Introduction

With the increasing demand for natural resources, the exploitation depth of oil and gas resources has been ever increasing. As a consequence, the influence of in-situ pressure and temperature on rock properties have become more and more important.

There are relatively few experimental studies about the wave propagation in fluid saturated rocks under different temperature conditions. Batzle and Wang (1992) analyzed the temperature dependence of pore fluids and its effect on seismic velocities. Rabbani et al. (2017) examined the influences of temperature on P-wave velocity in bitumen saturated carbonates. As for the temperature dependence due to the presence of micro-cracks, Xu et al. (2006) investigated the effects of the development of micro-cracks on the elastic properties of rocks with increasing temperature in the experimental studies. They found that temperature changes were a factor in the generation of thermal micro-cracks. However, because the mechanism of effect of temperature on velocity is difficult to determine, there has been little progress regarding how the temperature-dependencies of pore fluids and micro-cracks jointly affect the overall of rock behavior.

In this work, we propose a rock physics model to characterize the relationship between seismic properties and reservoir fluid temperature. This model combines the double-porosity medium model with the Batzle-Wang (BW) and David-Zimmerman (DZ) models. The combined model is used to analyze the influence of fluid properties and micro-cracks on wave response at different temperatures. We interpret experimental data for velocity in saturated carbonates at different temperature using the proposed model.

Laboratory Measurements

The samples were selected from two carbonate rocks from western Sichuan, China. The main mineral composition is dolomite with a small amount of clay. For all samples, the reservoir depth is more than 4500 m. The in-situ temperature at this depth is about 120 to 140°C. The pore structure of the samples is complex, consisting of intergranular pores and micro-cracks. The carbonate samples are cylindrical, with 30–42 mm in length and 25.2 mm in diameter. The basic physical properties of these rocks are shown in Table 1.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Lithology</th>
<th>Porosity (%)</th>
<th>Permeability (mD)</th>
<th>Density (kg/m³)</th>
<th>Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Carbonate</td>
<td>16.87</td>
<td>3.31</td>
<td>2320</td>
<td>Water/Oil</td>
</tr>
<tr>
<td>2</td>
<td>Carbonate</td>
<td>4.99</td>
<td>1.34</td>
<td>2670</td>
<td>Water/Oil</td>
</tr>
</tbody>
</table>

To measure the wave velocity, we use the ultrasonic wave pulse method. For the water- and oil-saturated experiments, the carbonate rock samples were first saturated. Then we dried the samples in the oven. A confining pressure of 80 MPa was applied, while the pore pressure was kept constant at 10 MPa. Temperature was maintained at 20°C for 30 min. By heating the fluid with a heating wire in the vessel, ultrasonic measurements were performed to record the ultrasonic waveforms. The temperature was then raised to 140°C for 30 min. The pore pressure of 10 MPa was maintained while the confining pressures of 20, 25, 30, 35, 40, 45, 50, 60, 70 and 80 MPa were applied. Based on the first arrivals of the compressional wave and shear wave, the P- and S-wave velocities are calculated under water- and oil-saturated conditions at different temperatures.

Selected waveforms measured on sample 1 are shown in Figure 1. We observe that the primary amplitude for water-saturated rock increases from 20 to 140°C, while the primary amplitude for oil-saturated rock decreases with the increase of temperature.
Rock Physics Model for Temperature-dependent Velocities

The pore space in some rocks cannot be adequately described as an assemblage of intergranular pores. This is because there are micro-cracks. To include the effect of such a double porosity medium on seismic waves, we employ the Biot-Rayleigh (BR) model (Ba et al., 2011). This model incorporates the Biot and Rayleigh equations for the oscillation of a fluid pocket.

To address the influence of temperature on the P-wave velocity, the relationship between temperature and fluid properties according to Batzle and Wang (1992) is first introduced into the BR model. The parameters $\rho_f, \eta_f$ and $K_f$ are then becoming functions of temperature $\rho_f(T), \eta_f(T), K_f(T)$. The form of these functions is given by the BW equations.

The micro-crack porosity cannot be directly measured. We use the DZ model to calculate the micro-crack porosity. This model assumes that a micro-crack is an elongated, flat and thin spheroidal. The micro-crack porosity of the corresponding differential pressure at each temperature is obtained from the relationship between micro-crack porosity and micro-crack density (David and Zimmerman, 2012)

$$\phi(p) = \frac{4\pi\alpha^3}{3} \gamma_\phi,$$

where $\alpha_s$ denotes the micro-crack aspect ratio, and micro-crack density $\gamma_\phi$ is obtained by using the expression of the effective elastic modulus. Once the differential pressure dependence of the micro-crack porosity is known, the distribution of the micro-crack porosity at different temperatures is obtained by fitting based on the micro-crack porosity at the same pressure.

By now, we have introduced four temperature-dependent parameters including fluid properties and microscopic pore structure. From the four parameters $\rho_f(T), \eta_f(T), K_f(T)$ and $\phi(T)$, the P-wave velocity is obtained for the whole temperature range of 0-300°C by using the BR model. These equations are solved by plane-wave analysis (Ba et al., 2017).

Results and Discussion

We model the P-wave velocity variation with temperature in two cases. In the first case, the micro-crack porosity is constant with temperature, and the grain bulk modulus and dry rock bulk modulus are both independent of the temperature change. The other case is, in addition to the influence of the fluid, the effect of temperature on the micro-crack porosity is considered.

Figure 2 shows the predicted results for samples under water- and oil-saturated conditions. The relevant physical parameters are listed in Table 1. The solid red and blue lines represent the water- and oil-saturated samples in the constant crack state, respectively. We observe that when the temperature is less than 50 °C, the P-wave velocity of the water-saturated sample slightly increases with the
increasing temperature. However, when the temperature exceeds 50°C, the P-wave velocity drops sharply. The P-wave velocity of the oil-saturated sample decreases with increasing temperature. This is because the different fluid properties cause different trends with temperature, mainly due to the temperature-dependence of the fluid bulk modulus. Furthermore, the bulk moduli of the fluids are controlled by the sound velocity $v_f$ of the fluid ($K_f(T) = \rho_f v_f^2$). That is, the temperature dependence of sound velocity in the fluid is reflected in the P-wave velocity-temperature relation.

Figure 2 Temperature-dependent P-wave velocities for different fluids (water, oil) of sample 1 (a) and sample 2 (b).

Considering the change of micro-cracks with temperature, the P-wave velocities of the water-saturated rock sample (red dashed line) and the oil-saturated sample (blue dashed line) are simulated. As the temperature increases, because in the monomineralic carbonate rocks, the anisotropic thermal expansion could occur, which causes micro-fracturing and thereby promoting the opening of the micro-cracks. When the micro-crack porosity changes with temperature, it influences the bulk modulus of the rock skeleton and reduces the P-wave velocity. Therefore, comparing the predictions of the constant micro-crack case (solid line), it can be seen in Figure 2 that the variable micro-crack in the influence of the temperature on the P-wave velocity of the fluid-saturated rocks is not dominant. The P-wave velocity prediction of the model agrees well with the experimental data.

Comparing the results of the velocity variation under the two cases of the simulation hypothesis are shown in Figure 3. The relative change in velocity is

$$\Delta V = \frac{V_v - V_0}{V_0},$$

(2)

where $V_v$ denotes P-wave velocity at 10°C, and $V_v (T = 20,140)$ denotes P-wave velocity at 20°C and 140°C, respectively.

Figure 3 Histogram of velocity variation of 2 carbonate samples under two conditions in (a) water- and (b) oil-saturated rocks at different temperature.
It can be clearly observed that in the velocity-temperature relationships of saturated rock, the effect of temperature on fluid is the main reason for the change of velocity. The change of micro-crack porosity caused by temperature is not the key factor causing the decrease in P-wave velocity. When the temperature increases from 20 to 140℃, the influence of oil-saturated on P-wave velocity is much stronger than that of water-saturated. These variations are related to the acoustic velocity of the fluids.

Conclusions

We develop and apply the double-porosity medium model, which incorporates the BW as well as the DZ models to model the temperature-dependencies of pore fluids and micro-crack on the overall rock behavior. The results show that the predicted P-wave velocity of carbonate samples decreases with the increasing temperature. The P-wave velocity in the water-saturated state increases slightly at lower temperature.

The proposed model is relatively versatile for predicting seismic properties as a function of temperature. In addition, it helps to distinguish between the effects of micro-crack and fluid bulk modulus on seismic velocity as a function of temperature. Through the analysis of the modelling parameters, when the micro-crack content changes with temperature, the P-wave velocity changes to a lesser extent. We conclude that the fluid characteristics account for most of the change in the P-wave velocity of the rock. These variations in the velocity-temperature relation should be accounted for in rock physics model building for geothermal reservoirs and deep reservoirs exploration.

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References