

Reflections Enhancement Processing For Multi-Component Cross-Well Seismic Data

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Abstract

Cross-well seismic data is five-times more structurally complex than surface seismic or VSP data. Despite the advantages of cross-well reflection image over conventional seismic and VSP images, the lack of standard processing methods is limiting the application of cross-well seismic data. Using the results of data modeling studies and a set of field data from west Texas oilfield, this paper describes efficient and time-inexpensive techniques for processing cross-well seismic data using in-house processing codes. The processing flow consists of two main steps: pre-processing and wave-field separation. In pre-processing, the high amplitude energies obscuring primary reflections were suppressed and the seismic wavelets were compressed to enhance reflectivity signatures. In wave-field separation, the multi-directional reflection is separated into up-going and down-going reflections. The application of resort-while-processing techniques and multi-quadrant dip-filter allows processing to take place in different sort domains and the full automation of the workflow. Overall, the processing reduced the multi-directional multicomponent wave-field to separate up-going and down-going P-reflections wave-field. This wave-field is structurally similar to the processed surface seismic data. The stacked image of the processed data revealed some horizontal reflectors that can be interpreted for the inter-well geology. The codes for data processing are developed for MATLAB environment and it is available for the purpose of research, teaching, and demonstration.

Keyword: Cross-Well Seismic Survey; Seismic Data Processing; Reflection Imaging; Wave-field Separation; Noise Attenuation.

Introduction

Surface seismic data and well logs have been used in oil and gas industry for decades to provide useful guide and insight to oil and gas exploration and reservoir management. While surface seismic data provide high coverage but low resolution, well log data give excellent resolution but low coverage. The resolution-coverage trade-off between well logs and surface seismic data is a source of seismic– well log mis-ties especially when velocity anisotropy and attenuation are prominent. Cross-well seismic technology provides excellent resolution and good coverage required to study the subtle geological structure of hydrocarbon plays (Raji *et al.*, 2016). Cross-well seismic survey provides higher resolution (<5 m) than surface seismic (30 -100 m) and Vertical Seismic Profiling (10 – 30 m), and higher coverage (up to 1 km) than Vertical Seismic Profiling (metres) and well log measurement (centimetres) (Rector *et al.*, 1995; Langan *et al.*, 1997 and Pereira and Jone, 2010). The utilities of cross-well seismic data for high-resolution image that bridge the gap between surface seismic data and well logs have been demonstrated in some cross-well geophysics papers including Lazaratos *et al.* (1991); Li and Stewards (1993); Harris *et al.* (1995); Langan *et al.* (1997); Raji *et al.* (2016); and Raji *et al.* (2017). Cross-well seismic technology offers cost effective method for monitoring field injection experiment, life-time performance of

hydrocarbon reservoirs, and for understanding large-scale surface seismic measurements (Daley *et al.*, 2008).

Despite the advantages of cross-well data over surface seismic and VSP data, cross-well geophysics is still underutilized and underdeveloped. This is because cross-well wave-field is very complex and is not completely understood (Pereira and Jones, 2010). Cross-well imaging is usually done by velocity tomography, not reflection imaging. Although velocity tomography is a robust imaging tool, it utilizes only the direct arrival waves that is just a section of the information present in the seismic records. Other information in the seismic records can be used to produce complimentary images (e.g., reflection image, or diffraction image) to obtain finer structural and stratigraphic details of the target zone. In addition to the inter-well image provided by cross-well tomogram, cross-well reflection imaging has the capability to illuminate sub-well depth where reservoir usually lies.

The problem with cross-well seismic imaging is data processing (Baker and Harris, 1984; Khalil *et al.*, 1991; Lazaratos *et al.*, 1991). Cross-well is at least five-times structurally complex than surface seismic data (Rector *et al.*, 1995). Unlike in surface seismic data where the principal recording is the energy reflected by the layers below the recorders, cross-well seismic survey records

different seismic arrivals including the P- and S-energies reflected by the layers above and below the recorders, as well as their converted waves. Extracting the geological information present in these multi-directional arrivals requires specialized techniques other than those used for conventional seismic data. The design of such techniques is usually driven by data modeling and wave-field analysis. Details of cross-well data modeling and wave modes characterization can be found in some geophysics papers including Van Schaack *et al.* (1995) and Raji *et al.* (2017). Cross-well data processing is, among others, faced with the task of identifying the different seismic arrival in the data, removing converted waves, and separating reflection arrivals into up-going and down-going parts. Cross-well seismic data processing is the subject addressed in this paper.

Although, there is no one-size-fits method for cross-well data processing, the processing methods are driven by the quality of the data and the set goals. The processing method described in this paper is consequent upon previous studies (Raji *et al.*, 2017) where the different wave modes in cross-well field data were analysed using wave-field modelling and characterized using wave-field decomposition. The distinguishing characteristics of the different wave modes were used to formulate the appropriate techniques to suppress or enhance the different wave modes. In the subsequent sections, the data gathering and methodology were described. Next, the workflow adopted for processing and the results achieved from the different processing stages are presented.

Methodology

Data Gathering

Cross-well seismic survey was conducted in a producing West Texas Carbonate Oilfield in 1991 as a part of a reservoir characterization and CO₂ flood project (Langna *et al.*, 1997). The survey consisted of source and receiver wells separated at the top by a distance of 605 ft (182 m). The source well consisted of 201 sources deployed to the depth between 8210 ft (2488 m) and 9209 ft (2790 m) at 5 ft (1.5 m) intervals. The receiver well consisted of 203 recorders deployed to depth level 8190 ft (2482 m) and 9199 ft (2788 m) at 5 ft (1.5 m) interval. The down-hole source is a cylindrical piezoelectric blender (Daley and Cox, 2001) driven with a linear sweep from 250 Hz-2000 Hz. Seismic arrivals were recorded by hydrophone receivers with a listen time of 200 ms. The full survey resulted in a raw data of

40800 traces. Each seismic trace consisted of 801 sample points at 0.25 ms sample interval. The full description of the data is available in (Langna *et al.*, 1997). The well deviation is negligible compared to the well depths. Data were sorted to different domains in order to analyse the different seismic arrivals. Signal to noise ratio differs from one data domain to another. A representative data showing the different seismic arrivals is presented in Figure 1. Data shown in Figure 1 is a common source gather from a source located at depth 8700 ft (2636 m). This data is subsequently known as sample data.

P-wave Reflection Processing

The key processing steps applied to the data included tube wave attenuation, removing direct arrival waves, deconvolution, de-signature, compressing the seismic wavelets, removing shear energy, removing converted waves, and separation of up-going from down going P-P reflections. Prior to wave-field processing, the header and data files were loaded into an in-house codes using SEISLAB interphase. SEISLAB (Rietsch, 2010) is an open source software that enables SEG Y formatted seismic data to be imported, viewed, and manipulated in MATLAB environment. After loading the data, missing headers such as Common Interval, Common Mid-Depth, Source ID, Receiver ID were computed and added to the data headers. After a careful study of the data in the different sort domains— Common Source Gather, CSG; Common Receiver Gather, CRG; Common Mid-depth Gather, CMG; and Common Interval-depth Gather, CIG), the data length was reduced from 200 ms to 100 ms. Energy bursts were surgically muted, and trace balancing was applied.

The presence of tube waves, P direct arrival, and S direct arrival in Figure 1 masked the primary energy that is needed to image the inter-well geology. The first task was to suppress or remove these high amplitude non-reflection events without damaging the true reflections. Tube waves attenuation was performed after transforming the data to frequency–wave-number ($f - kx$) domain. In $f - kx$ domain, tube waves lined-up within a narrow spectral band in the low f/kx corner. A multi-channel velocity band-reject filter was applied to suppress the events in the range of (and lower than) the tube wave velocity. Tube wave attenuation was performed by running the filter twice: first, in the CS gather and later, in CR gather, in order to suppress the tube waves generated in the source well and receiver well (Hardage, 1983; Stewart, 1985) consecutively. The frequency plot of the raw data is shown in Figure 2.

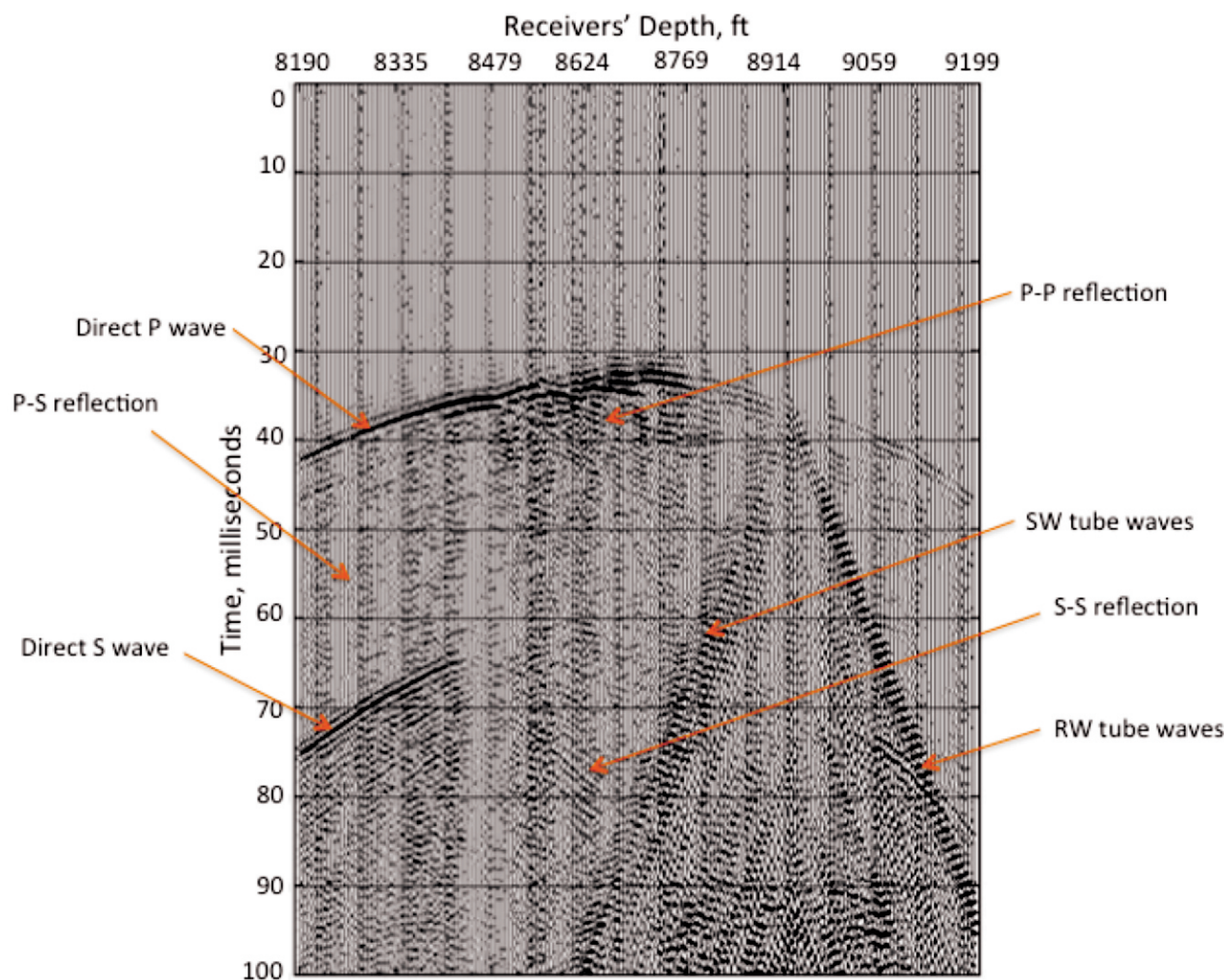


Fig. 1: Raw data showing some wave modes present in the data, SW is source well, RW is Receiver well, and R is receiver.

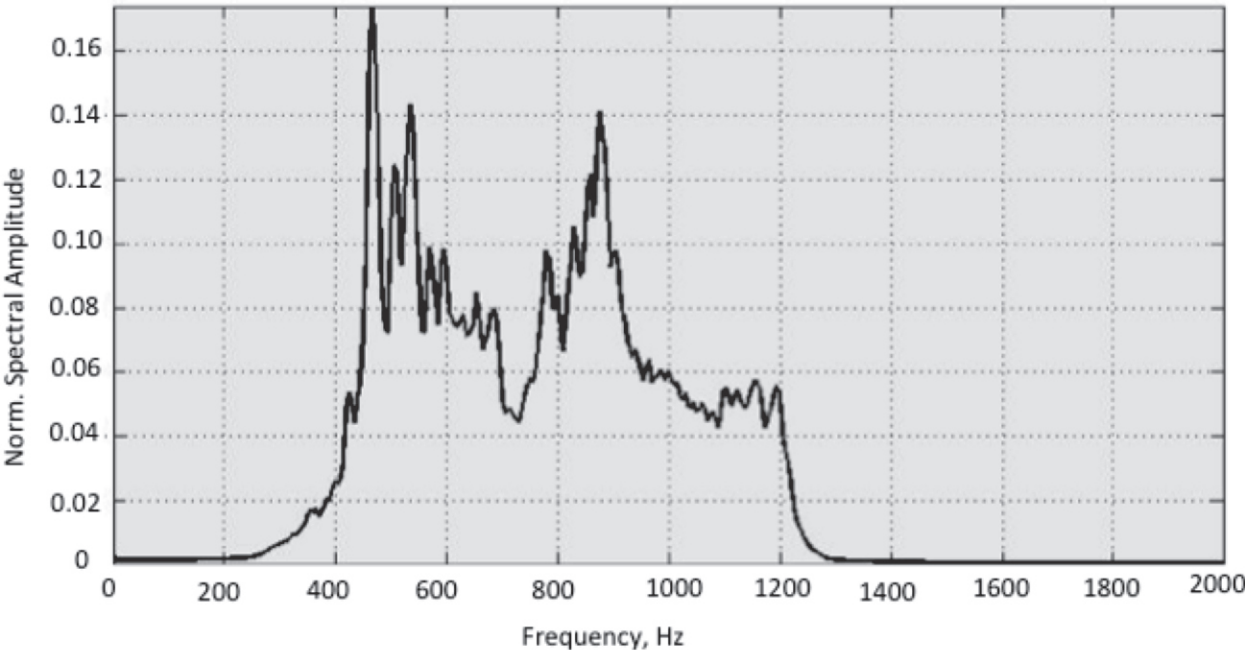


Fig. 2: Frequency spectrum of the raw data.

Following tube waves suppression, de-signature and deconvolution of seismic traces were performed to remove the effects of the source energy (source signature), compress the wavelets, and attenuate multiples. De-signature was done by using source impulse to deconvolve the seismic traces channel by channel. It was assumed that the trace with the least common mid-depth values in each CR gather travelled the shortest path, undergone the least changes due to attenuation and scattering (Raji and Rietbrock, 2013), hence was the closest to the source signature in term of waveform similarity. Therefore, source signature was extracted from the trace with the least CMD values in each CR gather. The extracted signature was used to de-signature the entire traces in each CR gather. Then the process is repeated at the next CR gather till the last one. Deconvolution was performed by modeling a zero-phase cross-correlation sweep using the frequency bandwidth used to generate the field data. The modeled energy was used to deconvolve the entire data in CS gather. De-signature and deconvolution were performed while the traces were aligned. Trace alignment was achieved by shifting all the traces using the picked first arrival travel time.

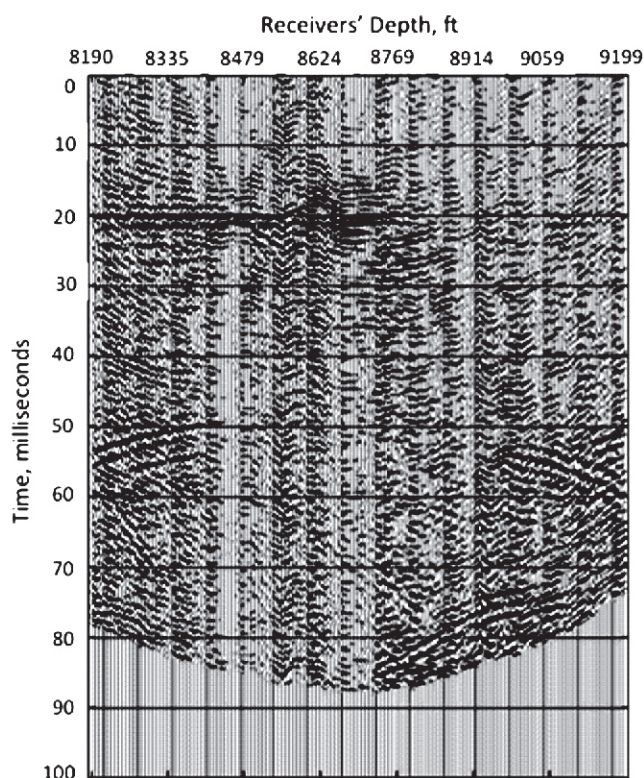


Fig. 3: Sample data with aligned traces after tube waves attenuation, de-signature, and deconvolution.

Next, first arrival P-waves were suppressed using mix-and-subtract method while the traces were still aligned. Trace mixing was performed using a 7-trace window median filter. Then, the pre-mixed traces were subtracted from the mixed traces. By this method, all the horizontally lined-up events at about 20 ms in Figure 3 were removed. Shear energy was removed by surgical muting of traces at about 45 ms (Fig. 3). Spectral analysis was performed to determine the events with extreme frequencies, and a band-pass filter (500 Hz-1000 Hz) was applied to remove the low frequency and high frequency noise. To suppress spectra leakages and frequency smearing, band-pass filtering was followed by 'tapering' using a long-tail Gaussian taper. To equalize the energy content of each trace, trace balancing was performed using the amplitude maxima in each trace.

Subsequently, converted waves were removed using velocity filtering techniques. A converted wave would have a velocity that is a mix of P-wave and S-wave velocities. This velocity would be lower than the P-P velocity, and higher than the S-S velocity. From previous studies (Langan et al., 1997, Zhu, 2014, Raji et al., 2016), P wave velocity in west Texas carbonate typically range from 16,500 ft/sec to about 23,000 ft/sec (equivalently, 4800 m/s – 7000 m/s) while S-wave velocity ranges from 8000 ft/sec to about 13000 ft/sec (2450 m/s – 4000 m/s). Since Shear energy had been muted prior to this stage, waves with velocity lower than 16000 ft/s (4848 m/s) were assumed to be converted waves and were therefore suppressed using a band-reject filter.

After the suppression of converted waves, the primary reflections appeared to have opposing dips. This was because they arrived at the recorder from opposite directions: some travelled upward to the recorder, while others travelled downward to the recorders.

When the data were transformed to frequency-wavenumber domain, the spectral of the down-going and up-going waves occupied different quadrants: up-going reflections occupies positive quadrant while the down-going reflections occupies negative quadrant. To separate the down-going reflections from the up-going reflections, series of multi-quadrant $f - k$ filters were designed and applied one after the other. One filter passed spectral with negative wavenumbers and rejected others; the other filter passed spectral with positive wavenumbers and rejected the others. Again, a long-tail Gaussian taper was applied to the data to suppress spectra leakages. At the end of this stage, the

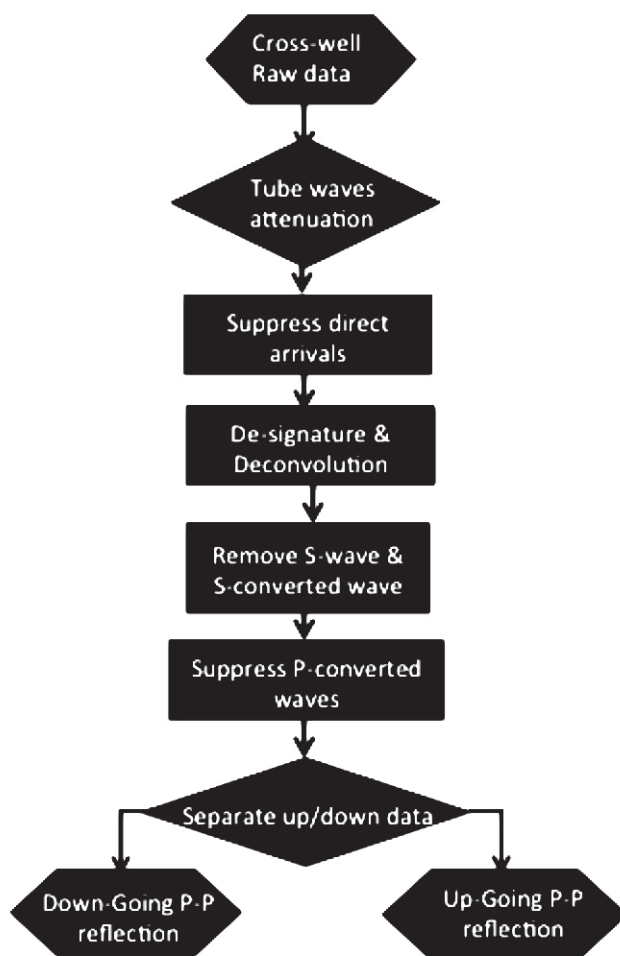


Fig. 4: Flowchart for the seismic processing

output data are the separated up-going P-P-reflection and down-going P-P reflections. The sequence of the processing techniques applied to the data is illustrated by a flowchart in Figure 4.

Result and Discussion

The goal of attenuating tube waves, applying deconvolution and de-signature to cross-well data was to achieve a 'clean' data that allows clear observation of different seismic events in the wave-field. Comparing Figure 1 to Figure 3, the combination of the three processing techniques improved the resolution of the data and achieved a clearer wave-field. As shown in Figure 1, source-well generated tube waves and receiver-well generated tube waves exhibited opposite dips. The source-well generated tube waves were better suppressed in Fourier-transformed CSG data, while the source-well generated tube waves were better suppressed in the Fourier-transformed CRG data. The advantages of mix and subtract method (Raji, 2016) for attenuating direct arrivals over velocity filtering method

is evident in Figures 5a & 5b where the reflection events around the direct arrivals, at about 200 ms, were preserved. Velocity filtering techniques commonly used for removing direct arrivals will suppress the shallow reflections around the direct arrivals. This will result into poor image of the shallow reflectors in the stacked and migrated seismic sections (Stewards, 1985; Steward and Marchisio, 1991).

The sample data (Fig. 5) after the removal of shear energy and filtering the events with extreme frequencies is shown in Figure 6a. In figure 6a, only P-wave and P-wave converted energy are present as the S-wave and S-converted waves have been 'surgically' muted. The data sample after removing P-converted waves is shown in Figure 6b. It is clear in Figure 6b that P–P reflections that were masked in Figure 6a are now easily noticeable after the removal of converted waves. The opposite dipping events seen in Figure 6b are up-going and down going reflections. Reflections produced by the reflectors above the recorder that travelled downward to reach the recorder are known as down-going reflections. Those produced by the reflectors below the recorder and travelled upward to reach the recorder are known as up-going reflection. The down- going P-P reflection data after the removal of the events with opposite dip are shown in Figure 7a, while the up-going P-P reflection data after the removal of the events with opposing dip are shown in Figure 7b. Literarily speaking, Figure 6b is the summation of Figures 7a and 7b.

The reflection processing was undertaken in the different sort domains where the undesired seismic arrivals can be best eliminated with the least damaging effect to the desired seismic arrivals. Attenuation of tube waves, suppression of converted waves and up-going/down-going separation were executed in frequency-wavenumber domain using different filters. In general, non-reflections arrivals in cross-well data are best suppressed by $f-k$ multi-channel filters after 2D – Fourier transformation of the data. This is because, in $f-k$ domain, reflections and non-reflection arrivals have different characteristics such as dip and move-out (Yilmanz, 1987). The use of mix-and-subtract method for suppressing direct waves was a key step in the processing. The method preserved the primary reflections found in the same time window with noise. The method is key to cross-well seismic processing because source and receivers are placed close to the target layers during data acquisition. The design and execution of sort-while-processing technique is another key technique in the seismic processing described above. the technique saved time and allows the automation of the entire workflow.

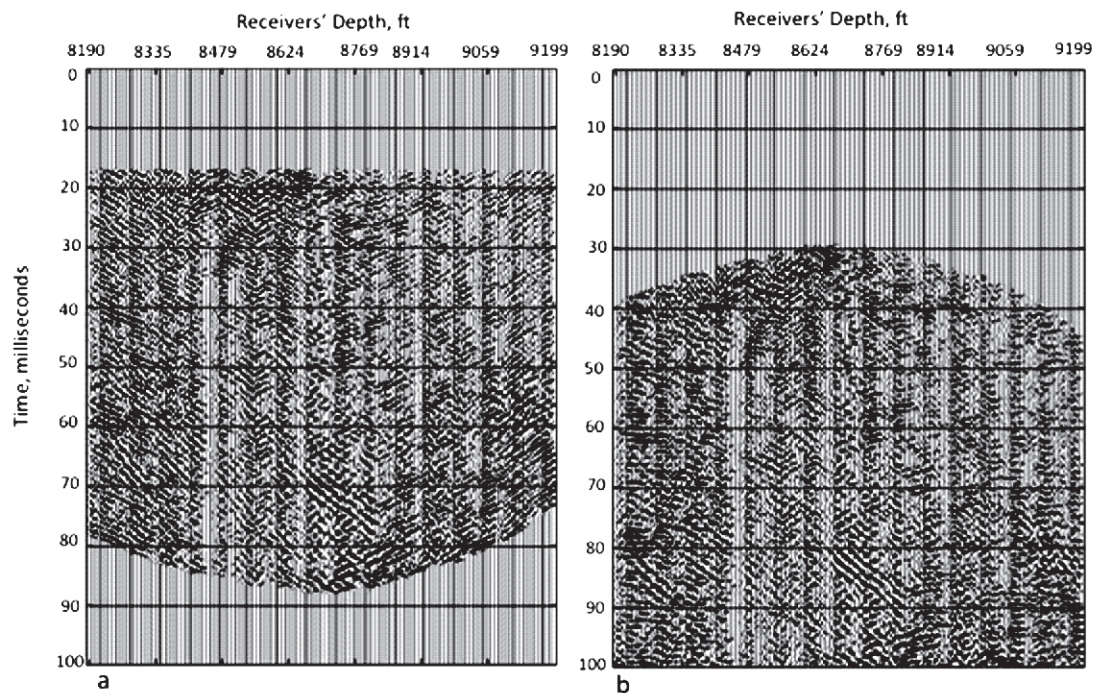


Fig. 5: Sample data after suppressing P wave direct arrivals (a) while traces are aligned, (b) while traces are de-aligned.

The data processing workflow described in this paper is divided into two parts: pre-processing; and wave-field separation. Pre-processing is a term used to describe the steps taken to suppress high amplitude energies obscuring the primary reflections. The result of this pre-processing produced high resolution seismic data dominated by reflections and converted waves. In wave-field separation, shear and converted waves were removed, and the multi-directional P reflections were separated into up-going and down-going reflections. The application of re-sort-while-processing and multi-channel dip filter allows the automation of the entire workflow. Wave-field processing yielded two structurally simple wave-fields that are separately dominated by up-going P and down-going P reflections. For the purpose of completeness, the brute-stacked reflection image of the up-going reflection data is shown in Figure 8. The image is constructed using first-pass brute-velocity to stack and migrate the data shown in Figure 7b). Velocity modeling is achieved by traveltimes velocity tomography. The reflection image (Fig. 8) is constructed using Reverse Time Migration (RTM) method. Figure 8 is not the final image. Refined velocity model and post imaging processing are required to produce the final RTM image.

Conclusion

The step-by-step procedure for enhancing reflection

arrivals in cross-well seismic data has been demonstrated using in-house processing codes. Results obtained showed that the procedure is efficient and capable of producing structurally simple reflection dominated data from the complex seismic arrivals recorded in the field. The processed cross-well seismic data is structurally similar to the processed surface seismic data and is image-able by the conventional imaging technique such as Reverse Time Migration. The brute image of the up-going reflection shows horizontal geological layers that are traceable from the source well to the receiver wells. With slight modification to the processing steps, the procedure described can be applied to process any set of cross-well seismic data to enhance P-wave reflections and S-wave reflections.

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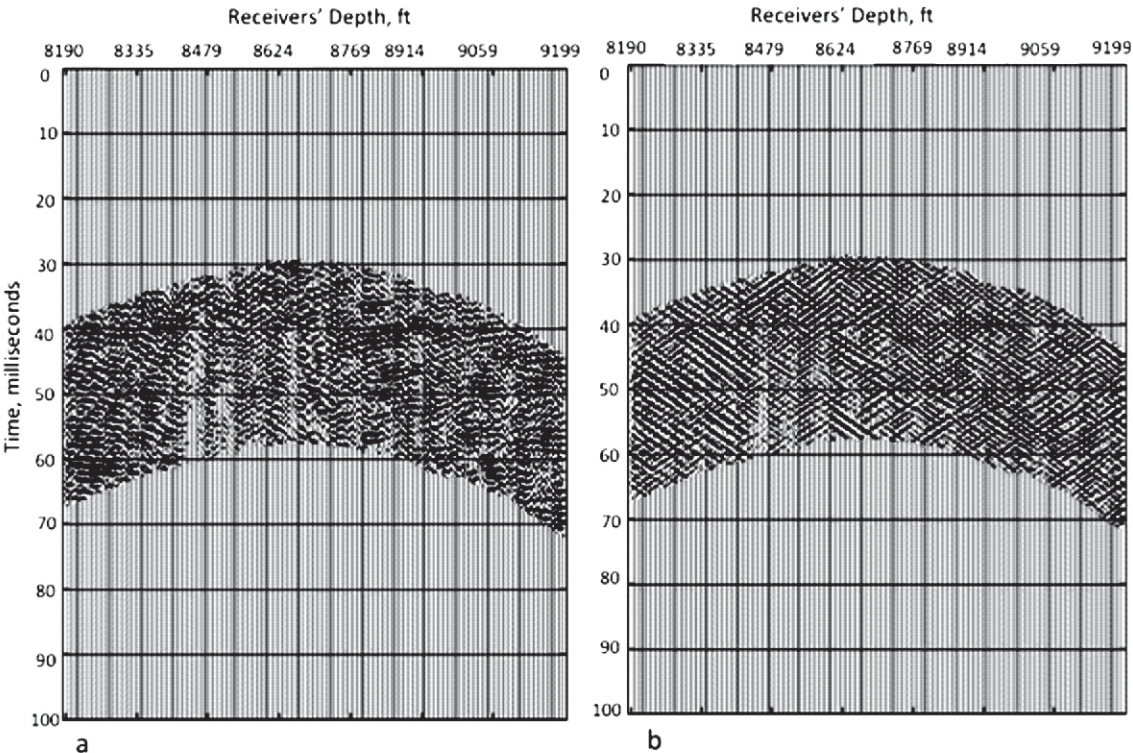


Fig. 6: (a)The sample data after removing shear energies and (b) after removing shear energies and converted waves.

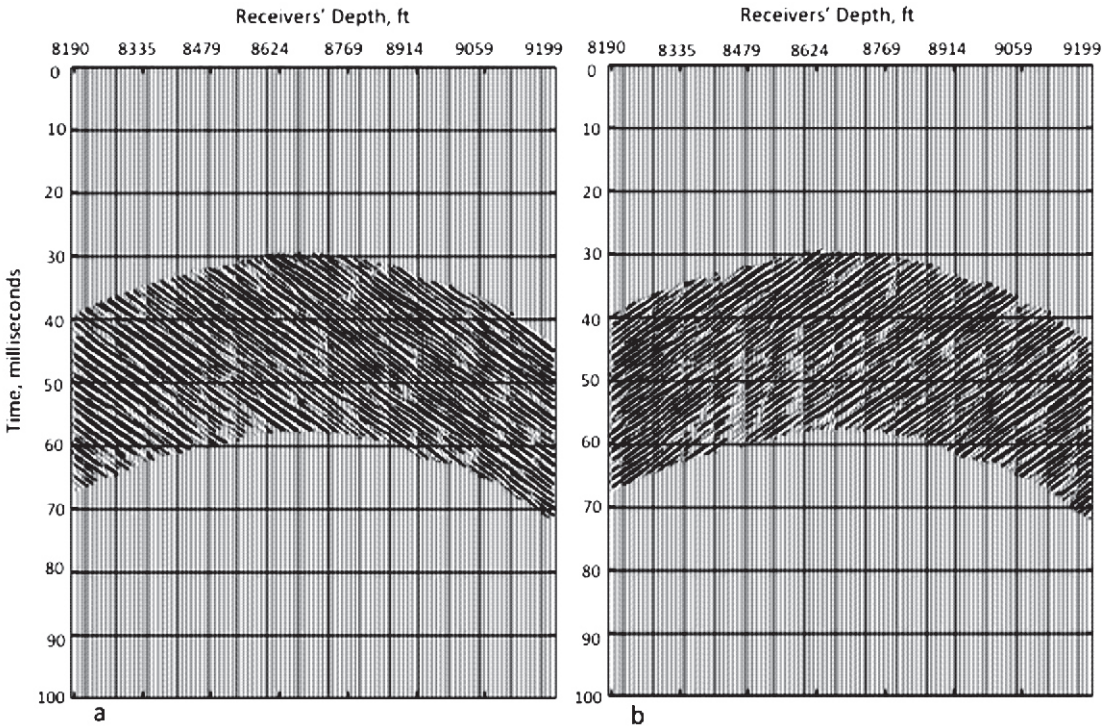


Fig. 7: Sample data after separating the data to (a) down-going reflections and (b) up-going reflection.

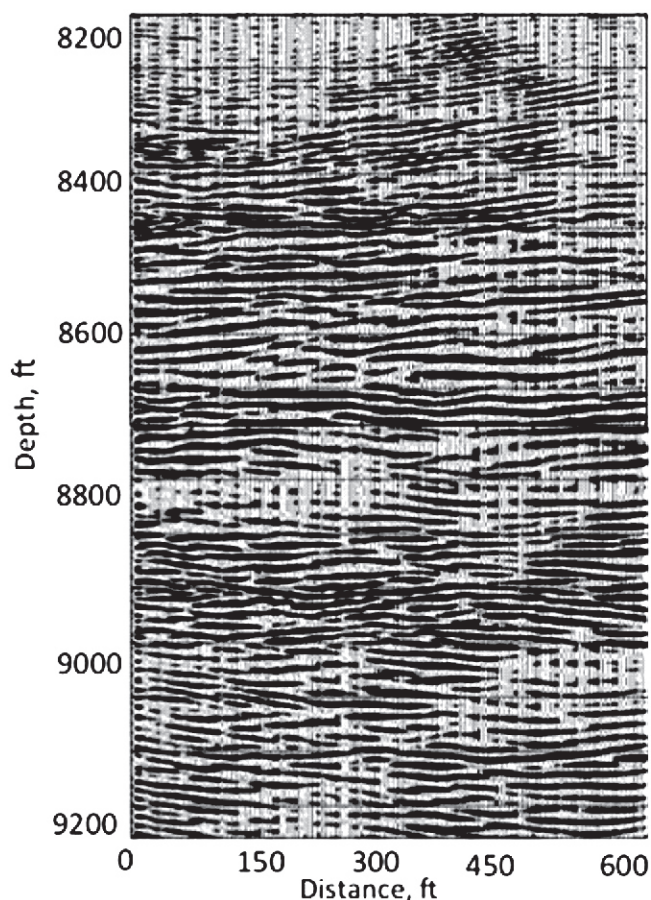


Fig. 8: Reflection Image of the up-going data constructed by RTM using brute velocity.

References

- Baker, L.J. and Harris, J.M. (1984). Cross-Borehole Seismic Imaging: *Geophysics Journal*, Vol. 97, pp. 151-160.
- Daley, T.M. and COX, D. (2001). Orbital Vibrator Seismic Source for Simultaneous P- and S-Wave Cross-Well Acquisition. *Geophysics Journal*, Vol. 66, pp. 1471-1480.
- Daley, T.M., Myer, L.R., Peterson, J.E., Majer, E.L. and Hoverstern, G.M. (2008). Time-Lapse Crosswell Seismic and VSP Monitoring of Injected CO₂ in a Brine Aquifer, *Environmental Geology*, Vol. 54, pp. 1657-1665.
- Hardage, B.A. (1983). *Vertical Seismic Profiling, Part A: Principles*, Geophysical Press, Amsterdam.
- Harris, J.M., Nolen-Hoeksema, R., Rector, J.W., Lazaratos, S.K. and Van Schaack, M.A. (1995). High-Resolution Cross-Well Imaging of a West Texas Carbonate Reservoir: Part I-Project Summary and Interpretation: *Geophysics Journal*, Vol. 60, pp. 667-681.
- Khalil, A.A., Stewart, R.R. and Henley, D.C. (1991). Full Waveform Processing and Interpretation of KiloHertz Cross-Well Seismic Data: *Geophysics Journal*, Vol. 58, pp. 1248-1256.
- Langan, R.T., Lazaratos, S.K., Harris, J.M., Vassiliou, A.A., JENSEN, T.L. and Fairborn, J.W. (1997). Imaging of a Stratigraphically Complex Carbonate Reservoir with Cross-well Seismic Data. *Carbonate Seismology*: pp. 417-424. doi: 10.1190/1.9781560802099.ch17

- Lazaratos, S.K., Harris, J.M., Rector, J.W. and Van Schaack, M.A. (1995). High-Resolution Cross-Well Imaging of a West Texas Carbonate Reservoir: Part 4—Reflection Imaging: *Geophysics Journal*, 60, pp. 702-711.
- Lazaratos, S., Rector, J.W., Harris, J.M., and Van Schaack, M. (1991). High-Resolution Imaging with Cross-Well Reflection Data: 61st Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, pp. 150-153.
- Li, G. and Stewart, R.R. (1993). Reflection Imaging for Cross-Well Seismic Data: Friendswood, Texas. *Crewes Research Reports*, Vol.5.
- Pereira A.M. and Jone, M. (2010). Fundamentals of Borehole Seismic Technology. Schlumberger, Texas, U.S.A.
- Raji, W.O. and Rietbrock, A. (2013). Determination of Attenuation (I/Q) in Reflection Seismic Data, *Journal of Geophysics and Engineering* Vol. 10, No. 4, pp. 1 - 8 (0 4 5 0 1 2) , <http://iopscience.iop.org>.
- Raji, W.O. (2016). Seismic Processing of Ultra-Shallow Reflection Surveys. *Ilorin Journal of Science*, Vol. 3, No. 1, pp. 17–26.
- Raji, W.O., Harris, J.M. and Lu, S. (2016). Seismic Velocity Tomography for CO₂ Monitor in Subsurface Geological Structures. *Journal of King Saud University-Science*. Vol. 28, No. 5. <http://dx.doi.org/10.1016/j.jksus.2016.10.006>.
- Raji. W.O., Harris, J.M. and Youngxin, G. (2017). Wave-Field Analysis of Cross-Well Seismic Data. *Arabian Journal of Geoscience*. Vol. 10, No. 217. DOI 10.1007/s12517-017-2964-6.
- Rector , J.W., Lazaratos, S.K., Harris, J.M. and Van Schaack, M.A. (1995). High-Resolution Cross-Well Imaging of a West Texas Carbonate Reservoir: Part 3-Wave-Field Separation of Reflections: *Geophysics*, 60, pp. 692-701.
- Rietsch, E. (2010). SEISLAB Software for the Analysis of Seismic and Well-Logs Data: A Tutorial.
- Stewart, R.R. and Marchisio, G. (1991). Cross-Well Seismic Imaging Using Reflections: Presented at the 61st SEG International Annual Meeting, Houston, Texas.
- Stewart, R.R. (1985). Median Filtering: Review and a New F/K Analogue Design: *J. Canadian Society of Exploration Geophysics.*, Vol. 21, pp. 54-63.
- Van Schaack, M., Harris, J.M., Rector, J.W. and Lazaratos, S. (1995). High-Resolution Cross-Well Imaging of a West Texas Carbonate Reservoir: Part 2-Wave-Field Modeling and Analysis. *Geophysics*, Vol. 60, No. 30, pp. 682-691.
- Yilmaz, O. (1987). *Seismic Data Processing*. Society of Exploration Geophysicists.
- Zhu, T. (2014). *Seismic Modeling, Inversion, and Imaging in Attenuation Media*. Ph.D. Thesis, Stanford University.
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