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Research Status of Reservoir Diagenesis and Methods for Investigating Microscopic Pore Structure

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Abstract

Diagenesis plays a critical role in reservoir formation, directly determining whether a given sand body can develop into a high-quality reservoir. The study of diagenetic facies focuses on the analysis of facies types, as well as their spatial distribution and assemblage patterns, enabling accurate identification of favorable reservoir distributions and facilitating predictions of their potential occurrence. In recent years, significant advancements have been achieved in reservoir diagenesis research, driven by improvements in experimental techniques and deeper theoretical understanding. This paper provides a comprehensive review of the current state of research on reservoir diagenesis and discusses its future development trends.

Keywords

Diagenesis; Clastic rocks; Pore structure; Diagenetic evolution.

1. Introduction

Reservoir diagenesis is an interdisciplinary field integrating sedimentology, petroleum geology, and geochemistry. Research in this domain is of significant importance for enhancing the understanding of reservoir formation, evolutionary processes, and hydrocarbon storage potential.

2. Diagenesis of Reservoir Rocks: Definition and Research Status

2.1. Definition and Characteristics

Diagenesis of reservoir rocks refers to the various physical, chemical and biological changes that occur in clastic sediments from the time of deposition until metamorphism. A series of diagenetic changes in clastic sandstones play a crucial role in the formation, preservation and destruction of pores in clastic reservoir rocks, and have a decisive impact on reservoir properties. Therefore, the research focus on diagenesis of reservoir rocks is on those diagenetic events that cause changes in physical properties (including the destructive effect on pores and the formation of secondary pores), and to explore the evolution law of pores in reservoirs, thereby predicting favorable oil and gas zones[1].

2.2. Overview of Research Status

The study of diagenesis of sandstone reservoirs has gone through a long process of gradual refinement and deepening, multi-disciplinary integration, and comprehensive analysis using various analytical and testing methods. Since the 1970s, scholars have begun to study diagenesis and proposed the view that reservoir quality is affected by diagenesis (Nagtegaal, 1979), breaking the traditional understanding that reservoirs are only controlled by sedimentary facies. Since then, the study of diagenesis has become an indispensable part of the research on tight sandstone reservoirs. With the continuous deepening of diagenesis research, in order to reveal the characteristics of diagenetic products, fluids, and environments during the diagenetic evolution process, and to reflect the types, intensities, and differences of diagenesis, scholars have proposed the concept of "diagenetic facies", which has become an important milestone in the study of diagenesis and has led the research towards systematization and quantification.

3. Basic Elements of Diagenesis in Reservoirs

After sedimentation and before metamorphism, various possible physical and chemical reactions occur between detrital materials and pore fluids. The ways, processes, and degrees of these reactions change with variations in rock composition, fluid properties, temperature, and pressure. In other words, rocks, fluids, temperature, and pressure are the basic elements or parameters and conditions for various diagenetic processes. Generally, the diagenetic system composed of rocks and fluids is considered an open, semi-open, or closed system. Therefore, accurately determining the reactants, products, and reaction conditions of a certain diagenetic reaction is one of the goals of diagenetic research; and on this basis, inferring or predicting the formation and evolution of pores.

3.1. Lithology

The lithology of clastic reservoirs includes the composition, structure, and fabric of detrital grains and interstitial materials (cement and matrix), which are mainly controlled by the depositional environment of the reservoir and the various diagenetic changes that occur after deposition. For example, authigenic minerals in rocks are formed due to the supersaturation of certain ions in the pore fluids of rocks under certain temperature and pressure conditions[2]. Therefore, the composition, structure, and fabric of authigenic minerals can directly reflect the diagenetic environment. Thus, systematically and accurately observing and analyzing the composition of rocks, especially the composition, structure, and fabric of authigenic minerals, can help analyze and determine the various diagenetic changes that have occurred, that is, infer the transformation of primary mineral composition, structure, and fabric caused by diagenesis from diagenetic products. This is because the dissolution of detrital mineral grains by groundwater solutions, the leaching of grains by fresh water, and the metasomatic reactions between minerals are all based on their compositional and structural differences and are highly selective. The conditions for selection are the basic factors and diagenetic environment that influence diagenesis.

3.2. Temperature

Temperature is one of the basic conditions for various diagenetic changes. Its magnitude not only affects the type and rate of diagenesis but also the direction of diagenetic processes. The determination and restoration of paleotemperature during diagenesis is crucial. Generally, the influence of paleotemperature on diagenesis can be summarized as follows:

Affecting the solubility of minerals: The solubility of most minerals increases with temperature.

Affecting mineral transformation: Actual data show that different geothermal gradients result in different depths of mineral transformation.

Affecting the reaction direction between pore fluids and rocks: Since the equilibrium constant of chemical reactions is controlled by temperature, changes in temperature will inevitably cause changes in reactions. At one temperature, a certain diagenetic reaction may form secondary pores, while at another temperature, it may form authigenic minerals and block pores.

Controlling the diagenetic evolution sequence of organic matter: Organic acids are an important way to form secondary pores by dissolving mineral grains. Organic matter changes into different chemical components with temperature, and different chemical components of organic acids have distinct effects on the dissolution of minerals.

In summary, paleotemperature is one of the main indicators for the division of diagenetic stages. The determination of paleotemperature is a major challenge in diagenetic research. Although various methods have been developed, commonly used methods include: fluid inclusion thermometry; vitrinite reflectance; clay mineral assemblage and transformation; and the distribution and evolution of authigenic minerals.

3.3. Pressure

The magnitude of pressure has a certain controlling effect on diagenetic reactions, mainly manifested in influencing the speed and direction of diagenesis. Common pressure parameters include hydrostatic pressure (Ph), pore fluid pressure (Pp), effective stress (Pf), overpressure (Pe), and total pressure (Pt)(Figure 1). When the pore fluid pressure is equal to the weight of the overlying water column, it is called hydrostatic pressure; pore pressure greater than the weight of the overlying water column is called overpressure. When the pore fluid pressure is greater than the hydrostatic pressure (ultra-high pressure), the effective stress decreases accordingly until it becomes zero. Pressure parameters directly control the mechanical compaction and pressure solution of reservoirs, and can be said to be an important factor directly controlling physical properties. In addition, the solubility of most minerals increases with increasing pressure. Therefore, in the middle and late stages of diagenesis, pressure is an indirect factor controlling physical properties.

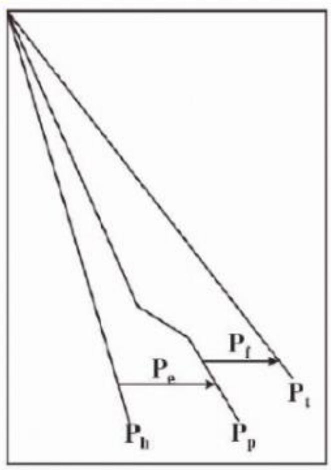

Figure 1 Schematic Diagram of Pressure Relationship

3.4. Fluids

The precipitation and dissolution of authigenic minerals observed in reservoirs are caused by a large amount of dissolved substances within the sedimentary basin. During diagenesis, there exist pore fluids or groundwater solutions of different compositions in the reservoir, which serve as the dynamic conditions for the redistribution of minerals. Therefore, their chemical composition and activity level play a crucial role in controlling diagenesis. Crustal fluids directly interact with various rocks within the crust, significantly influencing their structure, metamorphism, and formation products. The movement of the Earth drives changes in crustal fluids, altering their temperature, pH, and material content, leading to continuous changes in the diagenetic process. Due to the varying contents of organic matter, inorganic matter, and water in crustal fluids, chemical reactions in rocks can generate secondary porosity, and crustal fluids also have varying degrees of influence on secondary porosity. Specifically, pore fluids generally include pore water, oil, and gas, with pore water having the most prominent influence.

4. Main Diagenetic Processes

4.1. Compaction

Compaction refers to the process that occurs after sediment is buried, where with the increase of burial depth, under the weight of overlying water or sediment or the effect of tectonic deformation stress, water is expelled, porosity decreases, volume shrinks, and at the same time, the density of the sediment increases. The main indicators of mechanical compaction are as follows:

(1) With the increase of burial depth, compaction causes particles in the reservoir that did not come into contact earlier to squeeze each other, and the contact state of the particles changes successively from point contact, line contact, concave-convex contact to suture contact.

(2) Brittle deformation occurs in rigid particles, such as the brittle fracture of rigid particles like quartz and feldspar, and the opening of feldspar along cleavage fractures.

(3) Plastic deformation occurs in plastic particles, such as the deformation of mica and rock fragments. Mica often bends, and mudstone fragments can undergo pseudo-matrixization, etc.

(4) Particles undergo compaction orientation. This phenomenon is most common in matrix-supported sandstones, where elongated particles undergo limited rotation and turn to a position perpendicular or nearly perpendicular to the direction of pressure.

The degree to which sediment is compacted and consolidated can be referred to as the intensity of compaction(Table 1). A qualitative method to characterize the intensity of compaction is to describe the contact relationship of detrital particles under the microscope; as the compaction intensity increases, the contact of detrital particles successively changes from point contact, line contact, concave-convex contact to suture contact.

Table 1 Intensity Grading of Compaction Action3.2 Pressure Solution

Compaction intensity	Weak compaction	rapid compaction	strong compaction
The compactness of particles	＜70%	70%~90%	＞90%
Porosity lost after compaction	＜10%	11%~27%	27%
Porosity compaction gradient	＜1%，100m	＞1%，100m	0.5%，±100m

4.2. Pressure Solution

When the overburden pressure or tectonic stress exceeds the hydrostatic pressure that the pore water can withstand, it will cause lattice deformation or dissolution at the contact points of the grains. This local dissolution is called pressure solution. Pressure solution can occur in quartz, feldspar and other detrital grains, but it is more common in quartz in this area, manifested as concave-convex contacts or suture contacts between grains. After quartz pressure solution, the dissolution process dissolves the soluble SiO2 into the pore water, making the pore water oversaturated and causing SiO2 to precipitate as overgrowths. Under a scanning electron microscope, this is often accompanied by the precipitation of a large number of authigenic quartz crystals on the surface of detrital grains or the restoration of the regular geometric shape of detrital grains. Some sandstones, when viewed under a polarizing microscope, show no evidence of quartz overgrowth and the grains are closely interlocked.

Previously, these phenomena were regarded as the result of pressure solution. However, under a cathodoluminescence microscope, it can be clearly seen that the detrital quartz grains are not connected and most are "suspended" in the cement or only in point contact. Therefore, these phenomena are not entirely caused by pressure solution, but may be the combined result of authigenic quartz cementation, pressure solution, and compaction.

4.3. Cementation

Cementation refers to the process where minerals precipitate in the pores of detrital sediments and consolidate the sediments into rocks. Cementation is an important process in the transformation of sediments into sedimentary rocks and is one of the main reasons for the reduction of porosity and permeability in sedimentary layers. Cementation can occur at various stages of diagenesis. The cement can be dissolved or partially dissolved, forming secondary pores.

4.4. Metasomatism

Metasomatism refers to the phenomenon where one mineral replaces another. Metasomatism can occur at various stages of diagenesis and even during the epigenetic period. Metasomatic minerals can replace the edges of grains, eroding them into irregular shapes such as serrated or bay-like edges, or they can completely replace detrital grains, thereby forming pseudomorphs. Late-stage cements can metasomatize early-stage cements, and when the metasomatism is thorough, it can even cause the disappearance of the replaced mineral's trace, making the sediment unrecognizable and altering the rock's structure. At the same time, the porosity and permeability of the rock will also change accordingly. When in-situ transformation occurs during metasomatism and the newly formed minerals maintain the pseudomorphs of the original minerals, the metasomatism process adheres to the law of volume preservation and the law of mass action. In this case, the impact on porosity and permeability is relatively small.

5. Research Methods and Principles of Microscopic Pore Structure in Reservoirs

The basic concept of pore structure refers to the geometric shape, size, distribution and interconnection of pores and throats in reservoir rocks. The division of pore space in reservoir rocks into pores and throats is the fundamental prerequisite for studying pore structure. When fluids flow through the complex pore system in nature, they will pass through a series of alternating pores and throats. Whether during the secondary migration of oil displacing water in the pore medium during the sedimentary period or during the production process when oil is displaced from the pore medium, the flow is controlled by the smallest cross-section (i.e., the throat diameter). Clearly, the size and distribution of throats, as well as their geometric shapes, are the main factors affecting the storage and seepage capacity of reservoir rocks. All pores are controlled by the throats connected to them. Therefore, studying the size and distribution of throats is the central issue in researching the microscopic pore structure of reservoir rocks[3].

5.1. Image Analysis Method

The image analysis method involves using instruments and equipment to collect images of rock core sections and then observing the size, connectivity and distribution of pores and throats in the samples. Currently, this method mainly includes the cast thin section method, scanning electron microscopy (SEM) method and CT scanning method.

5.1.1. Cast Thin Section Method

The cast thin section method involves injecting colored organic glass or epoxy resin into the pores and fractures of rocks, allowing the resin to solidify, and then observing the thin sections of the rock cores under a microscope [4]. This method is used to study the porosity, pore-throat types, connectivity, coordination number of pore-throats, and detrital components in the thin sections. Due to its simplicity, ease of operation, and low cost, this method is currently the most commonly used in image analysis methods.

5.1.2. Scanning Electron Microscopy Method

The principle of scanning electron microscopy is that an electron gun emits an electron beam, which is accelerated and deflected, and then focused into a very fine electron beam on the surface of the sample. This electron beam scans the surface of the sample, and the interaction between the electrons and the sample generates various signals. These signals are processed and displayed on a fluorescent screen [5]. Under a scanning electron microscope, minerals have characteristics such as three-dimensional images, high resolution, and large depth of field. It can be used to analyze the three-dimensional morphology and connectivity of micro-pores and throats in the sample, the configuration relationship between pores and throats, the types of clay minerals and their occurrence forms, etc.

5.1.3. CT Scanning Method

CT, or computed tomography, uses an X-ray beam and a highly sensitive detector to perform cross-sectional scans around the core. During each scan, the detector receives the attenuated X-ray information passing through the core. After high-speed calculation by a computer, the X-ray absorption coefficient values of each point on the cross-section are obtained. Different data are then displayed on the image display with different gray levels, so that the pore structure of the cross-section can be clearly shown on the monitor [6]. Core CT scanning can provide information on the distribution of pores and throats in rocks, their connectivity, and physical parameters.

5.2. Capillary Pressure Curve Method

The capillary pressure curve of rocks reflects the relationship between the capillary pressure of rock pores and the saturation of the wet phase (or non-wet phase). Generally, the characteristics of the pore structure of the reservoir are studied through the shape of the curve and related parameters . The main measurement methods include mercury injection method, centrifuge method, and semi-permeable partition method. The measurement principles of these three methods are basically the same.

5.2.1. Mercury Injection Method

The mercury injection method (also known as the mercury intrusion method) is a commonly used method for determining the micro-pore structure characteristics, and it includes two types: the conventional mercury injection method and the constant rate mercury injection method. The conventional mercury injection method mainly involves injecting a certain volume of mercury into the rock pores and drawing the capillary pressure curve based on the pressure changes to further calculate the pore structure parameters of the rock sample. This method is simple to operate and was widely used in the early stage of oilfield development, but it has low accuracy and limited coverage, and cannot accurately distinguish the distribution of pores and throats. The constant rate mercury injection method is applicable when the mercury injection volume is low or the injection rate is constant. It measures the pore structure parameters by determining the capillary pressure curve of the rock, which can truly reflect the pore structure parameters of the rock, such as pores, throats, and pore-throat ratio. However, it takes a long time and has low accuracy, and is not suitable for low-permeability reservoir rocks.

5.2.2. Centrifuge Method

The centrifuge method uses the combined action of centrifugal force and displacement force to displace the wet phase from the porous medium with the non-wet phase. The relationship curve between capillary pressure and water saturation is obtained by recording the volume of the displaced fluid. This method has the advantages of simple operation, high measurement pressure, and wide application range, but it is relatively expensive.

5.2.3. Semi-permeable Partition Method

The semi-permeable partition method is a traditional method for measuring the capillary pressure of rocks. The semi-permeable partition mainly serves to separate the wet phase and the non-wet phase. The wet phase directly enters the core, and the non-wet phase enters the core through the displacement pressure, displacing the water in the core. The wet phase saturation at each pressure is calculated based on the cumulative volume of the displaced water. Based on the core saturation and pressure data, the displacement capillary pressure curve can be plotted. This method has test conditions close to the actual reservoir conditions and high construction accuracy, but it takes a long time, usually several months.

6. Research Trends in Diagenesis

6.1. Diagenesis of Reservoirs

1) Various diagenetic experiments will still be widely conducted, including: the cracking mechanism of organic matter under formation temperature, pressure and formation water conditions; the determination of dissolution rates and equilibrium constants of rock framework minerals and cements under formation water conditions; the specific influences and differences of organic and inorganic acids on mineral dissolution; the complexation mechanism of metal ions under organic acid conditions and their impact on diagenesis; and the simulation of formation water flow states and geological structure characteristics. The study of the dissolution characteristics and precipitation locations of minerals under static and dynamic conditions will further deepen the research on diagenetic basic theories, making each study have significant practical significance.

2) Diagenetic thermodynamic simulation based on chemical thermodynamic equilibrium theory will still play an important role in quantitative diagenetic research. The in-depth development of this research depends on the further improvement of thermodynamic parameters of various minerals in diagenetic environments, more accurate mineral models, and the further improvement of formation water testing techniques.

3) Formation water, as the medium of diagenetic reactions, holds an important position in diagenetic research. Formation water has multiple possible sources, such as sedimentary trapped water, surface water, mudstone extruded water, and organic matter pyrolysis products. The application of carbon, oxygen, strontium and other isotope values can analyze the source of formation water and whether the carbon in HCO3 is of organic or inorganic origin. In future research, this will remain a developing trend and be combined with other diagenetic research methods to mutually verify and explore the source of formation water and its impact on diagenesis, deepening the study of diagenesis.

6.2. Research Trends in Diagenesis of Clastic Rocks

1) In recent years, the exploration and development of unconventional reservoirs represented by tight sandstone gas reservoirs have become a research hotspot. Due to the limitations of the precision of analytical techniques, the diagenesis research in this area has not received sufficient attention. Therefore, studying the diagenesis of tight sandstone gas reservoirs from both scientific and practical perspectives is particularly important for the development of tight gas reservoirs. With the innovation of analytical techniques and the application of new technologies and theories such as structural diagenesis, the diagenesis of tight sandstone gas reservoirs will undoubtedly become a frontier area in the field of diagenesis, promoting further development of diagenesis.

2) The classification of diagenesis systems at different scales has become a new approach to exploring the temporal and spatial distribution and evolution of diagenesis. Some preliminary research ideas and methods have been formed. However, due to the complexity of diagenetic mechanisms and system simulation, the superposition of diagenetic processes, water-rock interaction, and reservoir heterogeneity, it is difficult to conduct comprehensive and mature quantitative research on the classification of diagenesis systems and their temporal and spatial distribution at the current technical and cognitive level. With the in-depth exploration of the evolution mechanism and laws of diagenetic systems, we can better understand the temporal and spatial attributes of diagenesis systems at different scales and promote the understanding of diagenetic structures in oil and gas basins.

3) The research on diagenesis is highly comprehensive. Grasping the basic geological information of the studied area, forming unique research ideas and models for diagenetic evolution, predicting and evaluating the temporal and spatial distribution of favorable oil and gas reservoirs in the study area, and better predicting the phase state and accumulation types of hydrocarbons to serve exploration and development. Of course, with the gradual deepening of exploration and development of clastic rock oil and gas fields and the further enrichment and innovation of diagenetic analysis techniques, this research idea will be further broadened and improved.

References

[1] Haiguang Hu,Xinhai Kong,Present Situation and Research Progress of Analysis Methods for Micro Pore Structure Characteristics[J].Journal of Shandong Institute of Petroleum and Chemical Technology,2023,37(02):28-31.

[2] XIA J,Microscopic pore structure characteristics of unconventional tight reservoirand its impact on development[D].Xi’an Shiyou University,2017.

[3] Zhuzheng Li,Tongshui Yang,Defeng Wu,et al.Diagenetic Characteristics of the Xujiahe Formation Reservoirs in the Hebaocang Area, Sichuan Basin,China[J]. Petroleum and Chemical Standard and Quality,2024,44(06):132-134.

[4] Lewei Hao,Qi Wang,Jun Tang,et al.Research progress of reservoir microscopic pore structure[J].Lithologic Reservoirs,2013,25(05):123-128.

[5] Jian Wang,Chonglong Gao,Lei Bai,et al.Diagenesis and pore evolution of Cretaceous Qingshuihe Formation reservoir in western section of southern margin of Junggar Basin[J].Petroleum Geology & Experiment,2023,45(04):632-645.

[6] Geological and Geochemical Characteristics and Diagenetic Evolution of Permian Basalts in Changbai Township,Yanyuan,Sichuan[J].Sichuan Nonferrous Metals,2023(03):41-46.