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Mechanism of genesis of long 7 authigenic Illite colluvium in the Xiasiwan area and its effect on physical properties

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Abstract: *In order to clarify the developmental characteristics and formation mechanism of authigenic illite in the Long 7 dense sandstone reservoir of the Yanchang Formation in the Shimoushiwan area and its influence on the physical properties of the reservoir, a study was carried out using thin section analysis, scanning electron microscopy, and X-diffraction. Thin-section analysis, scanning electron microscopy, X-diffraction and other testing methods were used to study the content, production and development mechanism of authigenic illite in the Long 7 reservoir. The results show that the authigenic clay minerals in the study area are mainly illite, with an average content of 4.3%, which is mainly endowed with three types of production, such as thin film, intergranular pore cementation and filling, etc. The illitization of montmorillonite and the formation of illite by the dissolution of potassium feldspar are the two main mechanisms of authigenic illite genesis in the study area. In the early orogenic B stage, the stratigraphic temperature reaches 70~100℃, and the authigenic illite formed by the dehydration of montmorillonite is mainly in the form of flakes and honeycomb. In the middle diagenetic stage A, the dissolution of potassium feldspar in the acidic diagenetic environment directly formed fibrous or filamentary authigenic illite. The authigenic illite developed in the form of granular envelope in the study area prevents the secondary increase of quartz to a certain extent and thus protects the preservation of primary pores, but it has great limitations. In general, the development of authigenic illite in the study area can block the pore space, which leads to the decrease of the quality of sandstone reservoirs and negatively affects the physical properties of the reservoirs.*

Keywords: *Ordos Basin; authigenic illite; Long 7 section; dense sandstone reservoir; Xiasiwan area*

1. Introduction

Authigenic illite is one of the common clay minerals in sandstone reservoirs, which is mostly formed in flowing K^+ alkaline aqueous media environment[1,2]. Its content in the reservoirs, its storage pattern and its development mechanism have a significant influence on the physical properties of the reservoirs[3]. In recent years, scholars at home and abroad have carried out studies from various perspectives, such as thermodynamics, kinetics, and geochemical simulation, to explore the developmental characteristics and genesis mechanisms of authigenic illite agglomerate in clastic reservoirs, and to discuss the relationship between illite agglomerate and reservoir development[4,5]. Authigenic illite cementation causes pore and throat necking and increases the degree of curvature and tortuosity, which in turn reduces the porosity and permeability of the reservoir and increases the difficulty of developing tight oil reservoirs[6]. However, the formation process of authigenic illite needs to consume a large amount of K+ , which can promote the dissolution of potassium feldspar to form secondary porosity, which is favorable to improve the reservoir quality[7]. Therefore, ilmenite cementation during diagenesis has a dual role in reservoir development, and analyzing the production, distribution, and formation mechanism of these ilmenites is of great significance for understanding the development of high-quality reservoirs.

The Triassic Yanchang Formation is the main oil-bearing formation in the Ordos Basin. Among them, section 7 of the Yanchang Formation develops high-quality lacustrine shale, which is the main hydrocarbon source rock for oil production in the Mesozoic of the Ordos Basin[8,9]. Section 7 of the Yanchang Formation has become one of the key layers for exploration and development, characterized by low porosity, low permeability, low abundance, low pressure and low production[10]. In the sandstone clastic composition of the reservoir, the feldspar content is very high, the quartz content is low, the

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heterogeneous content is generally high, and the development of illite-based clay minerals. The development of illite cementation in the process of rock-forming affects the physical properties of the reservoir to a large extent, and the development characteristics and formation mechanism of the authigenic illite cementation in this area need to be further explored, as well as its impact on the physical properties of the reservoir has not yet been finalized.

In this paper, we take the dense sandstone reservoir of the Long 7 section of the Extension Formation of the Xiashiwan Oilfield in the southeastern part of the Ordos Basin as the research object, and utilize the analytical test methods such as cast thin section, scanning electron microscope, and X-diffraction to carry out the study on the developmental characteristics of the ilmenite cement in the dense sandstone reservoir of the Long 7 section, and explore the mechanism of its formation, which is aimed at revealing the relationship between the formation and development of the ilmenite cement and the densification of reservoirs and to provide a basis for the study and evaluation of the basin's dense reservoirs. The aim is to reveal the relationship between the formation and development of illite cementation and reservoir densification, so as to provide a basis for the study and evaluation of dense reservoir in the basin.

2. Regional geological characteristics

The Ordos Basin is a large-scale multi-rotation Craton superposition basin with simple internal structure and no large-scale fault development. The tectonic unit of Yishang slope is a gentle large monocline tilted from east to west, and the nose-like structure formed by differential compaction is locally developed, which is the main oil and gas rich area in the basin[11,12]. The Triassic Yanchang Formation is mainly characterized by a set of inland depression lake basin clastic deposits, which record the evolutionary history of this large freshwater lake basin from its occurrence, development to its demise. The Extension Formation can be divided into 10 phases from top to bottom (long 1~long 10), of which long 1~long 6 is the upper combination of the Extension Formation, dominated by fluvial-phase deposition, and long 7~long 10 is the lower combination of the Extension Formation, dominated by lacustrine-phase deposition. The long 7 period is the largest lake flooding period, and the semi-deep lake-deep lake range of the lake basin reaches 6.5×10 km^2[13].

The study area is geographically located in the northwestern part of Ganquan County in the Ordos Basin, with an east-west width of 11.63 km, a north-south length of 21.35 km, and an area of 248.3 km^2. Tectonically, it belongs to the southern part of the Yi-Shan Slope in the Ordos Basin. The research target of this paper is the long 7 section of Triassic Extension Formation, which develops turbidite microphase deposition in the background of semi-deep lake-deep lake, dominated by multiple sets of large quasi-continuous distribution of fine sandstones and siltstones deposition, with the thickness of a single sand body ranging from 2 to 12m, a wide range of sand body spread, and a strong connectivity of multi-phase sand body superposition, which is a good and favorable reservoir in the research area.

3. Basic reservoir characteristics

3.1. Petrological characteristics of the reservoir

3.1.1. Characterization of debris particle fractions

The cast thin section identification and statistics show that the main lithology of sandstone in the Long 7 oil formation group in the study area is rock clastic feldspathic sandstone and feldspathic clastic sandstone (Fig 1). The sandstone clastic composition is dominated by feldspar and quartz, followed by various kinds of rock chips, clay minerals, calcite and a small amount of heavy minerals. Among them, the feldspar content is 36.9%~54.4%, with an average of 44.8%; among them, the potassium feldspar content generally ranges from 2.3% to 9.9%, with an average of about 6.2%; plagioclase feldspar content generally ranges from 12.0 to 43.9%, with an average of 38.6%; the quartz content ranges from 26.7% to 36.1%, with an average of 31.5%; and the rock debris mainly dominates the igneous rock debris, with the content ranging from 11.1% to 35.4%, average 23.7%. The sandstone is poorly sorted, and the clastic particles are mainly sub-angular and sub-rounded, and the particles are mainly in line contact, with a small amount of point-line contact. The cementation types are mainly pore-type cementation and basement-type cementation.

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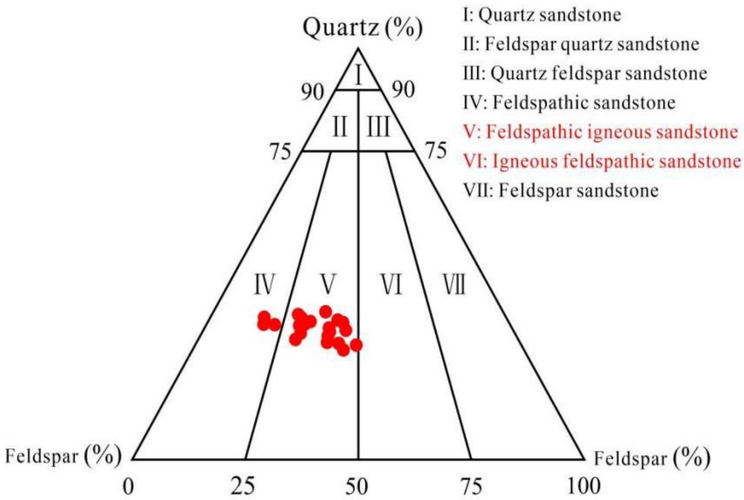

Fig. 1 Triangulation of the sandstone of the Long 7 reservoir in the study area

3.1.2. Characteristics of filler components

Microscopic thin section and scanning electron microscope observation show that the distribution of sandstone fillers in the Long 7 reservoir in the study area ranges from 0.46% to 9.83%, with an average content of 17.8%. The fills are mainly clay mineral cement, siliceous cement and carbonate cement, including iron dolomite, iron calcite and dolomite. Clay mineral cement is one of the most typical authigenic cement, mainly including chlorite, immonite, illite and kaolinite. The content of clay mineral cementation generally ranges from 2.56% to 23.71%, with an average of 14.20%. Clay mineral X-diffraction analysis showed that the illite cementation content ranged from 1.86% to 4.73%, with an average content of 4.23%, accounting for about 46.2% of the total clay minerals, followed by the ilmenite mixed layer, whose content ranged from 2.21% to 4.42%, with an average of 3.62%; and 21.7% of the total clay minerals, as well as a small amount of chlorite and kaolinite (Fig. 2). The chlorite content ranges from 1.64% to 3.52%, with an average of 2.65%, and kaolinite is less abundant, with contents ranging from 1.43% to 2.87%, with an average of 2.14%.

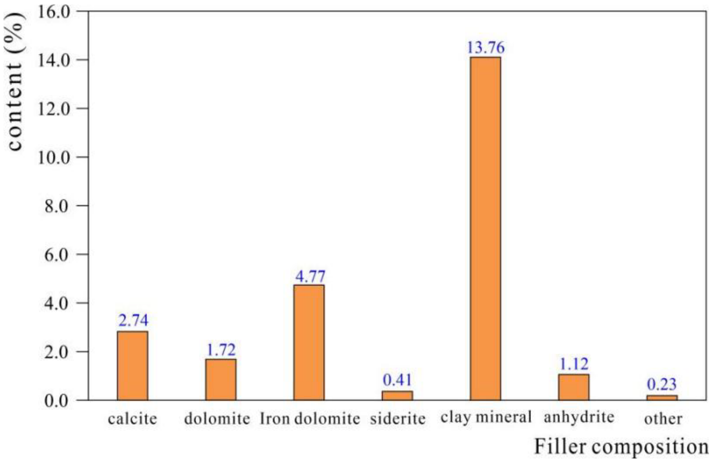

Fig. 2 Histogram of the compositional distribution of the long7 fill in the Extension Formation

3.2. Reservoir Physical Characteristics

The analysis of the core physical data shows that the porosity of the reservoir in the Chang7 oil formation group of the Yanchang Group in the study area ranges from 1.7% to 14.5%, with an average value of 7.41% and a median value of 7.04%. The porosity of sandstone reservoir is between 5%~11% about 83.2%. Permeability between 0.032mD~1.46mD, permeability geometric mean value 0.344mD, median value 0.292mD. permeability main body between 0.11mD~0.80mD accounts for about 83.2%. About 83.2% of the permeability body is between 0.11mD~0.80mD, about 3.5% of the permeability is greater than 0.8mD, and about 13.3% of the permeability is less than 0.11mD (Fig 3).

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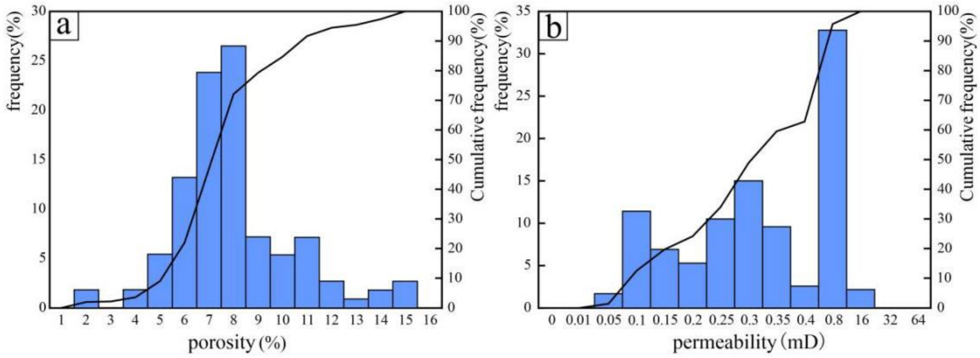
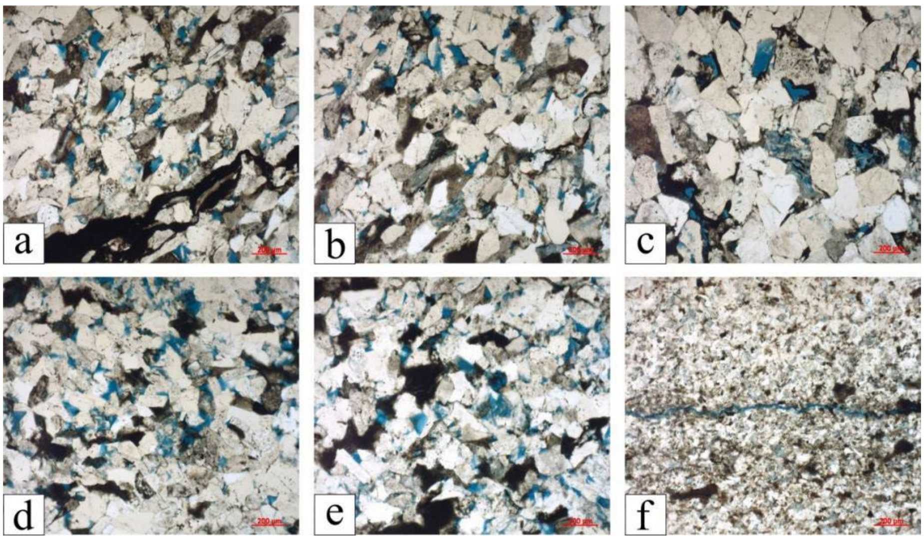


Fig. 3 Histogram of physical properties distribution of cores of surface conditions of the Long 7 oil formation in the study area

3.3. Reservoir storage space characteristics

Casting thin section observation shows that the pore types of the long 7 reservoir of the Extension Group in the study area can be categorized into primary pore, secondary pore and fracture according to its genesis, and the primary pore is mainly residual intergranular pore, and the dissolution pore mainly includes intergranular pore, feldspar pore, and rock debris pore. A large number of intergranular pores and a small number of microfractures are also seen. Statistical results show that the pore types of Chang7 oil formation are mainly residual intergranular pores, feldspar dissolution pores, and a small number of microfractures. Porosity generally ranges from 1.73% to 4.46%, with an average of 3.75%, of which intergranular pores generally range from 1.15% to 3.57%, with an average of 2.65%, and feldspar pore porosity generally ranges from 0.12% to 1.43%, with an average of 0.68%, and the pore diameter of reservoir sandstone generally ranges from 12.3 μm to 80.6 μm, with an average pore diameter of 48.16 μm (Fig. 4).



a: predominantly intergranular pores with a few intragranular lysimeters; b: intergranular pores and feldspathic intergranular pores; c: intergranular pores, feldspathic intergranular pores, and lithic lysimeters; d: feldspathic lysimeters with intragranular lysimeters; e: intergranular pores and feldspathic lysimeters with a few intragranular lysimeters; f: microfractures.

Fig. 4 Microscopic characterization of pore types in long 7 reservoirs in the study area

4. Characteristics of authigenic ilmenite cementation development and formation mechanism

4.1. Characterization of authigenic ilmenite endowment in Long 7

The molecular formula of illite is: $K_{0.75}$ ($Al_{1.75}$ (Mg^{2+} /Fe^{2+})$_{0.25}$)[$Si_{3.5}$ $Al_{0.5}O_{10}$]$(OH)_2$, which is a typical dioctahedral-type crystal with 2:1 type structural unit layer.[14]. Scanning electron microscope observation shows that the authigenic illite production in the clastic sandstone reservoirs of the Long 7

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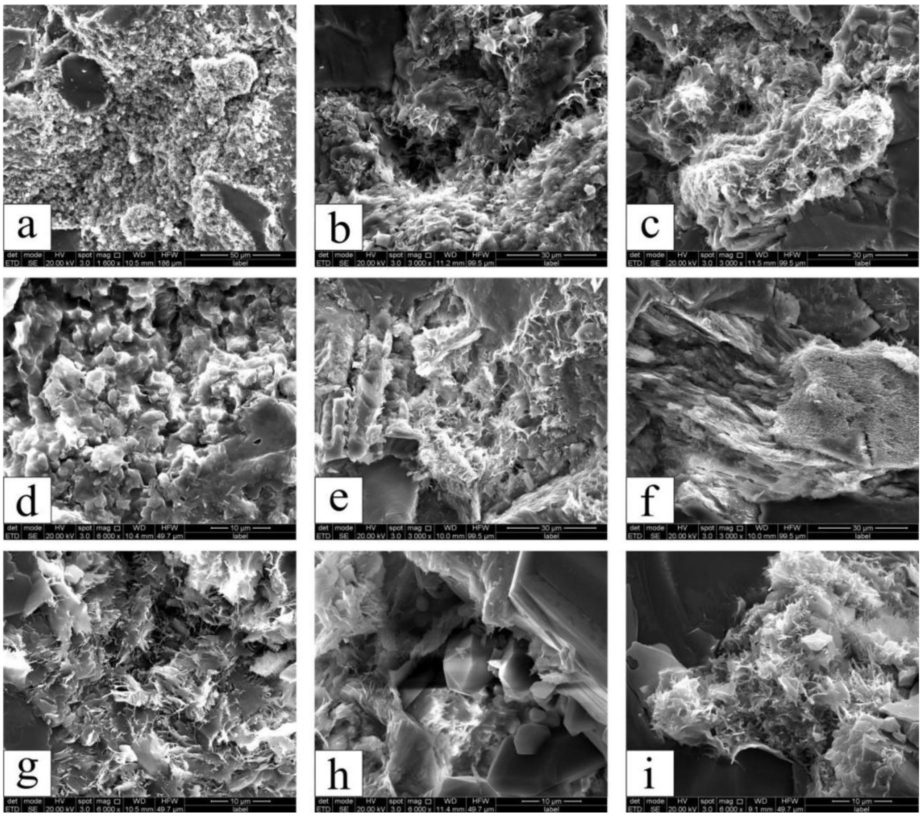
section in the study area can be divided into three main types, such as thin-film type, intergranular pore cementation, and filling type: ① authigenic illite in the form of granular envelope, which is wrapped around the surface of rock particles to form an illite envelope. Most of the ilmenite crystals are in the form of scattered and irregular flakes, and the aggregate has a honeycomb structure (Fig. 5a,b,c), and the coexistence of this type of ilmenite and ilmenite mixed layer can also be observed under the microscope (Fig. 5d). ② Fibrous and scaly ilmenite (Fig. 5e,f), produced at the edge of feldspar and volcanic debris particles that have been subjected to dissolution, grows vertically from the edge of the particles to the interior of the pore space, forming pore lining and bridging distribution on the surface of the particles and within the pore space (Fig. 5g). This type of illite is commonly coeval with kaolinite cementation and authigenic quartz (Fig. 5h). ③Authigenic illite produced as filamentous, velvety, and other crystals. This type of illite is mostly developed in a dispersed form on the surface of particles or in dissolution pores (Fig. 5i).



a: illite envelopes; b: illite envelopes; c: honeycomb, flake, and fibrous illite growing on the surface of feldspar grains; d: ilmenite mixing layers; e: flake illite, growing on the edges of feldspar solifluction grains; f: filamentous illite growing on the surface of volcaniclastic clasts; g: flake illite in a hitchhiking pattern in pore spaces; h: flake illite symbiotic with authigenic quartz: i: flake and fibrous Ilmenite.

Fig. 5 Scanning electron microscope characterization of ilmenite in the long 7 section of the study area

4.2. Causal mechanisms of authigenic illite cementation in Long 7

Authigenic illite is formed mainly in the mesolithic stage, through the transformation of preexisting clay minerals (e.g., montmorillonite, kaolinite), feldspars, and rock debris[14]. The authigenic illite is mainly formed through the transformation of preexisting clay minerals (such as montmorillonite, kaolinite, feldspar and rock debris). Comprehensive analysis of the diagenetic evolution of the Long 7 reservoir in the study area shows that there are two main mechanisms for the genesis of authigenic illite gum in the study area:

4.2.1. Ilmenite of montmorillonite

Volcanic activity was high during the Long 7 depositional period, and the contemporaneous volcanic material contained large amounts of montmorillonite[15,16]. Montmorillonite is converted to transformed illite mainly by both solid-state reactions (1) and dissolution-precipitation (2). Montmorillonite can be deposited primary or formed autochthonously[14]. Thermodynamically, the solid-state reaction mechanism is more soluble than the dissolution-precipitation reaction mechanism[17]. With increasing burial depth, montmorillonite dewatered and began to transform to illite when the formation temperature increased to 70~100°C (Early orogenic B stage). The solid-state reaction is essentially an accounting reaction, so the authigenic illite formed is similar to the preexisting montmorillonite, with monomers being flaky and aggregates having a honeycomb structure.

$$8Al^{3+}+4.5K^{+}+KNaCa_2Mg_4Fe_4Al_{14}Si_{38}O_{100}(OH)\cdot 10H_2O\ \text{(montmorillonite)}\rightarrow K_{5.5}Mg_2Fe_{1.5}Al_{22}Si_{35}O_{100}(OH)_{20}\text{(ilmenite)}\ +Na^{+}+2Mg^{2+}+2Ca^{2+}+2.5Fe^{3+}+3Si^{4+}+10H_2O \quad (1)$$

Dissolution-precipitation reaction is the original montmorillonite dissolved and precipitated to form new ilmenite, which is mostly in the form of slate and fibrous attached to the edges of detrital particles or clay minerals. Because the dissolution-precipitation reaction occurs later than the solid-state reaction, it is often observed under the microscope that fibrous illite grows at the end of the edge of the lamellar illite crystals.

$$1.57KNaCa_2Mg_4Fe_4Al_{14}Si_{38}O_{100}(OH)20\cdot 10H_2O\ \text{(montmorillonite)}\ +3.9K^{+}\rightarrow K_{5.5}Mg_2Fe_{1.5}Al_{22}Si_{35}O_{100}(OH)_{20}\text{(ilmenite)}+1.57Na^{+}+3.14Ca^{2+}+4.28Mg^{2+}+4.78Fe^{3+}+24.66Si^{4+}+57O^{2-}\ +11.4OH^{-}\ +15.7H_2O \quad (2)$$

It is worth noting that with the increase of stratigraphic burial depth and temperature, the ilmenization of montmorillonite can generally last from the ground temperature of 60℃to 120℃ before basically stopping, and the conversion reaction K^+ is generally produced by potassium feldspar in an acidic environment[18]. The silica produced is mostly in the form of authigenic quartz, so it is common for authigenic illite to coexist with authigenic quartz during this period (Fig. 5h). Secondary increase of quartz is common on the surface of rock grains not encapsulated by illite (Fig. 5c) .

4.2.2. Potassium feldspar formation by dissolution

Previous studies have shown that potassium feldspar illite needs to be lithified in a relatively confined diagenetic environment and a weakly acidic-acidic diagenetic fluid environment[19]. The study shows that the lithification of potassium feldspar requires a relatively closed lithogenic environment and weak acidic-acidic lithogenic fluids. With the further increase of the depth of the Long 7 stratum of the Extension Group, the compaction is further strengthened, and the rock-forming system is gradually closed, and the sandstone rock-forming evolution of the reservoir in the Long 7 section enters into the middle rock-forming stage. The organic acid produced by the maturation of organic matter enters the formation water, and under the high temperature acidic environment, potassium feldspar suffers from strong dissolution and dissolves to form a large amount of K^+ , at this time, illite can be directly altered from potassium feldspar, and develops along the feldspathic joints or dissolution surfaces. The reaction is as follows:

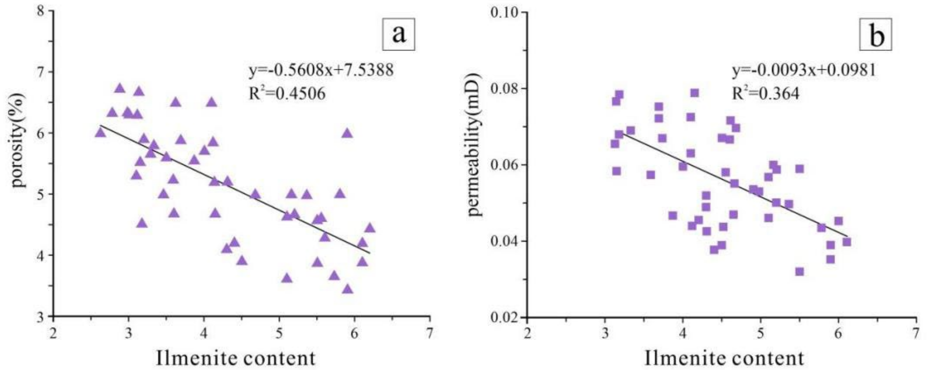
$$3KAlSi_3O_8\ \text{(potassium feldspar)}+H_2O+2H^{+}\rightarrow Al_2Si_2O_5(OH)_4\text{(ilmenite)}+6SiO_2+K^{+} \quad (3)$$

This reaction produces a large amount of siliceous precipitation, and thus ilmenite can be observed under the microscope, accompanied by authigenic quartz.X-diffraction analysis shows that the potassium feldspar content in the Long 7 reservoir sandstone in the study area generally ranges from 2.3% to 9.9%, with an average of about 6.2%. The large amount of acidic dissolution of potassium feldspar is the main cause of illite cementation during diagenetic A stage in the Long 7 reservoir sandstone.

5. Impact on reservoir physical properties

SEM observation and X-diffraction analysis show that authigenic illite is an important pore filler in the Long 7 tight reservoir sandstone in the study area, which has a great influence on the porosity and permeability of the reservoir. On the one hand, previous studies have confirmed that authigenic illite, developed in the form of granular envelope, prevents the secondary increase of quartz to a certain extent and thus protects the preservation of primary pores[20]. On the one hand, previous researchers confirmed that the development of authigenic illite in the form of granular envelope can prevent the secondary increase of quartz to some extent and thus protect the preservation of primary pore space. However, the degree of illite envelope development is relatively low in the Long 7 reservoir sandstone in the study area, and the clastic particles are often seen to be incompletely encapsulated, and secondary quartz production is observed in the unencapsulated areas (Fig. 5a,b). Thus, the influence of illite envelopes on the preservation of primary pores is more limited. On the other hand, since authigenic illite is mostly in crystalline forms such as flakes and fibers with a large specific surface area, the primary pore space as well as the secondary dissolution pore space in the sandstones was divided into a huge number of intergranular micropores. While reducing the pore volume, it also leads to the throat being complicated or even blocking the throat, which ultimately leads to the decline in the quality of sandstone reservoirs.

Statistical results show that the porosity and permeability in the Long 7 sandstone reservoirs decrease with the gradual increase of illite content, indicating that the development of authigenic illite has a negative effect on the physical properties of the reservoirs (Fig 6).



a: Relationship between illite content and porosity; b: Relationship between illite content and permeability.

Fig.6 Plot of long7 illite content versus reservoir physical properties in the study area

6. Conclusions

(1) Long 7 of the Extension Formation in the Shimojiwan area is a typical dense sandstone reservoir, which mainly develops feldspathic feldspathic sandstone and feldspathic feldspathic sandstone, poorly sorted, and dominated by angular-secondary rounded clastic particles. It mainly develops residual intergranular pores and secondary dissolution pores. The average porosity is 7.41% and the average permeability is 0.344mD, characterized by high porosity and low permeability, which is a typical low porosity-dense reservoir.

(2) Ilmenite is the most developed clay mineral in the reservoir of Long Section 7 in the study area, and it mainly exists in three types of production such as thin film, intergranular pore cementation and filling type. Authigenic illite is mainly formed in the mesolithic stage, which is transformed by the pre-existing clay minerals, feldspars and rock debris. In the study area, ilmenite is mainly formed through the transformation of montmorillonite and the dissolution of feldspar in the Long 7 reservoir. In the early diagenetic B stage, when the ground temperature reaches 70~100°C, montmorillonite dehydration starts to transform to illite, and the illite formed through the solid-state reaction is wrapped on the surface of the particles with the characteristics of illite-illite mixed layer, which is dispersed and irregularly lamellar, and the assemblage has a honeycomb structure; the authigenic illite formed through the dissolution-precipitation reaction is fibrous and adheres on the edges of the detrital particles or the clay minerals. In the mesolithic stage, organic acids enter the groundwater and cause the feldspar in the reservoir to be strongly dissolved, and authigenic illite can be formed directly by the dissolution of potassium feldspar under the high-temperature acidic environment.

(3) A large number of authigenic illite developed in the reservoir, and the authigenic illite developed in the form of granular envelope, although it prevents the secondary increase of quartz to a certain extent and thus protects the preservation of primary pore space, it has a very limited role in the construction of reservoir physical properties. Due to the unique structural characteristics of illite, the reservoir pore space will be divided, thus reducing the effective pore space quantity and quality, which has a strong destructive effect on the physical properties of the reservoir. Statistical results show that the total illite content in the Long 7 reservoir in the study area is negatively correlated with both reservoir porosity and permeability.

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