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A Review of Methods for Studying Reservoir Heterogeneity

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Abstract: Reservoir heterogeneity is an important influencing factor that affects the development effect of oil and gas reservoirs and improves the recovery rate. In recent years, the research methods and techniques of reservoir heterogeneity have made remarkable progress. The definition and development status of reservoir heterogeneity are systematically elaborated through literature research, and it is believed that reservoir heterogeneity is mainly researched from the aspects of macro and micro heterogeneity at present. Combined with the current research hot spots, the paper focuses on the principles and application examples of field outcrop profiling, high-resolution sequence stratigraphy, non-homogeneous composite index method, reservoir flow unit method, experimental data analysis and Lorentz curves, and reservoir geologic modeling, etc., and summarizes the main factors affecting reservoir non-homogeneity. This paper aims to deepen the understanding of reservoir non-homogeneity research and further provide theoretical reference and technical support for oil and gas reservoir development.

Keywords: Reservoir heterogeneity; oil reservoir; heterogeneity characterization.

1. Introduction

Reservoir heterogeneity refers to the uneven changes in spatial distribution and internal structure of reservoirs under the combined influence of depositional environment, diagenesis and late tectonic effects[1]. As an important component reflecting the reservoir storage performance, reservoir heterogeneity has been the focus of attention of scholars in the field of oil and gas field research at home and abroad. Reservoir heterogeneity can reflect the seepage characteristics of oil reservoirs, and it is an important geological factor to solve the contradiction of oil field development, improve the effect of water drive, and affect the distribution of oil reservoirs and hydrocarbon storage capacity.

This paper summarizes the research status and classification of reservoir heterogeneity through a large amount of literature research, summarizes the research methods of reservoir heterogeneity from different aspects to quantitatively characterize the reservoir heterogeneity, and analyzes the influencing factors of reservoir heterogeneity, in order to provide a geological basis for the rational development and utilization of hydrocarbons.

2. Research Status at Home and Abroad

The research of reservoir non-homogeneity originated in the 1970s~80s, and since its introduction, the research on reservoir non-homogeneity at home and abroad has formed a relatively mature theory and technology, and the research content and field are also expanding. Scholars mainly study reservoir heterogeneity in terms of the characterization method of reservoir heterogeneity, the main controlling factors of heterogeneity and their influence on oil and gas distribution. Overseas research on reservoir heterogeneity mainly covers: exploring the physical characteristics of reservoir pore permeability and its influence on reservoir seepage law according to different experimental means; using field outcrop data to conduct geological modeling and simulation research to quantitatively analyze reservoir heterogeneity. Domestic scholars believe that reservoir heterogeneity is the basis of the fluid properties and production characteristics inside the rock space, which directly affects the fluid distribution, flow characteristics and reservoir recovery effect in the reservoir. The research is usually guided by the theoretical basis of sedimentary petrology and reservoir geology, and the non-homogeneity of the reservoir is evaluated qualitatively and quantitatively through the study of sedimentation and diagenesis, combined with the physical analysis of the core and the permeability of the logging fine interpretation.

With the deepening of oil and gas reservoir theory and the needs of oilfield production, the study of reservoir heterogeneity has been developed to the impact on residual oil distribution and oil and gas reservoirs, and the research field has been gradually expanded from conventional reservoirs, such as carbonates and deltas, to unconventional oil and gas reservoirs, such as shale gas[2].

3. Types of Reservoir Non-homogeneity

At the early stage of research, the reservoir heterogeneity has not yet formed a unified understanding, and there are many classification schemes; Pettijohn et al. (1973), in the study of fluvial sedimentary reservoirs, for the first time put forward the hierarchy and classification of the study of reservoir heterogeneity, according to the size of the reservoir heterogeneity is divided into five kinds of reservoir group scale, interlayer scale, intralayer scale, core scale and sheet scale; Weber (1986) put forward a system that can be used to quantitatively study reservoir heterogeneity in the development and evaluation of oil fields. Weber (1986) proposed a system to quantitatively study reservoir non-homogeneity in oilfield development and evaluation, and increased the influence of tectonic features and the distribution of interlayer and the nature of crude oil on reservoir non-homogeneity; China's oil and gas reservoirs are diverse in genesis and have large changes in physical properties, with complex distribution of various types of reservoirs, rapid changes in the sands, and extremely strong reservoir non-homogeneity. Qiu Yinan (1987, 1989, 1992), on the basis of considering the scale of reservoir non-homogeneity and the actual development of production, divided reservoir non-homogeneity into four categories: interlayer non-homogeneity, inter-layer non-homogeneity, planar non-homogeneity and microscopic non-homogeneity (pore space, particles and filler), and at present, the main method of research on reservoir non-homogeneity is the classification method of Qiu Yinan[3].

Intralayer heterogeneity refers to the vertical change of reservoir properties within a single sand layer. interlayer non-homogeneity is mainly studied through the characteristics of interlayer particle size rhythm, permeability difference, discontinuous mud sandwich, calcium sandwich and physical sandwich size.

Interlayer heterogeneity refers to the regularity of the cross occurrence of sand bodies from various depositional environments in the longitudinal direction, as well as the development and distribution of compartments in the profile. Interlayer heterogeneity is commonly described by parameters such as layering coefficient, sandstone density, compartment distribution, and intercalation density.

Planar non-homogeneity refers to the non-homogeneity of the sand body in the plane and the non-homogeneity caused by the planar change of the physical properties of the reservoir. It is mainly applied to analyze the reservoir heterogeneity by the geometrical form, connectivity and thickness variation of the sand body, as well as the distribution law of porosity and permeability on the plane[4].

Micro non-homogeneity refers to the geologic factors affecting fluid flow in the reservoir's microscopic pore throats, including the degree of uniformity of the reservoir's rock pores and throats, as well as the configuration relationship between pores and throats. Usually, the study of reservoir heterogeneity is carried out based on the distribution of reservoir fillings and the connectivity coefficients, pore throat sizes, and structural parameters that characterize the pore throats in the piezomercury curves.

4. Research Methods of Reservoir Non-homogeneity

The geological problems of oil and gas field exploration and development are becoming more and more complicated, and in the technical background of geological modeling, geostatistics and high-resolution sequence stratigraphy, the research methods of reservoir heterogeneity are gradually diversified from qualitative description to quantitative analysis, with a clearer purpose.

4.1. Field outcrop profile study

Previous studies have shown that field outcrop profile study of reservoirs has the advantages of intuition, completeness, accuracy and verifiability, and can reveal important reservoir characteristics such as the size, geometry, internal structure and potential connectivity of the reservoir[5]. Field outcrop profile study is to find typical outcrop profiles according to the target layer in the study area, compare and divide the stratigraphy, describe the sedimentary phases in detail, and take intensive samples and profiles for actual measurement. Yuan Hongqi et al. (2023), in their study of the Permian Shanxi Formation in the Liujiang Basin, first carried out intensive sampling in the field outcrop area, analyzed the samples by using indoor testing methods such as thin-section identification, and on this basis conducted an all-around study of the depositional phases, reservoir lithology and pore characteristics, physical characteristics and diagenesis, etc., and used the Lorenz coefficient and the hierarchical analysis method, taking into account the factors of the mineral components and cementation types, to multiparameter Lorentz factor and hierarchical analysis are used to consider factors such as mineral components and cementation type, and multi-parameter characterization of reservoir heterogeneity is established to predict underground reservoirs[6].

4.2. High-resolution sequence stratigraphy methodology

High-resolution sequence stratigraphy was proposed by T. A. Cross, which mainly applies the principle of sedimentary dynamics to analyze the datum rotation and its characteristics, and can establish a fine sequence stratigraphic grid. This grid can effectively delineate the sedimentary units of the reservoir and reveal the inhomogeneous characteristics of the reservoir. Changes in the datum gyre directly affect the sediment supply and distribution pattern, thus controlling the heterogeneity of the reservoir.

High-resolution sequence stratigraphy methods have some applications in characterizing the macro- and micro-heterogeneity of reservoirs. Liuni et al. (2017) applied the principle of high-resolution stratigraphy to establish a high-precision stratigraphic lattice frame, determined the datum cyclotomy structure and its characteristics, and analyzed the correspondence between various types of datum cyclotomies and non-homogeneity, and concluded that the change in sediment supply caused by the structure of the datum cyclotomies and their accommodable space is a determining factor for the degree of reservoir non-homogeneity[7]; Hongwei Liang et al. (2013) extended the application of high-resolution sequence stratigraphy methods in the study of reservoir heterogeneity by analyzing the effects of different levels of datum rotations on reservoir microhomogeneity[8].

4.3. Non-homogeneous composite index method

The traditional non-homogeneity characterization method considers permeability as the main influencing parameter, and describes the degree of non-homogeneity of the reservoir based on quantitative parameters such as permeability grain size law, coefficient of variation, coefficient of sudden advancement, permeability gradient, and homogeneity coefficient. However, in some special reservoirs (e.g., tight reservoirs), the permeability of tight reservoirs is generally lower, and the degree of discrete is lower than that of high-porosity and high-permeability reservoirs. Describing reservoir heterogeneity from a single perspective will affect the accuracy of the understanding of heterogeneity. Selecting multiple parameters to comprehensively evaluate the heterogeneity results will be more objective and accurate, which is a more ideal method to study the heterogeneity of reservoirs.

Previous studies have shown that the comprehensive index method of non-homogeneity is to extract and process the required parameters on the basis of clear stratigraphic distribution. The research idea of this method mainly includes: stratigraphic division of oil formation group; logging interpretation of reservoir quadratic characteristics and statistics of the mean value of sand thickness, pore penetration, mud content and other parameters of each small layer; determining the formation parameters of reservoir non-homogeneity by principal component analysis; homogenization of each parameter and determining the weight of the parameter by using the coefficient of variation method, wave stacking and entropy weighting method; determining the type of reservoir and its planar distribution; and applying the method of heterogeneity composite index to the formation. It is of great significance to determine the development plan, improve the oil and gas recovery rate, oil production capacity and study the characteristics of residual oil distribution by using the non-homogeneous comprehensive index method [9][10].

4.4. Reservoir flow unit method

Reservoir flow unit refers to a longitudinally and horizontally continuous reservoir zone with similar internal permeability, porosity and stratification characteristics. Flow unit can effectively divide the type of reservoir heterogeneity, deepen the degree of reservoir heterogeneity research, improve the accuracy of permeability interpretation, and provide the basis for the deployment of oil and gas exploration in inhomogeneous reservoirs. Scholars at home and abroad have been studying reservoir heterogeneity for nearly 40 years, and their research methods and contents are constantly updated and expanded.

The research on the delineation of flow units is based on the fine anatomy of reservoir configuration and combined with 3D reservoir modeling, numerical simulation of reservoirs, and residual oil distribution model. At present, the methods of flow unit delineation can be divided into two categories: one is to establish reservoir structure and seepage barrier model through geological research, and combine the spatial spreading of sedimentary micro-phase, intercalation, porosity, permeability, fracture, pore-throat structure and other geological factors to delineate the flow unit of the formation group, such as the FZI (Flow Stratification Index) method, the pore-throat radius WinlandR35 value method, etc.[11]; and the other is the method of production dynamics One method is the production dynamic method, which divides the flow unit in the oil field area based on various types of data in the middle and late stages of oil and gas field development and regional faults and compartments, and adopts two methods, namely, the actual inter-well flow rate data of the production well group and the petrophysical properties of the reservoirs of the two wells to obtain the IFCI index, and thus divides the flow unit.

4.5. Experimental data analysis method

Reservoir heterogeneity has a significant impact on fluid flow, especially in fractured reservoirs and carbonate reservoirs. Reservoir micro- heterogeneity is an important way to study the distribution of residual oil and the effect of water-driven oil, and the reservoir micro- heterogeneity is characterized by the experimental data analysis method to clarify the nonhomogeneous genesis of the reservoir.

Experimental data analysis refers to the comprehensive use of cast thin section and scanning electron microscope data to study the petrological characteristics of the reservoir, the composition of the filler, the characteristics of the cement and the pore type, etc.; the pore structure of the reservoir refers to the size of the rock pore, the width of the throat and the fracture, which can accurately and comprehensively reflect the reservoir's storage performance[12]. Commonly used mercury pressure experimental method to study reservoir storage performance, pore throat structure characteristic parameters include reservoir discharge pressure, median pressure, median radius of the pore throat, sorting coefficient, coefficient of variation, maximum mercury saturation and mercury withdrawal efficiency.

4.6. Lorenz Curve Method

The Lorenz curve distribution theory is an important analytical method in the field of economics, which was firstly put forward by the economist Gini to describe the unbalanced situation of income or wealth distribution. The Gini coefficient, a numerical index calculated from the Lorenz curve, is often used to describe the phenomenon of uneven distribution, etc. Schmalz first applied the Lorenz curve to the field of petroleum geology in 1950[13].

The conventional coefficient of variation method can only reflect the degree of deviation of permeability, while the Lorenz curve can effectively characterize the degree of homogenization of the parameter as a whole. The calculation steps of Lorenz curve in the evaluation of reservoir heterogeneity are as follows: arrange the permeability values obtained from the physical analysis of the core in the order from smallest to largest, calculate the cumulative percentage of the permeability contribution value and the cumulative percentage of the number of samples, and then plot the corresponding Lorenz curve in the right-angled coordinate system[14]. If the Lorenz curve is a straight line with slope equal to 1, the reservoir is considered to be completely homogeneous; the larger the deviation of the Lorenz curve from the diagonal (i.e., the completely uniform distribution line), the more serious the non-homogeneity of the reservoir is; the value range is from 0 to 1, the closer the value is to 0 means the more uniform the distribution, and the closer the value is to 1 means the more inhomogeneous the distribution.

Lorentz curve is widely used in reservoir evaluation, not only limited to the analysis of permeability distribution, according to the same method to analyze the porosity, oil saturation and other reservoir parameters of homogeneity evaluation. In the process of water-driven oil recovery, by analyzing the permeability distribution of the reservoir, the efficiency of water injection and drive can be predicted and the water injection scheme can be optimized. Reservoirs with poor homogeneity are often prone to form non-homogeneous flow channels, leading to the phenomenon of water runoff, which reduces the recovery rate. Compared with traditional methods, Lorentz curve can reflect the distribution characteristics of reservoir parameters more intuitively and comprehensively, providing an important basis for reservoir evaluation and development.

4.7. Reservoir geological modeling method

Reservoir geological modeling can more comprehensively reflect the internal spatial development characteristics of the reservoir, fine characterization of hydrocarbons and the portrayal of non-homogeneity at all levels. According to the results of previous research, reservoir geological modeling can be divided into the establishment of stratigraphic grid and geological knowledge base, petrophysical response characterization, variance function analysis, three-dimensional geological modeling and other steps.

Different scholars have proposed different modeling methods according to different geological body levels and reservoir target parameters. He Wenjun et al. (2017) used sedimentary microphase and rock phase to establish a joint phase modeling method, reflecting the development characteristics of reservoir compartmentalization and frequent horizontal and vertical changes of the sand body[15]; Cao Peng et al. (2018) synthesized the characteristics of field outcrop profiles, single wells and inter-wells, clarified the main controlling factors of reservoir heterogeneity in the study area, and established a geological and numerical model of the reservoir on this basis, identifying the characteristics of the spatial distribution of the reservoir and quantifying the The distribution law of residual oil[16]; Tang Yanshuai et al. (2021) selected sequential simulation method to establish petrographic model and physical property model for the strong heterogeneity of reservoir in the study area, and used the modeling results of geological modeling constraints to validate the actual development of the oilfield[17]; the continuous development of the research of geological modeling of the reservoir will provide an effective guide to improve the accuracy of the assessment of the reservoir resources and the subsequent development of the oilfield and simulation of predicted production.

5. Influencing Factors of Reservoir Heterogeneity

Previous studies have shown that the key factors affecting reservoir heterogeneity are tectonic evolution, sedimentation and reservoir diagenesis, which are the internal factors affecting oilfield development. The combined effect of reservoir non-homogeneity and development factors is the key to influence the distribution of residual oil.

Tectonic evolution refers to the influence of faults and fractures on non-homogeneity, which mainly changes the connectivity and fluid distribution of the reservoir through fracture and folding. Tectonic stress and the longitudinal and transverse distribution of sand bodies have a strong influence on the formation and development of fractures, thus changing the reservoir planar heterogeneity.

There is a close connection between sedimentation and reservoir heterogeneity, which largely determines the compositional components of sediments and the structural characteristics of reservoir rocks. In addition, sedimentation also influences the development of sand bodies in the reservoir as well as the type and intensity of diagenesis, which is the basis for the non-homogeneity of the reservoir. Due to the different hydrodynamic conditions in different sedimentary zones, it will lead to the reservoir showing certain differences in rock mineral characteristics and physical properties. Wei Xian et al. (2024), in their study of the factors controlling reservoir heterogeneity in the Pearl River Formation of the Liuhua D oilfield, concluded that sedimentary microphases with strong hydrodynamics, such as submerged diversion channels and estuarine dams, have weak reservoir heterogeneity, and that gray sandstone and tuff deposited in the course of the sea level rise form compartments with a regional isolation effect, and the reservoir heterogeneity is strong[18].

The diagenetic effects controlling the heterogeneity of the reservoir mainly include mechanical compaction, cementation and dissolution, and the different diagenetic effects of the reservoir rocks are judged by scanning electron microscope photographs. Zou Min et al. (2022), in their study of dense sandstone reservoirs in the long 8 section of the Extension Formation in the Honghe Oilfield, concluded that reservoir heterogeneity is affected by factors such as sedimentation, diagenesis, and tectonics in the transforming effect, and diagenesis is the main factor leading to reservoir heterogeneity in the study area[19].

6. Conclusion

Reservoir non-homogeneity is the result of the combination of multiple factors, and the superposition of various factors makes reservoir non-homogeneity have the complex characteristics of multi-scale and multi-type. The study of reservoir non-homogeneity mainly includes the evaluation of reservoir non-homogeneity, the main controlling factors of reservoir non-homogeneity, and the impact of reservoir non-homogeneity on oilfield development. Domestic research on reservoir heterogeneity mainly focuses on four aspects: interlayer, inter-layer, planar and microscopic heterogeneity.

The research methods of reservoir non-homogeneity are becoming more and more diversified, and the research content is gradually changing from qualitative description to quantitative analysis. Combining field outcrop section research, high-resolution stratigraphy, non-homogeneity comprehensive index method, reservoir flow unit method, experimental data analysis, Lorentz curve method, and reservoir geologic modeling, etc., we can realize fine characterization of reservoir non-homogeneity and in-depth analysis of the main controlling factors, which provides theoretical basis for rational development of reservoirs and provides theoretical basis for rational development of reservoirs. It provides theoretical basis and technical support for the rational development of oil and gas reservoirs.

The future development direction of reservoir non-homogeneity mainly includes multi-scale comprehensive characterization of reservoir non-homogeneity, the influence mechanism of non-homogeneity on multiphase flow and residual oil, the use of machine learning and artificial intelligence to predict reservoir non-homogeneity, and the research on the influence of non-homogeneity in complex reservoirs on the development dynamics. With the continuous improvement and innovation of research methods, the study of reservoir non-homogeneity will be more in-depth and refined, providing a strong guarantee for the efficient development of oil and gas fields.

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