Introduction

In recent years, fluid mobility attribute extracted from low-frequency information of poststack seismic data has been widely used in reservoir characterization. Fluid mobility of gas-bearing reservoirs can be estimated by combining the low-frequency reflection asymptotic analysis theory with the generalized S-transform method, which can detect the location of the reservoirs (Silin et al., 2004; Chen et al., 2012). In order to further improve the accuracy of the estimated fluid mobility attribute, researchers have tried to perform calculations by integrating different time-frequency analysis methods (Huang et al., 2013; Xue et al., 2018). Synchrosqueezed Generalized S-transform (SSGST) has higher time-frequency resolution than conventional time-frequency analysis methods (Chen et al., 2017). The method has potential for calculating fluid mobility. Compared to poststack seismic data, prestack seismic data contains more information about reservoirs and fluids. At present, fluid detection is mainly based on AVO analysis by prestack seismic data. The conventional AVO analysis ignores the change of the reflection coefficient with frequency. By frequency-dependent AVO analysis, reflection coefficient dispersion can improve the accuracy of hydrocarbons detection (Chapman et al., 2006).

Based on the frequency-dependent AVO analysis technology and the calculation method of poststack fluid mobility, we propose prestack fluid mobility which means that fluid mobility varies with angle/offset (FVA/FVO). By establishing models of reservoirs with different fluids, the corresponding prestack fluid mobility is estimated. The results show that prestack fluid mobility can distinguish the oil-bearing reservoir (class III AVO) from the water-bearing reservoir (class IV AVO). Further, based on SSGST method, we obtain the prestack fluid mobility attribute from the field data. Then the SSGST-based prestack fluid mobility method is applied to characterize hydrocarbon reservoirs in Tarim Basin. The application results show that prestack fluid mobility can reduce the uncertainty of identifying the fluid properties and predicting the distribution of reservoir.

Prestack fluid mobility principle

According to the low-frequency asymptotic analysis theory, reservoir fluid mobility can be expressed as

$$ F = \frac{1}{P} \left( \frac{\partial R}{\partial f} \right)^2, $$

where $F$ is defined fluid mobility, $R$ is reflection coefficient, $f$ is frequency. In the case of few or no wells, $P$ is regarded as a constant. Reflection coefficient $R$ can be calculated by Aki & Richards approximation formula. The Aki & Richards approximation formula and the velocity dispersion formula (Kjartannson, 1979) are used to derive the dispersion formula of P-wave reflection coefficient.

$$ R(\theta) = A + B \sin^2 \theta + C \sin^2 \theta \tan^2 \theta, $$

where

$$ A = \frac{1}{2} \left( \frac{\Delta V_p}{V_p} + \frac{\Delta \rho}{\rho} \right), B = \frac{\Delta V_p}{2V_p} - \frac{V_s^2 \Delta V_s}{V_p^2} - 2 \frac{\Delta \rho}{\rho} \frac{\Delta \rho}{\rho}, C = \frac{1}{2} \frac{\Delta V_p}{V_p} \frac{\Delta V_p}{V_p}, $$

$$ \frac{\Delta \rho}{\rho} = 2 \frac{\rho_2 - \rho_1}{\rho_1} \frac{\Delta V_s}{V_s} = 2 \frac{V_{s(1)} - V_{s(1-1)}}{V_{s(1)} + V_{s(1-1)}} \frac{V_{s(1-1)}^2}{V_p^2} = \frac{1}{2} \left( \frac{V_{s(1)}^2 - V_{s(1-1)}^2}{V_{p(1)}^2 + V_{p(1-1)}^2} \right). $$

Kjartannson's velocity dispersion formula is:

$$ V_{p(i)}(f) = V_{p(i)} K(f), $$

where $K(f) = \left( \frac{f}{f_0} \right)^{1/2}$, $V_{p(i)}$ represents the P-wave velocity at the reference frequency $f_0$, and $V_{p(i)}(f)$ represents the P-wave velocity at any frequency. By combining equations (2) and (3), the frequency-dependent prestack reflection coefficient $R$ can be expressed as
The reflection coefficient of the stratum reflection interface is divided into two parts, which respectively represent the contribution of the elastic part and the viscoelastic part to the reflection coefficient. $R(\theta)\text{ is the reflection coefficient at the reference frequency, which is a constant that is independent of frequency and quality factor($Q$).}$

$$
R(\theta, f) = R(\theta) + \left( (C - B) \sin^2 \theta + \frac{1}{2} \sec^2 \theta \right) \frac{1}{\pi Q} \ln \left( \frac{f}{f_0} \right),
$$

(4)

As follows from equation (5), the fluid mobility is related to frequency, incident angle and $Q$. If the frequency and $Q$ are constants, we can get the fluid mobility variation with angle (FVA). In actual applications, we replace reflection coefficient by instantaneous seismic amplitude or energy (Zeng et al., 2017). Therefore, submitting seismic amplitude $a(f)$ into equation (1) yields:

$$
F(\theta, f) = \left[ \left( (C - B) \sin^2 \theta + \frac{1}{2} \sec^2 \theta \right) \frac{1}{\pi Q} \right]^2 \left( \frac{1}{f} \right)^2,
$$

(5)

In order to get prestack fluid mobility and detect oil and gas reservoirs by using partial stack gathers, the following two steps need to take place: Firstly, the fluid mobility of the partial stack gathers is calculated by the equation (8). Secondly, FVO is calculated by equation (9):

$$
F_{\text{vo}} = F_{\text{f}} - F_{\text{n}} = \frac{1}{C} \left( \frac{\partial \text{SSGST}_f(\bar{f}, b)}{\partial f} \right)^2 - \frac{1}{C} \left( \frac{\partial \text{SSGST}_n(\bar{f}, b)}{\partial f} \right)^2,
$$

(9)

where $F_{\text{f}}$ represents fluid mobility of the partial stack gathers at far offsets, $F_{\text{n}}$ represents fluid mobility of the partial stack gathers at near offsets.

### Model test

In this section, in order to study the relationship between fluid mobility and incident angle for different AVO classes, two-layer media model of different AVO classes is established according to the effects of fluid dispersion and attenuation on AVO analysis.

<table>
<thead>
<tr>
<th>Model</th>
<th>$v_p$(m/s)</th>
<th>$v_s$(m/s)</th>
<th>$\rho$(g/cm$^3$)</th>
<th>$Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate rock</td>
<td>6000</td>
<td>3800</td>
<td>2.71</td>
<td>1000</td>
</tr>
<tr>
<td>Carbonate reservoir(water)</td>
<td>4001</td>
<td>2085</td>
<td>2.52</td>
<td>8</td>
</tr>
<tr>
<td>Carbonate reservoir(oil)</td>
<td>5034</td>
<td>4550</td>
<td>2.62</td>
<td>3</td>
</tr>
</tbody>
</table>


The model parameters are shown in Table 1, which are obtained from the actual data. The first layer is high-speed carbonate rock \((v_p = 6000 \text{ m/s}, \nu_s = 3800 \text{ m/s}; \rho = 2.71 \text{ g/cm}^3; Q = 1000)\). When \(Q\) is 1000, the seismic wave is not considered to be attenuated. The second layer is a carbonate fracture-cavity reservoir. When the reservoir contains water, P-wave velocity is 4001 m/s, S-wave velocity is 2085 m/s, density is 2.52 g/cm³, and \(Q\) is 1000. When the reservoir contains oil, P-wave velocity is 5034 m/s, S-wave velocity is 4550 m/s, density is 2.62 g/cm³, and \(Q\) is 3.

\[\text{(a)}\] \[\text{(b)}\] \[\text{(c)}\]

**Figure 1** P-wave reflection coefficients and FVA of theoretical model. (a) P-wave reflection coefficients variation with angle in the low- and high-frequency limit \((9-80\text{Hz})\), (b) fluid mobility of water-bearing reservoir variation with angle in the low- and high-frequency limit, (c) fluid mobility of oil-bearing reservoir variation with angle in the low- and high-frequency limit.

Fig.1 shows P-wave reflection coefficients and FVA for model. According to Fig.1a, when the reservoir contains water, the reflection coefficient shows the class IV AVO anomaly; when the reservoir contains oil, the reflection coefficient shows the class III AVO anomaly. According to Fig.1b and Fig.1c, In the range of 0-30 degrees, fluid mobility of water-bearing reservoirs decreases with increasing angle, while fluid mobility of oil-bearing reservoirs increase with increasing angle. Besides, the change trend is more obvious at low frequency than at high frequency.

**Application results and discussion**

\[\text{(a)}\] \[\text{(b)}\] \[\text{(c)}\] \[\text{(d)}\]

**Figure 2** Prestack seismic data and FVA of oil well A and water well B. (a) the 0-30 degree prestack seismic data of Well A, (b) FVA of Well A, (c) the 0-30 degree prestack seismic data of Well B, (d) FVA of Well B.

In order to illustrate the feasibility of fluid prediction by prestack fluid mobility, we process prestack seismic data of typical oil well A and water well B by SSGST-based prestack mobility calculation method. Fig.2a shows prestack seismic data of Well A and the top interface of the oil-bearing the reservoir is at the about 3410-3418 ms. Reflection amplitude decrease with increasing angle (class III anomaly). Fig.2b shows the FVA of Well A. Fluid mobility of water-bearing reservoir increase with increasing angle. Fig.2c shows prestack seismic data of Well B and the top interface of the water-bearing the reservoir is at the about 3390-3398 ms. Reflection amplitude of water-bearing reservoir decrease with increasing angle (class IV anomaly). Fig.2d shows the FVA of Well B. Fluid mobility of water-bearing reservoir increase with increasing angle. The results of the actual application are consistent with the results of the model trial above.
In order to further verify the feasibility of fluid prediction through prestack fluid mobility, we used this method to process partially stack gathers intersecting water well B and oil well C. Fig.3a shows that poststack seismic section has reservoirs with obvious "beaded" reflection characteristics. According to Fig.3b, the poststack fluid mobility section eliminates some anomalous amplitudes and indicates the reservoir locations of water well B and oil well C. However, it cannot distinguish Oil-bearing reservoirs from oil-bearing reservoirs. In Fig.3c, FVO of the oil-bearing reservoir of well C is positive in red, which is consistent with the characteristics of the FVA corresponding to class III; FVO of the water-bearing reservoir of well B is negative in blue, which is consistent with the characteristics of the FVA corresponding to class IV. Because the FVO of oil-bearing reservoirs and water-bearing reservoirs is quite different, FVO can be used to better identify fluid properties.

**Figure 3** Poststack seismic section and fluid mobility section intersecting water well B and oil well C. (a) poststack seismic section intersecting water well B and oil well C, (b) poststack fluid mobility section intersecting water well B and oil well C, (c) FVO section intersecting water well B and oil well C.

**Conclusions**

Based on the frequency-dependent AVO analysis and the calculation method of fluid mobility, we propose a prestack fluid mobility (FVA/FVO) calculation method. According to model test, there is a difference between the FVA of class IV and FVA of class III: the fluid mobility of class IV decreases with increasing angle, while the fluid mobility of class III increases with increasing angle. This phenomenon is more obvious under low frequency conditions. The SSGST-based prestack fluid mobility calculation method is applied to the actual seismic data. The results show that compared with poststack fluid mobility, FVO can better distinguish oil-bearing reservoirs from water-bearing reservoirs. FVO combined with poststack fluid mobility can reduce the uncertainties in fluid identification and reservoirs prediction, which provide a feasible way to directly predict hydrocarbon reservoirs in the absence of well data.

**References**


