Introduction

The ultra-deep (>7km) carbonate formations have increasingly played a critical role in onshore oil and gas exploration and development in China (Zhao et al., 2014a). Those rocks typically have vuggy-fracture and faulting-cavity reservoir system, which are mainly caused by the extensive exposure, weathering, denudation, and karstification process during the regional multi-stage tectonic activities (Zhu et al., 2015). Consequently, it exhibits unique physical properties which is distinct from the shallow buried reservoir rocks. Understanding the seismic rock physics of the ultra-deep carbonate under high pressure and high temperature conditions is of great significance for quantitative seismic interpretation for better reservoir characterization and development. Therefore, the elastic characteristics of those reservoir rocks as well as their seismic responses with different reservoir types and quality need to be systematically investigated, thereby laying the foundation for further AVO (amplitude-versus-offset) and DHI (direct hydrocarbon indicators) analysis. In this study, the investigated logging and seismic data is from the ultra-deep carbonate reservoirs located at Tarim basin, Northwestern China. On the basis of the well logging data analysis and an established rock physics model, this paper is to explore how the geological factors control the elastic properties and AVO responses of ultra-deep carbonates.

Rock physics characteristics of ultra-deep carbonate reservoirs

Figure 1 displays the well logging data of ultra-deep carbonate formation, with three types of reservoir (vuggy-fracture, weak-dissolution, and faulting-cavity) being shown in the yellow, green, and red rectangle respectively. As we can see from the first column of the logging data, overall, the reservoir formation is quite clean with very small amount of shale content. The yellow area corresponds to the vuggy-fracture reservoir system, where the caliper slightly expands, and porosity increases. Also, Vp, Vs, Vp/Vs ratio, density exhibit a decreasing trend. It is apparent that the corresponding FMI image shows the occurrence of fractures. In the green area corresponding to the weak-dissolution reservoir system, the petrophysical characteristics of caliper, Vp, Vs, Vp/Vs ratio, and density does not change significantly. This is understandable, since the weak dissolution process generate more micro-scale pores which can be also found in the corresponding FMI image, therefore producing less influences on the rock physical properties. By contrast, if the reservoirs have gone through extensive dissolution or karstification process, it exhibits significantly different rock physics characteristics. As being noted in the red rectangle of Figure 1, caliper and porosity increase sharply, while Vp, Vs, Vp/Vs ratio and density decrease remarkably. Clearly, the corresponding FMI image shows a cavity at 7310-7312m. It is interesting to notice that the GR in the cavity zone increase significantly, which is mainly due to the dissolution cavity are partially filled with clastic sediments.

Figure 1 Logging data of lithology, caliper, GR, porosity, P-wave velocity, S-wave velocity, Vp/Vs ratio, and density as a function of depth for the ultra-deep carbonate formation of Well A. The yellow, green, and red rectangle indicate the vuggy-fracture reservoir, weak-dissolution reservoir, and faulting-cavity reservoir respectively. The FMI image for the corresponding reservoir type are shown in the right.
Figure 2 shows actual core photo indicating the typical pore systems of two types of reservoir. Since venting occurs in the faulting-cavity reservoir (red rectangle in Figure 1), cores are not available. Figure 2a corresponds to the weak-dissolution reservoir, in which few cracks are present while dissolution pores are developed. Figure 2b corresponds to the reservoir type of vuggy-fracture system, where the vuggy pores and cracks are connected together. For vuggy-fracture reservoir, vuggy pores are mainly considered as the storage space, and cracks act as the fluid flow conduit (Zhao et al., 2014b).

**Figure 2** Core photos of Well A: a) is taken from 7266.65m, corresponding to the green rectangle zone in Figure 1; b) is taken from 7218.95m, corresponding to the yellow rectangle zone in Figure 1.

**Impact of reservoir type and reservoir quality on elastic characteristics**

For ultra-deep carbonate reservoir, the reservoir types are closely associated with the reservoir quality. In general, the weak-dissolution reservoir, the vuggy-fracture reservoir system, and faulting-cavity reservoir represent the Class III, Class II, Class I reservoir, respectively. Based on the rock physics analysis of logging data for 17 wells, Figure 3a illustrate the impact of reservoir type on the elastic characteristics of ultra-deep carbonate formation. It is apparent that P-wave velocity and density decrease with the improvement of reservoir quality. This is understandable, since both the pore space and occurrence of cracks can significantly reduce the velocity and density. Especially for the faulting-cavity reservoir, P-wave velocity and density are quite low, in comparison with other type of reservoir. The faulting-cavity reservoir is considered as the sweet spot of ultra-deep carbonate reservoir, which are mainly developed near the fault zone. Surface water seeps along the fault zone, and hence the carbonate formation are extensively dissolved to form cavity. During the stage of drilling this type of reservoir, venting or mud loss often takes place.

Figure 3b) shows the histogram of P-impedance for different reservoir types of all wells. Clearly, the average P-impedance of faulting-cavity reservoir (Class I reservoir) is 30% lower than the non-reservoir rocks. This also explains why the seismic attributes of reflectivity change is considered as a reliable indicator for sweet spot of ultra-deep carbonate reservoir. By contrast, the average P-impedances of vuggy-fracture (Class II reservoir) and weak-dissolution (Class III reservoir) are 12% and 8% lower than the non-reservoir rocks. In particular, the distinction between the Class III reservoir and non-reservoirs are quite ambiguous. This might pose challenges of using seismic elastic attributes (or reflectivity) to seismically detect the weak-dissolution reservoir.

**Figure 3** a) Crossplot of density and P-wave velocity for different reservoir types b) Histogram of P-impedance distribution of different reservoir types.
Rock physical model for ultra-deep carbonate reservoirs

To accurately capture the effect of physical parameters on the elastic characteristics of ultra-deep carbonates, it is essential to incorporate the precise fluids properties into rock physics modeling. The primary characteristics of the fluids in the targeted carbonate is that it has very high GOR ranging from 200-600 L/L. We employ the FLAG program developed by Fluids consortium University of Houston and Colorado school of Mines to compute the velocity, bulk modulus, and density as a function of GOR, as shown in Figure 4. It is clear that at certain temperature and pressure conditions, the increase of GOR significantly reduce the bulk modulus and density.

We use the differential effective medium (DEM) theory to quantify the effect of vuggy porosity and cracks on the overall elastic responses of dry rock. The mixture of oil and water can be modelled using voigt patchy saturation model (Mavko et al., 2009). Then Gassmann’s fluid substitution is applied to capture the fluids properties with high GOR on the elastic properties of the saturated carbonates. The detailed modeling steps can be found in Zhao et al. (2014b). The mineral content of solid matrix is assumed to be 95% limestone and 5% shale, the matrix porosity is set as 0.02, and the crack density is changed from 0 to 0.25. Figure 5 displays the rock physics modeling template of P-impedance versus Vp/Vs ratio, with the scattered data being taken from well A. The modeling results suggest that crack density and fluids saturation are two main factors controlling the seismic elastic characteristics of the ultra-deep carbonate reservoir rocks. With the increase of crack density and oil saturation, both P-impedance and Vp/Vs ratio exhibit an almost linear decreasing trend. The comparison of Figure 5a and 5b also demonstrate the importance of incorporating the GOR effect for rock physics modeling. Most of the scattered data points falling between the boundary of the rock physics template correspond to the weak-dissolution and vuggy-fractur reservoir system, while a small part of data points falling out of the boundary correspond to the faulting-cavity reservoir.

Seismic AVO signatures of ultra-deep carbonate reservoirs with high quality

Figure 6a shows the angle gather of field seismic data at the position of well A, which is transformed from the offset-domain common-image gathers. As displayed in Figure 6b, for the top reflection of the
targeted faulting-cavity reservoir occurring at well, the negative seismic amplitude roughly exhibit a decreasing trend with incident angle, which corresponds to the typical class III AVO responses. This can be understood, since the faulting-cavity reservoir in Figures 1 and 5 show considerable low P-impedance and Vp/Vs ratio characteristics. The class III AVO responses of the faulting-cavity reservoir is also further confirmed by the theoretical modeling results. The AVO analysis results suggest that, even for the ultra-deep carbonate formation, the faulting-cavity reservoir is still possible to generate Class III AVO responses, which is caused by the combined effect of fluids (oil with high GOR) and high crack density. This will also lay the foundation for seismic characterization of the sweet spot of the ultra-deep carbonate reservoirs.

Figure 6 a) The real angle gather at the well A position. The maximum incident angle obtained here is 30°. The red rectangle indicates the top reflection of the targeted faulting-cavity reservoir, b) The corresponding variation of the real seismic amplitude with incident angle after normalization c) The theoretical modelling amplitude variation with incident angle after normalization.

Conclusions

The investigated ultra-deep carbonate reservoirs in the Tarim basin typically have three types of reservoir: weak-dissolution (Class I), vuggy-fracture (Class II), and faulting-cavity (Class III), which have different rock physics characteristics based on the well logging data analysis. With the increase of reservoir quality, the P-impedance of reservoir rocks exhibit an enhanced contrast with the non-reservoir rocks. Rock physics modeling demonstrates that the oil saturation and crack density are two main physical factors controlling the seismic elastic characteristics of ultra-deep carbonate reservoirs. The Vp / Vs ratio and P-impedance decrease almost linearly with the increase of oil saturation and crack density. Analysis of the field angle gather suggests that the ultra-deep faulting-cavity reservoir is still possible to generate Class III AVO responses, which is also confirmed by the theoretical modeling results.

Acknowledgement

This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA14010203).

References