Introduction

Shear wave velocity is the basic data for reservoir prediction and fluid detection. Therefore, an effective method to accurately predict S-wave velocity is one of the important research requirements. Although methods based on rock physics have become mainstream in petroleum industry, compared with clastic rocks, research on carbonate rocks with complex pore structure is relatively sparse. In view of the complexity and particularity of carbonate reservoirs, many studies have focussed on improving the accuracy of shear wave velocity or the effects of practical application. Kumar and Han (2005) studied the influence of pore shape on shear wave velocity and put forward a method to estimate the aspect ratio of different types of pores. Vega et al. (2007) studied the applicability of the fluid replacement model in heterogeneous carbonate rocks and pointed out that the patchy saturation model can predict greater velocity changes. Based on the conventional sand-mudstone model, Xu and Payne (2009) constructed a rock physics model of carbonate rock by using a V-R-H model and differential equivalent medium model (DEM). As a result, there are many S-wave prediction methods around. But for some areas where the mineral content is unknown, if the input matrix mineral bulk modulus parameters are not accurate, the application of the Xu-Payne model will be greatly limited. How to accurately obtain the matrix modulus from known information has become a very important problem.

In this paper, we propose a workflow for successfully predicting S-wave velocity in tight carbonate areas. In view of the general lack of mineral content and shear wave information in logging data, we carried out the inversion of the matrix modulus firstly by a self-adapting method, and then according to the characteristics of microcrack development in tight carbonate rocks, simplifying the pore type. Through the rock physics model, the shear wave velocity in this area is predicted successfully.

Methodology

There are many factors that affect the velocity of carbonate rocks, such as the content of various minerals, porosity, pore structure and saturation. The comparison results for the effect of variation of shale and lime-stone content on velocity and density are shown in Figure 1. It shows that the velocity of carbonate rocks is more sensitive to variations in the shale content.

![Figure 1](Image)

**Figure 1** Comparison of the effect of variation of shale and limestone content on velocity and density((a) effect of shale content (b) effect of limestone content).

![Figure 2](Image)

**Figure 2** Comparison of the effect of porosity and aspect ratio on velocity and density((a) effect of porosity (b) effect of pore aspect ratio).
Figure 2 depicts the effects of porosity and pore aspect ratio on the velocity and density. Both velocity and density will decrease with an increase of porosity, but velocity will increase with an increase of pore aspect ratio. In other words, when the pore aspect ratio is very small (less than 0.1, like a crack), P-wave and S-wave velocity will obviously decrease. Therefore, we should pay more attention to the discussion of shale content and pore aspect ratio in carbonate rock.

There are many wells with unknown mineral content information in the target area. In order to effectively obtain the equivalent matrix modulus, we use a self-adapting matrix bulk modulus extraction method. Based on the Biot-Gassmann theory, we get the following relationship for the fluid term:

$$f = \beta^2 M$$  \hspace{1cm} (1)

where $\beta$ is the Biot-Willis parameter.

Similarly, Russell et al. (2003) proposed the fluid factor:

$$f = (Z_p^2 - cZ_s^2)/\rho_{sat}$$  \hspace{1cm} (2)

and

$$c = (V_p/V_s)\frac{3}{2} = 2(1 - \sigma_{dry})/(1 - 2\sigma_{dry})$$  \hspace{1cm} (3)

where $\rho$, $Z_p$ and $Z_s$ are respectively the density, P-wave impedance, S-wave impedance, and $c$ is a constant related to Poisson’s ratio for dry rock.

Taking a single logging depth point as the research object, we use the fitting formula for saturated dolomite (Castagna et al., 1999) to estimate the initial shear wave velocity, which is only used to calculate the target parameters $K_0$ for inversion:

$$V_s = 0.583V_p - 0.078$$  \hspace{1cm} (4)

where $V_p$ represents the result of actual measurement. The fitting formula can be used to calculate a temporary S-wave impedance.

Then we set the range of Poisson's ratio for dry rock to 0 ~ 0.4, which is the range of Poisson's ratio in sedimentary rocks. The range of matrix modulus is set according to equation (5) (Pride and Gangi, 1992):

$$K_0 = K_{dry} (1 + \alpha \phi) / (1 - \phi)$$  \hspace{1cm} (5)

where $K_0, K_{dry}$ and $\phi$ are respectively the matrix modulus, dry rock bulk modulus and porosity, and $\alpha$ is the consolidation coefficient of rock. We have already known that the matrix modulus is the largest, the saturated rock modulus is the second, and the dry rock modulus is the lowest. Based on this, we get the variation range of modulus:

$$K_{sat} < K_0 = K_{dry} (1 + \alpha \phi) (1 - \phi) < K_{sat} (1 + \alpha \phi) (1 - \phi)$$  \hspace{1cm} (6)

The key lies in the setting of $\beta$. We use Gassmann-Biot-Geertsman equation to solve the problem:

$$(Y - 1) \beta^2 + [Y \phi(K_0/K_{nl} - 1) - y + N/K_0] \beta - \phi(Y - N/K_0) (K_0/K_{nl} - 1) = 0$$  \hspace{1cm} (7)

and

$$Y = 3(1 - \sigma_{dry})/(1 + \sigma_{dry}), \quad N = \rho_{sat} V_p^2$$  \hspace{1cm} (8)

Equations (7) and (8) are a standard unitary quadratic equation with $\beta$ as a variable. Most of the parameters in the equation are known, and the solution can be obtained by solving the unitary quadratic equation.

After we set the value range of the unknown parameters, two different fluid terms are calculated, the absolute value of the difference between the two terms is set as inversion objective function, and the method of finding the global optimal solution is used to invert the optimal Poisson's ratio of dry rock and the equivalent matrix modulus $K_0$.

For a well with known mineral content, we test this method (Figure 3). The equivalent matrix modulus calculated by self-adapting method is still between the upper limit of Voigt and the lower limit of Reuss, so the result of this method is acceptable for the target well with unknown mineral content.
As usual, we use the aspect ratio to describe the pore structure. According to the Xu-Payne model, if it is assumed that all pore types are included, the calculation process will become very troublesome, which seriously restricts the application of the model. Following Kumar and Han, we assume that the interparticle pore is the most common pore type in carbonate rocks, which gives a reference porosity-velocity trend. If the measured P-wave velocity is higher than the trend line, the pores are assumed to be composed of stiff pores and interparticle pores, and if the measured P-wave velocity is lower than the trend line, the pores are assumed to be composed of microcracks and interparticle pores.

From Figure 4 we can see that almost all the points are below the trend line. It can be inferred that the pore types in this area are mainly microcracks and interparticle pores, which is in line with our consistent understanding of tight carbonate rocks.

After determining the pore type, we assume the content and aspect ratio of the two pores and use DEM and Gassmann equation to calculate the bulk modulus of rocks saturated with different fluids. Considering the non-uniform distribution and non-uniformity of fluid in pores, the effective saturated bulk modulus is obtained by using the Patchy saturation model, and finally the predicted P-wave and S-wave velocities are obtained.

Comparing the calculated P-wave velocity with the P-wave velocity of the logging, if the difference between them is small (within the error range), the output calculated S-wave velocity is the best S-wave velocity estimated. If the difference between the P-wave velocities is large, then we change the aspect ratio and percentage content of the two kinds of pores, and repeat the previous step until the error meets the requirements.

**Examples**

Well A and B of a tight carbonate rock area are used to test the workflow established in this paper. Firstly, we use the above method to calculate P-wave and S-wave velocity. And then we compare results with log data to verify the reliability and applicability in a tight carbonate rock area. The results
are shown in Figure 5. From Figure 5 we can see that the P-wave and S-wave velocity calculated by the workflow are in good agreement with the log data. The relative error is very small, and for the vast majority it is less than 0.1.

![Figure 5](image)

**Figure 5** P-wave comparison and S-wave prediction result((a) the result of well A (b) the result of well B).

**Conclusions**

According to the characteristics of a tight carbonate reservoir, the volume fraction of interparticle pore and microcrack pore is calculated by using a rock physics model under the constraint of P-wave velocity, and the S-wave velocity can be accurately predicted by substituting the volume fraction and the corresponding aspect ratio. When the predicted results of P-wave are in good agreement with the measured P-wave results, it can be considered that the S-wave velocity is also reasonable. The applicability and effectiveness of the whole process for calculating shear wave velocity in tight carbonate reservoir has been verified.

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**References**