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Summary of Research and Development of Reservoir Pore Structure

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Abstract

As an important index of rock internal space characteristics, reservoir pore structure directly affects oil and gas storage capacity and seepage efficiency, and is a key factor in the exploration and development of unconventional oil and gas resources such as shale gas and tight oil. In recent years, with the advancement of unconventional oil and gas exploration to deep and ultra-deep layers, the study of reservoir pore structure has shown a development trend from qualitative analysis to quantitative characterization, from two-dimensional observation to three-dimensional reconstruction, and from single-technology characterization to full-aperture joint characterization. This paper systematically reviews the content evolution of reservoir pore structure research, the development of characterization technology, joint characterization methods and the research focus of different reservoirs, analyzes the existing problems and looks forward to the future research direction, in order to provide theoretical reference for reservoir evaluation and efficient development.

Keywords

Reservoir Pore Structure; Shale; Tight Sandstone; Carbonate Rock; Full Aperture Characterization; Three-Dimensional Reconstruction.

1. Introduction

Reservoir pore structure refers to the geometry, size, distribution and connectivity of pores and throats of rocks, which is the core element to describe the internal spatial characteristics of reservoirs. In the field of oil and gas exploration and development, the pore structure directly determines the reservoir capacity and seepage efficiency of the reservoir, which is particularly critical for the exploration breakthrough and efficient development of unconventional oil and gas resources such as shale gas and tight oil. It can not only guide the screening and prediction of reservoir 's ' dessert area ', but also provide microscopic basis for the optimization of development plan (such as fracturing parameter design, water injection development adjustment), and then enhance oil and gas recovery.

At present, with the advancement of unconventional oil and gas exploration and development to deep and ultra-deep layers, the study of reservoir pore structure has expanded from traditional conventional reservoirs to complex reservoirs such as shale and tight sandstone dominated by nanopores. The research technology has developed from a single qualitative observation to a multi-method collaborative quantitative-three-dimensional-full aperture characterization system. Based on the existing research results, this paper systematically combs the content evolution, technical development, joint characterization application and different reservoir research focuses of reservoir pore structure research, analyzes the existing problems and looks forward to the future trend, so as to provide reference for subsequent reservoir evaluation and development.

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2. Evolution of Reservoir Pore Structure Research Content

2.1. Basic Cause Analysis Stage

The study of early reservoir pore structure focuses on qualitative genetic analysis, focusing on the control of sedimentary environment and diagenesis on pore development. For example, Luo Yueming et al.pointed out that compaction and cementation are the main factors to destroy primary pores, and dissolution can form secondary dissolution pores and improve reservoir pore space through the study of Upper Paleozoic reservoirs in Daniudi Gas Field, Ordos Basin. Fan Aiping et al.proposed that sedimentation (controlling rock grain size and sorting) and diagenesis (clay mineral cementation, quartz overgrowth) jointly determine the pore structure basis of low porosity and low permeability reservoirs for the reservoirs of Shan 1 and He 8 in the East 2 area of Sulige gas field.

With the deepening of research, the influence of mineral composition and organic matter characteristics on pore genesis has been further revealed. In the study of organic-rich shale, Cao Yan et al.pointed out that type I kerogen has much higher organic pore development potential than type III kerogen due to its strong hydrocarbon generation ability. Brittle minerals such as quartz and pyrite can resist compaction and provide support for pore preservation. Clay minerals are easy to expand and deform, which is easy to block the throat.Liu Shugen [7]et al.also found that the overpressure environment can offset the mechanical compaction of the overlying strata and delay the collapse of micropores (< 2nm), which has become a key factor in the preservation of deep shale pores.

2.2. Quantitative Characterization and Classification Evaluation Stage

The traditional quantitative characterization takes the basic parameters such as porosity, permeability and pore throat median radius as the core, and divides the pore structure types by mercury injection curve and physical property experiment. For example, in the study of volcanic reservoirs in Songliao Basin, based on porosity (2% -14.4%), permeability (0.01× 10^3μm 2-1.35 ×10^3μm 2) and median radius of pore throat (0.016μm-0.299μm), Chen et al[1].divided the pore structure of reservoirs into class I-IV, among which class I reservoirs (porosity > 10.5 %, median pore throat > 0.16μm) have the best reservoir performance.

In recent years, quantitative parameters have been refined and multi-dimensionally expanded, and parameters such as fractal dimension, pore-throat ratio, and connectivity have been widely used. Wang He et al[5].analyzed the pore structure of tight sandstone by fractal dimension, and found that the larger the fractal dimension, the higher the roughness of the pore surface, the more uneven the distribution, and the greater the fluid seepage resistance. Qi Nan et al[2] used constant-rate mercury injection technique to distinguish pores and throats, and obtained the frequency distribution of pore-throat radius ratio. They pointed out that the pore-throat ratio is 62.5μm, >100×10^3μm^2), micropore low permeability reservoir (1-62.5μm, 1-100×10^3μm^2), nanopore ultra-low permeability reservoir (< 1μm,< 1×10^3μm^2） Provide a basis for targeted characterization.

2.3. Multi-dimensional Correlation Research Stage

The correlation between pore structure and fluid activity has become the focus of research. Taking the tight sandstone of the fourth member of Quantou Formation in Xinmiao Oilfield of Songliao Basin as an example, Ma et al[16]., through nuclear magnetic resonance (NMR) T2 spectrum analysis, found that the movable fluid saturation was positively correlated with the pore throat radius, and the movable fluid saturation was significantly improved when the pore throat median was greater than 0.1μm. Ren Shuyue[17] pointed out that throat sorting (coefficient of variation <0.5) is the key to control gas seepage efficiency in the study of He 8

reservoir in the west of Sulige. The better the sorting, the higher the permeability contribution rate.

The mutual feedback relationship between pore structure and development response is also gradually clear. Taking Gaosheng Oilfield in Liaohe Oilfield as an example, Tang Hongming et al.found that steam flooding development will lead to the increase of reservoir porosity but the decrease of throat radius, which will enhance the heterogeneity of pore throat. Wang Jingyao et al[10].found that the long-term effect of CO_2 and rock can increase the porosity, but the proportion of small pores increases. It is necessary to optimize the development parameters to avoid the blockage of seepage channels. In addition, reservoir evaluation and productivity prediction based on pore structure are also widely carried out. Guo Xusheng et al.established the correlation model of ' organic matter pore development degree-pore connectivity-gas content ' through the analysis of shale pore structure of Longmaxi Formation in Fuling shale gas field, which effectively guided the deployment of high-yield wells.

3. Development of Pore Structure Characterization Technology

3.1. The Evolution of Qualitative Characterization Technology

The early qualitative characterization relies on optical microscopy and casting thin section method, and the resolution is low (>0.3μm), which is only suitable for medium-large pore observation. For example, Chen Huanqing et al[1].identified the mold pores and intergranular dissolved pores of volcanic rocks in Songliao Basin through casting thin sections, but could not observe nanoscale pores.

The emergence of scanning electron microscopy (SEM) technology has promoted the characterization accuracy to 6nm, which has become the core means of conventional pore observation. Dong Lei et al[3].used ordinary SEM to observe shale fracture and pore morphology, combined with energy spectrum analysis of mineral components ; field emission scanning electron microscopy (FE-SEM) further improved the resolution to 0.5-2nm.used FE-SEM to discover nanopores (80-200nm) in shale for the first time, subverting the traditional understanding that micron-sized pores are the only reservoir space. Environmental scanning electron microscope (ESEM) breaks through the limitation of sample conductivity and can observe water-bearing and oil-bearing samples in natural state. Yu et al.used ESEM to directly observe the water absorption and expansion process of clay minerals in shale and analyze reservoir water sensitivity.

Atomic force microscopy (AFM) achieves a fine characterization of the surface properties of nanopores with a resolution of 0.1nm. obtained the three-dimensional morphology of shale nanopores by AFM, calculated the number of pores, average pore size and other parameters, and found that the specific surface area measured by AFM was closer to the true value than the low-temperature nitrogen adsorption. Jiao Kun et al.used AFM to study the surface roughness of shale, and pointed out that the higher the roughness, the stronger the gas adsorption capacity, which provided a new basis for the evaluation of shale gas storage capacity.

3.2. Quantitative Characterization Technology Development

The fluid injection method has developed from conventional mercury injection to high precision. Conventional mercury intrusion method can analyze 10nm-400μm pores, but it is easy to produce artificial cracks. The constant-rate mercury intrusion method can distinguish pores and throats at a low rate of 0.00005mL/min.Qi et al[2].used this technique to measure the throat radius distribution of tight sandstone and found that 0.12μm is the lower limit of its characterization. The high-pressure mercury intrusion method (up to 414MPa) can be analyzed to 0.0018μm micropores. Liu et al[7].used high-pressure mercury intrusion to reveal

the distribution differences between mesopores (2-50nm) and micropores in ultra-deep shales in the Sichuan Basin.

Gas adsorption method has become the core means of nanopore quantification. The nitrogen adsorption method (2-200nm) calculates the specific surface area by BET model and analyzes the mesoporous distribution by BJH model. Dong et al[3].used nitrogen adsorption to measure that the mesoporous volume of Longmaxi shale accounted for 60 %. The CO2 adsorption method (0.35-2nm) calculates the micropore parameters through the DR model, and combined the two methods to realize the quantitative characterization of the full pore size (0.35nm-200nm) of shale. Zhao Xi et al.also pointed out that argon adsorption is more accurate than nitrogen in micropore characterization because of its stable molecular cross-section, but it is less applied due to the limitation of gas source.

Nuclear magnetic resonance (NMR) technology achieves simultaneous quantification of pores and fluids. Sun Ying et al[8].pointed out in the review that NMR can invert the pore throat radius distribution (8nm-80μm) through the correlation between T_2 relaxation time and pore size, and non-destructive testing is suitable for core and logging. established the conversion model of NMR T_2 value and mercury injection pore throat radius to realize the logging evaluation of tight sandstone pore structure. In addition, two-dimensional NMR spectrum can also distinguish bound water and movable fluid. Bai et al.used 2D NMR to analyze the shale of Qingshankou Formation in Songliao Basin, and found the signal characteristics of residual organic matter after extraction, which provided a basis for the evaluation of movable oil.

3.3. Breakthrough of Three-dimensional Characterization Technology

The three-dimensional reconstruction of micron-sized pores is realized by laser confocal microscopy (CLSM) with a resolution of 0.1μm. Xunsun Xianda et al.used CLSM to scan the volcanic reservoir layer by layer and reconstruct the three-dimensional structure of micropores, and found that the porosity of local micropores could reach 30%. Su et al[11].established a three-dimensional model of rock slices through CLSM, calculated the three-dimensional average pore throat diameter, and improved the characterization accuracy of heterogeneous reservoirs.

CT scanning technology breaks through from macro to nano scale. In the review, Shao Guoyong et al[9].pointed out that macro-CT (>0.6mm) is suitable for large-scale pore distribution, micro-CT (>1μm) can characterize micropores in tight sandstone, and nano-CT (>50nm) can realize three-dimensional visualization of nanopores in shale. used nano-CT to reconstruct the pores of Longmaxi Formation shale, and found that the pores were mainly aggregated and isolated, and the connectivity was controlled by the distribution of organic matter. Liu Shugen et al[7].also used CT scanning to study the micro-fractures of ultra-deep shale, and found that although the volume of micro-fractures accounted for only 0.7%, they contributed more than 70 % of the permeability.

Focused ion beam-scanning electron microscopy (FIB-SEM) achieves three-dimensional accurate reconstruction of nanoscale pores. Curtis et al.used FIB to slice the shale with a thickness of 10nm, and combined with SEM imaging to complete three-dimensional reconstruction. Wang et al[5].used FIB-SEM to analyze the shale of the Longmaxi Formation in the Sichuan Basin, and proposed a flow model of ' nanopore reservoir-grain edge fracture connectivity-page fracture infiltration ' to provide support for the study of shale gas migration mechanism.

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4. Development and Application of Full Aperture Joint Characterization Technology

4.1. The Background of the Rise of Joint Characterization Technology

The limitation of aperture coverage of a single technology promotes the development of joint characterization. For example, the mercury intrusion method has a large pore size of 200nm, and NMR is weaker than AFM in nanopore resolution. Wang He[5] pointed out that the pore span of unconventional reservoirs is 0.35nm-1mm, and multi-technology cooperation is needed to achieve full-aperture coverage.Cao Yan et al[6].also emphasized that the principle differences of different technologies (such as mercury intrusion based on capillary force and adsorption based on surface action) need to be corrected jointly to eliminate system errors.

4.2. Mainstream Joint Representation Scheme

Gas adsorption-mercury injection combination is the core scheme of shale full pore size characterization. Tian Hua et al.combined CO_2 adsorption (50nm) to analyze the pores of Longmaxi Formation shale in southeastern Sichuan, and found that micropores contribute 30% of the specific surface area, and mesopores and macropores control seepage ; taking the shale of Longmaxi Formation in southeastern Sichuan as an example, Jiang Zhenxue et al.normalized the mercury injection and adsorption data with 6nm as the connection point, realized the characterization of 0.35nm-10μm full pore size distribution, and formulated the industry standard (NB / T 14008-2015).

Nuclear magnetic resonance-mercury injection combined to improve the characterization accuracy of tight reservoirs.Xiao et al.combined NMR and constant-rate mercury intrusion to obtain pore distribution by subtracting throat distribution from T2 spectrum, and found that the radius ratio of pores to throats in tight sandstone is mostly 5-20. Liu et al.established the quantitative relationship between NMR T2 value and pore throat radius ($T2=CR^n$), and corrected the coefficients C and n by mercury intrusion data to reduce the pore size distribution error of NMR inversion to less than 10 %.

Multi-technology joint to achieve qualitative-quantitative-three-dimensional verification. For tight sandstone gas reservoirs, combined with FE-SEM (qualitative observation), N_2 adsorption (mesoporous quantitative), micron CT (three-dimensional structure) and NMR (fluid analysis), a multi-dimensional characterization system of ' pore morphology-pore size distribution-connectivity-fluid occurrence ' was constructed. In the study of tight reservoir of Shahezi Formation in Xujiaweizi fault depression, Guo Siqi et al.combined NMR, high-pressure mercury injection and nitrogen adsorption to verify the reliability of NMR conversion pore size distribution, and the coincidence degree of the three peak intervals reached 85%.

4.3. Typical Application Cases

In terms of shale reservoirs, Liu Shugen et al.combined FE-SEM, nano-CT and CO_2 / N_2 adsorption for the Lower Paleozoic deep shale (>3500m) in the Sichuan Basin, and found that the micropore volume of overpressure shale is 20% -30% higher than that of normal pressure shale, and the pore shape coefficient of solid asphalt is moderately correlated with overpressure (R^2=0.62), which provides a basis for the evaluation of deep shale gas preservation conditions. Cao Yan et al.combined AFM-IR and SANS to reveal the chemical heterogeneity of shale organic matter in the Longmaxi Formation, and found that the organic pore development density of the macerals of the sapropel group is 3-5 times that of the vitrinite.

In terms of tight sandstone reservoirs, Ouyang Siqi et al[15]., taking the sandstone in Heshui area of Ordos Basin as an example, combined with constant rate mercury injection (throat analysis), NMR (fluid evaluation) and micron CT (connectivity), divided the reservoirs into three categories : high quality (pore-throat ratio 30%), medium (pore-throat ratio 8-15,

movable fluid saturation 15%-30%), poor (pore-throat ratio >15, movable fluid saturation<15%), to guide the selection of development wells. Ma et al.combined NMR and mercury injection to establish a ' pore throat structure-movable fluid-productivity' correlation model for tight sandstone in the fourth member of Quantou Formation in Songliao Basin, and the productivity prediction coincidence rate was 80%.

5. Research Progress of Pore Structure in Different Types of Reservoirs

5.1. Shale Reservoir (Unconventional Reservoir Representative)

The pore types of shale are mainly nanopores, which are divided into organic matter pores, inorganic mineral pores and microcracks. Dong Lei et al.pointed out that organic pores (5-750nm) are developed in kerogen and solid bitumen, which are the main reservoir space of shale gas. Inorganic mineral pores include clay mineral intergranular pores (2-50nm), quartz intergranular pores (50-200nm) and dissolution pores (>200nm). Liu et al.found that the contribution rate of inorganic mineral pores in the Longmaxi Formation shale in the Sichuan Basin was 40%[13]. Although the volume proportion of micro-fractures (opening<0.05mm) is small, it can significantly improve connectivity. Shao Guoyong et al.used micro-CT to find that the micro-fractures of Longmaxi Formation shale in Jiaoshiba area contribute more than 70% of the permeability.

The key controlling factors of shale pore development include TOC content, maturity and mineral composition. Cao Yan et al.showed that the pore volume of shale organic matter with TOC > 2% was 2% of TOC, and the pore collapse was caused by the carbonization of organic matter. The shale with quartz content > 40 % can resist compaction, and the pore retention rate is higher than that of quartz content 6000m). The overpressure (pressure coefficient>1.5) can delay the trend of porosity decreasing with depth. When the burial depth increases by 1000m, the porosity of overpressure shale decreases by 5% -8% less than that of normal pressure shale.

5.2. Tight Sandstone Reservoir

The pores of tight sandstone reservoirs are mainly micropores-mesopores (1-50nm), with poor throat sorting and weak connectivity. Qi Nan et al.pointed out that the pore throat radius of tight sandstone in Yanchang Formation of Ordos Basin is mostly 0.05-0.5μm, the coefficient of variation is greater than 0.6, and the heterogeneity is strong. Ma et al.found that the pore types of tight sandstone in the fourth member of Quantou Formation in Songliao Basin are mainly intergranular dissolved pores (30% -50%) and intragranular pores (20% -30%), and the throat is mainly fine throat (< 0.1μm), which restricts fluid flow.

The controlling factors of tight sandstone pore structure include sedimentation and diagenetic transformation. Ren Shuyue et al.pointed out that the porosity of coarse-grained sandstone in the braided river delta front is 5% -10% higher than that of fine-grained sandstone in the flood plain because of good sorting in the study of the reservoir of the 8th member of the west of Sulige. During diagenesis, chlorite film can protect primary intergranular pores, while illite cementation is easy to plug throats. Luo Yueming et al.found that the preservation rate of sandstone pores with chlorite content>5% increased by 20%. In addition, structural fractures can improve connectivity. Bai et al.used multi-scale CT to find that the permeability of the fracture development zone is 10-100 times that of the fracture-free zone.

5.3. Carbonate Reservoir

The pore types of carbonate reservoirs are complex, including intercrystalline pores (2-50nm), dissolution pores >50nm) and fractures, with strong heterogeneity. Chen Huanqing et al.pointed out that the intergranular pores of Cambrian dolomite in the Tarim Basin contribute 40 % of the pore volume, while the dissolution pores (diameter>100μm) of Ordovician limestone are the key to high-yield reservoirs. Guan et al.used Micro-CT to find that the opening

of carbonate fractures is positively correlated with pore connectivity, and fractures with opening >10μm can form effective seepage channels.

The research technology of carbonate rock pore structure is mainly based on the combination of imaging and logging. Jin et al.used FE-SEM and energy spectrum analysis to identify the dissolution characteristics of carbonate minerals and found that the dissolution rate of calcite was 15% -20% higher than that of dolomite. Based on imaging logging and nuclear magnetic resonance, Shou et al.established a triple pore structure evaluation model of carbonate rock' matrix pore-dissolved pore-fracture ' to realize reservoir classification and productivity prediction.

6. Summary

1.The study of reservoir pore structure has developed from the early qualitative analysis of sedimentary diagenesis (such as compaction and dissolution identification) to the quantitative classification and evaluation based on parameters such as fractal dimension and pore throat ratio, and further extended to the multi-dimensional correlation study of ' pore structure-fluid activity-development response ' (such as the positive correlation between movable fluid saturation and pore throat radius, and the protection of deep pores by overpressure). Among them, the development mechanism of organic matter pores in organic-rich shale (the development potential of type I kerogen pores is better than that of type III) and the results of tight sandstone throat sorting control seepage efficiency have laid a core theoretical foundation for unconventional reservoir evaluation.

2.Qualitative characterization techniques were upgraded from optical microscope (>0.3μm) to FE-SEM (0.5-2nm) and AFM (0.1nm) to realize nanopore visualization. The quantitative technology was extended from conventional mercury intrusion (10nm-400μm) to gas adsorption (0.35-200nm) and NMR (8nm-80μm), covering the whole nanometer scale. Three-dimensional characterization techniques (micro/ nano CT, FIB-SEM) were used to realize the non-destructive reconstruction of pore-throat network. On this basis, full-pore joint characterization (such as CO_2 adsorption-N_2 adsorption-high pressure mercury intrusion, NMR-constant speed mercury intrusion) has become the mainstream, which solves the limitation of pore size coverage of a single technology and achieves a comprehensive characterization of 0.35nm-1mm pores.

3.The shale reservoir is dominated by nanopores (organic matter pores 5-750nm, inorganic mineral pores 2-200nm), and TOC content, maturity and overpressure are the key control factors. Tight sandstone is dominated by micropore-mesoporous (1-50nm), and sedimentary sorting and chlorite film protection are the core of pore preservation. The pore types of carbonate rocks are complex (intercrystalline pores, dissolution pores, fractures), and the combination of imaging logging and FE-SEM is the main characterization method. The differentiation research of different reservoirs provides a microscopic basis for targeted development.

4.There are still some problems in the current research, such as the contradiction between accuracy and scale, the lack of in-situ characterization, and the imperfection of special reservoir methods. In the future, it is necessary to solve the problem of " real formation condition characterization " and " multi-scale data coupling " through in-situ technology breakthrough, dynamic monitoring upgrade and multi-scale fusion. At the same time, the dynamic model of pore evolution and the development adaptation system are constructed to promote the transformation of research from ' static description ' to ' dynamic prediction-development adaptation ', and provide more solid micro-support for the efficient development of unconventional oil and gas.

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