematic diagrams show how the VSP technique could be used to detect mine voids.

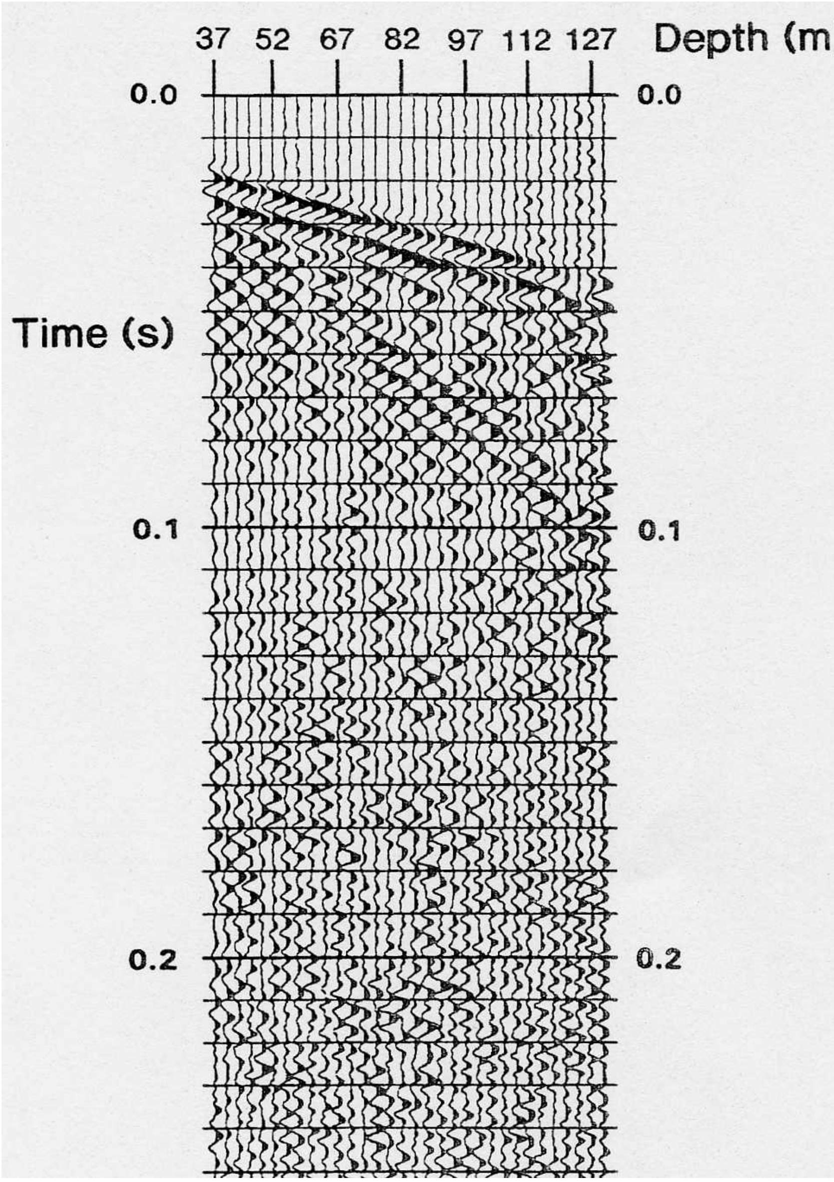

Figure 5. Raw coal VSP data recorded in the Central Appalachian coal basin show good data quality (Gochioco, 1998 - circa 1990). A wall-locking geophone tool was used as the receiver and an 8-gauge seisgun was used as the source.

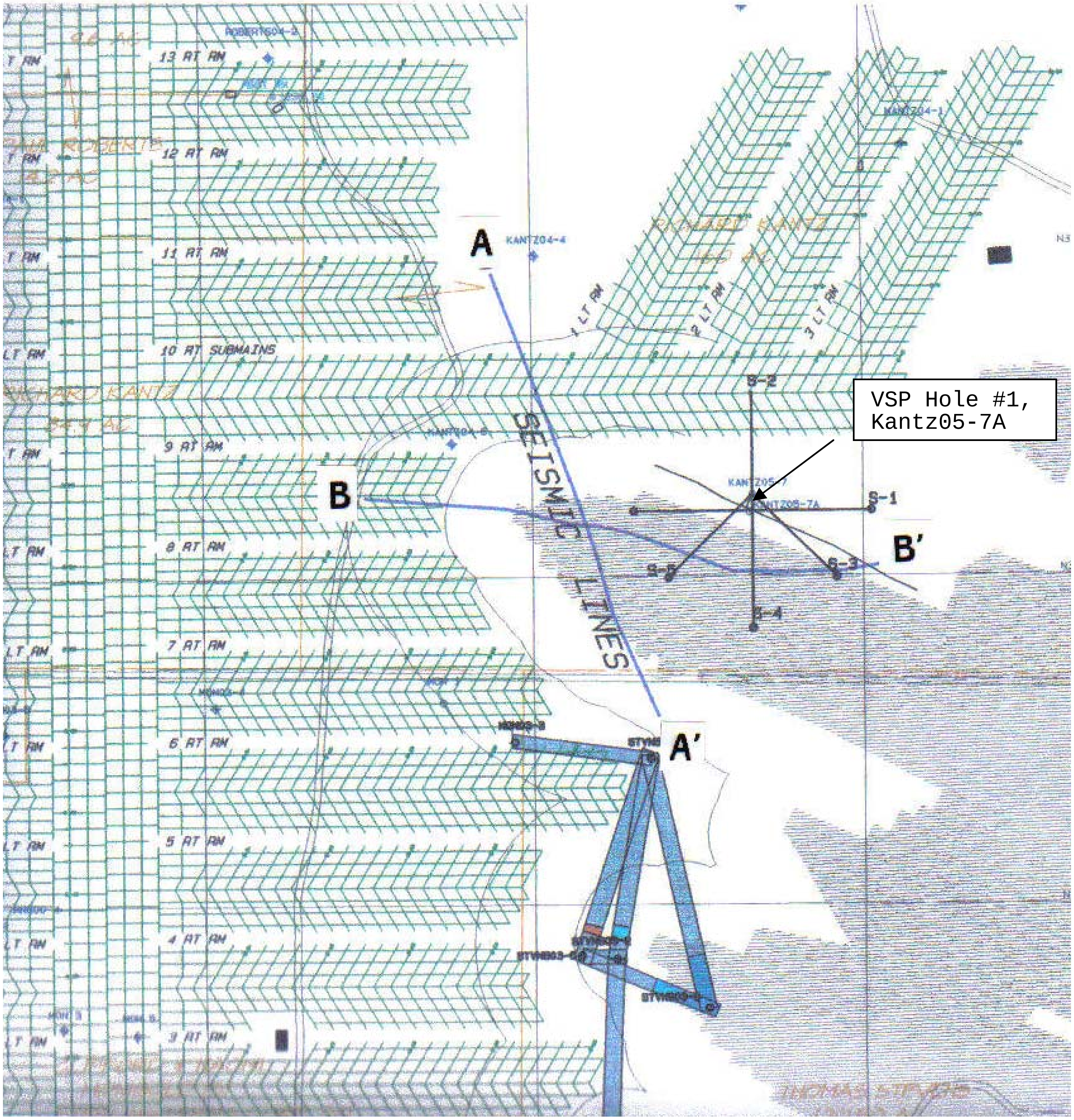

Figure 6. Expanded scale of study area highlighting the locations of VSP Hole#1 with respect to the surface seismic Lines 2B and 3A and the old Sterling Mine works (dark shaded). The blue-shaded arrowhead-like diagram is associated with past hole-to-hole tomography surveys conducted by the coal company.

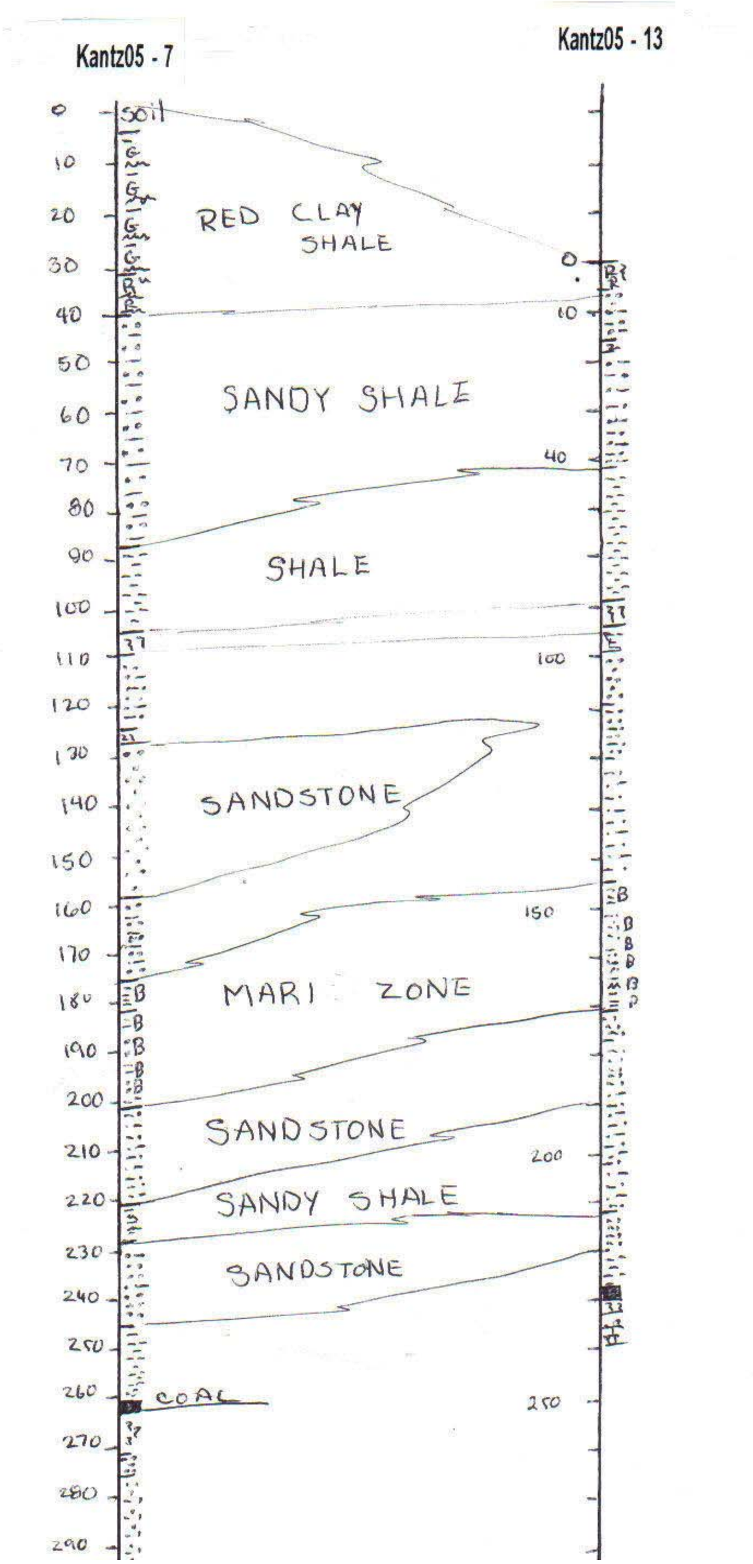

Figure 7. Geologic cross section of Kantz05-7 and Kantz05-13. Drillhole Kantz05-13 is located about 330 ft southwest of VSP Hole #1 and near the end of seismic Line 2B. The depth to the top of the coal seam in VSP Hole #1 is about 261 ft beneath the surface.

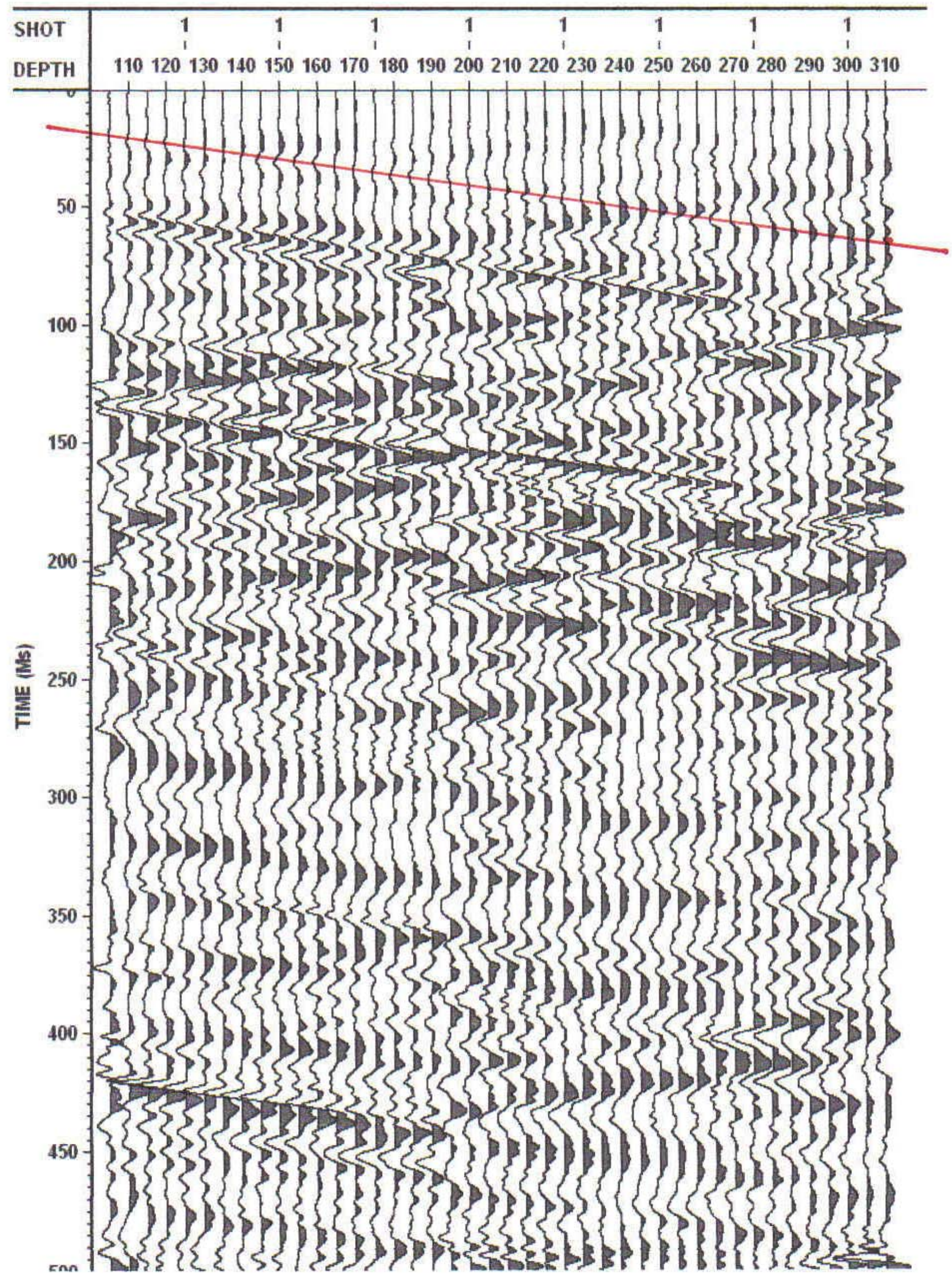

Figure 8. Raw VSP data from source location S-1.

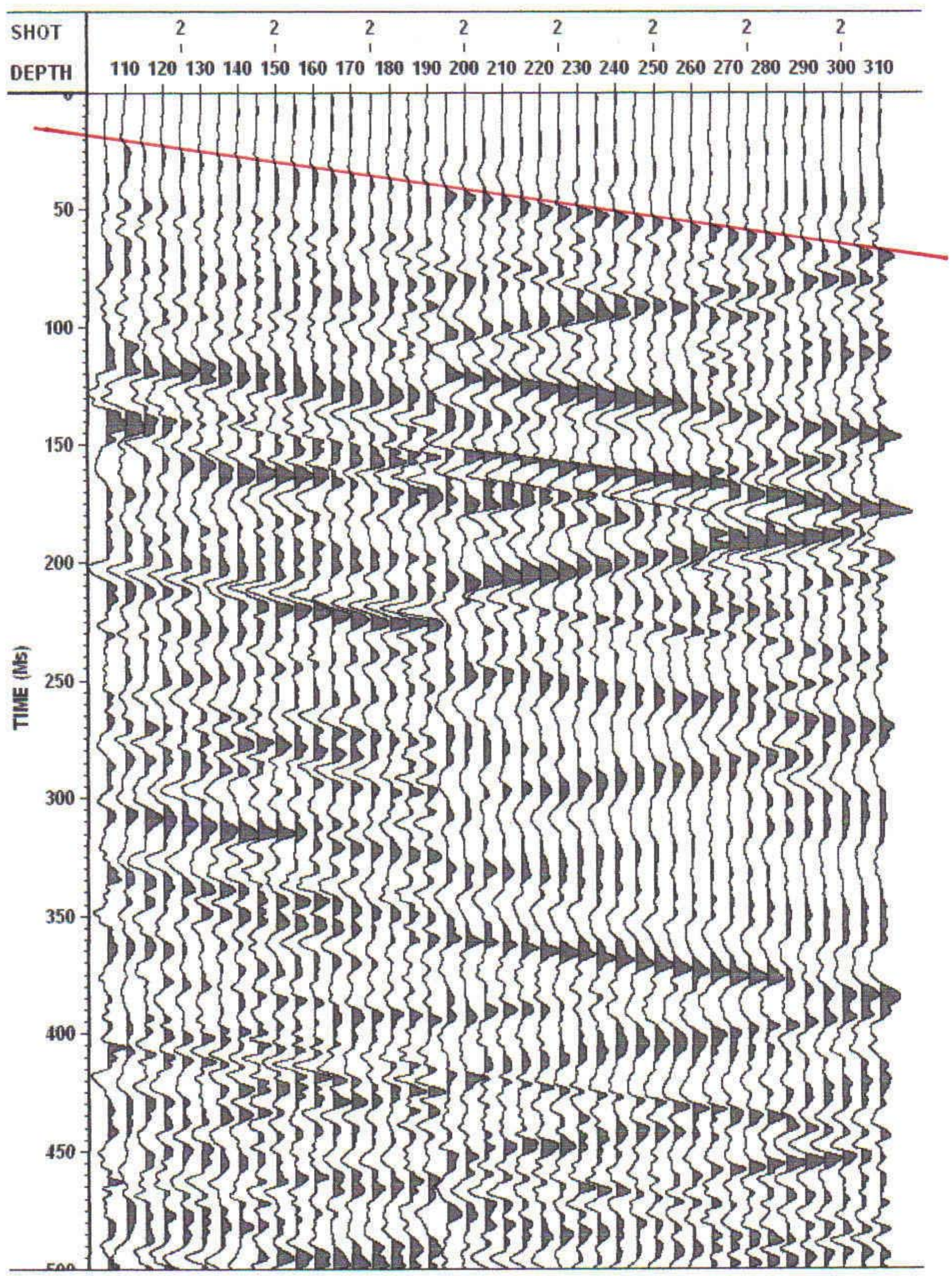

Figure 9. Raw VSP data from source location S-2.

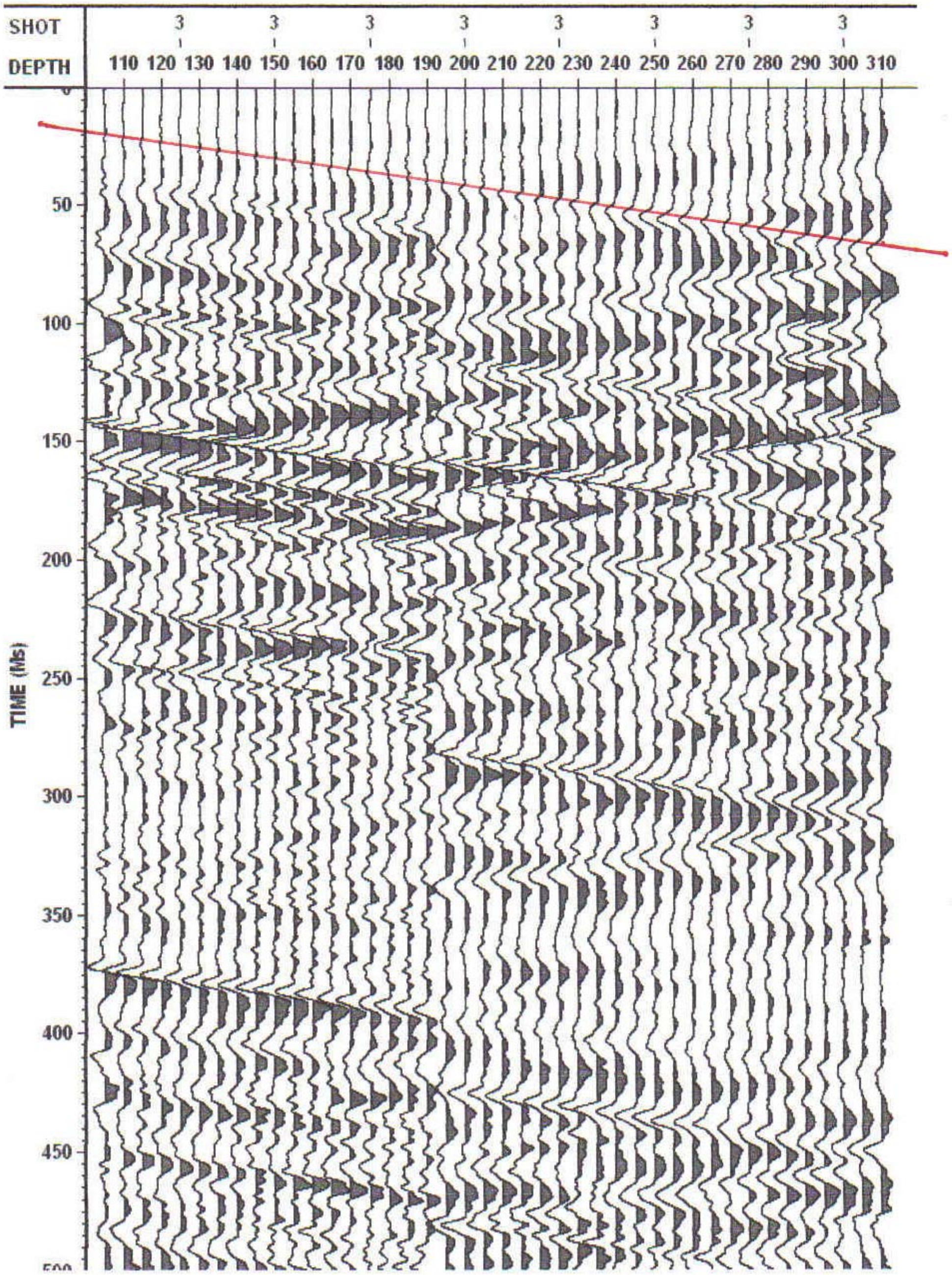

Figure 10. Raw VSP data from source location S-3.

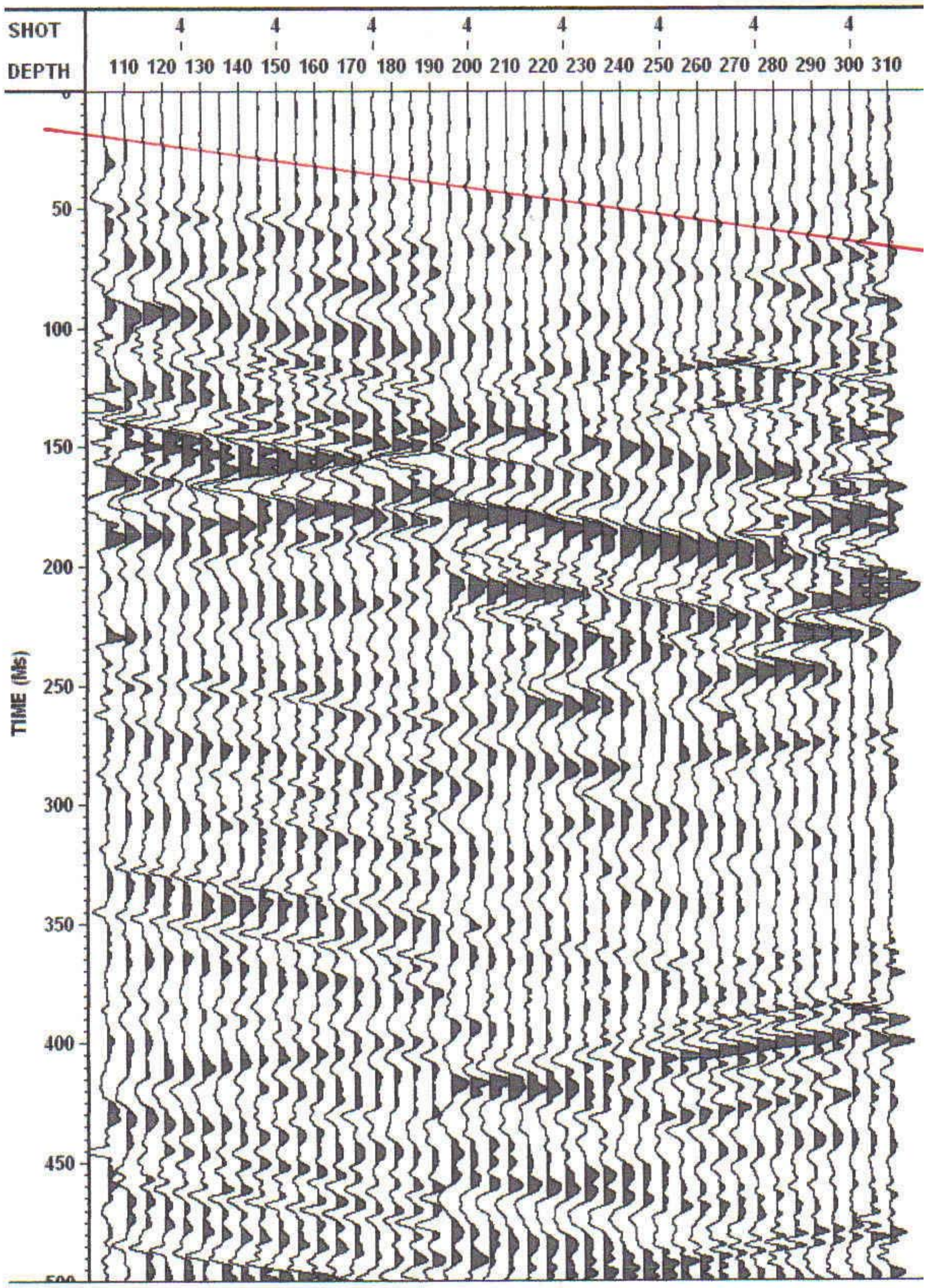

Figure 11. Raw VSP data from source location S-4.

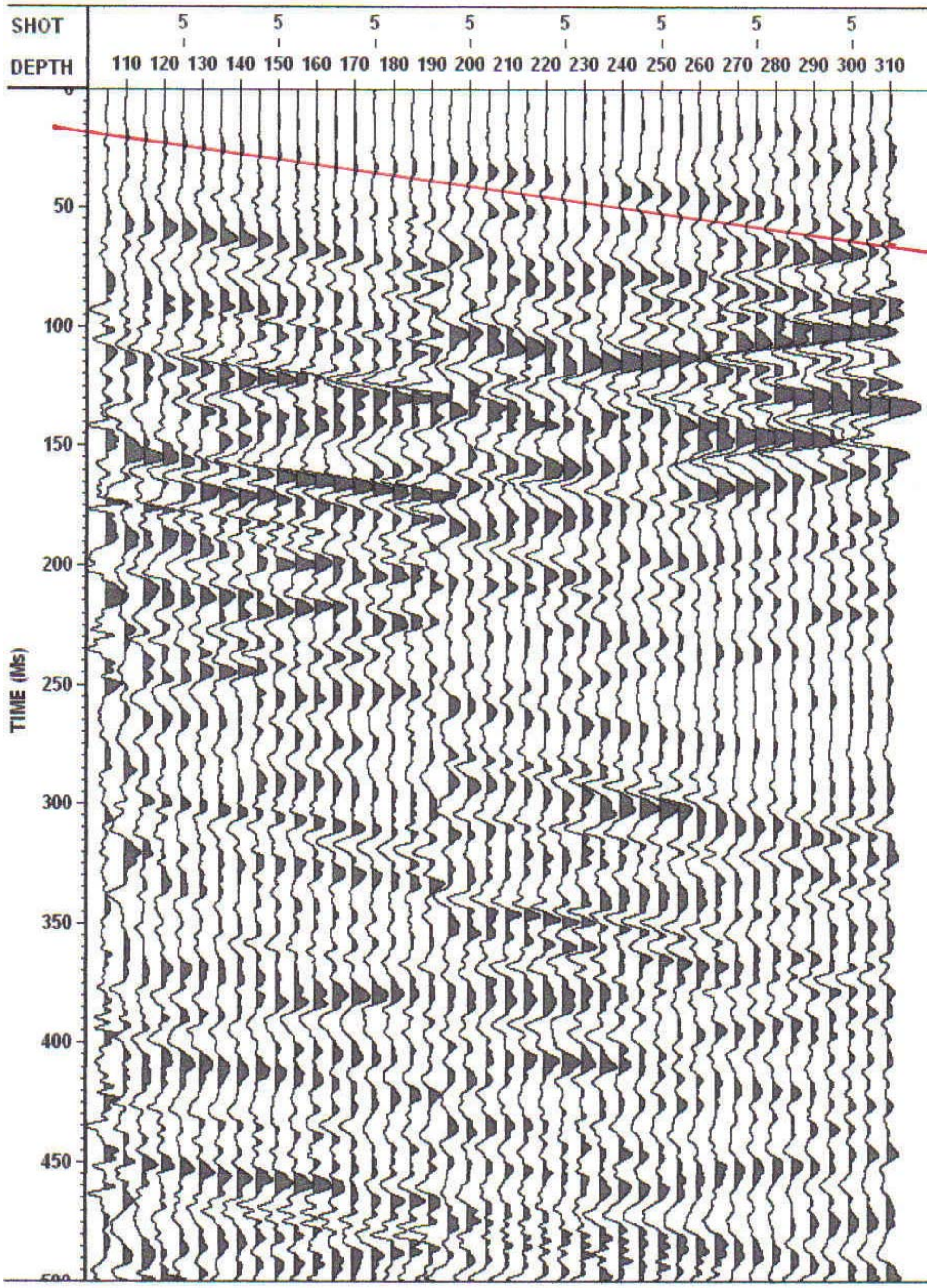

Figure 12. Raw VSP data from source location S-5.

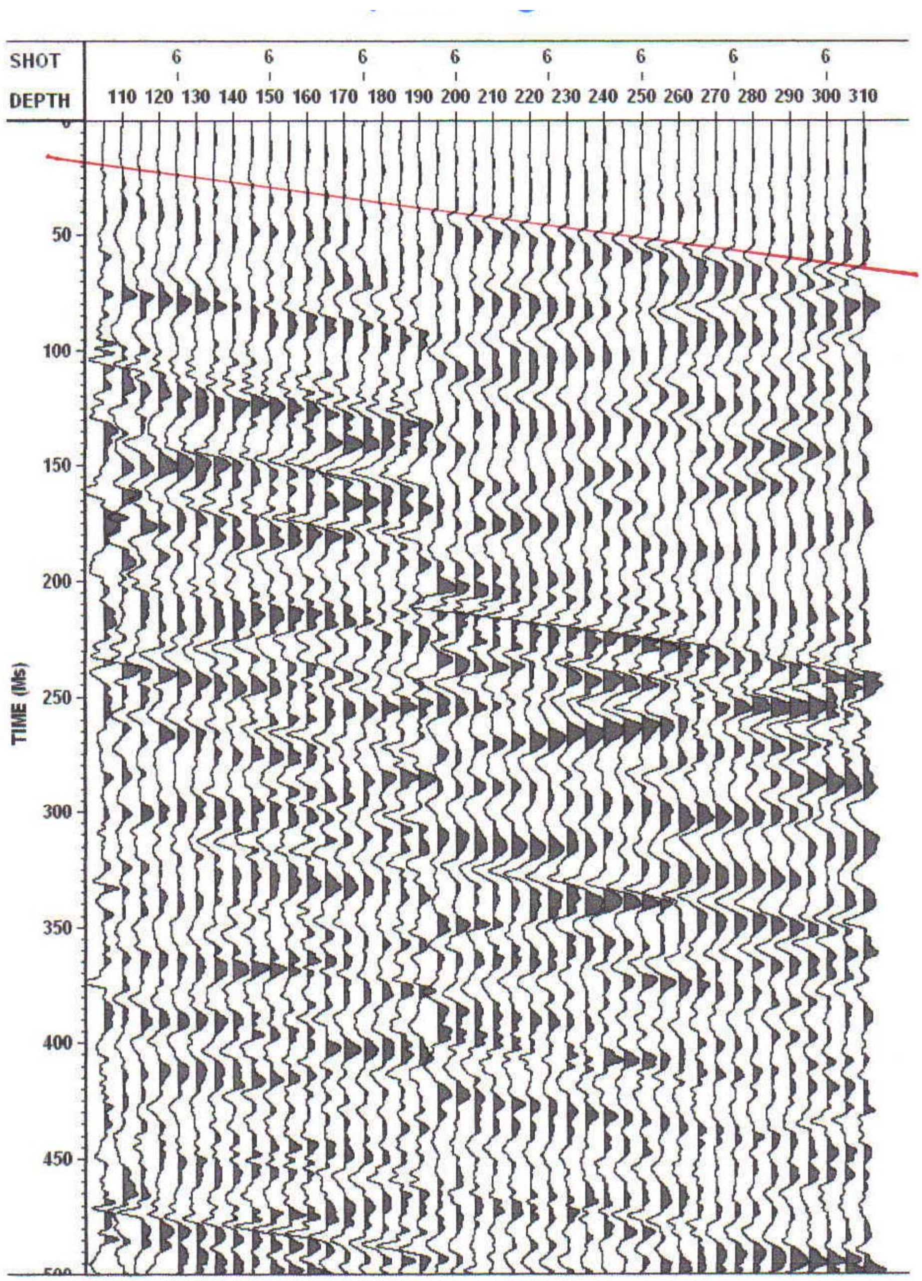

Figure 13. Raw VSP data from source location S-6.

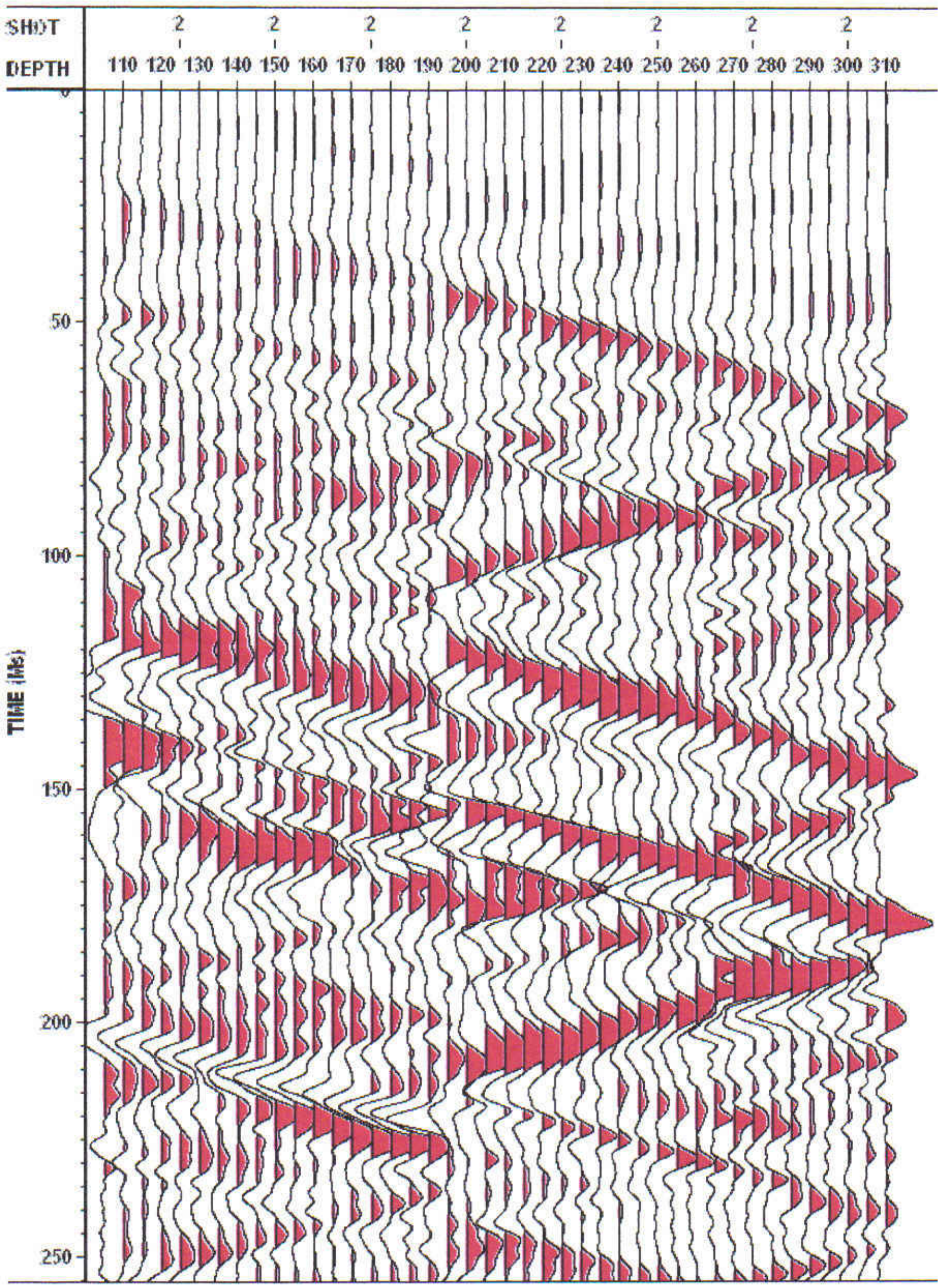

Figure 14. Expanded scale of raw VSP data from source location S-2.

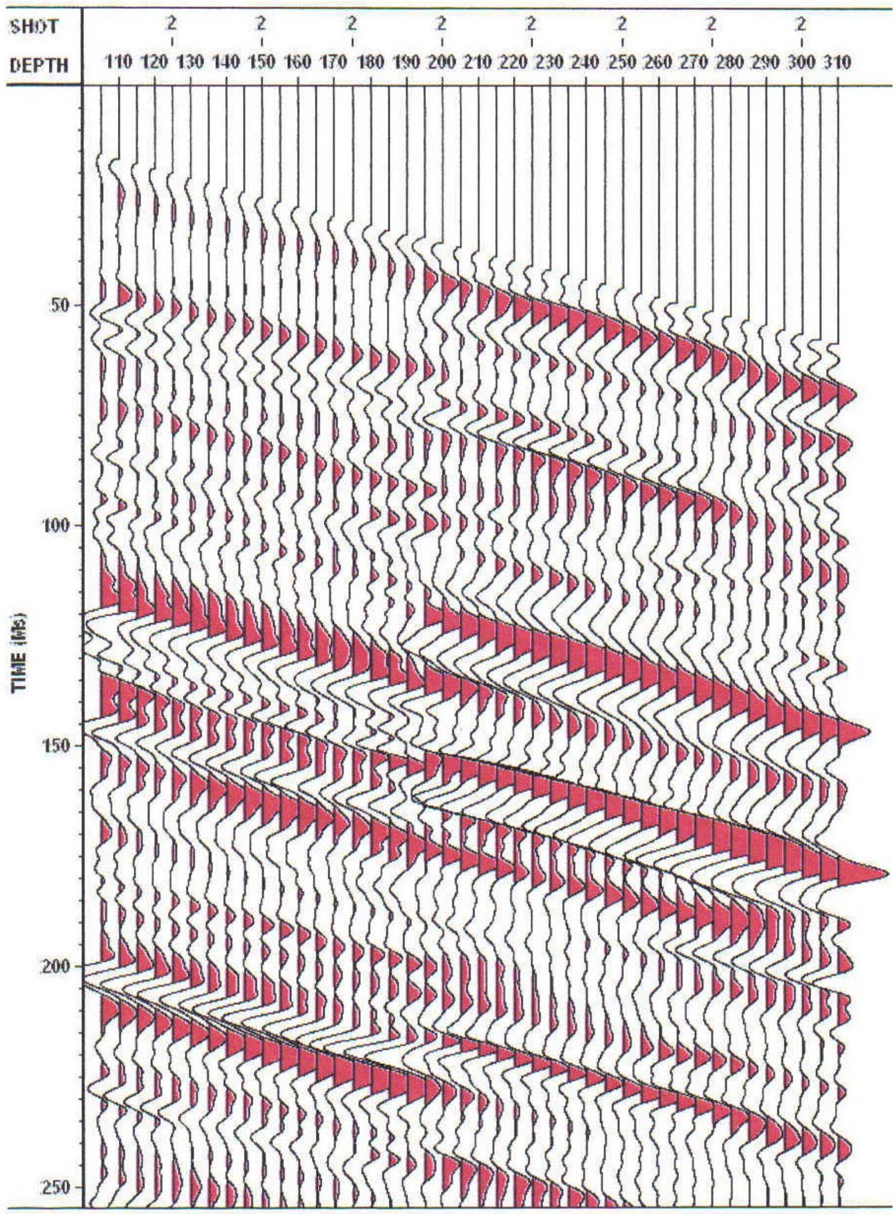

Figure 15. All upgoing waves had been attenuated to highlight downgoing waves from the S-2 source location.

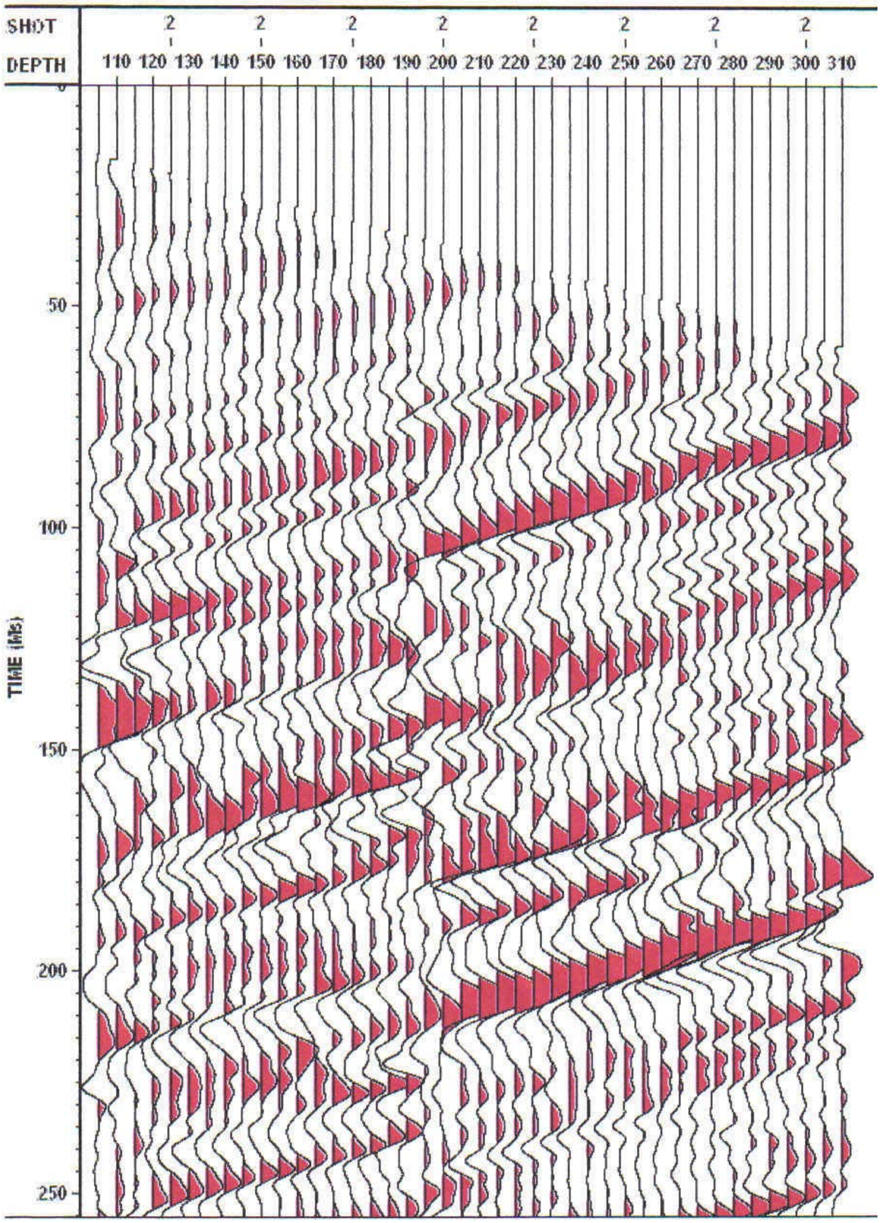

Figure 16. All downgoing waves had been attenuated to highlight upgoing waves from the S-2 source location.

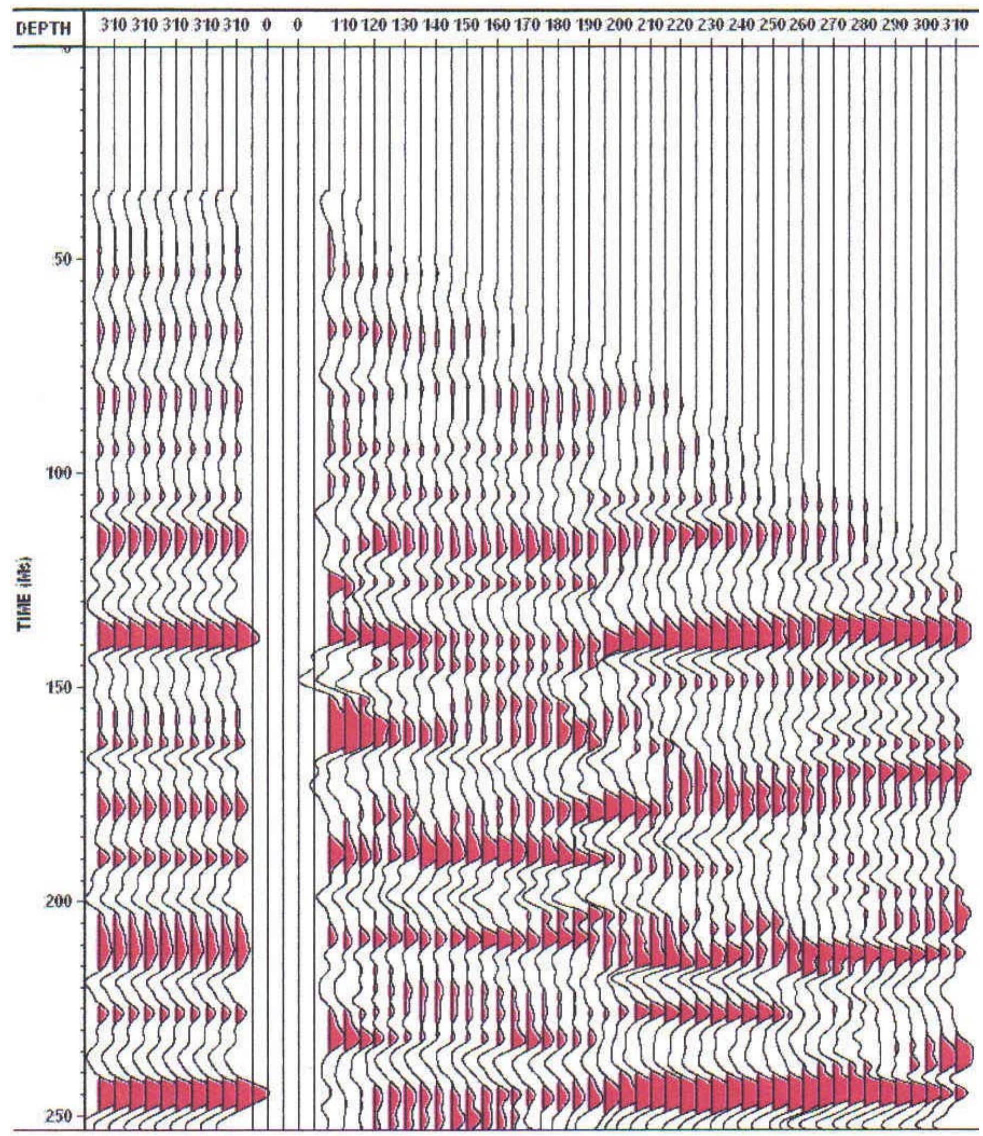

Figure 17. VSP seismogram (left) and data transformed into two-way travel time (right) from the S-2 source location.

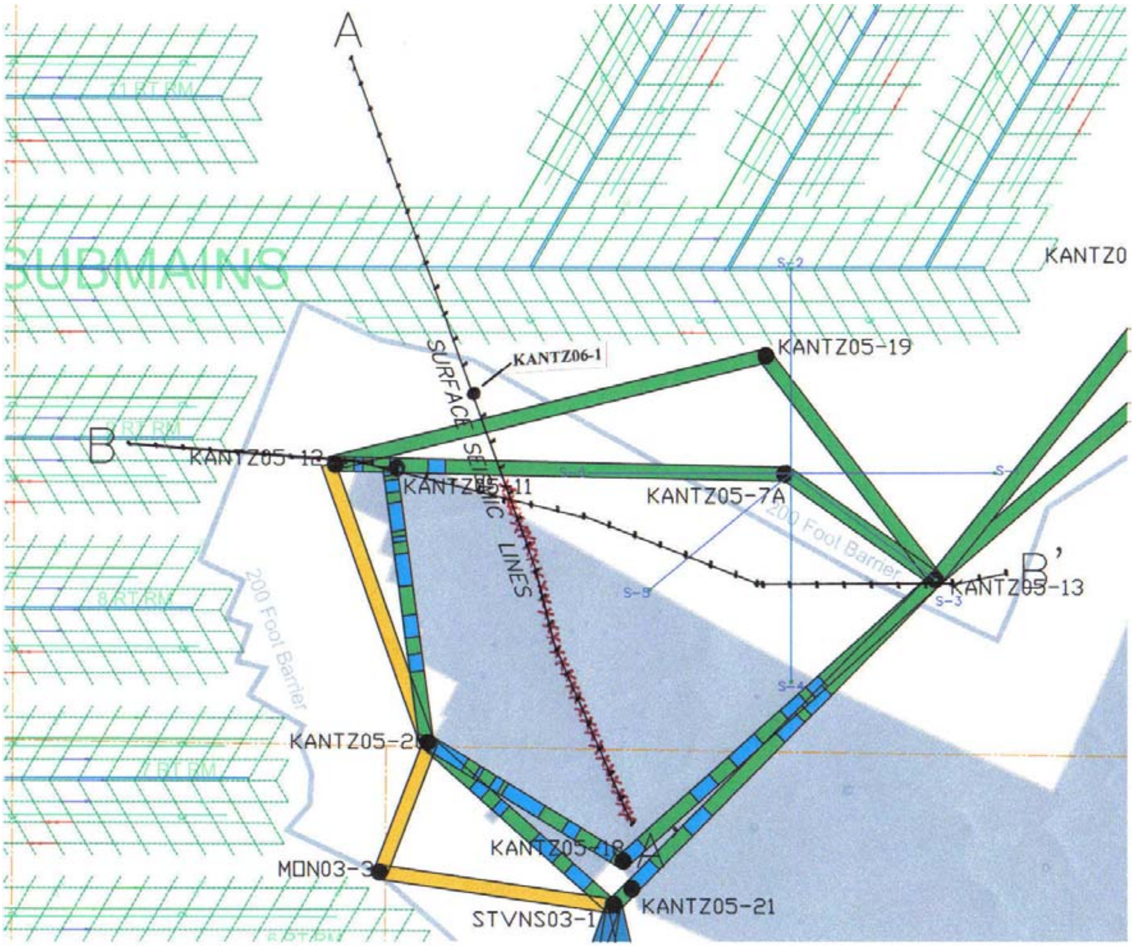

Figure 18. Surface seismic data and hole-to-hole tomograms correlated and showed the extent of the old mine works at this location to be smaller in scale. Hole Kantz05-7A is now about 250 ft away instead of the 80 ft. The coal company had already planned to maintain the required 200-ft barrier in future mine development.

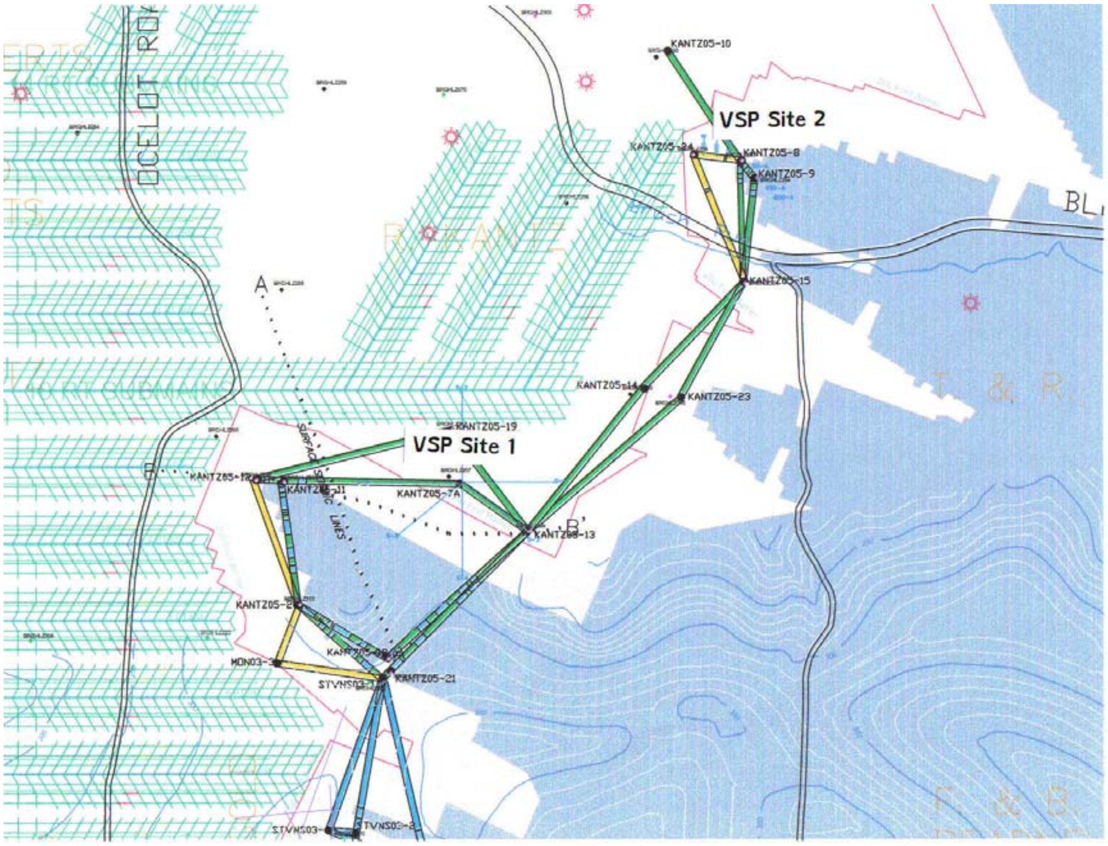

Figure 19. Map shows the location of VSP Hole #2 site with respect to the VSP Hole #1 site.

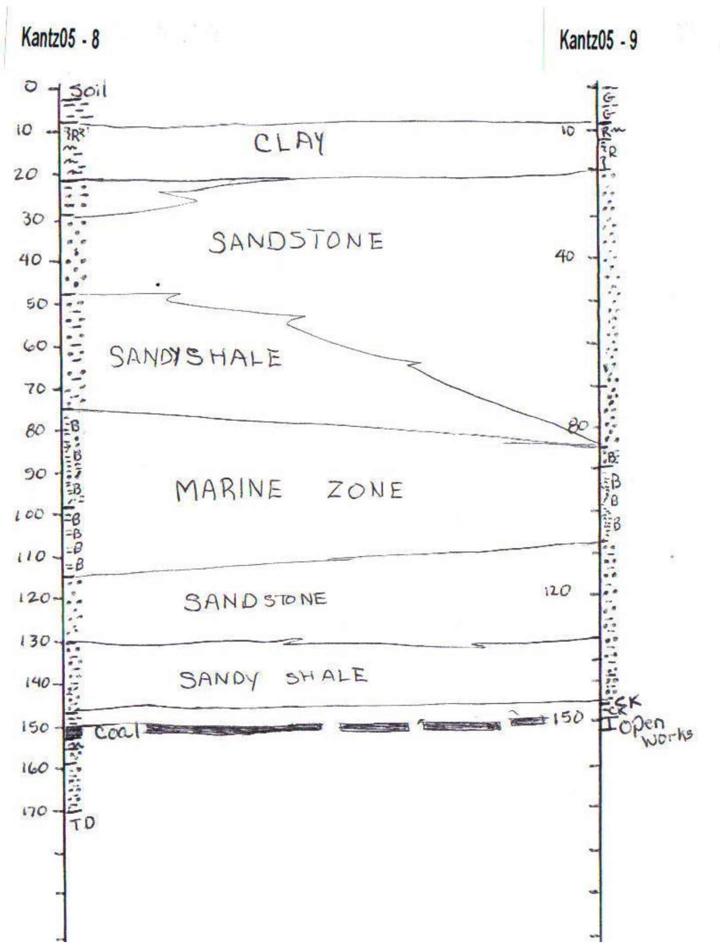

Figure 20. Geologic cross section of drillholes Kantz05-8 and Kantz05-9. Tim Miller provided his interpretation of the subsurface in which the estimated boundary of the old mine works is near the mid-point between the two holes.

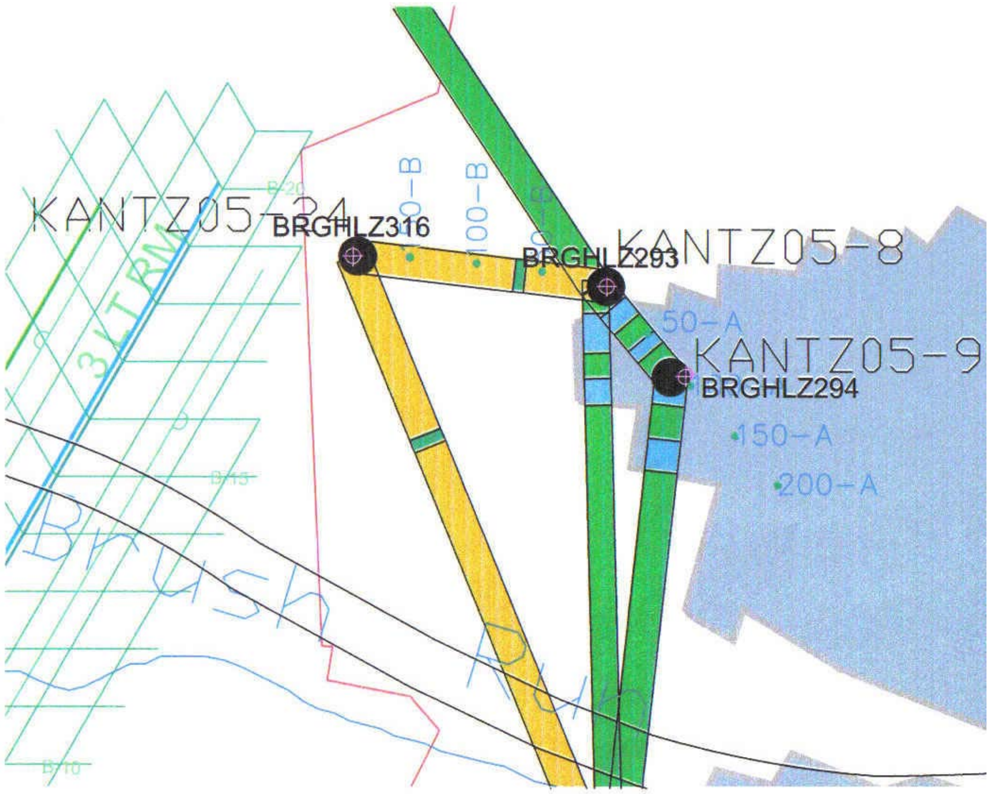

Figure 21. Expanded scale map highlighting the location of Kantz05-8 and Kantz05-9. The hydrophone string was lowered in VSP hole #2, Kantz05-8. Hole-to-hole tomography survey results conducted in 2005 verified the estimated locations of old mine works at this location. Solid green band is solid coal while blue-green band is detected old mine works.

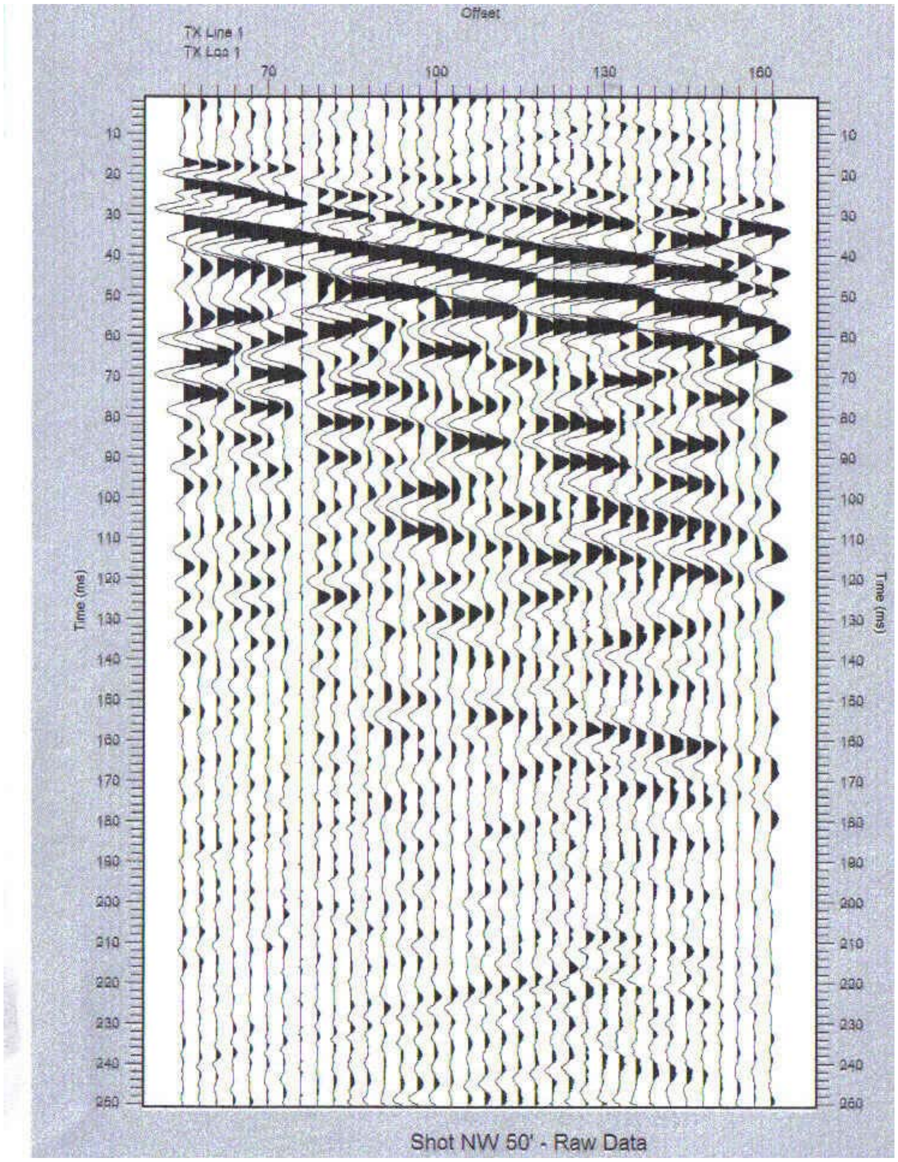

Figure 22. Raw VSP data with source offset of 50 ft NW (solid coal) of VSP hole #2.

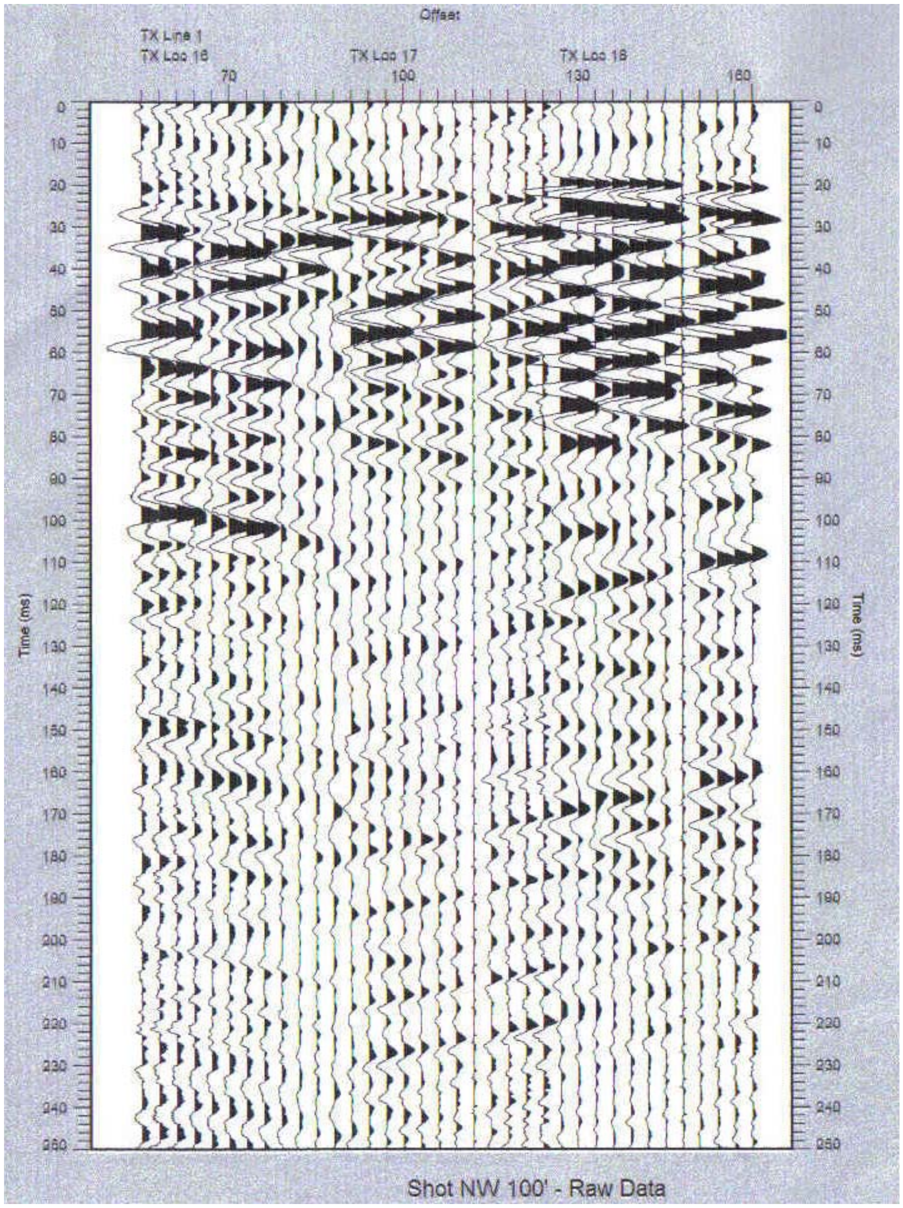

Figure 23. Raw VSP data with source offset of 100 ft NW (solid coal) of VSP hole #2.

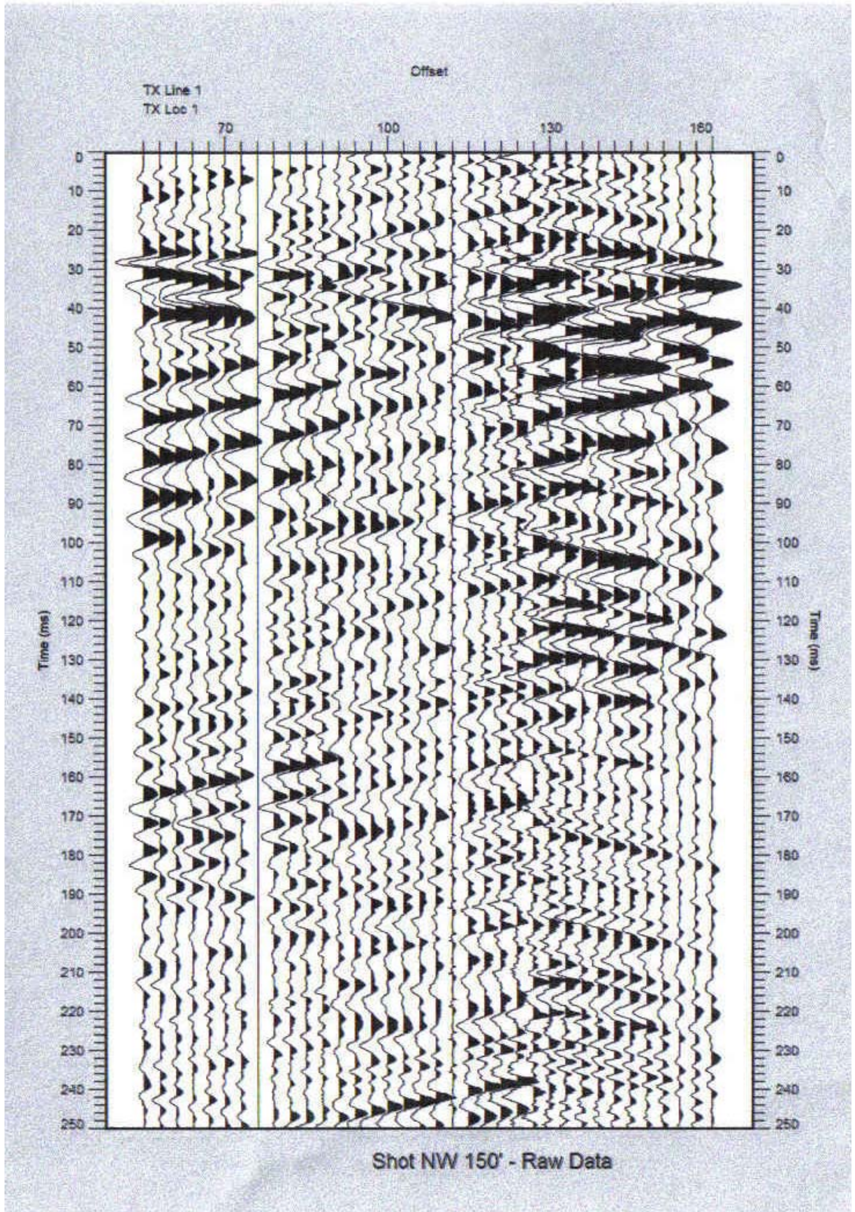

Figure 24. Raw VSP data with source offset of 150 ft NW (solid coal) of VSP hole#2.

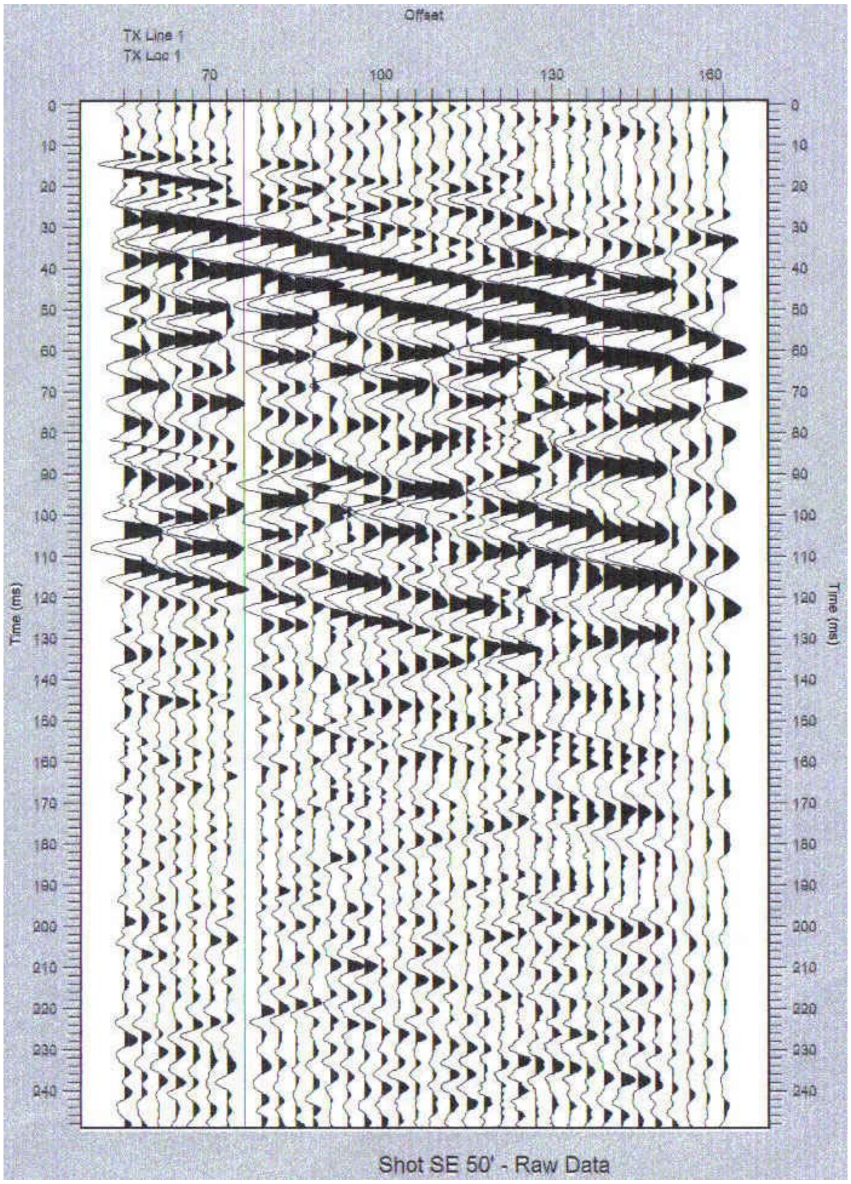

Figure 25. Raw VSP data with source offset of 50 ft SE (towards mine works) of VSP hole#2.

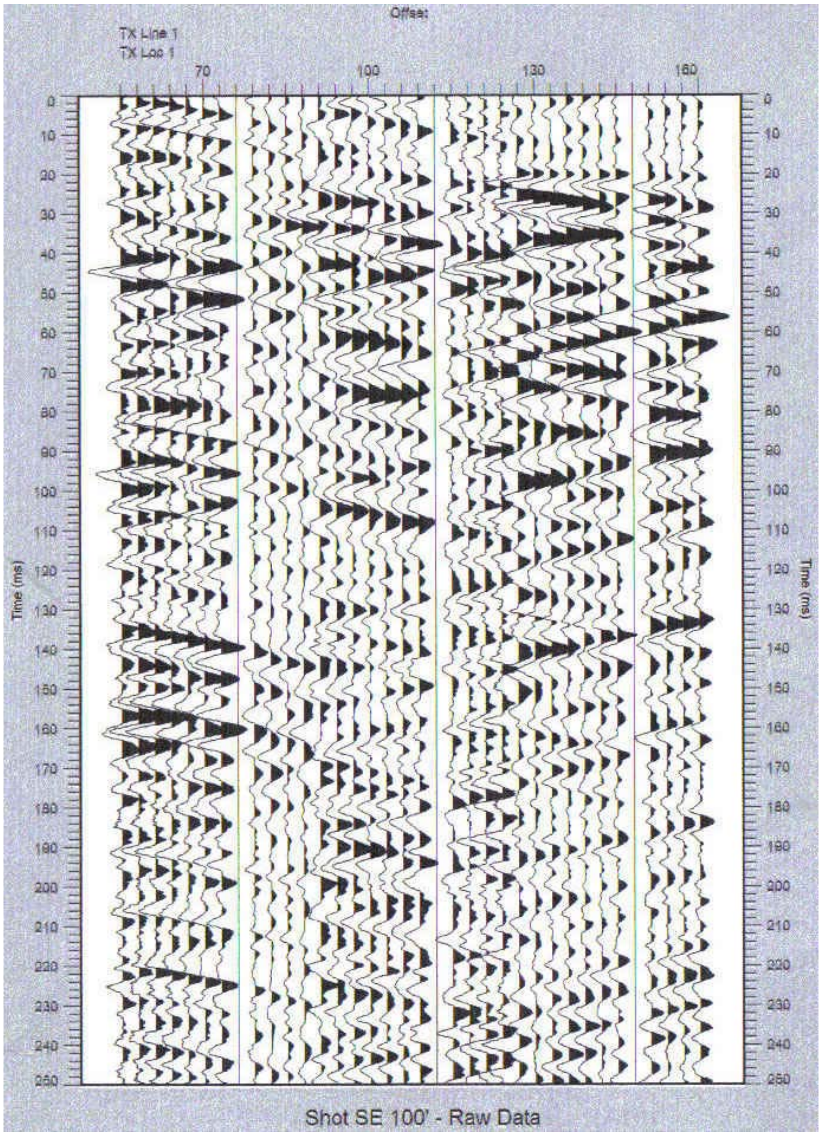

Figure 26. Raw VSP data with source offset of 100 ft SE (towards mine works) of VSP hole#2.

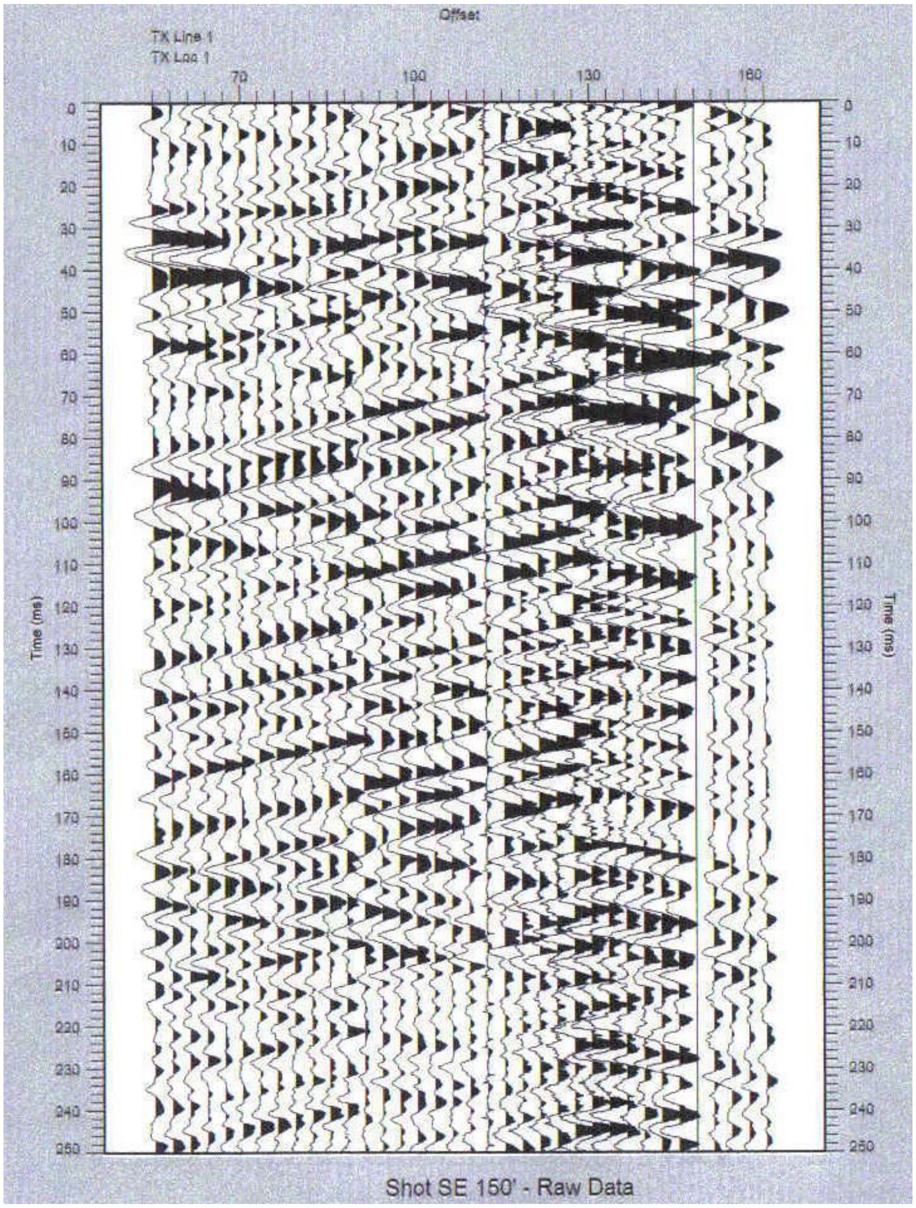

Figure 27. Raw VSP data with source offset of 150 ft SE (towards mine works) of VSP hole#2.

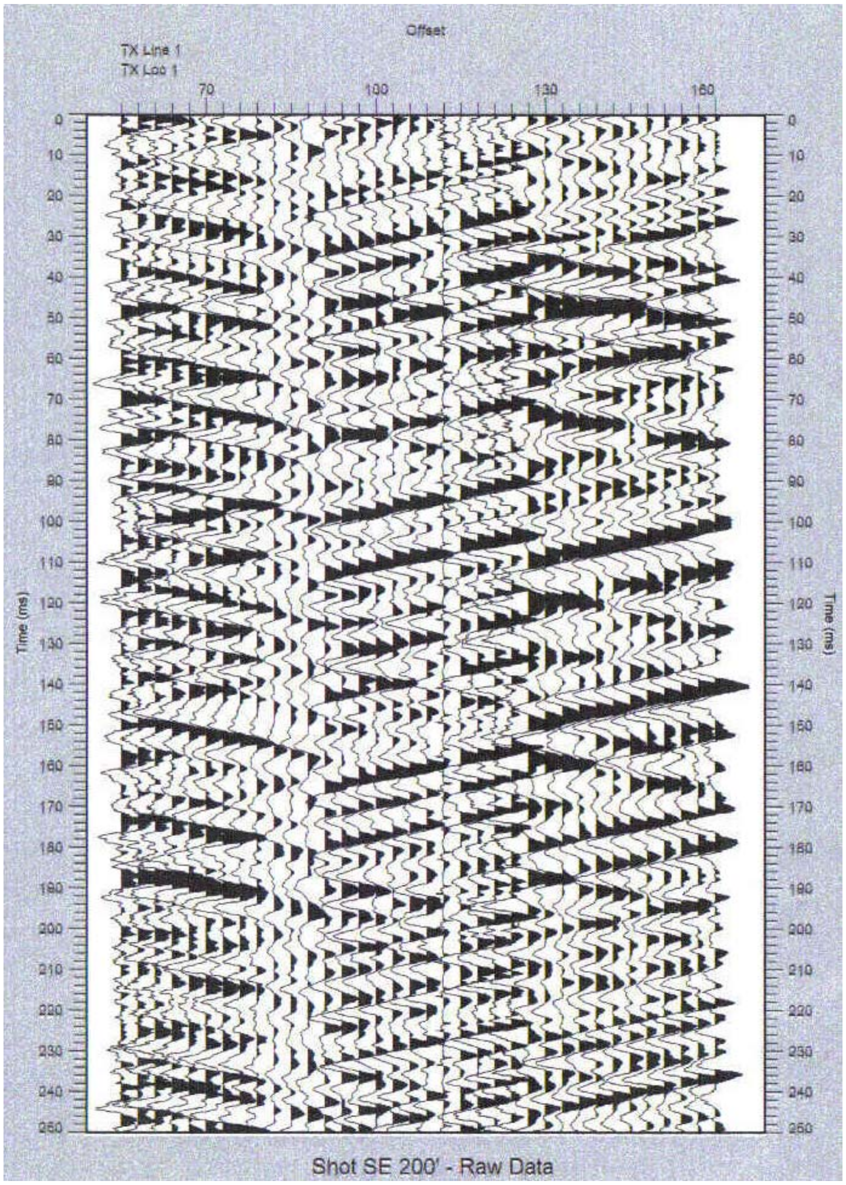

Figure 28. Raw VSP data with source offset of 200 ft SE (over old mine works) of VSP Hole #2.

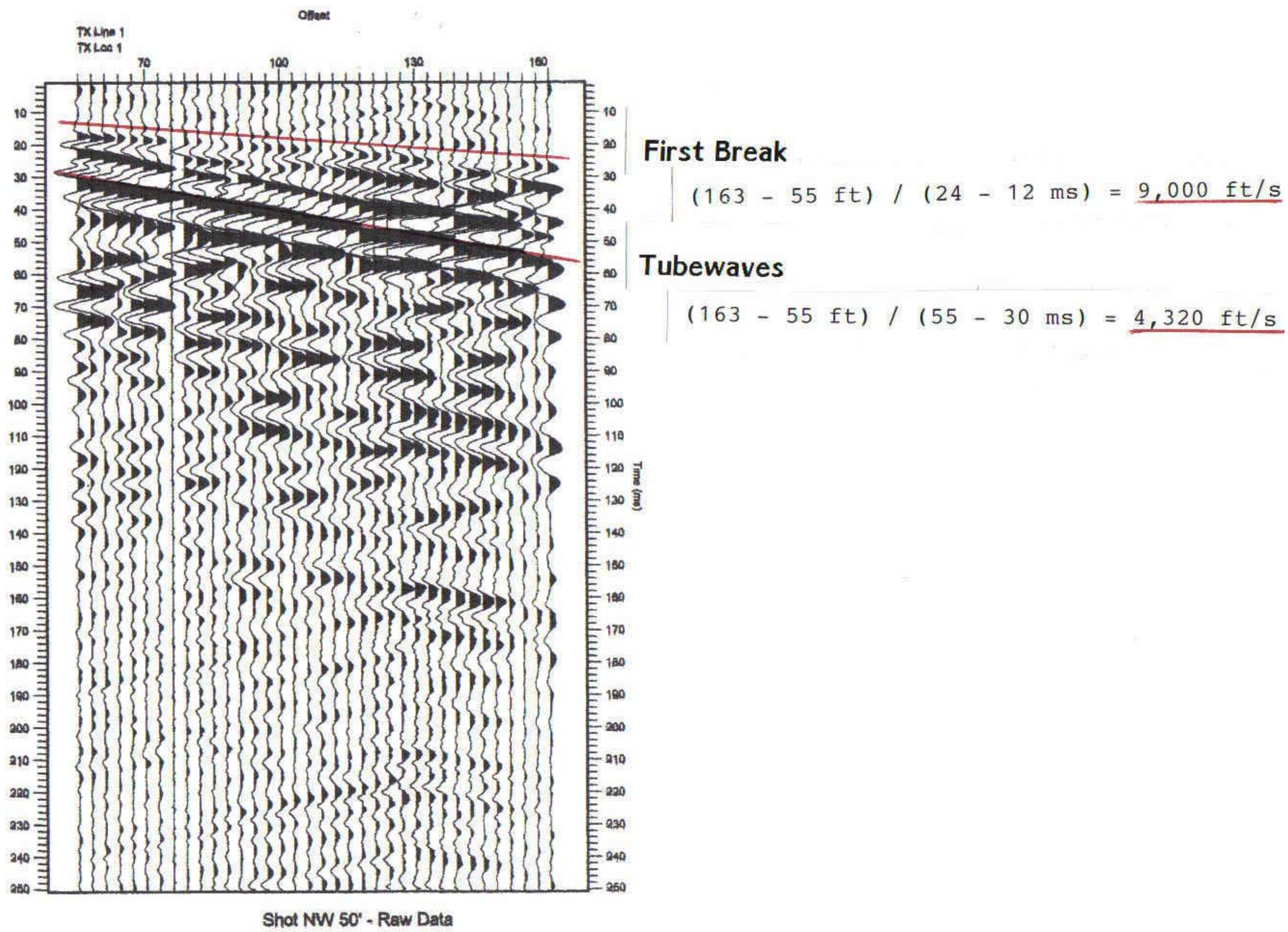

Figure 29. Raw VSP data of 50-ft source offset (NW direction) with interpreted and calculated velocities of the first breaks and tubewaves.

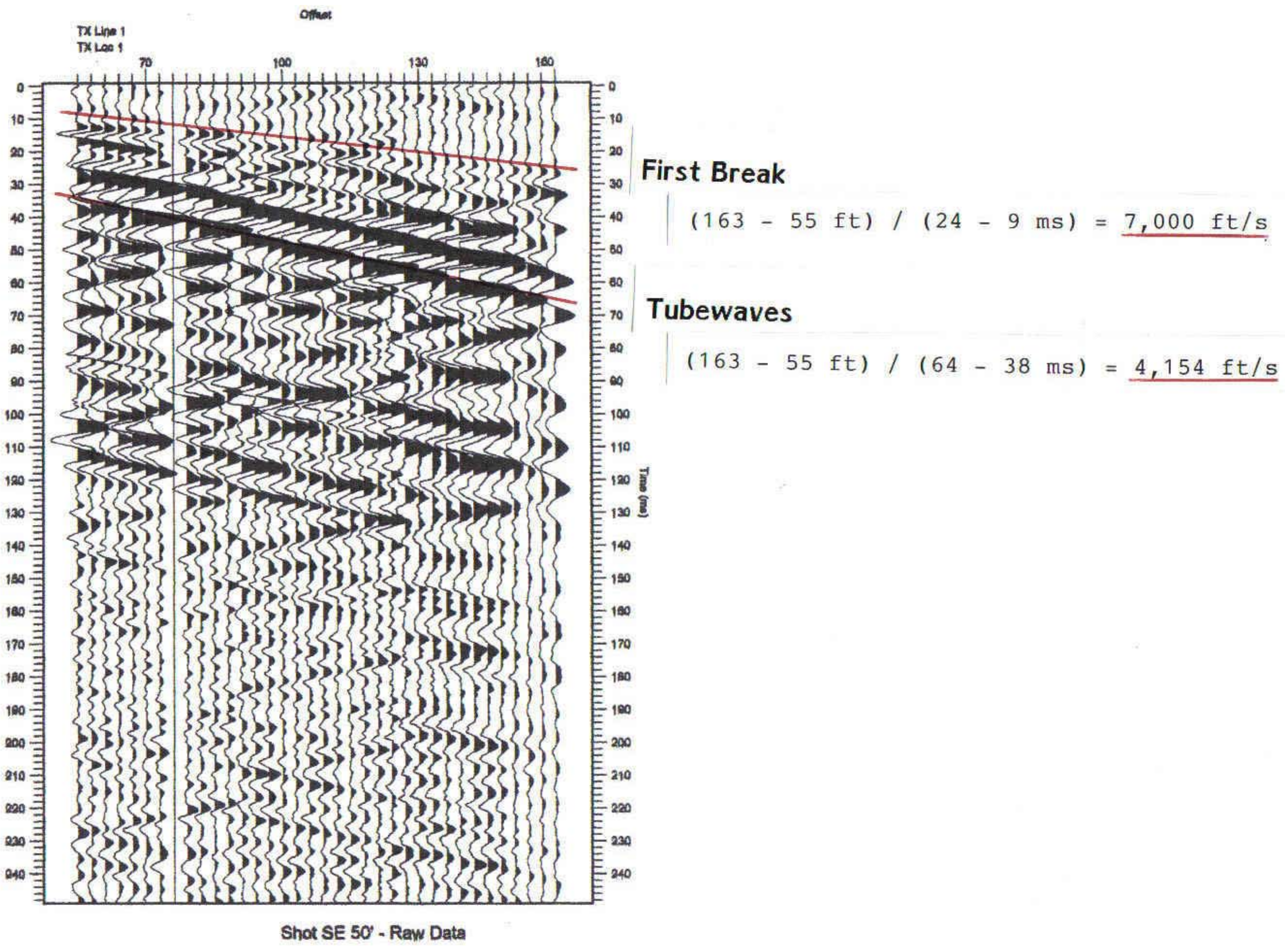

Figure 30. Raw VSP data of 50-ft source offset (SE direction) with interpreted and calculated velocities of the first breaks and tubewaves.

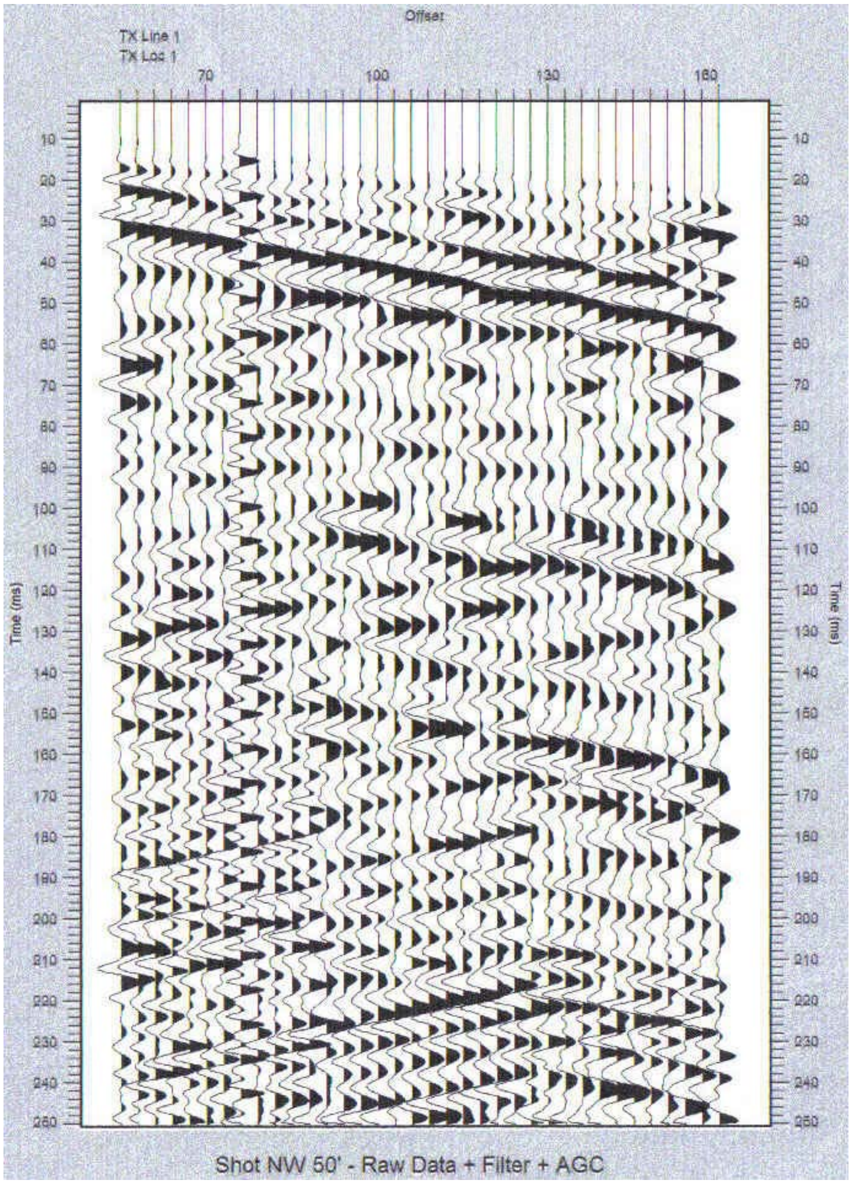

Figure 31. VSP data with 50-ft source offset (NW direction) after bandpass filter and AGC were applied.

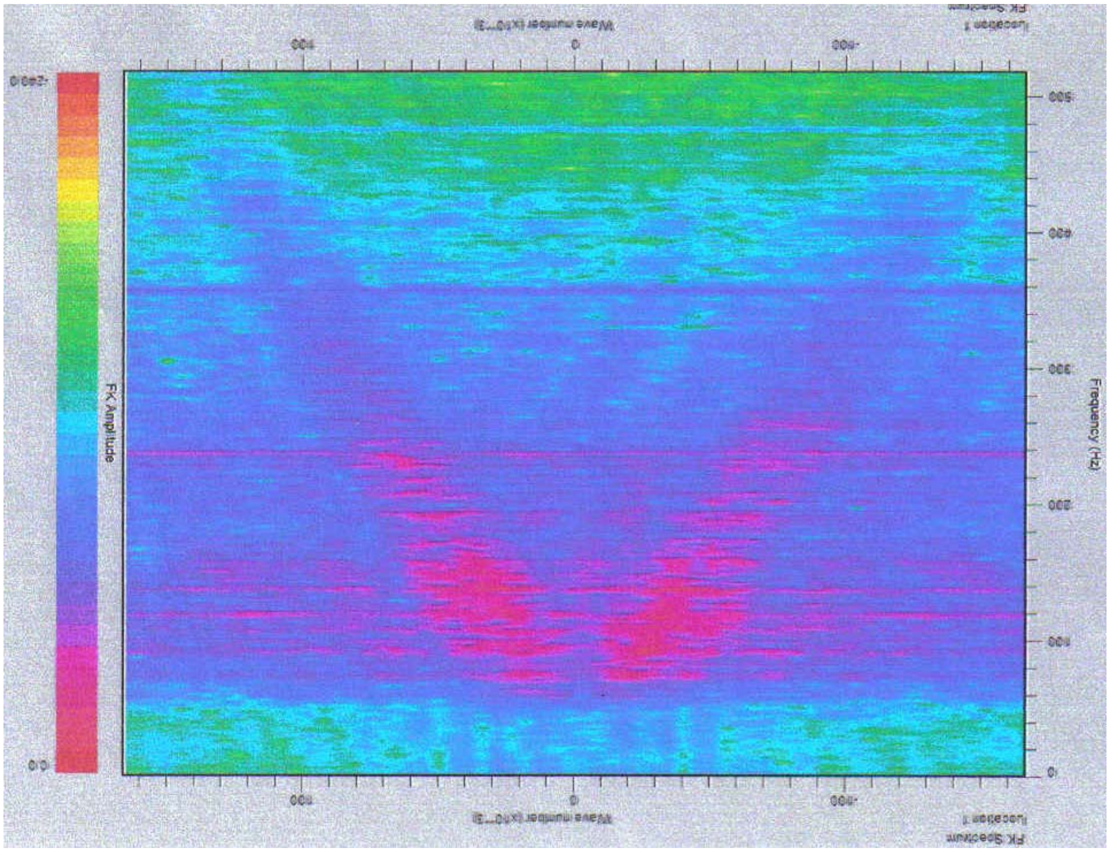

Figure 32. FK-plot of Figure 31 showing the seismic energy distribution of the upgoing (left) and downgoing (right) waves.

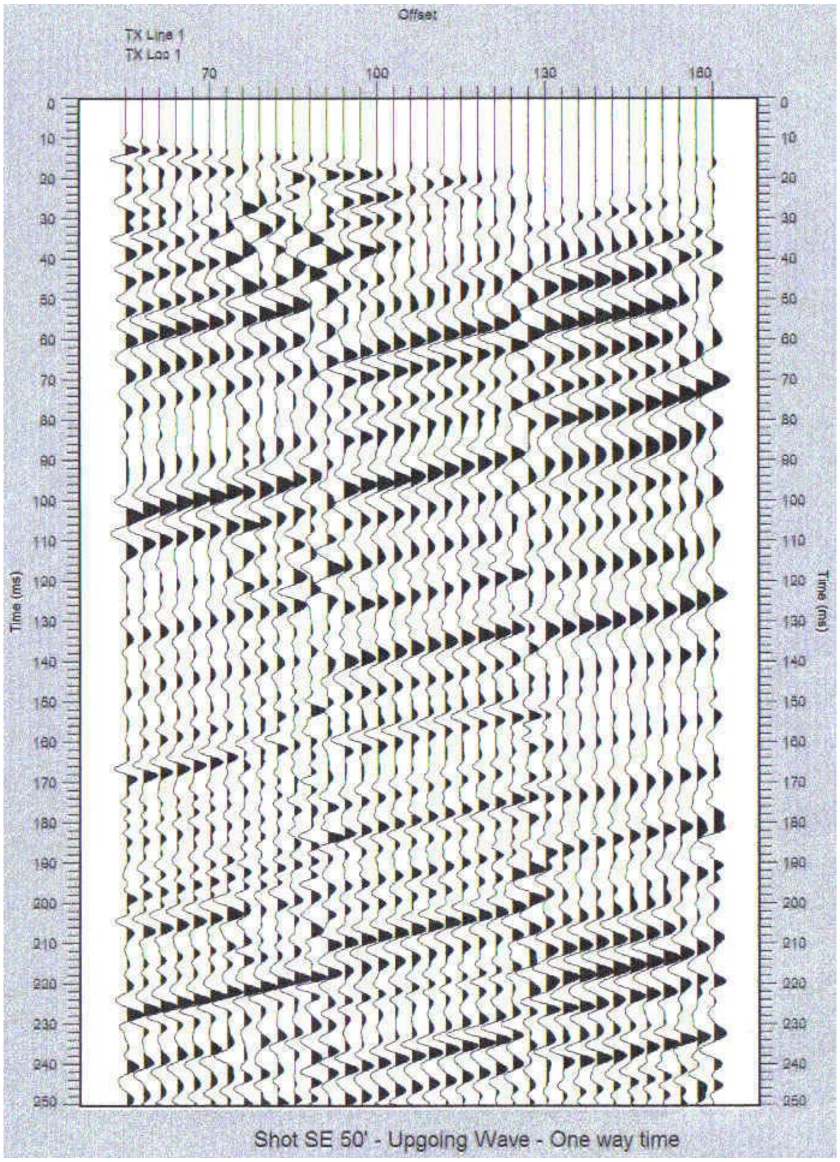

Figure 33. VSP data with 50-ft source offset (NW direction) after attenuating the downgoing waves.

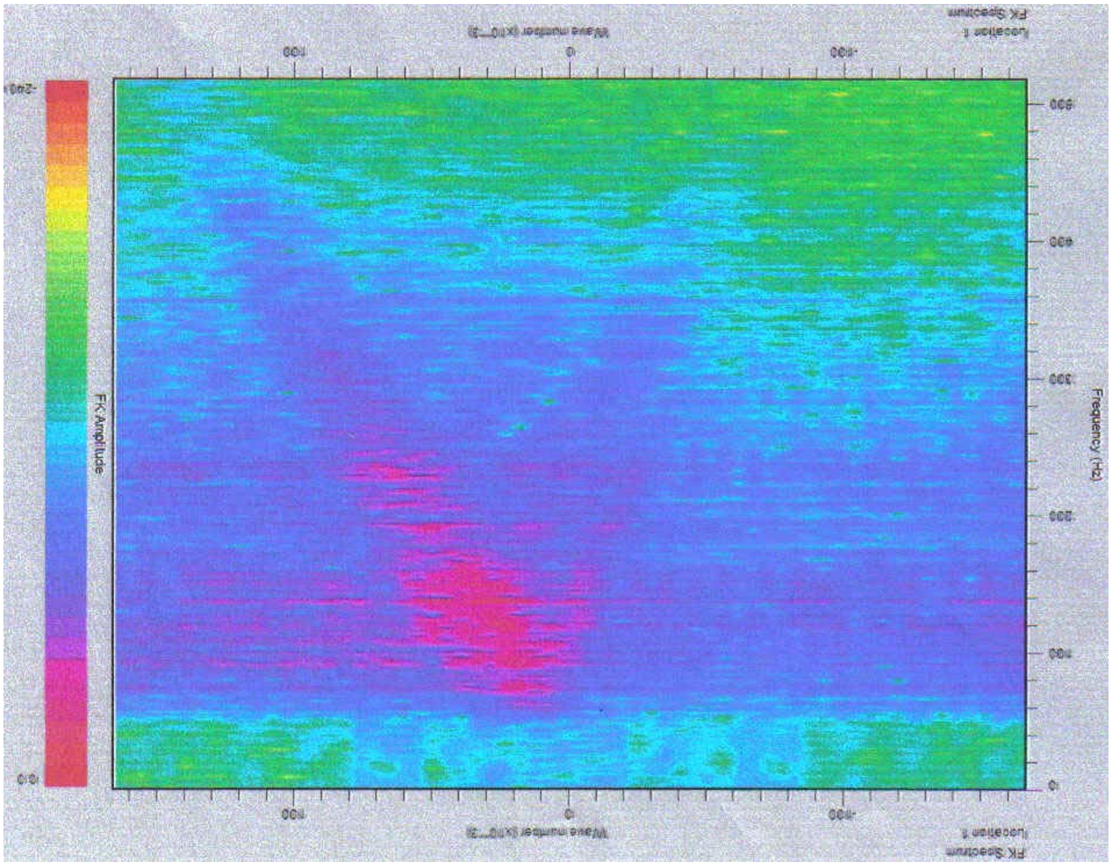

Figure 34. FK-plot of Figure 33 showing the seismic energy distribution of the remaining upgoing waves.

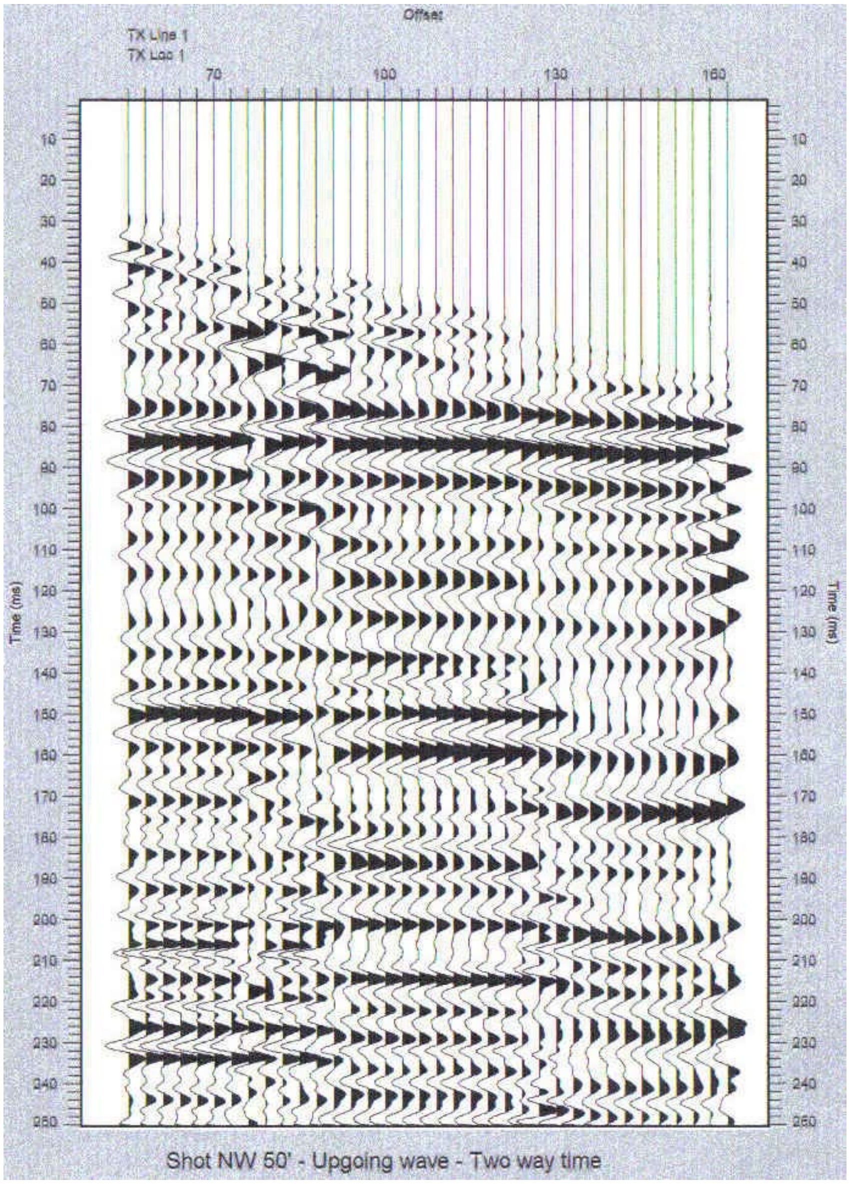

Figure 35. VSP data with 50-ft source offset (NW direction) in which the upgoing waves had been converted into two-way travel time.

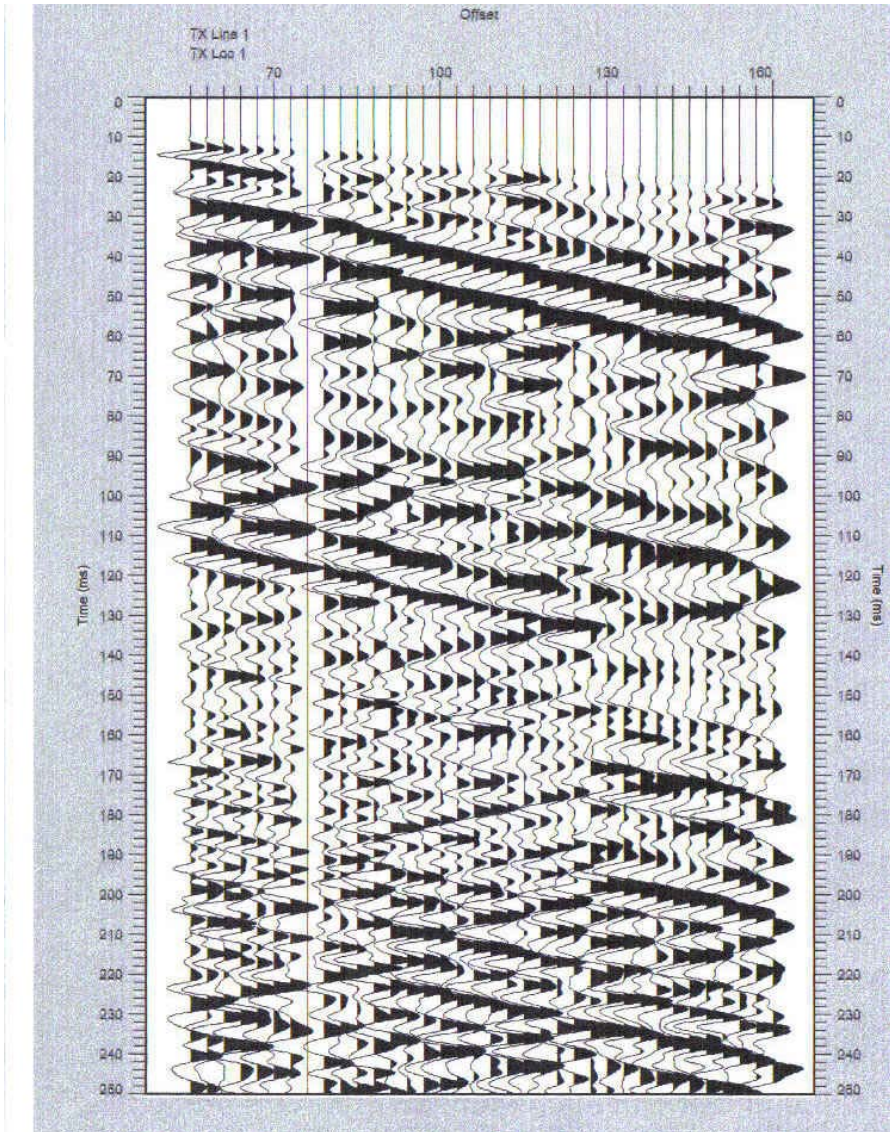

Figure 36. VSP data with 50-ft source offset (SE direction) after bandpass filter and AGC were applied.

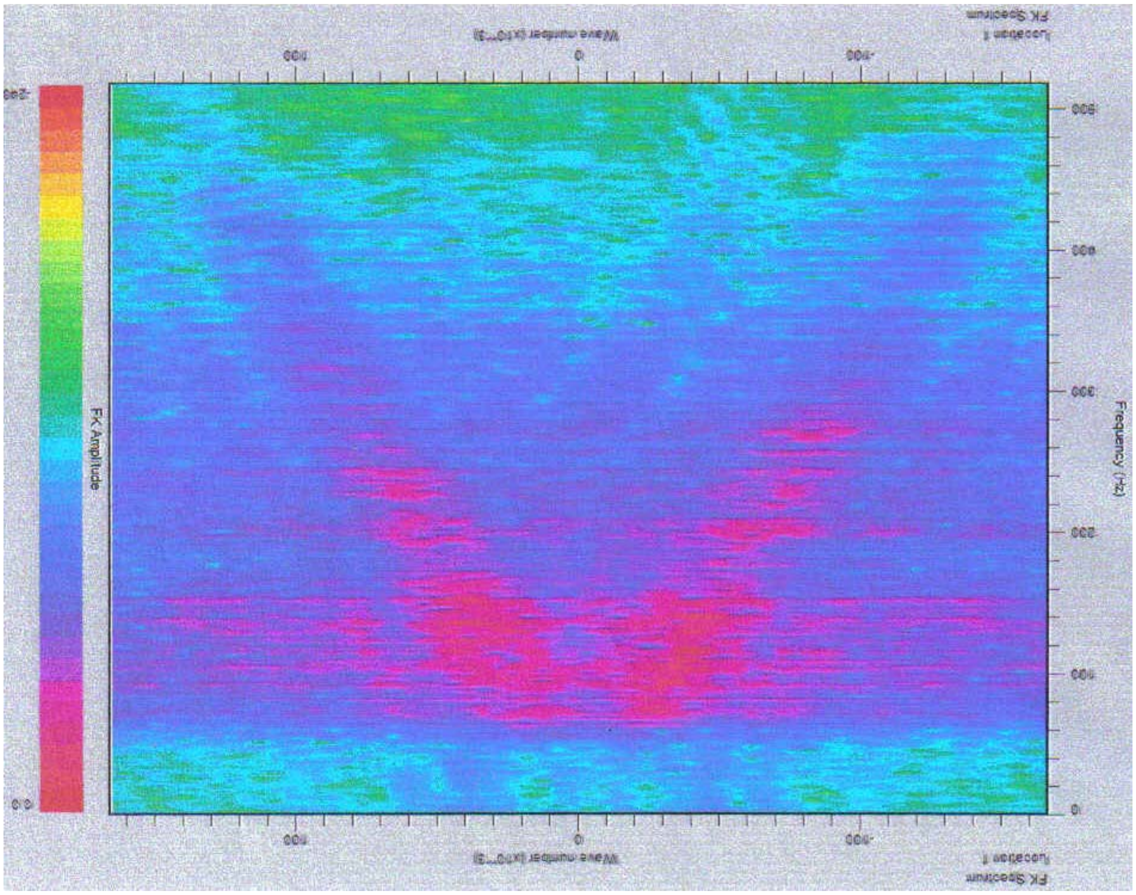

Figure 37. FK-plot of Figure 36 showing the seismic energy distribution of the upgoing (left) and downgoing (right) waves.

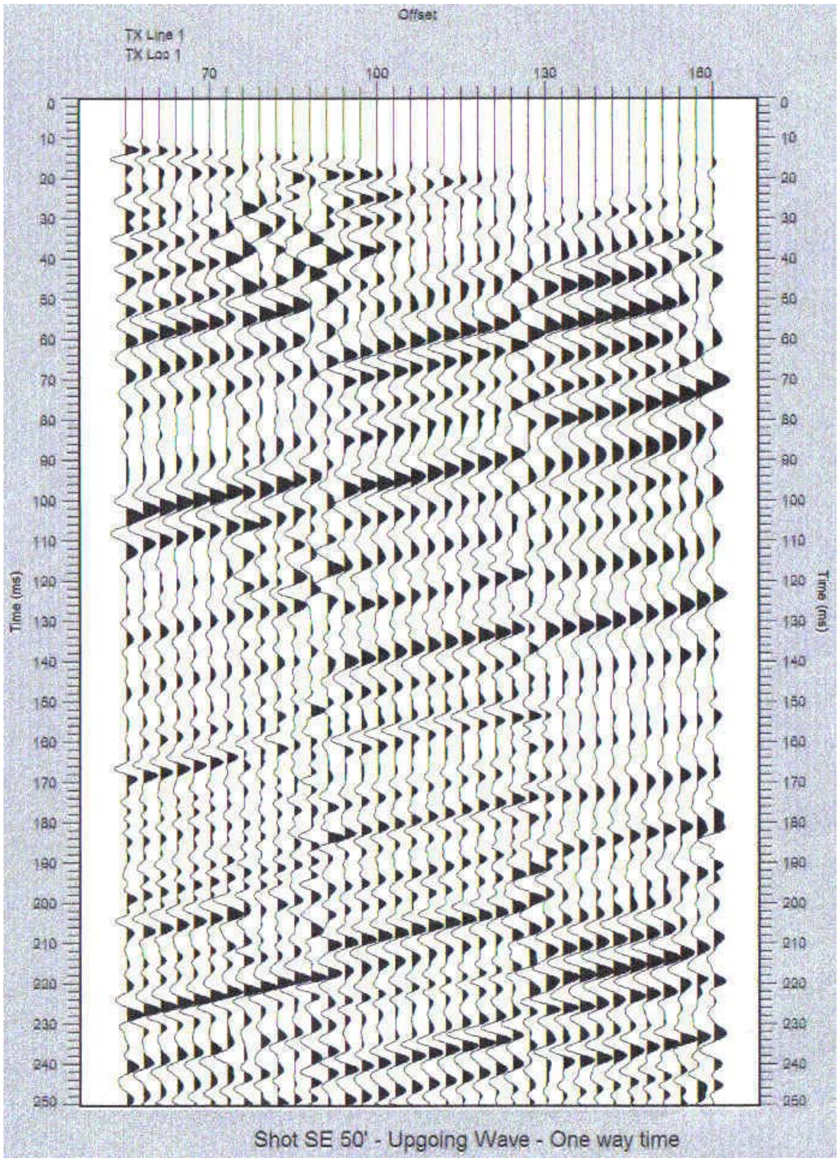

Figure 38. VSP data with 50-ft source offset (SE direction) after attenuating the downgoing waves.

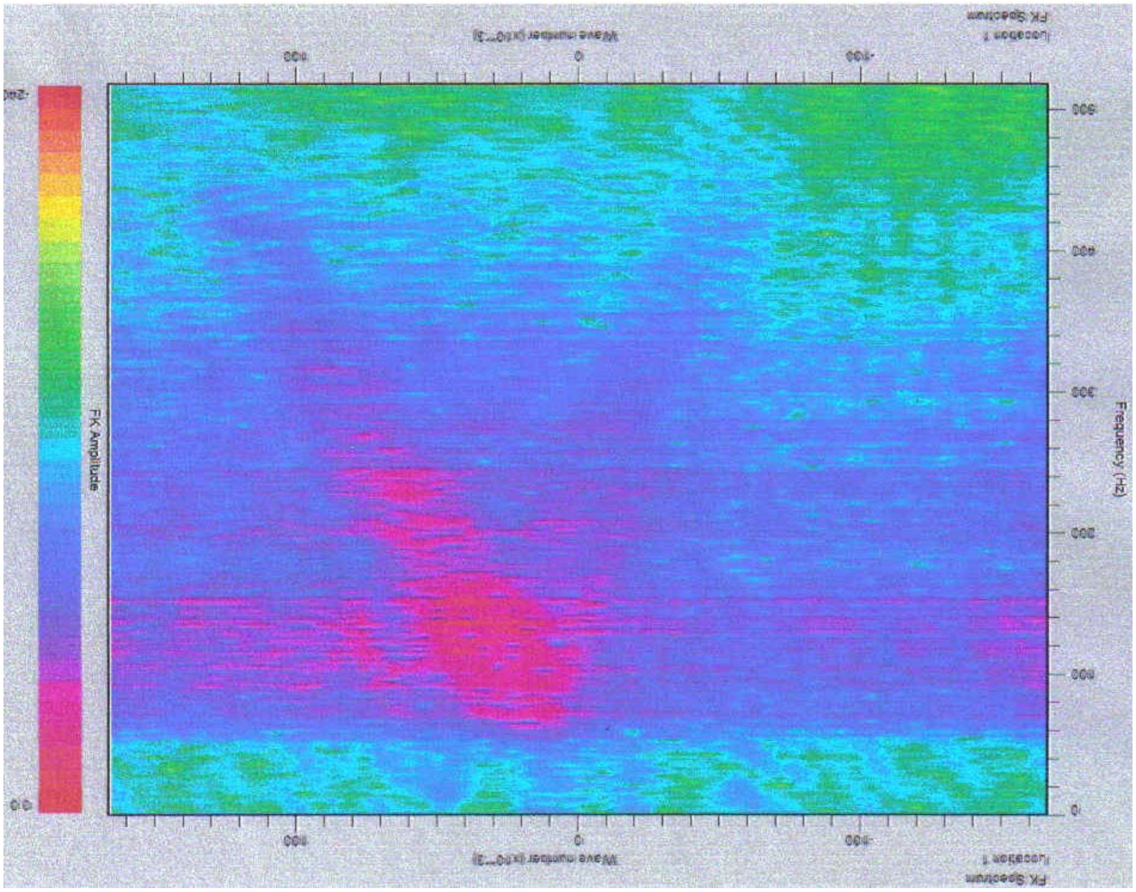

Figure 39. FK-plot of Figure 38 showing the seismic energy distribution of the remaining upgoing waves.

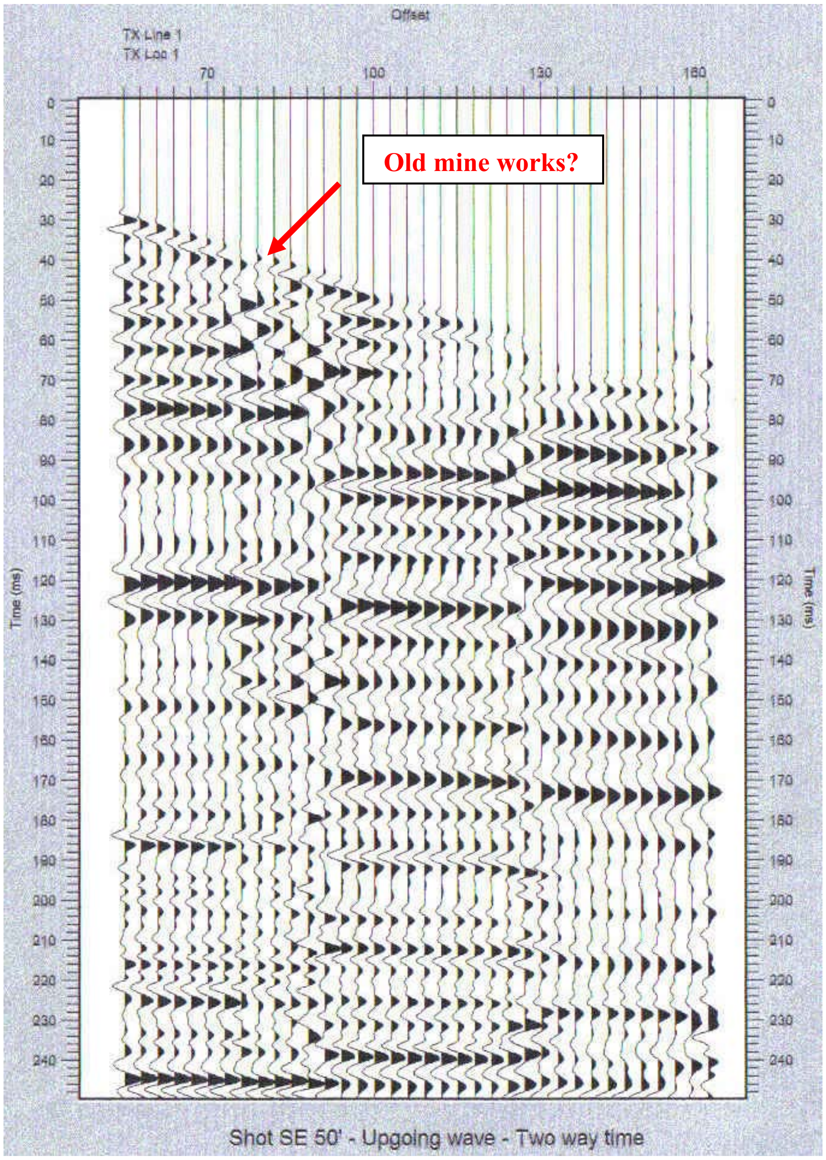

Figure 40. VSP data with 50-ft source offset (SE direction) in which the upgoing waves had been converted into two-way travel time.

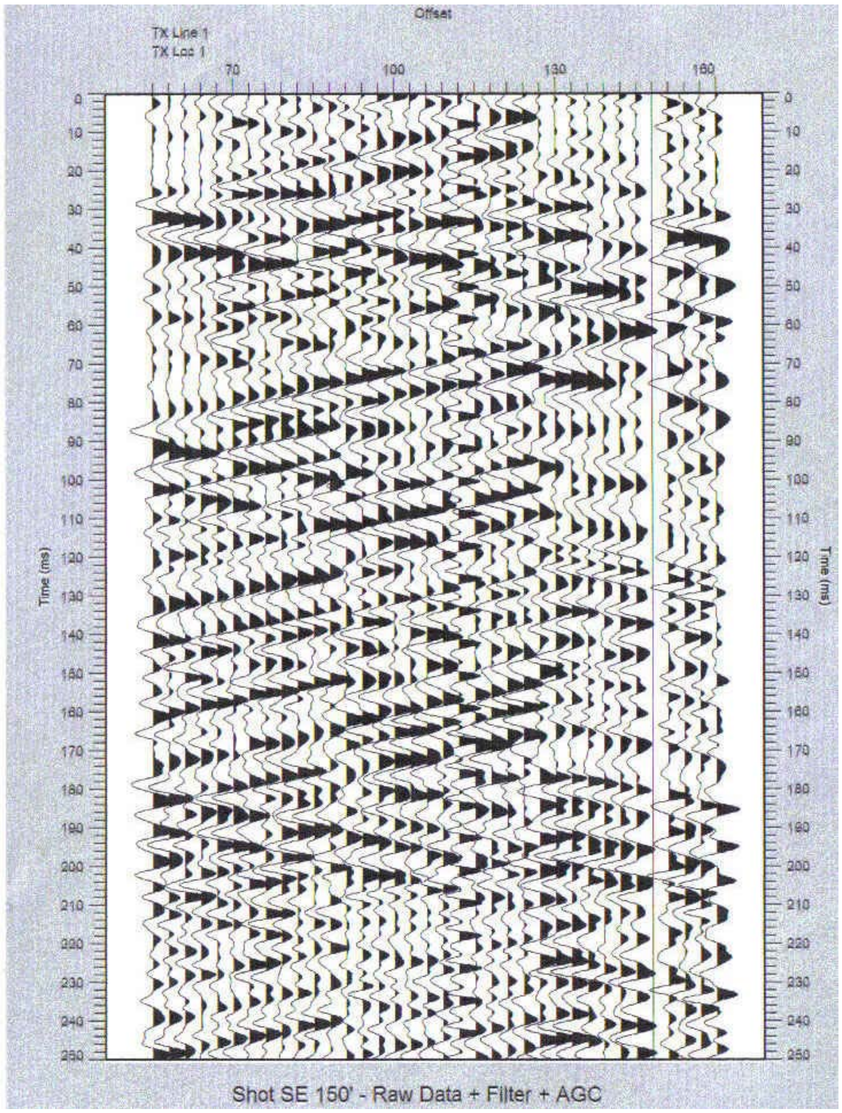

Figure 41. VSP data with 150-ft source offset (SE direction) after bandpass filter and AGC were applied.

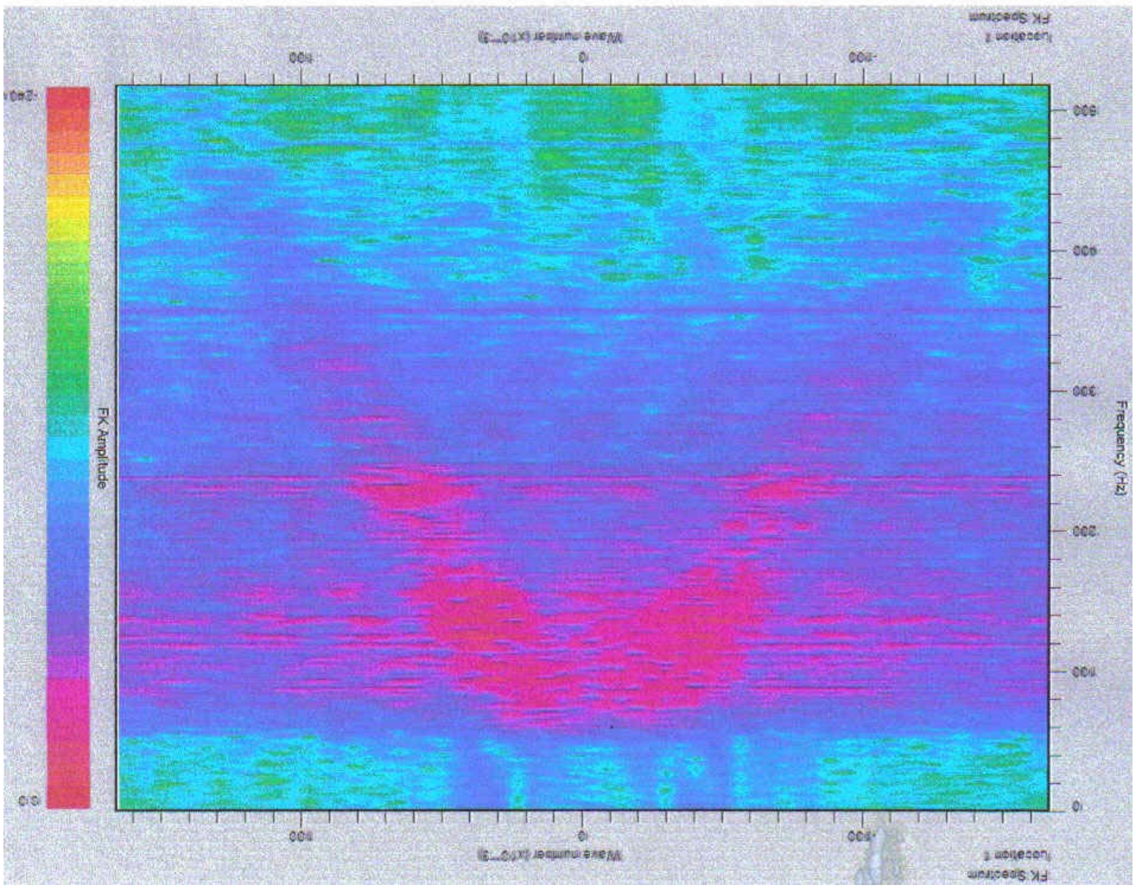

Figure 42. FK-plot of Figure 41 showing the seismic energy distribution of the upgoing (left) and downgoing (right) waves.

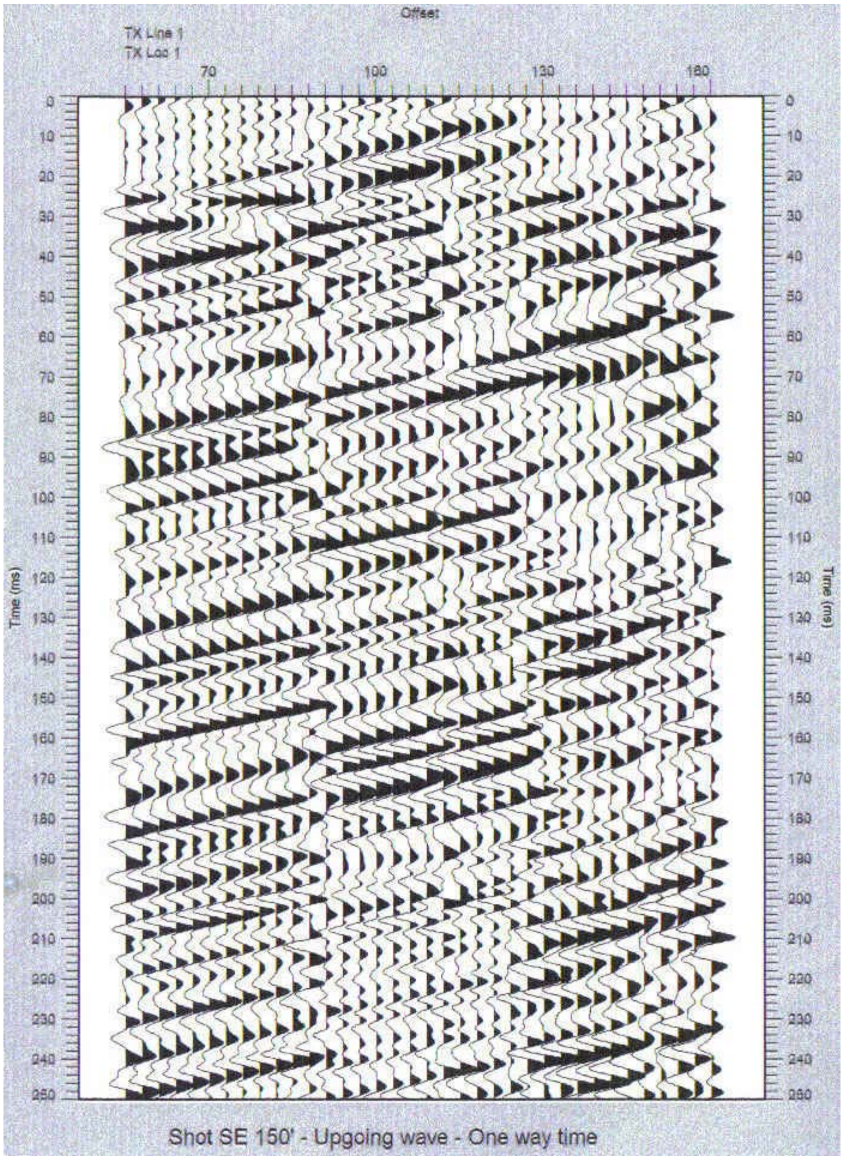

Figure 43. VSP data with 150-ft source offset (SE direction) after attenuating the downgoing waves

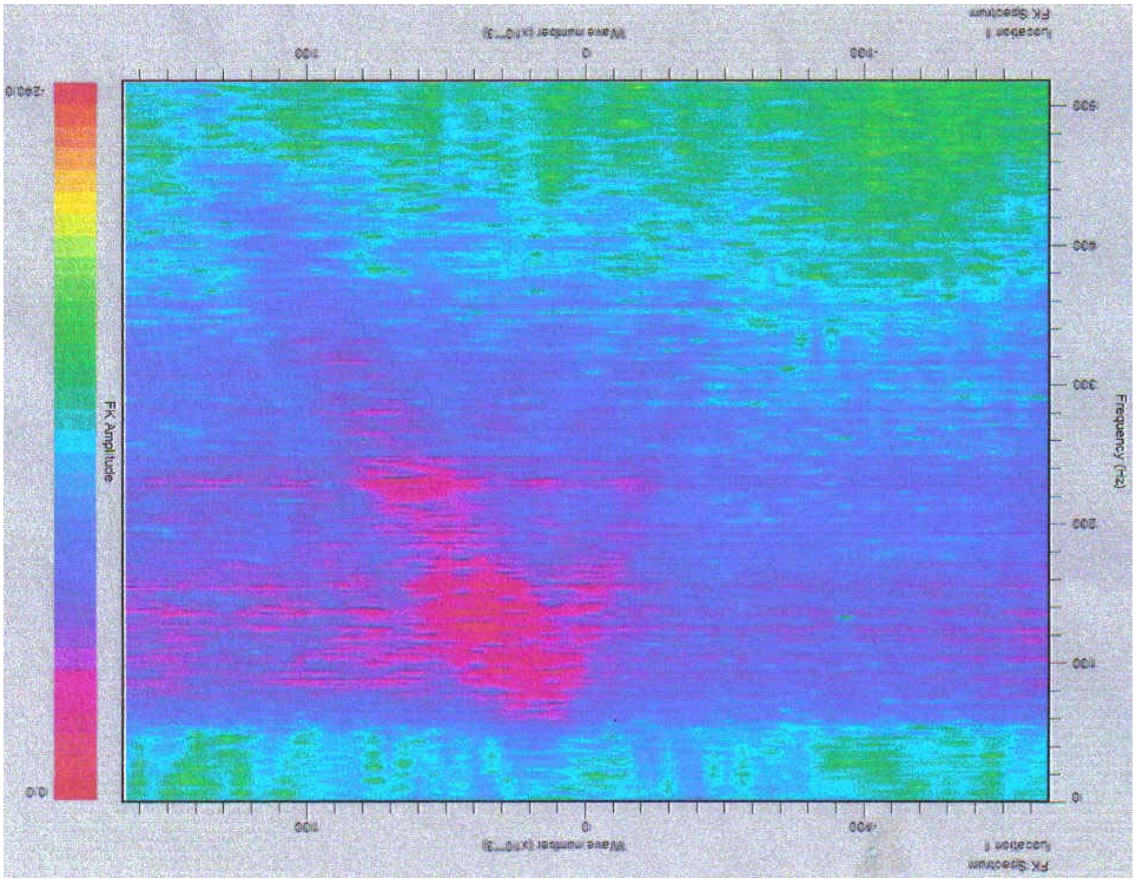

Figure 44. FK-plot of Figure 43 showing the seismic energy distribution of the remaining upgoing waves.

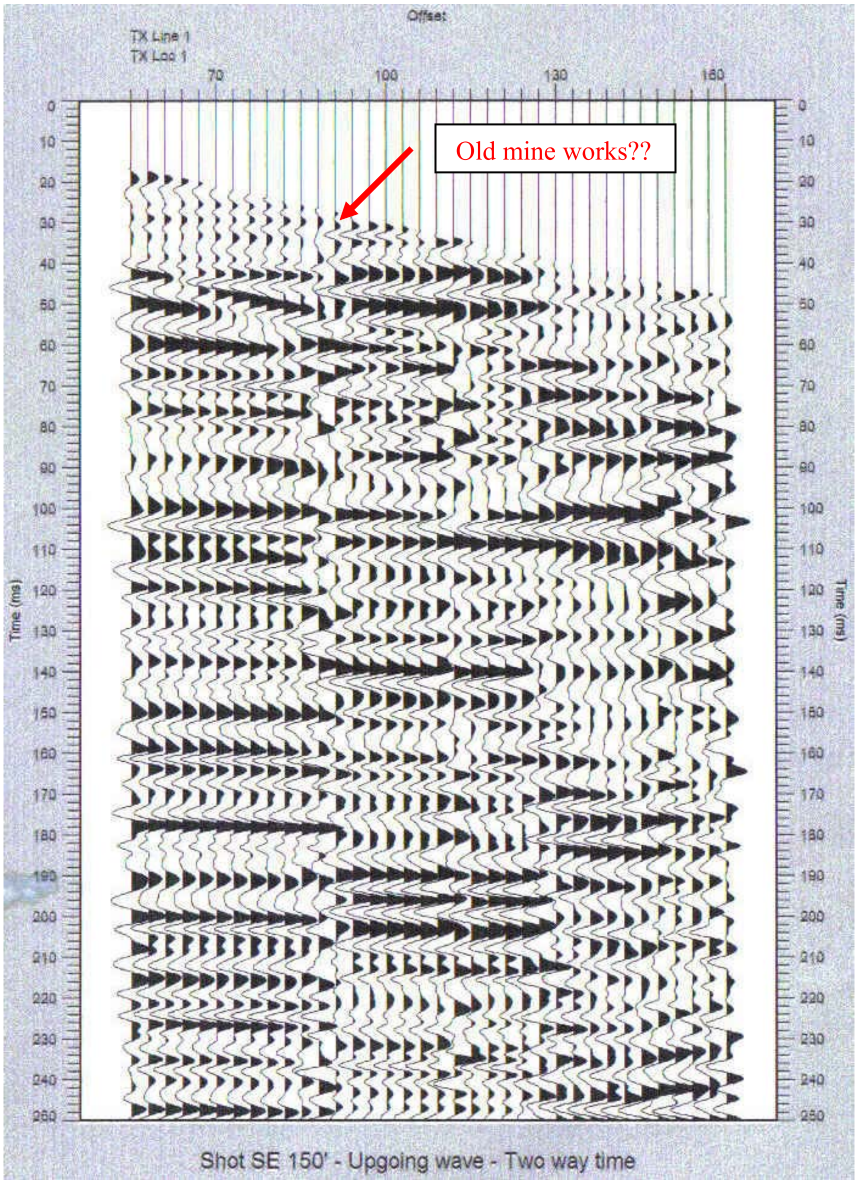

Figure 45. VSP data with 150-ft source offset (SE direction) in which the upgoing waves had been converted into two-way travel time.