Multi-wave Pre-stack Joint Inversion of Carbonate Formation - A Case Study of Qixia Formation, Middle-Lower Permian, Sichuan Basin

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Abstract. The study area is Longnvsi (LNS) in the central Sichuan Basin, Western China, and the target layer is the Qixia Formation of Lower Permian, with characteristic of thin dolomite reservoirs, low porosity as well as rapid changes and discontinuity of reservoirs in the lateral direction. It's difficult to predict reservoirs only by PP-wave data. With the development of multi-component exploration, multi-wave seismic data analysis enhances confidence in interpretation by providing PS-wave data for imaging the subsurface. PS seismic data exhibit significant changes in amplitude and character of seismic events that may not be observed on PP seismic data. When PP and PS data are analyzed together, multi-wave seismic exploration has potential and advantages in fluid and lithology prediction. In this paper, logging analysis is carried out for the target layer, which shows that the reservoir response characteristics of P-wave velocity and S-wave velocity are different, then these sensitive elastic parameters of the reservoir can be determined. By comparing the seismic response characteristics of PP-wave and PS-wave, the reservoir seismic amplitude is also different. The difference between P-wave and S-wave in logging and seism is the basis for PP+PS joint inversion. We tried to perform PP+PS joint pre-stack inversion under the theory of P-wave and PS-wave elastic impedance inversion. In this process, we illustrate some key technologies, such as multi-wave calibration, multi-wave wavelet estimation and PP-PS seismic matching. Compared with PP seismic pre-inversion alone, the PP+PS joint inversion increases the constraint conditions, reduces the inversion ambiguity, gives markedly superior estimates of the P-wave and S-wave impedance and V_P/V_S, and improves the vertical resolution and lateral continuity of elastic parameters. This method has obtained good results in the prediction of carbonate reservoirs in the Lower Permian in the central Sichuan Basin. The lithological interface described is reasonable, especially the distribution characteristics of dolomite reservoirs. It enriches the research ideas for dolomite reservoirs prediction, and it has practical applicability to take advantage of multi-wave data in carbonate reservoir prediction.

Keywords: PP+PS joint pre-inversion · Dolomite reservoirs · Converted wave · PP-PS wave correlation

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1 Introduction

Multi-component seismic recording obtains more seismic information than conventional single-element techniques (Stewart et al. 2003). Due to the different propagation mechanisms, the PP and PS waves respond differently to the reservoir. PP-wave is sensitive to rock matrix and the type of pore fluid, while PS-wave is only affected by rock matrix. Multi-component seismic exploration has potential or advantages for: (1) imaging structure through gas clouds, (2) increased resolution, (3) fluid and lithology discrimination, (4) imaging low-acoustic impedance reservoirs, and (5) fracture detection by analysis of shear wave splitting (Garotta et al. 2002). At present, the interpretation technology of multi-wave seismic data has been well developed, especially the practical applications in lithology prediction and fluid identification. Multi-component seismic interpretation technologies are mainly based on the attributes difference between PP- and PS-wave, such as amplitude ratio and velocity ratio (Ensley 1983; Garotta et al. 1985; Miller 1996; MacLeod et al. 1999; Thompson et al. 2000; Goodway and Tessman 2000; Michelena et al. 2001; Stewart et al. 2003). Many studies have also been carried out on multi-wave joint inversion. Joint inversion of PP- and PS-wave seismic data can enhance the lithology and fluid prediction accuracy due to the additional constraint of the PS-wave (Du et al. 2016, 2019). However, at present, multi-wave joint inversion research mainly focuses on method exploration, with few industrial applications, and most of them are carried out in the PP-wave domain and the PS-wave domain separately in practical application. Besides, the existing multi-wave joint inversion is mostly used in clastic formations, but less in carbonate reservoirs.

In order to explore the application of PP-and PS-wave seismic data in carbonate reservoir prediction, the dolomite reservoir of the Qixia Formation in the Lower Permian in the central Sichuan Basin was taken as an example. The research and application of PP-PS joint pre-inversion were carried out by the PP and PS seismic data simultaneously. Through seismic rock physics analysis, the geophysical characteristics of the P-wave and S-wave in the reservoir were clarified. Then we carried out some key technologies, such as multi-wave seismic calibration, PP and PS-wave combined horizon interpretation, and fine-matching of PP and PS. Based on P-wave and PS-wave elastic impedance inversion theory, PP+PS joint inversion was conducted to obtain elastic parameters such as P-wave impedance, S-wave impedance, and V_P/V_S.

2 Geologic Setting

The carbonate reservoirs of the Permian Qixia and Maokou Formation in the central Sichuan Basin are important exploration strata. Many exploratory wells drilled into dolomite reservoirs in the Qixia and Maokou Formation have obtained high-yield industrial gas flow, which indicates that the dolomite reservoirs have great oil exploration potential. The intraplatform grain beach dolomite reservoirs developed in the Lower Permian Qixia Formation have the characteristics of deep burial, thin reservoir thickness, lateral discontinuous distribution, and low porosity. Comprehensive analysis shows that the Qixia Formation is mainly limestone, with high argillaceous content and darker color at the bottom, thinner dolomite in the middle and upper part. Besides, Qixia Formation is mainly fine-medium crystalline dolomite in the reservoir, followed by limestone dolomite and dolomitic limestone. There are 2–3 layers of reservoirs in the Qixia Formation. The thickness of a single layer is thin (1–8 m), and the cumulative thickness is 2–15 m. The reservoirs exhibit large lateral changes and strong heterogeneity, resulting in large differences in natural gas production capacity from different wells. Statistical analysis of drilling in the study area demonstrates that the reservoir porosity ranges from 2.2% to 4.9%, with an average porosity of 3.84%, and the characteristics of low porosity and low permeability are obvious. The above-mentioned characteristics have brought great difficulty to the seismic prediction of favorable reservoirs. It is difficult to meet the requirements of fine reservoir prediction and gas detection through conventional post-stack or pre-stack PP-wave inversion.

In 2014, the wide azimuth digital 3D-3C seismic data was acquired in Longnvsi (LNS) area. This observing system was beneficial for the prediction of target layer. Relatively high-quality PP-and PS-wave data were obtained by multi-wave processing, which provided an effective data basis for multi-wave joint inversion study.

3 Reservoir Characteristics

The geophysical response characteristics of the reservoir are the research foundation of reservoir prediction. This paper focuses on analyzing the logging response characteristics of reservoirs and multi-wave seismic response characteristics, confirming that the S-wave velocity difference can be used to identify reservoirs, so as to select the geophysical parameters and methods of reservoir inversion. Thus, effectiveness of reservoir inversion results is ensured.

3.1 Rock Physics

Figure 1 is the comprehensive well log interpretation diagram of well M129 in the Qixia Formation. There are four thin dolomite reservoirs (marked in red) distributed in the middle and upper parts of the Qixia Formation, and the thickness of each reservoir is less than 10 m. Compared with the limestone surrounding rock, the P-wave velocity decreases, and the S-wave velocity increases for the dolomite reservoir, which results in the Vp/Vs decreasing significantly. Hence, the combination of P-wave and S-wave log can better identify dolomite reservoirs.

3.2 Analysis of Multi-wave Seismic Response Characteristics

According to the seismic wave propagation theories, PP-wave can propagate in gas, liquid, and solid, which is sensitive to lithology and fluid; while S-wave only propagate in solids, so S-wave is only related to lithology in theory.

Such propagation characteristics make seismic response of the reservoirs differently. Figure 2 shows the PP- and PS-wave seismic section of well M129-M31-M41-NJ-M23. Dolomite thickness in well M129 is 14.1 m; M31 is 16.6 m; M41 is 5.5 m, and NJ is 6.2 m (also marked in Fig. 4 and Fig. 5). Dolomite in the Qixia Formation (between P1m and P1q) is developed around wells M129 and M31. In the dolomite reservoir, it exhibits peak reflection on the PP-wave section but weak or blank reflection on the PS-wave section

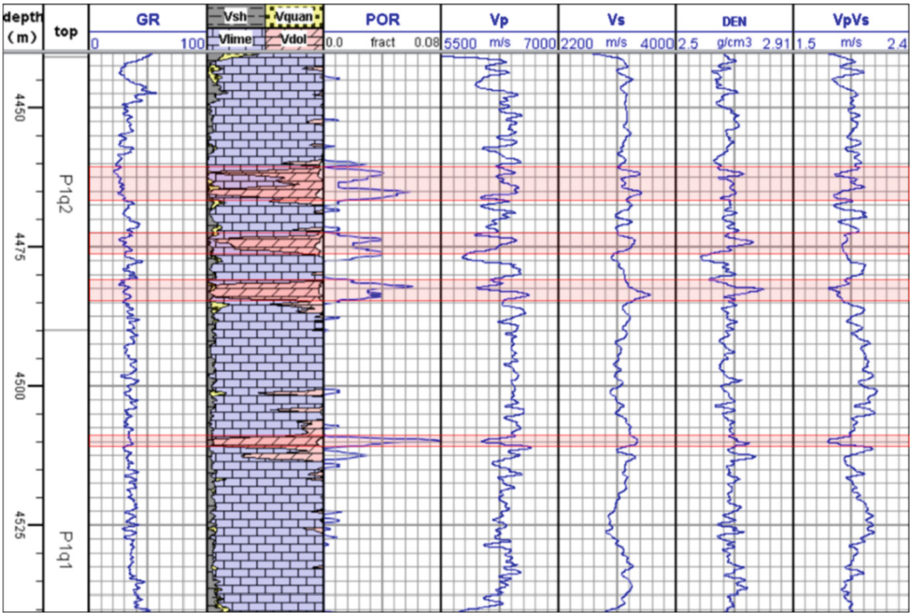

Fig. 1. Comprehensive well log interpretation of well M129 in the Qixia Formation.

(the yellow arrow); while in the undeveloped dolomite positions, such as the location near well NJ and M41, both the PP-and PS-wave appear as weak reflections. Therefore, there is a difference in seismic response between P-and PS-wave in the dolomite reservoir position, which is the foundation for multi-wave joint inversions.

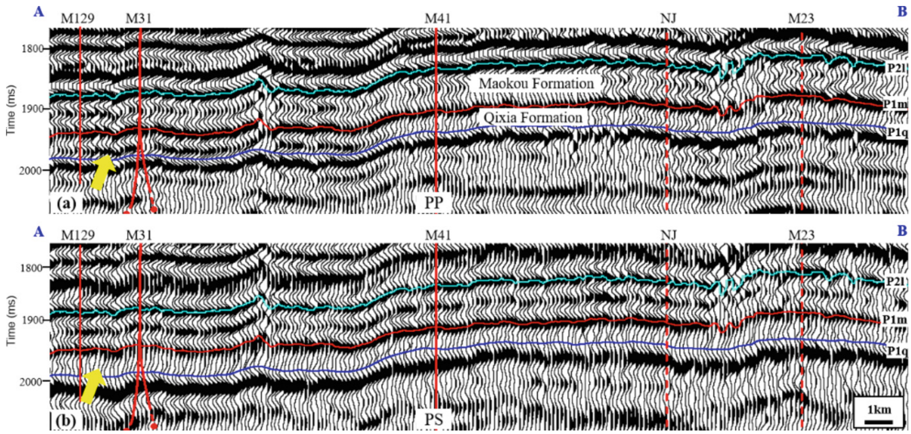

Fig. 2. Seismic section of (a) PP-wave and (b) fine matched PS-wave data crossing wells M129, M31, M41, NJ and M23 in the Permian Qixia Formation and Maokou Formation, and the plane position is showed in Fig. 5 as LINE AB. Horizons P2l and P1 m represents the top and bottom of the Maokou Formation respectively, and horizon P1q represents the bottom of the Qixia Formation.

4 PP+PS Joint Pre-stack Inversion

Through multi-wave seismic calibration, wavelet extraction and fine matching of multi-wave seismic data, seismic data corresponding to PS-wave was obtained, which laid a good foundation for pre-stack joint inversion. Similar to single P-wave elastic impedance inversion process, the multi-wave pre-stack joint inversion process is formulated through adding the PS-wave data.

4.1 Multi-wave Calibration and Wavelet Extraction

Multi-wave seismic calibration consists of two parts, namely PP domain calibration and PS domain calibration (Fig. 3). During PS domain calibration, only a certain angle of PS-wave synthetic record can be calculated as there is no reflected PS-wave at zero incidence. The PP-wave synthetic record is similar to the PP seismic section, showing the characteristics of weak wave peak in the reservoir location (indicated by the yellow arrow); while the PS-wave synthetic record shows blank reflections in the reservoir location, which is similar to PS seismic section. Both PP and PS data present the high correlation between seismic and synthetic record. At the same time, the frequency of the target layer of the PP-and PS-wave is calculated, and the wavelet of PP-and PS-wave are extracted.

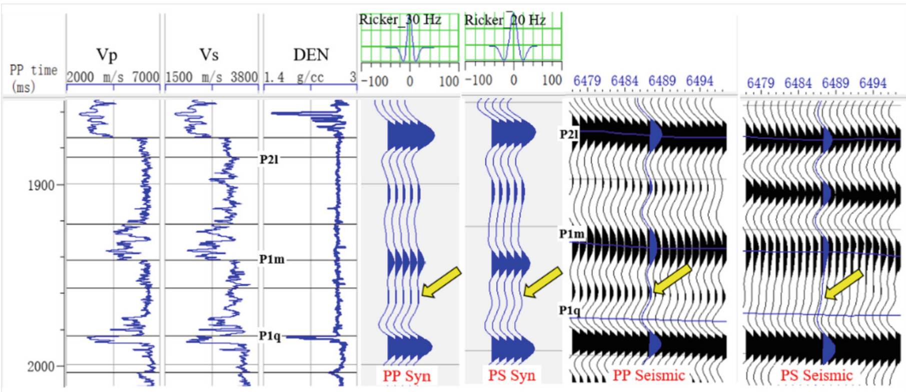

Fig. 3. Well-to-seismic correlation for PP-wave and PS-wave of well M129.

4.2 Event Correlation of PP-and PS-Wave

A crucial step in PP-PS joint inversion is the alignment. As PS travel time differs from PP travel time for the same seismic reflectors, the PS time should be aligned with PP time by compression. For this, the PS events need to match the PP events from the same geologic strata with the help of well data and synthetic records. (Gaiser 1996; Van Dok and Kristiansen 2003; Hardage et al. 2011). To ensure that reflection time of the same geological interface is uniform on PP-wave and PS-wave, it is necessary to take an appropriate V_p/V_s to compress the PS data. In this study, by referring to the relationship between the PP-wave and PS-wave section, combined with the VSP data and the velocity ratio (V_p/V_s) spectrum, the initial V_p/V_s in the whole work area were analyzed, and the key lithological interfaces of the PP-wave and PS-wave sections were further interpreted in detail. Then the PS-wave data is finally obtained in PP time through multi-layer fine matching. From the perspective of matching stereoscopic display effects (Fig. 2), from shallow to deep, PP-and PS-wave data are of clear imaging, high S/N, and good consistency in reflective characteristics of the main lithological interface, which is beneficial to the joint interpretation and inversion of PP-and PS-wave data.

4.3 Inversion Method

Elastic impedance inversion is a widely used pre-stack reservoir prediction method. It contains the information of the seismic reflection amplitude varying with the angle of incidence, and can better characterize the lithology of the formation and the change law of the reservoir. The seismic input of conventional elastic impedance inversion only contains PP-wave data. The multi-wave joint inversion carried out in this paper requires the input of PP-wave and PS-wave data at the same time.

Connolly (1999) derived the angle-dependent elastic impedance formula based on the simplified formula of Aki & Richards, which contains the information of P-wave velocity, S-wave velocity, density and incident angle:

$$EI = \rho^{1-4Ksin^2\theta} v_p^{1+tan^2\theta} v_s^{-8Ksin^2\theta} \tag{1}$$

Among them, θ is the incident angle of the PP wave, and k(V_p/V_s) is the velocity ratio. When the incident angle θ is 0, the elastic impedance EI is the acoustic impedance. The introduction of θ makes the formula include the AVO information that P-wave reflection changes with the incident angle, which is more realistic than the normal incidence assumption.

After the P-wave elastic impedance was proposed, Duffaut et al. (2000) proposed the PS-wave elastic impedance suitable for PS-wave seismic data. The expression is as follows:

$$SEI = \rho^{c(\theta)} v_s^{a(\theta)} \tag{2}$$

Among them,

$a(\theta) = 4ksin\theta[1 - 1/2(1 + 2k)sin^2\theta]$,
$c(\theta) = (1 + 2k)sin\theta[1 - k(1 + 3/2k)/(1 + 2k)sin^2\theta]$

Combining the depth of the Qixia Formation and the range of incidence angle (0°−30°), while taking account of the signal-to-noise ratio (S/N) and the fold number, the PP-wave and PS-wave gathers are divided into six part-stack sections of near (0°−10°), middle (10°−20°) and far (20°−30°) angles. In the study, six sub-angle stacked section data were used as input data, and the multi-wave pre-stack joint inversion was carried out using the methods provided by formulas (1) and (2).

5 Inversion Analysis

Carrying out multi-wave pre-stack joint inversion according to the elastic impedance inversion, we obtained the P-wave impedance, S-wave impedance and V_p/V_s. The left part in Fig. 4 is the result of the single PP-wave pre-stack inversion, while the right part is the result of the joint inversion of the PP- and PS-wave. From top to bottom are P-impedance, S-impedance, and V_p/V_s section. Comparing the results of PP+PS pre-stack joint inversion with single PP pre-inversion (Fig. 4), it shows that: for P-wave impedance, the overall effect of combined PP-PS inversion is similar to that of single PP inversion, but the PP+PS inversion is significantly improved where the S/N of PP-wave data is poor. The amplitude and time information of the PP and PS data are compared and calibrated with each other, which increases the PP+PS inversion constraints, effectively reducing the ambiguity and uncertainty. In the multi-wave inversion, the argillaceous limestone at the bottom of the Maokou Formation is more continuous, and each lithological interface become much clearer.

For the S-wave impedance, the joint inversion is significantly better than single PP-wave inversion. This is because the addition of PS-wave data avoids the assumption that the V_p/V_s are constant, it directly extracts the S-wave data from the PS-wave seismic data, which can more accurately invert the parameters related to the S-wave. Comparing the inversion results of the PP+PS and PP, S-impedance and P-impedance are in good agreement for the PP+PS joint pre-inversion, and the results are consistent with the well data, which contributes to reservoir evaluation. Similar to P-impedance, S-impedance derived from the joint inversion clearly characterizes the lithological interface.

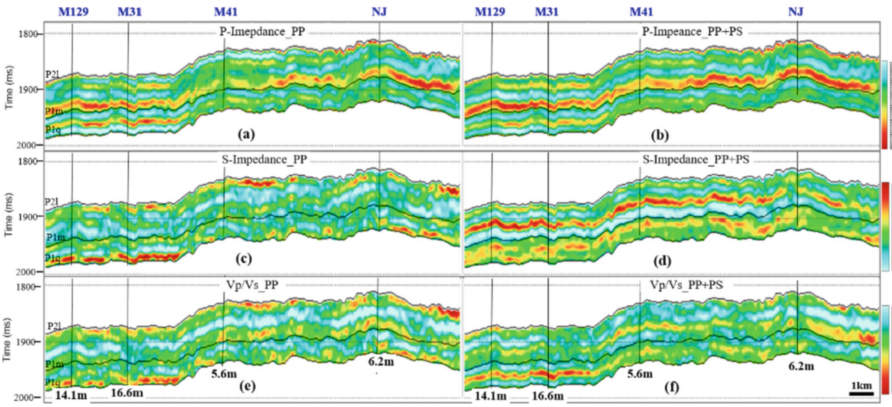

Fig. 4. Elastic parameter sections derived from convention PP-wave pre-stack inversion (on the left) and PP+PS pre-stack inversion (on the right): (a) P-Impedance from PP, (b) P-Impedance from PP+PS, (c) S-Impedance from PP, (d) S-Impedance from PP+PS, (e) V_p/V_s from PP, (d) V_p/V_s from PP+PS.

Due to the improvement of the S-wave impedance, the inversion effect of V_p/V_s has also been significantly improved. Note the position of the dolomite reservoir in well M31, the low V_P/V_S of the multi-wave inversion is more obvious than that of the conventional P-wave inversion.

Based on the results of individual PP-wave inversion and PP+PS joint inversion, the V_P/V_S slice of the Qixia Formation was extracted (Fig. 5). Figure 5a is the result of single PP wave inversion, and Fig. 5b is the result of PP+PS joint inversion. The overall characteristics of the two slices are basically the same, but the details are different. The multi-wave joint inversion results are more conducive to the description of the dolomite distribution of the reservoir, and the predicted distribution of the dolomite reservoir has clear characteristics. The prediction results show that dolomite reservoirs are mainly distributed in relatively high parts of paleomorphology and carbonate in-platform sedimentary environment, which is consistent with the regional geological understanding of dolomite reservoirs in this area. Through the comparison of reservoir prediction results with actual drilling data, the coincidence rate of PP+PS joint inversion prediction reached 87.5%, while that of single PP inversion was 81.2%, showing the obvious advantage and high accuracy of multi-wave joint inversion. In particular, the reservoirs near well M42 and NS1 predicted by the joint inversion are in good agreement with the well interpretation results.

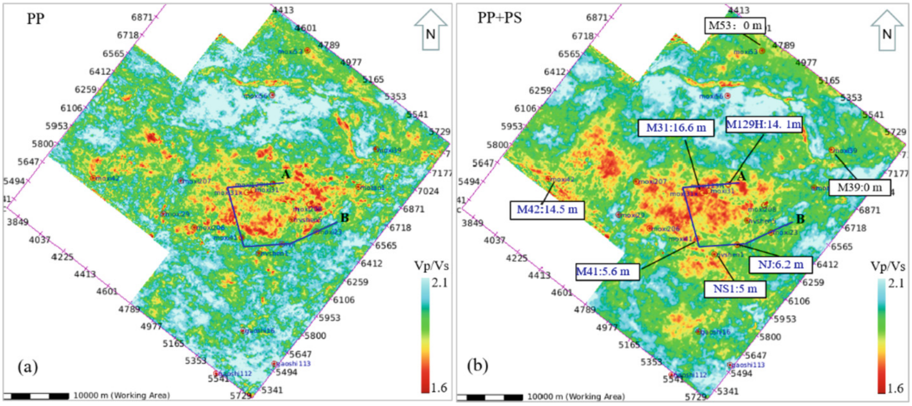

Fig. 5. V_P/V_S inversion slice of the Qixia Formation by (a) conventional PP-wave pre-stack elastic parameter inversion and (b) PP+PS pre-stack elastic parameter inversion. Thickness of dolomite in the Qixia Formation of several wells is marked. Line AB shows the location of PP- and PS-wave section in Fig. 2.

6 Conclusions

Multi-wave well seismic calibration and PP-PS wave correlation are the basis of the multi-wave joint pre-stack inversion, and they make notable effects on quality of the inversion result.

For the dolomite reservoirs of the Lower Permian Qixia Formation in the central Sichuan Basin in Western China, the logging and seismic response characteristics of the reservoir were analyzed, and a multi-wave (PP+PS) pre-stack joint inversion process was developed. Compared with the single PP-wave inversion, the multi-wave joint pre-stack inversion effectively reduces ambiguity and improves stability and prediction accuracy. The resolution and the S/N of P-wave impedance, S-wave impedance and $V_{\mathrm{p}}/V_{\mathrm{s}}$ derived from joint inversion have been greatly improved. Especially the $V_{\mathrm{p}}/V_{\mathrm{s}}$ clearly characterizes the distribution of dolomite reservoirs, indicating that the multi-wave joint inversion has great potential and advantage in carbonate reservoir prediction.

References

Connolly, P.: Elastic impedance. Lead. Edge **18**(4), 438–452 (1999)

Du, Q.Z., Yan, H.Z.: PP and PS joint AVO inversion and fluid prediction. J. Appl. Geophys. **90**, 110–118 (2013)

Du, B.Y., Yang, W.Y., Wang, E.L., Wang, H.-Q., Li, H.-S., Yan, G.-H.: Joint pre-stack inversion of multiple waves based on Russell approximation. Chin. J. Geophys. **59**, 3016–3024 (2016)

Du, B.Y., Yang, W.Y., Zhang, J., Yong, X.S., Gao, J.H., Li, H.S.: Matrix-fluid decoupling-based joint PP-PS-wave seismic inversion for fluid identification. Geophysics **84**(3), R477–R487 (2019)

Duffaut, K., Landrø, M., Rognø, H., Al-Najjar, N.F.: Shear wave elastic impedance. Lead. Edge **19**(11), 1222 (2000)

Ensley, R.A.: Direct hydrocarbon detection with P- and SH-wave seismic data. Presented at the 53rd Annual SEG Meeting, Las Vegas (1983)

Gaiser, J.E.: Multicomponent V_P/V_S correlation analysis. Geophysics **61**, 1137–1149 (1996)

Garotta, R., Marechal, P., Magesan, M.: Two-component acquisition as a routine procedure for recording P-waves and converted waves. Can. J. Expl. Geophys. **21**, 40–53 (1985)

Garotta, R., Granger, P.Y., Dariu, H.: Combined interpretation of PP and PS data provides direct access to elastic rock properties. Lead. Edge **21**(6), 532–535 (2002)

Goodway, W., Tessman, D.J.: Blackfoot 3C/3D, a Vector-Seis case history. Presented at the SEG/EAGE Summer Research Workshop, Boise, Idaho (2000)

Hardage, B.A., DeAngelo, M.V., Murray, P.E., Sava, D.: Multicomponent seismic technology. SEG Geophysical References Series 18 (2011)

MacLeod, M.K., Hadley, M.J., Reynolds, K.J., Tura, A.: Multicomponent analysis of OBC data. In: 31st Annual Offshore Technology Conference, OTC, p. 10940 (1999)

Michelena, R.J., Donati, M.S., Valenciano, A.A., D'Agosto, C.: Using multicomponent seismic for reservoir characterization in Venezuela. Lead. Edge **20**, 1036–1041 (2001)

Miller, S.L.M.: Multicomponent seismic data interpretation. M.Sc. thesis, University of Calgary (1996)

Stewart, R.R., Gaiser, J.E., Brown, R.J., Lawton, D.C.: Converted-wave seismic exploration: application. Geophysics **68**(1), 40–57 (2003)

Thompson, C., Helgesen, H.K., Battie, J.E.: 2D-4C seismic exploration data for risk reduction, Fles prospect, offshore Mid-Norway. Presented at the SEG/EAGE Summer Research Workshop, Boise, Idaho (2000)

Van Dok, R., Kristiansen, P.: Event registration and VP-VS correlation analysis in 4C processing. In: 73rd Annual International Meeting, SEG, Expanded Abstracts, pp. 785–788 (2003)