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Research paper

Calibration of the mudrock compaction curve by eliminating the effect of organic matter in organic-rich shales: Application to the southern Ordos Basin, China

Chao Li [a, b], Likuan Zhang [a, *], Xiaorong Luo [a], Liqiang Zhang [c], Caizhi Hu [d], Yukai Qi [d], Yuhong Lei [a], Binfeng Cao [a], Ming Cheng [a], Yuxi Yu [a]

[a] *Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, China*
[c] *School of Geosciences, China University of Petroleum (East China), Qingdao 266580, China*
[d] *SINOPEC Petroleum Exploration & Production Research Institute, Beijing 100083, China*

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ABSTRACT

The mudrock log-derived compaction curve is a significant tool for investigating the primary migration of hydrocarbon, predicting fluid overpressure, estimating formation erosion thicknesses and restoring the buried history and paleo-structure of a basin. However, the presence of kerogen in organic-rich shales can create typically high logging values of the acoustic transit time. Thus, the abnormally high values of the acoustic transit time for organic-rich rocks may not truly reflect the porosity variations of subsurface rocks, leading to great uncertainties in the understanding of the mudstone compaction and a certain amount of error in the abnormal fluid pressure estimation when using the mudrock log-derived compaction curve. Therefore, it is necessary to recalibrate the mudstone compaction curve by eliminating the increment of the acoustic transit time caused by the kerogen content of organic-rich mudstones. Taking the southwest Ordos Basin as an example, this paper presents a new equivalent volume model based on the composition of organic-rich shale in which the kerogen content is also considered. Based on the quantitative relationship between the rock composition and the acoustic transit time, a quantitative formula for calculating the acoustic transit time increment caused by the kerogen is derived. This formula shows that the increment depends not only on the organic content but also on the occurrence state, pore size, pore fluid composition and other factors. X-ray diffraction (XRD) data were used to determine the main mineral composition of the mudstone and to calculate the acoustic transit time of the rock skeleton. Then, the mudstone compaction curve in the Zhenjing area was calibrated by combining the measured porosity and total organic carbon (TOC) of the mudstone based on the correction formula. The compaction characteristics varied significantly between before and after the calibration. The slope of the normal compaction trend (NCT) line decreased by 30–55%, and the acoustic transit time deviation from the NCT in the undercompaction interval decreased significantly. The overpressure at the maximum burial depth estimated by the equivalent depth method is in better agreement with the results obtained by numerical simulation after the calibration, and the porosity determined from the well log after the calibration is also closer to the true measured value. The method proposed in this paper is of great significance for improving the reliability and accuracy of compaction research on organic-rich mudstones, especially for the accurate estimation of abnormal pressure in the source rock layer. Additionally, it can be used as an effective reference for mudstone compaction studies in similar geological settings areas or basins.

1. Introduction

Mudstones and shales are the most common sedimentary rocks (Aplin et al., 1995, 2006; Bjørlykke and Høeg, 1997), and their

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* Corresponding author.
E-mail address: zhanglikuan@mail.iggcas.ac.cn (L. Zhang).

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deposits may act as sources, seals, and even reservoir (unconventional) layers for conventional and unconventional hydrocarbon resources. Investigations of shales and mudstones have become increasingly important in conventional and unconventional hydrocarbon exploration. Mudstones and shales have a great impact on the geophysical responses and fluid flow properties of subsurface strata (Mondol et al., 2007; Ramdhan and Goulty, 2011). Sediment compaction is an important phenomenon in sedimentary basins. In shallow and medium burial, changes in the physical and acoustic properties are mainly dominated by mechanical compaction. Mechanical compaction in response to the effective stress due to the overburden load of sediments and pore pressure variations in sedimentary basins causes a decrease in the porosity and an increase in the bulk density of sediments (Athy, 1930; Rubey, 1927; Burland, 1990; Osborne and Swarbrick, 1997).

Mechanical compaction may control the reduction of the porosity, influence the geometry and physical properties of sedimentary rocks, and play an especially important role in the generation of overpressures (Luo and Vasseur, 1992; Swarbrick and Osborne, 1998; Tingay et al., 2009; Nooraiepour et al., 2017). When mudstones and shales undergo rapid burial, overpressure is generated because the pore fluid cannot escape sufficiently rapidly through the low-permeability overburden for the pore pressure to remain in hydrostatic equilibrium. Consequently, the sediment retains greater porosity than it would have if the pore pressure were hydrostatic. This mechanism of overpressure generation is known as compaction disequilibrium, and it is one of the most commonly observed mechanisms of abnormal pressure generation in sedimentary basins (Luo and Vasseur, 1992; Goulty, 1998; Yang and Aplin, 2004; Tingay et al., 2009; Zhang, 2013; Sargent et al., 2016).

In the process of hydrocarbon exploration and development, overpressure generation, distribution and estimation are vitally important for reserve prediction and safe drilling. To accurately predict the pore pressure due to compaction disequilibrium, the compaction history and paleo-geometry must be established, and porosity versus depth curves have to be reconstructed. Athy (1930) proposed an exponential function that expresses the relationship between the shale porosity and depth of the normal compaction trend (NCT), or that under compaction-equilibrium conditions, and this function is currently the most commonly used of its type. Given the irreversibility of the compaction, the current statistical relationship between the porosity and depth may be approximately representative of the mudstone compaction history under similar depositional conditions (Magara, 1978). Data on the rock density or porosity acquired previously by laboratory measurements can now be easily obtained through the introduction of sonic and formation density logs. A large number of studies have confirmed that the acoustic transit time can effectively reflect the formation porosity. In consolidated clastic strata with uniformly distributed small pores, a good linear relationship exists between the porosity and acoustic time (Wyllie et al., 1958). In water-saturated and continuously deposited sand and shale formations, the relationship between the acoustic transit time and depth of normal compaction strata can also be expressed in a form similar to that of the relationship between the porosity and depth. The acoustic time-depth relationship is known to be approximately a straight line in a semilog coordinate system. When undercompaction occurs, and an overpressure is generated, the porosity or acoustic time is reversed and deviates from the NCT. In an undercompaction formation, the porosity/acoustic transit time and pore pressure are higher than those in a normally compacted section. Researchers have proposed various methods to predict the pressure from mudstone properties derived from well log data (acoustic transit time/velocity and resistivity), and among them, the equivalent depth method is the most widely used (Magara, 1978; Bowers, 2001; Luo et al., 2003; Gutierrez et al., 2006; Zhang, 2013).

The overpressure of source rocks plays a key role in hydrocarbon migration and accumulation (Magara, 1978). Therefore, it is important to study the overpressure generation and distribution in source rocks. The accuracy of the overpressure prediction from logging depends on the reliability and objectivity of the compaction curve. However, the acoustic transit time of mudstone is affected by many factors, such as the composition, pore fluid properties, and borehole conditions, and it does not always reflect the real mudstone compaction conditions. Different methods have been proposed to eliminate or reduce the impacts of these factors (Zhang et al., 2002; Luo et al., 2003). However, because the physical properties of kerogen may cause a high acoustic transit time (Passey et al., 1990), the anomalously high value of the acoustic time in organic-rich intervals often does not accurately reflect the variation of the mudstone porosity, and the existing methods cannot determine the degree of the effect of the kerogen on the acoustic time or whether obvious errors are introduced in the overpressure estimation (Kalani et al., 2015a). Previous studies did not consider the impact of organic matter during compaction; instead, all the high acoustic time anomalies were attributed to undercompaction, which introduced great uncertainty. Therefore, a quantitative method to calculate the acoustic time increment caused by organic matter is needed.

As one of the most prolific hydrocarbon source rocks in the Ordos Basin, the Zhangjiatan Shale in the Yanchang Formation was deposited in a fresh-brackish, sublittoral to profundal lacustrine environment (Zhang et al., 2008). It is 30–100 m thick and contains types I and II_1 organic matter, with an average total organic carbon (TOC) content of 6%–14%, and up to 30% (Wang et al., 2014). The shale reached its maximum burial depth of 3000 m in the late Early Cretaceous at 100 Ma, and the vitrinite reflectance (Ro) ranges from 0.7% to 1.3% (Wang et al., 2014). Zhangjiatan shale generally shows a high natural gamma (66–208 API), high natural potential (−35~-8 mV), high acoustic time (generally exceeding 250 μs/m) and high resistivity (7–323 Ω m). The porosity of the shale is mainly distributed in the range of 0.8–2%, which corresponds to an organic matter abundance of 0–10%, but the porosity of the shale reservoir does not obviously increase with the organic matter abundance (TOC). Thus, the organogenic pores that generally occur within organic matter are less abundant in most of the organic matter in Zhangjiatan Shale samples (Lei et al., 2015), because of their low thermal maturity, as indicated by the Ro values, which are commonly less than 1.3%. Due to its rapid burial in the Jurassic-Early Cretaceous, the Yanchang Formation reaches its maximum depth at the end of the Early Cretaceous, resulting in compaction disequilibrium. Hence, the paleo-pressure plays an important role in the primary migration of oil and gas (Yang et al., 2013).

In this article, we found that due to the unique physical properties of kerogen, organic-rich shales show abnormally high values of the acoustic time. To calculate the acoustic time increment caused by the organic matter, we modified the equivalent rock volume model and established non-source rock and source rock models based on whether organic matter is present in the source rock. Based on the principle of mudstone compaction and the Wyllie equation, a correction formula for the acoustic time increment caused by organic matter is derived. We apply this correction formula to the Zhenjing area, which is an important tight oil region located in the southwest of the Ordos Basin. Rock pyrolysis data, shale porosity test data and X-ray diffraction (XRD) data are used to obtain the key parameters and calculate the abnormal increment of the acoustic time caused by the kerogen. The reliability of the quantitative correction method is verified by the correlation between the calculated porosity and the measured porosity, the