

WAVEFIELD SEPARATION FOR SHEAR WAVE REFLECTION ENHANCEMENT IN SEISMIC RECORDS

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Abstract

S-waves in borehole seismic data can provide velocity, attenuation, anisotropy and reflectivity information that are crucial for delineating reservoir geometry and fluid flow structures. Despite the success and other potential benefits of including shear waves in the interpretation of seismic data to discriminate gas related amplitude anomalies from non-hydrocarbon related amplitude anomalies, little efforts have been applied to the development of shear wave technology. S-waves processing is yet to become a routine in borehole geophysics. This paper describes a procedure and some techniques for processing shear waves in a multi-component borehole seismic data— as a precursor for S-wave reflection imaging. The procedure is divided into three key stages, namely: suppression of P-wavefield in the multi-component data; attenuation of non-reflection arrivals in the S-wavefield; and separation of S-S reflection into up-going and down-going components. A set of high-resolution crosswell data acquired in a west Texas Oil field, U.S.A is used to test the method. The processed data confirmed the appropriateness of the method presented in this paper. The results yielded separated up-going and down-going S-S reflections that are traceable to the various reflectors depths. Shear wave reflection processing is a key stage in the development of shear wave technology for in oil and gas application.

Keyword: Crosswell seismic data, Shear waves; S-wavefield; S-S reflections processing; Wavefield decomposition.

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1.0: Introduction

Joint P- and S-wave interpretation of subsurface structures provides reliable interpretation of subsurface stratigraphic layers. While P-wave (compressional wave) is sensitive to fluid saturation and fluid compressibility, S-wave (shear wave) is more sensitive to reservoir heterogeneity – such as changes in porosity and permeability that may affect fluid flow. Shear waves respond to a different combination of elastic constants and density than P-waves (Helbig and Mesdag, 1982; Tatham and Steward, 1993). The inclusion of S-wave in routine interpretation of hydrocarbon-saturated units can aid interpreters to discriminate AVO that is due to pore fluid from those due to the changes in the lithologic properties. Studies by Tatham and Krug (1985), Tatham and McCormack, (1991) showed that the combination of P-wave and S-wave data in estimating the thickness of gas-reservoirs for cases with and without P-wave bright spots is more accurate than those from P-wave interpretation only. Despite these advantages and other numerous potential applications of S-wave in mitigating cases of wet wells, shear wave seismology for

hydrocarbon applications is still underdeveloped. Reflected S wave is yet to become the standard for imaging subsurface structures. Only few papers (e.g., Lazaratos et al., 1995; Zhu, 2014; Raji, 2017) include shear wave data in velocity modeling or reflection imaging. Probable reason for the underdevelopment of S-wave technology for crosswell seismology could be the lack of standard procedure for processing shear wave modes in the presence of other competing wave modes present in a crosswell data.

The developments in crosswell seismology is focused on P-waves. Very little attention has been devoted to shear waves. Li and Steward (1993) conducted a physical modelling study for Crosswell data and proposed a CDP-based processing method for enhancing P-reflections in crosswell data. Some of the concepts were expanded by Li and Steward (1992a; 1992b). Lazaratos et al. (1994; 1995) discussed the procedure for processing and imaging P-wave reflection using a set of data acquired by Chevron in a West Texas Oil Field, U.S. Harris et al (1995) used P-wave travel time tomography and P-reflection imaging to study the internal structure and CO₂

flow in a McElroy Carbonate Reservoir. Examples of other studies on crosswell data include Cai and Schuster, 1993; Van Shaack et al., 1995; Rector et al., 1994; Rector et al., 1995; Raji et al., 2017; Raji et al., 2018. Raji et al. (2017) performed elastic and acoustic data modelling of a crosswell data acquired in a West Texas oil field. The study shows that reflected, transmitted, converted, and tube waves are very prominent in crosswell seismic data and that full wavefield can be decomposed to P-only or S-only wavefield. However, most crosswell study have only used P-wave reflections and P-direct arrival to obtain information about the subsurface medium between the boreholes.

Historically, the underdevelopment of shear wave technology for crosswell data can be traced to the negligence of S-wave in surface seismic data – the conventional seismic data. The problems of S-wave in surface seismic include the cost of acquiring direct shear wave data; the cost and damaging effect of massive shear wave sources, and the poor resolution of shear waves. But in crosswell data, S-wave has resolution that is four - five times higher than the resolution of P-wave in surface seismic data. The source and receivers used in crosswell acquisition are capable of generating and recording P- and S-waves simultaneously (Daley and Cox, 2001) at no additional cost. So the inclusion of S-wave in the routine processing, application, and interpretation of crosswell data is not expensive. All that is needed is the development of the technology. The development and application of the techniques required to process reflected shear waves in crosswell data is the goal of this paper.

The S wavefield of crosswell data is structurally more complex than P-wavefield (Fig 1). Among others, the S-wave direct arrivals are corrupted by the late P-wave arrivals and converted S-waves. Therefore, direct shear wave processing for velocity tomography is rigorous than direct P-wave processing. The S-wavefield is populated by S-direct arrival, S-S and S-P reflections, up and down going S-waves reflections, slow P-converted waves, and tube waves among others (Raji et al., 2017). Consequently, S-wave reflection processing for crosswell data requires some additional steps and techniques than those required to process P-wave reflections. The

presence of anisotropy due to subsurface layering, particularly the fine bedding in shale unit, and the consequent complication in stacking velocity, made the processing of SV data to be more challenging than SH data (Tatham and Steward, 1993). The steps and techniques required to isolate, process, and enhance reflected S-waves data in the presence of the different wave modes in crosswell data is the object of this paper. In general, the sequence of the steps may vary slightly depending on data quality. The processing workflow described in this paper is divided into three main stages: (i) reduction of full crosswell data into S-wavefield; (ii) suppression of converted waves, and other non-reflection events in S-wavefield; and (iii) separation of reflected S-wave into Up-going reflections and down-going reflections.

2.0: Field Acquisition Geometry and Data description

As part of a reservoir characterization project, high-resolution crosswell seismic survey was conducted in a section of the west Texas oilfield to monitor fluid flow in a carbonate reservoir (Langna et al., 1997). The acquisition geometry comprised 201 sources and 203 receivers. Sources were deployed in one well from depth level 8210 ft (~2488 m) to 9209 ft (~2790 m) at 5 ft (~1.5 m) intervals. The sources are cylindrical piezoelectric blender (Daley and Cox, 2001) driven with a linear sweep from 250 - 2000 Hz. The receivers are deployed in the second well from depth level 8190 ft (~2482 m) to 9199 ft (~2788 m) at 5 ft (1.5 m) intervals. The source and receiver well are separated at the top by a nominal distance of 605 ft (~182 m). Seismic arrivals were recorded by hydrophone receivers within a listen time of 200 ms. The full survey resulted in a raw data of over 40,803 traces. The full description of the survey is given in Langna et al. (1997) and Raji (2016).

A representative raw field data is shown in Figure 2a. Figure 2a is common shot gather from a shot located at depth 8315 ft (~2520 m). This data is subsequently known as sample data. Each trace in the data consists of 801 sample points with 0.25 ms sample time. Figure 2b is the frequency spectrum of the full data.

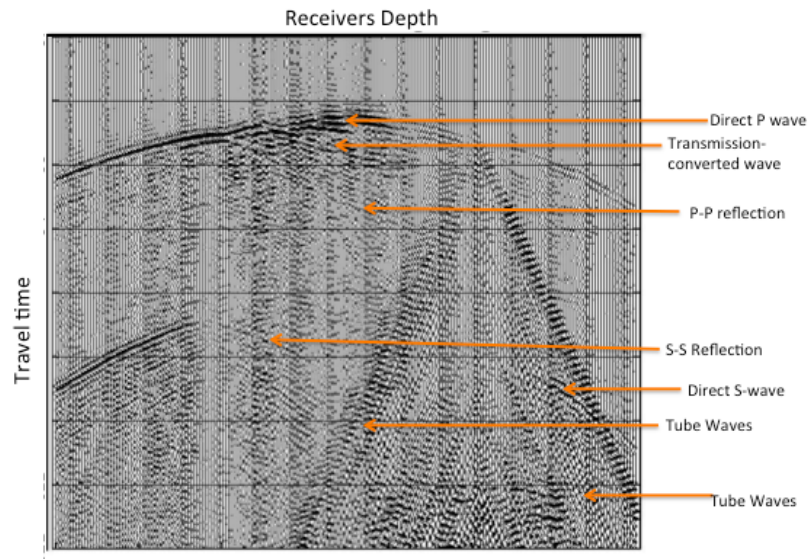


Figure 1: A typical crosswell wavefield showing different arrivals (Raji et al., 2017)

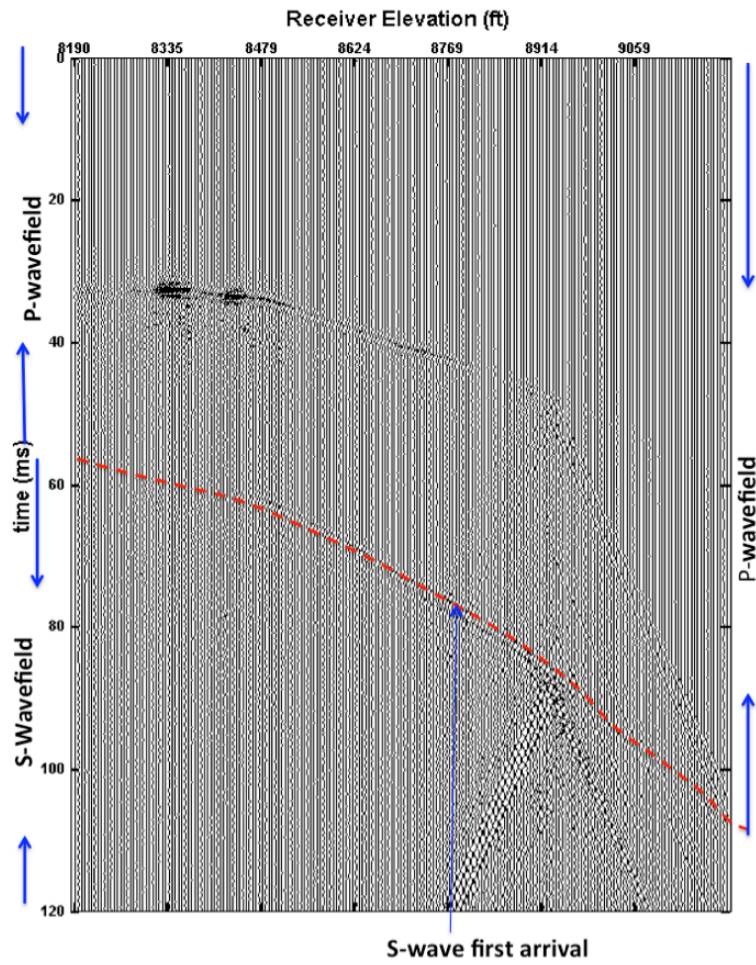


Figure 2a: Raw field data. The red line roughly separates the data into P- and S-wavefields

3.0: Data processing

In this study, crosswell data processing for S-wave reflections enhancement is divided into three key stages: (i) suppression of P-wavefield; (ii) attenuation of non-reflection arrivals in S wavefield; and (iii) separation of S-reflection data to up-going and down-going components. The three key stages in data processing are described in the subsequent sections. First, raw data were sorted to the different data domains (common source gather, CSG; common receivers gather, CRG; common

3.1: Suppression of P-wavefield in the Full Data

Before removing P-wave from the full wavefield, tube waves are attenuated. Tube waves are the high-energy low-velocity linear events running from the top through to the bottom of data. The two types of tube waves in Figures 1 and 2 have opposing dips: the tube wave travelling from the top of the receivers' well to the bottom, TB1; and the tube waves travelling from the bottom of the receiver well to the top, TB2. As we can see that the tube waves obscured the reflections in the data. It is therefore necessary to attenuate them before suppressing the P-wavefield in order to gain better

Following tube wave suppression, S direct waves were aligned at 60 ms using the first break travel time picks for shear waves (Fig. 4a). Trace alignment allows the accurate estimation of the time window for direct S-wave. The map of the traveltimes used to align the traces is shown in Figure 4b. For the purpose of this study, the full wavefield is divided into P-wavefield and S-wavefield (Fig. 2a). P-wavefield is used to describe all the seismic arrivals – reflections and non-reflections found between the P-wave first arrivals and the S-wave first arrival (in this case, from 0 to 60 ms), while S-

3.2: Suppression of Non-Reflection Arrivals in the S-Wavefield

The non-reflection arrivals in the S-wavefield include direct waves, converted waves, the multiples, and the noise. These non-reflection arrivals are the many obstacles to overcome in order to achieve interpretable S-reflection image. The first important task is to suppress direct waves without damaging the subtle reflections around them. Direct waves were suppressed using the mix-and-subtract techniques while the traces are aligned. A median filter of 9-trace window length was used for mixing the traces. Then, the mixed traces were subtracted from the pre-mix traces. The data in figure 5a after the attenuation of direct S-wave is shown in Figure 5b. Although velocity filtering is often used for suppressing direct waves, velocity filtering for direct waves processing has a damaging consequence on the reflections terminating at the direct arrival window. Mix-and-subtract technique preserves these reflections. Hardage (1985) and Stewart (1985) gave detailed reviews of the design and application of median filtering in seismic data processing. The procedure described by Hardage (1985) is modified to serve the purpose of

depth gather, CDG; and common offset gather) in order to analyse the different seismic arrivals. Signal to noise ratio (S/N) differs from one data domain to another. The frequency plot for the full data is shown in Figure 2b. Spectral analysis and filter test on the data showed that tube waves occupy the high amplitude low frequency left corner of the spectrum, most of the seismic events fall between 400 -1200 Hz. The notch at about 700-750 Hz is a low amplitude high frequency noise associating with some reflections (Li et al., 1992; Raji et al., 2017).

control of the direct S-wave and the reflections around them. To attenuate tube waves, data is transformed to the frequency-wavenumber (f, k) domain. In f, k domain, tube waves are lined up within a narrow spectral band in the positive and negative quadrants. Multi-channel velocity band-reject filters were applied to the data to suppress the tube waves. Next, data is resorted into CR domain and a similar operation was performed in f, k . Suppression of tube wave in CS and CR gathers ensure that the tube waves generated in the source and receiver wells are properly suppressed (Hardage, 1985). The data after tube waves suppression is shown in Figure 3.

wavefield is used to describe the seismic arrivals - reflections and non-reflection found in the direct shear wave space to 120 ms. The data was truncated at 120 ms for the purpose of display. The P-wavefield was completely suppressed by setting all the signals to zeros using top muting technique within a time-window of 60 ms while data were aligned. To suppress spectral leakages due to filters' operation, a boxcar-shaped taper was applied to the data. The sample data after the suppression of P-wavefield is shown in Figure 5a.

removing (up-going and down-going) direct S-waves from later arriving reflections in field data. As shown in Figure 5a compared to figure 5b, reflection event are better noticed after the suppression of direct arrivals.

Following suppression of direct S-waves, deconvolution and de-signature were performed. To designate the traces, the source signature was extracted from the trace with the least common mid depth value in each CR gather. The extracted signature was used to de-signature the traces in that CRG. The trace with the least CMD is assumed to have travelled the least distance from source to receiver, and hence is the closest to the source signature (in terms of waveform and energy) because it underwent the least change due to the earth filtering effects - attenuation. Deconvolution was performed by deconvolving the entire traces in the data with a zero phase cross-correlation sweep (modeled using the frequency band) that was used to generate the field data. The goals of deconvolution and de-signature were to compress the seismic wavelets, attenuate multiples, and improve the resolution of the data. To attenuate coherent and non-coherent noise, a series of band-pass filters were tested to determine the optimum filter for the operation.

Each time a band-pass filter is applied, the resultant data and its frequency spectrum are compared with the previous data, channel by channel, and with their respective frequency spectrum. The filter test showed that the band 400 -500 1100-1200.

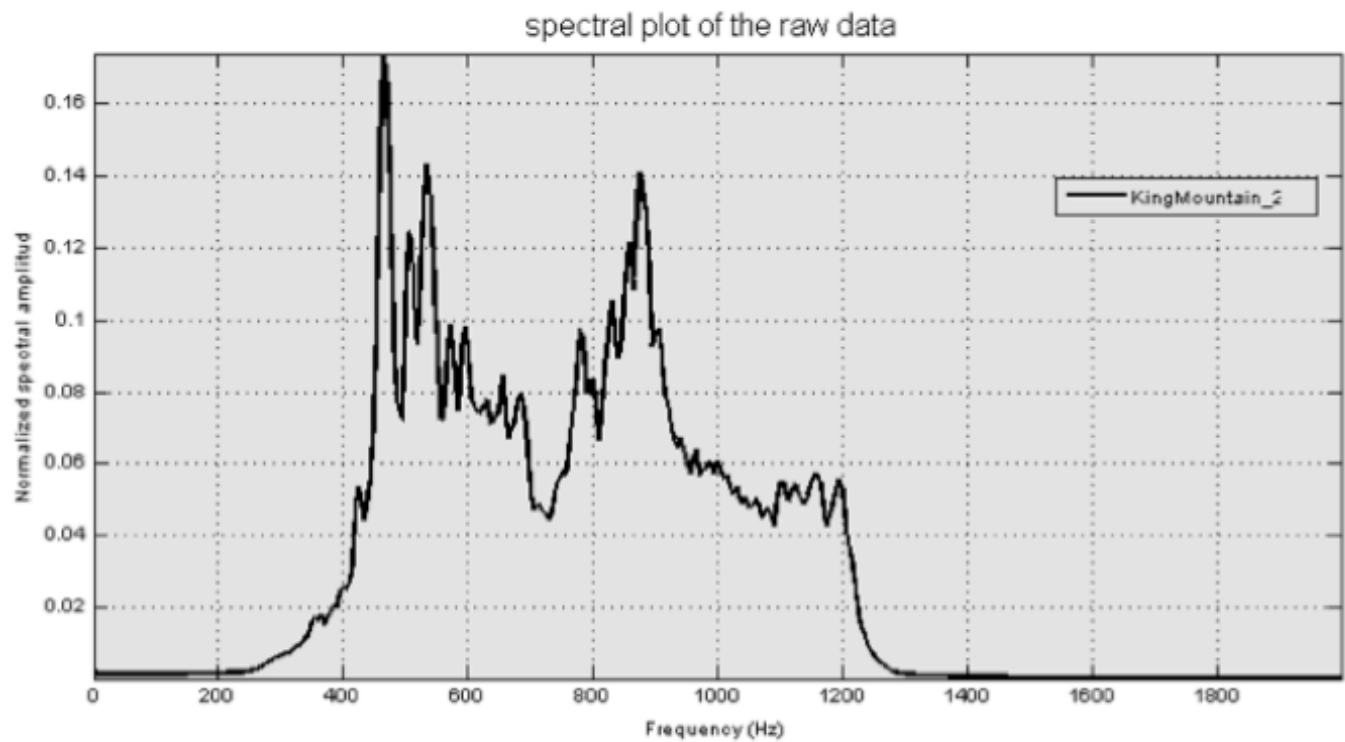


Fig. 2b: Amplitude- frequency spectrum of the data

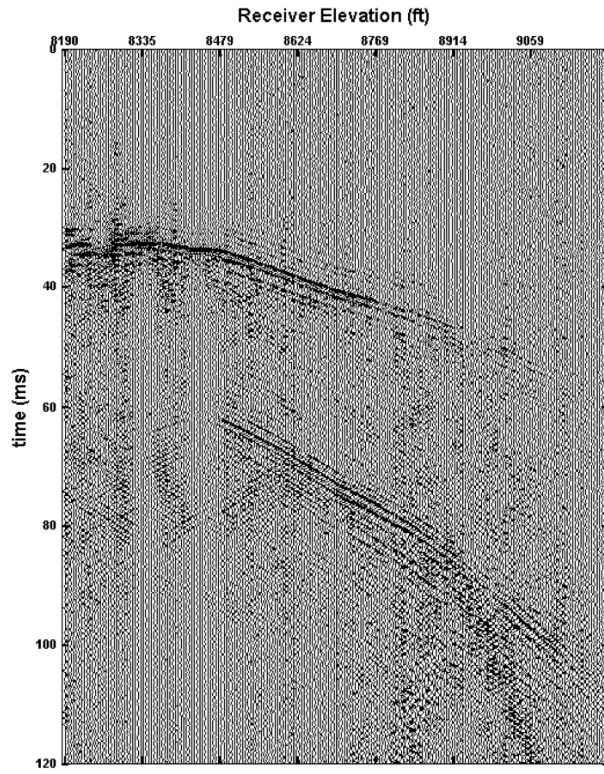


Fig. 3: Field data after tube wave attenuation

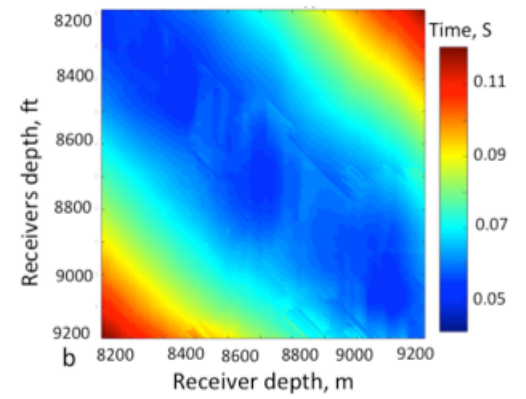
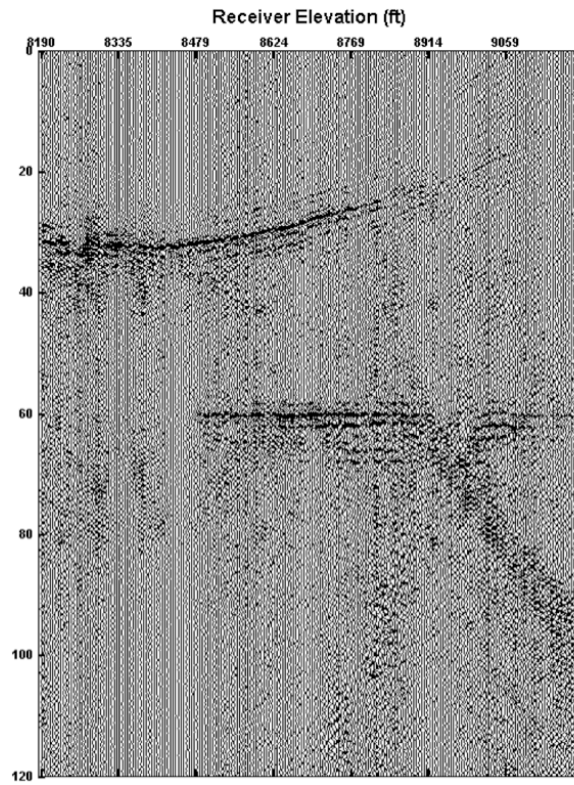


Fig. 4: (a)Data showing aligned S direct waves, and (b) map of S of S-wave Travel time

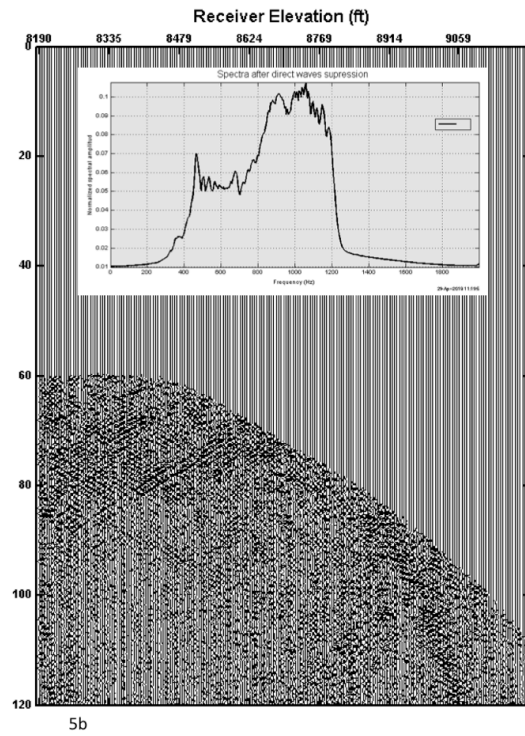
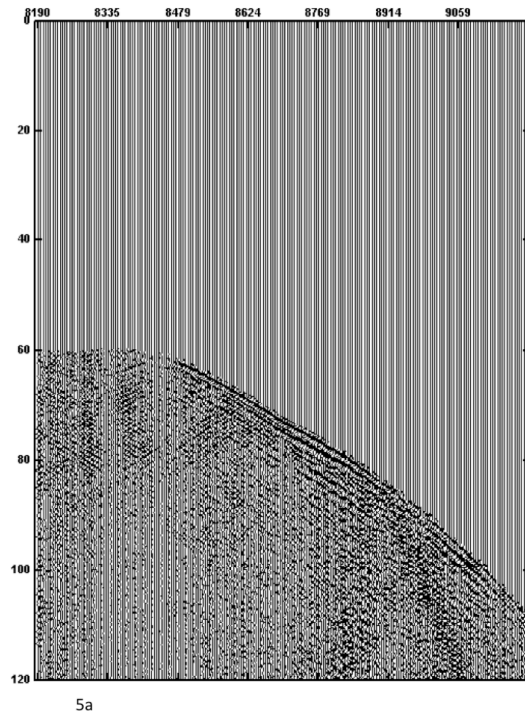


Fig. 5: (a) Datas howing S-wavefield only after the removal of P-wavefield, (b) Figure 5a after attenuating direct waves. Figure 5b inset- the amplitude spectrum of the data.

Produced the best results with the least damaging effects. Consequently, a band filter of 400 -500 1100-1200 was applied to the entire data to suppress noise. To suppress spectral leakages consequent to filter's operation, a Gaussian taper was applied. Following this, the trace were balanced using the maximum amplitude in each trace

3.3: Separation of up –going and down-going Shear Wave Reflections

Unlike in surface seismic survey where reflections travel upward to the recorders, in crosswell acquisitions, reflections could travel upward or downward to the recorder, depending on the position of the reflectors to the recorders. Reflections originating from layers above recorder and travelling downward to the recorder are known as down-going reflections, while the reflections originating from layers below the recorders and traveling upward to the recorders are known as up-going reflections. These two reflections travel in opposite directions. This explains why some reflections are crossing one another in Figures 5b and 6. The main goal of this section is to suppress the converted waves and separate the up-going reflections from the down-going reflections. By this separation, the resulting data, either the up-going or down-going, is structurally similar to processed surface seismic data.

Before up and down reflections separation, converted waves in the data were removed using a band reject velocity filter. Generally, a converted S-wave (e.g., S-P wave) is expected to have velocities that are higher than the velocities of S-S reflections. Using the velocity range of S-wave known from well logs, velocity band-reject filters were designed and applied to suppress the converted waves. The data after suppressing converted waves is shown as Figure 6. After the removal of converted waves, up and down-going separation of S-reflections was performed in the frequency-wavenumber (f, k) domain. Events with different dips or dip directions that may interfere in the time-depth (t, z) domain can be separated or isolated in the f, k domain. So the data was transformed from t, z domain to f, k domain using 2D Fourier transform. In f, k domain the up-going reflections and the down-going reflections occupied the positive and negative

quadrants respectively. The convention is that an event will have a negative dip if the reflection time increase as the depth increases while an event will have a positive dip is the reflection time increases while the depth decreases. Positive dip in the t, z domain is associated with positive wave numbers in f, k and negative dips in the t, z domain are associated with negative wavenumbers in the f, k domain (Khalil et al., 1991).

Given the above described phenomenon, two f, k filters were designed and applied to the data one after the other. One filter rejected the data in the positive quadrant but passed the ones in the negative quadrant. The other filter passed the data in the positive quadrant and rejected the ones in the negative quadrant. Following this, trace balancing was done for the up-going and down-going data separately based on the peak amplitude criterion. The up and down S-reflection data for the data sample are shown in figures 7a and 7b respectively. After the separation of the S-S reflections, many continuous reflection events are now seen on both records. Most of these events represents symmetrical shear, S-S reflections produced by subsurface interfaces between the sources' and receivers' borehole. The final data in figure 7a or 7b is structurally similar to the processed surface seismic data. Therefore, the data can be imaged qualitatively using some conventional imaging algorithms.

4.0: Discussion

The procedure for wavefield processing for shear wave reflection enhancement has been described using set of crosswell data acquired in West Texas, USA. The results showed that S-S reflection can be isolated from a multicomponent crosswell data and decomposed into up-going and down-going S-S reflections that can be separately imaged to illuminate subsurface structures and stratigraphic layers. The procedure can be summarized in three main steps: (i) suppression of P-wave field, (ii) attenuation of non-reflections in the S-wavefield and; (iii) separation of S-S reflections into the up-going and down –going reflections. For the purpose of convenience, the full wavefield was roughly divided into two: the P-wavefield and the S-wavefield.

P-wavefield was used to describe the first 60 ms part of the data when traces were aligned. This part of the data is dominated by P direct arrivals, P converted waves, transmission converted waves, and P-P reflections. S-wavefield is used to describe the remaining part of the data starting from the S-direct arrivals at about 60 ms down to 120 ms.

As seen in figure 3 compared to figure 2a, removal of tube waves that dominated the high energy spectra allowed a clearer observations of some reflections in Figure 3 that were not visible in Figure 2. Specifically, P-reflections originating from about 35 ms /8600 ft and the S-wave down-going reflections originating at about 72 ms /8190 ft were not visible prior to tube waves attenuation. Following the suppression of P-wave field, the S-wavefield become more accessible and the different arrivals became clearer. The Mix-and-subtract method used to eliminate the S direct arrivals was very efficient and has no damaging effect on the reflections. A comparison of the 5a and 5b show that the subtraction of the mixed-traces from pre-mix traces eliminated all the linear events that dominated the top section of the S-wavefield. These linear events in Fig.5a have high energies that obscured reflections terminating in the direct arrival space. A critical step in the mix-and-subtract method is the determination of optimum window length for the median filter. Too short window length will yield undesirable results while too long window length will introduce artifacts to the data.

To eliminate the converted waves and noise present in the data in Figure 5b, band pass, and notch filters were applied to the data successively. Removal of converted waves from the data in figure 6 was achieved using apparent dip discrimination. S-S reflections and S-converted reflections that are interfering in the t, x domain had different dips and wave numbers in the f, k domain. So, converted waves were isolated and suppressed in the f, k using dip discrimination. The absence of converted waves in the data in Figure 6 compared to Figure 5b accounts for the visible continuous reflections seen in Figure 6. The separated down-going and up-going reflections data are displayed in Figures 7a and 7b respectively. Despite some smearing, the $f-k$ filter performed well in separating the up and down-going reflections. These reflections are generated from layers at different depth as indicated by the shot gather. Any event that does not follow any specific reflection path can be canceled out by further processing such as binning in reflection mapping and summation of different receiver's map. Data in figure 7a and 7b can be processed to produce S-wave reflection images of subsurface layers and structures to compliment P-wave reflection images. While P images may reflect fluid saturated intervals, S-wave images can indicate reservoir heterogeneities, such as changes in porosity and permeability, that are essential to hydrocarbon flow within the reservoir unit. The procedure and results of crosswell seismic data imaging using reverse time migration is given in Raji (2016).

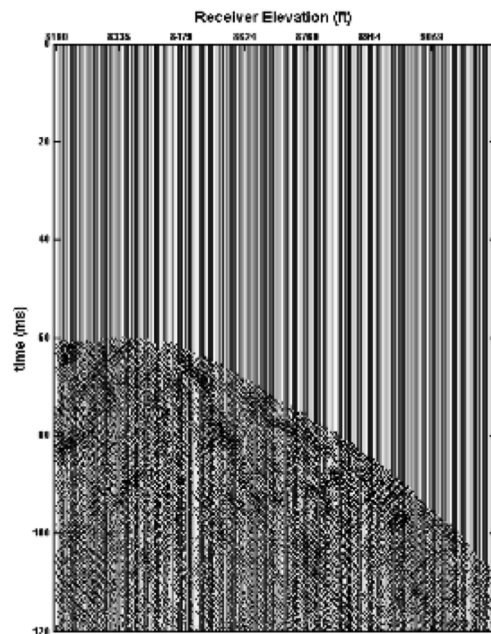


Fig 6: Processed data after removing converted waves

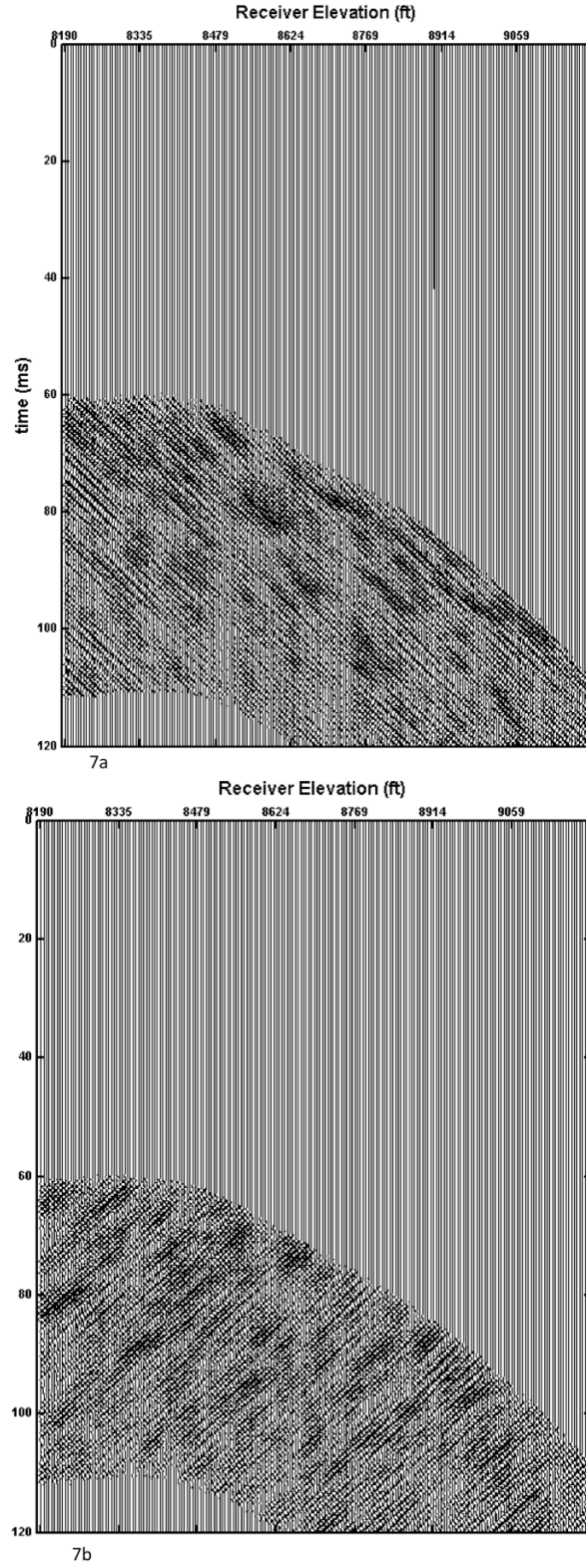


Fig.7: (a) S-S down-going reflections, and (b) S-S up-going reflections

5.0: Conclusion

An efficient procedure for S-wave reflections processing in a multi-component seismic data has been described. A set of data from West Texas Oil-Field was used to test the procedures and show the out-put of the different processing steps. The results of the processing confirmed the appropriateness of the procedure described and the techniques applied in the workflow. The final results yielded separated up-going and down-going S-S reflections that are traceable to the various reflector depths. The separated up-going or down-going data is

structurally similar to the processed surface seismic data. The data can be imaged using some conventional imaging algorithms (e.g., CDP mapping, RTM) for qualitative interpretations of subsurface structures and stratigraphy. By the description given in this paper, S-wave reflections can be processed independent of P-wave reflections in the same data. Preferably, P-wave reflections first, then S-wave reflections. As more is expected from seismic imaging with improved technology, it is expected that S-wave will take on further precursory roles in reservoir mapping and realistic subsurface imaging of fluid flow.

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