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S-WAVE VELOCITY ESTIMATION AND RESERVOIR TYPE IDENTIFICATION BASED ON PARTIALLY CONNECTED POROSITY MODEL OF CARBONATE RESERVOIR

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ABSTRACT

Zhou, X.-Y., Gan, L.-D., Yang, T.-Q., Jiang, X.-Y. and Wei L.-L., 2023**.** S-wave velocity estimation and reservoir type identification based on partially connected porosity model of carbonate reservoir. *Journal of Seismic Exploration, 32: 51-65.*

With the deepening of global oil and gas exploration and development, the exploration direction has gradually shifted from conventional oil and gas reservoirs to special oil and gas reservoirs, such as carbonate reservoirs and tight reservoirs, which often have very complex pore structures. The partially connected pore model is an equivalent medium model to describe the multi pore structure. The model divides the pores into an isolated pore system dominated by micropores and a connected pore system dominated by macropores, which has achieved good results in the application of tight gas bearing sandstone. But when the model is applied in carbonate reservoirs, due to a huge amount of model parameters and complex mineral composition of carbonate rocks, the effect of direct application of the model is non-ideal. In this paper, through the steps of environmental correction, optimization log interpretation, sensitivity analysis of model parameters and determination of key parameters, a petrophysical modeling process suitable for carbonate reservoirs is established, and the S-wave velocity of two different reservoir space types of the Dengying Formation in Central Sichuan paleo-uplift is predicted, and considerable results are obtained. In addition, the soft pore scale factor inversed in the modeling process has indicative significance for the identification and division of reservoir space types.

KEY WORDS: carbonate reservoirs, petrophysical modeling,
optimization log interpretation, S-wave velocity estimation,
partially connected pore model,

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INTRODUCTION

With the deepening of global oil and gas exploration and development, the exploration direction has gradually shifted from conventional oil and gas reservoirs to special oil and gas reservoirs, such as carbonate reservoirs and tight oil and gas reservoirs (Zhao et al., 2014; Jia et al., 2014). These reservoirs usually have very complex pore structures: uneven size, diverse morphology and multiple connectivity. Among the existing equivalent medium models, those concerning the influence of pore structures are mainly Gassmann equation and the inclusion model. From the perspective of pore connectivity, these two models represent two extreme cases, that is, the Gassmann equation is only applicable to high porosity and permeability rocks with very good pore connectivity, while the inclusion equivalent medium model assumes that the pores are isolated from each other. The assumptions of different pore structures lead to differences in the calculation results of the two models. The fluid substitution result based on Gassmann equation is low and the other is high (Yan, 2012; Mori and Tanaka, 1973; Gassmann, 1961). Yan (2012) proposed a porous equivalent medium model - partially connected pore model, which effectively combines the Gassmann equation and the Mori-Tanaka inclusion model. The model can describe the medium with complex pore structures and more reliably characterize the elastic properties of complex reservoir rocks (Yan, 2012; (Yan et al., 2016) However, due to the complex mineral composition, diversified reservoir space and a large amount of parameters of partially connected pore model in carbonate rocks, the effect of direct petrophysical modeling in carbonate rocks is non-ideal. In view of this situation, a petrophysical modeling process of carbonate rocks based on partially connected pore model is established involving the preparation of logging data and the optimization of model parameters, and good results in practical application proves the effectiveness of this method.

Partially connected pore model

Partially connected pore model is a new porous equivalent medium model. According to the characteristics of pore size, shape and connectivity, pores are divided into connected system dominated by macropores and isolated system dominated by micropores. The pore structure model is established considering that it is composed of more than two kinds of simple pores. On this basis, three pore structure parameters (the **aspect ratio** α_i, the scale factor v_i and the connectivity coefficient ξ) are defined (Yan et al., 2016):

$$\alpha_i \tag{1}$$

$$v_i = \frac{\phi_i}{\phi_{all}} \tag{2}$$

$$\xi = \frac{\phi_{con}}{\phi_{all}} \tag{3}$$

The aspect ratio α_i here is the same with that in other models, indicating the ratio of short axis to long axis of pores; the scale factor represents the content of various pores, that is, the ratio of the volume of each pore to the total porosity; considering the connectivity of pores, all pores are divided into the connected and the unconnected. The ratio of connected pores to total pores is the connectivity coefficient.

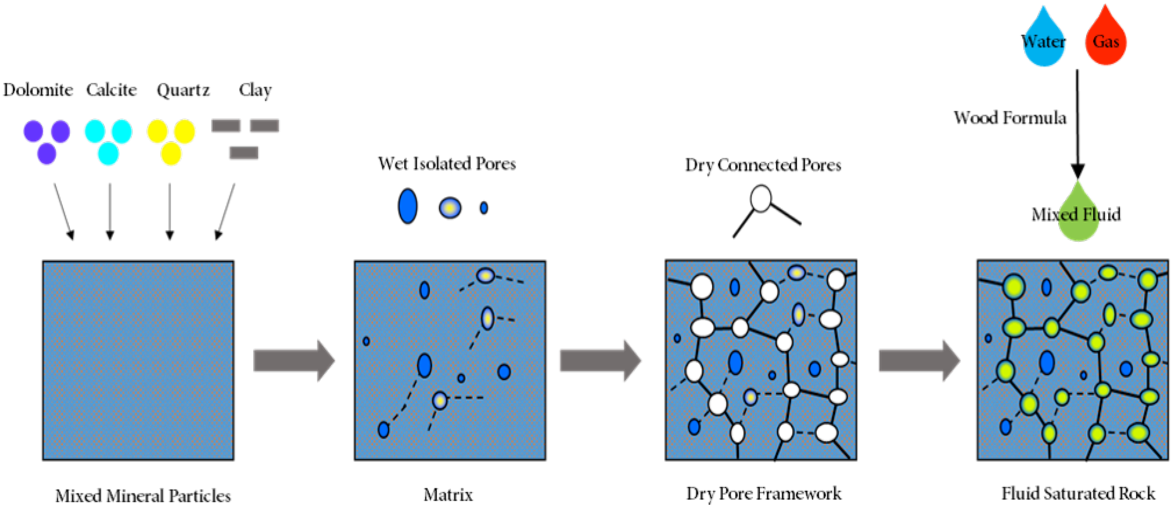


Fig. 1. Schematic diagram of partial pore model.

As shown in Fig. 1, the model mainly includes four parts.

Part I: mixed mineral particles

The elastic modulus of mixed minerals is calculated by Hill average formula.

Part II: the matrix composed of mixed mineral particles and wet isolated pores

$$K_{mat} = \frac{\left(1-\phi_{mat}\right)K_{min} + \phi_{mat}\left(1-S_{iso}\right)\sum_{i=1}^{n} v_i K_{f1} P_i + \phi_{mat} S_{iso} \sum_{i=1}^{n} v_i K_{f2} \tilde{P}_i}{\left(1-\phi_{mat}\right) + \phi_{mat}\left(1-S_{iso}\right)\sum_{i=1}^{n} v_i P_i + \phi_{mat} S_{iso} \sum_{i=1}^{n} v_i \tilde{P}_i} \tag{4}$$

In formula (4), the matrix porosity is defined as $\phi_{mat} = \frac{\phi - \phi_{con}}{1-\phi_{con}}$ K_{min} is the elastic modulus of mixed minerals. S_{iso} is the volume fraction of fluid 2 in isolated pores. K_{f1} and K_{f2} denote respectively the bulk modulus of fluid1 and fluid 2. P_i and $\tilde{P}_i$ are the parameters related to fluid and pore morphology.

Part III: the framework formed by adding dry connecting pores into the matrix

$$\begin{cases} K_{dry} = \dfrac{(1-\phi)K_{min} + \phi_{iso}(1-S_{iso})\sum_{i=1}^{n} v_i K_{f1} P_i + \phi_{iso} S_{iso} \sum_{i=1}^{n} v_i K_{f2} \tilde{P}_i}{(1-\phi) + \varphi_{con}\sum_{i=1}^{n} v_i \hat{P}_i + \phi_{iso}(1-S_{iso})\sum_{i=1}^{n} v_i P_i + \phi_{iso} S_{iso} \sum_{i=1}^{n} v_i \tilde{P}_i} \\ \mu_{dry} = \dfrac{(1-\phi)\mu_{min}}{(1-\phi) + \varphi_{con}\sum_{i=1}^{n} v_i \hat{Q}_i + \phi_{iso}(1-S_{iso})\sum_{i=1}^{n} v_i Q_i + \phi_{iso} S_{iso} \sum_{i=1}^{n} v_i \tilde{Q}_i} \end{cases}, \tag{5}$$

where φ is the total porosity. $\phi_{iso} = \phi\left(1-\xi\right)$ is the proportion of isolated pores to the total volume of rock. μ_{min} is the elastic modulus of mixed minerals. Q_i , $\tilde{Q}_i$ and $\hat{P}_i$ are parameters related to fluid and pore morphology.

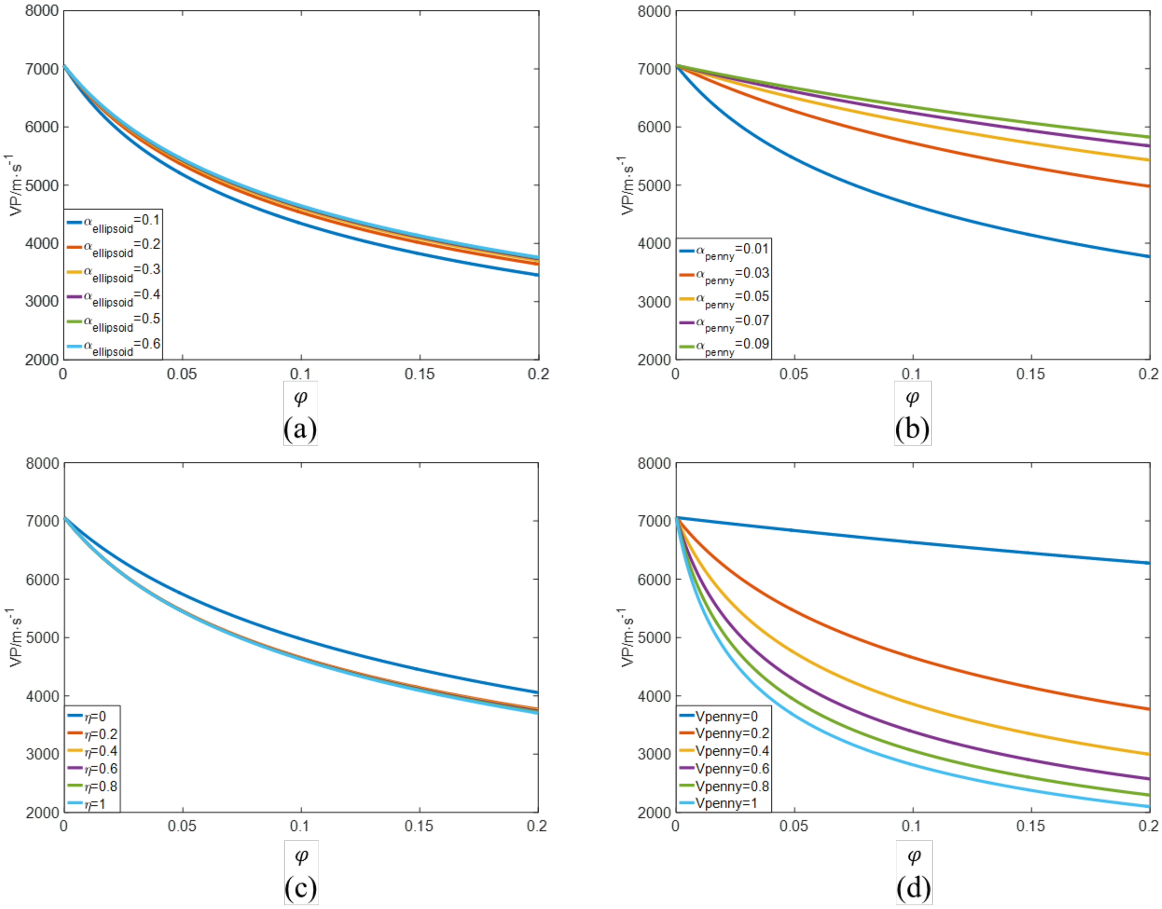
Part IV: fluid in connected pores

The Gassmann equation is used to replace the fluid in the connected pores, so that the dry connected pores are saturated with fluid.

$$\begin{cases} K = K_{dry} + \dfrac{\left(1 - K_{dry} / K_{mat}\right)^2}{\phi_{con} / K_f + \left(1 - \phi_{con}\right) / K_{mat} - K_{dry} / K_{mat}^2} \\ \mu = \mu_{dry} \end{cases} . \qquad (6)$$

SENSITIVITY ANALYSIS OF MODEL PARAMETERS

For carbonate reservoirs, on the premise of given mineral volume model, the effects of different model parameters on modeling results are analyzed. Due to the complex pore structure and well-developed fractures, ellipsoid (hard pores) and coin (soft pores) pore shapes are adopted. The aspect ratio of hard pores (default 0.5) and soft pores (default 0.01), the connectivity coefficient (default 0.2), and the soft pore scale factor (default 0.2) are analyzed with the method of controlling variables, that is, only one parameter is analyzed at a time, and other parameters take the default value.



(a) (b) (c) (d)

Fig. 2. The influence of different model parameters on P-wave velocity (a) the hard pore aspect ratio (b) the soft pore aspect ratio (c) the connectivity coefficient (d) the soft pore scale factor.

Fig. 2 shows the influence of different key model parameters on P-wave velocity. Figs. 2a, 2b, 2c and 2d, respectively, illustrate the variation of P-wave velocity with the change of hard pore aspect ratio, soft pore aspect ratio, connectivity coefficient and soft pore scale factor. It can be seen from the figure that P-wave velocity is sensitive to the soft pore scale factor and the soft pore aspect ratio, while the connectivity coefficient and hard pore aspect ratio are relatively insensitive parameters. Among them, the soft pore scale factor and the soft pore aspect ratio are a pair of coupling parameters. The soft and hard pore aspect ratio of the same target interval are roughly stable in the same work area, so the soft pore scale factor should be the model parameter that has the greatest impact on the P-wave velocity.

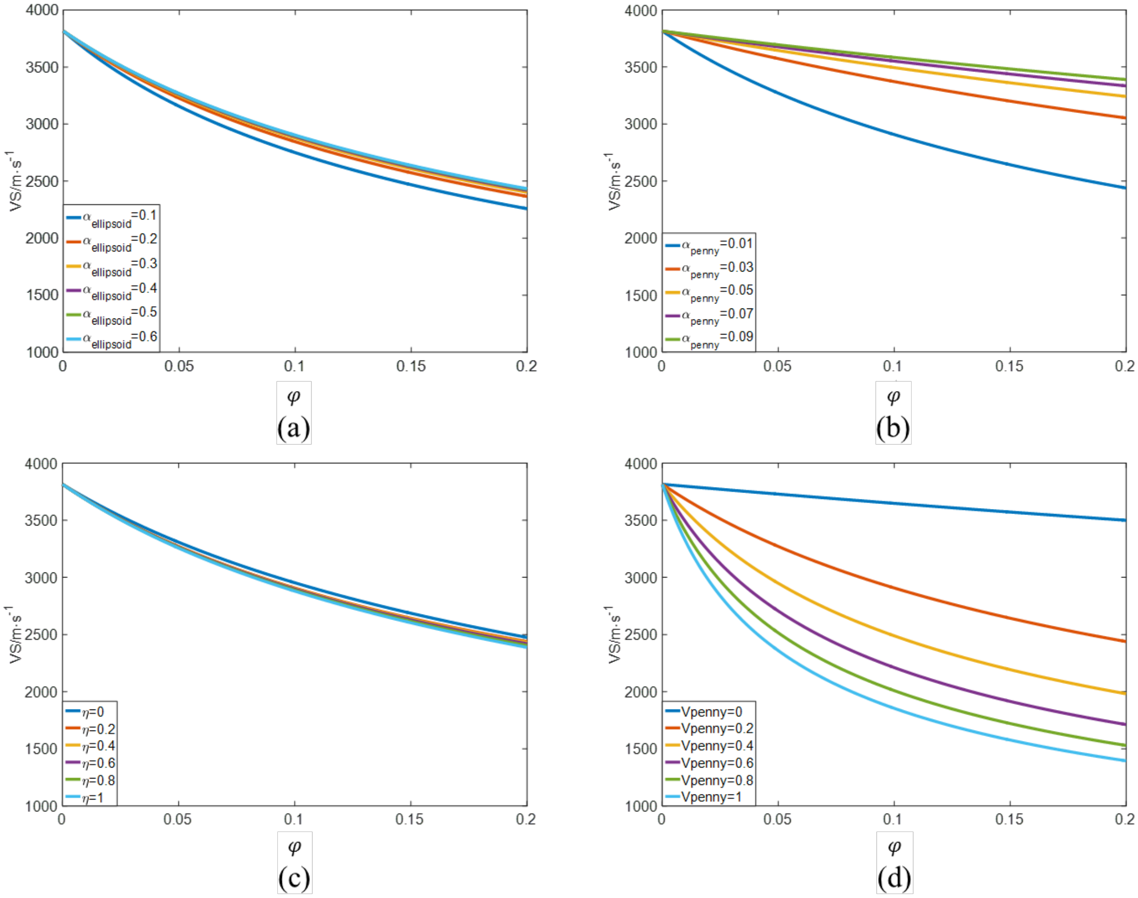


Fig. 3. The influence of different model parameters on S-wave velocity (a) the hard pore aspect ratio (b) the soft pore aspect ratio (c) the connectivity coefficient (d) the soft pore scale factor.

Similarly, the S-wave velocity is analyzed with the change of model parameters, as shown in Fig. 3. By comparing and analyzing the four diagrams, it also comes to the conclusion that the change of soft pore scale factor has the greatest impact on S-wave velocity.

MODELING PROCESS AND KEY STEPS

In view of the fact that the partially connected pore model can accurately describe the complex pore structure, it is proposed to use the model for petrophysical modeling in the Dengying Formation reservoir of central Sichuan paleo-uplift. Due to the development of carbonatite fracture-cavity, ellipsoidal pores (the pore aspect ratio of 0.5) and coin pores (the pore aspect ratio of 0.01) are used for initial modeling, in which the initial soft pore scale factor and connectivity coefficient are given to 0.3 and 0.2. Fig. 4 shows the predicted (red) and measured (blue) curves of density, P-wave velocity and S-wave velocity obtained by petrophysical modeling using two conventional interpretation mineral volume models (a and e) of well A in the work area. It can be seen that the predicted results of both models are non-ideal, indicating that an improved modeling process is needed when using the partially connected pore model for petrophysical modeling.

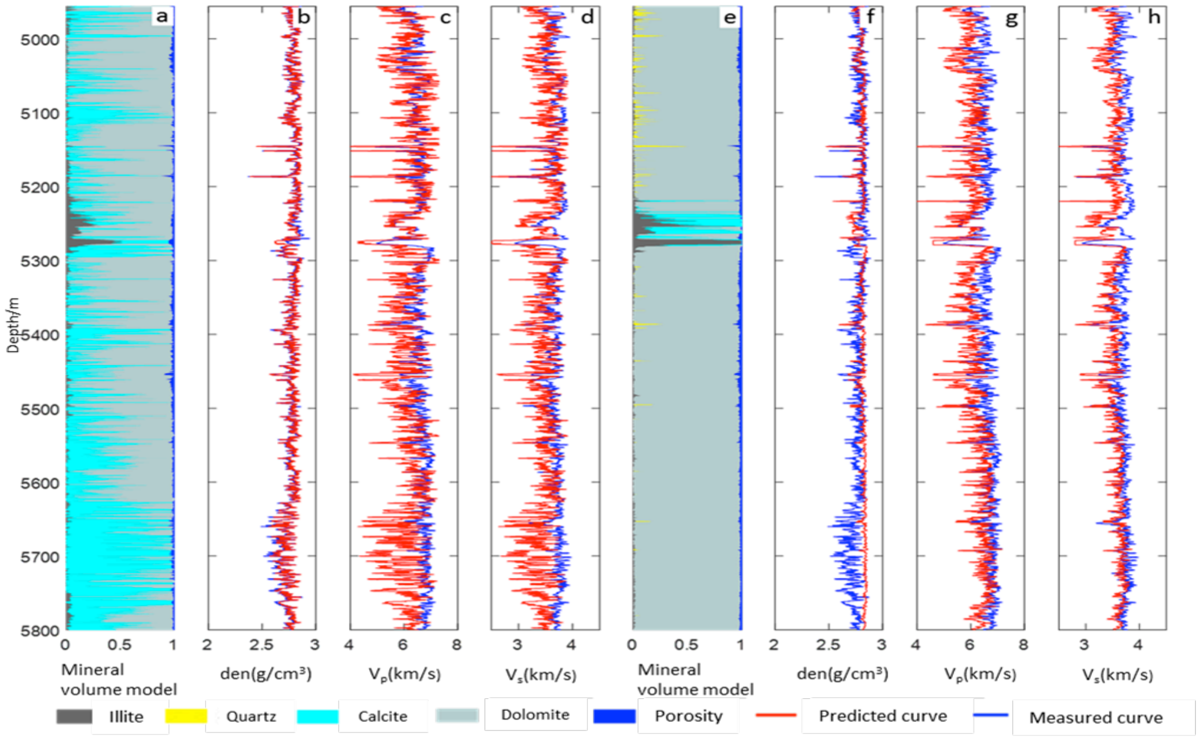


Fig. 4. Mineral volume models and modeling results of conventional logging interpretation of well A (a) the conventional interpretation model I, (b) (c) (d) the predicted results obtained from model I, (e) the conventional interpretation model II, (f) (g) (H) the predicted results obtained from model II

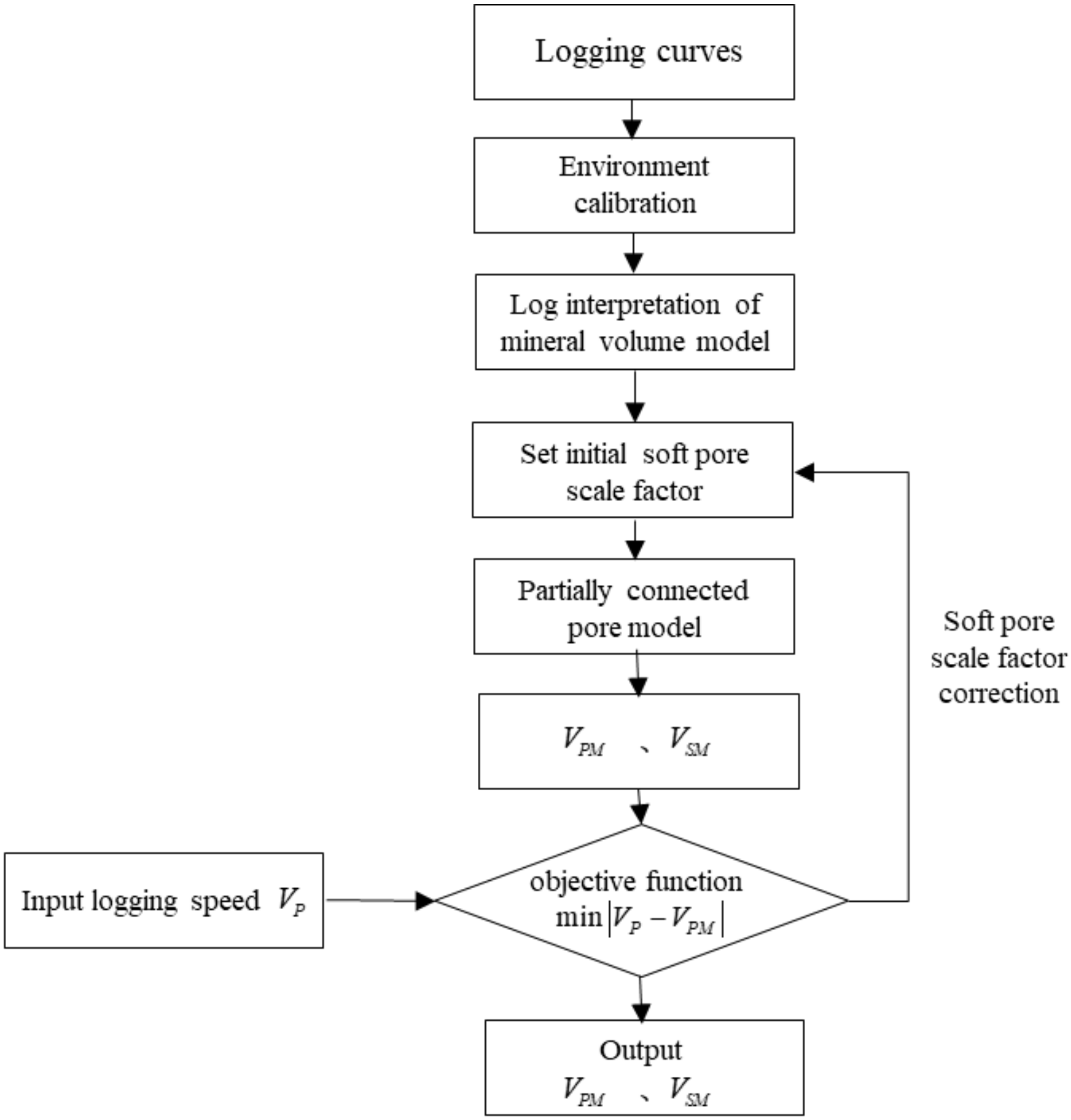


Fig. 5. The flow based on partially connected pore model.

Fig. 5 is a petrophysical modeling process of carbonate rocks based on partially connected pore model proposed in this paper, which includes two parts: logging data preparation and model parameters optimization. It can be divided into three steps.

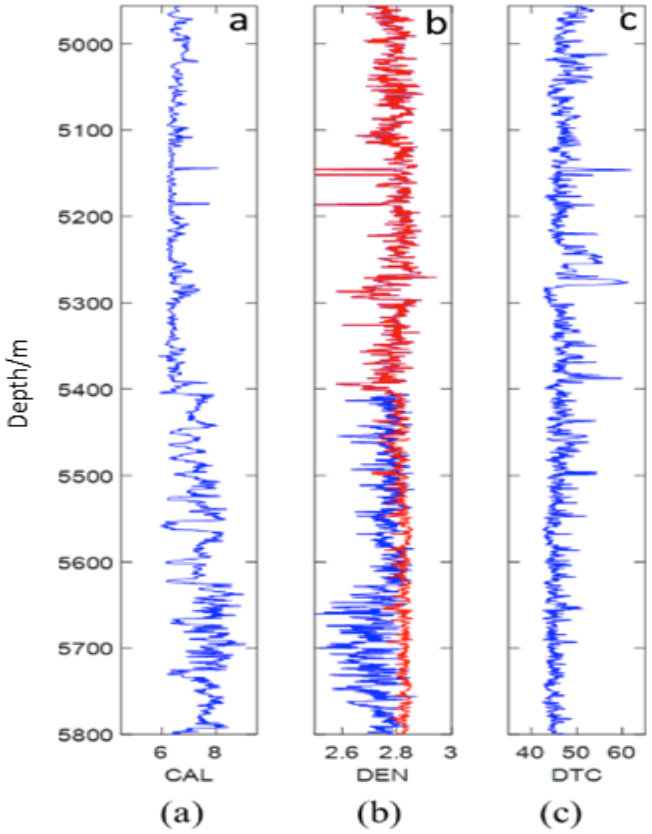


Fig. 6. Environmental correction of the density curve (a) the well diameter curve (b) the measured density (blue) and the corrected density (red) (c) the acoustic time difference curve.

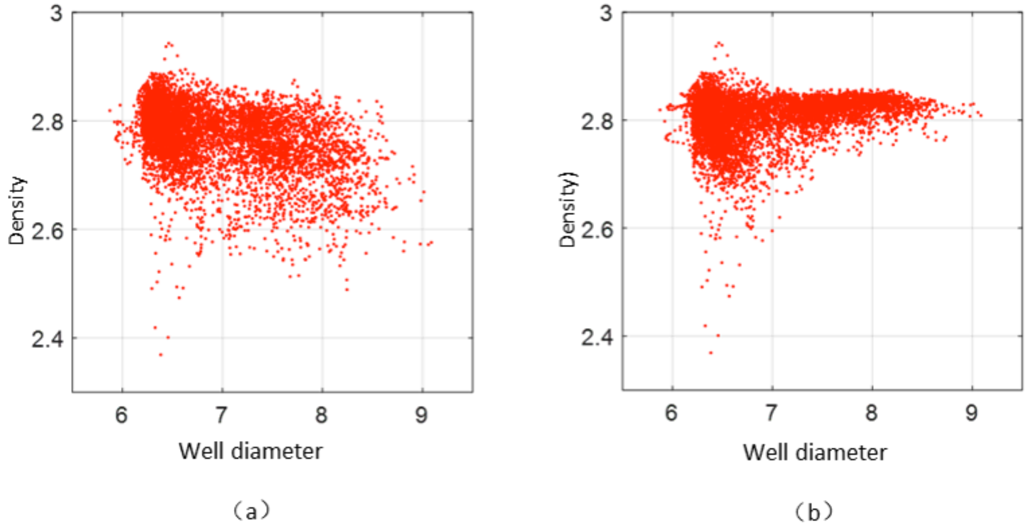


Fig. 7. The crossplot of well diameter and density (a) before correction (b) after correction.

Environmental correction

Borehole collapse usually leads to the distortion of logging curves, which has a great impact on logging interpretation and petrophysical modeling (Liu and Tan, 1993). Therefore, it is necessary to check whether the existing logging curve is affected by diameter expansion before petrophysical modeling. If there is no diameter expansion or the diameter correction has been done, continue to the next step, otherwise the affected curve needs to be corrected.

It can be seen from Fig. 4 that the density at the bottom of the reservoir may have abnormal values. Compare the well diameter curve (Fig. 6a), the density curve (blue curve in Fig. 6b,) and the acoustic time difference curve (Fig. 6c). In the 5400-5800 m well section, due to the expansion of well diameter, the density curve decreases significantly, while the acoustic time difference curve is basically stable. Therefore, the porosity can be calculated by using the acoustic time difference curve, and then the density value can be deduced according to the calculated acoustic porosity, and this density value can be approximately regarded as the corrected value of density logging (red curve in Fig. 6b) (Gong et al., 2008; Liu et al., 2014). Through the crossplot of well diameter and density before and after correction (Fig. 7), it can be seen that the decreasing trend of density with the increase of well diameter has been improved.

Optimization log interpretation

By comparing the two mineral volume models with conventional interpretation and the predicted results in Fig. 4, it can be seen that the first model has better prediction effect on density while the other has better prediction effect on velocity. The two models have great differences and can not meet the requirements of petrophysical modeling. Due to the complexity of carbonate reservoir, if the mineral volume model obtained from conventional logging interpretation can not meet the accuracy requirements of petrophysical modeling, it is necessary to reinterpret the mineral volume model before petrophysical modeling.

A new optimization log interpretation method based on multi-mineral model is proposed in this paper, which can not only use various logging interpretation models flexibly, but also greatly improve the utilization of logging information and the ability to analyze multi-mineral components (Wang et al., 2000). Firstly, according to the geological characteristics of the work area, the models of "dolomite + calcite + clay" (Fig. 8a) and "dolomite + quartz + clay" (Fig. 8e) are adopted for optimization log interpretation and petrophysical modeling. It is found that the S-wave prediction result of "dolomite + quartz + clay" (Fig. 8i) is the best in the upper part of the reservoir. In the lower part of the reservoir, the S-wave prediction result of the "dolomite + calcite + clay" is better. Therefore, the model of "dolomite + calcite + quartz + clay" is adopted for reinterpretation and petrophysical modeling. It is found that the predicted curves are basically consistent with the measured curves, so this model is used to interpret all wells in the work area.

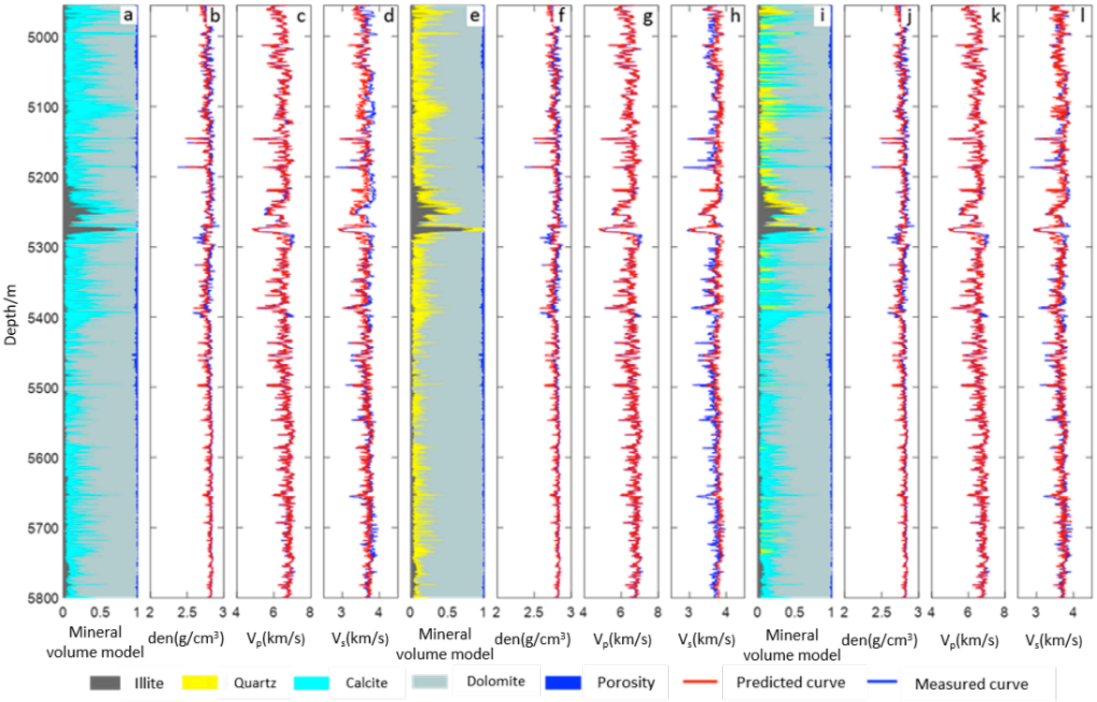


Fig. 8. Mineral volume models and predicted results of optimized logging interpretation of well A.

Optimization of soft pore scale factor

In order to improve the accuracy of modeling, the P-wave velocity can be used to invert the soft pore scale factor and predict the S-wave velocity. At each depth point, the soft pore scale factor is taken as the fitting parameter, and the best soft pore scale factor is determined by minimizing the error between logging P-wave velocity and predicted P-wave velocity. The specific calculation process is as follows:

(1) The initial soft pore scale factor is 0, the setting range is 0 to 1, and the step is 0.05;
(2) Input the mineral volume model, porosity, velocity and other logging data for logging interpretation, and conduct petrophysical modeling;
(3) Judge whether the termination condition is met , that is $|V_P - V_{PM}|$ *to obtain the minimum value; If yes, accept the current soft pore scale factor; If not, keep the previous value and continue the cycle until the end;*
(4) Output the final result.

APPLICATION EFFECT

The reservoir space of Dengying Formation in the study area has complex genesis and many types, mainly including secondary pores, holes and fractures. Among them, the fracture-pore-hole composite reservoir space and the pore-hole composite reservoir space are high quality reservoirs. (Xu, 2011; Mo et al., 2013). The petrophysical modeling and analysis of two types of reservoir spaces are carried out using the modeling process proposed in this paper.

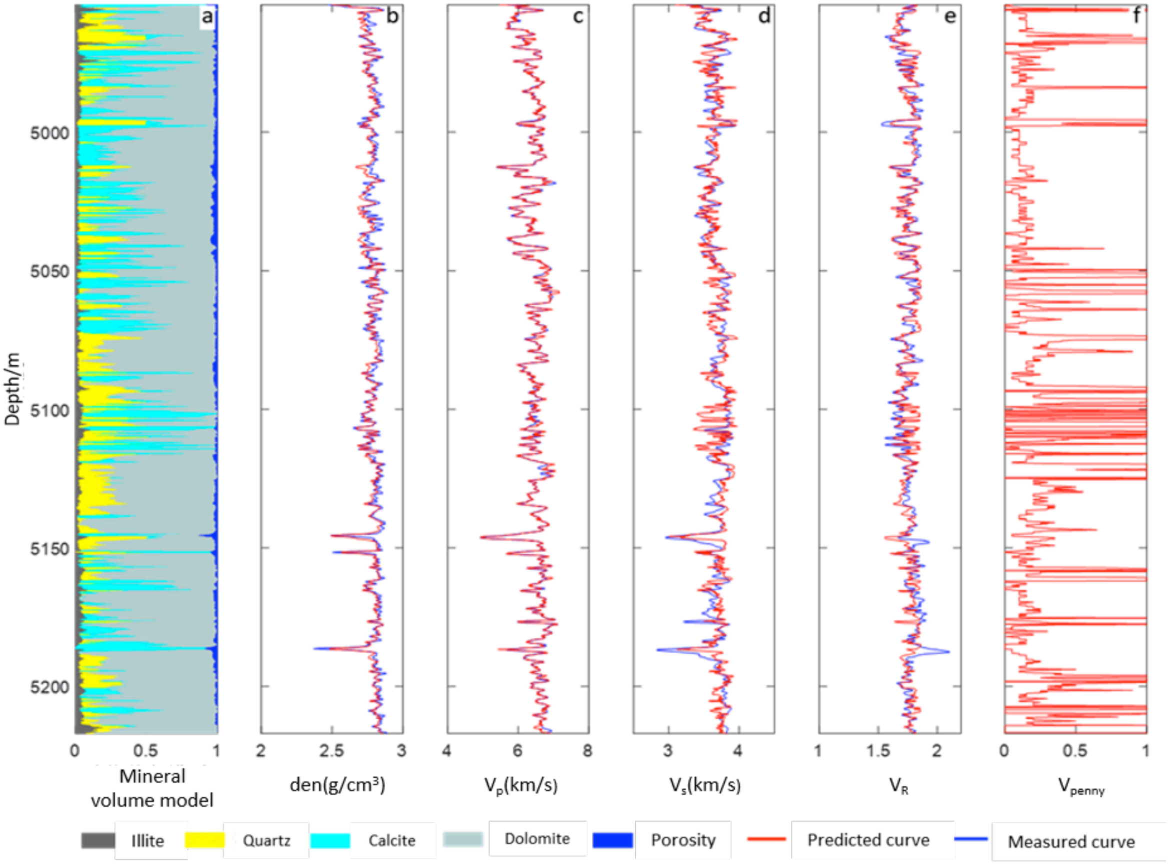


Fig. 9. Modeling results of fracture-pore-hole reservoir space.

Fracture-pore-hole reservoir

Fracture-pore-hole reservoir space is developed with fractures and dissolution caves. Fig. 9a shows the mineral volume model of logging interpretation, and Fig. 9b, c, d, e respectively shows the comparison between the measured curves (the blue curves) and the predicted results (the red curves) of density, P-wave velocity, S-wave velocity and P-S wave velocity ratio. It can be seen that the predicted curves greatly match the measured curves. Not only the overall trend is consistent, but also the internal details are similar. The correlation coefficient of S-wave velocity is 0.665 and the one of P-S wave velocity ratio is 0.6544. Fig. 9f shows the soft pore scale factor inversed with the P-wave velocity. The soft pore scale factor is relatively high as a whole, which is consistent with the relative development characteristic.

Pore-hole reservoir

The dissolved pores are developed in the pore-hole reservoir space and the fractures are not developed. Fig. 10a shows the mineral volume model of logging interpretation. Figs. 10b, c, d, e respectively show the comparison between the measured curves (the blue curves) and the predicted results (the red curves) of density, P-wave velocity, S-wave velocity and P-S wave velocity ratio. The correlation coefficient of S-wave velocity is 0.7028 and the one of P-S wave velocity ratio is 0.7536. Fig. 10f shows the soft pore scale factor inversed with the P-wave velocity. The soft pore scale factor is relatively low, which is consistent with the characteristic of undeveloped fractures in the reservoir.

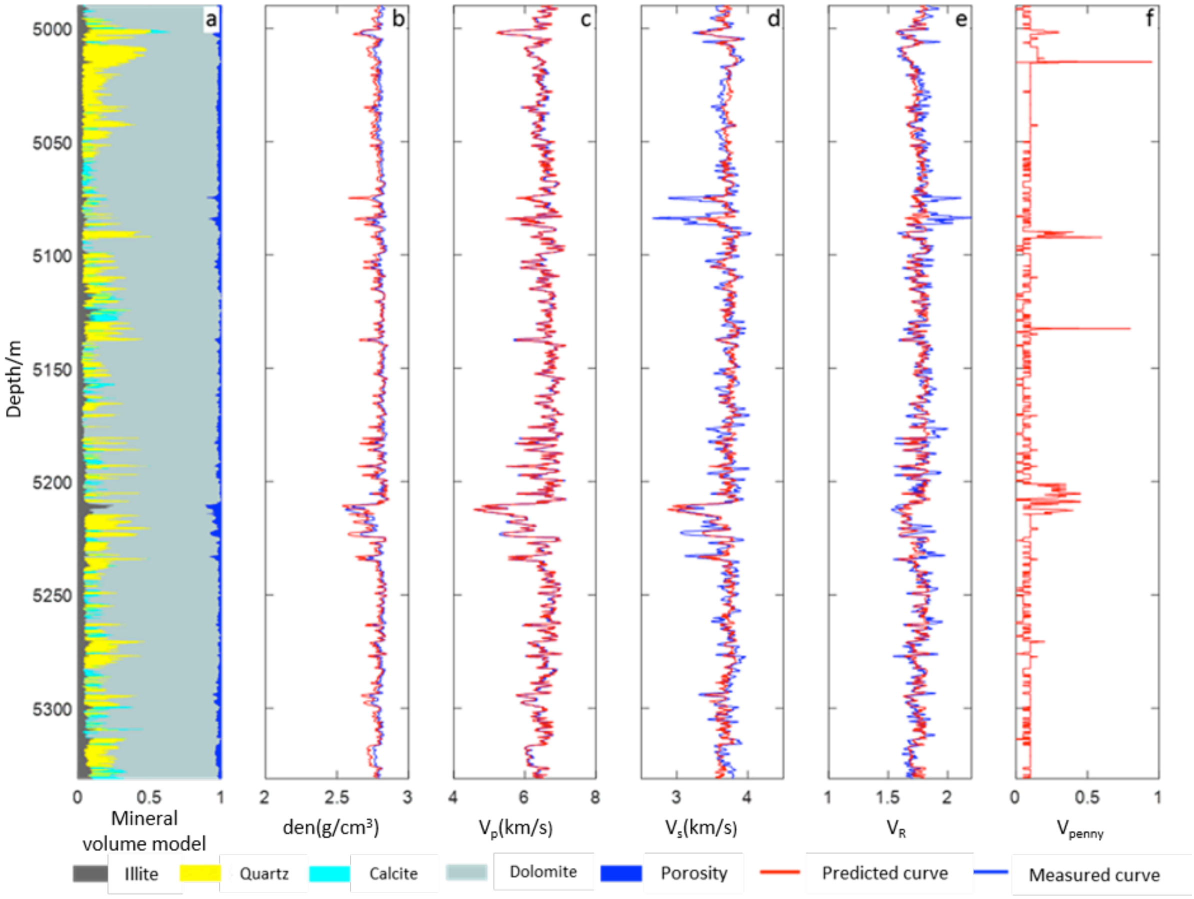


Fig. 10. Modeling results of pore-hole reservoir space Conclusions and suggestions.

A petrophysical modeling process of carbonate reservoir based on partially connected pore model is established in this paper, which has achieved good results in the application of the Dengying Formation in the middle Sichuan paleo-uplift. The soft pore scale factor obtained by inversion in the modeling process has indicative significance for the identification and classification of reservoir space types.

In addition, since the partially connected pore model is mainly applicable to isotropic medium reservoirs, the prediction effect of pore-hole reservoirs is better than that of fracture-pore-hole reservoirs. The Gassmann equation used is a low-frequency approximation, ignoring the dispersion and attenuation caused by the relative motion of fluid and framework (Gassmann, 1961). The next step can be considered to combine the anisotropic petrophysical model with the partially connected pore model, and incorporate the local or global flow of fluid into the petrophysical modeling process, so as to obtain more accurate predicted results in carbonate reservoirs.

REFERENCES

Gassmann, F., 1961. Über die Elastizität poröser Medien. Vierter Naturgesellsch. Zürich, 96: 1-23.

Gong, H., Su, M., Wang, Z, ……….., 2008. Analysis of environmental influence factors on well data and study on practical correction method. Computing Techniques for Geophysical and Geochemical Exploration, 30(1): 43-47.

Jia, C., Zheng, M. and Zhang, Y., 2014. Four important theoretical issues of unconventional petroleum geology. Acta Petrol. Sin., 1: 1-10.

Liu, G. and Tan, Y., 1993. Borehole diameter correction for acoustic and density logging data. Oil Geophys. Prosp., 28: 232-240.

Liu, Z., Wang, J., Yang, X., ……….., 2014. Analyzing on applicability of expanding influence correction method of density logging in the coalbed methane reservoir. Progress in Geophysics, 29(5): 2219-2223.

Mo, J., Wang, X. and Leng, S., ………., 2013. Reservoir characteristics and control factors of Sinian Dengying Formation in central Sichuan. Geol. China, 40: 1505-1514.

Mori, T. and Tanaka, K., 1973. Average stress in matrix and average elastic energy of materials with misfitting inclusions. Acta Metallur., 21: 571-574.

Wang, Y., Xia, H., Chen, K., ………., 2000. Optimized log interpretation for carbonate reservoirs in the Tarim Basin. J. Southw. Petrol. Inst., 22(4): 18-21.

Xu, C., 2011. The Study of Prediction for the Carbonate Rocks in Moxi, Central Sichuan Paleouplift. Northeast Petroleum University.

Yan, X., 2012. Seismic Rock Physical Modeling and Application of Tight Reservoir. Res. Inst. Petrol. Explor. Develop., CITY???.

Yan, X., Li, X., Wei, X., ………, 2016. Rock physics modeling in partially connected porous medium. Expanded Abstr., 86th Ann. Internat. SEG Mtg., Dallas.

Zhao, W., Hu, S. and Liu, W., ………., 2014. Petroleum geological features and exploration prospect in deep marine carbonate strata onshore China: A further discussion. Natur. Gas Indust., 34(4): 1-9.