ISSN 2663-1563 Vol. 7, Issue 1: 23-28, DOI: 10.25236/AJAGE.2025.070104

A Review of Evaluation Methods for Heterogeneity in Tight Sandstone Reservoirs

Mengyao Ran[1,a,*], Ziyi Wang[2,b], Jianyu Yang[1,c], Kaiwen Nan[1,d]

[1]School of Petroleum Engineering and Environmental Engineering, Yan'an University, Yan'an, Shaanxi, China
[2]School of Physics and Electronic Information, Yan'an University, Yan'an, Shaanxi, China
[a]515374102@qq.com, [b]3526342237@qq.com, [c]42221910@qq.com, [d]2200457132@qq.com
[*]Corresponding author

Abstract: *Dense sandstone reservoirs, as one of the important unconventional oil and gas resources currently, exhibit particularly prominent heterogeneity characteristics, which have a profound impact on the efficiency and effectiveness of oil and gas exploration and development. This paper systematically reviews various evaluation methods for the heterogeneity of dense sandstone reservoirs. Specifically, it includes characterization methods for intra-layer heterogeneity, comparative analysis of inter-layer heterogeneity, spatial distribution patterns of planar heterogeneity, and fine delineation techniques for microscopic heterogeneity. These evaluation methods provide powerful tools for us to comprehensively understand the complexity of dense sandstone reservoirs. At the same time, this paper also delves into the various factors that influence reservoir heterogeneity, such as depositional environment, diagenesis, tectonic movements, and how these factors work together to shape the heterogeneous characteristics of dense sandstone reservoirs. Finally, this paper looks ahead to the future directions of research on the heterogeneity of dense sandstone reservoirs, aiming to provide more solid theoretical support and practical guidance for the precise evaluation and efficient development of dense sandstone reservoirs.*

Keywords: *Tight Sandstone Reservoir; Heterogeneity; Evaluation Method*

1. Introduction

Tight sandstone reservoirs are characterized by complex properties such as low porosity and low permeability, and exhibit significant heterogeneity, posing considerable challenges to oil and gas exploration and development. Heterogeneity not only affects the storage performance of the reservoir but also directly relates to hydrocarbon migration, accumulation, and development effectiveness. Therefore, accurate evaluation of heterogeneity in tight sandstone reservoirs is a critical aspect of oil and gas exploration and development. This paper reviews the evaluation methods for heterogeneity in tight sandstone reservoirs, aiming to provide a reference for researchers in related fields.

2. Concept and Classification of Heterogeneity in Tight Sandstone Reservoirs

2.1 Concept of Heterogeneity

Reservoir heterogeneity refers to the spatial variability of parameters that characterize the reservoir, which is a universal characteristic of reservoirs. In reservoir evaluation for development, reservoir heterogeneity not only involves the heterogeneity of the rocks that host fluids but also encompasses the heterogeneity of the properties and occurrences of the fluids present in the rock spaces [1].

2.2 Classification of Heterogeneity

Based on different research scales and objects, heterogeneity in tight sandstone reservoirs can be classified into four categories: intra-layer heterogeneity, inter-layer heterogeneity, planar heterogeneity, and microscopic heterogeneity. Intra-layer heterogeneity focuses on variations in lithology, physical properties, and oil-bearing characteristics within a single sand layer. Inter-layer heterogeneity refers to differences among sand layers within a sand layer group or oil layer group. Planar heterogeneity

ISSN 2663-1563 Vol. 7, Issue 1: 23-28, DOI: 10.25236/AJAGE.2025.070104

reflects changes in the geometric shape, size, porosity, and permeability of the reservoir across a plane. Microscopic heterogeneity involves the size, type, and distribution of pores and throats, pore structure characteristics, grain heterogeneity, and matrix heterogeneity [2-4].

3. Evaluation Methods for Heterogeneity in Tight Sandstone Reservoirs

3.1 Evaluation Methods for Intra-layer Heterogeneity

Intra-layer heterogeneity is an important component of heterogeneity in tight sandstone reservoirs [5, 6]. Its evaluation methods mainly include the following aspects:

(1) Grain Size and Grain Size Sequence Analysis

Grain size is a representation of the size of sediment particles, and its composition and distribution are controlled by factors such as sediment source supply, transportation conditions, depositional dynamics, and topography. In clastic rock reservoirs with weak diagenetic changes, the rhythmicity of grain size directly controls the rhythmicity of the permeability profile. Through grain size analysis, we can understand the characteristics of particle size, sorting, roundness, etc., within the reservoir, and then judge the degree of reservoir heterogeneity.

(2) Bedding Structure Analysis

Bedding types are controlled by depositional environments and flow conditions, and different bedding types have significant differences in permeability and ultimate recovery rates. Through bedding structure analysis, we can understand the development of bedding within the reservoir, such as parallel bedding, cross-bedding, etc., and then judge the characteristics of reservoir heterogeneity.

(3) Interbed Analysis

Interbeds refer to discontinuous non-permeable or low-permeability layers within the reservoir, which act as local barriers in fluid flow. The presence of interbeds can significantly affect the permeability of the reservoir. Through interbed analysis, we can understand the distribution, thickness, lithology, and other characteristics of interbeds within the reservoir, and then judge the degree of reservoir heterogeneity.

(4) Microfracture Analysis

In very tight reservoirs, a large number of microfractures are often present. The presence of microfractures can change the permeability of the reservoir and may even form cross-layers. Through microfracture analysis, we can understand the development of microfractures within the reservoir, including the density, orientation, length, and other characteristics of the fractures, and then judge the characteristics of reservoir heterogeneity.

(5) Permeability Variation Coefficient, Skewness Coefficient, and Range

The permeability variation coefficient, skewness coefficient, and range are important parameters for measuring intra-layer heterogeneity in reservoirs. By measuring the permeability at different locations within the reservoir and calculating these parameters, we can quantify the degree of reservoir heterogeneity. The variation coefficient reflects the degree of dispersion of permeability data, the skewness coefficient reflects the ratio of the maximum permeability to the average permeability, and the range reflects the ratio of the maximum permeability to the minimum permeability.

3.2 Evaluation Methods for Inter-layer Heterogeneity

Inter-layer heterogeneity refers to the differences between individual sand layers within a sand layer group or oil layer group [7, 8]. Its evaluation methods mainly include the following aspects:

(1) Analysis of Cyclic Stratigraphy

Cyclic stratigraphy reflects the variation patterns of reservoir layering. Through the analysis of cyclic stratigraphy, we can understand the development of reservoir layering and thus judge the characteristics of inter-layer heterogeneity in the reservoir.

(2) Stratigraphic Division Coefficient and Sandstone Proportion

The stratigraphic division coefficient and sandstone proportion are important parameters for

ISSN 2663-1563 Vol. 7, Issue 1: 23-28, DOI: 10.25236/AJAGE.2025.070104

measuring inter-layer heterogeneity in reservoirs. The stratigraphic division coefficient reflects the number of reservoir layers, while the sandstone proportion reflects the proportion of sandstone layers in the reservoir. By calculating these parameters, we can quantify the degree of inter-layer heterogeneity in the reservoir.

(3) Degree of Permeability Heterogeneity between Sand Layers

The degree of permeability heterogeneity between sand layers is a key indicator for measuring inter-layer heterogeneity in reservoirs. By measuring the permeability of different sand layers and calculating parameters such as the variation coefficient, skewness coefficient, and range, we can quantify the degree of inter-layer heterogeneity in the reservoir.

(4) Analysis of Inter-layer Barriers and Faults

Inter-layer barriers and faults have a significant impact on fluid flow in the reservoir. Through the analysis of inter-layer barriers and faults, we can understand the distribution, thickness, and nature of barriers and faults within the reservoir, and thus judge the degree of inter-layer heterogeneity in the reservoir.

3.3 Evaluation Methods for Planar Heterogeneity

Planar heterogeneity refers to the heterogeneity caused by variations in the geometric shape, size, porosity, and permeability of reservoirs across a plane. Its evaluation methods mainly include the following aspects:

(1) Analysis of Sand Body Geometry

Sand body geometry is an important indicator reflecting planar heterogeneity in reservoirs. By analyzing the geometry of sand bodies, we can understand the distribution, shape, and size of sand bodies within the reservoir, and thus judge the degree of planar heterogeneity in the reservoir.

(2) Analysis of Sand Body Distribution and Continuity

The distribution and continuity of sand bodies have a significant impact on fluid flow in the reservoir. By analyzing the connectivity, distribution direction, and aspect ratio of sand bodies within the reservoir, we can understand these characteristics and thus judge the degree of planar heterogeneity in the reservoir.

(3) Analysis of Physical Property Variations across the Plane

Variations in physical properties across the plane are direct indicators reflecting planar heterogeneity in reservoirs. By measuring porosity, permeability, and other physical parameters at different locations within the reservoir and plotting contour maps, we can intuitively understand the changes in reservoir properties across the plane and thus judge the degree of planar heterogeneity in the reservoir.

3.4 Evaluation Methods for Microscopic Heterogeneity

Microscopic heterogeneity is an important component of heterogeneity in tight sandstone reservoirs and directly affects the microscopic displacement efficiency of injected agents. Evaluation methods for microscopic heterogeneity mainly include the following aspects:

(1) Analysis of Pores and Throats

The size, type, and distribution of pores and throats are important indicators reflecting microscopic heterogeneity in reservoirs. By observing thin sections of the reservoir rocks and conducting mercury injection tests, we can understand the development of pores and throats within the reservoir and thus judge the degree of microscopic heterogeneity in the reservoir.

(2) Analysis of Grain Heterogeneity

Grain heterogeneity involves factors such as rock composition and arrangement. By conducting grain size analysis and observing with scanning electron microscopes, we can understand the composition, arrangement, and morphology of grains within the reservoir and thus judge the degree of microscopic heterogeneity in the reservoir.

(3) Analysis of Interstitial Material Heterogeneity

ISSN 2663-1563 Vol. 7, Issue 1: 23-28, DOI: 10.25236/AJAGE.2025.070104

Interstitial material heterogeneity involves factors such as the content and type of matrix and cement. By observing thin sections of the reservoir rocks and conducting X-ray diffraction analysis, we can understand the composition, content, and distribution of interstitial materials within the reservoir and thus judge the degree of microscopic heterogeneity in the reservoir.

(4) Quantitative Evaluation Methods for Microscopic Heterogeneity

In recent years, with advancements in experimental techniques and data analysis methods, quantitative evaluation methods for microscopic heterogeneity have gradually been applied. For example, some researchers have proposed a quantitative evaluation method for microscopic heterogeneity in tight sandstone reservoirs based on high-pressure mercury injection data and thin section observation data. By integrating existing evaluation methods through principal component analysis, they have proposed a more accurate method for quantitatively evaluating microscopic heterogeneity in tight sandstone reservoirs.

4. Factors Affecting the Heterogeneity of Tight Sandstone Reservoirs

4.1 Sedimentary Factors

Sedimentation is the foundation for the formation of reservoir heterogeneity. Factors such as the intensity and direction of water flow, the pale topography of the depositional area, the depth of the water basin, and differences in the supply of clastic materials can all influence the characteristics of sediment particles, such as their size, arrangement direction, bedding structure, and sand body geometry, thereby contributing to the heterogeneity of the reservoir [9, 10].

4.2 Diagenesis

Diagenesis is a key factor in altering the heterogeneity of reservoirs. Diagenetic processes such as compaction, pressure solution, cementation, and recrystallization can change the original distribution of porosity and permeability, increasing the degree of reservoir heterogeneity. For example, the spatial distribution of carbonate cements is one of the main controlling factors for the permeability distribution in reservoirs.

4.3 Structural Factors

Tectonic processes are one of the important factors contributing to the heterogeneity of reservoirs. Tectonic fractures can alter the direction of reservoir permeability, resulting in significant differences in permeability both vertically and horizontally. In addition, tectonic processes such as folding and faulting can also have an impact on the heterogeneity of reservoirs.

5. Application and Challenges of Evaluation Methods for Heterogeneity in Tight Sandstone Reservoirs

5.1 Application Example

Taking the Chang 6 oil reservoir formation in the Huaqing area of the Ordos Basin as an example, this reservoir is a tight sandstone reservoir formed by deep-water gravity flows, characterized by overall tightness and strong heterogeneity. Researchers conducted in-depth studies on the microscopic heterogeneity of this reservoir through experimental means such as grain size analysis, thin section examination, high-pressure mercury injection, and real sandstone two-phase flow models. The results indicate significant heterogeneity in the rock skeleton particles, diagenesis, and pore-throat structure of the reservoir. Based on these findings, researchers proposed targeted development strategies, providing strong support for efficient oilfield development.

5.2 Challenges Faced

Despite significant progress in evaluation methods for heterogeneity in tight sandstone reservoirs, numerous challenges remain. On the one hand, the formation mechanisms of reservoir heterogeneity are complex and diverse, involving the combined effects of sedimentation, diagenesis, tectonics, and other factors, which affects the accuracy and reliability of evaluation methods. On the other hand,

ISSN 2663-1563 Vol. 7, Issue 1: 23-28, DOI: 10.25236/AJAGE.2025.070104

existing evaluation methods mostly focus on single-scale studies at either the macro or micro level, lacking multi-scale comprehensive evaluation methods and technical means. Furthermore, with the continuous advancement of oil and gas exploration and development technologies and the deepening research on reservoir heterogeneity, higher requirements are being placed on the precision and efficiency of evaluation methods.

6. Future Research Directions and Prospects

6.1 Strengthen Research on Multi-scale Comprehensive Evaluation Methods

In response to the issue of existing evaluation methods mostly focusing on single-scale studies at either the macro or micro level, future efforts should strengthen research on multi-scale comprehensive evaluation methods. By combining various means and technical methods such as geology, geophysics, and geochemistry, a multi-scale comprehensive evaluation from the macro to the micro level can be achieved, improving the accuracy and reliability of evaluations.

6.2 Explore New Experimental Techniques and Data Analysis Methods

With the continuous advancement of experimental techniques and data analysis methods, future efforts should actively explore the application of new experimental techniques and data analysis methods in the evaluation of heterogeneity in tight sandstone reservoirs. For example, high-resolution CT scanning imaging technology can be used to intuitively understand the internal structure and pore distribution of the reservoir; machine learning algorithms can be used for rapid analysis and processing of large amounts of experimental data, improving the efficiency and accuracy of evaluations.

6.3 Strengthen Research on the Formation Mechanisms of Reservoir Heterogeneity

In response to the complex and diverse formation mechanisms of reservoir heterogeneity, future efforts should strengthen research on these mechanisms. By deeply analyzing the influence mechanisms and patterns of various factors such as sedimentation, diagenesis, and tectonics on reservoir heterogeneity, theoretical support can be provided for the improvement and refinement of evaluation methods.

6.4 Promote the Engineering Application of Reservoir Heterogeneity Evaluation Methods

Regarding the engineering application of reservoir heterogeneity evaluation methods, future efforts should actively promote their engineering application. By strengthening cooperation and exchange with oilfield enterprises, research findings can be converted into actual productivity, providing strong support for oil and gas exploration and development.

7. Conclusion

The research on evaluation methods for the heterogeneity of tight sandstone reservoirs is of great significance to oil and gas exploration and development. This paper reviews the concept, classification, and evaluation methods of tight sandstone reservoir heterogeneity, and discusses the factors influencing reservoir heterogeneity and future research directions. By summarizing existing research findings, it aims to provide a theoretical reference for the precise evaluation and development of tight sandstone reservoirs. Future research should focus on strengthening the study of multi-scale comprehensive evaluation methods, exploring new experimental techniques and data analysis methods, enhancing research on the formation mechanisms of reservoir heterogeneity, and promoting the engineering application of reservoir heterogeneity evaluation methods.

Acknowledgements

This work was supported by 2024 Shaanxi Provincial Undergraduate Innovation and Entrepreneurship Training Program(S202410719127), Shaanxi Provincial Department of Science and Technology 2024 Natural Science Basic Research Program Project (2024JC-YBQN-0347), Yan'an University Doctoral Research Initiation Project (YAU202303785).

ISSN 2663-1563 Vol. 7, Issue 1: 23-28, DOI: 10.25236/AJAGE.2025.070104

References

[1] Yuan Hongqi, Deng Xinyu, Du Huiyao, et al. Characterization methods for the heterogeneity of outcrop tight sandstone reservoirs in the Shanxi Formation, Permian, Liujiang Basin [J]. Petroleum and Natural Gas Geology, 2023, 44(02): 468-479.

[2] Zhang Qian. Quantitative characterization of strong heterogeneity in tight sandstone reservoirs in the Shan 234-Shan 235 wellblock [D]. Northwest University, 2019.

[3] Tian Jingchun, Liu Weiwei, Wang Feng, et al. Heterogeneity characteristics of tight sandstone reservoirs in the Upper Paleozoic of the Gaoqiao area, Ordos Basin [J]. Petroleum and Natural Gas Geology, 2014, 35(02): 183-189.

[4] Bai Yunyun, Shi Yangyang. Heterogeneity characteristics of tight gas reservoirs in the He-8 upper submember of the Su 48 block, Sulige Gas Field [J]. Journal of Yulin University, 2022, 32(06): 12-17.

[5] Yue Liang, Meng Qingqiang, Liu Ziliang, et al. Physical properties and heterogeneity characteristics of tight sandstone reservoirs: A case study of the sixth member of the Xujiahe Formation in the Guang'an area, central Sichuan Basin [J]. Petroleum and Natural Gas Geology, 2022, 43(03): 597-609.

[6] Lv Tianxue, Zhang Guoyi. Research on quantitative characterization methods for micro-pore heterogeneity in tight sandstone gas reservoirs [C]. Exploration and Development Research Institute, Jilin Oilfield Company, 2020: 6.

[7] Long Shengfang, Wang Yushan, Li Guoliang, et al. Heterogeneity characteristics of tight reservoirs in the lower submember of He-8 in the Su 49 block, Sulige Gas Field [J]. Lithologic Reservoirs, 2021, 33(02): 59-69.

[8] Ma Liyuan, Hu Caizhi, Qiu Guiqiang, et al. Reservoir heterogeneity and structural patterns of the Chang 8 member in the Zhenjing area, Ordos Basin [J]. Acta Sedimentologica Sinica, 2020, 38(05): 1088-1098.

[9] He Tuoping. Evaluation of reservoir heterogeneity in the Chang 63 tight sandstone of the Huaqing area [D]. Xi'an Shiyou University, 2020.

[10] Chen Chaobing, Chen Xinjing, Wang Chao, et al. Analysis of factors influencing the heterogeneity of tight sandstone reservoirs [J]. Groundwater, 2020, 42(05): 152-154.