LA-UR- 09-06751

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Time-Lapse VSP Data Processing for Monitoring CO_2 Injection

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[1] Now at: Rock Solid Images

Introduction

As a part of the effort of the Southwest Regional Partnership on Carbon Sequestration supported by U.S. Department of Energy and managed by the National Energy Technology Laboratory, two sets of time-lapse VSPs were acquired and processed in oil fields undergoing CO_2 injection. One set of VSPs was acquired at the Aneth oil field in Utah, the other set at the Scurry Area Canyon Reef Operators Committee (SACROC) field in West Texas.

One baseline and two repeat VSP surveys were conducted from 2007 to 2009 at the Aneth oil field in Utah for monitoring CO_2 injection. The aim of the time-lapse VSP surveys is to study the combined enhanced oil recovery (EOR) and CO_2 sequestration in collaboration with Resolute Natural Resources, Inc. VSP data were acquired using a cemented geophone string with 60 levels at depth from 805 m to 1704 m, and CO_2 is injected into a horizontal well nearby within the reservoir at depth approximately from 1730 m to 1780 m. For each VSP survey, the data were acquired for one zero-offset source location and seven offset source locations (Figure 1). The baseline VSP survey was conducted before the CO_2 injection. More than ten thousand tons of CO_2 was injected between each of the two repeat VSP surveys. There are three horizontal injection wells, all originating from the same vertical well. One is drilled towards Southeast, directly towards the monitoring well (Figure 2), and the other two towards Northwest, directly away from the monitoring well. The injection is into the top portion of the Desert Creek formation, just beneath the Gothic shale, which acts as the reservoir seal.

The initial baseline acquisition was done in October 2007; subsequent time-lapse acquisitions were conducted in July 2008, and January 2009. The acquisition geometry is shown in Figure 1. Shot point 1 is the zero-offset source location, Shot points 2 to 8 are the seven offset VSPs, arranged in a quarter circle on the Northwest side of the monitoring well. The horizontal injection well is shown in green. The black lines in Figure 1 show the approximate reflection coverage at reservoir depth from the respective offset source locations. VSP source location 5 is in a direct line with the injection. The 60 geophone sondes were cemented into the monitor well just before the baseline VSP acquisition and consisted of 96 geophone channels, with 18 three-component geophones (at the bottom of the string) and 42 single vertical component phones above. For this study, only the vertical geophone data were used.

A different monitoring scheme was used at the SACROC field, in cooperation with Kinder Morgan (see Figure 3). There are two sets of VSP surveys acquired in the same well, one in July of 2008, and the other in April of 2009. Each survey consists of one zero-offset VSP, two far-offset VSPs (3752 ft and 2783 ft offsets), and one walkaway VSP. The geophone depths range from 500 ft to 5700 ft measured from the Kelly Bushing for the near and far offset VSPs. Walkaway VSPs were recorded in the deepest part of the well. The walkaway line is oriented North-South. The shotpoints were positioned with an interval of 120 ft, with the center of the spread approximately 55 ft due East of the monitoring well (Figure 3). There were 95 shotpoints processed in 2008 and 94 in 2009 (after deleting bad shots). The walkaway VSP was recorded at a depth range from 5100 to 5700 ft (13 levels) in 2008, and from 5000 to 5700 ft (15 levels) in 2009. In between the two VSP surveys, CO_2 was injected in two wells (56-4 and 56-6) close to the monitoring well, at two intervals (depths of approximately 6500 and 6700 ft).

Data Processing

Standard VSP processing steps are used to process the baseline VSP data. These include removing the reference signal, muting, sorting, vertical summing, reversing traces with reversed polarity, notch and bandpass filtering, first break picking, T-gain, wavefield separation, up-wave enhancement, deconvolution, velocity model building, and VSP-CDP transform. Because the datasets are to be used for time-lapse applications, care is taken to get the best data from the raw dataset. This is particularly true for the Aneth base line data set since it is rather noisy. The raw and final processed data are shown in Figures 4 and 5. By comparison, the raw data from SACROC has a much higher signal to noise ratio (Figure 6). In addition, for the SACROC walkaway VSPs, the three component data was rotated to maximize the P wave arrival, using a velocity model generated from the zero offset VSP data and ray tracing. We do not do this for the subset of 3 component data in the Aneth data set in order to maintain consistency with the single component geophones in the array.

The pre-processed field data are then processed to separate the upgoing and downgoing wavefields using median filtering. The upgoing wavefield is then deconvolved using a source signature obtained from the downgoing wavefield. The upgoing wavefield is transformed into a VSP-CDP image using the velocity field determined from the zero-offset VSP survey and formation tops from logs and geological information.

Unlike surface seismic 4D studies, there is no established time-lapse VSP processing flow. Each study has to be tailored to the field and acquisition conditions. In both studies, we use seismic vibrators as sources. At Aneth we have cemented the geophones in the monitoring well to minimize the differences in separate acquisitions. However, there are still significant differences in the raw data. This is particularly evident in the Aneth surveys, partly due to a different acquisition crew and surface conditions, and partly due to the cement curing in the monitoring borehole. An example of the differences in the resulting VSP-CDP transform images from the 2007 and 2008 is shown in Figure 7.

We then derived a series of steps to equalize the different data sets so we can make a valid comparison of the images. These steps include:

1. First break time alignment: Aligning the first break of a repeat survey with the baseline.

2. Match filtering: The spectrum of the repeat survey is match to the baseline survey inside a specific window by the use of the Wiener-Levinson algorithm.

3. Gain equalization: global gain equalization is then applied to all three data sets.

The result is that the data sets are much better matched to each other. The result after the matching is shown in Figure 8.

Results and Discussions

We then take the difference between the baseline and repeat survey images. We first show the results from the Aneth survey. Figure 8 shows the difference images for Shot point 5, directly in line with the horizontal injection well. Figure 9 shows the difference for Shot point 6, which is slightly north of the injection well. The injection location is just below the lowest geophone. At the level of the injection, we can see distinct changes in the difference images. In the Shot point 5 images (Figure 8), we see changes in the reflectivity immediately above the injection zone, especially for the 2008-2009 image. In the Shot point 6 images (Figure 9), we can see even larger changes in the reflectivity above the injection zone than those for Shot point 5. It is interesting to observe that the Shot point 5 difference images do not show as strong a reflectivity change as the Shot point 6, which may suggest that the CO_2 is preferentially migrating north from the injector.

Next we show the results from the SACROC walkaway VSP surveys. Both the data and image quality for these surveys are superior to those from Aneth (see Figure 6). There are a number of reasons for this. The issues associated with acquisition are discussed earlier. In addition, for the Aneth images, we are dealing with single shot points, thus there is only a single fold for each reflection point, and the images show low signal-to-noise ratios. For the SACROC walkaway VSP survey, on the otherhand, there are multiple folds for the majority of the reflection points in the images, and thus the signal-to-noise ratios are higher than the Aneth data. This, combined with the better quality raw data, gives us images superior to those from the Aneth survey. The baseline 2008 and 2009 walkaway VSP-CDP transform images are shown in Figure 10, and the difference image is shown in Figure 11. Looking at Figure 11, we can identify a change in reflectivity at the center of the walkaway line, at between 900 to 1000 ms in two-way time. This approximately corresponds to the injection zones next to the monitoring well.

We have shown processing results from time-lapse offset VSP surveys from two CO_2 monitoring studies conducted by the U.S. Southwest Regional Partnership on Carbon Sequestration, at the Aneth oil field in Utah, and at the SACROC oil field in Texas. It is shown that the CO_2 injection produced an interpretable signature in the VSP-CDP transform images. It is also demonstrated that the acquisition and survey design have a significant impact on the results. These preliminary observations are from the VSP surveys only, and any concrete conclusions regarding the location and migration of injected CO_2 need to be corroborated with other independent studies.

Acknowledgements

We would like to thank Janusz Peron and Michelle Zhao for their assistance in the processing of the VSP data. LH and JR acknowledge the support of the U.S. Department of Energy and National Energy Technology Laboratory through the Southwest Regional Partnership on Carbon Sequestration and contract DE-AC52-06NA25396 to Los Alamos National Laboratory.

Suggestions for Further Reading:

For basic reading regarding VSP processing, see: Vertical Seismic Profiling by Hardage (Pergamon, 2000). For background on the Aneth oil field monitoring studies, see "VSP monitoring of CO2 injection at the Aneth oil field in Utah" by Huang et al. (AGU Fall Meeting, 2008; Proceedings of 8th Annual Conference on Carbon Capture and Sequestration, 2009), and "Microseismic monitoring of CO2 injection in the Aneth oil field, San Juan County, Utah" by Rutledge et al. (AGU Fall Meeting, 2008). For general time lapse seismic monitoring studies, see: Time-lapse Seismic in Reservoir Management by Jack (SEG 1997).

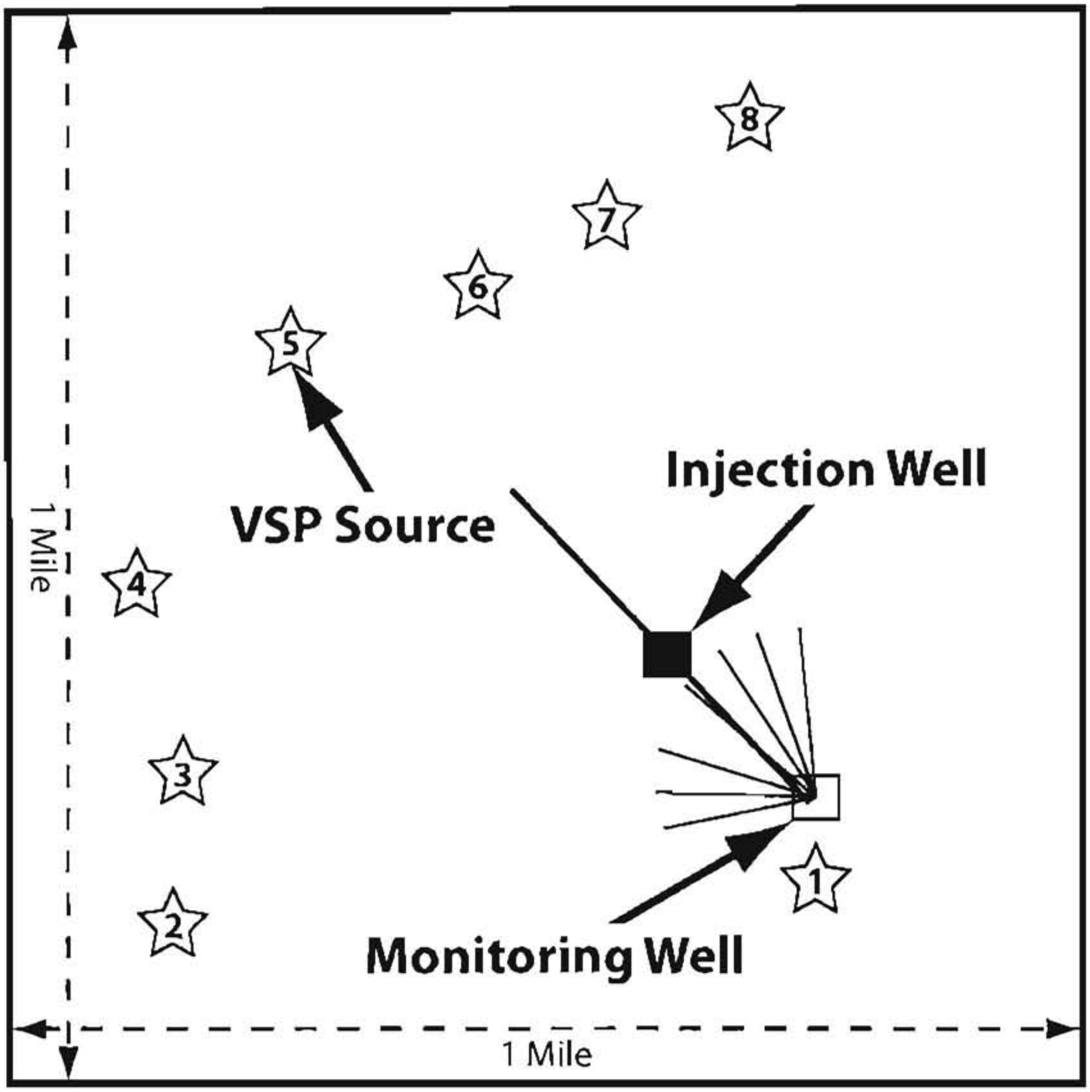

Figure 1: A map showing relative locations of monitoring and injection wells, and source locations for time-lapse VSP surveys at the Aneth oil field, Utah.

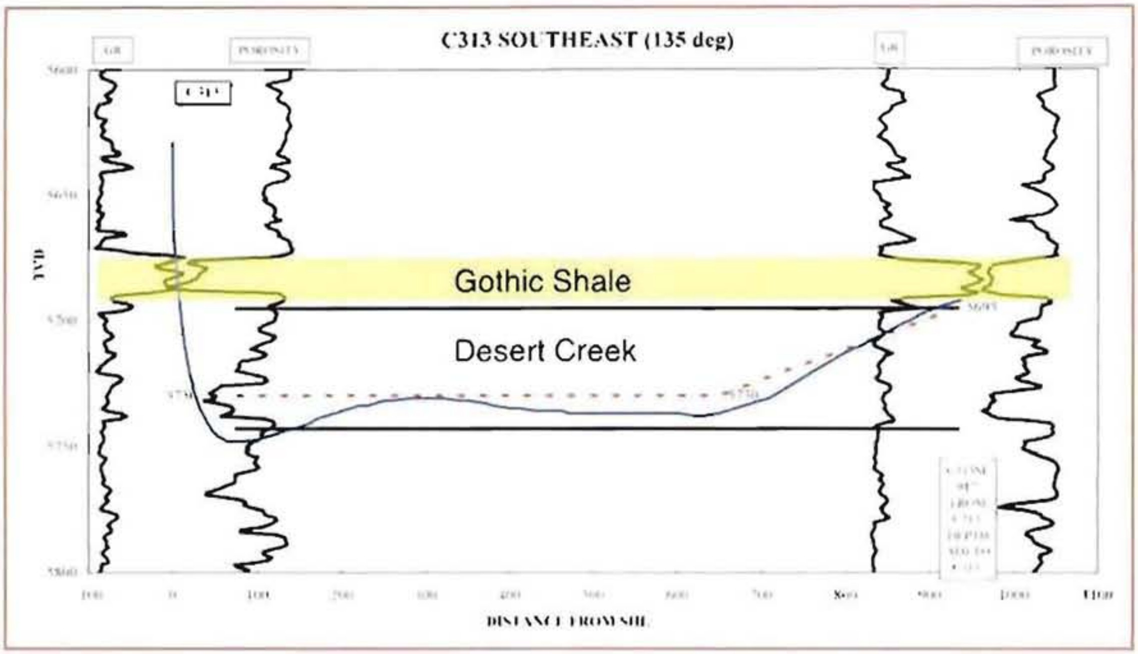

Figure 2: Schematic diagram of the injection well (C313) trajectory towards the monitoring well.

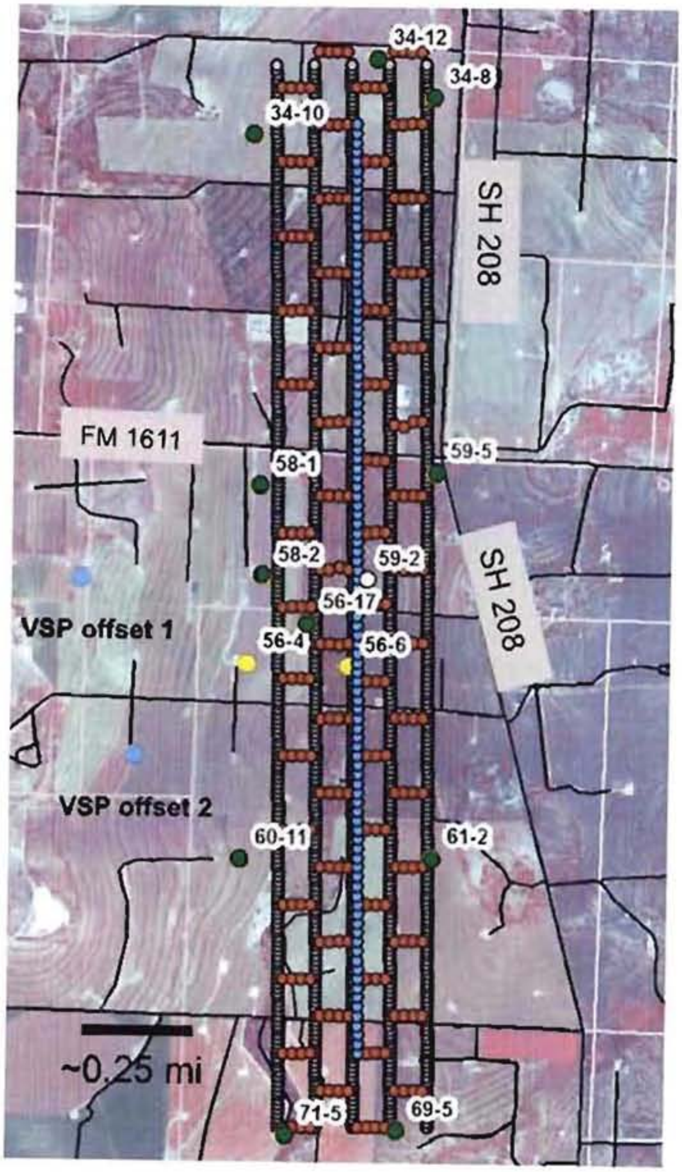

Figure 3: A map showing the location of the N-S walkaway VSP shot locations (blue, including the two offset shot locations), the monitoring well (59-2, white), and the two injection wells (56-4 and 56-6, yellow) at SACROC oil field, Texas.

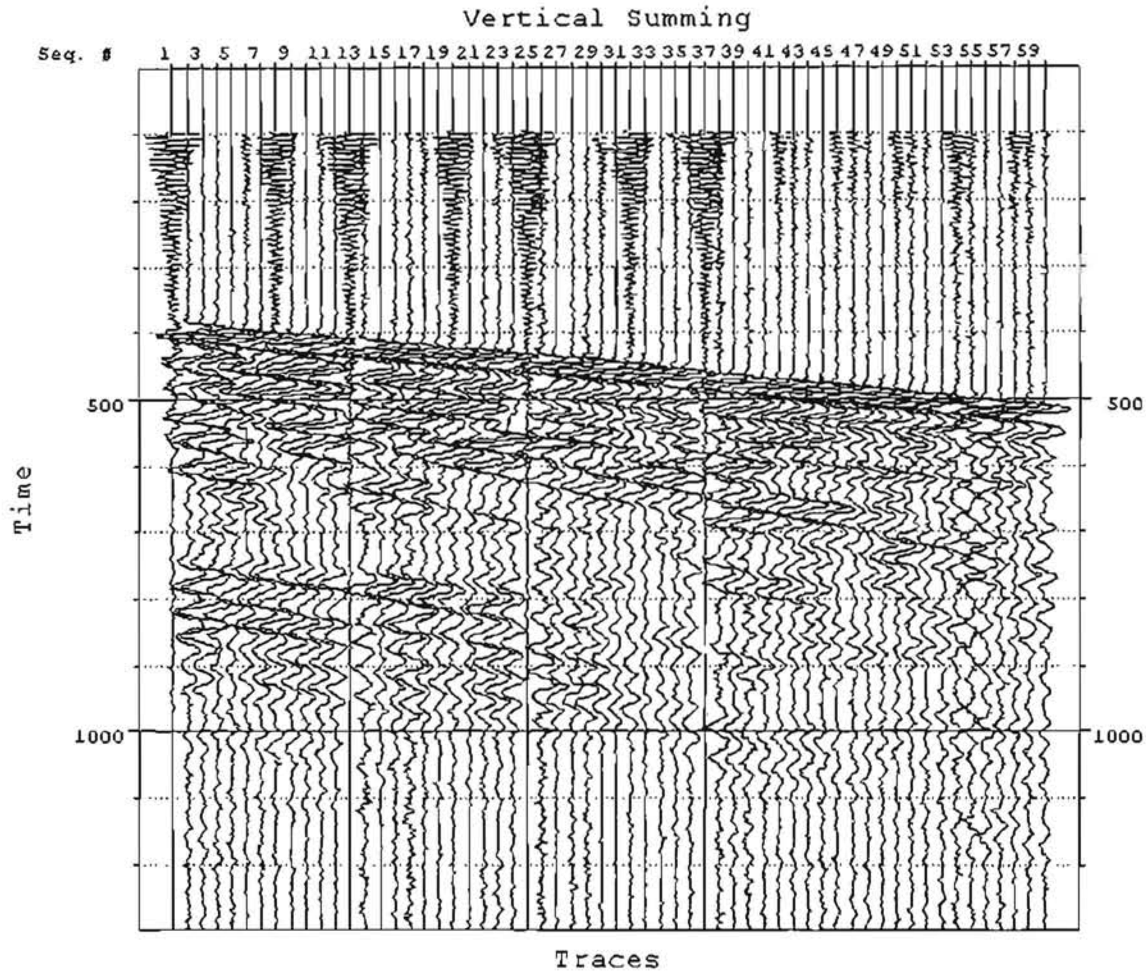

Figure 4: Raw field VSP data after vertical summing for Shot point 5 for the baseline survey at Aneth.

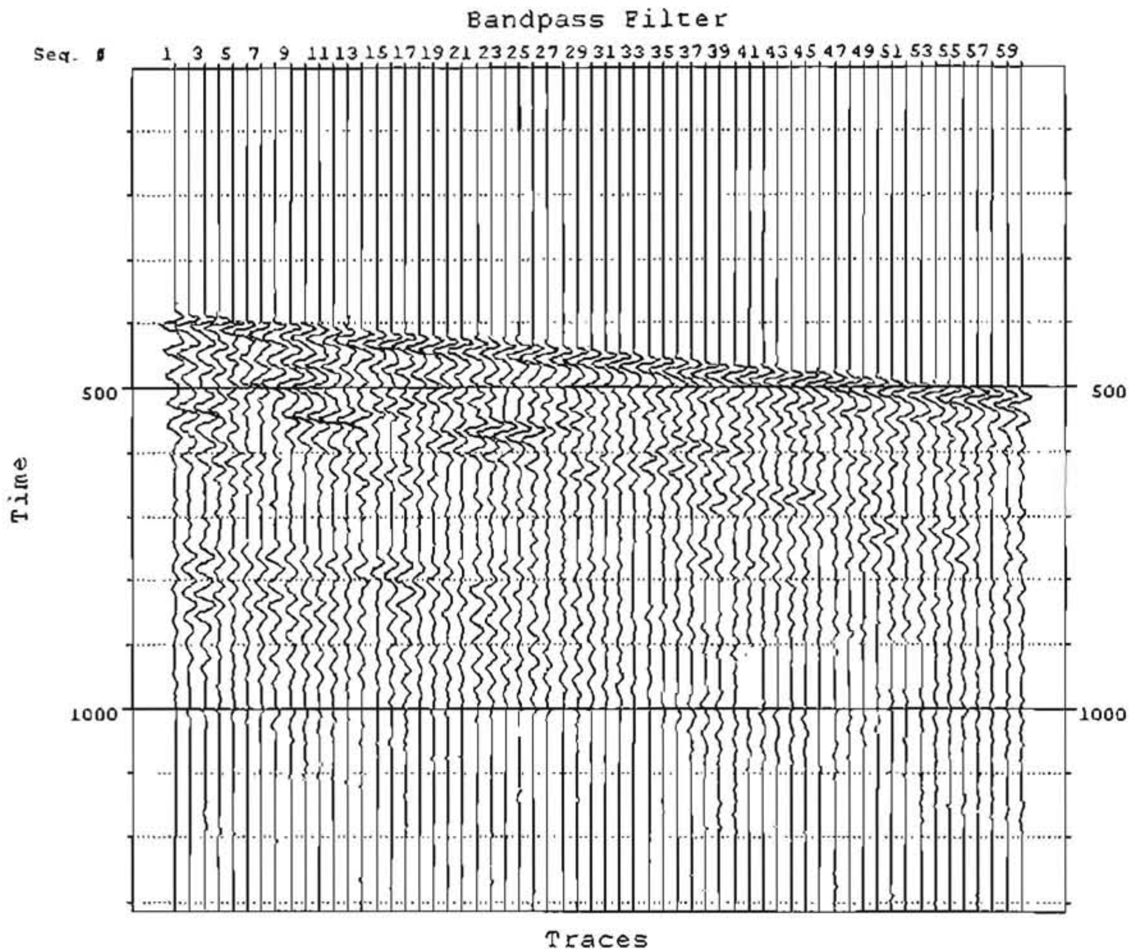

Figure 5: Final processed VSP wavefield for Shot point 5 for the baseline survey at Aneth.

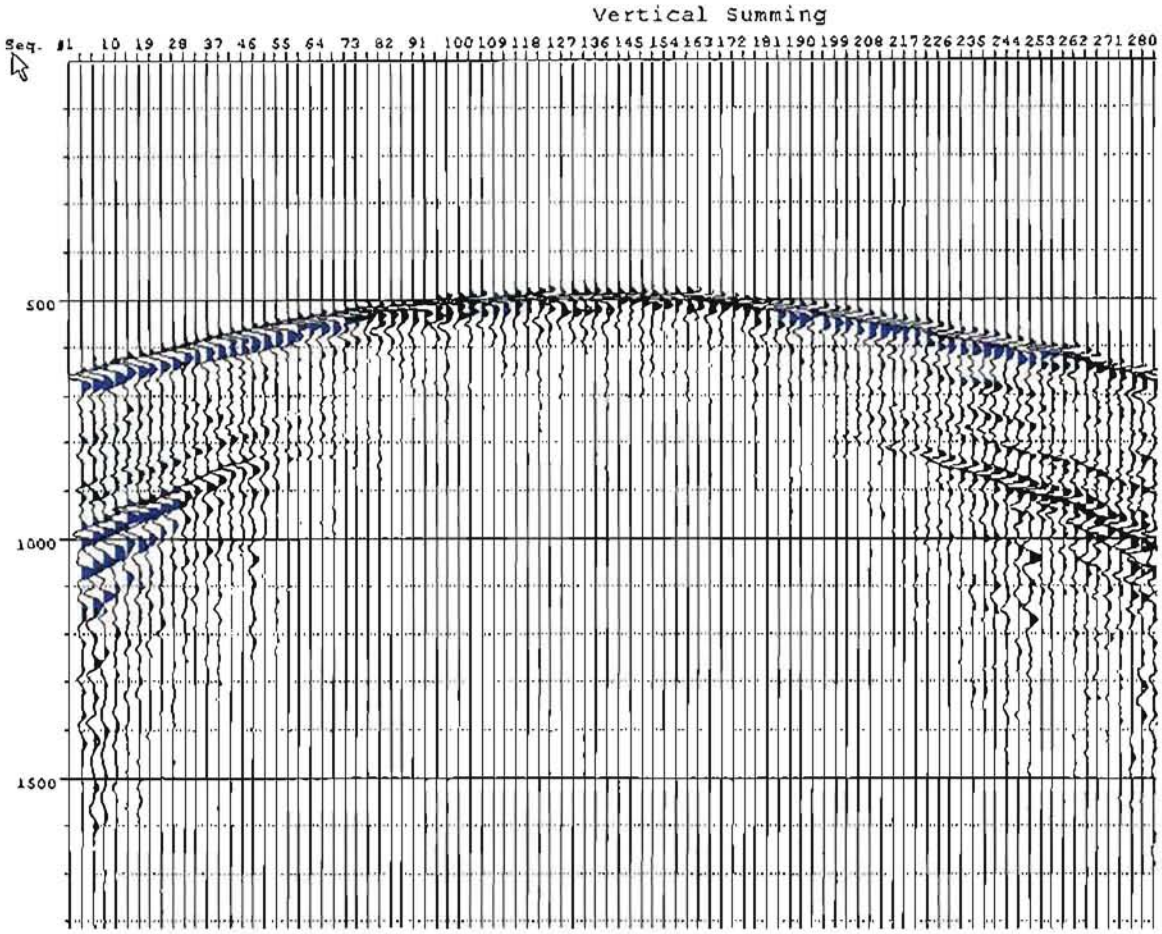

Figure 6: Raw field data (receiver gather) after vertical summing for the vertical component for the baseline walkaway VSP data collected at SACROC.

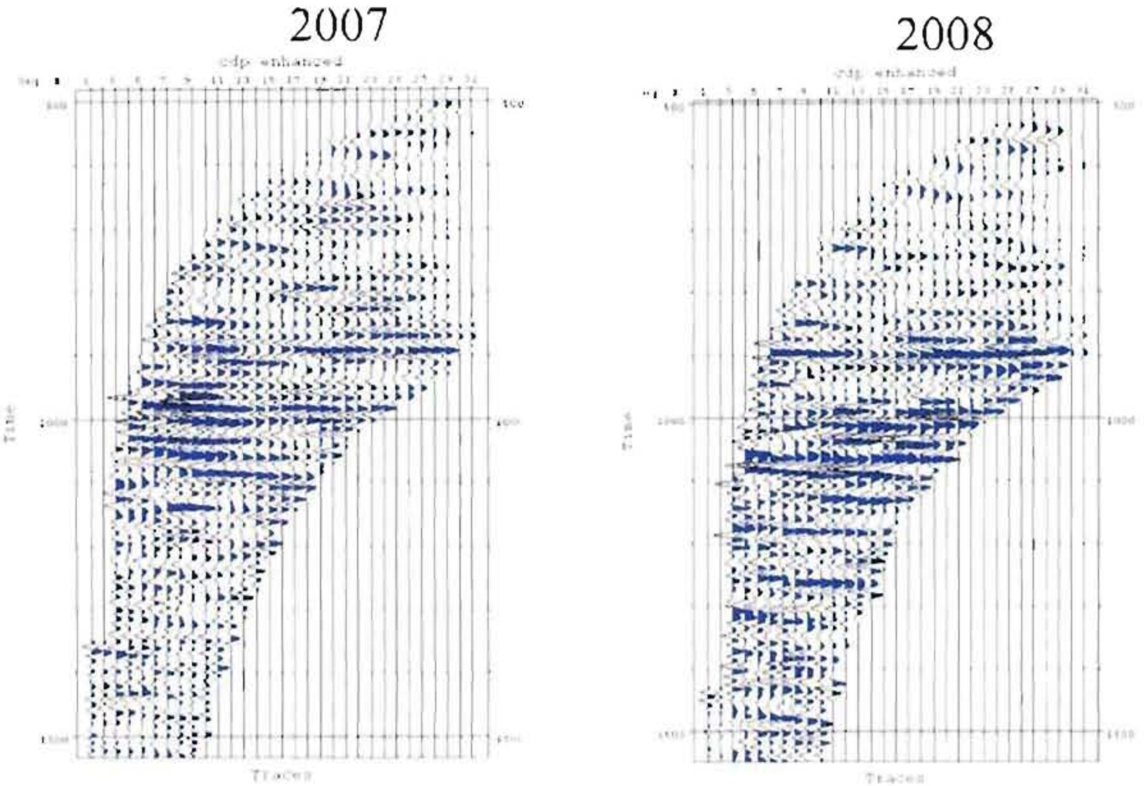

Figure 7: Comparison of the VSP-CDP transform images from Shot point 5 for the baseline (2007) and first repeat (2008) survey at Aneth, before any steps to match the two data sets.

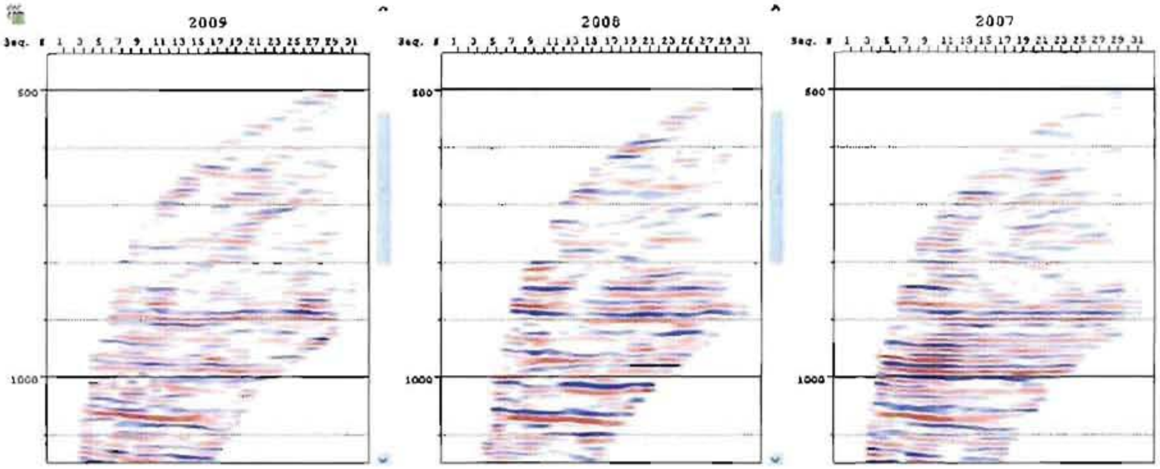

Figure 8: Comparison of the VSP-CDP transform images from Shot point 5 at Aneth after the datasets were matched as described in the text.

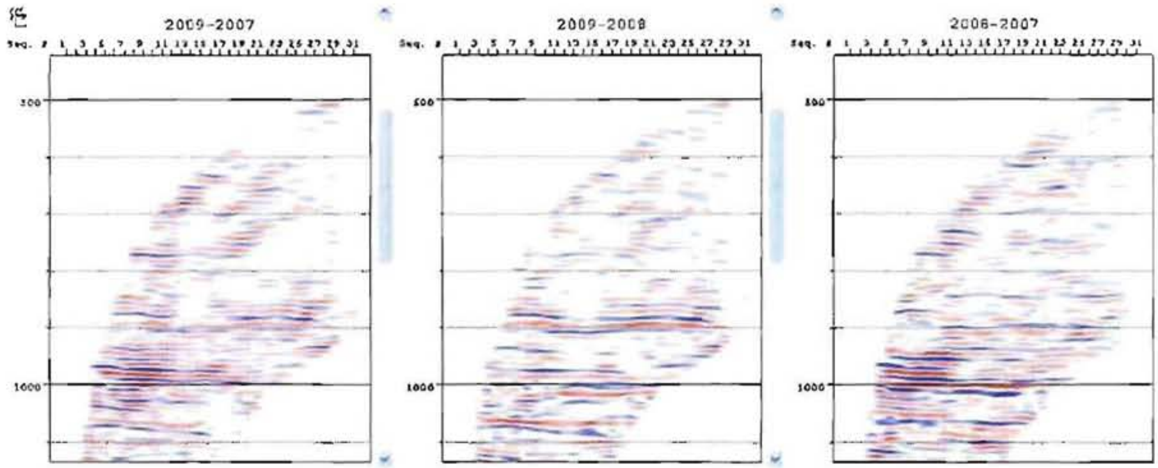

Figure 9: Difference images between the three surveys for Shot point 5 at Aneth. From the right: the difference between the baseline and the first repeat survey (2008-2007); the difference between the first and second repeat surveys (2009-2008); and the difference between the baseline and second repeat survey (2009-2007). The injection zone is located at the bottom of the borehole, corresponding to a two way time of around 900 ms.

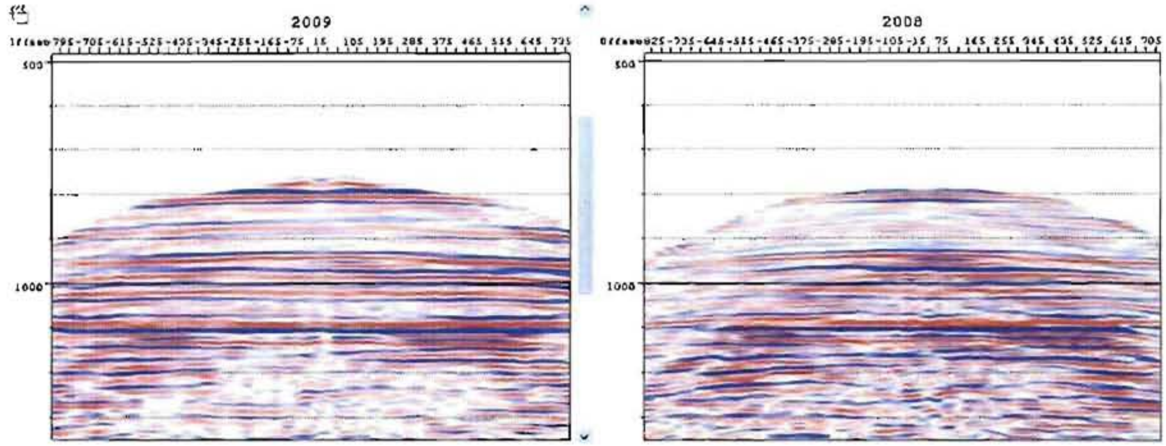

Figure 10: VSP-CDP images of the baseline (2008) and repeat (2009) walkaway VSP surveys at SACROC, after the images were matched as described in the text.

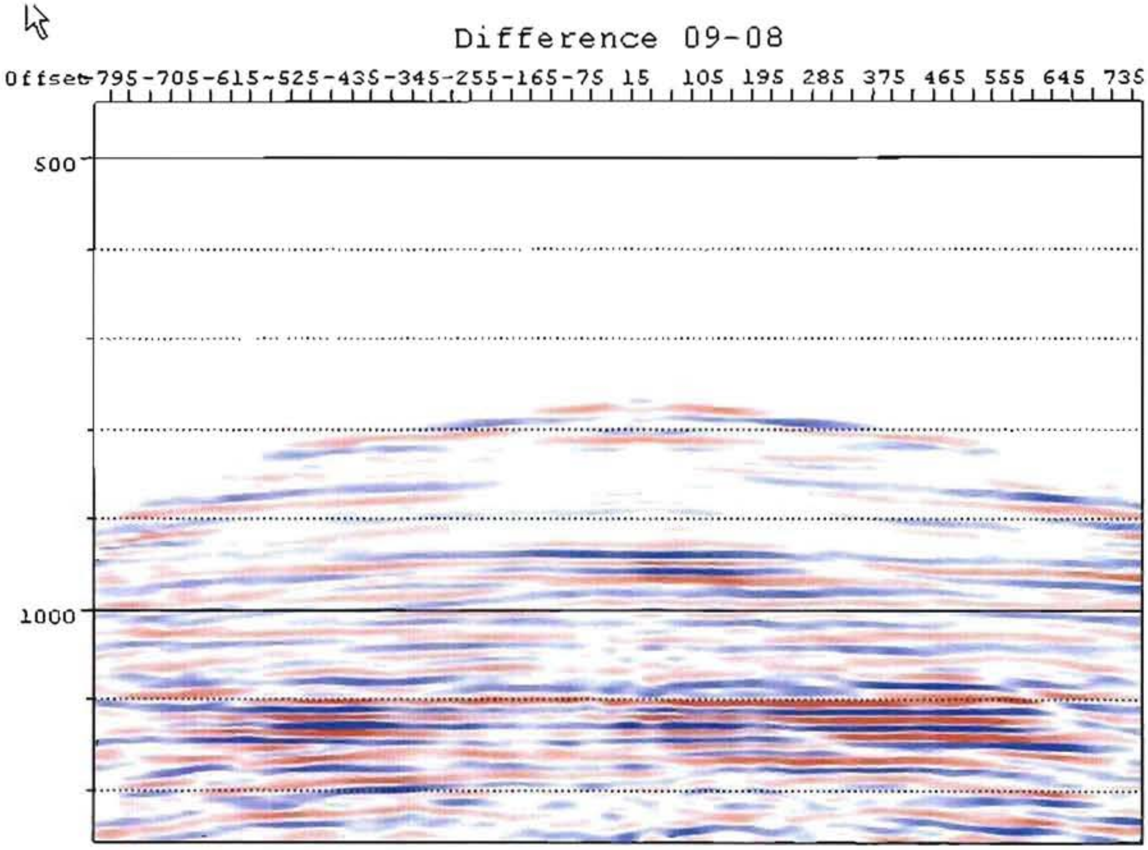

Figure 11: Difference image between the baseline and repeat walkaway VSP surveys at SACROC. The injection zone is approximately located at the center of the walkaway line, at a position between 900 to 1000 ms in time.