

# DIRECT PREDICTION METHOD OF FRACTURING ABILITY IN SHALE FORMATIONS BASED ON PRE-STACK SEISMIC INVERSION

CHANG WANG<sup>1,2</sup>, CHENG YIN<sup>1,\*</sup>, XUEWEN SHI<sup>2</sup>, SHULIN PAN<sup>1</sup>, QIYONG GOU<sup>2</sup>,  
DONGJUN ZHANG<sup>2</sup>, CHENWEI ZENG<sup>3</sup> and CHUNYANG FANG<sup>4</sup>

<sup>1</sup> School of Geosciences and technology, Southwest Petroleum University, Chengdu 610500, P.R. China. 306001759@qq.com

<sup>2</sup> Shale gas Research Institute, Petro China Southwest Oil & Gasfield Company, Chengdu 610051, P.R. China.

<sup>3</sup> CPEC Southwest Engineering Construction Company, Chengdu 610213, P.R. China.

<sup>4</sup> Economic and Information Technology Bureau of Chengdu Economic and Technological Development Zone, Chengdu 610000, P.R. China.

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## ABSTRACT

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The prediction of brittleness is an important research field for shale gas exploration and development. Currently, the most common way to evaluate the brittleness is calculating the average of the sum of normalized Young's modulus and Poisson's ratio. But this method needs pre-stack seismic inversion, petrophysics model calculation and normalization which is not an efficient way to obtain brittleness index directly and may introduce iterative error in the process. This paper derives a novel elastic impedance (EI) approximation which establishes a direct relationship with brittleness index. After that, we discussed the accuracy of *EI* approximation in Goodway's model, the results show the approximation is very close to Zoeppritz matrix when the incident angle is less than 30 degrees. Then we establish a method under Bayesian framework for improving the accuracy of brittleness index prediction. We find the predicted brittleness index fits very well with the real model data even SNR = 3. Finally, we apply our theory to shale gas block in southern Sichuan Basin, it shows that the predicted brittleness index not only fits well with well-logging, but also indicates the highest brittleness layer which is consistent with the rock core experiment results.

KEY WORDS: shale gas, brittleness index, pre-stack seismic inversion, elastic impedance, Bayesian framework.

## INTRODUCTION

Pre-stack seismic inversion is an important method in reservoir prediction and fluid characterization which is widely used in shale gas exploration and development. Because the difference of seismic inversion theory, pre-stack seismic inversion can be divided into AVO inversion and full wave inversion. Full wave inversion makes full use of the wavefield information, it automatically considers the wave propagation issues of reflected wave, transmitted wave, scattered wave and diffracted wave. The advantages of full wave inversion are that it is not restricted to reflected wave information, and comprehensive use of full wavefield to invert elastic parameters directly. Because of its huge amount of calculation, high requirements on computer performance, so that it is not widely used now. Compared with full wave inversion, AVO inversion plays a popular role in pre-stack inversion and gets further development. For better noise immunity, Connolly (1999) proposed the concept of elastic impedance and established elastic impedance inversion which has become a mainstream method in oil&gas field for reservoir prediction and fluid characterization.

Zoeppritz (1919) matrix is the foundation of pre-stack seismic inversion. Because of the complexity of solving nonlinear equation, in the early years, it was not commonly used. To solve the problem, many scholars deduced AVO reflection coefficient approximation and made it widely used in exploration and development. Aki and Richards (1980) simplified the matrix and proposed a reflection coefficient approximation, which not only reduced computation but also ensure the accuracy. Ostrander (1984) explained the situation that the P-wave reflection coefficient variation with incident angle and systematically elaborated the corresponding characteristics of AVO in gas-bearing sandstone which proved that AVO was used widely in the engineering of seismic exploration. Following scholars have done further research. Shuey (1985) proposed an AVO approximation in terms of Poisson's ratio, S-velocity and density which plays an important role in prediction of gas-bearing sandstone reservoir. Fatti (1994) proposed a novel AVO approximation based on P-Impedance, S-Impedance and density. For better fluid characterization, Russell (2011) made an axis rotation and put forward to Russell Fluid Factor, to extract the parameter accurately, then proposed an AVO approximation based on fluid factor.

Connolly considered the conception of *EI* and proved the better noise immunity than AVO inversion. Whitcombe (2002) rewrote *EI* equation and calibrated *EI* equation to the scale of acoustic impedance. For the density is relatively stable in deep formation, Wang (2006) proposed *EI* approximation in terms of Lamé parameter directly which reduced cumulative error in Lamé parameter prediction. Peng (2008) proposed multi-angle extended *EI* approximation and obtained good application in carbonate reservoirs. Zong (2011) explored *EI* theory in carbonate reservoir for fluid characterization, and made a workflow under Bayesian framework. Yin (2013) developed *EI* inversion based on pore fluid sensitive parameters, which has good application effect in the field. Li (2014) proposed two terms

*EI* equation based on fluid factor, established workflow including regularization restrain method. Luo (2015) put forward azimuth *EI* equation for HTI media. Liu (2016) proposed *EI* based on basis pursuit inversion for deep reservoir fluid identification. And now, the research in *EI* field is developing rapidly.

Now, shale gas has become an important alternative resource, the technologies of exploration and development have received wide attention. Shale gas is an unconventional resource stored in shale formation which needs hydraulic fracturing to form a network for industrial production. Besides natural fracture or fracturing network, one of the most important conditions is the ability of the reservoir reconstruction. For the shale formation, the higher brittleness, the easier fracturing. Based on petrophysics research, Young's modulus is positive to brittleness, and Poisson's ratio is negative to brittleness. Many scholars put out several brittleness index expression to evaluate fracture ability of the rocks. The mainstream method is to extract Young's modulus and Poisson's ratio by pre-stack seismic inversion, and then calculate the average of the sum of normalized Young's modulus and Poisson's ratio. In this paper, a novel elastic impedance equation is proposed to specify the relationship between brittleness index with *EI* directly. And then established an accurate method to obtain brittleness index under Bayesian framework. After that, the *EI* approximation accept analysis of accuracy and the result is closed to the Zoeppritz's maxtrix and Aki-Richard's approximation in the range of incident angle less than 30 degrees. Finally, the method accepts model test and field data practical application, the result shows that our theory and method has certain noise immunity and effective application.

## THEORY AND METHODS

### Elastic impedance approximation in terms of brittleness index

After studying and analyzing the Barnett shale, Rickman (2008) thought that Young's modulus and Poisson's ratio can represent shale's brittleness, where Young's modulus is positively correlated with brittleness index, and Poisson's ratio is negatively correlated with brittleness index. The research led way in the direction of brittleness evaluation by elastic parameters. Following former's research, Guo (2013) proposed an equation to identify brittleness index. Sharma (2015) believed that a novel parameter which combined Young's modulus and density play better in compressibility than Young's modulus in shale reservoir. After the research and proposed a brittleness index as:

$$BI = \frac{E\rho}{\sigma} \quad , \quad (1)$$

where,  $E$  represents Young's modulus,  $\sigma$  represents Poisson's ratio and  $\rho$  represents density.

Because of the different dimension between Young's modulus and Poisson's ratio, it makes difficulties for brittleness evaluation. For the convenience of identification, normalization was introduced in eq. (1):

$$BI = \frac{BI - BI_{\min}}{BI_{\max} - BI_{\min}} \quad (2)$$

Aki-Richards (1980) proposed AVO approximation based on P-velocity, S-velocity and density, which is written as:

$$R_{pp}(\theta) = \frac{1}{2} \sec^2 \theta \frac{\Delta \alpha}{\alpha} - 4 \frac{\beta^2}{\alpha^2} \sin^2 \theta \frac{\Delta \beta}{\beta} + \frac{1}{2} (1 - 4 \frac{\beta^2}{\alpha^2} \sin^2 \theta) \frac{\Delta \rho}{\rho} \quad (3)$$

where  $\alpha$  represents P-velocity,  $\beta$  represents S-velocity,  $\rho$  represents density. Following eq. (3), Zong et al. (2011) have proposed an AVO approximation called YPD approximation to establish the relationship between Young's modulus, Poisson's ratio and density with seismic reflection coefficient:

$$R_{pp}(\theta) = \left( \frac{1}{4} \sec^2 \theta - 2k \sin^2 \theta \right) \frac{\Delta E}{E} + \left( \frac{1}{4} \sec^2 \theta \frac{(2k-3)(2k-1)^2}{k(4k-3)} + 2k \sin^2 \theta \frac{1-2k}{3-4k} \right) \frac{\Delta \sigma}{\sigma} + \left( \frac{1}{2} - \frac{1}{4} \sec^2 \theta \right) \frac{\Delta \rho}{\rho} \quad (4)$$

where  $k$  is  $V_s / V_p$ , and introducing a differential expression:

$$d \frac{E \rho}{\sigma} = dBI = dBI \frac{\Delta E}{\Delta E} + dBI \frac{\Delta \rho}{\Delta \rho} - dBI \frac{\Delta \sigma}{\Delta \sigma} \quad (5)$$

Divided both sides, eq. (5) is written as:

$$\frac{\Delta BI}{BI} = \frac{\Delta E \rho}{\sigma} = \frac{\Delta E}{E} + \frac{\Delta \rho}{\rho} - \frac{\Delta \sigma}{\sigma} \quad (6)$$

And the AVO approximation to express  $BI$  was shown below:

$$R_{pp}(\theta) = \left(\frac{1}{4}\sec^2 \theta - 2k \sin^2 \theta\right) \frac{\Delta BI}{BI} + \left(\frac{1}{4}\sec^2 \theta \frac{(2k-3)(2k-1)^2}{k(4k-3)} + 2k \sin^2 \theta \frac{1-2k}{3-4k}\right) \frac{\Delta \sigma}{\sigma} + \left(\frac{1}{2} + 2k \sin^2 \theta - \frac{1}{4}\sec^2 \theta\right) \frac{\Delta \rho}{\rho} \quad (7)$$

To compare with the AVO method, elastic impedance method plays better results in the field applications. It also takes advantages in noise immunity and stability. Connolly defined  $EI$  Approximation (Connolly, 1999), which was written as:

$$R_{pp}(\theta) = \frac{EI(\theta)_{n+1} - EI(\theta)_n}{EI(\theta)_{n+1} + EI(\theta)_n} = \frac{1}{2} \frac{\Delta EI}{EI} = \frac{1}{2} \Delta \ln(EI) \quad (8)$$

To extended eq. (7) in the form of  $EI$  and introduced approximations:

$$R_{pp} = \frac{1}{2} \Delta \ln(EI) = \frac{\Delta x}{2x} \quad (9)$$

Introduce eqs. (8) and (9) into eq. (7) and take the integral on both sides of the equation then ignore the term of integral constant.

$$\begin{aligned} \ln(EI) = & \left(\frac{1}{2}\sec^2 \theta - 4k \sin^2 \theta\right) \ln(BI) \\ & + \left(\frac{1}{2}\sec^2 \theta \frac{8k^3 - 16k^2 + 11k - 3}{k(4k-3)} + 4k \sin^2 \theta \frac{2k-2}{3-4k}\right) \ln(\sigma) \\ & + (1 + 4k \sin^2 \theta - \sec^2 \theta) \ln(\rho) \end{aligned} \quad (10)$$

Logarithm on both sides of eq. (10) and get the  $EI$  equation which represent brittleness index directly:

$$\begin{aligned} EI(\theta) &= (BI)^A (\sigma)^B (\rho)^C \\ A &= \frac{1}{2}\sec^2 \theta - 4k \sin^2 \theta \\ B &= \frac{1}{2}\sec^2 \theta \frac{8k^3 - 16k^2 + 11k - 3}{k(4k-3)} + 4k \sin^2 \theta \frac{2k-2}{3-4k} \\ C &= 1 + 4k \sin^2 \theta - \sec^2 \theta \end{aligned} \quad (11)$$

Because of the dimension of  $EI$  varies with the target parameters, the stability of the results will be influenced, which leads to obtain inaccurate  $EI$  inversion. For the problem, a normalization factor was introduced into the eq. (11) to processing the results in the dimension of acoustic impedance (AI). The standardized  $EI$  equation was written as:

$$EI(\theta) = EI_0 \left( \frac{BI}{BI_0} \right)^A \left( \frac{\sigma}{\sigma_0} \right)^B \left( \frac{\rho}{\rho_0} \right)^C, \quad (12)$$

$$EI_0 = [(E\rho / \sigma)^2 (8\sigma^3)]^{-0.25}$$

where  $BI$ ,  $\sigma$ , and  $\rho$  respectively mean brittleness index, Poisson's ratio and density.

### Inversion method based on Bayesian framework

Inverted elastic impedance volume does not have a clear physical meaning, but they contain abundant information of elastic parameters (such as P-velocity, S-velocity, density, and so on), through Bayesian method, the potential target parameters can be extracted from elastic impedance volume at different angles. Most of isotropic elastic parameters can be calculated by P-velocity, S-velocity and density and transformed by each other, therefore the reservoir can be described in detail.

Elastic parameters extraction is an important step in  $EI$  inversion. Since eq. (12) is nonlinear, it is difficult to solve the equation directly. For simplifying eq. (12), transform the equation into linear equation, take the logarithms of both sides of this equation, it can be written as:

$$\ln \frac{EI(\theta)}{EI_0} = A(\theta) \ln \left( \frac{BI}{BI_0} \right) + B(\theta) \ln \left( \frac{\sigma}{\sigma_0} \right) + C(\theta) \ln \left( \frac{\rho}{\rho_0} \right) \quad (13)$$

In the case of different angles, elastic parameters are also different at the corresponding sample point. Therefore, for three elastic impedance volume at different angles, by introducing three different incident angles can combine nine coefficient  $A(\theta_1), A(\theta_2), A(\theta_3)$ ,  $B(\theta_1), B(\theta_2), B(\theta_3)$ ,  $C(\theta_1), C(\theta_2), C(\theta_3)$  the equation can be written as:

$$\begin{cases} \ln \frac{EI(t, \theta_1)}{EI_0} = A(\theta_1) \ln \frac{BI}{BI_0} + B(\theta_1) \ln \frac{\sigma}{\sigma_0} + C(\theta_1) \ln \frac{\rho}{\rho_0} \\ \ln \frac{EI(t, \theta_2)}{EI_0} = A(\theta_2) \ln \frac{BI}{BI_0} + B(\theta_2) \ln \frac{\sigma}{\sigma_0} + C(\theta_2) \ln \frac{\rho}{\rho_0} \\ \ln \frac{EI(t, \theta_3)}{EI_0} = A(\theta_3) \ln \frac{BI}{BI_0} + B(\theta_3) \ln \frac{\sigma}{\sigma_0} + C(\theta_3) \ln \frac{\rho}{\rho_0} \end{cases} \quad (14)$$

To extract brittleness index by least square method, the form of matrix can be written as:

$$\begin{bmatrix} \ln \frac{BI(t_1)}{BI_0} & \ln \frac{\sigma(t_1)}{\sigma_0} & \ln \frac{\rho(t_1)}{\rho_0} \\ \ln \frac{BI(t_2)}{BI_0} & \ln \frac{\sigma(t_2)}{\sigma_0} & \ln \frac{\rho(t_2)}{\rho_0} \\ M & M & M \\ \ln \frac{BI(t_n)}{BI_0} & \ln \frac{\sigma(t_n)}{\sigma_0} & \ln \frac{\rho(t_n)}{\rho_0} \end{bmatrix} \begin{bmatrix} A(\theta_1) & A(\theta_2) & A(\theta_3) \\ B(\theta_1) & B(\theta_2) & B(\theta_3) \\ C(\theta_1) & C(\theta_2) & C(\theta_3) \end{bmatrix} = \begin{bmatrix} \ln \frac{EI(\theta_1)}{EI_0} \\ \ln \frac{EI(\theta_2)}{EI_0} \\ \ln \frac{EI(\theta_3)}{EI_0} \end{bmatrix} \quad (15)$$

Here we assume  $d = Gm$  :

$$d = \begin{bmatrix} \ln \frac{EI(\theta_1)}{EI_0} \\ \ln \frac{EI(\theta_2)}{EI_0} \\ \ln \frac{EI(\theta_3)}{EI_0} \end{bmatrix} \quad G = \begin{bmatrix} A(\theta_1) & A(\theta_2) & A(\theta_3) \\ B(\theta_1) & B(\theta_2) & B(\theta_3) \\ C(\theta_1) & C(\theta_2) & C(\theta_3) \end{bmatrix}$$

$$m = \begin{bmatrix} \ln \frac{BI(t_1)}{BI_0} & \ln \frac{\sigma(t_1)}{\sigma_0} & \ln \frac{\rho(t_1)}{\rho_0} \\ \ln \frac{BI(t_2)}{BI_0} & \ln \frac{\sigma(t_2)}{\sigma_0} & \ln \frac{\rho(t_2)}{\rho_0} \\ M & M & M \\ \ln \frac{BI(t_n)}{BI_0} & \ln \frac{\sigma(t_n)}{\sigma_0} & \ln \frac{\rho(t_n)}{\rho_0} \end{bmatrix} \quad .$$

Suppose the likelihood function and sensitive parameters obey a normal distribution. A relationship exists in the Bayesian framework is:

$$p(m | d, I) \propto p(d | m, I) \cdot p(m, I) \quad , \quad (16)$$

$p(m | d, I)$  is posterior probability distribution of sensitive parameters,  $p(d | m, I)$  is the likelihood function and  $p(m, I)$  is prior probability density function. Assume seismic noise is a likelihood obeys Gaussian distribution:

$$p(d | m, I) = \left( \frac{1}{\sqrt{2\pi}\sigma_n} \right)^{3N} \exp\left( -\frac{(Gm - d)^T (Gm - d)}{2\sigma_n^2} \right) \quad . \quad (17)$$

Suppose model parameters also obey Gaussian distribution:

$$p(m, I) = \left( \frac{1}{\sqrt{2\pi}\sigma_m} \right)^{3N} \exp\left[ -\frac{1}{2\sigma_m^2} m^T m \right] \quad . \quad (18)$$

Add function (17) and (18) to function (16), posterior probability distribution of sensitive parameters can be written as:

$$\begin{aligned} p(m | d, I) \propto p(d | m, I) \cdot p(m, I) &= \left( \frac{1}{\sqrt{2\pi}\sigma_n} \right)^{3N} \exp\left( -\frac{(Gm - d)^T (Gm - d)}{2\sigma_n^2} \right) \cdot \left( \frac{1}{\sqrt{2\pi}\sigma_m} \right)^{3N} \exp\left[ -\frac{1}{2\sigma_m^2} m^T m \right] \\ &\propto \exp\left[ -\frac{(Gm - d)^T (Gm - d)}{2\sigma_n^2} - \frac{1}{2\sigma_m^2} m^T m \right] \end{aligned} \quad (19)$$

The objective function is:

$$J(x) = \frac{-(Gm - d)^T (Gm - d)}{2\sigma_n^2} - \frac{1}{2\sigma_m^2} m^T C_m^{-1} m \quad (20)$$

$C_m^{-1}$  is a covariance matrix of inversion parameters. Find the partial derivative of objective function  $J(x)$  about and make it equal to zero optimal estimate of the sensitive parameters is :



$$m = (G^T G + \frac{\sigma_n^2}{Q} I)^{-1} G^T d \quad Q_{ii} = \begin{cases} \frac{1}{\sigma_1^2}, 0 < i \leq N \\ \frac{1}{\sigma_2^2}, N < i \leq 2N \\ \frac{1}{\sigma_3^2}, 2N < i \leq 3N \end{cases}$$

$\sigma_1, \sigma_2, \sigma_3$  are variances of brittleness index, Poisson's ratio and density.

## EXAMPLES AND RESULTS

In order to verify the effectiveness and applicability of the method, the classical model was used to analyze the accuracy of the equation. The model data is as follows:

Table 1. Model for gas-bearing sandstone and shale gas designed by Goodway (1997) .

Formation	$V_P(m/s)$	$V_S(m/s)$	$\rho(g/cm^3)$	$\sigma$	$V_P/V_S$
Shale gas	2898	1290	2.425	0.38	2.25
Gas-bearing sandstone	2857	1666	2.275	0.24	1.71
Shale gas	2898	1290	2.425	0.38	2.25

Based on above model data, the accuracy of the novel *EI* equation is analyzed. Then, compare the result with the Zoeppritz matrix, Aki-Richard approximation reflection coefficient and AVO based on brittleness index. The comparison results are as follows:

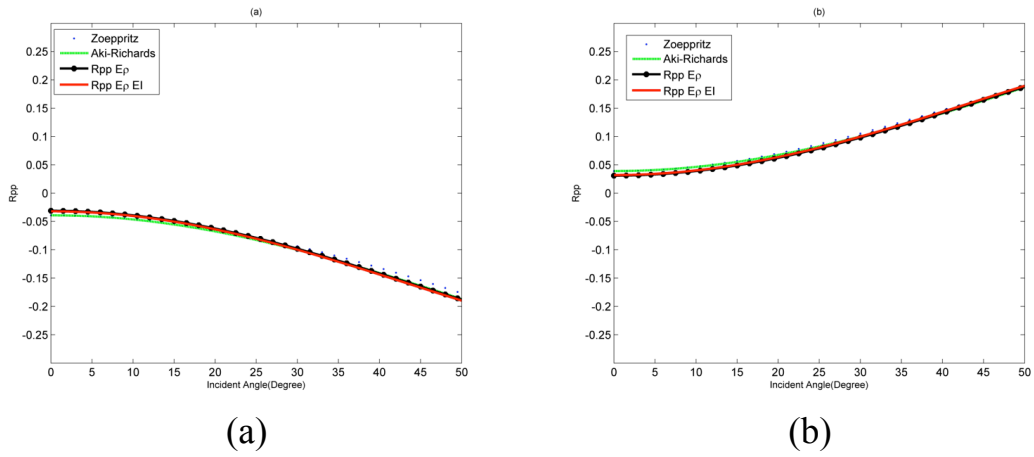


Fig. 1. (a) Comparison of different approximate reflection coefficients on above interface; (b) Comparison of different approximate reflection coefficients on below interface. (Green line represent the inversion result of Zoeppritz matrix, red line represent the inversion result of Aki-Richards approximation, black line represent inversion result of AVO approximation based on brittleness index, and red line represent the inversion result of the novel  $EI$  approximation).

As seen in the figure, the inversion result of the novel  $EI$  approximation has high accuracy when the incident angle is less than 30 degrees which meets the application requirements of seismic inversion and identification of high brittleness layers.

After verifying the accuracy of the equation, the stability of the equation is also needed to be verified. Choosing well data as model. Substituting data into the above method, and then calculating elastic impedance curves. The results are as follows:

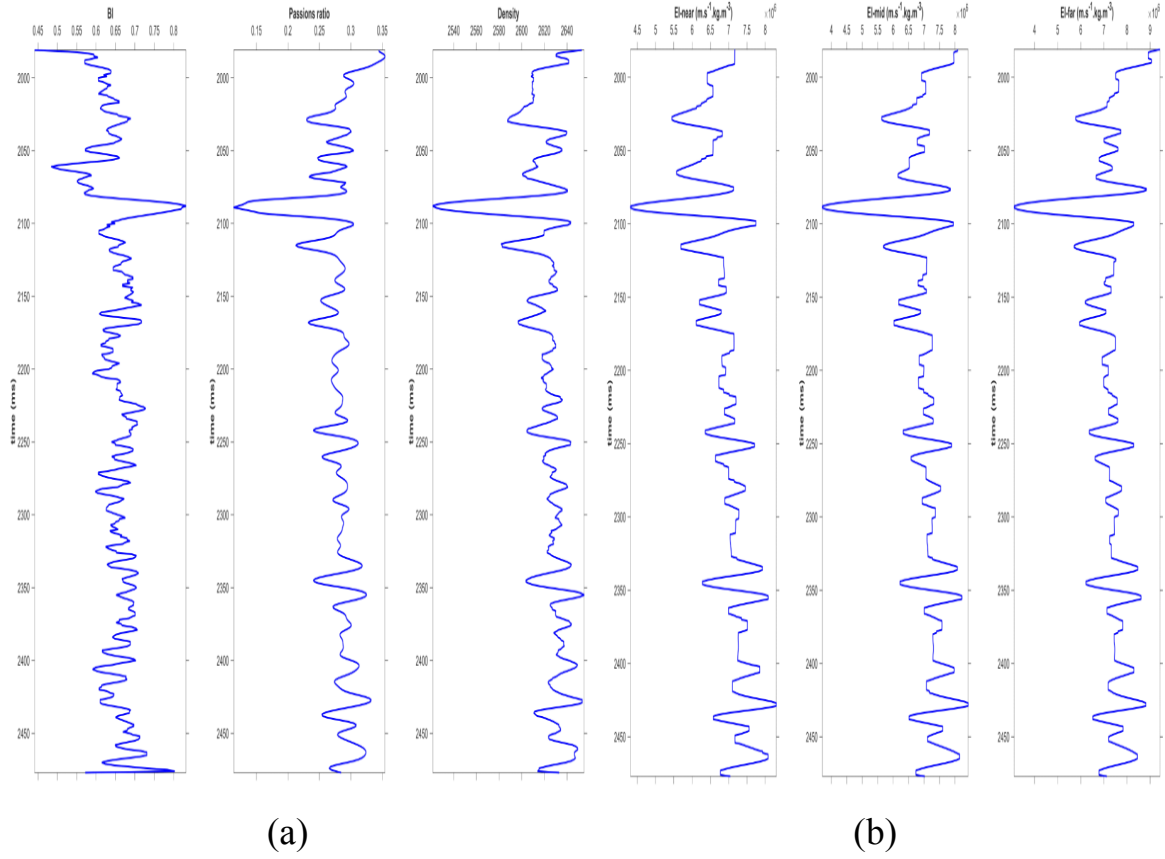


Fig. 2. (a) Calculated inversion parameters in terms of brittleness index, Poisson's ratio and density; (b) Elastic impedance at different angles calculation result.

Picking Ricker wavelet with main frequency of 35 Hz to get synthetic seismogram in the condition of no noise case and signal-to-noise of 3, respectively. The synthetic seismogram is as follows:

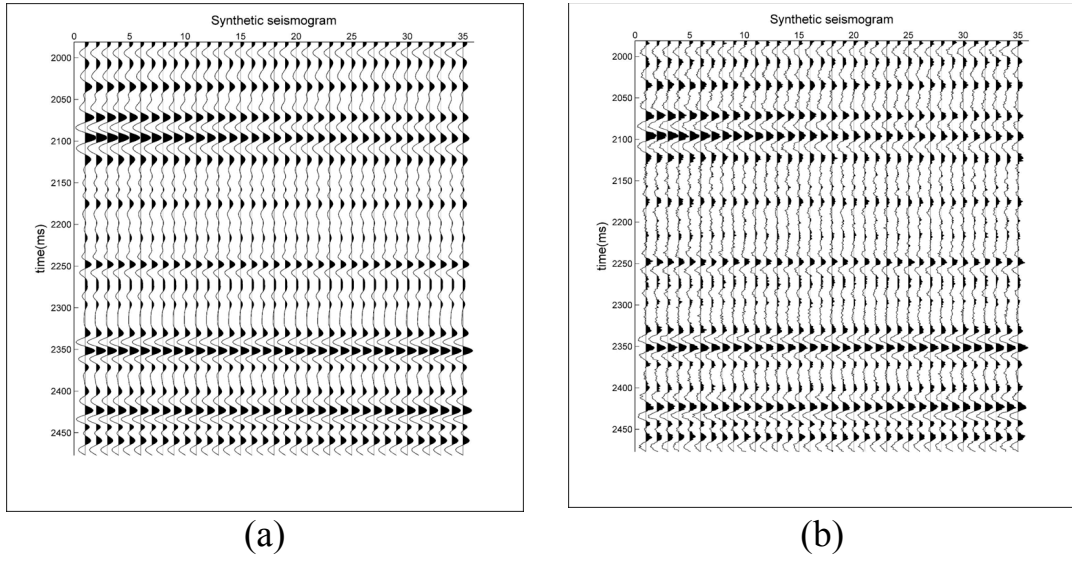


Fig. 3. (a) Synthetic seismogram without noise; (b) Synthetic seismogram with SNR = 3.

Finally, extracting brittleness index based on the novel elastic impedance inversion method:

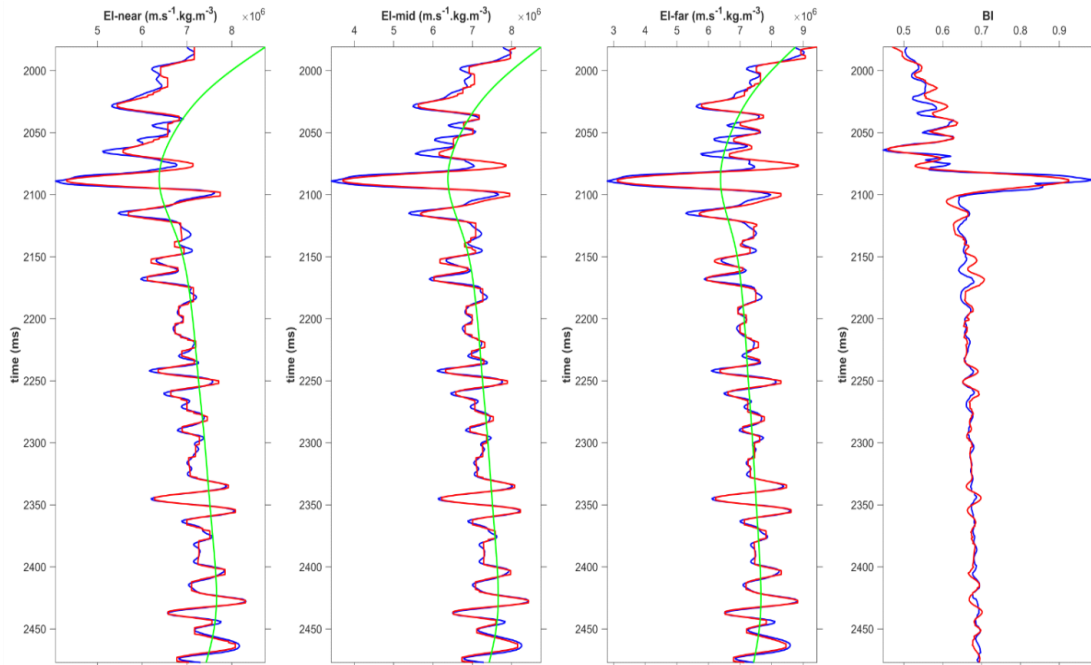


Fig. 4. The comparison between inversion results and real data without noise. (Red lines are inversion results, blue lines are real data and green lines are model trends).

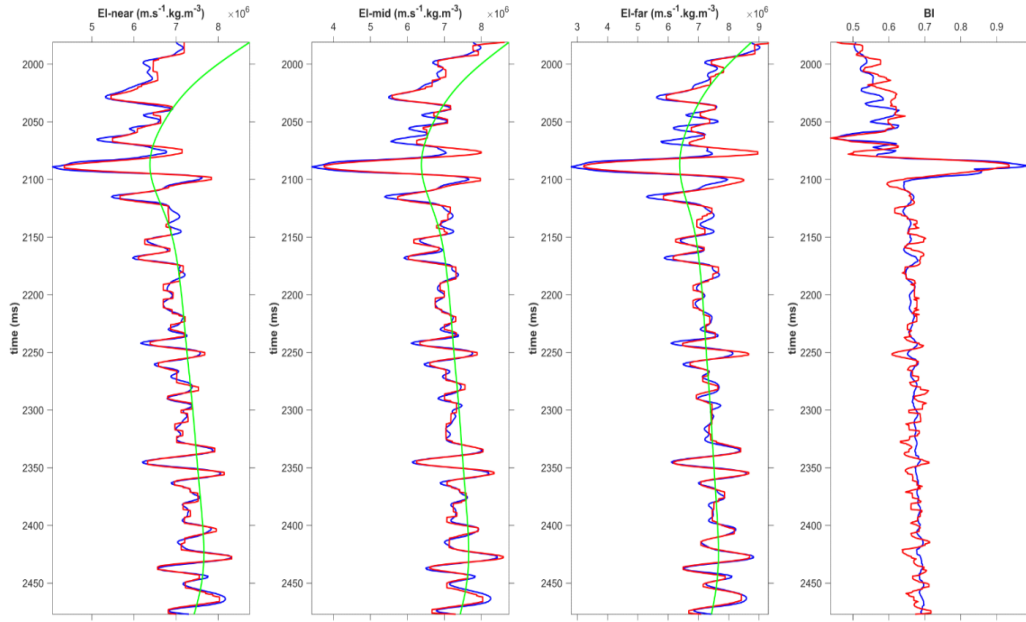


Fig. 5. The comparison between inversion results and real data with SNR = 3. (Red lines are inversion results, blue lines are real data and green lines are model trends).

Fig. 4 and Fig. 5 respectively show the comparison between the inversion results and real data in the case of no noise and signal-to-noise of 3. For both figure, even if the synthetic seismogram set with random noise with signal-to-noise of 3 is used for inversion, the inverted brittleness index is still in good agreement with the real data which indicate that our method has good noise immunity.

On this basis, the prior distribution of brittleness index is obtained through statistical analysis, this paper assumes that the parameter distribution conforms to the mixed Gaussian distribution, and estimates the weight, mean, variance and likelihood of each physical parameter distribution.

Fig. 6 shows the Gaussian distribution components for brittleness index, Fig. 7 shows the comparison between the prior distribution of brittleness realized by Bayesian framework and the actual brittleness, It can be seen that the Bayesian framework can better simulate and restore the real distribution. Based on constructed statistical model, the random distribution sample space of elastic impedance corresponding to each sample point in the prior distribution sample of brittleness index is obtained and combined with the brittleness index sample to obtain the joint distribution sample space (Fig. 8). In Fig 9, the red line represents inverted data, the blue line represent model data, the final inversion result shows it fits well with model data, which shows the effectiveness of the method.

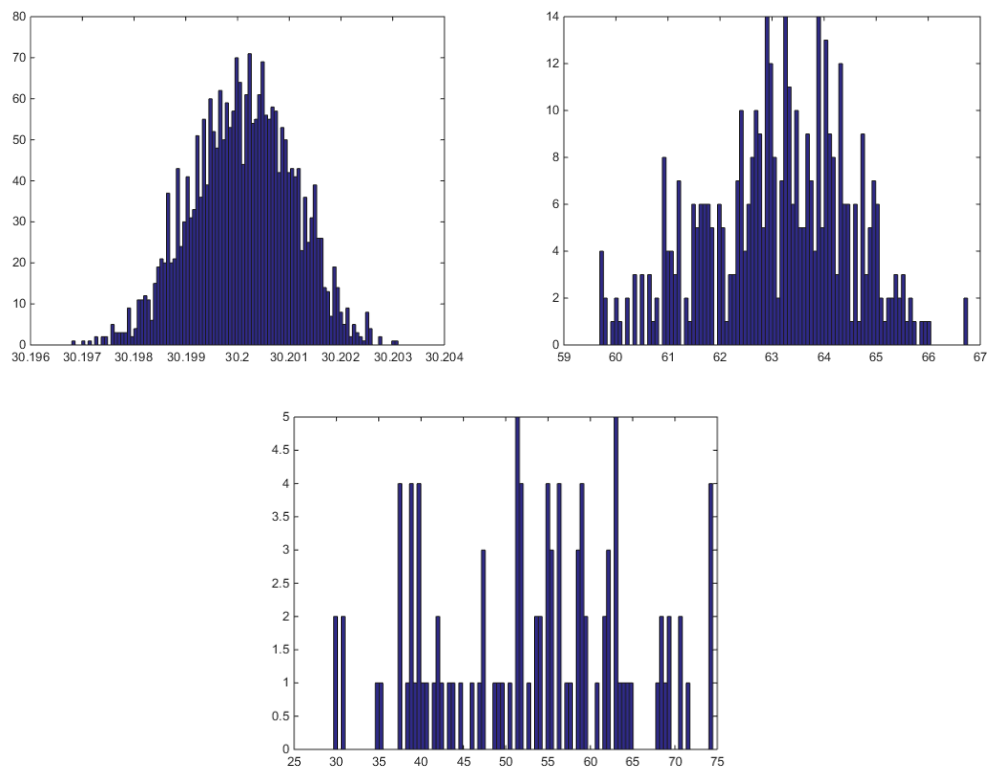


Fig. 6. Gaussian component histogram of brittleness index from well logging.

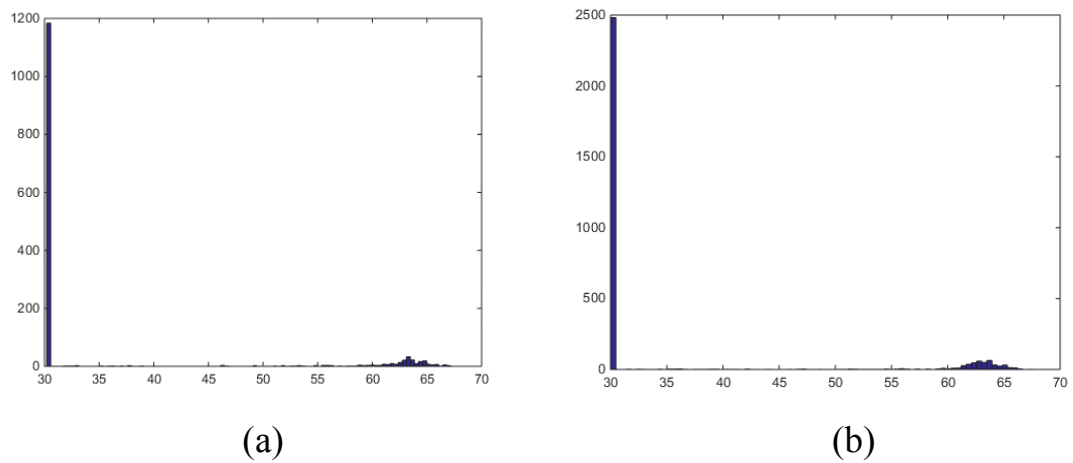


Fig. 7. (a) Prior distribution of brittleness index by actual well data; (b) simulated brittleness index by Bayesian framework

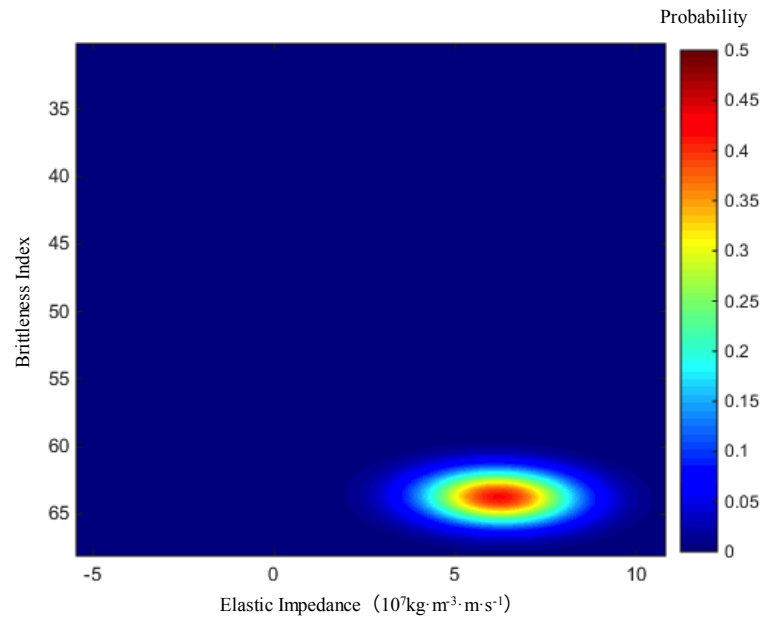


Fig. 8. Joint probability distribution of brittleness index and elastic impedance.

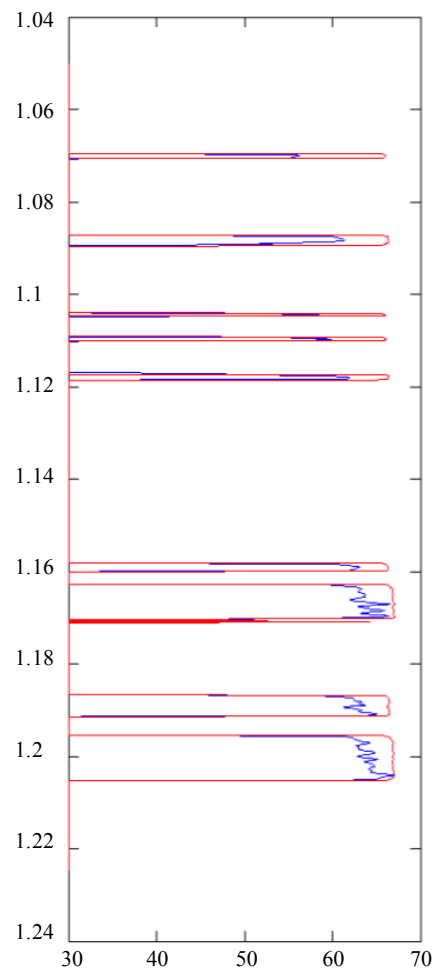


Fig. 9. Brittleness index inversion result.

The proposed method is applied to the field data to verify the feasibility. This block located in southern Sichuan basin. Due to the influence of multi-stage geological activities, the geological structure of the block is relatively complex which makes exploration and development very difficult. After nearly 60 years of exploration and development, the block proved to be rich in oil and gas. The Longmaxi formation is mainly argillaceous hydrocarbon source rock which has high TOC, porosity, gas saturation and brittleness characteristics. The bottom of the Longmaxi formation has proven to be a high-quality shale gas reservoir and developed stably which is a favorable block for shale gas exploration and development.

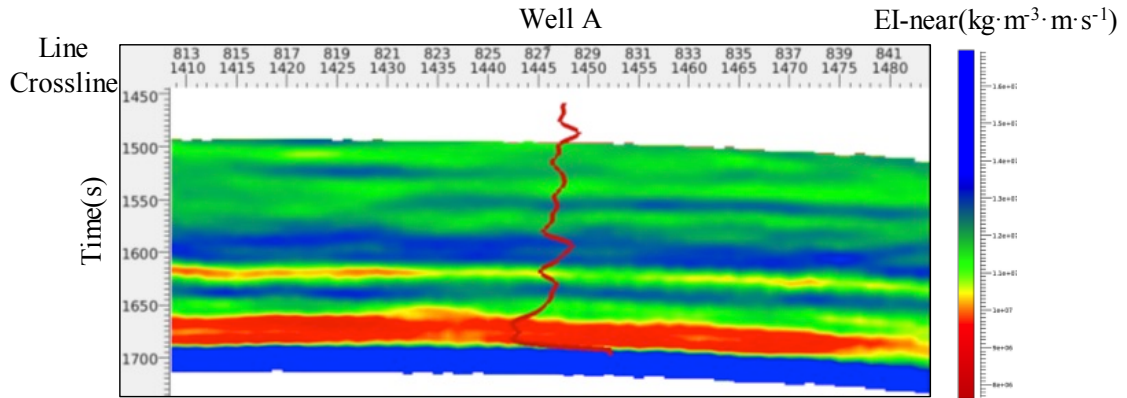


Fig. 10. Near-angle stack elastic impedance inversion result.

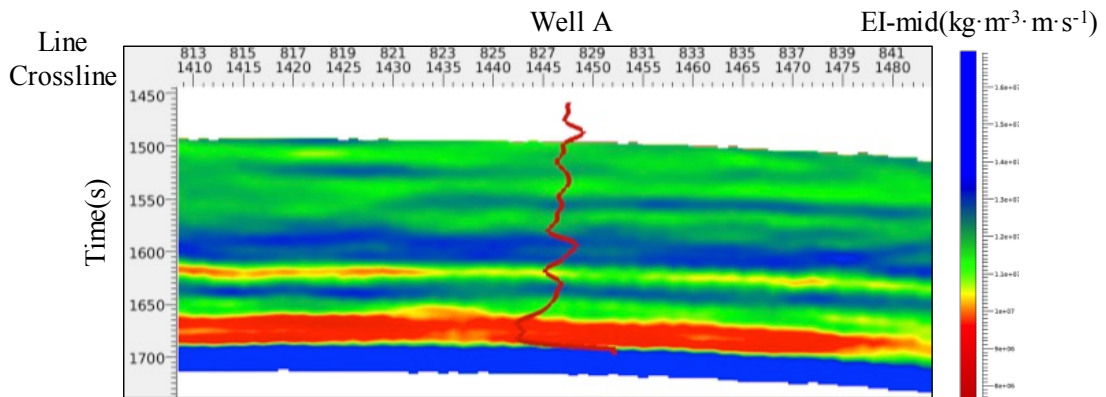


Fig. 11. Middle-angle stack elastic impedance inversion result.



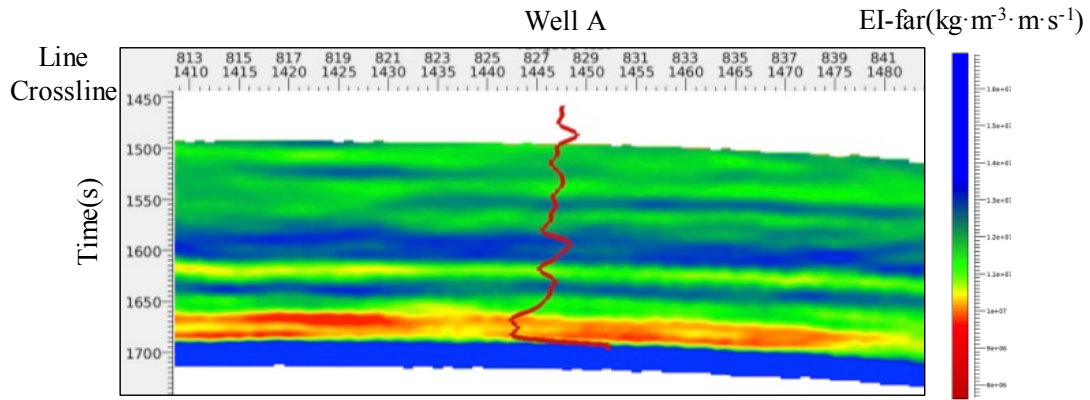


Fig. 12. Far-angle stack elastic impedance inversion result.

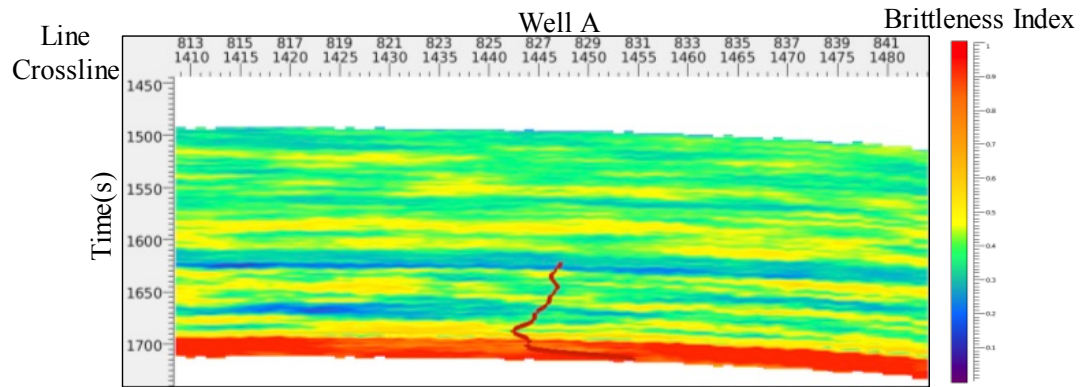


Fig. 13. Brittleness index inverted result.

Figs. 10 to 12 show EI inversion result at different angles. Fig. 13 shows the brittleness index result. The results reveal that the inverted EI and brittleness index are in good agreement with well-logging data. The brittleness index inverted result shows high brittleness layer is at bottom of Longmaxi formation which is consistent with the conclusion obtained from the experiment.

## DISCUSSION AND CONCLUSIONS

This paper derives a novel elastic impedance (EI) approximation in terms of brittleness index, Poisson's ratio and density and establishes an accurate inversion method to obtain brittleness index under Bayesian framework. The method is tested with theoretical model and real data. Due to the high precision and good stability, we believe our method can provide support for optimization of target in horizontal well drilling and design of hydraulic fracturing. So, it might have broad applications for prospect development.

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