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Editorial: Quantitative characterization and engineering application of pores and fractures of different scales in unconventional reservoirs—Volume II

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Editorial on the Research Topic
Quantitative characterization and engineering application of pores and fractures of different scales in unconventional reservoirs—Volume II

Introduction

With the depletion of conventional oil and gas resources in the world, unconventional oil and gas resources have become the focus and hotspot of exploration and development (Li et al., 2019; Yin et al., 2020a; Fan et al., 2020; Li, 2022a). In recent years, a series of unconventional oil and gas resources (e.g., tight sandstone gas, shale gas, coalbed methane, and gas hydrate) have been explored and developed in China, among which tight sandstone gas and shale gas have been commercially exploited (Wu et al., 2022; Xie et al., 2022). Tight sandstone gas is the earliest unconventional gas developed in China, which plays an important role in China's total natural gas reserves and production, with a total resource of about 17.4×10^{12}–25.1×10^{12} m^3, and its recoverable resource is about 8.8×10^{12}–12.1×10^{12} m^3 (Zou et al., 2018).

In the past decade, China has achieved significant exploration and development achievements in shale gas. Eight shale gas fields have been built in and around the Sichuan Basin (e.g., Fuling, Luzhou, Changning, Weiyuan, and Zhaotong). In 2021, China's shale gas production reached 230 $m^3 \times 10^8$ m^3, mainly from shale formations shallower than 3,500 m. Deep shale gas resources (more than 3,500 m) will be long-term exploration and development targets for more than 80% of the total resources (Li J. et al., 2022a). Both tight sandstone and shale reservoirs have the characteristics of ultra-low porosity and permeability, and shale reservoirs have the worst physical properties (Li J. et al., 2022b; Fan et al., 2022). Therefore, quantitatively characterization of such reservoirs' multi-scale pore and fracture characteristics is of profound significance for tight oil and gas.

This Research Topic is Volume II of a series "*Quantitative characterization and engineering application of pores and fractures of different scales in unconventional reservoirs*." The set of 39 studies in this Research Topic aimed to understand multiple methods for quantitative characterization of the pore and fracture systems, as well as provide a general framework for future research efforts.

Quantitative characterization of multi-scale pores in unconventional reservoirs

Tight sandstone reservoirs

The results of qualitative and quantitative characterization of multi-scale pores are abundant, and systematic theoretical methods and characterization techniques have been formed. Guo et al. (ID: 959796) take the Chang 6 Member of the Yanchang Formation in the Huaqing area of the Ordos Basin as an example. The pore-throat heterogeneity of tight sandstone reservoirs and its influence on the fluid occurrence state were studied using thin sections, scanning electron microscope (SEM), X-ray diffraction (XRD), constant velocity Mercury intrusion, and nuclear magnetic resonance (NMR) tests. Luan et al. (ID: 963316) take the Chang 8 Member of the Yanchang Formation in the Shuimogou area in the southern Ordos Basin as an example, the sedimentary facies types, microscopic pore structures, diagenesis, influencing factors of physical properties, and hydrocarbon enrichment of tight oil reservoirs were studied. Wang et al. (ID: 996167) take the Paleogene reservoirs in the Gaoshangpu area of the Nanpu saga as an example, it shows that compaction is the main cause of reservoir densification, argillaceous and calcareous cementation is the secondary cause, and later dissolution is another main cause of reservoir enhancement. Wei et al. (ID: 1011219) identified macro-micro characteristics of glutenite reservoirs in the Dinan 15 well area in the Junggar Basin and established criteria for identifying favorable reservoir studies. How to accurately predict hydrocarbon enrichment and high-yield areas in ultra-low permeability sandstone reservoirs is a hot spot in petroleum geology. Liao et al. (ID: 1013776) take the Chang 6 Member of the Yanchang Formation in the Huaqing area as an example, the analysis of dominant facies, lithologic assemblages and electrical properties formulated the evaluation criteria for hydrocarbon enrichment. Through observations under an optical microscope and SEM, casting thin sections, and plane porosity measurements, Yang et al. (ID: 1016973) investigated the diagenesis differences in the third member of the Shahejie Formation in the root and central portions of a fan deltan the eastern Laizhou Bay Sag. Evaluating tight oil reservoir properties is significant to exploring tight oil and gas. The reservoir characteristics of the Chang 1 Member in the Wanhua area and the effects of superimposed sand bodies, structures, and paleogeomorphology on hydrocarbon accumulation were studied by Ji et al. (ID: 1023844). Tan et al. (ID: 1028439) studied the controlling effect of source-reservoir assemblage on the gas accumulation in the Xujiahe Formation, and they think the type of source-reservoir combination mainly controls the development scale of natural gas, and the areas with close source-reservoir contact and high hydrocarbon generation intensity are high-quality reservoir development areas. Kuang and Liu (ID: 1033344) think the controlling factors of the petrophysical properties of the conglomerate reservoirs in the Baikouquan Formation in the northwestern margin of the Junggar Basin include sedimentation, diagenesis, and tectonic movements, while that of the sandstone reservoirs mainly include sedimentation and diagenesis. Si et al. (ID: 1042927) considered that compaction, calcite and siliceous cementation, and illite packing are primarily responsible for reservoir densification of the Gaotaizi oil layer in the Qijia area. Qiu et al. (ID: 1046489) evaluated the reservoir quality of tight oil sandstones in Chang 7 Member of Ordos Basin by NMR, clay mineral analysis, high-pressure Mercury injection analysis, and logging interpretation technology. Based on petrographic observations, micro–Raman spectroscopy, and fluorescent spectrometry, petroleum inclusions, CH_4-bearing inclusions, and CO_2-bearing inclusions were discovered in quartz-hosted minerals. Tang et al. (ID: 1059909) investigated two types of sandstone reservoirs with different pressure states and fluid evolution of the Shahejie Formation in the Western slope belt, Dongpu sag.

Shale reservoirs

Shale is a kind of fine-grained sedimentary rock denser than conventional sandstone and conglomerate reservoirs. The conventional reservoir characterization techniques are difficult to apply to shale. Multiple methods are generally used to realize the qualitative and quantitative characterization of shale pore characteristics (Li H. et al., 2022; Li J. et al., 2022a; Li J. et al., 2022b). Scholars have made extensive studies on marine, transitional and continental shales. Based on the results of high-pressure Mercury intrusion, low-pressure N_2, and CO_2 adsorption and organic geochemical experiments, XRD and SEM observations, Xiao et al. (ID: 981037) investigated the effects of organic and inorganic compositions on the development of pore structures of the Upper Permian Shanxi shale in the southern Yan'an area. Han et al. (ID: 981127) take the black shale from the Upper Ordovician and Lower Silurian in the Southern Sichuan Basin as an example, and discussed the effectiveness of shale pore detection by multiple methods. Peng et al. (ID: 985302) studied the geological conditions of shale gas accumulation in the marine-continental transitional facies sediments in the South North China Basin using sedimentary, logging, seismic, core, geochemical, physical property, and SEM data. Wang et al. (ID: 1012607) take the Chang 7 Member shale in the Yan'an area as an example, the results show that it has complete gas-generating conditions. Shale gas accumulation requires three necessary accumulation elements, i.e., gas source, reservoir, and good preservation conditions. Integrating SEM, NMR, LTNA, MICP experiments, and other basic measurements, Zhou et al. (ID: 1055541) studied the nano-scale pore category, structure, and corresponding controlling factors of Dongyuemiao lacustrine shale in the Eastern Sichuan Basin. The quartz has no significant effect on the formation of nano-scale pores. The intraparticle pores within calcite particles constitute part of mesopore-macropore but not micropores. Clay minerals are conducive to the formation of micropores but play a negative role in mesopore-macropores. The Lower Permian Shanxi Formation in the Eastern Ordos Basin is a set of transitional shale, Cai et al. (ID: 1061211) evaluated the pore fluid based on a series of NMR experiments, and they believe the total content of movable pores and bound pores in the Lower shale is the highest, while that in the Upper shale is lower. Zhang et al. (ID: 1052734) divided the lithofacies types of the Da'anzhai Member in the

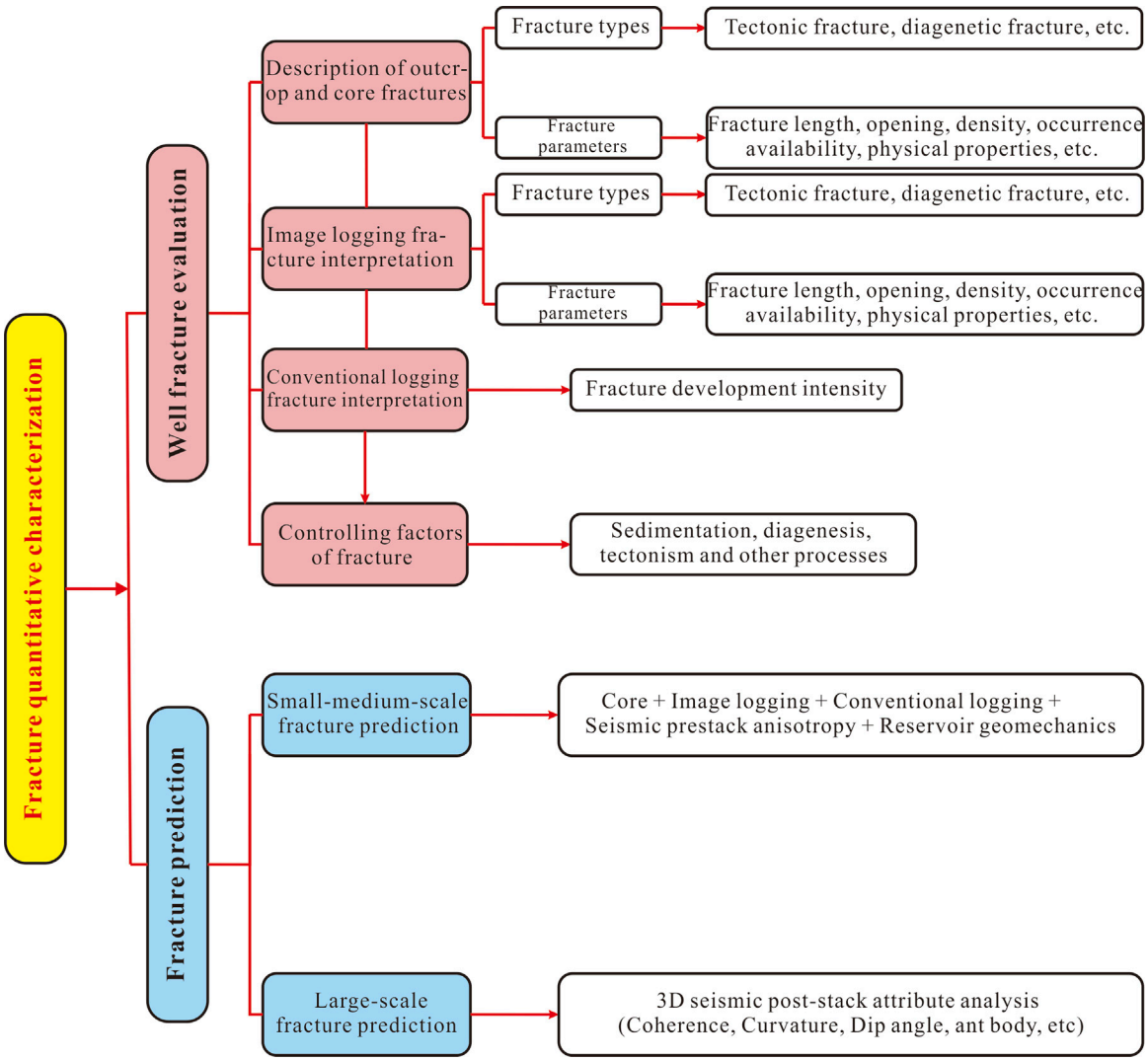

FIGURE 1
Characterization method of natural fracture (Lv et al., 2021; Li, 2022c).

Well Ren'an 1 into six types. The thick clay shale lithofacies have the highest TOC content and are mainly developed in the depositional environment of warm and humid, deep water, quiet, low salinity, and abundant terrigenous clasts.

In addition, there are also many researches related to volcanic and carbonate reservoirs. Fu et al. (ID: 983572) studied the relation of the "four properties" and fluid identification of the carboniferous weathering crust volcanic reservoir in the Shixi Oilfield. The cross-plot method determines lower limits of the reservoir's physical properties and oil saturation, yielding porosity >9%, permeability >.2 MD, and oil saturation >45%. Ren et al. (ID: 984463) studied the effects of diagenesis on the quality of deep dolomite reservoirs of the Upper Cambrian Xixiangchi Formation. Hu et al. (ID:1022911) believe that the key factors affecting hydrocarbon accumulation in the Xixiangchi Formation are sufficient oil and gas supply, development of inherited paleo-uplift, effective transportation system, and favorable reservoir-forming combination. Zhang et al. (ID:1015460) selected 11 carbonate samples from three deep reservoirs in Tarim Basin. The carbonate reservoir dissolution process was simulated using an advanced continuous flow reaction system at high temperature and high pressure. The dissolution rate of the dolomite reservoir has a trend of increasing and then decreasing under the deeply buried environment, which proves that there is an optimal dissolution range of dolomite in the deeply buried environment. Gu et al. (ID: 1041164) studied the effects of diagenesis on the quality of the Dengying Formation deep dolomite reservoir by the petrology, geochemistry, and *in situ* U-Pb dating. Qu et al. (ID: 1043148) also made quantitative characterization and origin of differences in pore parameter distribution of the Lower Cambrian Longwangmiao Formation in the Gaoshiti area of the central Sichuan Basin.

In general, since the pores of shale reservoirs are mainly nano-scale, the pore size is composed of nano- and micron-scale. Therefore, it is impossible to rely on a single method to characterize shale pores. Generally, the combination of multiple methods is used to achieve qualitative and quantitative characterization. Almost all of the above studies have adopted this method. In addition, it applies to shale

reservoirs and tight sandstone, carbonate, volcanic, and other tight reservoirs.

Quantitative characterization of multi-scale fractures in unconventional reservoirs

Natural fractures can improve the porosity of tight reservoirs and control the seepage system of such reservoirs. The fracture development is the key to the high and stable production of tight oil and gas (Yin et al., 2020b; Yin and Wu, 2020). However, they may also communicate with the upper strata, which is not conducive to preserving tight reservoirs. In recent years, quantitative characterization of natural fractures has been established based on the outcrop, core, multi-type thin sections, image/conventional logging, and seismic data (Figure 1) (Yin and Ding, 2019; Yin and Gao, 2019; Li et al., 2020; Li et al., 2021; Forstner and Laubach, 2022; Wang et al., 2021; Wang and Wang, 2021). According to this research method, scholars have done many studies.

The paleo-tectonic stress field controls tectonic fractures. Zhang et al. (ID: 1024748) used the finite element numerical simulation technology to analyze the distribution of the paleo-tectonic stress field of the Longmaxi Formation in the Lintanchang area. Then they predicted the fracture development areas under the superposition of two stages of tectonic stress. It is found that the comprehensive fracture coefficients of the anticline core and fault areas are both greater than 1.1, which are the areas with the most developed tectonic fractures, and these areas have poor shale gas preservation conditions. The shale is in a state of "breaking without cracking," and shale gas can be well preserved. The preservation of shale gas is closely related to tectonic fractures, the structural preservation conditions are the key factors in controlling the rich and integrated shale gas reservoirs in the Wuxi area of Chongqing City. Li et al. (ID: 1032597) found that there are three structural preservation modes of shale gas in the study area, i.e., lost destruction type, lost residual type, and trap preservation type. The trap preservation type is more conducive to the preservation of shale gas, which is the most favorable structural mode for shale gas exploration. Frackability is of great significance to shale gas development, Guo et al. (ID: 993829) take the Longmaxi Formation shale in the Changning and Luzhou Blocks in the southern Sichuan Basin as an example, and the Analytic Hierarchy Process (AHP) method was adopted to establish a comprehensive evaluation index of shale fracturability. The modulus brittleness index, mechanical brittleness index, *in-situ* stress difference coefficient, rock compressive strength, and TOC content are the most important evaluation indexs.

For the engineering application, Yang et al. (ID: 970719) carried out the experimental evaluation and numerical simulation research on the adaptability of CO_2 flooding in beach-bar sand reservoirs of the Shahejie Formation in the Dongying Sag. Yang et al. (ID: 1029309) also conducted indoor water flooding experiments after polymer gel injection using artificial cores, and a set of criteria for determining reservoir-matched polymer gel profile control agents was proposed. Liu et al. (ID: 1037532) put forward a coupled CFD-DEM method to simulate the particle plugging process of propagating fracture, and the effects of positive pressure difference, fracture roughness, particle concentration, and particle shape on the plugging mechanism were examined.

Among these 39 studies, we received a paper about the Lunpola Basin and the southern East China sea shelf. Zhang et al. (ID: 1034069) summarized the oil and gas accumulation conditions of the Lunpola Basin and pointed out the favorable zones with the most exploration potential. Wang et al. (ID: 1015832) analyzed the burial history of wells and simulation wells in SECS by the data of drilling, seismic, and source rocks. Moreover, favorable oil-gas accumulation modes in Lower-Middle Jurassic were proposed by combining them with studies on oil-gas accumulation elements and conditions.

Summary

In summary, the 39 high-quality papers on this Research Topic represent a step forward in understanding the quantitative characterization and engineering application of pores and fractures of different scales in unconventional reservoirs. We appreciate the opportunity to present this hot Research Topic and hope that readers will benefit from the breadth and scope of the research. More importantly, we hope these studies offer new directions for future research that will guide future scientific community efforts. Many researchers have contributed to the hot Research Topic, and we have applied for Volume III. We hope more scholars will be involved in the Research Topic, especially on the quantitative characterization of multi-scale fractures. It will offer new directions for future research that guide the quantitative characterization of multi-scale pores and fractures of unconventional reservoirs in the future.

Author contributions

HL, SY, and WD, edited the Research Topic of quantitative characterization and engineering application of pores and fractures of different scales in unconventional reservoirs—Volume II. HL and SY wrote and revised the manuscript.

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Conflict of interest

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