Journal of Natural Gas Science and Engineering 36 (2016) 267–279

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

A new method for assessing Young's modulus and Poisson's ratio in tight interbedded clastic reservoirs without a shear wave time difference

Shuai Yin [a, b, c], Wenlong Ding [a, b, c, *], Yuming Shan [d], Wen Zhou [d], Ruyue Wang [a, b, c], Xuehui Zhou [a, b, c], Ang Li [a, b, c], Jianhua He [a, b, c]

[a] School of Energy Resources, China University of Geosciences, Beijing, 100083, China
[b] Key Laboratory of Strategic Evaluation of Shale-gas Resources, Ministry of Land and Resources, Beijing, 100083, China
[c] Key Laboratory of Geological Evaluation and Development Engineering of Unconventional Natural Gas Energy, Beijing, 100083, China
[d] College of Energy Resource, Chengdu University of Technology, Chengdu, Sichuan 610059, China

ARTICLE INFO

Article history:
Received 11 August 2016
Received in revised form
19 October 2016
Accepted 22 October 2016
Available online 22 October 2016

Keywords:
Sichuan Basin
Interbedded clastic reservoir
Young's modulus
Poisson's ratio
Shear wave time difference

ABSTRACT

Tight clastic reservoirs are an important aspect of hydrocarbon exploration and development worldwide. The Xu5 section of the Upper Triassic Xujiahe Formation in the western Sichuan Basin of central China contains tight terrestrial clastic reservoirs. The depth of these reservoirs is greater than 3000 m, while the thickness is generally greater than 500–580 m; the tight sandstone and shale reservoirs are frequently interbedded. Based on the proportion of sandstone and shale, the reservoirs can be divided into four types: sand-rich, interbedded Type I, interbedded Type II, and shale-rich. Horizontal wells and multistage fracturing are used due to the complexity and significant heterogeneity of the tight clastic reservoirs in the study area. The Young's modulus and Poisson's ratio of the reservoir rocks are the two most significant parameters that must be evaluated when implementing these key techniques. Based on mechanical and acoustic tests, a new assessment system for the Young's modulus and Poisson's ratio based on the Hoek-Brown criterion was proposed. This evaluation system does not require the shear wave time difference; thus, the increase in error caused by the unreliability of the shear wave time difference can be avoided when assessing strata with complex geological structures. This method can be directly applied in single wells using only conventional longitudinal wave time difference log data. After converting the wave velocity of the high experimental frequency into the wave velocity of the logging frequency using the acoustic dispersion technique, the analysis results were applicable to the log evaluations. The relationship between the Hoek-Brown criterion parameters and the mechanical and acoustic parameters of the rock were systematically analyzed. By distinguishing the lithologies, the equations for the Young's moduli of tight sandstones and shales were established based on the Hoek-Brown criterion. The Young's modulus can be expressed using only the longitudinal wave velocity (V_P). A significant negative correlation exists between the Poisson's ratio and Young's modulus; therefore, the Poisson's ratio can be evaluated from the Young's modulus. The errors of the Young's modulus and Poisson's ratio predicted by the proposed assessment method are small, which meets engineering requirements and validates the accuracy of the method.

1. Introduction

Tight clastic reservoirs are an important aspect of hydrocarbon exploration and development worldwide. Tight clastic rocks include tight sandstones and shales, which both have characteristics of low porosity, low permeability and strong heterogeneity (Bustin et al., 2008; Ding et al., 2013; Feucht and Logan, 1990; Holt et al., 2015; Nelson, 2009; Sheory, 1997; Zeng and Li, 2009). These inherent properties make the geological structures of these reservoirs difficult to predict, and it is very difficult to evaluate each parameter during seismic and log evaluation (Adel and Mansoor, 2010; Shi et al., 2013; Zhao and Zhou, 2016). The pore throat

* Corresponding author. School of Energy Resources, China University of Geosciences, Beijing, 100083, China.
E-mail address: dingwenlong2006@126.com (W. Ding).

http://dx.doi.org/10.1016/j.jngse.2016.10.033
1875-5100/

structures of tight sandstones and shales differ at the micro-scale. For example, mercury injection test data show that the pore throat diameters of tight sandstones range from 0.12 to 0.9 μm, while those of shales range from 0.008 to 0.05 μm, which differs by one order of magnitude (Nelson, 2009). This difference in pore throat diameters leads to differences in the fluid states and rock mechanical properties of these reservoirs. The fluid compositions in tight sandstones mainly include bound water, free water and free gases, while those in shales mainly include bound water, absorbed gases and free gases (Bustin et al., 2008). Tight sandstones have greater rigidity and strength than shales (Feucht and Logan, 1990; Sheory, 1997); the V_P/V_S ratios (the ratio of the longitudinal wave velocity to the shear wave velocity) of tight sandstones are lower (1.5–1.75) than those of shales (1.6–2) (Pickett, 1963).

Tight clastic reservoirs are difficult to develop; thus, horizontal wells and multistage fracturing are needed. The elastic parameters of the reservoir rocks are some of the most significant input parameters during the implementation of these techniques (Zhang, 2013). The rock's elastic parameters include the Young's modulus, Poisson's ratio, shear modulus and bulk modulus. The Young's modulus and Poisson's ratio have the most widespread applications, and these are the two key rock mechanical parameters that are evaluated in this paper. The rock's elastic properties comprehensively reflect its mineral constituents, grain arrangement, fluid components and gas saturation. Consequently, accurately evaluating the Young's modulus and Poisson's ratio of tight clastic reservoirs has great significance for the drilling and completion of wells, fracturing evaluation, stress field simulation, fracture prediction and reservoir assessment (He et al., 2015; Li et al., 2013; Jiu et al., 2013; Zhang, 2013).

Two methods can be used to determine the Young's modulus and Poisson's ratio of a rock based on experimental tests. The first method is based on mechanical tests, and the results are static values. The second method first obtains the rock's acoustic parameters using acoustic tests and then calculates the dynamic mechanical parameters using physical equations (Holt et al., 2015; Rasoul et al., 2014). The static elastic parameters must meet engineering requirements, so static calibration is required for the dynamic mechanical parameters. This method can be used to perform log evaluations of the Young's modulus and Poisson's ratio of rocks in single wells, but the shear wave time difference is required in the evaluation process. Conventional logging generally uses only longitudinal wave tests without shear wave information, and only full wave acoustic logging provides a shear wave test. However, full wave acoustic logging is very expensive, so it is only used in a few wells in the early exploration stages (Feng and Gray, 2016). For tight clastic reservoirs with complex geological conditions, especially highly interbedded sandstones and shales, the reliability of the shear wave time difference cannot be ensured. Therefore, conventional methods could generate significant errors from the log evaluations of the reservoir elastic parameters.

The Hoek-Brown rock strength criterion was proposed by Hoek et al. (2005) and has been widely used to predict rock fracturing behavior and the shear and elastic characteristics of rock under various confining pressures (Eberhardt, 2012; Hoek et al., 2005; Hoek, 2007; Liao et al., 2012; Ma et al., 2011; Marinos et al., 2005; Rousseeuw, 1998). This criterion is applicable to igneous, metamorphic and sedimentary rocks, and it has high precision (Ma et al., 2011; Liao et al., 2012). Based on a systematic experimental analysis, this study proposes a new assessment method based on the Hoek-Brown criterion, which is suitable for assessing the Young's modulus and Poisson's ratio of highly interbedded terrestrial sandstone and shale reservoirs. The major advantage of this method is that it does not use the shear wave time difference. Therefore, this method has wider applicability than conventional methods for evaluating the elastic parameters of tight clastic reservoirs with complex geological conditions.

The study area (the Xinchang area) is located in the central Chuanxi Depression in the Sichuan Basin (Fig. 1a), and the target layer is the Xu5 section of the Upper Triassic Xujiahe Formation (T_3x^5). Based on the proportion of sandstones and shales, the reservoirs can be divided into four types: sand-rich, interbedded Type I, interbedded Type II, and shale-rich (Fig. 2). The sand-rich sandstones are generally more than 10 m thick; the sandstones are interbedded with thin shales; and the sandstone ratio (ratio of the thickness of the sandstones to the total thickness) is generally greater than 60%. The interbedded sandstones (Type I and Type II) are usually less than 10 m thick; the total thickness of the sandstone is similar to that of the shale; and the sandstone ratio ranges from 40% to 60%. In the shale-rich type, thick shales are interbedded with thin sandstones; the sandstone is usually less than 5 m thick; and the sandstone ratio is generally less than 40%. Based on the single well capacities, the layers of the interbedded reservoirs (sandstone ratios ranging from 40% to 60%) have the most active natural gas shows, possess the greatest capacity and degree of fracture development, and are the major gas production intervals. The sand-rich reservoirs can also have significant capacity, while the capacity of the shale-rich reservoirs is relatively poor.

Using the tight terrestrial clastic reservoirs in the Xu5 section of the study area as an example, we designed mechanical and acoustic synchronization tests and acquired the corresponding parameters. The dispersion correction technique was used to transform the velocity from the high experimental frequency to the logging frequency to make the experimental test results suitable for log evaluations. After distinguishing among the lithologies (tight sandstones and shales), the Young's modulus and Poisson's ratio of the rock were predicted using this new method, and the predicted results were compared with the measured values to validate the accuracy of this method.

2. Databases

2.1. Structure and strata

Fig. 3 shows the stratigraphic column of the Upper Triassic Xujiahe Fm. in the Xinchang area. From bottom to top, the Xujiahe Fm. is composed of the Xu2 (T_3x^2) to Xu5 (T_3x^5) sections. The Xu2 section (T_3x^2) and Xu4 section (T_3x^4) are large sets of sandstones that are interbedded with thin shales, while the Xu3 section (T_3x^3) and Xu5 section (T_3x^5) are interbedded tight sandstones and shales. The Xu5 section is composed of shore-shallow lacustrine sediments with mainly lake mud and beach bar microfacies. The thickness generally ranges from 500 m to 800 m, and most of the section is more than 700 m thick. The dominant lithologies in the Xu5 section are shales, siltstones, lithic sandstones and fine sandstones; these rocks are mainly gray and gray black, indicating a weak reducing sedimentary environment. The study area was a typical peripheral foreland basin during the sedimentary period of the Xu5 section and was affected by the late phase of the Indosinian movement. The tectonic sequence of the target layer is classified as a "binary systems tract" (Liu et al., 2015), which includes a strong orogenic period and a tectonically quiet period. Fig. 1b shows a structure map of the top of the Xu5 section in the Xinchang area. This area has a wide and gentle nose structure that extends to the NE and is high in the west, low in the east, steep in the south, and gentle in the north. Faults are mainly present in the eastern part of the study area, while faults are not present in the central and western areas. These are mostly minor faults with small throws and short lengths and are mainly located in the bottom of the Xu5 section (Fig. 1c).