Formation mechanism of authigenic chlorite in tight sandstone and its influence on tight oil adsorption, Triassic Ordos Basin, China

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Abstract
In this study, the formation mechanism of authigenic chlorite in tight reservoirs and its influence on the adsorption capacity to tight oil have been analyzed. The occurrence states of chlorite and the formation mechanism have been analyzed by thin section (TS) and field emission scanning electron microscopy (FE-SEM) measurements. Due to the alteration of volcanic rock fragments, the mudstone pressurized water, and the dissolution of early chlorite, the material source has been provided for the formation of chlorite. The formation time of chlorite with different occurrence states is in the following order: grain-coating chlorite ® pore-lining chlorite ® pore-lining chlorite in dissolved pores ® rosette chlorite. Authigenic chlorite developed in the reservoirs has influenced the change of the reservoir quality in two respects. On the one hand, authigenic chlorite can protect the residual pores, improve the anti-compaction capacity of the reservoir, and provide certain inter-crystalline space. On the other hand, it can hinder pore space and inhibit throat, resulting in a decrease in the connectivity of pores and the increase in the heterogeneity of the reservoir. Tight oil absorbed by the chlorite is mainly in the form of the thin film and aggregates. Through in situ testing of environmental scanning electron microscope (ESEM) and energy dispersive spectrum (EDS), the adsorption capacity of chlorite with different occurrence states to tight oil, being in the following order: rosette chlorite > pore-lining chlorite > pore-lining chlorite in dissolved pores > grain-coating chlorite. Furthermore, the controlling factors on reservoir quality, the content of chlorite and content of Fe and K have been

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investigated, and the adsorption capacity of different chlorite types has been studied, which can provide guidance for analysis of the control factors on the difference in adsorption capacity of different occurrence states of chlorite to tight oil in tight reservoirs.

Keywords
Authigenic chlorite, formation mechanisms, tight oil, adsorption capacity, Ordos Basin

Introduction
With the successful exploration and development of unconventional oil and gas, tight oil and gas have become more and more important in world energy, being the priority choice for energy replacement (Alotaibi et al., 2015; Denne et al., 2014; Jia et al., 2012; Kuhn et al., 2012; Landon et al., 2001; LeFever et al., 2013; Sonnenberg et al., 2018; Wu et al., 2016, 2019; Zou et al., 2012). The tight oil reservoirs in China are mainly lacustrine deposits, and the production of lacustrine tight oil has reached 1.5 million tons per year (Wu et al., 2019). In lacustrine clastic reservoirs, the content and type of clay minerals have a significant influence on the reservoir’s physical properties. Therefore, it is very important to study systematically the clay mineral types and the formation mechanism in order to predicate efficiently the favorable reservoirs. In lacustrine clastic reservoirs, chlorite is the most common clay mineral, and its content and distribution might control the reservoir’s physical properties. In addition, chlorite is an important product of diagenesis, and is significant for the formation of high-quality reservoirs (Ehrenberg, 1993; Zhu et al., 2017). Therefore, it is very important to systematically study the occurrence states and formation mechanism of chlorite. Chlorite is a specific type of clay mineral, with typically high content of iron and magnesium (Worden et al., 2020). The chlorite is well developed at low temperature, prograde metamorphic rocks, in retrograde alteration products of ferroan metamorphic minerals, being a low-temperature alteration product of biotite in acid igneous rocks and a hydrolysis alteration product (Worden et al., 2020). Chlorite is an important constituent of fine-grained sediments deposited in both marine and continental environments. Significantly, chlorite is also an important clay mineral in coarse-grained clastic sediments such as sandstones, especially in the lacustrine sandstone reservoirs (Worden et al., 2020). As an important anti-compaction mineral in sandstones, chlorite has attracted widespread attention for more than 50 years (Huang et al., 2004; Tian et al., 2008; Worden et al., 2020; Yao et al., 2011; Zhou et al., 2016).

At present, the research about chlorite focuses mainly on the types of chlorite, the protective effect of chlorite on reservoir properties, the material source of chlorite and the formation time of different types of chlorite, etc. Huang et al. (2004) considered that the formation of authigenic chlorite is mainly controlled by the mineral properties, the chemical composition of pore fluid, the development of early clay minerals and appropriate pore systems. However, many scholars believe that the development of chlorite was initiated earlier, and had formed completely by the time when quartz underwent secondary enlargement and carbonate cementation (Anna et al., 2009; Zhou et al., 2017). Currently, there are two opinions about the beginning time of chlorite formation. One believes that chlorite was formed immediately after deposition (Grigsby, 2001), and the other believes
that chlorite precipitation occurred between the early diagenetic stage A and the late-middle diagenetic stage (Anna et al., 2009; Tian et al., 2008). Previous studies on chlorite mainly focused on its content, occurrence and distribution (Tian et al., 2008), and its influence on the preservation of primary reservoir pores, in addition to the formation time and formation mechanism (Yang et al., 2012), and its influence on the change of the physical properties of reservoirs (Ding et al., 2010; Huang et al., 2004; Lan et al., 2011). However, there are few studies about the occurrence states, the microstructure and the genetic types of chlorite.

In previous studies, qualitative analysis about the adsorption capacity of chlorite to tight oil has been conducted, with focus mainly on the pores (Ding et al., 2010; Huang et al., 2009; Tian et al., 2008; Zhou et al., 2016, 2017). Through study, it is believed that micrometer pores and nanometer pores are important spaces for storage of tight oil (Gong et al., 2015; Zou et al., 2012). However, minerals are the key to the storage space. The adsorbed tight oil is an important unconventional resource, being significant supplements to the global energy supply and commonly occurs on the surface of pores and minerals (Li and Wu, 2019). It is widely believed that the adsorption capability of different minerals to tight oil, and the charge of rock surface depends mainly on the oil components, mineralogy and morphology properties of the rock. Different from shale, the amount of tight oil that can be absorbed in the pores of tight sandstone is mainly controlled by inorganic minerals (Faghihi et al., 2019). The measure of the adsorption capability of minerals has mainly concentrated on the amount of adsorption of tight oil on the mineral surface in a dilute solution. For example, several studies have indicated that clay minerals have stronger adsorption capacity than quartz and feldspar due to their large specific surface area (Chalmers and Bustin, 2007; Clarkson and Bustin, 1999; Li and Wu, 2019; Ross and Bustin, 2009). However, research on the microscopic relationship between chlorite and tight oil has not yet been reported. In addition, there is no quantitative analysis of the occurrence states of chlorite and the adsorption capacity of chlorite to tight oil. In order to analyze the relationship between tight oil and chlorite, the study about the formation process and types of chlorite should be conducted firstly. Therefore, we conduct the following studies: (1) The occurrence states of chlorite in study area; (2) the adsorption capacity of chlorite to tight oil with different occurrence states; (3) the formation mechanism of authigenic chlorite; (4) the controlling factors on the tight oil adsorption capacity of chlorite with different occurrence states.

The southwest Ordos Basin is the most important area for exploration and development in the PetroChina Changqing oil field (Zhu et al., 2017). In the Chang 8 Member of the Triassic Yanchang Formation, the tight sandstone reservoirs are low porosity, low permeability, with good oil-bearing conditions, containing with large amount of chlorite, and widely distributed (Yao et al., 2011; Zhou et al., 2019). In previous studies, the diverse types of the chlorite in tight sandstone reservoir have been noted in the study area, and their controls on the reservoir quality have been reported (Zhou et al., 2016, 2017). However, there are few analysis about the occurrence states the formation mechanisms of different chlorite, and the relationship between chlorite and its adsorption capacity to tight oil. Therefore, it is very important to study the formation mechanism of authigenic chlorite and its influence on the adsorption capacity to tight oil, which is helpful for reducing the exploration risk before drilling, and predicting the potential resources of adsorbed tight oil in the lacustrine tight sandstone reservoirs.
Geological setting

The Ordos Basin is a large-scale Mesozoic and Cenozoic continental lacustrine sedimentary basin, located on the western margin of the North China platform in eastern China, with an area of about $25 \times 10^4 \text{km}^2$ (Yang and Zhang, 2005). The Huaqing area is located in the southwestern part of the basin, mainly controlled by the northern Yishan slope (Figure 1(a)), which is a simple monocline, with an average structural slope of 1/100, with a series of low-amplitude nose structures developed (Ding et al., 2010). Oil and gas accumulation is not related to the structure but mainly related to lithologic reservoirs (Yao et al., 2011). The results of hydrocarbon exploration and development show that the shallow-lacustrine sand-rich deltas and deep-lacustrine gravity flowing reservoirs are the main reservoir rocks in the Ordos Basin (Figure 1(b)) (Sun et al., 2020). The Yanchang Formation is the main target layer for oil and gas exploration and development in this area (Yang et al., 2016), and the tight oil is sourced from the adjacent Chang 7 source rocks. In addition, the matching of source-reservoir-cap assemblages is excellent. The hydrocarbon resources are abundant and the exploration potential is great in the study (Fu, 2018; Yang and Zhang, 2005).

The Yanchang Formation is about 200–1400 m in thickness, and deposited in a large lacustrine system in the Upper Triassic (Wang et al., 2017). There are ten oil reservoirs (Chang 1 Member to Chang 10 Member) from top to bottom in the Yanchang Formation (Liu et al., 2020). The Yanchang Formation experienced multiple stages of transgression and regression, giving rise to many sets of sandstone and mudstone. The Chang 8 tight oil reservoir is the main exploration and development horizon (Zhao et al., 2018). In the study area, the braided river delta front sub-facies and underwater distributary channels of fan delta front are well developed (Figure 2) (Yang et al., 2016). The Chang 8 oil reservoir in the study area consists mainly of medium-fine lithic feldspar with medium structural maturity, medium-good sorting, mainly sub-angular roundness, and predominated by point-line contact between grains (Ding et al., 2010).
The volcanic materials formed in the same period are widely distributed in the sandstones of the Yanchang Formation, and the biotite is well developed (Zhang et al., 2011). The residual feldspar is mainly albite (or acidic plagioclase), and there is an albition of plagioclase (Huang et al., 2009). During the depositional period of Chang 8 oil reservoir, the water environment has become brackish water (Ding et al., 2010). The enrichment of these rock minerals and the environments of water bodies are favorable for the development of authigenic chlorite.

**Samples and methods**

In the southwest of the Ordos Basin, the tight oil is mainly stored in Chang 8 oil reservoirs of the Triassic Yanchang Formation, and eight samples have been collected, including five samples of oil-immersed sandstones, one sample of oil-spot sandstone, and two samples of oil-traced sandstones (45 × 25 mm) (Table 1). All the core samples have been observed by hand-specimen, with focus on sedimentary characteristics.

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**Figure 2.** Stratigraphic histogram of Yanchang Formation in the study area, southwest of the Ordos Basin (modified from Fu, 2018).
Chlorite has been observed and quantified by a series of laboratory techniques, including thin section, scanning electron microscopy and X-ray diffractions (Ding et al., 2010; Huang et al., 2004; Worden et al., 2020; Zhou et al., 2016). In this study, the thin section (TS), X-ray diffraction (XRD), and field emission scanning electron microscopy (FE-SEM) have been used to ascertain the occurrence states and contents of chlorite. In addition, the environmental scanning electron microscope (ESEM) and energy dispersive spectrum (EDS) have been used to determine the adsorption capacity during in-situ testing. Combined with physical properties and element content, the adsorption capacity and the controlling factors have been determined.

**ESEM observation**

Manometric, concentration, gravimetric, and energy dispersive spectrum methods are common methods for determining the adsorption capacity of mineral surfaces (Busch and Gensterblum, 2011; Gong et al., 2015; Qian et al., 2017), especially the energy dispersive spectrum, which is the most important in-situ testing method. Environmental scanning electron microscopy (ESEM) has been used to observe the pores and throats of oil-bearing sandstone on a micrometer to nanometre scale under a low vacuum mode, and the micro-occurrence states of tight oil have been simultaneously characterized. The X-ray Energy dispersive spectrum (EDS) has been used together with ESEM to quantitatively determine the relative carbon content of hydrocarbons at a detection range between one to several microns (Gong et al., 2015). Quanta FEG450 field emission scanning electron microscope has been used in this experiment, in low vacuum mode with a chamber pressure and working voltage of 10 Pa, 15 kV, respectively, which can prevent the destroying of the original occurrence state of the tight oil. The size of the electron beam spot was 4.5 nm (corresponding beam current value is 7 nA), and the operating temperature was 20°C. An ultra-thin window (UTW) detector has been used in the spectrometer to detect elements with atomic number of 4 (Be) ~92 (U), and the peak value of the same element in the same sample was positively correlated with its content. Because of the difference in micro-pore throat structure and oil and gas filling process between different samples, comparison should not be done simply. The experimental samples are made of oil-bearing core samples (nearly 1 cm×1 cm in Planarar size, and almost 0.1~0.2 cm in height), and the fresh oil-bearing surface has been knocked out with gold-coated and put into the electron

| Sample | Depths (m) | Porosity (%) | Permeability ($\times 10^{-3}$ $\mu$m$^2$) | Lithology | Cores oil-bearing level |
|--------|------------|--------------|---------------------------------|-----------|-------------------------|
| S1     | 2138.10    | 15.00        | 1.250                           | Gray-brown fine sandstone | immersion   |
| S2     | 2192.60    | 11.08        | 0.521                           | Gray-brown fine-silt sandstone | immersion   |
| S3     | 2174.53    | 12.40        | 0.096                           | Gray-brown siltstone      | oil trace   |
| S4     | 2242.40    | 10.20        | 0.406                           | Gray fine sandstone       | oil spot    |
| S5     | 2235.60    | 9.69         | 0.110                           | Gray-brown siltstone      | oil trace   |
| S6     | 2062.20    | 11.18        | 0.740                           | Gray fine sandstone       | immersion   |
| S7     | 2287.45    | 11.68        | 0.568                           | Gray-brown fine sandstone | immersion   |
| S8     | 2189.40    | 13.22        | 0.524                           | Gray-brown fine sandstone | immersion   |
microscope observation chamber quickly to ensure that hydrocarbons are not lost during the observation process.

**Analysis of porosity and permeability**

The eight samples were firstly extracted with chloroform (>99.9%) and dried under vacuum (110°C within 48 h), and then tested for helium porosity and nitrogen permeability using a Pore PDP-200 automatic porosity and permeability measuring instrument under a confining pressure of approximately 150 psi and 500 psi, in accordance with the SY/T 6385–2016 Standard of China. The maximum instrument porosity was 40%, with the relative error less than 0.01%, and the maximum permeability was $10 \times 10^{-3} \mu m^2$, with the corresponding error less than $0.00001 \times 10^{-3} \mu m^2$.

**TS analysis**

Thin sections have been used to characterize the petrology of detrital and the clay composition, pore types and mineral growth order. All samples have been impregnated with blue epoxy under vacuum and covered with coverslips, and stained with alizarin red-S and potassium ferricyanide for carbonate mineral identification. The stain standards are 0.1 g alizarin red-S, 0.5 g potassium ferricyanide and 0.2% HCL, samples were treated with about 1 min, and were observed under Zeiss optical microscope equipped with the Image-Pro Plus software.

**FE-SEM observation**

Field emission scanning electron microscopy (FE-SEM) has been used to characterize the morphology of pores, authigenic clay minerals, carbon cement and the growth order in the samples. All samples (nearly 1 cm × 1 cm in Planarar size, and almost 0.1~0.2 cm in height) with fresh surfaces and gold-coated have been examined under Merlin Compact scanning electron microscope with an accelerating voltage and resolution of 20 V–30 kV and 1.6 nm, respectively. The observation and test have been conducted in accordance with the SY/T5614-2011 Standard of China. The chlorite of different types is easily identified at high magnifications.

**XRD analysis**

The whole-rock and clay fraction mineralogy have been identified using a Rigaku Ultima type IV X-ray diffractometer of Japan (Cu Kα, $\lambda = 0.154$ nm), according to the SY/T 5163–2010 standard (Wu et al., 2019). The samples were hand-milled into powder firstly, and then the whole-rock was identified. Finally the clay component was separated by stock-flotation method and heated at 450°C. The mineral composition has been deduced (Sun et al., 2020).

All experiments have been completed in Lanzhou Oil and Gas Resource Center, Institute of Geology and Geophysics, Chinese Academy of Sciences.

**Results**

**Petrographical and physical properties of sandstone**

Based on the results of the hand-specimen, SEM and thin section analysis, the Chang 8 oil reservoirs have been classified as gray-brown fine lithic arkose and feldspathic arenite, and the rock composition is shown in Table 2. The detrital mineralogy is dominated by quartz grains,
ranging from 21.9% to 48.3%, with an average of 33.2%. The feldspar content changes from 23.7% to 59.2%, with an average of 35.2%, consisting mostly of plagioclase and potash feldspar. The content of volcanic rock fragments ranges from 1.3% to 21.1% (with an average of 11.9%), the content of sedimentary rock fragments ranges from 0.3% to 7.0% (with an average of 3.4%), and the content of metamorphic rock fragments ranges from 3.4% to 35.6% (with an average of 16.3%). Biotite is relatively developed in the study area, and its content ranges from 0.5% to 30.6%, with an average of 4.6%. According to the XRD result, the authigenic clay minerals in Chang 8 oil reservoirs are mainly the chlorite, and the content of chlorite ranges from 6.43% to 9.81%, with an average of 8.02% (Table 3).

Tight sandstones are widely distributed in the study area, and most of them are oil-bearing. The porosity and permeability of the samples are shown in Figure 3. The porosity of these samples ranges from 9.69% to 15.00%, with an average of 11.81%, and permeability ranges from $0.096 \times 10^{-3} \text{m}^2$ to $1.250 \times 10^{-3} \text{m}^2$, with an average of $0.527 \times 10^{-3} \text{m}^2$. There is a positive correlation between porosity and permeability, with a correlation coefficient of 0.461 (Figure 3).

**Occurrence states of authigenic chlorite**

Chlorite in the Chang 8 oil reservoir of the Triassic Yanchang Formation in the study area of the Ordos Basin is mainly authigenic chlorite and altered chlorite. According to the TS and FE-SEM observation of the crystals of authigenic chlorite and their contact with mineral particles, four occurrence states of authigenic chlorite have been identified, including the

### Table 2. Rock composition of Chang 8 oil reservoir.

| Types     | Quartz (%) | Feldspar (%) | Volcanic (%) | Metamorphic (%) | Sedimentary (%) | Biotite (%) | Others (%) |
|-----------|------------|--------------|--------------|-----------------|----------------|-------------|------------|
| Max       | 48.3       | 59.2         | 21.1         | 35.6            | 7.0            | 30.6        | 16.9       |
| Min       | 21.9       | 23.7         | 1.3          | 3.4             | 0.3            | 0.5         | 0.2        |
| Average   | 33.2       | 35.2         | 11.9         | 16.3            | 3.4            | 4.6         | 3.2        |

### Table 3. Mineral composition of Chang 8 oil reservoir in the study area.

| Samples | Quartz (%) | Potash feldspar (%) | Plagioclase (%) | Calcite (%) | Clay (%) | Others (%) | Chlorite (%) | Illite (%) | I/S (%) |
|---------|------------|---------------------|-----------------|-------------|----------|------------|--------------|------------|---------|
| S1      | 58.4       | 9.6                 | 17.2            | —           | 14.4     | 0.4        | 9.81         | 3.82       | 0.77    |
| S2      | 50.3       | 13                  | 20.1            | 1.9         | 12.7     | 1.1        | 7.75         | 3.67       | 1.28    |
| S3      | 51.1       | 9.3                 | 20.1            | 5.6         | 12.4     | 1.5        | 9.80         | 2.27       | 0.33    |
| S4      | 50.1       | 23.5                | 12.5            | 3.8         | 8.7      | 1.4        | 6.43         | 1.01       | 1.26    |
| S5      | 41.4       | 16.6                | 24.1            | 3.7         | 12.4     | 1.8        | 8.57         | 3.21       | 0.62    |
| S6      | 54         | 19.1                | 15.2            | 0.6         | 9.2      | 1.9        | 7.13         | 1.56       | 0.51    |
| S7      | 54.8       | 28.8                | 5.8             | 2.2         | 8.2      | 0.2        | 6.73         | 1.06       | 0.41    |
| S8      | 60.5       | 20.8                | 7.6             | 0.7         | 9.6      | 0.8        | 7.97         | 1.21       | 0.42    |
Grain-coating chlorite (Ch-A), pore-lining chlorite (Ch-B), pore-lining chlorite in dissolved pores (Ch-C) and rosette chlorite (Ch-D) (Jeffry et al., 2001), which are described below.

**Grain-coating chlorite (Ch-A).** This type of chlorite is most common in the study area, and is mainly distributed on the surface of particles (Huang et al., 2004). Single chlorite crystals are tiny, and lie parallel or oblique to the particle surface at the pore contact points and parallel to the particle surface at the particle-particle contact points. Grain-coating chlorite frequently occurs on the surface of particles with a thickness of 1–8 μm (Figure 4(a)).

**Pore-lining chlorite (Ch-B).** This type of chlorite is the primary occurrence form of authigenic chlorite. It is mainly enwrapped on the particle surfaces, only on the surface of granules, with the same pore contact as grain-coating forms. Chlorite crystals grow vertically towards the pore center in a sheet-shape on the surface of the particles, and vertically towards the pore direction in a leaf-shaped or needle-shaped on the inner coating. The closer to the pore, the better their self-formation, and the thinner their leaves. The thickness of pore-lining chlorite is generally 3–10 μm, but some can reach to 16 μm (Figure 4(b)).

**Pore-lining chlorite in dissolved pores (Ch-C).** This type of chlorite mainly occurs in the dissolved pores, especially the feldspar dissolved pores. This type of chlorite is similar to that of pore-lining chlorite, grown primarily in the shape of a sheet, perpendicular to the pores, and can grow out of the dissolved pores, but still controlled by the dissolved pore size (Figure 4(c)).

**Rosette chlorite (Ch-D).** This type of chlorite covers the surface of particles directly or as pore-lining chlorite, being highly self-formation, as a rosette aggregate (Figure 4(d)), often distributed in pores, with no inherited growth relationship with granular encapsulated chlorite. The size of rosette-like chlorite in the study area ranges from 5 μm × 12 μm to 12 μm × 18 μm.
Tight oil adsorption capacity to of chlorite with different occurrence states

Figure 5 shows the ESEM images and EDS results of tight oil adsorbed on authigenic chlorite with different occurrence states. As shown in the EDS results (Figure 5(a2-d2)), the main enrichment elements are C, Si, Al, Fe, Mg, etc. The results indicate that tight oil adsorbed on the chlorite in the reservoirs, which is consistent with previous study (Qian et al., 2017). Chlorite in different occurrence states controls the adsorption form and capacity of tight oil. The tight oil adsorbed on grain-coating chlorite is in thin film form with unequal thickness, having the characteristics of light and shade on the ESEM image (Figure 5(a1)), and the corresponding carbon content is 4.50% (Figure 5(a2)). For the pore-lining chlorite, adsorbed tight oil is in the thin film form, with small amount of aggregates (Figure 5(b1)). The thickness is obviously thicker than the grain-coating chlorite, with brighter white color under ESEM, and the corresponding carbon content is 14.71% (Figure 5(b2)). And the adsorbed tight oil on the pore-lining chlorite in dissolved pores is similar to the pore-lining chlorite (Figure 5(c1)), and the corresponding carbon content is 6.57% (Figure 5(c2)). While the adsorbed tight oil on the rosette chlorite has a better brightness, and mostly in the form of pellets (Figure 5(d1)), and the corresponding carbon content is 21.88% (Figure 5(d2)).

Based on the results of 128 EDS points, the adsorption capacity of chlorite to tight oil are diverse in different samples (Figure 6). Sample 1 has the highest carbon content, with an average of 30.33%. In contrast, sample 7 has the lowest carbon content, with an average of 13.53%. As shown in Table 4, the adsorption capacities of chlorite with different occurrence
Figure 5. The adsorption capacity of tight oil with different occurrence states of chlorite types. (a1) The thin film form of grain-coating chlorite, Sample S3, 2174.53 m, ESEM; (a2) Corresponding EDS result of (a1); (b1) The thin film form and aggregates form of pore-lining chlorite, Sample S2, 2138.10 m, ESEM; (b2) Corresponding EDS result of (b1); (c1) The thin film form and aggregates form of pore-lining chlorite in dissolved pores, Sample S5, 2235.60 m, ESEM; (c2) Corresponding EDS result of (c1); (d1) The aggregates form of pore-lining chlorite, Sample S4, 2242.40 m, ESEM; (d2) Corresponding EDS result of (d1).

Ch-A = grain-coating chlorite; Ch-B = pore-lining chlorite; Ch-C = pore-lining chlorite in dissolved pores; Ch-D = rosette chlorite.
states are quite different. The rosette chlorite has a stronger adsorption capacity to tight oil, ranging from 15.78% to 74.55%, with an average of 33.02%. However, the grain-coating chlorite has the lowest adsorption capacity to tight oil, with the carbon content ranging from 3.32% to 11.44%. The adsorption capacities of pore-lining chlorite range from 13.25% to 27.25%.

![Figure 6. The adsorption capacity of tight oil with different occurrence states of chlorite in the study area.](image)

### Table 4. The adsorption capacity of tight oil with different chlorite types in the study area.

| Samples | Test points | Grain-coating chlorite | Pore-lining chlorite | Rosette chlorite | Pore-lining chlorite (dissolved pores) |
|---------|-------------|------------------------|----------------------|------------------|----------------------------------------|
| Sample 1| 14          | 7.72–11.44             | 24.07–45.12          | 38.18–74.55      | 21.54–27.39                           |
|         |             | 9.58                   | 32.47                | 46.65            | 24.47                                  |
| Sample 2| 27          | 4.92–9.68              | 12.73–38.07          | 24.36–47.54      | 13.81–38.72                           |
|         |             | 7.58                   | 24.08                | 40.95            | 16.77                                  |
| Sample 3| 10          | 4.07–6.86              | 19.12–30.97          | 16.88–32.37      | 17.03–22.35                           |
|         |             | 5.47                   | 25.05                | 26.21            | 19.69                                  |
| Sample 4| 14          | 4.03–9.5               | 20.00–33.73          | 19.33–31.42      | 11.77–12.50                           |
|         |             | 5.22                   | 26.34                | 25.38            | 12.14                                  |
| Sample 5| 15          | 3.93–11.28             | 13.25–21.36          | 21.42–44.38      | 6.32–16.68                            |
|         |             | 4.66                   | 18.44                | 33.86            | 12.05                                  |
| Sample 6| 12          | 4.59–6.31              | 14.25–56.60          | 15.78–23.03      | 16.00–18.53                           |
|         |             | 5.45                   | 27.07                | 20.04            | 17.27                                  |
| Sample 7| 18          | 3.32–6.47              | 28.49–31.78          | 32.35–49.38      | 14.46–20.61                           |
|         |             | 4.43                   | 30.14                | 37.49            | 18.66                                  |
| Sample 8| 18          | 3.53–10.39             | 18.08–45.53          | 19.42–34.52      | 15.04–29.21                           |
|         |             | 7.68                   | 32.44                | 29.29            | 20.76                                  |
| Average |             | 7.02                   | 27.25                | 33.02            | 19.24                                  |

Table 4. The adsorption capacity of tight oil with different chlorite types in the study area.
to 56.60%, with an average of 27.25%. But the adsorption capacities of pore-lining chlorite in dissolved pores range from 6.32% to 38.72%, with an average of 19.24%.

**Discussion**

*Formation mechanism of authigenic chlorite*

Authigenic chlorite was precipitated predominantly in diagenetic fluids with high pH value (alkali-rich environment) and rich in Fe$^{2+}$ and Mg$^{2+}$, and is widely distributed in Mesozoic-Cenozoic lacustrine sandstone reservoirs in Ordos Basin (Huang et al., 2004). The mineral characteristics, growth order and element percentage under microscope are used to determine the formation time and formation environment of authigenic chlorite (Ding et al., 2010; Huang et al., 2004).

**Material source.** The growth of chlorite in the reservoir is related to the supply of corresponding ions in the pore fluid medium. Therefore, the diagenetic environments of the reservoir should be determined first. According to the EDS analysis of different occurrence states of chlorite (Ch-A and Ch-B) in the study area (Figure 7), the contents of Mg$^{2+}$ and Al$^{3+}$ are similar in different occurrence states of authigenic chlorite, but the contents of Fe$^{2+}$ in pore-lining chlorite decrease from the core to the margin of the lining chlorite zone. This result indicates that during the formation of chlorite, Fe$^{2+}$ has been consumed, and a lot of Fe$^{2+}$ has been formed in the formation water. Therefore, the chlorite was developed in a semi-closed diagenetic system, and the formation water was always flowing, with the entrance and exit of ions (Ding et al., 2010).

The chlorite in the Chang 8 oil reservoir is iron-rich, mainly composed of brunsvigite and diamante (Zhang et al., 2011; Zhou et al., 2017). The material source is the key to explaining the formation mechanism. Chlorite is a kind of layered silicate mineral, mainly formed in an iron-rich, alkaline-reduction environment (Huang et al., 2004). The sedimentary environment of the Chang 8 oil reservoir of the Yanchang Formation in the study area was the delta front sedimentary environment, rich in biotite and feldspar sandstone, and the water environment had become the main brackish water body (Ding et al., 2011; Lan et al., 2011). A large amount of iron-rich magnesium minerals carried by the river deposited by flocculation, providing a source of iron-magnesium materials required for the formation of grain-coating chlorite (Yao et al., 2011). This is one of the reasons for the highest content of iron and magnesium in the early grain-coating chlorite. In addition, the volume fraction of iron and magnesium in volcanic debris and plastic debris (mainly mica, slate and phyllite) in the sandstone deposits is over 10%, and the hydrolyzation and dissolution during the depositional stage have also provided the material source for the formation of grain-coating chlorite (Yao et al., 2011). Biotite and chlorite have similar crystal structures, chlorite grows directly on the detrital biotite, allowing easy identification of alteration process (Worden et al., 2020). As shown in Figure 8(a), the chloritization of biotite during the process of rock formation was obviously in this study area. These thin crystals are roughly distributed along the extension direction of the cleavage Planar of biotite. This phenomenon may be related to the hydrolysis or replacement of biotite (Morad and Aldahan, 1986). When the Mg$^{2+}$ replaced K$^+$ and Fe$^{2+}$ ions in the biotite crystal, and formation water entered into the biotite crystals to become structural water; biotite \( [K[(Mg,Fe)\_3[AlSi_2O_{10}](OH)]_2] \) was thus transformed into chlorite \( (Fe_{14}Mg_{12}Al_{2.5})(Al_{0.7}Si_{3.3})O_{10}(OH)_{8} \) (Tian et al., 2008;
Xiao and Chen, 2020; Zhu et al., 2017). The detailed chemical reaction formula is shown in formula (1) or (2).

\[
\begin{align*}
K \{ (Mg, Fe)_3 [AlSi_3 O_{10}] (OH)_2 \} + Mg^{2+} + H_2O &\rightarrow \\
(Fe_{14}Mg_{12}Al_{2.5})(Al_{0.7}Si_{3.3})O_{10}(OH)_8 + Fe^{2+} + K^+ + H^+ &\text{(Chlorite)}
\end{align*}
\]
The EDS result of Figure 5(a2) shows the high content of Ti, the main element of igneous accessory mineral, revealing that igneous accessory mineral compound also tends to be enrichment in grain-coating chlorite. This phenomenon also verifies the fact that the volcanic rocks fragments have the minerals rich in iron-magnesium, which provided the material source for the formation of chlorite. According to the result of EDS (Table 5), the content of Fe and Mg is the highest in grain-coating chlorite, which is consistent with the results of the previous study (Wooldridge et al., 2019).

Due to the above reasons, the iron content of the pore fluids within the sandstone increased continuously. When the high content of iron and magnesium ion in the pore fluid reached a certain level, chlorite was precipitated from the alkaline pore water

\[
K\{(\text{Mg, Fe})_3[\text{AlSi}_3\text{O}_{10}](\text{OH})_2\} + \text{H}^+ \rightarrow \\
(\text{Biotite}) \\
(\text{Fe}_{14}\text{Mg}_{12}\text{Al}_{2.5})(\text{Al}_{0.7}\text{Si}_{3.3})\text{O}_{10}(\text{OH})_8 + \text{Fe}^{2+} + \text{K}^+ + \text{SiO}_2
\]

(Chlorite)

The EDS result of Figure 5(a2) shows the high content of Ti, the main element of igneous accessory mineral, revealing that igneous accessory mineral compound also tends to be enrichment in grain-coating chlorite. This phenomenon also verifies the fact that the volcanic rocks fragments have the minerals rich in iron-magnesium, which provided the material source for the formation of chlorite. According to the result of EDS (Table 5), the content of Fe and Mg is the highest in grain-coating chlorite, which is consistent with the results of the previous study (Wooldridge et al., 2019).

Due to the above reasons, the iron content of the pore fluids within the sandstone increased continuously. When the high content of iron and magnesium ion in the pore fluid reached a certain level, chlorite was precipitated from the alkaline pore water

| Table 5. The main element content of chlorite with different occurrence states in the study area. |

| Types                  | Test points | Na       | Mg        | Al        | Si        | K          | Fe         |
|------------------------|-------------|----------|-----------|-----------|-----------|-------------|------------|
| Grain-coating chlorite | 30          | 1.52–6.95| 3.69–29.38| 11.13–32.48| 14.46–61.71| 0.71–6.46   | 3.02–67.93 |
| Pore-lining chlorite   | 51          | 0.63–16.98| 2.81–18.21| 7.92–33.64| 14.20–76.79| 1.25–8.06   | 6.45–31.57 |
| Pore-lining chlorite   | 6.36        | 10.63    | 24.36     | 43.05     | 3.68      | 18.22       |
| Pore-lining chlorite   | 23          | 2.61–17.80| 1.39–30.86| 5.05–34.11| 32.82–91.00| 1.14–7.19   | 1.42–23.06 |
| Rosette chlorite       | 24          | 1.73–3.76| 2.2–30.83 | 17.98–44.30| 27.41–62.24| 1.06–2.99   | 4.59–35.98 |
|                        | 2.46        | 8.47     | 27.78     | 41.71     | 2.12      | 23.25       |

Figure 8. The chloritization of biotite and feldspar during the process of rock formation. (a) Photomicrograph of FE-SEM showing the chloritization of biotite, Sample S7, 2187.45 m; (b) Photomicrograph of FE-SEM showing the chloritization of feldspar, Sample S8, 2189.40 m. Ch-A = grain-coating chlorite; Ch-C = pore-lining chlorite in dissolved pores, Bt = biotite; Fsp = feldspar.
(Worden et al., 2020). As shown in Figure 8(b), the chloritization of feldspar also occurred in the study area, which may be related to the dissolution of feldspar. When the feldspar was dissolved during deposition, the chemical properties of fluids changed. During this process, the early formation water was rich in iron and magnesium ions, thus promoting the alteration of potassium feldspar. With increase in burial depth and ground temperature, potash feldspar was transformed into chlorite when the formation was rich in magnesium ions and was weakly alkaline (Jeffry, 2001; Worden et al., 2020; Yao et al., 2011). This is the main reason for the formation of chlorite in feldspar dissolved pores (Figure S1). The detailed chemical reaction formula is shown in formula (3) and (4).

\[
\begin{align*}
\text{KAlSi}_3\text{O}_8 + \text{Fe}^{2+} + \text{Mg}^{2+} + \text{H}_2\text{O} & \rightarrow (\text{Fe}_{14}\text{Mg}_{12}\text{Al}_{2.5})(\text{Al}_{0.7}\text{Si}_{3.3})\text{O}_{10}(\text{OH})_8 \\
\text{Potash feldspar} & \quad \text{(Chlorite)} \\
+\text{SiO}_2 + \text{H}^+ + \text{K}^+ & \\
\text{NaAlSi}_3\text{O}_8 + \text{Fe}^{2+} + \text{Mg}^{2+} + \text{H}_2\text{O} & \rightarrow (\text{Fe}_{14}\text{Mg}_{12}\text{Al}_{2.5})(\text{Al}_{0.7}\text{Si}_{3.3})\text{O}_{10}(\text{OH})_8 \\
\text{Potash feldspar} & \quad \text{(Chlorite)} \\
+\text{SiO}_2 + \text{H}^+ + \text{Na}^+ & 
\end{align*}
\]

According to the results of EDS, the pore-lining chlorite in dissolved pores has similar element content with grain-coating, with a higher content of Na and K (Table 5), which indicates that the dissolution of feldspar is one of the material sources. The main reason for this is that the pore-lining chlorite in the dissolved pore is rich in Na and K ions than other occurrence states of chlorite. However, due to the continuous consumption of iron ions, the content of iron ions in the pore-lining chlorite in dissolved pore is lower than that of other chlorite.

Pore-lining chlorite is similar to grain-coating chlorite, but it is not clear about the origin of pore-lining chlorite. Some pore-lining chlorite possibly originated when the thick grain-coating chlorite grew so extensively that they blocked pore throats and then filled pores (Armitage et al., 2013). Other types of pore-lining chlorite probably originated from volcanic rock fragments or possibly allogetic lithic grains rich in Fe and Mg (Worden et al., 2020). In this study, there has obvious inheritance between the pore-lining chlorite and the grain-coating chlorite (Figure 4). Therefore, the material source of pore-lining chlorite may be provided by iron-rich magnesium minerals (such as volcanic rock fragments or biotite) and feldspar dissolution.

From the grain-coating chlorite and pore-lining chlorite in the development site of rosette chlorite, it can be seen that obvious dissolution occurred (Figure 4(d)), which may provide the material source required for the formation of rosette chlorite. In addition, the mudstone pressurized water may provide a large amount of iron and magnesium needed for the formation of rosette chlorite during the hydrocarbon charging process (Huang et al., 2009; Zhou et al., 2019). The sufficient material source is an important reason for the formation of rosette chlorite rich in iron ions. This is the main reason why a lot of authigenic quartz have been developed in the development site of rosette chlorite (Figure 4(d)).

**Formation time.** The formation time of chlorite with different occurrence states can be recognized by the contact relationship between particles and cement of authigenic chlorite.
(Huang et al., 2004; Tian et al., 2008). Under the TS and FE-SEM, the grain-coating chlorite decreases in thickness obviously (Figure 9(a)), while the pore-lining chlorite is uniform in thickness (Figure 9(b)). This indicates that the formation time of grain-coating chlorite is earlier, but later than the initial compaction stage (synsedimentary stage) (Ding et al., 2010). According to the double-layer structure characteristics of the chlorite under the SEM (Figures 4(b) and 7), the development of the pore-lining chlorite is obviously later than the development of the pore-coating chlorite. Besides, after the formation of pore-lining chlorite, the quartz crystallites is still visible, which are mainly developed in the residual intergranular pores cemented by the chlorite rim, and the chlorite blades are often embedded in the quartz crystallites (Figure 9(c)). This indicates that the formation time of quartz crystallites is later than that of pore-lining chlorite. The grain-coating chlorite on the surface of feldspar particles has undergone intragranular dissolution, and still maintained its original appearance (Figure 9(d)), which indicates that the formation time of grain-coating chlorite is earlier than the dissolution. Furthermore, a small amount of pore-lining chlorite is developed within the feldspar dissolution pores, which suggests that the fluid in the pore is favorable for the growth of authigenic chlorite following feldspar particle dissolution (Ding et al., 2010; Tian et al., 2008). Under the SEM, the rosette chlorite is distributed on the

Figure 9. TS and FE-SEM characteristics of authigenic chlorite. (a) Grain-coating chlorite developed in pores. No chlorite rims in grain contacts. Sample S1, 2138.10 m, TS; (b) Chlorite rim developed in residual pores. Sample S4, 2242.40 m, TS; (c) Rare crystal plates of chlorite insert authigenic quartz, showing the time sequence. Sample S3, 2174.53 m, FE-SEM; (d) Chlorite developed on the particle surface or in the dissolved pores. Sample S7, 2187.45 m, FE-SEM. Ch-A = grain-coating chlorite; Ch-B = pore-lining chlorite; Ch-C = pore-lining chlorite in dissolved pores; Ch-D = rosette chlorite.
surface of the pore-lining chlorite (Figure 4(d)), indicating that the formation of rosette chlorite is later than that of the pore-lining chlorite. The pore-lining chlorite in dissolved pore and the rosette chlorite are both belong to the pore-filling chlorite (Zhou et al., 2017). The content of rosette chlorite is small, the crystal size is large, and the degree of self-shape is high. There is no obvious vertical or parallel relationship between the crystal extension direction and the particle surface. Comparing the crystalline forms of rosette chlorite and pore-lining chlorite in dissolved pore, it is generally believed that the formation of rosette chlorite is late (Zhou et al., 2019). Therefore, the chlorite formation may be mainly followed by the order: grain-coating chlorite (Ch-A) → pore-lining chlorite (Ch-B) → pore-lining chlorite in dissolved pores (Ch-C) → rosette chlorite (Ch-D).

Chlorite, a kind of aluminosilicate clay rich in Fe$^{2+}$ and Mg$^{2+}$, may be either detrital or authigenic in sandstones (Worden et al., 2020). Based on the origin and morphological characteristics of authigenic chlorite, combined with the diagenesis process of Chang 8 sandstone in the study area (Tian et al., 2008; Yao et al., 2011; Zhou et al., 2019), the formation process of authigenic chlorite has been analyzed, and can be divided into four stages (Figure 10). Through this study, the formation mechanism of chlorite in the study area has been made clear.

Stage A: the formation stage of grain-coating chlorite. During stage A of the early diagenesis period, the original pores were filled with formation water. The early river sediments carried a large amount of iron and magnesium ions in Chang 8 sandstones, and a lot of iron and magnesium ions were released into the sandstones due to the hydrolysis of volcanic debris (including slate, phyllite, biotite). With the accumulation of these cations continuously, the pore water was converted from acidic to alkaline, providing sufficient material source and diagenetic environment for the formation of grain-coating chlorite.

Stage B: the formation stage of pore-lining chlorite. Due to the hydrocarbon charge during stage A of the early diagenesis period, the water environment had been changed,
and promoted the early potassium enrichment. The dissolution of sodium minerals also provided a large amount of K and Na ions. This is an important factor for the formation of pore-lining chlorite which is rich in K and Na ions. The pore water medium gradually became alkaline, promoting the precipitation of chlorite. During this period, in the iron-magnesium-rich alkaline environment, chlorite crystals could continuously precipitate out of the pore water, and grow vertically toward the pore center. At this stage, due to the large pore space and sufficient material supply, the precipitated chlorite crystals are coarse and have a high degree of self-formation.

Stage C: the formation stage of pore-lining chlorite in dissolved pores. At the beginning of the stage A of middle diagenesis period, due to the hydrocarbon charge, a large amount of acidic substances were carried into the reservoir by oil and gas, and the medium changed from alkaline to acidic. The acidic conditions could inhibit the precipitation of chlorite, and the pore-lining chlorite stopped growing at this stage. When the feldspar was dissolved, abundant K and Na ions were provided. The K and Na ions are difficult to be discharged in the dissolved pores, and an alkaline micro-environment formed gradually, promoting the precipitation of chlorite in the dissolved pores. Due to the narrow space of the dissolved pores, the crystals of this occurrence state of chlorite are small, poorly crystallized and disordered. In addition, pore-lining chlorite in the dissolved pores is formed, with the characteristics of rich in K\(^+\) and Na\(^+\), and poor in Fe\(^{2+}\) and Mg\(^{2+}\).

Stage D: the formation stage of rosette chlorite. During the hydrocarbon filling process, the mudstone pressurized water provided a large amount of iron and magnesium ions. These materials can provide the material source required for the formation of rosette chlorite after the formation of water was converted to alkaline. The rosette chlorite could grow in residual inter-granular pores. Therefore, the rosette chlorite is characterized by coarse crystal and high degree of crystal self-formation.

The influence of authigenic chlorite on reservoir quality

The reservoir quality is dependent on the pore network, which is controlled by residual pore conservation in general. Chlorite can indiscriminately coat all framework grains, including quartz, K-feldspar, plagioclase, Fe-ooids, and lithic grains (Worden et al., 2020). The chlorite grows as crystals that are perpendicular to grain surfaces, typically forming extensive coats, commonly covering all exposed surfaces. As the grain-coating chlorite developed, it can prevent the supersaturated silica from accessing quartz grain surfaces to grow quartz by normal epitaxial processes (Huang et al., 2004). Therefore, the pore-coating chlorite can help to prevent the destruction of residual pores. The development of minerals and their resistance to compaction is also the key factor in controlling the quality of reservoirs. According to a large number of TS and FE-SEM results, in the region with grain-coating developed, the authigenic quartz is relatively little (Figure 4(a) and (b)). In contrast, in the area with no grain-coating chlorite or the grain-coating chlorite is thin, there is a large amount of authigenic quartz (Figures 4(d) and 9(d)). This illustrates that the grain-coating chlorite can prevent authigenic quartz from nucleating on the surface of detrital quartz and restrain the development of authigenic quartz (Worden et al., 2020). Figure 11(a) shows that quartz and chlorite is a key factor in protecting the primary pores from being destroyed in reservoirs, which is consistent with the previous researches (Baker et al., 2000; Ding et al., 2010; Ehrenberg, 1993; Huang et al., 2004; Liu et al., 2009; Pittman, 1992; Salman et al., 2002; Yao et al., 2011). The quartz and chlorite both have a strong positive
relationship with porosity, and the correlation coefficient is 0.654 and 0.337, respectively (Figure 11(a)). This indicates that the presence of chlorite is favorable for the preservation of reservoir porosity. However, poorly sorted sediments often have lower primary-depositional porosity, and more susceptible to pore-filling chlorite (include the pore-lining chlorite, pore-lining chlorite in dissolved pore and rosette chlorite). As shown in Figure 11(b), the chlorite has no contribution to the permeability, which reveals that with the development of chlorite, the pore-throat connectivity has no significant change. This may be related to the growth of chlorite in the pore and throats, especially the pore-filling chlorite, which is detrimental to reservoir quality because it occupied pores (reducing porosity), and blocked the throats (reducing permeability). Due to the double action of chlorite on the reservoir quality, there are no changes in the permeability of the reservoir.

In order to better illustrate the influence of chlorite on reservoir quality, the reservoir quality factor is introduced (Q factor = $\sqrt{\frac{K}{\varphi}}$). Where the $\varphi$ and K are the porosity and permeability of reservoirs, respectively (Gong et al., 2015). The Q factor of the reservoir reflects the pore-throat connectivity and uniformity of the reservoir. The closer the value is to 1, the better the reservoir quality. The relative plot between chlorite content and Q factor is shown in Figure 12, which is helpful in study the controlling factors of chlorite on reservoir quality. The content of chlorite has a negative correlation with the Q factor, with correlative coefficient of 0.238. It shows that the development of chlorite has two sides to the change of reservoir quality. On the one hand, these authigenic chlorites can hinder the pore space and inhibit the throat, resulting in reducing the connectivity of pores, and increasing the heterogeneity of the reservoir. On the other hand, there are some positive influences on reservoir quality. For example, authigenic chlorite can protect the residual pores and improve the anti-compaction capacity of the reservoir, and provide individual intercrystaline space for tight oil stored. These indirect controlling factors also have significant influence on the pore development at the later stages.

The controlling factors of the adsorption capacity of chlorite with different occurrence states

The relationship between adsorption capacity and physical properties. The factors influencing the adsorption capacity of the reservoir include the reservoir’s physical properties, the mineral properties, and the oil component (Taheri-Shakib et al., 2019). In traditional adsorption
simulation experiments, the samples are usually crushed into powders or use single mineral directly (Su et al., 2018; Sui et al., 2020). In these experiments, the possible influence of reservoir physical properties on adsorption capacity has been ignored (Szymula and Marczewski, 2002). Therefore, the adsorption capacity of chlorite to tight oil in the reservoir is different from the simulation experiment of single mineral adsorption. The adsorption capacity of chlorite may be controlled by the size of the storage space and storage performance. In order to make clear about whether there is a connection between the physical properties and chlorite, in this study, the relationship between the Q factor and the carbon content with different chlorite has been established (Figure 12). The Q factor contained in eight samples suggested that Q factor is not relative to adsorption capacity of chlorite (Figure 13(a)). This may be related to the occurrence states of chlorite. To further compare the relationship between the adsorption capacity and chlorite with different occurrence

![Figure 12](image1.png)

**Figure 12.** The relationship between the content of chlorite and Q factor.

![Figure 13](image2.png)

**Figure 13.** The relationship between chlorite adsorption capacity and reservoir quality. (a) Adsorption capacity of total chlorite, (b) Adsorption capacity of chlorite with different occurrence states.
states, the relationship between Q factor and the carbon content with grain-coating chlorite, pore-lining chlorite, rosette chlorite and pore-lining chlorite in dissolved pores has been found (Figure 13(b)). It is found that only the pore-lining chlorite and grain-coating chlorite are positive relative to Q factor, with the correlative coefficient of 0.338 and 0.191 respectively. The results indicate that only chlorite developed in regions with good pore-throat connectivity might have a positive influence on adsorption capacity. Note that the current quality of tight sandstone reservoirs has been comprehensively affected by original pores and throats and mineral diagenesis. Because the physical properties of the reservoir are not the main reason for the difference in the adsorption capacity of chlorite, then the influence of the properties and the content of chlorite on its adsorption capacity should be discussed.

The relationship between adsorption capacity and the element content of chlorite. According to the study results, the adsorption capacity of chlorite with different occurrence states is in the following order: rosette chlorite > pore-lining chlorite > pore-lining chlorite (dissolved pores) > grain-coating chlorite (Table 4). In order to solve the problem of the difference in adsorption capacity of different occurrence states of chlorite, the mechanisms of why tight oil can be adsorbed on the surface of chlorite should be studied first. The adsorption of tight oil on the mineral surface is the result of the change in zeta potential under specific reservoir conditions (Alotaibi et al., 2011), with the tight oil having a negative surface potential (Hiorth et al., 2010). Therefore, if the mineral surface charge is positive, the negative charge oil will be adsorbed on the mineral surface. Previous studies have shown that extra divalent cations in the reservoirs would produce more positive charges on the rock surface, which acted as attractive sites for negative ends of polar components in crude oil (Alotaibi et al., 2011; Xu et al., 2008). Moreover, the minerals contained more Fe\(^{2+}\) have stronger positive charge than other divalent cations (Xi et al., 2019). Besides, the chlorite is rich in iron ions, and the content of Fe\(^{2+}\) is the key factor for adsorption capacity of chlorite. Similarly, when Fe\(^{2+}\) replaces Al\(^{3+}\) in the chlorite crystals, disrupting the original balance, it is bound to adsorb monovalent cations between chlorite crystal layers, especially K\(^+\) (Tian et al., 2008; Xi et al., 2019). The adsorption of interlayer cations can further promote the adsorption of electronegative polar components in tight oil (Qian et al., 2017). Therefore, the content of K\(^+\) is also the key factor for adsorption capacity of chlorite. Chlorite is the carrier of tight oil adsorption, and its content will inevitably influence the adsorption capacity. Figure 14 indicates that the content of chlorite is a key factor for methane adsorption capacity of chlorite in tight sandstone reservoirs. The percentage of chlorite has influenced the adsorption capacity greatly, with R\(^2\) as high as 0.442, which means that during oil and gas infilling period, the higher chlorite content in the reservoir, the more tight oil can be absorbed by chlorite. Therefore, the adsorption capacity of chlorite in tight reservoirs is mainly determined by its content. Previous studies also reported the positive correlation between minerals and the adsorption capacity (Marcano et al., 2020; Pernyeszi et al., 1998).

The mineral content is the final result of the various elements that make up the mineral aggregate, and the various elements are the main reason for the difference in adsorption capacity. The EDS results showed the elemental composition of chlorite in different developmental degree. The EDS results of Figure 5 showed that various chlorites have different carbon content and element content. Therefore, the relationship between adsorption capacity and element content of different occurrence states of chlorite has been established (Figure 15). The content of Fe\(^{2+}\) and K\(^+\) of all the grain-coating chlorite is a positive correlation with the carbon content, with the correlation coefficient of 0.497 and 0.378,
respectively (Figure 15(a)). This result indicates that for the grain-coating chlorite, the key to influence the adsorption capacity of chlorite is the properties of the minerals. This may be related to the fact that the Al$^{3+}$ inside the chlorite crystal has been continuously replaced by Fe$^{2+}$, and the charge balance of the chlorite crystal has been destroyed, promoting the
attraction of related ions in the layers or interlayer, and thus promoting the adsorption of negativity organic molecules in the tight oil. In addition, when Si$^{4+}$ in silicate tetrahedron on the lattice surface in chlorite are replaced by Al$^{3+}$, which has a strong adsorption capacity for interlayer K$^+$, Al$^{3+}$ can absorb negativity organic molecules in the tight oil.

In addition, according to the results of EDS, the content of Fe$^{2+}$ and K$^+$ contained by all the pore-lining chlorite is a negative correlation with the carbon content, with the correlation coefficient of 0.259 and 0.436, respectively (Figure 15(b)). This shows that for pore-lining chlorite, the adsorption capacity of tight oil may not be completely affected by the property of the minerals. Combined with the previous analysis, the adsorption capacity of this type of chlorite to tight oil may be more affected by the reservoir quality. The adsorption capacity of rosette chlorite to tight oil has an obvious positive correlation with K$^+$, with the correlation coefficient of 0.847 (Figure 15(c)). This result indicates that the adsorption capacity of rosette chlorite to the tight oil may mainly controlled by the content of K$^+$, which is distributed in interlayer. The adsorption capacity of pore-lining chlorite in dissolved pores has no relative to the content of K$^+$, while has positive relative to Fe$^{2+}$, with the correlation coefficient of 0.531 (Figure 15(d)). This indicated that this type of chlorite could absorb tight oil, which may be related to the fact that the Al$^{3+}$ inside the chlorite crystal was continuously replaced by Fe$^{2+}$. This result shows that for different occurrence states of chlorite, the adsorption mechanism of tight oil may also be different.

Conclusion

A systematic study has been carried out to investigate the formation mechanism of authigenic chlorite in tight sandstone and its influence on adsorption capability to tight oil. The following conclusions have been drawn from this study:

1. According to the morphology and location of chlorite, the occurrence states of chlorite are divided into four types, including the grain-coating chlorite, pore-lining chlorite, rosette chlorite, and the pore-lining chlorite in dissolved pores. Combined with the content of the element of chlorite in different occurrence states and the sedimentary environments, the material source of chlorite in different occurrence states has been determined for Chang 8 oil reservoirs in Ordos Basin. The formation time of chlorite in different occurrence states is in the following order: grain-coating chlorite $\rightarrow$ pore-lining chlorite $\rightarrow$ pore-lining chlorite in dissolved pores $\rightarrow$ rosette chlorite.

2. The development of chlorite has a great influence on the change of reservoir quality, mainly on two sides. On the one hand, the development of chlorite can hinder the pore space and inhibit throat, reducing the connectivity of pores and increasing the heterogeneity of the reservoir. On the other hand, the development of chlorite, especially the grain-coating chlorite, can protect the residual pores, improve the anti-compaction capacity of the reservoir, and prevent the growth of authigenic quartz, and can also provide certain inter-crystalline pores.

3. Different occurrence states of chlorites have different adsorption capacities to tight oil. The adsorption capacities are in the following order: rosette chlorite $>$ pore-lining chlorite $>$ pore-lining chlorite in dissolved pores $>$ grain-coating chlorite. The controlling factors on the adsorption capacity of different types of chlorite are different. The adsorption capacity of grain-coating chlorite may be related to the content of Fe$^{2+}$ and K$^+$, and the adsorption capacity of pore-lining chlorite may be related to the reservoir quality.
The adsorption capacity of pore-lining chlorite in dissolved pores and rosette chlorite may be related to the content of Fe$^{2+}$ and K$^+$, respectively.

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**Supplemental material**
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