Journal of Engineering Science and Technology Review 11 (4) (2018) 101 - 110

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Research Article

Indicative Factors of Reservoir Sensitivity Based on Pre-stack Inversion

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Received 19 March 2018; Accepted 21 August 2018

Abstract

With the deepened exploration and development of petroleum, pre-stack inversion can predict reservoir and petroleum distribution by extracting elastic parameters by virtue of the gathers. Because of the abundant information, pre-stack inversion has gradually become a focus of research. Existing studies indicate that pre-stack amplitude variation with angle simultaneous inversion has a favourable application effect in conventional shallow sandstone gas reservoirs, but has poor impact in deeply hidden-type reservoirs. For improved the precision of description and prediction of hidden-type reservoirs, the Shahejie Formation in the Gangbei District of the Gangzhong Oil Field was used as an example, and a method of predicting complicated structure-lithology reservoir based on improved Fatti reflection coefficient approximation formula was proposed in this study. Based on petrophysical analysis and coordinate transformation theory, with elastic parameters which were obtained by the new technology, the indicative factors of reservoir sensitivity were established, resulting in forming a series of accurate reservoir prediction methods. Results show that the improved inversion method can accurately describe sand bodies in a complicated structure-lithology reservoir. Indicative factors of reservoir sensitivity show favourable linear correlation with sand bodies and it can indicate reservoir distribution more effectively than the conventional method. Prediction results are in agreement with actual drilling results. The study provides a theoretical reference for identifying complicated structure-lithology reservoirs.

Keywords: Pre-stack simultaneous inversion, Petrophysical elastic parameters, Fatti reflection coefficient approximation formula, Reservoir prediction

1. Introduction

Seismic inversion is a process of obtaining spatial structure and physical properties of underground strata using seismic data with known geological laws and logging information as the constraints. Based on different mathematical-physical models, it can be divided into post-stack inversion and pre-stack inversion. Pre-stack inversion is a technology based on pre-stack gathers. It directly predicts distributions of petroleum and reservoirs according to the lithology and the properties of pore fluid reflected by change laws of amplitude with offset or angle of incidence. This technology has been researched and expounded by Aki and Richard[1], Connolly[2], Fatti[3], etc. Pre-stack inversion has gradually replaced conventional post-stack inversion to become an indispensable core technology in petroleum reservoir prediction, due to its characteristics such as abundant information and high prediction accuracy. As an important branch of pre-stack inversion, pre-stack amplitude variation with angle (AVA) simultaneous inversion is an inversion method which is combining pre-stack with post-stack under logging constraints. It can simultaneously obtain many parameters, such as pressure-wave (P-wave) impedance, shear-wave (S-wave) impedance and density. At present, AVA inversion is a pre-stack inversion technology with the best actual application effects in the exploration of lithological petroleum reservoir [4,5].

Currently, the objective of petroleum exploration and development has transitioned from structural petroleum reservoir into hidden petroleum reservoir and lithological petroleum reservoir, resulting in higher requirements for exploration accuracy. Precise prediction of lithological petroleum reservoir and thin-layer petroleum reservoir has become a critical problem requiring urgent solutions in petroleum research. Traditional post-stack seismic inversion can only obtain wave impedance information, so its ability to solve geological problems is restricted, and meeting present requirements for fine description of oil reservoir is difficult. Pre-stack inversion technology can obtain not only wave impedance and many other elastic parameters by fully using pre-stack gathers, such as shear impedance, Poisson's ratio, and Lame coefficient. The technique can provide abundant means for reservoir description and strengthen the ability of complicated reservoir description and fluid detection. The technique of pre-stack inversion still mainly centers on describing and studying structural petroleum reservoir using all kinds of methods, and the majority of studies have focused on reservoir and oil-bearing prediction centered on shallow sandstone gas reservoir. However, the effect on deep-hidden petroleum reservoir is rarely studied.

At present, studies on pre-stack inversion are mainly about amplitude variation with offset (AVO) inversion based on Zoeppritz simplified equation and elastic impedance inversion of angle stacking. However, the restrictions of the

*E-mail address: 501096@yangtzeu.edu.cn
ISSN: 1791-2377
doi:10.25103/jestr.114.13

signal-noise ratio and the non-uniqueness of inversion results affect the accuracy and effectiveness of inversion. Pre-stack simultaneous inversion integrates post-stack wave impedance and pre-stack AVO properties into the inversion process using angle stacking data cubes, which maintains the consistency of various elastic parameters and enhances the stability and the reliability of results. Many scholars have conducted profound studies on pre-stack AVA inversion in recent years, such as Yu[14], Chen[15], Gui[16], Maleki[17], Mirshnichenko[18], Azevedo[19], Alerdi[20,21,22]. As a result, these studies presented many favorable application effects in fine prediction of complicated reservoir and fluid recognition.

In this study, with full consideration of regional well-posed of petrophysical laws, AVO response type at target formation is determined through AVO forward modeling analysis. Coordinate transformation theory is used to realize fine prediction and description of sub-layer reservoir based on pre-stack AVA simultaneous inversion theory.

2. State of the art

Pre-stack AVA simultaneous inversion is based on the Zoeppritz equation. Elastic parameters such as P-wave velocity, S-wave velocity, and density are inverted using a priori constrained information from logging data. Then, under the guidance of petrophysical statistical analysis, lithology and oil-bearing properties are explained and predicted. For a long time, many scholars have researched on the technology of pre-stack AVA inversion in the reservoir and oil-bearing properties.

Aki and Richard[1] established a reflection-transmission coefficient equation using the Zoeppritz equation, P-wave velocity, and S-wave velocity in their book *Quantitative Seismology*. Furthermore, with profound research on pre-stack inversion, a series of approximate equations for different geological assumptions has emerged.

Yang et al.[23] established AVA three-parameter inversion technology by applying Fatti approximate formula. This method can show relatively stable lithological parameters (P-wave impedance, S-wave impedance, and density). The three properties can realize comprehensive description of underground strata, but the method to predict Poisson's ratio which is an important property that reflects underground lithological distribution was still lacking. Only by predicting Poisson's ratio which is used to obtain the distribution of underground lithological, could the risk of lithological exploration be reduced further. Gui et al.[24] proposed approximate expressions of reflection coefficient directly expressed by P-wave velocity, Poisson's ratio, and density, and they could be used to extract Poisson's ratio directly. Azevedo et al.[25] directly inverted density, P-wave velocity, and S-wave velocity models with gathering and sorting pre-stack seismic data by angle, inverted simulated elastic model by taking genetic algorithm as a global optimizer and obtained a reliable underground elastic medium model with high resolution. The primary properties of underground can be obtained by AVA simultaneous inversion. But the coincidence of log and seismic is ordinary, because the method extracts properties directly and fails to take comprehensive consideration of the influence of complicated underground conditions on properties.

As a result, multiple AVA linear inversion methods have been developed based on AVA three-parameter inversion technology, such as generalized linear inversion, conjugate gradient method of local optimization, and simulated annealing algorithm of global optimization.

Levy et al.[6] verified that the wavelet or pulse response could be applied to generalized linear inversion. Zhang et al.[7] improved inversion accuracy of wide-angle seismic data using generalized linear inversion algorithm by establishing an AVO forward-modeling process. Fang et al.[8] conducted generalized linear inversion by combining Bayesian approach, featuring high accuracy, strong applicability, and strong noise immunity. However, the problem of generalized linear inversion lies in extremely high reliance on the accuracy of the initial model. For the complicated structure-lithology petroleum reservoir, establishing an accurate initial model is usually difficult because of low-frequency property of earthquake and excessive reservoir complexity. Consequently, the indication of reservoir and oil-bearing property cannot reach the expected effect.

Zhu et al.[9] used a conjugate gradient method formed by combining non-heuristic and heuristic inversion methods, which could rapidly obtain inversion results and low requirements for the initial model. Huang et al.[10] improved pre-stack inversion based on generalized linear inversion theory, regularized constrained damping factor, and conjugate gradient algorithm, which effectively reduced the ill-posedness of inversion and improved inversion convergence. Wang et al.[11] applied the conjugate gradient method to sweet spot prediction of shale gas and used wide-angle seismic data to improve the accuracy of inversion result. Gonzalez et al.[12] conducted regularization and non-regularization deconvolution algorithm, which effectively improved vertical resolution. As conjugate gradient method of local optimization has advantages of non-heuristic and heuristic inversion methods, petroleum reservoir prediction has reached goals in many regions, but for complicated structure-lithology petroleum reservoir, it is very difficult to obtain satisfying result of seismic prediction. Moreover, the conjugate gradient method has limited ability in improving accuracy; thus, it cannot meet the accuracy requirements for the reservoir.

Zhang[13] used simulated annealing algorithm of global optimization by combining regularization method and fast simulated annealing algorithm to determine the effects of regularization parameters, and obtain a global optimal solution. Simulated annealing algorithm of global optimization can obtain a global optimal solution, but the calculation is time-consuming. Consequently, this method has a poor effect in conventional reservoir and petroleum indication. Therefore, many scholars have studied frequency-domain pre-stack AVA simultaneous inversion method based on frequency decomposing technology to improve inversion accuracy and effectiveness.

Li et al.[26,27] conducted forward modeling of thin-bedded using wave theory and phase shift in the depth domain. Guo[28] used generalized propagation matrix theory to implement the analytical calculation of non-elastic layered medium model and obtain seismic wave frequency-dependent reflection coefficient. They then obtained an accurate theoretical basis related to thin-bedded, which laid a foundation for studies of other researchers. Pei[29] analyzed thin reservoirs with isotropic media using thin seismic inversion technology of whole bandwidth seismic information. However, complicated underground conditions are always under anisotropic distribution, so present studies cannot meet exploration and development requirements as yet.

Thus, prior studies on pre-stack AVA inversion mainly focus on how to efficiently and accurately acquire formation elastic parameters, and there are few studies concerning petrophysical (bridge of logging and seismic), AVO forward modeling analysis, and quantitative explanation method. On this basis, we used the deep thin reservoir composed of sand and mudstone of Bin III sub-layer in the Gangbei district of the Gangzhong Oil Field as the study object. Furthermore, reservoir indicative factors were established using the rotation of coordinates based on petrophysical, AVO forward modeling analysis, and improved Fatti equation. Then, fine prediction of reservoir in target formation was conducted.

The rest of this study is organized as follows. Section 3 presents the inference of pre-stack simultaneous inversion principles based on the improved Fatti equation and advantage analysis of this method. Section 4 shows the established model of reservoir indicative factors based on rotation of coordinates, and finally, the conclusions are summarized in Section 5.

3. Methodology

3.1 Pre-stack AVA simultaneous inversion

The Zoeppritz equation can accurately describe the response relationship of the change of reflection and transmission coefficients of plane-wave with incident angle as well as elastic parametric differences between upper and lower formation at the interface between semi-infinite media. Moreover, it can accurately reflect the relation between wave amplitude and angle of incidence. However, it cannot be used for analytical solving because of too many variables. Thus, it needs to be simplified and approximated. For instance, Aki proposed a linear approximation method based on assumption of weak elastic parametric and used P-wave reflection coefficient to express P-wave, S-wave, and density. Thus, using pre-stack seismic data to extract underground media elastic parameters becomes a possibility. However, in reservoir prediction research, P-wave and S-wave impedance are usually used but not velocities. Therefore, if the Aki formula is used for inversion, the secondary transformation of inversion results needs to be conducted. To reduce error accumulation in inversion results, Fatti et al. further changed the Aki formula and put forward the Fatti reflection coefficient approximation formula, which is separately expressed by P-wave impedance, S-wave impedance, and density. The formula is expressed as follows:

$$R(\theta) = C_1 \bullet \frac{\Delta Z_p}{Z_p} + C_2 \bullet \frac{\Delta Z_s}{Z_s} + C_3 \bullet \frac{\Delta\rho}{\rho} \tag{1}$$

where Z_p is P-wave impedance; Z_s is S-wave impedance; ρ is density; $\Delta Z_p / Z_p$ is P-wave impedance reflection coefficient in normal incidence; $\Delta Z_s / Z_s$ is S-wave impedance reflection coefficient in normal incidence; θ is the angle of incidence of plane wave; $Z_p = V_p * \rho$, $Z_s = V_s * \rho$, $C_1 = (1+\tan^2\theta)/2$, $C_2 = 4\gamma^2 \sin^2\theta$, $C_3 = 2\gamma^2 \sin^2\theta - \tan^2\theta / 2$ and $\gamma = V_s / V_p = 0.5$.

Under the circumstances with multiple angles of incidence, Equation (1) can be expressed as the following matrix form:

$$\mathrm{R}(\theta) = \mathrm{Gx} \tag{2}$$

where $R(\theta)$ is reflection coefficient due to change of incident angle, G is the AVO forward operator and can be expressed as $[C_1 \quad C_2 \quad C_3]$, and x is the model parameter vector $[\ \Delta Z_\mathrm{p} / Z_\mathrm{p} \quad \Delta Z_\mathrm{s} / Z_\mathrm{s} \quad \Delta\rho / \rho\ ]^T$.

Under normal conditions, Equation (2) is an overdetermined equation, so the solution of the inversion problem can be constructed by least squares.

$$\mathrm{x} = \left(\mathrm{G}^\mathrm{T}\mathrm{G}\right)^{-1} \mathrm{G}^\mathrm{T}\mathrm{R} \tag{3}$$

Generally, AVO inversion is ill-posed, so a stable result cannot be obtained by directly solving Equation (3). Therefore, some constraint conditions should be added to strengthen the stability of the inversion process.

In the practical study, favorable linear correlations exist among three parameters: P-wave impedance, S-wave impedance, and density. Thus, the above inversion problem can be improved based on the Gardner formula under "wet" background (mudstone saturated water) assumption, in which the ratio of P-wave velocity to S-wave velocity is a constant.

Given that $\gamma = V_s / V_p = \text{constant}$ after multiplying fractions at the right side of the equation by density simultaneously, the logarithm of two ends of the equation is used to obtain the following:

$$\ln\left(\mathrm{Z_p}\right) = \ln\left(\mathrm{Z_s}\right) + \ln(\gamma) \tag{4}$$

Considering the Gardner Formula ($\rho = \mathrm{aV_s^b}$), two ends of the equation are multiplied by ρ^{b}. Then, the logarithm of both ends of the equation is used to obtain the following equation:

$$\ln(\rho) = \frac{\mathrm{b}}{1+\mathrm{b}} \bullet \ln\left(\mathrm{Z_p}\right) + \frac{1}{1+\mathrm{b}} \bullet \ln(\mathrm{a}) \tag{5}$$

Hence, the following can be obtained by extending Equations (4) and (5) under the assumed "wet" background condition:

$$\ln\left(\mathrm{Z_s}\right) = \mathrm{k} \bullet \ln\left(\mathrm{Z_p}\right) + \mathrm{k_c} + \Delta\mathrm{L_s} \tag{6}$$

$$\ln(\rho) = \mathrm{m} \bullet \ln\left(\mathrm{Z_p}\right) + \mathrm{m_c} + \Delta\mathrm{L_D} \tag{7}$$

where Z_p, Z_s, and ρ are logging data and k, k_m, m *and* m_c are solved through least squares fitting by using interactions among P-wave impedance, S-wave impedance and density. ΔL_s and ΔL_D describe the deviation degrees of S-wave impedance and density from the trend line, respectively.

Finally, the improved Fatti formula can be expressed as follows:

$$R(\theta) \approx \tilde{C}_1 \bullet \frac{\Delta Z_p}{Z_p} + C_2 \bullet \Delta L_s' + C_3 \bullet \Delta L_D' \tag{8}$$

where $\widetilde{C}_1 = C_1 + kC_2 + mC_3$, $\Delta L_s{}'$ is the differential of ΔL_s about Z_p, and $\Delta L_D{}'$ is the differential of ΔL_D about Z_s.

Based on Equation (8), pre-stack AVA simultaneous inversion technology is used to obtain elastic parameters such as P-wave impedance, S-wave impedance, and density at the same time from pre-stack CDP gathers or several angle stacking data cubes through iterative computation. Compared with conventional simultaneous inversion based on reflection coefficient approximation formulas such as Aki-Richards, simultaneous inversion based on improved Fatti formula has the following advantages:

(1) The formula that is improved by the Fatti formula is a single-variable function of P-wave impedance, so the algorithm is more stable with small calculated quantity.

(2) The approach is an inversion process that is effectively constrained by petrophysical analysis and geological factors based on the assumption of "wet" background formation.

(3) Owing to the linear feature of the formula, noise channels can be processed by methods such as pre-whitening and stabilization.

3.2 Establishment of reservoir sensitivity indicative factor

The indicative factor of sensitive reservoir is the key to reservoir prediction. In consideration of the regional applicability of the elastic parameters and AVO properties, the indicative factors exhibit great differences in different regions. The priori information of log data in the Gangbei district was sufficiently used. Various elastic parameter curves obtained using various actual logging curves and petrophysical analysis were calculated. Differential analysis of reservoir and non-reservoir logging response relation was conducted. Given the above conditions, establishment criteria for combination of elastic parameters to which the reservoir was sensitive in the study area were determined successively.

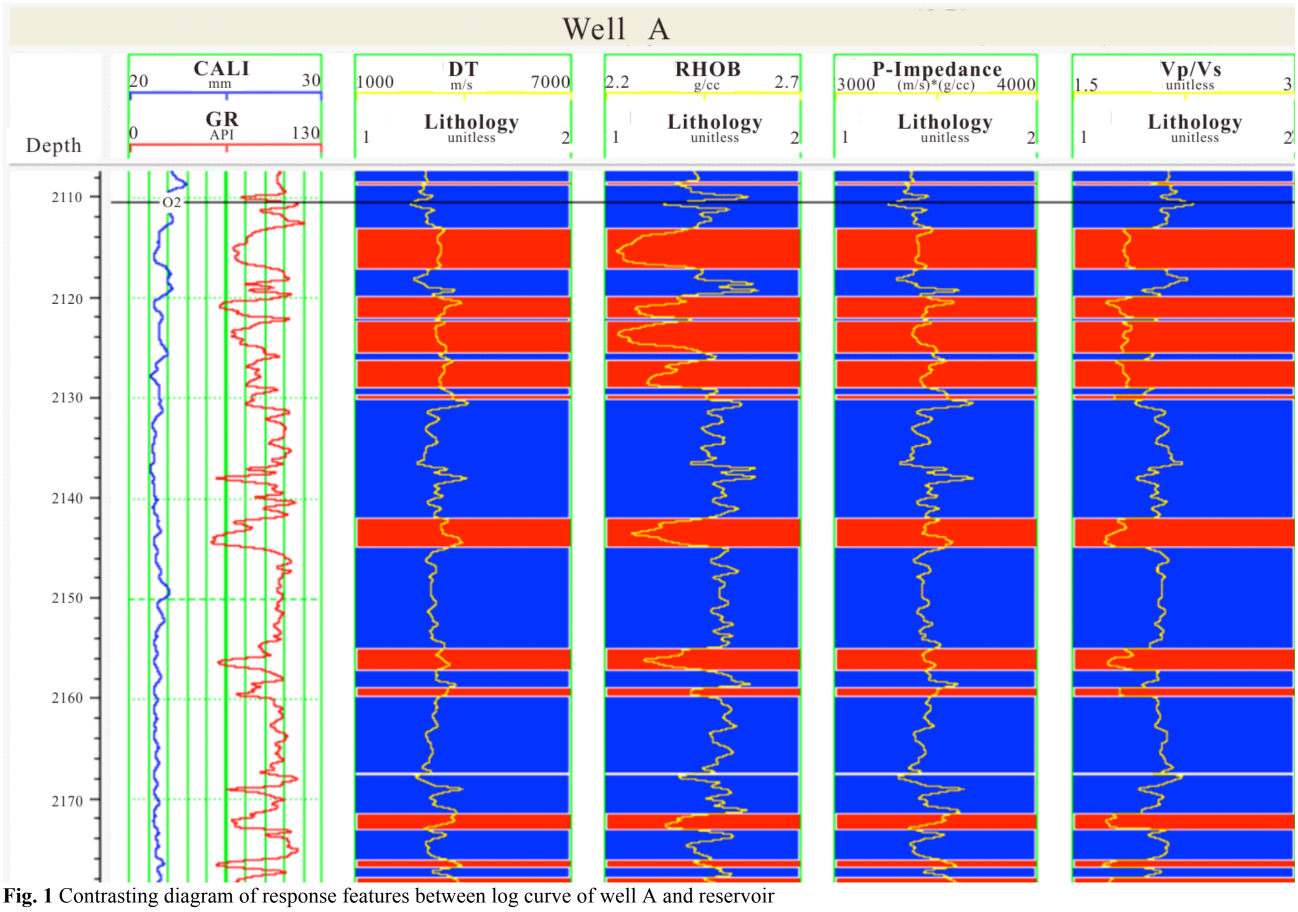

Fig. 1 Contrasting diagram of response features between log curve of well A and reservoir

With wells data analysis, typical well A was used as an example. Figure 1 shows the response features of logging data (acoustic, density, and P-wave impedance) and the reservoir of well A. Based on calculated porosity results obtained and reservoir evaluation by logging (the lower limit of porosity in the reservoirs was 6%), reservoirs and non-reservoirs could be definitely marked off on the single well. The red band in Fig. 1 is the segment of effective reservoir, and the blue band is the non-reservoir layer. The figure indicates that the difference of logging response between reservoirs and non-reservoirs was quite obvious. The layer of reservoir presented low gamma, high P-wave velocity, low density, relatively high P-wave impedance, and low P-wave/S-wave ratio. By contrast, the layer of non-reservoir presented high gamma, low P-wave velocity, high density, relatively low P-wave impedance, and high P-wave/S-wave ratio. P-wave impedance difference between reservoir and non-reservoir was small with high coincidence degree. Thus, conventional post-stack wave impedance inversion had poor identification of the reservoir. However, the P-wave/S-wave velocity ratio could identify the reservoir very well. Therefore, the reservoir could be depicted by elastic parameters such as P-wave/S-wave velocity ratio extracted from pre-stack gathers in the study area so as to effectively improve the precision and the accuracy of reservoir prediction.

Based on the qualitative evaluation of wells, the quantitative statistical analysis was conducted for logging information of over 30 wells in the study area by lithology. The lithology of target reservoir in the study area mainly consisted of sandstone and mudstone, as well as a small quantity of shale, and the target reservoir is a typical thin reservoir. With multi-well consistent processing, the multi-well statistical table in the study area shows that porosity and oil-bearing property were influenced by lithological content. P-wave velocity within sandstone layer as explained by logging was mainly at 2,850-4,160 m/s and mean peak value was approximately 3,300 m/s. P-wave velocity within mudstone layer explained by logging was mainly at 2,600-4,100 m/s, and mean peak value was approximately 2,950 m/s. Even though the density curve showed that density in sandstone layer with high porosity obviously decreased (as shown in Fig. 1), the density of sandstone within the entire target formation in the study area was slightly lower than the density of mudstone. Furthermore, the coincidence of density distribution was high. Mean peak value was mainly within 2.33-2.43 g/cm^3. Overall, as the reservoir presented typical high P-wave velocity and low density with high coincidence degree under the effects of porosity and oil-bearing properties, the conventional wave impedance inversion method cannot effectively differentiate lithology and reservoir.

On the condition that logging response laws in this area were ensured consistent, logging data of typical well A were finally selected to conduct petrophysical analysis so as to realize the establishment of reservoir sensitivity indicative factors. Petrophysical analysis results are shown in Fig. 2, in which red, orange, and yellow respectively indicate oil, oil-water, and water layers. Furthermore, light blue and purple correspond to dry layers and mudstone segments, respectively. The points in the red region at the left side correspond to the red-marked segment of single-well curve on the right side. In addition, the figure indicates the following.

(1)Reservoir and non-reservoir can be accurately identified in the cross-plot of P-wave impedance and P-wave/S-wave velocity ratio.

(2)In the cross-plot, the boundary between reservoir and non-reservoir can be approximated as a straight oblique line;

(3)Separation windows of oil, oil-water, and water layers are very small, so fluid prediction using pre-stack simultaneous inversion in the study area is very difficult.

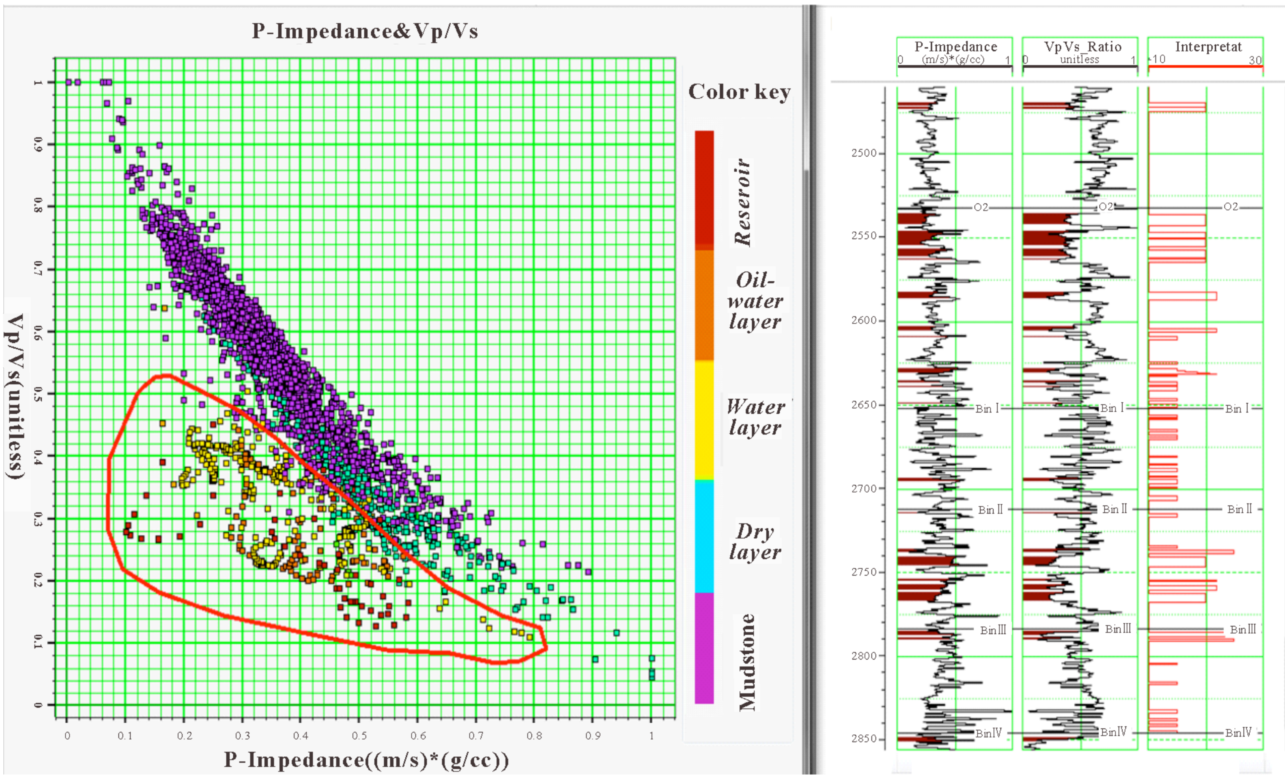

Fig. 2. Crossplot of elastic parameters of well A

Based on the relationship between P-wave impedance and P-wave/S-wave velocity ratio, the theory of coordinate transformation was introduced. P-wave impedance and P-wave/S-wave velocity ratio were used to jointly establish a new reservoir indicative factor that can be directly used for reservoir depiction. The low value of indicative factor can directly correspond to sand body development zone.

Mathematically, the coordinate transformation is a kind of linear transformation, and the linear relationship between P-wave impedance and P-wave/S-wave velocity ratio is inferred through cross-plot analysis as follows (separation line between reservoir and non-reservoir):

$$Z_p = a + c*(V_p/V_s) \quad (9)$$

In Equation (9), both *a* and *c* are constants. The value of *c* decides the rotation angle of the coordinate axis. *Reser* was used to express the reservoir sensitivity indicative factors after coordinate transformation:

$$Reser = Z_p * sin(\theta) + (V_p/V_s) * cos(\theta) \quad (10)$$

In Equation (10), *Reser* is the reservoir sensitivity indicative factor, Z_p is the P-wave impedance, V_p/V_s is the P-wave/S-wave velocity ratio, and θ is the rotation angle.

4 Result analysis and discussion

4.1 Study area

The study area is located in the north of coastal fault in the Gangzhong Oil Field in China. The method proposed in this study was used to conduct reservoir prediction study in this area, which can be used to prove its feasibility and analysis results.

Located at the east of the Beidagang secondary structural belt in the Huanghua Depression, the Gangzhong Oil Field is formed on the paleogeographic background of the northeast slope in Gangxi Arch. The area has a large fault-controlled nose structure with a reservoir burial depth of 1,750-3,600 m. The oil-bearing area is 36.6 km^2 and the oil reserves in place are $4{,}011 \times 10^4$ t. The study area, Gangbei district, is located in the north region of the main oil-source fault and coastal fault, and drilled formations from the bottom up are the Mesozoic Group, Paleogene System, Neogene System, and Quaternary System. The favorable reservoir is mainly distributed at the Shahejie Formation on the Neogene System (as shown in Fig. 3) and Dongying Formation on the Tertiary System. The reservoir in the target formation, Shahejie Formation, mainly consists of a dark gray and brown-gray mudstone intercalated thin-layer that consists of oil shale and argillaceous siltstone. According to the comparison of cycles, hierarchical control and step-by-step division from large to small and from coarse to fine, the Shahejie Formation can be divided into 8 units, 36 sub-layers, and 72 single sand bodies. Thus, it is a typical thin sandstone reservoir. The number of completed wells in the study area reaches 70, including exploratory wells, evaluation wells, and development wells with an over 40-year history of development thus far. At present, the oil field has entered the middle and later stages of development. Complicated spatial distribution features of sand bodies and high difficulty in predicting remaining oil distribution laws will be the main factors influencing follow-up optimization and adjustment of the development scheme.

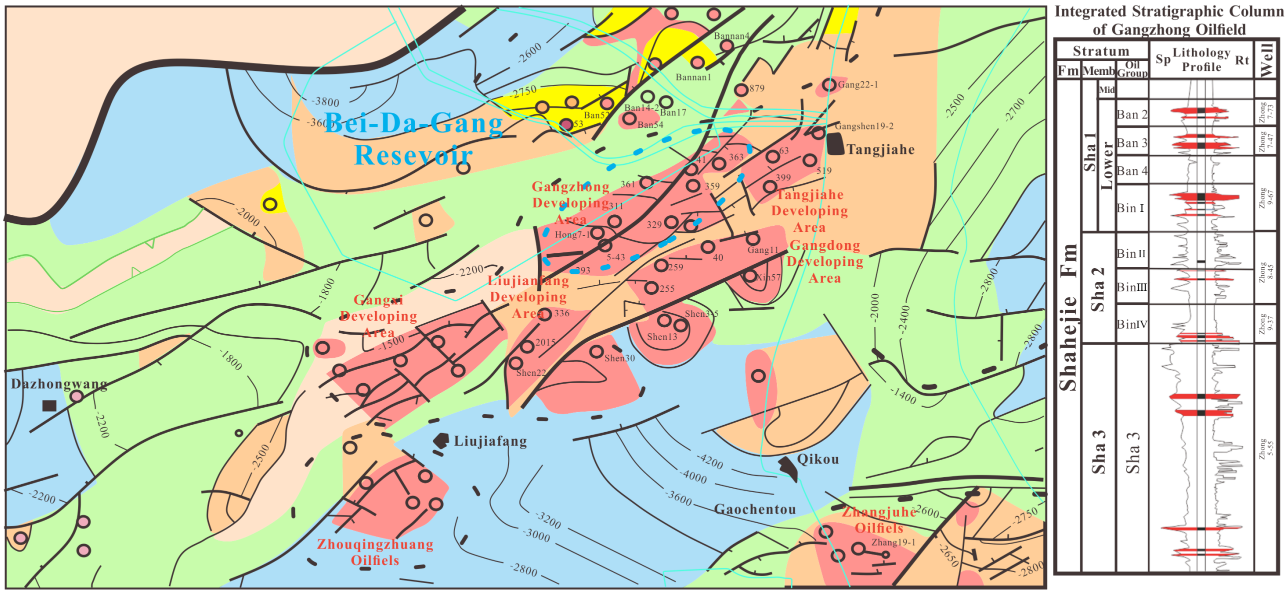

Fig. 3. Location plan of the study area (red color is favorable oil-bearing region)

4.2 Feasibility analysis

Given that reservoir sensitivity factors are established by the proposed method based on petrophysical analysis, pre-stack inversion can directly complete certification of method feasibility in aspects of logging information. The feasibility, which is still necessary to certify in aspects of seismic cube, can be based on AVO forward modeling of well. Firstly, whether the AVO response relation of theoretical forward model is consistent with the AVO response of actual gathers should be studied. Secondly, the AVO response type of the reservoir in the study area should be determined. Taking well A as an example, pre-stack AVO forward modeling analysis was conducted. The results showed that seismic reflection amplitude at the top interface of the Bin III sub-layer which is the main target layer was reduced as offset increased (Fig. 4) with typical I-type AVO abnormal response. Moreover, this result was consistent with AVO response features of actual seismic gathers beside the well with favorable well-seismic coincidence. Furthermore, pre-stack gather signal-to-noise ratio was high, indicating that pre-stack gather quality met the requirements for simultaneous inversion.

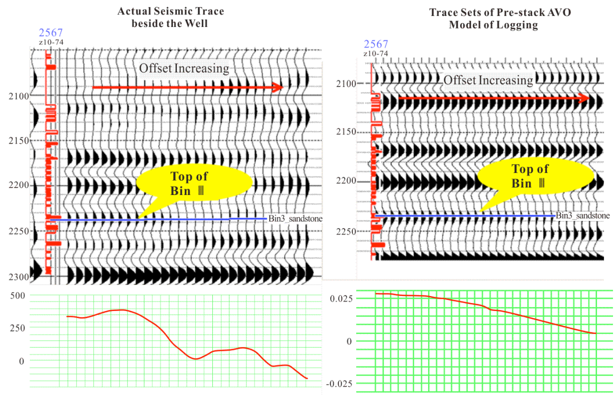

Fig. 4. Comparative analysis chart of AVO undisturbed formation forward model and through-well actual seismic gather

Based on feasibility analysis of pre-stack simultaneous inversion using AVO forward model, the proposed method in this study was used for reservoir prediction in the Gangbei district.

4.3 Analysis of application effects

Data cubes of P-wave impedance and P-wave/S-wave velocity ratio obtained by pre-stack AVA simultaneous inversion were used to establish reservoir sensitivity indicative factors with the guidance of petrophysical statistical analysis. Based on the abovementioned statistical analysis of reservoir sensitivity, low values of reservoir sensitivity indicative factors responded to the sand body development zone. After repeated comparison, it was determined that the reservoir sensitivity indicative factor value smaller than 0.62 referred to sand body development segment. The smaller the value, the more developed the sand body. The prediction results depicted by inversion and reservoir indicative factor properties were verified by well point. Figure 5 shows the sand body comparison diagram of key well reservoirs in this area. Figure 6 shows the through-well profile of reservoir indicative factors passing through key wells in this area. Comparison indicates that connecting-well sand body distribution features were basically identical with the connecting-well stratigraphic comparison section, indicating the effectiveness of sand formation prediction using pre-stack simultaneous inversion in this area under a distinguishable seismic scale.

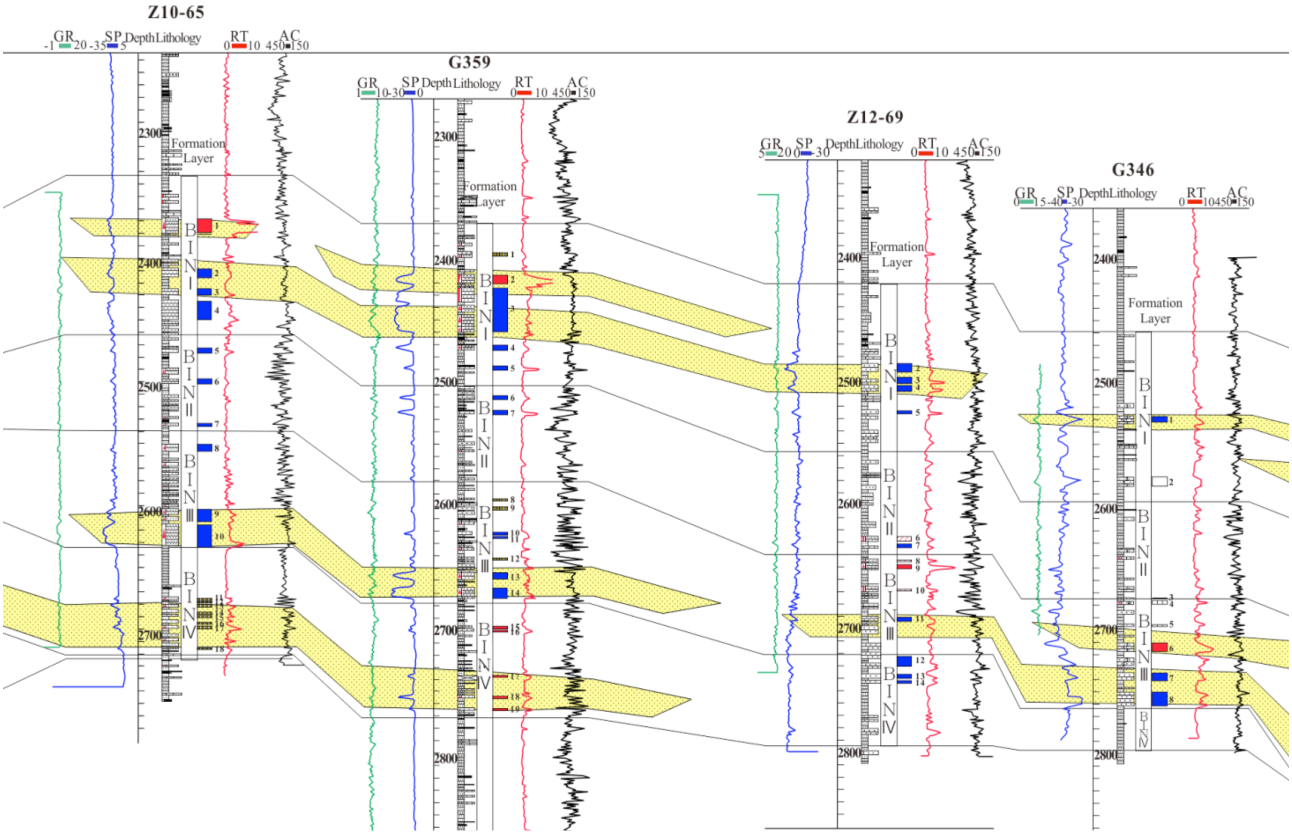

Fig. 5. Well-tie stratigraphic comparison sections passing through key wells

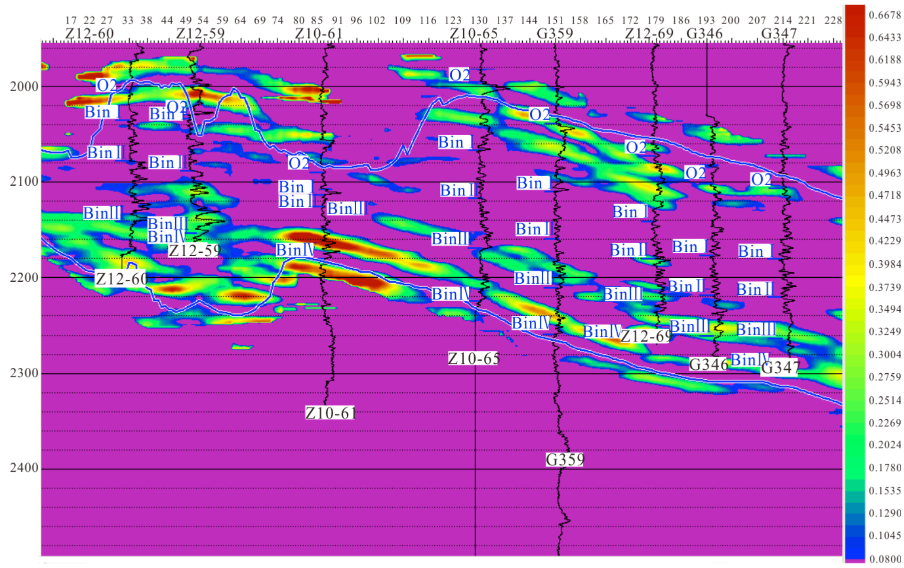

Fig. 6. Profile of reservoir sensitivity indicative factors passing through key wells

Distribution diagram of reservoir indicative factor properties on the plane which extracted along interpretation horizon of the Bin III sub-layer (Fig. 7) could depict the sedimentation of the underwater alluvial fan and long-shore bar that is controlled by the structure in the study area. The favorable reservoir mainly shows the geological characteristics of the braided channel micro-phase. Further, using the reservoir critical value (0.62) of reservoir attribute cube taken as the standard, the total thickness of sand bodies in the objective interval was extracted to predict the planar distribution of sand bodies. Figure 8 shows the distribution prediction graph of sand body thickness in the Bin III sub-layer on the plane. Thus, sand bodies that presented sheet distributions on the plane were nearly parallel to fracture because of the control of structure, which accorded with sedimentation laws. The main sand body development zone is located to the north of the coastal fault and basically distributed along the coastal fault which is distributed in the black-line region in Fig. 7. Therefore, the high-value region in the northeast is the key region for follow-up rolling development and deployment of well locations.

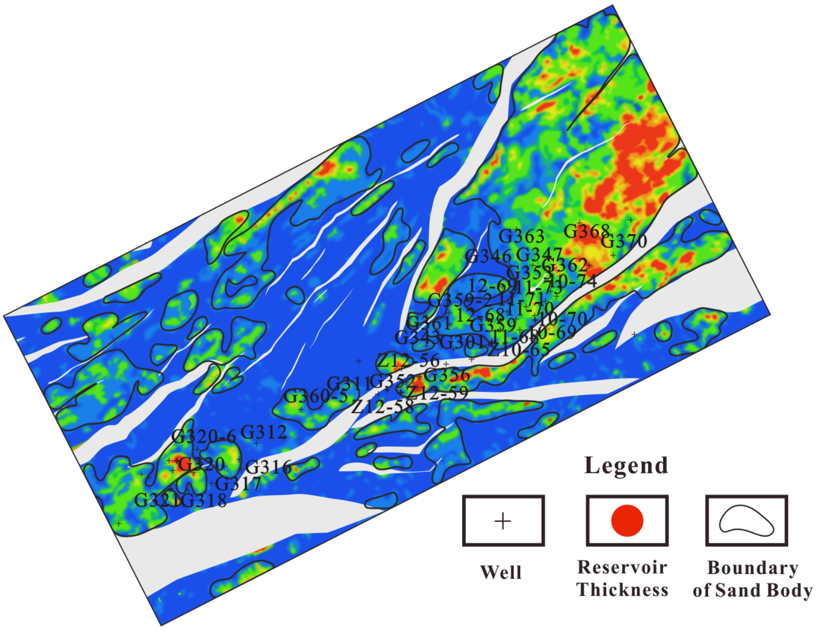

Fig. 7. Slicing of reservoir indicative factor properties

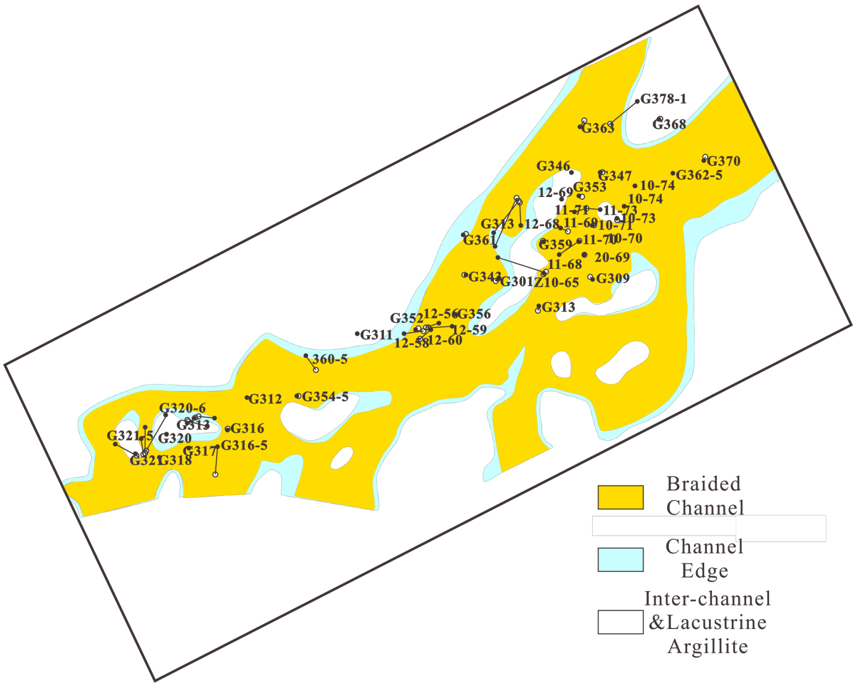

Fig. 8. Prediction graph of planar distribution of sand body thickness of the Bin III sub-layer

Thus, it can verify that pre-stack simultaneous inversion can predict thin reservoirs composed of sand and mudstone in this area very well regardless of longitudinal, transverse, or sedimentary characteristic analysis.

5. Conclusions

A quantitative explanation method of pre-stack AVA simultaneous inversion in the field of deep-layer hidden petroleum reservoir was studied. Reservoir indicative factors were established in this study through the pre-stack AVA simultaneous inversion method based on improved Fatti approximation formula and theory of coordinate rotation. The established method for determining reservoir indicative factors was applied to a deep thin reservoir composed of sand and mudstone. The feasibility of this method was verified, and the reliability of the result was analyzed. Finally, the following conclusions were drawn：

(1)Based on logging response characteristic analysis, the study area was a typical thin reservoir composed of sand and mudstone with high P-wave velocity and low density. Porosity and oil-bearing property had unobvious influences on wave impedance. Thus, conventional wave impedance inversion method cannot easily differentiate between lithology and reservoir.
(2)Based on petrophysical analysis, AVO forward modeling technology was used to determine the AVO response type in the study area (I-type AVO abnormal response). It was consistent with AVO response characteristics in actual seismic gathers, and beside the well it was a favorable coincidence between logging and seismic. Thus, the feasibility of this method in the study area was verified.
(3)According to pre-stack AVA inversion results based on improved Fatti approximation formula, reservoir indicative factors established based on rotation of coordinates were used to predict reservoir distribution using single parameters, which improved quantitative explanation accuracy of pre-stack AVA simultaneous inversion.
(4)Through connecting-well comparison and comparative analysis of planar distribution, it was verified that prediction results were identical with actual drilling results, indicating that this method obtained highly accurate and reliable prediction results.

Based on petrophysical analysis, pre-stack AVO forward model, and pre-stack AVA simultaneous inversion, reservoir distribution in the study area was accurately predicted through the establishment of reservoir indicative factors using the rotation of coordinates. Thus, the prediction accuracy of pre-stack AVA simultaneous inversion was improved. However, due to limitations of AVA simultaneous inversion theory, the method had limited ability in elevating resolution ratio of reservoir prediction. In particular, conducting prediction work of single sand bodies is difficult. In future studies, new methods for improving the resolution ratio of reservoir prediction under the current major trends need to be developed.

Acknowledgements
The study was supported by the Scientific Research Program of the Department of Education of Hubei Province (Grant No. Q20161305).

References

1. Aki, K., Richards, P. G. 1980, "*Quantitative seismology*: Theory and methods", New York: W.H. Freeman and Co. Company, U.S.A., 1980, pp.100-170.
2. Connolly P.A. "Elastic impedance". *The Leading Edge*, 18(04), 1999, pp.438-452.
3. Fatti J L, Smith G C, Vail P J, et al. "Detection of gas in sandstone reservoirs using AVO analysis: A 3-D seismic case history using the geostack technique". *Geophysics*, 59(09), 1994, pp.362-376
4. Whitecombe D N. "Elastic impedance normalization". *Geophysics*, 67(01), 2002, pp.60-62.
5. Whitecombe D N, Connolly P A, Reagan R L, et. al. "Extended elastic impedance for fluid and lithology prediction". *Geophysics*, 67(01), 2002, pp.62-67.
6. Levy S, Clowes R M. Debubbling. "A generalized linear inverse approach". *Geophysical Prospecting*, 28(06), 2010, pp.840-858.
7. Fengqi Zhang, Fuji Wei, Yanchun Wang et al. "Generalized linear AVO inversion with the prioriconstraint of trivariate cauchy distribution based on Zoeppritz equation". *Chinese Journal of Geophysics*, 56(06), 2013, pp.2098-2115.
8. Yuan Fang, Fengqi Zhang, Yanchun Wang, et. al. "Generalized linear joint PP-PS inversion based on two constraints". *Applied Geophysics*, 13(01), 2016, pp.103-115.
9. Peimin Zhu, Jiaying Wang, Zhengbin Zhan, et. al. "Stochasitic conjugate gradient inversion". *Oil Geophysical Prospecting*, 35(02), 2000, pp.208-213.
10. Handong Huang, Yanchao Wang, Fei Guo, et. al. "Zoeppritz equation-based prestack inversion and its application in fluid identification". *Applied Geophysics*, 12(02), 2015, pp.199-121.
11. Kangning Wang, Zandong Sun, Ning Dong. "Prestack inversion based on anisotropic Markov random field-maximum posterior probability inversion and its application to identify shale gas sweet spots". *Applied Geophysics*, 12(04), 2015, pp.533−544.
12. Gonzalez H, Avendaño S, Camacho G. "A proposal for regularized inversion for an ill-conditioned deconvolution operator". *CT&F-Ciencia, Tecnologia y Futuro*, 05(03), 2017, pp.47-60.
13. Hongbing Zhang, Zuoping Shang, Changchun Yang, et. al. "Estimation of regularization parameters in wave impedance inversion". *Chinese Journal of Geophysics*, 48(01), 2005, pp.181-188.
14. Zhen Yu, Yanchun Wang, Jing He, et. al. "High-resolution fluid prediction method based on prestack AVA simultaneous inversion and geostatistical inversion". *Geophysical Prospecting for Petroleum*, 49(03), 2014, pp.154-163.
15. Li Chen, Zhongyu Fang, Zhiwei Dan, et. al. "Application of prestack simultaneous inversion in reservoir prediction in M region". *Techniques for Geophysical and Geochemical Exploration,* 37(01), 2015, pp.85-90.
16. Jinyong Gui, Jianhu Gao, Xueshan Yong, et. al. "Prestack simultaneous inversion method of elastic parameters concerning compact reservoir sensitivity". *Petroleum Exploration*, 54(05), 2015, pp.541-550.
17. Maleki M, Alamshahi R. "Using AVA Geostatistical inversion for thin layer reservoir characterization -A carbonate reservoir case study". In: *78th EAGE Conference and Exhibition*, Vienna, Austria: EAGE, 2016, pp.201601341.
18. Miroshnichenko D, Kerusov I, Chaikovskaya E, et. al. "Using elastic AVA inversion for the reservoirs prediction in Deepwater Turbidite Series Offshore West Africa". In: *International Conference and Exhibition*, Saint Petersburg, Russia: EAGE, 2016, pp.20160262.
19. Azevedo L, Nunes R, Soares A, et. al. "Geostatistical seismic AVA inversion". *Geophysical Prospecting*, 66(01), 2017, pp.342-347.
20. Aleardi M, Tognarelli A. "The limits of narrow and wide-angle AVA inversions for high Vp/Vs, ratios: An application to elastic seabed characterization". *Journal of Applied Geophysics*, 131, 2016, pp.54-68.
21. Aleardi M, Ciabarri F, Peruzzo F, et. al. "Bayesian estimation of reservoir properties by means of wide-angle AVA inversion and a petrophysical Zoeppritz equation". In: *78th EAGE Conference and Exhibition*, Vienna, Austria: EAGE. 2016, pp.027104.

22. Aleardi M, Ciabarri F, Mazzotti A. “Probabilistic estimation of reservoir properties by means of wide-angle AVA inversion and a petrophysical reformulation of the Zoeppritz equations”. *Journal of Applied Geophysics*, 10(02), 2017, pp.147-172.
23. Peijie Yang, Xing Mu, Xingyao Yin. “Prestack three-parameter simultaneous inversion method and its application”. *Acta Petrolei Sinica*, 30(02), 2009, pp.232-236.
24. Jinyong Gui, Xingyao Yin, Danping Cao. “Study of Poisson's ratio inversion method based on elastic impedance inversion theory”. *Geophysical Prospecting for Petroleum*, 50(05), 2011, pp.463-469.
25. Lifeng Liang, Hongbing Zhang, Zhiwei Dan et al “Prestack density inversion using the Fatti equation constrained by the P- and S-wave impedance and density”, *Applied Geophysics*, 13(01), 2017, pp.133-141.
26. Xueying Li, Shumin Chen, Jianmin Wang, et.al. “Forward modeling of time-frequency characteristics of thin layer”. *Chinese Journal of Geophysics*, 55(10), 2012, pp.3410-3419.
27. Xueying Li, Huijian Wen, Shumin Chen, Jinamin Wang, et. al. “Forward modeling of time-frequency characteristics of equal-thickness interbed”. *Chinese Journal of Geophysics*, 56(03), 2013, pp.1033-1042.
28. Zhiqi Guo, Cai Liu, Xiangyang Li, Huitian Lan. “Frequency-dependent AVO response simulation and analysis of non-elastic layered medium seismic waves”. *Chinese Journal of Geophysics*, 59(02), 2016, pp.664-672.
29. Sijia Pei. “*Study of sand-mudstone thin interbed structural characterization based on seismic waveform inversion*”. Doctoral Dissertation of Jilin University, China, 2017, pp.12-18.