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RESEARCH PAPER

Ternary analytic porosity-reduction model of sandstone compaction trend and its significance in petroleum geology: A case study of tight sandstones in Permian Lower Shihezi Formation of Shilijiahan area, Ordos Basin, China

XIA Lu[1, 2], LIU Zhen[1, 2, *], LI Weilian[1, 2], LU Chaojin[1, 2], YANG Xiaoguang[1, 2], LIU Mingjie[3]

1. State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China;
2. College of Geosciences, China University of Petroleum, Beijing 102249, China;
3. School of Geoscience and Technology, Southwest Petroleum University, Chengdu 610500, China

Abstract: The tight sandstones in the Permian Lower Shihezi Formation of Shilijiahan area in the Ordos Basin was taken as study object in this research to quantitatively determine the effects of burial depth, burial time and compaction strength on porosity during densification of reservoir. Firstly, sandstone compaction profiles were analyzed in detail. Secondly, the theoretical study was performed based on visco-elasto-plastic stress–strain model. Thirdly, multiple regression and iterative algorithm were used respectively to ascertain the variation trends of Young's modulus and equivalent viscosity coefficient with burial depth and burial time. Accordingly, the ternary analytic porosity-reduction model of sandstone compaction trend was established. Eventually, the reasonability of improved model was tested by comparing with thin-section statistics under microscope and the models in common use. The study shows that the new model can divide the porosity reduction into three parts, namely, elastic porosity loss, visco-plastic porosity loss and porosity loss from cementation. And the results calculated by the new model of litharenite in He 2 Member are close to the average value from the thin-section statistics on Houseknecht chart, which approximately reveals the relative magnitudes of compaction and cementation in the normal evolution trend of sandstone porosity. Furthermore, the model can more exactly depict the compaction trend of sandstone affected little by dissolution than previous compaction models, and evaluate sandstone compaction degree and its contribution to reservoir densification during different burial and uplift processes.

Key words: Ordos Basin; Permian Lower Shihezi Formation; compaction; Bingham model; Young's modulus; equivalent viscosity coefficient; tight sandstone

Introduction

With the rapid advancement of petroleum exploration, tight sandstone gas has become the new research focus[1]. According to the latest petroleum resources assessment in China, there exist abundant tight sandstone petroleum resources in the Ordos Basin, Sichuan Basin, and other basins[2]. The researches on densification of sandstone reservoirs can help reveal the forming process of tight reservoirs and deepen the accumulation mechanisms of tight sandstone oil and gas. Many factors can affect the development of pore space in sandstone, such as the burial depth, contents of quartz and plastic grains, grain size, sorting, rounding, early cementation, depositional setting, tectonic compression, abnormal overpressure, and burial history[3–5]. Moreover, many researches showed that compaction was closely related to burial time[6–9]. The porosity reduction process with the increase of burial depth can be expressed quantitatively by a mathematical equation. As early as the 1930s, Athy proposed an exponential relation between mudstone porosity and burial depth under the condition of normal compaction[10]. Athy's exponent equation was then used to describe the porosity evolution of sandstone. Afterwards, some researchers proposed several modified compaction models[11–13], but most of these models concentrated on the effect of burial depth. Later on, the binary-function model of burial time and burial depth was proposed[14], which has been accepted by and drawn attention

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*** Corresponding author.** E-mail: liuzhenjr@163.com
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from more and more researchers[15–18]. At present, the sandstone compaction models commonly used take burial depth and time into account. However, they do not look deeply into the variations of elastic modulus and viscosity coefficient in burial process and could not determine quantitatively the relative contributions of compaction and cementation to reservoir densification in different burial and uplift stages. The tight sandstone in the Permian Lower Shihezi Formation of Shilijiahan area in the Ordos Basin was taken as an example in this study. Based on previous study, we delved deeper into the variation trends of elastic modulus and viscosity coefficient during burial process and established the ternary analytic porosity-reduction model of sandstone compaction trend through sandstone compaction profile, theoretical model derivation and geological statistics. The new model could characterize more exactly the effect of burial process, including subsidence and uplift, on sandstone compaction degree. This study will promote the quantitative analysis of sandstone reservoir densification and improve the precision of tight sandstone reservoir evaluation to some extent.

1. Regional geology and research idea

The Shilijiahan area in the Ordos Basin lies to the south of the Boerjianghaizi fault (Fig. 1). The Permian is the main target formation of natural gas in this area, which can be divided into the Shanxi, Lower Shihezi, Upper Shihezi and Shiqianfeng formations. This study object is the Lower Shihezi Formation, including the He1, He2 and He3 members from bottom to top. Mainly made up of litharenite, the reservoirs are tight sandstone reservoirs[19]. According to porosity and permeability data measured on litharenite samples from the He1 Member in study area, most core samples have porosity of less than 10% and the absolute majority of sandstone samples have permeability of less than 1×10^{-3} μm^2 (Fig. 2).

The porosity reduction trend on the compaction profile can indicate compaction degree[20–21]. The corresponding relationships between sandstone porosity and burial depth and geological age were worked out first, and then sandstone compaction profiles in depth and time domains were drawn, respectively, to analyze single-well and multi-well compaction trends. Well J32 compaction profile was taken as a typical example to illustrate the sandstone compaction profile in single well (Fig. 3a). In this well, the burial depth, geological age and corresponding porosity on compaction trend profile of the Lower Shihezi Formation are respectively 2 800–2 900 m (Fig. 3a), 260–270 Ma (Fig. 3b) and 3%–5%. Furthermore, compaction data of Wells Jin7, Jin10 and Jin32 with abundant data was superimposed into one semi-log coordinate system (Fig. 4a). It can be seen from Figs. 3b and 4a that the single-well and multi-well compaction profiles in time domain basically show similar shape and trend, namely, their compaction tendency can be divided into three segments (Fig. 4b): Cretaceous sandstones (upper segment), Jurassic and Triassic sandstones (middle segment) and Permian sandstones (lower segment).

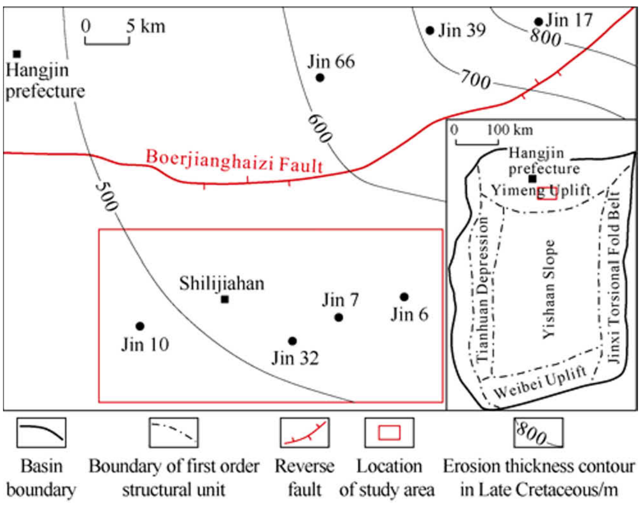

Fig. 1. Tectonic location of the study area.

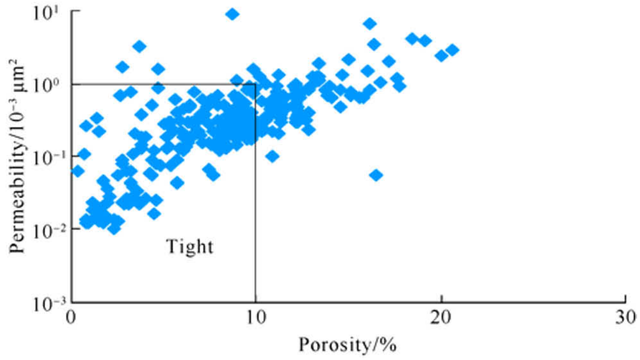

Fig. 2. Cross-plot of porosity and permeability from core measurements of the litharenites in the He1 Member.

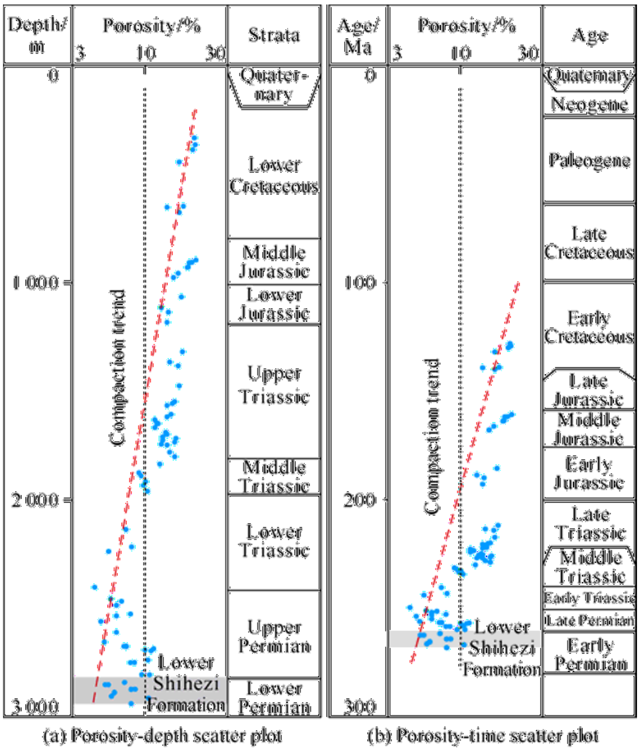

Fig. 3. Present-day sandstone compaction profiles of Well Jin 32.