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Influence of Reservoir Diagenesis on Physical Properties

Chenhui Shi [1, 2]

[1] School of College of Earth Science and Engineering, Xi 'an Shiyou University, Xi'an Shaanxi, 710065, China

[2] Shaanxi Provincia Key Laboratory of Petroleum Accumulation Geology, Xi'an Shiyou University, Xi'an Shaanxi, 710065, China

Abstract

Reservoir diagenesis is a core geological process that controls key physical properties such as porosity and permeability and determines the capacity of oil and gas storage and seepage. This paper systematically discusses the dual influence mechanism of diagenesis on the physical properties of reservoirs, reveals the causes of the strong heterogeneity of reservoirs, and explores its application value in geological exploration.Research indicates that diagenesis shapes the final reservoir space through both destructive and constructive processes. Destructive effects (such as mechanical and chemical compaction, siliceous and carbonate cementation) generally reduce primary porosity, among which the cementation of clay minerals such as illite causes particularly significant damage to permeability. Constructive effects (especially organic acid dissolution and structural fracture) are the key to forming secondary pores and improving the physical properties of deep and tight reservoirs. In the field of unconventional oil and gas, the study of diagenesis has significant guiding significance for evaluating the fracturing ability and fluid mobility of reservoirs.

Keywords

Diagenesis; Reservoir Physical Property; Destructive Diagenesis; Constr-Uctive Diagenesis.

1. Introduction

The porosity and permeability of reservoir rock are core physical parameters [1] to measure its reservoir and seepage ability, which directly determine the productivity and economic value of oil and gas reservoirs. These physical properties are not static, but undergo a series of complex physical, chemical and biological changes after sediment burial, i.e., the transformation results of diagenesis. With the development of global oil and gas exploration and development to deep and unconventional fields, a deep understanding of reservoir diagenesis and its control mechanism on physical properties has become a key geological scientific problem for predicting high-quality reservoirs, improving exploration success rate and optimizing development strategies.

Diagenesis is a dynamic, multi-stage geological process, which runs through the whole history of sediments from shallow burial to deep burial and even later uplift [2]. It can not only destroy primary pore space and make reservoirs compact, but also significantly improve reservoir permeability by producing secondary pores and fractures. This constructive and destructive action changes from one to the other and superposes in time and space, and finally shapes extremely complex heterogeneity of reservoirs. For example, in typical tight sandstone gas areas such as Ordos Basin, although strong early compaction and cementation generally reduce primary porosity, in some areas, strong dissolution can still form high quality reservoirs with porosity exceeding 10% and permeability greater than 1.0mD. This strong heterogeneity is the visual embodiment of differential diagenesis.

The purpose of this paper is to systematically summarize the influence mechanism of various diagenesis on reservoir physical properties, and to deeply discuss the controlling factors and evolution sequence of diagenesis and its application in oil and gas exploration and development in combination with the recent frontier research achievements of typical basins at home and abroad (such as Songliao, Ordos, Sichuan, Persian Gulf, etc.).

2. Destructive Diagenesis and its Restriction on Reservoir Physical Properties

Destructive diagenesis is the dominant factor leading to pore reduction, throat plugging and physical property deterioration of reservoir, mainly including mechanical compaction, chemical compaction (pressure solution) and various cementation [3], which are especially active in the early burial stage and often greatly reduce the initial porosity of rock.

2.1. Compaction and Pressure Solution

Mechanical compaction takes place at the initial stage of formation burial and is driven mainly by the static pressure of overlying formation [4]. Its physical processes are grain rearrangement, deformation of plastic particles (such as mudstone cuttings) and extrusion of soft components, resulting in irreversible rapid reduction of primary intergranular pores. The study of Chang 2 reservoir in Zichang area of Ordos Basin shows that compaction is the primary destructive factor resulting in low porosity and low permeability characteristics in this area [5]. Compaction is particularly fatal for poorly sorted sandstone rich in plastic cuttings, which can be rapidly densified.

With the increase of burial depth and temperature, chemical action begins to dominate, i.e. pressure solution. In the high stress area of particle contact point, minerals (mainly quartz) are partially dissolved, and dissolved silica migrates with pore fluid to the nearby low pressure area and precipitates again, forming quartz secondary enlargement. This process not only directly reduces pore space, but more importantly, cementation occurs at throat, which causes destructive blow to permeability. Pressure solution is very common in quartz sandstone, and it is the main reason for general deterioration of physical properties of deep-buried sandstone reservoirs.

2.2. Agglutination

Cementation refers to the process of supersaturated mineral precipitation and pore filling in pore water [6]. It has various types and different destruction modes to physical properties.

Carbonate cementation: calcite, dolomite and other carbonate mineral cementation is common and strong. They often grow in a paracrystalline manner and wrap multiple particles. They can plug a large number of pores and throats at one time, causing a sharp simultaneous decrease in porosity and permeability. However, carbonate cements are easily dissolved under the action of acid fluids in the later period, so their distribution areas may also become potential constructive diagenetic zones.

Siliceous cementation: mainly occurs in the form of quartz secondary enlargement and authigenic quartz microcrystals. Although quartz enlargement grows slowly, its stability is high. Once formed, it is difficult to be dissolved later, and the damage to pores is permanent. Siliceous cementation is an important densification factor in Sangonghe Formation and other reservoirs in Junggar Basin.

Clay mineral cementation: Kaolinite often fills pores with book-like aggregates, producing a large number of micropores, which can maintain a certain porosity but seriously reduce permeability. Illite often grows in throats as hair-like and thread-like bridges, which greatly increases the seepage resistance of fluids, which is a typical reason for the phenomenon of "high porosity and low permeability". Chlorite often occurs as a pore lining, and early ring chlorites can inhibit quartz enlargement and preserve part of pores, but thick or multi-layered chlorites films can also block throats.

Other cements: cements such as sulfate (gypsum, anhydrite) and zeolite are also common in certain diagenetic environments. They fill pores heavily and significantly reduce physical properties.

3. Constructive Diagenesis and its Optimization of Reservoir Physical Properties

Constructive diagenesis can create new reservoir space or improve pore connectivity, which is the key to keep high physical properties in deep and tight reservoirs, and mainly includes dissolution and fracture.

3.1. Dissolution

Dissolution is the most important mechanism for forming secondary pores [7]. (For example, organic acid produced by organic matter maturity, atmospheric fresh water or deep thermal fluid) will cause dissolution when it reacts with unstable components in rocks. Aluminosilicate minerals such as feldspar and debris are easily dissolved to form intragranular dissolved pores and mold pores; dissolution of early carbonate cements or particles (oolite and bioclast) can produce ultra-large pores; dissolution of salt rock and gypsum can even form karst caves in gypsum salt layer development areas.

Recent in-depth research on the tight sandstone of the Shan 2-He 1 formation in the Ordos Basin has revealed the special importance of volcanic tuffaceous components in dissolution [8]. This research has identified a variety of diagenetic facies, among which clastic and tuffaceous dissolution facies and tuffaceous dissolution facies have undergone strong dissolution transformation, with an average porosity greater than 10% and an average permeability exceeding 1.0mD. They are classified as high-quality Class I reservoirs. Through mercury injection curve analysis, it is found that this kind of reservoir dominated by dissolution has larger pore throat radius and better connectivity.(105 - 135°C) and lowδ13C values (-20.2‰-10.52‰) of carbonate cements confirm that acidic fluids produced by decarboxylation of organic matter are the key mechanism for triggering large-scale dissolution and forming high-quality reservoirs. This case vividly illustrates that even in the context of strong compaction, localized and effective dissolution events are sufficient to fundamentally change the fate of reservoirs.

3.2. Fracture and Other Constructive Actions

Fracture refers primarily to fracture networks generated by tectonic stress [9]. For tight sandstone, shale, or carbonate rocks with very low porosity, the contribution of fractures is critical. Fracture systems themselves provide limited reservoir space, but can greatly increase the permeability of the rock and become the main conduit for oil and gas seepage. Open sutures (a type of pressure solution fracture) have been shown to increase pore connectivity and permeability in Permian-Triassic carbonate reservoirs in the Persian Gulf.

In addition, some mineral transformations can be constructive. For example, the alteration of feldspar to kaolinite (kaolinization) reduces the volume and may produce intercrystalline pores. The transformation of clay minerals may also modify the pore structure

4. Reservoir Heterogeneity and Analysis of Main Controlling Factors

The complexity of diagenesis directly results in strong heterogeneity of reservoir, which is not generated randomly, but controlled by many factors such as original sedimentary material, diagenetic fluid and basin dynamics background.

4.1. Concept of "Diagenetic Facies" and Reservoir Classification

The concept of diagenetic facies is widely used to describe the spatial difference of diagenesis [10]. It refers to rock units that have undergone similar diagenetic evolution and have specific diagenetic mineral assemblages and pore structures. Reservoir classification and evaluation based on diagenetic facies is an effective way to predict high-quality reservoirs at present. For example, in the study of Ordos Basin, scientists divided the tight sandstone into 7 diagenetic facies according to petrological, mineralogical and physical data, and clearly classified the dissolution facies as high-quality reservoirs. Similarly, in shale reservoirs, the diagenetic responses of different facies are also quite different. The study of Lianggaoshan Formation shale in Sichuan Basin found that the reservoir properties (porosity and volume of macropores and microfractures) of organic-rich laminated clayey shale are obviously better than those of silty mudstone and fine siltstone.

4.2. Coupling Control of Sedimentation and Diagenesis

The "innate" sedimentary characteristics of reservoir fundamentally restrict its diagenetic path and ultimate physical properties, that is,"sedimentation controls facies, diagenetic controls reservoir".

Material composition control: pure quartz sandstone has strong anti-compaction and anti-pressure solution ability, primary pores are well preserved, and provide channels for later constructive fluids. Sandstone rich in volcanic debris and feldspar, although easily compacted and altered, also provides material basis for later dissolution, and may evolve into high-quality secondary pore development zone.

Sedimentary structure and structural control: Well-sorted and well-rounded coarse sandstones have high original porosity and permeability, which is conducive to the flow of diagenetic fluids and promotes the widespread occurrence of dissolution and other processes. On the contrary, fine-grained sediments with high shale content have low original porosity and permeability, limited fluid activity, and are prone to strong compaction and cementation and rapid densification. Studies in the Persian Gulf have clearly pointed out that the grain-dominated facies have the characteristics of high porosity and high permeability after constructive diagenetic transformation such as dolomitization; The argillaceous dominant facies usually show low porosity and low permeability.

4.3. Fluid-rock Interaction and Diagenetic Evolution Sequence

Properties of diagenetic fluids (temperature, pH, ion concentration) and flow history drive all chemical diagenesis Organic acids and CO_2 released by hydrocarbon source rocks during hydrocarbon generation are key acidic fluids to initiate large-scale dissolution of adjacent reservoirs [11]. The study of shale in Sichuan Basin also shows that the reservoir properties (porosity, proportion of medium and large pores) increase first and then decrease with the increase of organic maturity (Eq Ro), reaching the optimum at 1.6%, which vividly reflects the dynamic game between hydrocarbon generation (pore generation) and diagenesis (pore destruction).

For example, the sequence of Sangonghe Formation in Junggar Basin has been determined as: early calcite cementation → early chlorite cementation → acid dissolution/quartz/kaolinite cementation → illite cementation → gypsum/anhydrite cementation → late calcite cementation → ferrocalcite/anhydrite cementation, and mechanical compaction runs through the whole process. It is very important to establish such a sequence for understanding the evolution history of pores and judging the matching relationship between the accumulation period and the effective reservoir development period.

5. Geological Significance and Exploration and Development Applications

The deep study of diagenesis has been from theoretical understanding to production practice, and plays an indispensable guiding role in each link of oil and gas exploration and development.

5.1. Guiding Reservoir Evaluation and "Sweet Spot" Prediction

In the exploration stage, the spatiotemporal distribution of high-quality reservoirs ("sweet spots") can be effectively predicted based on the study of diagenetic facies and diagenetic evolution sequences.

5.2. Optimization of Unconventional Oil and Gas Development Strategies

In unconventional areas such as shale oil and tight sandstone gas, diagenesis research is the basis for evaluating reservoir fracturability and fluid mobility. For example, the identification of diagenetic facies rich in brittle minerals (such as quartz and carbonate) and moderate clay mineral content is helpful to select fracturing intervals. The identification of natural fracture systems (such as open suture lines) can guide horizontal well trajectory design and fracturing network optimization.

5.3. Assisting Remaining Oil Tapping and Enhancing Oil Recovery

In the middle and later stages of development, reservoir heterogeneity leads to complex distribution of remaining oil. Fine diagenetic facies study can reveal micro-pore throat structure differences, characterize the distribution of dominant seepage channels and interlayer, thus providing geological basis for adjusting injection and production scheme, implementing water shutoff profile control and designing tertiary oil recovery scheme. The study of Mengo Sandstone in Congo Basin establishes geological model by integrating logging, core and test data, and accurately points out that the middle fan area is the most favorable drilling target area, which provides a reference for re-evaluation and potential tapping of similar complex reservoirs.

6. Summary

Reservoir diagenesis is a dynamic and complex geological process, which fundamentally reshapes the pore structure and physical properties of reservoir through the interweaving and superposition of destructive and constructive actions, and is the core geological factor causing strong heterogeneity of reservoir. The formation of high-quality reservoirs often depends on the effective matching of favorable sedimentary material base and constructive diagenetic events (especially acid dissolution related to organic hydrocarbon generation) in time and space.

The current research has moved from qualitative description to quantitative characterization and process simulation. For example, the technology of "casting thin section scanning + large field stitching + human-computer interaction recognition" has realized accurate quantitative analysis of diagenesis; diagenetic coefficient model based on well logging information can realize lateral prediction of diagenetic facies zone. In addition, multi-information fusion (core, thin section, well logging, geochemistry, seismic, etc.) has become a standard paradigm for comprehensive reservoir diagenetic research.

In a word, a deep understanding of the influence mechanism and control factors of reservoir diagenesis on physical properties is not only the core content of deepening oil and gas geological theory, but also the practical requirement of efficient exploration and development of oil and gas resources and ensuring national energy security.

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