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Wavefield analysis of crosswell seismic data

Wasiu O. Raji^{1,2} · Youngxin Gao² · Jerry M. Harris²

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Abstract Despite the numerous advantages of crosswell seismic data over surface seismic data, crosswell seismic geophysics is still underutilized and underdeveloped. The factors limiting the full utilization of crosswell data include the lack of standardized methods for processing and imaging the data. This is because crosswell data is not completely understood. To improve the understanding of crosswell data, we performed acoustic and elastic modeling of a west Texas carbonate oilfield data using finite difference methods and crosswell geometry. To account for the different wave modes in the field data, we decomposed the full data into its constituent wave modes. Results of the forward modeling show that elastic synthetic data is a better representation of crosswell field data than the popular acoustic synthetic data. Wavefield decomposition gave insight into the time-space kinematics behavior of the different wave modes that constitute the full data. Overall, the study improved our understanding of crosswell field data. The learning from this study has been utilized to perform data-driven reflection enhancement processing where the discerned characteristic of different seismic arrival is utilized to suppress unwanted and enhanced the desired wave modes. The processing reduced the complex data to only up-going P-P reflections that can be imaged to reveal the subtle geological structures of the oilfield.

Keywords Crosswell field data · Elastic waves · Acoustic waves · Finite difference method · Wavefield decomposition

Introduction

With emphasis on applying cost-effective technologies that will lead to profitable growth in hydrocarbon portfolios and higher hydrocarbon recovery rates, there are increased opportunities to use crosswell technology to identify by-passed hydrocarbon, delineate saturation in recoverable oil zone, and monitor the lifetime performance of hydrocarbon reservoirs. Crosswell acquisition provides opportunities for cost effective acquisition of small to medium scale seismic data. Where wells already exist, the cost of crosswell seismic data acquisition is much less expensive than the cost of acquiring surface seismic data, even though the resolution of crosswell data is higher than the resolution of surface seismic data (Pereira and Jone 2010). Vertical seismic profiling (VSP) and crosswell (XW) are intermediate scale geophysical surveys that fill the resolution–coverage trade-off between surface seismic acquisition (Km) on one hand, and well logs and core data measurements (cm–m) on the other hand. VSP and XW are useful tools for monitoring field injection experiment and for understanding large-scale surface seismic measurements (Daley et al. 2008). Details of VSP and XW data acquisition are given in Balch and Lee (1984) and Harris et al. (1995), respectively. Crosswell survey has higher resolution (<5 m) than VSP survey (10–30 m) and surface seismic measurements (30–100 m). In crosswell survey, energy sources and receivers are placed at subsurface near the target layer thereby enabling propagation of high frequency waves with minimal attenuation (Raji and Rietbrock 2013) thereby yielding high-resolution data.

Despite these advantages, crosswell technology is underutilized and underdeveloped. Crosswell wavefield is not completely understood. Crosswell imaging is popularly

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done by velocity tomography. Although velocity tomography is a robust imaging tool, it utilizes only the direct arrival waves—a small portion of the information present in the seismic record (Van Shaack et al. 1995). The fidelity of velocity tomograms largely depends on the accuracy of the travel time picks. Other information (than direct waves) present 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. Reflection processing of crosswell data is difficult due to the complexity of its wavefield (Beydoun and Mendes 1989; Baker and Harris 1984; Khalil et al. 1991; Lazaratos et al. 1993). The different wave modes present in the field data are not completely known. This is probably one of the reasons commercial software for crosswell data processing are not readily available in the market. Unlike in surface seismic where the principal recording is the up-going P-wave, crosswell system records different seismic arrivals. As shown in the later section of this paper, these arrivals include P and S direct waves, up-going and down-going P-P reflections; up-going and down-going S-S reflections; mode converted reflections (P-S; S-P), reflected refractions, refractions, tube waves, etc. Acoustic synthetic data is often used to model crosswell field data, and imaging techniques for crosswell data are based on the acoustic wave theory (Hu et al. 1988; Devaney 1984; Harris 1987; Van Shaack et al. 1995). In reality, crosswell field data is more complex than acoustic data. The Imaging techniques built for acoustic waves may be insufficient to image the complex wave modes in real crosswell data. As shown in the later section of this paper, the complex wave modes seen in the crosswell field data cannot be explained by acoustic wavefield. To understand and utilize the different wave modes containing salient information on the geology of the acquisition area, we need to account for all the wave modes seen in the field data using a data model that better-fits the field data than the acoustic synthetic data.

The overall goal of this study is to improve our understanding of the crosswell field data. To do this, we need to (i) produce a data model that features all the wave modes seen in the field data but not seen in the acoustic data and (ii) understand and characterize all the constituent wave modes present in the full field data. To effectively process crosswell seismic data, we have to understand the distinguishing characteristics among the different wave modes in the data. First, we will model elastic and acoustic data for a west Texas oilfield using similar crosswell geometry, compare the synthetic data with field data, and comment on the suitability or fitness of the two synthetic data to the field data. Second, we will decompose the complex wavefield into its constituent wave modes, identify, and characterize the different wave modes in the full data. Third, we will use the experience gained from the study to perform reflection enhancement processing of field data.

Data simulation and wavefield decomposition

Crosswell seismic profile is a form of down-hole seismic technology where sources are deployed to one well and receivers are deployed to another well, with the source and receiver wells being separated by a reasonable distance. The rock volume between the two wells is imaged from the data acquired, either in a form of velocity tomogram or reflection image. A crosswell profile may have hundreds shot points and hundreds of receiver points. Depending on the technology and the frequency of the recording system, the source and receiver wells may be separated by a distance up to 1 km. The nominal spacing of sources and receivers along the borehole typically ranges between 1 m and 5 m. A schematic diagram of typical crosswell survey geometry is shown in Fig. 1.

For data modeling, we used a 2-dimensional Finite Difference Velocity-Stress Staggered Grid (FDVSG2D) simulation code originally written by Wu et al. (2005). In the code, we defined piezoelectric sources and hydrophone receivers in two separate wells. Number of sources and receivers, their spacing and depths, and the wellhead separation are defined in the code as described in the field acquisition report. These parameter are not mentioned here for proprietary reason. The computation mesh for the forward modeling comprise of 1000 by 1600 cells of size 1 m by 1 m each with

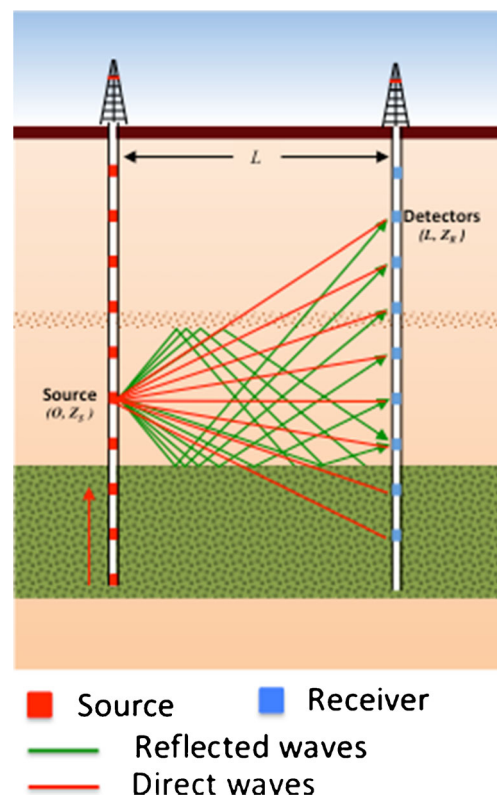


Fig. 1 Schematic diagram of a crosswell seismic survey. The geometry consists of many source points (red) and many receiver points (blue). Source and receiver wells are separated by a distance, L meters

source and receiver spacing of 5 m along the wells. The geological models are discretized to the size of the computation mesh. The geological models (Fig. 2) are built from the interpolation of the logs acquired in the source and receiver wells. The source and receiver wells are placed within the computation mesh. The source signature is a Ricker wavelet of 800 Hz. Using the acoustic and elastic versions of modified FDVSG2D, we modeled the full survey for a west Texas Carbonate Oilfield.

For the elastic modeling, four components of the waves: horizontal velocity, V_x ; vertical velocity, V_z ; horizontal stress, T_x ; and vertical stress, T_z were recorded by the hydrophones for every short. The radiation pattern of the source is shown in Fig. 3. After a comparison of the velocity and stress seismograms with the field record, we adopted the stress seismogram and computed the average elastic seismogram, T as:

$$T = \frac{1}{2}(T_x + T_z)$$

The elastic data, acoustic data, and the field data for common source gather #102 are shown in Fig. 4. From the comparison, it is obvious that almost every wave mode seen in the field data (Fig. 4b) can be found in the elastic synthetic data (Fig. 4a). Some of the wave modes seen in the field and elastic synthetic data but not present in the acoustic data (Fig. 4c) include transmitted-converted waves and reflected-converted waves. At this point, we are able to establish that elastic synthetic data gave better fit to the field data than the acoustic synthetic data. Subsequently, we use elastic synthetic data to study the field data.

Next, we decompose the elastic synthetic wavefield to its constituent wave modes in order to identify and characterize the different wave modes present in the field data. The decomposition was achieved using a one-dimensional viscoelastic code (ViscoZD). ViscoZD is a forward modeling code for calculating full frequency-dependent synthetic seismograms for horizontally layered geologic model. The code is built with special features that allow users to decompose the full wavefield into the constituent arrivals by excluding or precluding some wave modes during simulation. Before the decomposition exercise, the code is used to reproduce the full synthetic gather for common shot gather #102 and #123. The 2D elastic data is compared with the 1D viscoelastic data in Fig. 5. As shown by this comparison, the 2D elastic and 1D viscoelastic data for Common Source Gather # 102 show strong similarities.

All the wave modes seen in the 2D elastic data and the field data are also seen in the 1D viscoelastic data. From this comparison, we noted that 1D data could be used to explain the different arrivals in the 2D elastic data and the field data. Next, we decompose the 1D viscoelastic data into its constituent wave modes to explain the different seismic arrivals in the full 2D and field data. 1D data is used for the decomposition study because it is easier to decompose than the 2D data.

The viscoelastic algorithm has some features that allow forward modeling process to exclude or preclude certain wave modes as shown in equation templates 1, 2, and 3. Equation 1 defines the full wavefield. In Eqs. 2 and 3, the simulator will only compute the wave modes defined in the rectangular box. By this exclusive forward modeling, the different components of the wavefield is calculated and isolated from the full

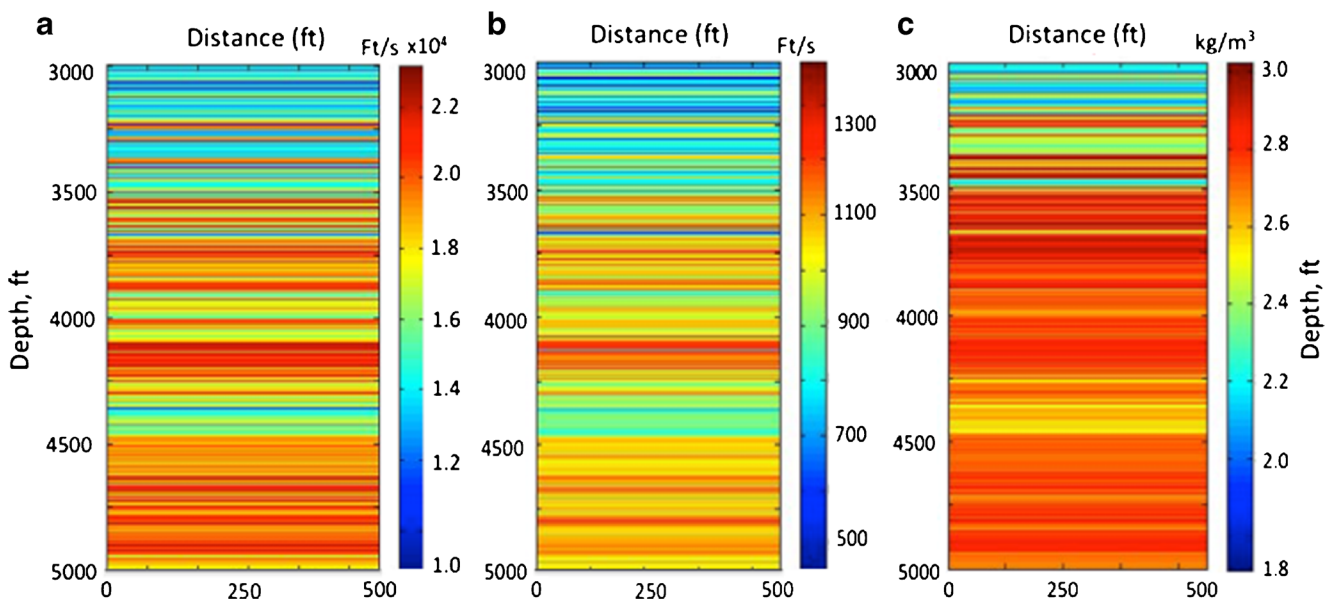


Fig. 2 Geological models. **a** P-wave velocity model, **b** S-wave velocity model, and **c** density models used to generate the synthetic data. This model is created from the interpolation of the log values at the source and receiver well

$$\begin{aligned}
 \begin{bmatrix} c_{pd}^{(j+1)} \\ c_{sd}^{(j+1)} \\ c_{pu}^{(j)} \\ c_{su}^{(j)} \end{bmatrix} &= \begin{bmatrix} t_{ppd}^j & t_{psd}^j & r_{ppu}^j & r_{psu}^j \\ t_{spd}^j & t_{ssd}^j & r_{spu}^j & r_{ssu}^j \\ r_{ppd}^j & r_{psd}^j & t_{ppu}^j & t_{psu}^j \\ r_{spd}^j & r_{ssd}^j & t_{spu}^j & t_{ssu}^j \end{bmatrix} \begin{bmatrix} c_{pd}^{(j)} \\ c_{sd}^{(j)} \\ c_{pu}^{(j+1)} \\ c_{su}^{(j+1)} \end{bmatrix} \quad \text{Equation Template 1} \\
 \begin{bmatrix} c_{pd}^{(j+1)} \\ c_{sd}^{(j+1)} \\ c_{pu}^{(j)} \\ c_{su}^{(j)} \end{bmatrix} &= \begin{bmatrix} t_{ppd}^j & t_{psd}^j & r_{ppu}^j & r_{psu}^j \\ t_{spd}^j & t_{ssd}^j & r_{spu}^j & r_{ssu}^j \\ r_{ppd}^j & r_{psd}^j & t_{ppu}^j & t_{psu}^j \\ r_{spd}^j & r_{ssd}^j & t_{spu}^j & t_{ssu}^j \end{bmatrix} \begin{bmatrix} c_{pd}^{(j)} \\ c_{sd}^{(j)} \\ c_{pu}^{(j+1)} \\ c_{su}^{(j+1)} \end{bmatrix} \quad \text{Equation Template 2} \\
 \begin{bmatrix} c_{pd}^{(j+1)} \\ c_{sd}^{(j+1)} \\ c_{pu}^{(j)} \\ c_{su}^{(j)} \end{bmatrix} &= \begin{bmatrix} t_{ppd}^j & t_{psd}^j & r_{ppu}^j & r_{psu}^j \\ t_{spd}^j & t_{ssd}^j & r_{spu}^j & r_{ssu}^j \\ r_{ppd}^j & r_{psd}^j & t_{ppu}^j & t_{psu}^j \\ r_{spd}^j & r_{ssd}^j & t_{spu}^j & t_{ssu}^j \end{bmatrix} \begin{bmatrix} c_{pd}^{(j)} \\ c_{sd}^{(j)} \\ c_{pu}^{(j+1)} \\ c_{su}^{(j+1)} \end{bmatrix} \quad \text{Equation Template 3}
 \end{aligned}$$

Equation describing full wavefield and decomposed wavefield: (a) Description of full wavefield in the (ViscoZ) simulator: (b) Description of P-P reflection and its transmission waves; (c) Description of S-S reflection and its transmission waves. t is transmission, r is reflection, p is the compressional wave, S is the shear waves, u is up-going, d is down-going. J is the layer index.

wavefield. In the equation template, t , r , p , s , d , u are transmission, reflection, P-waves, S-waves, down-going waves, and up-going waves, respectively.

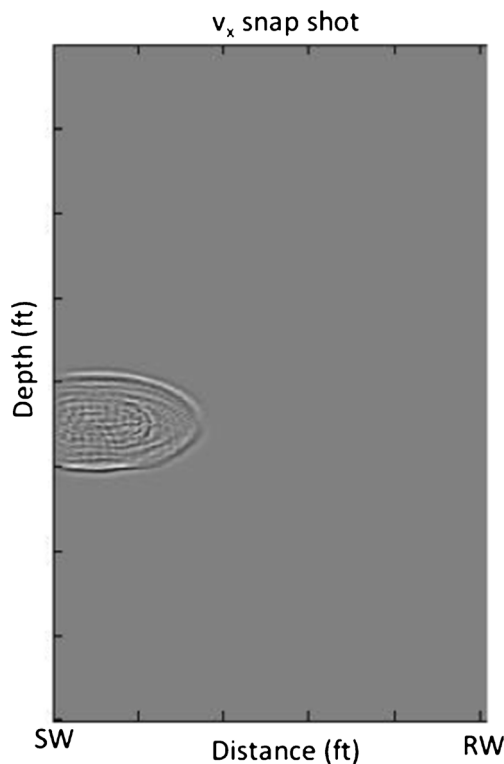


Fig. 3 The radiation pattern of the horizontal source showing wave propagation from the source well (SW) to the receiver well (RW)

The isolated wave modes are compared with the full 1D and 2D elastic data in time and space to discern the characteristics of the different wave mode. The full 1D viscoelastic data and some of the isolated wave modes are shown in Fig. 6. The learning from this decomposition provided salient information about the different wave modes, especially some wave modes like transmitted-converted waves and reflected-converted waves that are hardly noticeable. The wavefield decomposition approach is used to analyze the full wavefield to identify the different wave modes in the 2D elastic data as shown in Fig. 7.

Reflection enhancement processing

Many authors including Baker and Harris (1984); Beydoun and Mendes (1989); Khalil et al. (1991); Lazaratos et al. (1993), Rector et al. 1995 have discussed the superiority of crosswell reflection images over velocity images. The advantages of crosswell reflection imaging over crosswell velocity imaging include improved vertical resolution and reduction in image artifact caused by aperture limitation. Poor ray coverage is a common issue in crosswell tomography (Lazaratos et al. 1995; Raji et al. 2016) but reflection imaging provides good illumination of the well bottom where the reservoir usually lies. The many obstacles to overcome in crosswell reflection imaging include data processing. The important task in crosswell seismic data processing includes suppressing coherent non-reflection arrivals and high

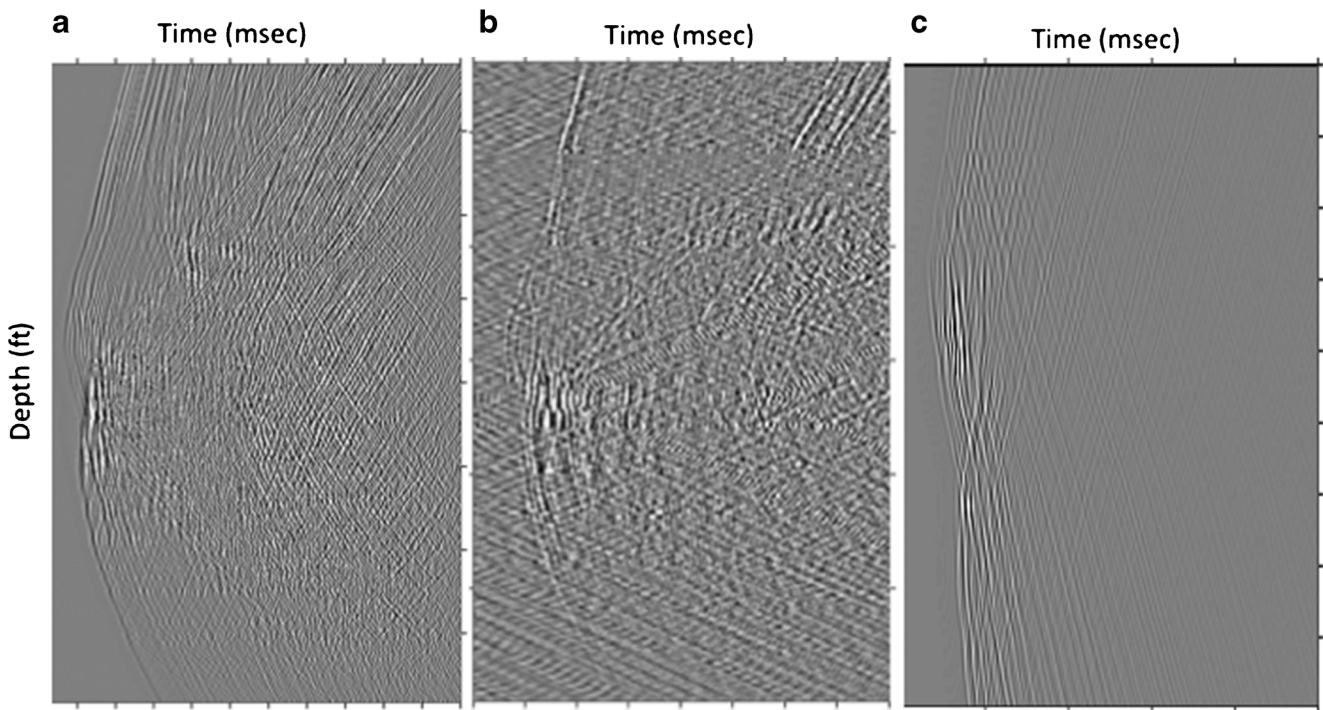


Fig. 4 Comparison of field and synthetic data for common source gather #102: **a** Synthetic elastic data, **b** Field data from a west Texas oil field, and **c** synthetic acoustic data

amplitude energies obscuring the true reflections. Another important task to accomplish in crosswell processing is separating the up-going wavefield from the down-going wavefield.

Crosswell reflection processing may be thought to be similar to VSP processing, but the presence of wide angle

(greater than 45°) reflection, up-going and down-going reflection arrivals in crosswell recording require some advancement to VSP processing. The purpose of this section is to utilize the learning and experiences from the previous section to process crosswell seismic data. The data modeling and wavefield decomposition discussed in the previous

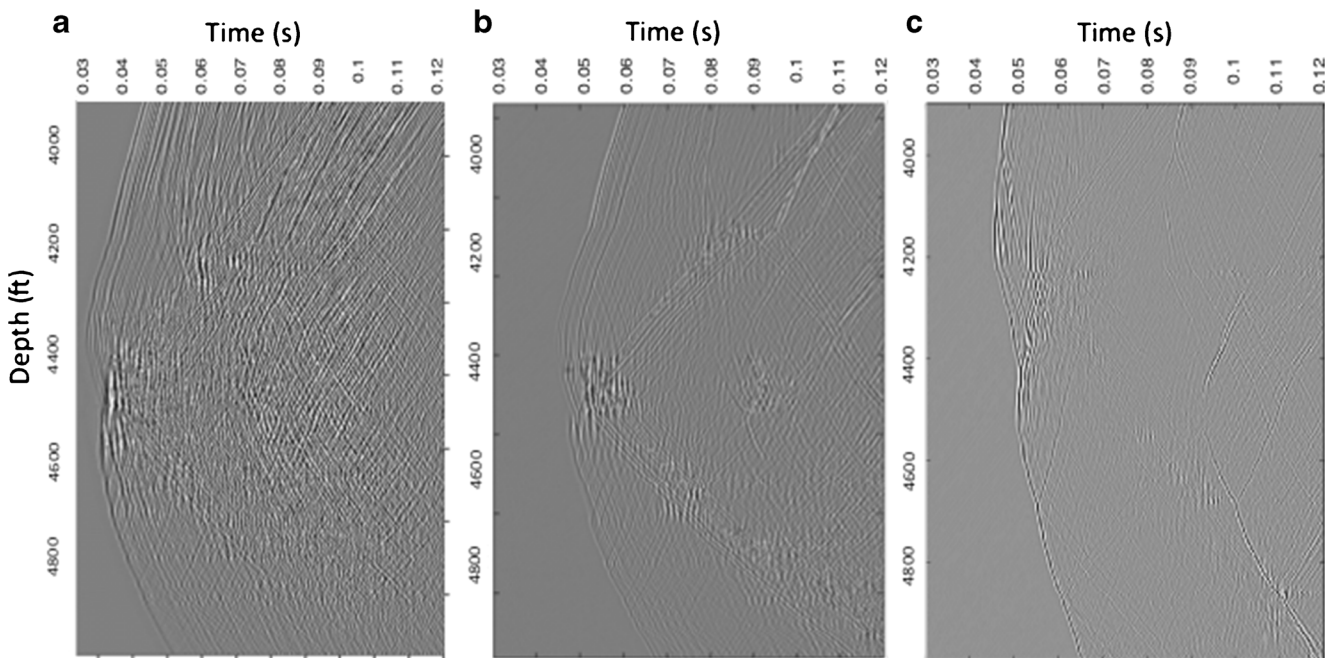


Fig. 5 Comparison of 2D elastic data with 1D Viscoelastic data. **a** 2D elastic data for Common Shot Gather #102, **b** 1D data for Common shot Gather #102, and **c** 1D viscoelastic data for Common Shot Gather #123

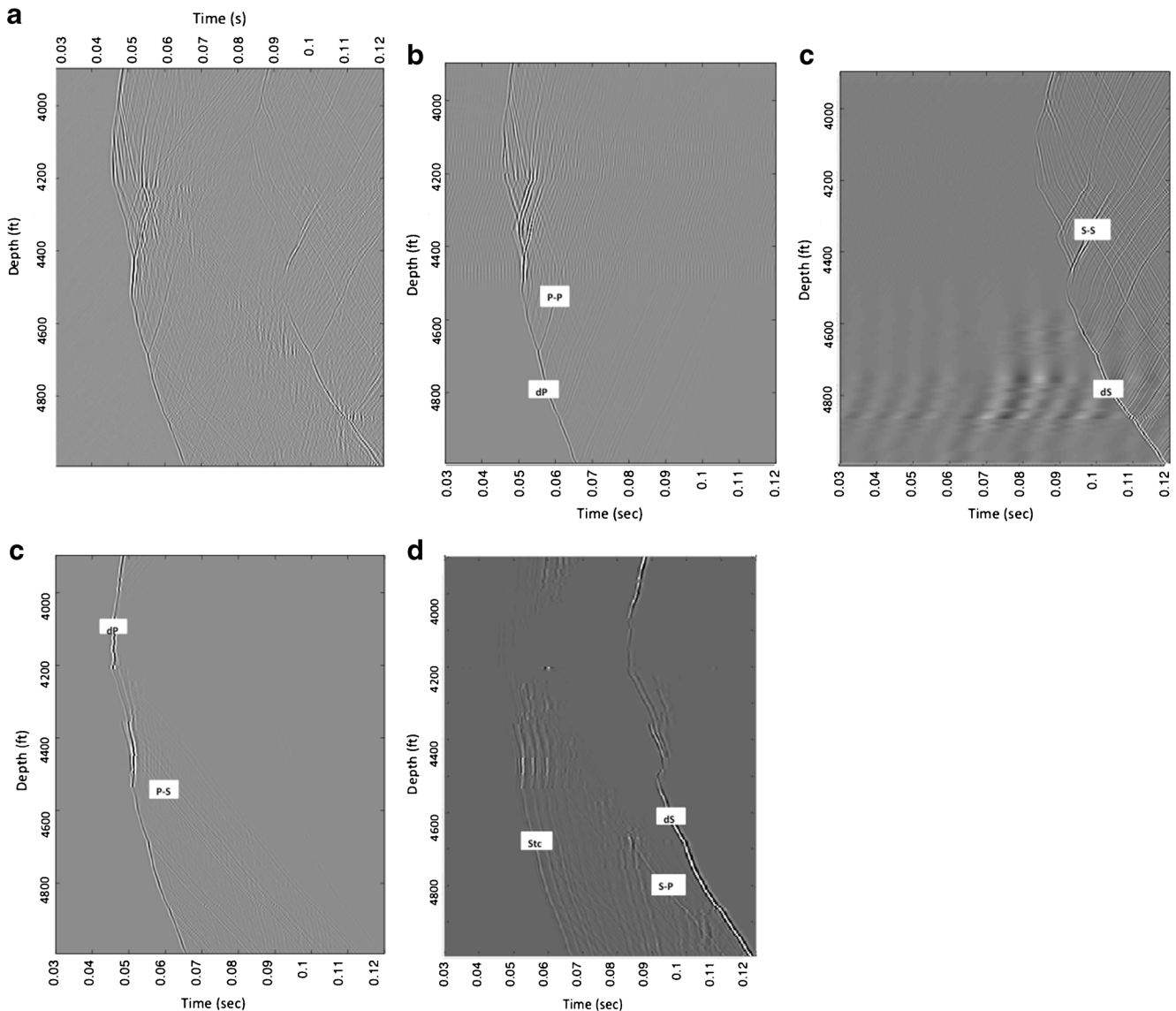


Fig. 6 The full and decomposed Data for CSG #123. **a** The full wavefield. **b, c, d, e** are the decomposed wavefield; dP is direct P wave; P-P is P-P wave reflection; dS is direct S wave; S-S is S-S wave reflection; Stc is S wave transmission conversion; S-P is S-P reflection; and P-S is P-S wave reflection

section improved our understanding of the characteristics of the individual wave modes and, therefore, informed the choice of the best techniques for processing the field data. This section does not give details of data processing, it only summarizes the procedure for reflection enhancement using field data example. Detailed description of the processing methods is a subject of a future paper.

The techniques applied to process the data in Fig. 8 consists of two main stages: (i) pre-processing and (ii) wavefield separation. In preprocessing, the data is first sorted into the different data domains (common shot gather, common receiver gather, common depth gather, and common offset gather) to determine the best domain to apply the processing. Following this, we observed that processing

is best done in common receiver gather (CRG) because CRG show the highest signal-to-noise ratio among the four data domains. However, some processing steps were applied in two or more data domain. First, designature, deconvolution, and suppression of high amplitude energies were done. Deconvolution and designature were performed while the traces are aligned. Trace alignment is achieved using direct arrival travel times picked in the data. The suppression of high amplitude energies (e.g., direct arrivals and tube waves) was effected using multi-domain multi-channel $f-k$ filters. To preserve reflections in the same time window with direct waves, we used trace mix-and-subtract technique (Raji 2016). The raw data after preprocessing is shown in Fig. 9a.

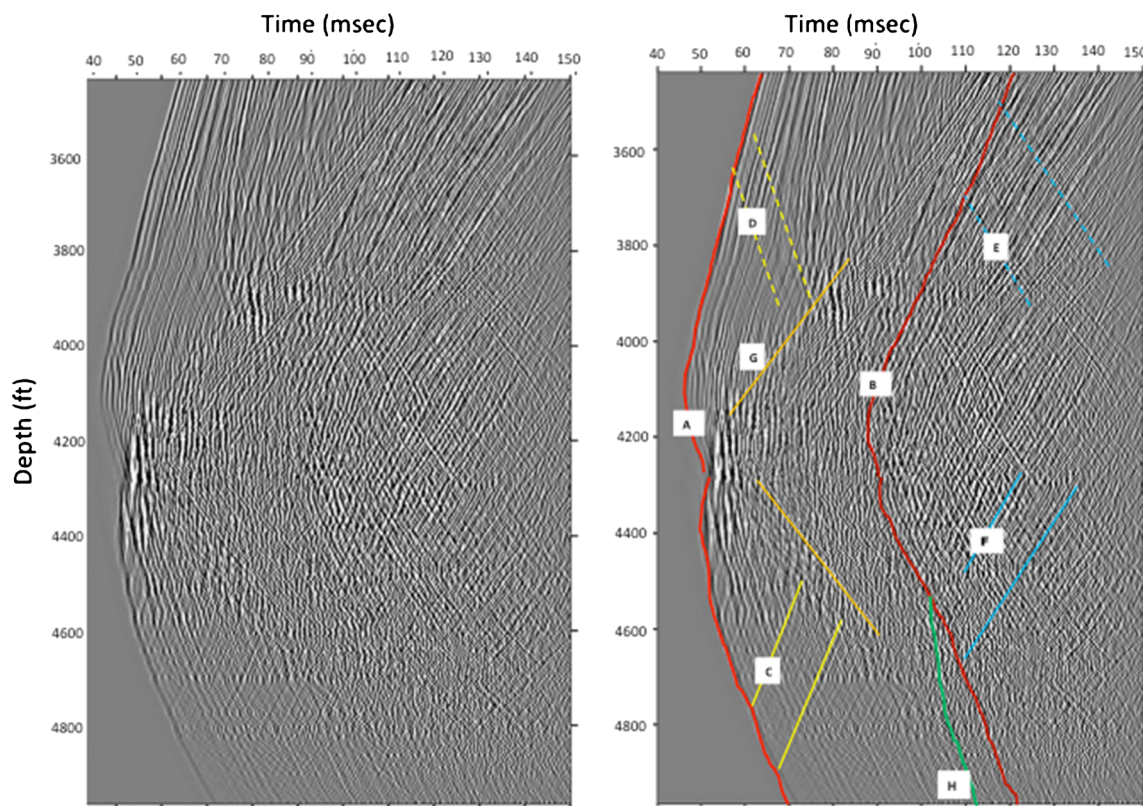
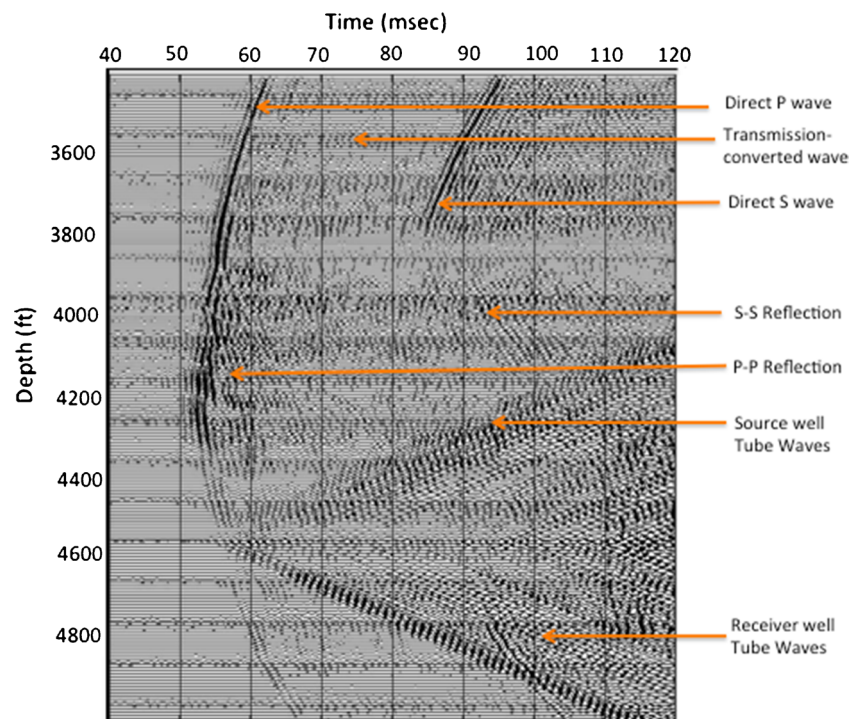


Fig. 7 The different wave modes identified in the 2D elastic data through the decomposition techniques, CSG #102. **a** P direct arrival. **b** S direct arrival. **c** P- P down-going reflections. **d** P-P up-going reflections. **e** S-S up-going reflections. **f** S-S down-going. **g** P-S conversion. **h** S-P refraction

In wavefield separation, all other wave modes, except P-P up-going waves were suppressed. First, direct shear waves are

aligned using the shear wave direct arrivals travel time. Then, shear energy was removed by surgical muting of the energies

Fig. 8 Field data (CRG from a receiver at 4250 m) showing the different seismic arrivals in the raw data before processing



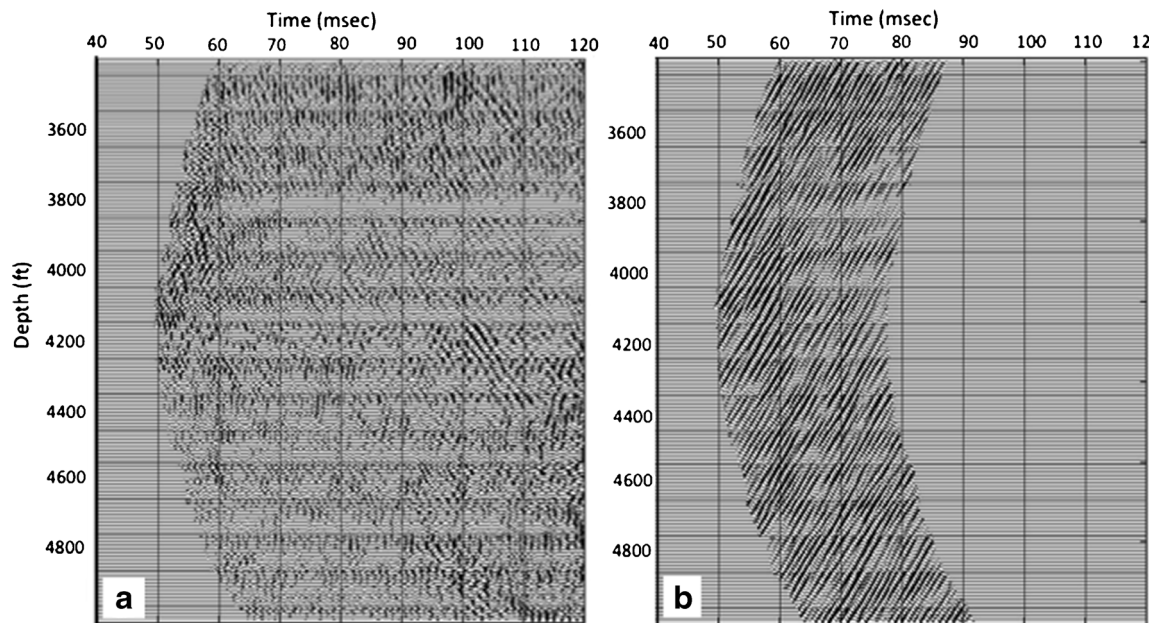


Fig. 9 **a** Field data after pre-processing and **(b)** field data after preprocessing and wavefield separation

from the S-wave direct arrivals up to data length (120 ms). S-wave muting was performed while traces are aligned. Next, the converted waves were removed, and finally, the down-going P-waves were suppressed leaving behind only the up-going P-P reflections (Fig. 9b). Wavefield separation was performed using a series of multi-channel dip filters operated in the Fourier domain. The method took advantage of the difference in the dip move-out of P-P reflections and other wave modes. Wavefield separation reduced the complex seismic arrivals to simple P-P up-going reflections analogous to the processed surface seismic data.

Discussions

Geophysics researchers have severally used acoustic models to represent field crosswell seismic data assuming the media around the wells to be acoustic. However, acoustic synthetic data does not account for the complex wave modes seen in the crosswell field data. To account for every wave modes seen in the field data, we forward-modeled elastic and acoustic data using the crosswell acquisition geometry of a data set recorded in a west Texas oilfield. Comparisons of the acoustic and elastic synthetic data with the field data (Fig. 4) show that elastic synthetic data gave a better fit to the field data than the acoustic synthetic data. The elastic data accounts for the different wave modes seen in the field data in time and space. Some wave modes present in the field and elastic synthetic data but missing in the acoustic data include transmission-converted waves and some reflection-converted waves.

To identify and characterize all the wave modes present in the field data, the full wavefield is decomposed into its

constituent waves using visco-elastic simulation. The decomposition technique has some features that allow deterministic exclusion of certain wave modes from the forward modeling. Wave modes exclusively forward modeled include the direct arrivals P-waves; P-P reflections; direct arrival S-waves; S-S reflections, reflection converted waves (P-S reflection and S-P reflections) and transmission-converted waves. The decomposed wavefield is compared with the full wavefield to check the consistency of the decomposition: the full wavefield is the approximate summation of the decomposed wavefields. The wavefield decomposition explains the time-space kinematic behavior of the different wave types seen in the full data, thereby enabling the design of methods to suppress or enhance the different arrivals. The decomposition also provided some insights to the hardly-noticed wave modes (e.g., S-waves transmission-converted). It is almost unthinkable that S-wave transmission-converted waves can travel nearly fast as P-wave direct waves (Fig. 6e). A plausible explanation for this observation is that the S-waves got converted to P-wave very close to the source: it traveled with P-wave velocity nearly all the way.

The learning and experience gained from the elastic forward modeling and wavefield decomposition studies provided salient information on the distinguishing features among the different waves modes present in the field data. These distinguishing features were used to discriminate one seismic arrival from the other during reflection enhancement processing of the field data. The reflection processing entailed two main steps: preprocessing and wavefield separation. In preprocessing, the high amplitude energies obscuring the reflection arrivals are suppressed, then the source energy is designatured and the multiples are suppressed by deconvolution. Mix-and-subtract technique was used to preserved the reflections found in the same

time window with direct arrival waves. In Wavefield separation, all the remaining arrivals, except the P-P up-going reflections were removed using series of multi-channel $f-k$ dip filters. The product of the data processing is a coherent P-P up-going reflections data (Fig. 9b), which is structurally similar to the processed surface seismic data.

Conclusion

Crosswell seismic data offers excellent opportunity for cost effective monitor for hydrocarbon production and reservoir characterization. A factor limiting the full utilization of crosswell seismic data is the lack of standard procedure for data processing. This is because the constituent wave modes in the field data are not completely understood. This study simulated elastic and acoustic crosswell data after a well-known west Texas oilfield, compared the acoustic, elastic, and field data, and concluded that crosswell field data is structurally more elastic than acoustic. The different wave modes in the field data were identified and characterized by wavefield decomposition. The decomposition gave insight to the time-space kinematic behavior of the different wave modes seen in the full field data. The distinguish characteristic of the different wave modes is used to formulate techniques for enhancing or suppressing the different seismic arrivals during reflection processing of the data. Finally, the study evolved a processing sequence that eliminated the coherent noise and reduce the complex wave modes to up-going P-P reflection that is analogous to the processed surface seismic data – that can be imaged by some existing imaging algorithms.

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