**Diagenesis and Porosity Prediction of Tight Sandstones in the Shihezi Formation, Southern Ningwu Basin: ~~enlightenment~~ Insights for Tight Sandstones Gas Exploration**

**Abstract:** The sandstone reservoirs of the He8 member within the Lower Permian Shihezi Formation are important targets for oil and gas exploration in the southern Ningwu Basin. This study utilized thin-section identification, scanning electron microscopy, and X-ray diffraction analysis to evaluate the impact of diagenesis and mineral composition on the sandstone reservoirs in the He8 member. Additionally, a multiple linear regression prediction model was developed to predict the distribution of promising sandstone reservoirs in the study area.

The results of the analysis reveal that the sandstone of the He8 member is mainly composed of feldspathic lithic sandstone and lithic sandstone. The main reservoir type is characterized by the presence of secondarily dissolved pores and micropores within kaolinite aggregates resulting in low porosity (ranging from 0.2% to 10.7%) and permeability. These characteristics indicate that the He8 member is a tight sandstone reservoir. This reservoir has undergone compaction, cementation, and dissolution diagenesis, and is presently in the stage of mesodiagenesis B. The rigid framework of quartz, dissolution of feldspar grains, and intergranular pores of kaolinite are significant contributors to reservoir quality and the main drivers of porosity.

This study developed a multivariate linear regression model based on the mineral content of quartz, feldspar, carbonate minerals, kaolinite, smectite, and rock fragments. The model accurately predicts the porosity of the studied reservoirs. The model indicates that the north of the Jingle South sub-depression contains favorable reservoir space in the tight sandstone reservoir of the He8 member. The findings of this study are important for characterizing tight sandstone reservoirs in the study area and improving the prediction of favorable reservoir locations.

1. **Introduction**

Tight sandstone gas is a significant contributor to the world's oil and gas resources (Zou et al., 2013; Jia et al., 2016) due to its widespread distribution and vast reserves. There have been significant discoveries of large gas fields in the Ordos Basin, specifically in Sulige, Daniudi, and Shenmu, with geological reserves exceeding 100 billion cubic meters (Jia et al., 2022). Considering the recent discoveries in the Ordos Basin, it is important to investigate the tight sandstone reservoirs in neighboring basins such as the Ningwu Basin. However, previous work in this area has mainly focused on the exploration and development of coalbed methane (Wei et al., 2018; Zuo et al., 2017; Sun et al., 2017), while the basic characteristics of tight sandstone reservoirs in this region remain unclear. The study of tight sandstone reservoirs is gaining importance in oil and gas exploration (Zou et al., 2018). These reservoirs exhibit widespread gas content, but the degree of enrichment is primarily determined by their storage capacity (Li et al., 2012). It is generally believed the degree of development of pores or fractures in tight sandstone reservoirs control the enrichment and high production of tight sandstone gas (Wang et al., 2012). Fine characterization of the petrological characteristics of sandstone reservoirs and clarification of their impact on storage space are important in evaluating the quality of tight sandstone reservoirs. This is crucial for identifying sweet spot intervals and predicting favorable areas (Lai et al., 2016; 2018).

The composition and evolution of minerals determine the formation and distribution of areas of high reservoir quality in tight sandstone reservoirs (Cui et al., 2017). Generally, medium to coarse-grained sandstone reservoirs with a high percentage of rigid particle and good sorting exhibit better reservoir quality (Taylor et al., 2010). Authigenic clay minerals play a crucial role in controlling the preservation and destruction of reservoir space, which largely determines the microscopic pore structure characteristics and reservoir quality (Lai et al., 2018; Xi et al., 2022). Huang et al. (2009) suggested that presence of authigenic illite and kaolinite serve as indicator minerals associated with the dissolution of unstable particles such as feldspar and the development of secondary pores, which are beneficial to the preservation of secondary pores formed by mineral dissolution. Baker (2000) and Yan et al. (2014) observed the protective mechanism of chlorite attached to the surface of particles in the form of pore liners or particle envelopes for pores in sandstone reservoirs. However, there has been little research on the influence of mineral genesis on sandstone reservoirs in the southern Ningwu Basin. In recent years, researchers have linked diagenesis evolution with mineral composition and logging response to predict high-quality sandstone reservoirs (Ran et al., 2016; Cui et al., 2017). While machine learning methods require a large amount of data, which limits their use in predicting high-quality reservoirs in early exploration areas, multiple linear regression can effectively predict reservoir quality based on appropriate test data (Chen et al., 2021).

This study analyzes the mineralogical characteristics, reservoir physical properties, pore space types, and diagenesis of tight sandstone reservoirs in the southern Ningwu Basin using scanning electron microscopy, thin section identification, and XRD test results. The specific aims of our work are: (1) the establishment of a sandstone reservoir porosity prediction model based on mineral content using multiple linear regression, and (2) the prediction of favorable areas for hydrocarbon accumulation in the study area based on the aforementioned model to guide the exploration and development of tight sandstone gas in the southern Ningwu Basin.

1. **Geological setting**

The Ningwu Basin is located in the central part of northern China (Fig. 1a). The Ningwu south block lies in the south of the Ningwu Basin, forming a pattern surrounded by the Lvliangshan Uplift in the west and the Wutaishan Uplift in the east (Fig. 1b). It has a length of about 200 km and a width of 20-30 km, with a total area of approximately 4875.28 km² (Xu et al., 2018). The Ningwu south block can be divided into five tectonic belts based on its structural features, including the Zhongzhuang steep slope belt, the Jingyou slope belt, the Fengrun nosing structure belt, the Jingle south sub-depression, and the Ningwu sub-depression (Wei et al., 2018; Fig. 1b).

In the Ningwu Basin, the late Carboniferous-early Permian strata comprise the Benxi, Taiyuan, Shanxi, and Shihezi Formations in a stratigraphic sequence. Three coal-bearing formations, the Benxi, Taiyuan, and Shanxi Formations, are the source rocks of the tight sandstone gas in the reservoirs in the study area. Vertically, the sandstone of the Shihezi Formation provides a reservoir for the formation of coal bearing gas reservoirs. Based on sedimentary cycle characteristics, lithology, and logging curves, the Lower Shihezi Formation is divided into the He 8, He 7, He 6, and He 5 members from the bottom to the top (Yang, 2021). Among them, the He 8 member is the target layer of this study and contains interbedded gray and light gray mudstones and fine to medium-grained sandstones (Fig. 2). The thickness of the He8 member of the Shihezi Formation in the study area ranges from 30 m to 99 m (average = 73 m), showing a gradual thinning trend from southwest to northeast (Fig. 2). The sandstone thickness is higher in the Jingle south sub-depression and the northern part of the Zhongzhuang steep slope belt, with a cumulative thickness ranging from 34 m to 65 m (average = 44 m) (Fig. 3).

1. **Sampling and methodology**

All the samples used in this study were collected from three different tectonic belts, the Fengrun nosing structure belt (the NT1 and NT8 wells), the Jingleng south sub-depression (the NT2 and NT4 wells), and the Zhongzhuang steep slope belt (the N7 well) (Fig. 1, 2). 60 samples were collected for XRD testing and thin-section identification, and 11 samples were collected for scanning electron microscopy (SEM).

(1) XRD testing: First, 5 g of the sample was ground into powder in an agate mortar. The powder was repeatedly washed with distilled water and then placed in a 2000 mL quartz crucible, to which 1500 ml of distilled water was added and thoroughly mixed. The mixture was dried at 50°C. Then, the upper part of the solution (<2 μm suspension) was aspirated into a centrifuge tube, centrifuged at 2500 rpm for 20 min, and the sample of the sediment particles (<2 μm) at the bottom of the centrifuge tube was extracted. The mineral content was semi-quantitatively determined using a Bruker D8 Advance X-ray diffractometer with a Cu target (parameters: Kα1 = 1.54060 A°, 2.2 kW, 40 kV, tube flow 40 mA, scanning range 0-167°, step width 0.037). The whole rock composition and clay mineral content were determined based on the peak area on the diffraction spectrum, with a relative error of 5%.

(2) Thin-section analysis is used to determine the mineralogical composition, diagenetic relationships, and pore types of sandstones (Hu et al., 2019; Wang et al., 2023a). All thin sections were vacuum-impregnated with blue epoxy resin and semi-stained with alizarin red for carbonate mineral identification using an optical microscope to highlight the pores. Under the microscope, blue indicates pore space, and red indicates calcite cementation.

(3) SEM observation: 11 sandstone samples were obtained from wells NT1 and NT8 along the bedding and vertical bedding with an area of approximately 1cm×1cm and a thickness of approximately 5mm, respectively. The sample was placed in a vacuum coating machine for vacuum-pumping, and then gold plating was done on the fresh fractures of the sample. These samples' pore and mineral morphology were observed using an FE-SEM (quantum 200F SEM). The SEM was operated in low vacuum mode. The accelerating voltage was 30 kV and the working distance was about 10 mm. The SEM resolution was 1.2 nm. The specific operating parameters of the SEM are described in previous studies (Schieber et al., 2013; 2016; Xi et al., 2018).

1. **Results**

##### 4.1 Petrological features

The studied samples from the He8 member of the southern Ningwu block exhibit high quartz content, abundant rock fragments, and low feldspar content (Fig. 4a). The quartz content ranges from 16% to 85% (average = 61.6%). The percentage of rock fragments ranges between 8% and 50% (average = 34.9%), with the fragments being mainly composed of acidic extrusive rocks followed by metamorphic rocks, intermediate basic extrusive rocks, sedimentary rocks, and a small amount of tuff. The feldspar content ranges from 9% to 34% (average = 18.8%), and the potassium feldspar content is extremely low (0% to 5%, average = 2.2%). The sandstones of the He8 member are dominated by lithic-feldspathic sandstones and lithic sandstones, with only two samples of feldspathic-quartz sandstone and lithic feldspar sandstone (Fig. 4b). The grain size is mainly medium to fine sand with good sorting. The main type of cementation is contact cementation. The argillaceous matrix is 0%~18%, the cement content is 1%~6%, and it is dominated by calcareous material. In addition, there are few authigenic siliceous minerals and clay minerals, and the clay minerals are characterized by being kaolinite-rich (34%-80%, average 57.5%), chlorite-poor (5%-20%, average 10.0%) and illite-poor (2%-24%, average 10.8%).

##### 4.2 Reservoir porosity and permeability

The porosity of the sandstone samples from the He8 member in the study area ranges from 0.20% to 10.70% (average = 4.76%), which is classified mainly as low to extremely low porosity. The permeability ranges from 0.01×10-3 to 0.26×10-3μ m2 (average 0.08×10-3μ m2), mainly belonging to low to ultra-low permeability, with typical tight sandstone characteristics. However, the overall physical characteristics of the reservoir in well NT8 to well NT1 are significantly better. In addition, there is a relatively strong positive correlation between the porosity and permeability of the sandstone reservoirs in the analyzed samples (Fig. 5), indicating that most of the pores in the He8 member reservoir are interconnected. However, the porosity and permeability of the He8 sandstone member of the established trillion cubic meter Linxing-Shenmu gas field in the northeastern Ordos Basin (porosity distribution range of 2% to 14%, permeability distribution range of 0.01×10-3 μ m2 to 10×10-3 μ m2; Yang, 2021) are much better than those of the analyzed samples.

##### 4.3 Pore types of the tight sandstone reservoir

The pore spaces of the sandstone in the He8 member of the study area are mainly secondary pores, followed by primary pores and microfractures (Fig 6. a, b, e, f). However, due to the abundance of rock fragments, including acid extrusive rocks and metamorphic rocks in the He8 sandstone member, the primary intergranular pores were filled and lost during burial compaction. Only a small number of primary pores were preserved in some samples with abundant rigid particles and good sorting, mainly in the form of triangular or triangle-like features (Fig. 6b, d). Overall, the secondary pores are dominant. A large number of secondary pores are present, including intergranular dissolution pores, intragranular dissolution pores, and moldic pores in the feldspar. Micropores within clay aggregates are also present. Among them, intergranular dissolution pores and intragranular dissolution pores are the most common (Fig. 6c, d, f). Intragranular dissolution pores have a honeycomb appearance because of detrital feldspar or rock fragment dissolution (Fig. 6d), and the moldic pores are mainly the result of the complete dissolution of unstable detrital grains (Fig. 6a, c). The authigenic clay minerals, including illite and kaolinite, contained a large number of micro-nano-scale intergranular pores (Fig. 6g, h, i). Microfractures with good connectivity and long extensions are also common in the He8 member, and these have increased the storage space of the reservoir to some extent. Fig6b shows a tensional fracture with a relatively flat attitude and a certain opening that is often filled with Fe-calcite. Fig 6e shows shrinkage fractures formed due to the strong contraction of rock fragments during the later stage, and these are distributed along the grain rims with large openings and uneven rims.

1. **Discussion**

#### 5.1 Diagenesis and pore evolution

##### 5.1.1 Compaction

Research indicates that when the buried depth of sediment is less than 2500 m, compaction is the main factor that damages the reservoirs' physical properties and pore structure (Higgs et al., 2007; Dutton and Loucks, 2010). The main reason for this is that the rearrangement and deformation of particles reduces the size of some primary intergranular pores, which reduces reservoir performance. In the study area, the maximum burial depth (3200 m) of the He8 member during geological history is shallower than that of the strongly compacted Xujiahe Formation in the Sichuan Basin (Lai et al., 2014; Xu et al., 2022; Fig.1a) and the He8 member in the western Ordos Basin (Li et al., 2016; Fig.1a). In addition, the rigid particles are mainly in linear or point to line contact (Fig. 6a, b, c), and the rock fragments are occasionally characterized by compression deformation (Fig. 6d, e). This indicates that the compaction intensity in the study area is relatively low. The porosity loss due to compaction and cementation and the porosity increase due to the dissolution of sandstone reservoirs in the He8 member of the study area during the diagenetic process were calculated based on the quantitative calculation of sandstone porosity (Beard and Weyl, 1973; Yang, et al., 2022),. The primary porosity was calculated using φ1=20.91+22.90/S0 (Beard and Weyl, 1973; Xu et al., 2022) (1).

Where: φ1 is the original porosity; S0= (d75/d25)1/2 (2)

Where: d75 is the grain diameter in the cumulative curve when the cumulative content is 75%, d25 is the grain diameter at a cumulative content of 25% in the accumulation curve.

Through experiments and calculations, it is concluded that the average S0 is 1.50, and the average primary porosity (φ1) of the sandstone reservoir in the He8 member of the study area is 36.10%. The remaining porosity after compaction（φ2, Eq. (3)) varies from 3.59% to 17.47% (average, 9.41%) (Fig 7), and the porosity loss after compaction ranges from 18.63% to 32.87% (average, 26.69%), which is slightly lower than that of the Xujiahe Formation in the Sichuan Basin (Xu et al., 2022) and the Sulige He8 member in the Ordos Basin (Bai et al., 2018; Wei et al., 2021).

φ2=C+(P1×P0/Pt) (3)

Where: φ2 refers to the remaining porosity after compaction; C is the cement content; P1 is the interparticle plane porosity; P0 is the measured porosity; Pt is the total plane porosity (Table 1).

##### 5.1.2 Cementation

When the buried depth of sediment exceeds 2500 m, the porosity loss depends on the content of quartz, carbonate minerals, and other types of cement (Paxton et al., 2002; Zou et al., 2007). On the one hand, the cementation and filling of authigenic minerals reduces the reservoir space of sandstone and promotes the transformation of primary pores into intergranular pores. On the other hand, clogging of the pore throats leads to poor pore connectivity of the pore spaces in the sandstone (Pittman and Larese, 1991; Lai et al., 2018).

The main types of cement in the analyzed samples of the sandstone reservoirs in the He8 member are siliceous material, carbonates, and clay minerals. Siliceous cementation is in the form of secondary enlarged edges (Fig. 8a, b) growing around detrital quartz grains, and authigenic quartz crystals filling pores (Fig. 8a). The hardness of quartz increases the compaction resistance of sandstone reservoirs, and this allows some primary pores to continue to exist at the grain rims while improving the physical properties of tight sandstone reservoirs (Xi et al., 2019; Wang et al., 2023). The main types of carbonate cementation are Fe-calcite and Fe-dolomite. Due to the presence of coal measures in the study area, the decomposition of bacteria during eodiagenesis caused the early stratigraphic water to be acidic and lacking in carbonate cement. During the late burial process, the thermal evolution of organic matter in the source rock generated hydrocarbon and decarboxylates to produce organic acids and CO2, which kept the stratigraphic water acidic and led to the inability of CaCO3 to precipitate. Due to the consumption of organic acids and CO2 in the mesodiagenesis stages, the pH value of pore water gradually became alkaline which was conducive to the precipitation of calcareous cements, such as Fe-calcite or Fe-dolomite that filled the intragranular dissolution pores in the feldspar grains and intergranular pores (Fig. 8c, d). The clay mineral types of the sandstone reservoirs are mainly kaolinite, and chlorite and illite can also be observed; however, montmorillonite has basically disappeared. Based on the calculation of the remaining porosity after cementation (Eq. (4)), the remaining porosity φ3 ranges from 0.22% to 2.82% (average, 1.22%), and the porosity loss due to cementation changes from 2.40% to 16.80% (average, 8.19%) in the sandstone reservoir in the analyzed samples.

φ3=P1×P0/Pt (4)

Where: φ3 refers to the remaining porosity after cementation.

##### 5.1.3 Dissolution

Tight sandstone reservoirs generally lose a large number of primary pores due to compaction and cementation during burial evolution. However, the excellent porosity values in deeply buried sandstone indicate that the porosity loss during compaction and cementation processes may be compensated for by subsequent porosity increases caused by dissolution (Taylor et al., 2010; Lai et al., 2018). The dissolution of sandstone reservoirs in the He8 member of the analyzed samples may have occurred during shallow burial due to the presence of climatically controlled atmospheric fresh water and during deep burial where the presence of organic acid-rich fluids had an effect. During the shallow burial period of the strata, the organic matter was temporarily immature, and the dissolution fluid was mainly atmospheric freshwater that infiltrated from the surface; the presence of the dissolution fluid was mainly manifested by the dissolution of rock fragments, feldspar, and carbonate minerals. As the burial depth of the stratum increased, the decarboxylation of the rich organic matter in the mudstone in the coal-bearing strata also produced CO2-rich or organic acid-rich fluids, which enhanced the acidity of the pore water. Rock fragments and feldspar were also dissolved again under acidic conditions, forming secondary pores (Fig. 6a, c). Feldspar can also dissolve along weak points such as joint and fracture surfaces, forming a windowpane shape (Fig. 6c). The effect of dissolution on pore evolution can be quantitatively characterized based on the formulae of the increasing porosity after dissolution (Eq. (5)). Through calculations, it can be shown that the porosity increase caused by the dissolution of the tight sandstone reservoirs in the analyzed samples changes from 0.59% to 7.88% (average, 3.54%). In the early and middle stages, the porosity increase due to dissolution was 1.49% and 2.05%, respectively.

φ4=P2×P0/Pt (5).

Where: φ4 refers to the increasing porosity after dissolution; P2 is the dissolution plane porosity.

##### 5.1.4 Diagenetic sequence and pore evolution stage

Based on the distribution and formation sequence of the authigenic minerals observed under the microscope, and referring to the classification standard for the diagenetic stages of clastic rocks (acidic water medium conditions) in the oil and gas industry (SY/T5477-2003), it is believed that the reservoir of the He8 member underwent syndiagenesis stages, eodiagenesis stages A and B, and the mesodiagenesis stage A, and is presently mainly in the mesodiagenesis stage B. The main mineral assemblages are characterized by the predominance of kaolinite, which has been converted to illite, with montmorillonite having basically disappeared. Quartz overgrowths typically occur around grains or develop as authigenic quartz crystals, resulting in tight reservoirs. A degree of microfractures has developed in the He8 member due to the high quartz content. The homogenization temperature test inclusions results indicate that the formation temperature ranged from 90 to 159 ℃, indicating the paleo-geothermal range of the A-B stage of mesodiagenesis.

Eodiagenesis stage A: The burial depth of the strata was relatively shallow, and the ground temperature was relatively low during this time, resulting mainly in compaction and weak cementation. The pore type was mainly intergranular pores, and the porosity rapidly decreased from the original 36.10% to about 14.10% (Fig. 9a). Eodiagenesis stage B: with the increase in the burial depth of the strata, the intergranular pores gradually decreased with the increase in compaction, and the compaction continued to reduce the porosity by 4.69% (the porosity was 9.41% at this time). Due to the influence of atmospheric fresh water, feldspar and rock fragments began to dissolve, resulting in a porosity increase of about 1.49% (the porosity was 10.90% at this time). The formed dissolution products, such as quartz and kaolinite, filled the primary pores of the reservoir, resulting in a porosity reduction of about 3.10% after cementation (Fig. 9b, at this time, the porosity was 7.80%). Mesodiagenesis stage A: the stratigraphic depth continued to increase to more than 3000 m, and the organic matter matured and generated hydrocarbons at this time; also, a large amount of organic acids or CO2 fluids were generated, and these dissolved the feldspars and rock fragments in the sandstone once again, forming intergranular or intragranular dissolution pores that enhanced the porosity by 2.05% (the porosity was 9.85% at this time). The simultaneously produced dissolution products of quartz and clay minerals, including kaolinite, as well as Fe-calcite and Fe-dolomite in the mid- to late-stage further began to cement and fill the pores, resulting in a porosity reduction of 4.60% (Fig 9c, where the porosity was 5.25%). After the mesodiagenesis stage B: with the consumption of organic acids, the stratigraphic water environment gradually became alkaline, and iron calcite and iron dolomite filled the remaining primary pore space and secondary dissolution pores, resulting in a porosity reduction of 0.49%; at this time, the porosity decreased to 4.76%.

#### 5.2 Effect of mineral composition on porosity

##### 5.2.1 Rigid minerals

The effects of cementation and dissolution on reservoir porosity heterogeneity are significant (Wang et al., 2020). Clarifying the formation and sources of minerals is crucial for elucidating the formation mechanism of tight sandstone reservoirs (Wang et al., 2018) and the formation and evolution of primary and secondary pores (Ma et al., 2017). The reservoir of the He8 member of the analyzed samples exhibits synergistic development characteristics of multiple pore types dominated by secondary pores, with the development of fractures supplemented by primary pores. Both quartz and feldspar show a positive correlation with porosity (Fig. 10a, b), as higher amounts of detrital quartz enhance the compaction resistance of the sandstone reservoir, causing some primary pores to be preserved at the grain rims. Acidic fluid easily enters sandstone intervals during the later period of acid water filling, which promotes water-rock reactions and facilitates the formation of secondary dissolution pores (Lai et al., 2014). Dissolution pores usually originate directly from chemically unstable minerals of original components like detrital feldspar, generating large numbers of secondary dissolution pores under the influence of early atmospheric freshwater and acidic conditions caused by organic acid injection. The feldspar grain content in the He8 member of the analyzed samples (average = 15.6%) is comparable to that in the Linxing-Shenfu block (average = 17.6%; Yang et al., 2021), while the high content of kaolinite and the low abundance of illite indicate an acidic diagenetic environment. Therefore, the feldspar in the He8 member of the analyzed samples experienced prolonged dissolution during burial diagenesis, and secondary dissolution pores became the main contributor to porosity.

Although carbonate minerals are also chemically unstable minerals and can generate a large number of secondary dissolution pores, the content of carbonate minerals is not significantly correlated with porosity (Fig. 10c), indicating that carbonate minerals have a dual impact on the reservoir space of sandstone reservoirs: on the one hand, carbonate minerals accumulate in the primary intergranular pores as cements; on the other hand, the early formation of carbonate minerals can cause the sandstone to have strong compaction resistance, which protects some of the primary intergranular pores (Xing et al., 2022); the early formation of carbonate minerals is also the material basis for the formation of intergranular and intragranular dissolution pores under the injection process of organic acid or CO2 fluid.

##### 5.2.2 Plastic minerals

The sandstone in the He8 member of the analyzed samples is enriched with rock fragments. Although the rock fragments were dissolved under the action of atmospheric fresh water and organic acids in the eodiagenesis and mesodiagenesis stages, respectively, there is a certain negative correlation between the rock fragment content and porosity (Fig. 11a), indicating that the enrichment of rock fragments blocked some pores to some extent. The rock fragment types of the He8 member of the analyzed samples are mainly composed of acidic extrusive rocks and metamorphic rock fragments, including plastic phyllite and slate (Fig. 12a, b). These rock fragments often have strong plasticity and are extremely prone to deformation and pore-clogging during the later burial and compaction process, which is not conducive to the intrusion of large quantities of acidic fluids in the later stage, thereby reducing the development of dissolution pores to a certain extent.

There is a strong positive correlation between kaolinite content and porosity in the He8 member of the analyzed samples (Fig. 11b). A large number of intergranular pores in the kaolinite can be observed under the microscope (Fig. 6g, h; Fig. 12c), indicating that the formation of kaolinite has a positive effect on the reservoir space of the sandstone. The kaolinite of the analyzed samples exists in the form of book-like aggregates (Fig. 6h, i; Fig. 12c), which is a typical product of an acidic dissolution environment (Liu et al., 2019). The widespread occurrence of the shale interlayer in the He8 member in the study area has had an important influence on the formation of kaolinite (Fig. 2). During the eodiagenesis and mesodiagenesis stages, influenced by atmospheric fresh water and the continuous decomposition of aquatic plants producing humic acid, the first dissolution of unstable minerals, including feldspar, and the transformation into kaolinite occurred. With the increase in the burial depth and the increase in the temperature and pressure conditions during the middle stage of thermal evolution (Ro=0.5%～1.0%), the degree of the thermal degradation of humic kerogens gradually increased. This thermal degradation is manifested as the loss of carboxyl groups and the formation of a large number of short-chain carboxylic acids, which caused the pore fluid at this time to exhibit strong acidity. This led to the second dissolution of feldspar and its transformation into kaolinite and the generation of a large number of secondary pores (Surdam et al., 1985).

Illite is a product of alkaline or alkaline rock-forming environments, and therefore, its content shows an opposite trend to that of kaolinite. A negative correlation was observed between illite and porosity in the He8 member of the analyzed samples (Fig. 11d), suggesting that the formation of illite reduced some of the reservoir space. Intergranular pores of illite grains formed under conditions dominated by alkaline diagenesis can be the main contributor to porosity, such as the dissolution pores in the sandstone reservoirs formed under alkaline rock-forming environments in the Sulige gas field, which account for 81% of the current total porosity (Bi et al., 2015). However, the predominance of kaolinite in the study area indicates that the environment was mainly acidic for a considerable period of time, and most of the illite coexists with kaolinite in the study area (Fig. 6g, h; Fig. 12d), suggesting that the illitization of kaolinite is a major source of illite formation in the study area. Some studies have indicated that the pores in tight sandstones formed under acidic rock-forming conditions may be lost during the later alkaline rock-forming process (Huang et al., 2009; Bi et al., 2015), and one possible reason for this is that the generated illite blocks some of the pores, which is also one of the reasons for the negative correlation between illite and the porosity of the analyzed samples.

The negative correlation between chlorite and porosity in the He8 member of the analyzed samples (Fig.11c) indicates that its impact on reservoir porosity was negative. Chlorite is a silicate mineral that can indicate alkaline dissolution environments (Li et al., 2011). Similar to illite, a large amount of chlorite in the form of thin films in intergranular pores positively affects the pore properties of sandstone reservoirs. In contrast, a small amount of chlorite in a scattered state tends to occupy part of the reservoir space (Xing et al., 2022). The formation of authigenic chlorite requires an alkaline diagenetic environment and an adequate source of iron ions (Zeng, 1996). Although the study area is rich in igneous rock fragments containing iron ions, the lack of a long-term alkaline diagenetic environment restricted the formation of a large amount of authigenic chlorite.

At the same time, due to the relatively closed conditions of the low porosity and low permeability of the reservoir, fluid migration was slow, and most of the chlorite filled the pore space, reducing the reservoir space.

In summary, the reservoir space of sandstone reservoirs is jointly controlled by multiple minerals during diagenesis, and the impact mechanisms of different minerals on porosity are different. Feldspar, quartz, and kaolinite are the main contributors to porosity, while rock fragments, illite, and chlorite had a negative impact on the development of reservoir pores in the study area.

#### 5.3 Mineral content and porosity prediction models

##### 5.3.1 Multiple linear regression model building and validation

Reservoir space development is controlled and restricted by various factors and can be summarized as being mainly controlled by sedimentation and diagenesis. However, its impact mode and degree are distinct in different regions or depths of reservoirs (Zhang, 2019). In the study area, the formation of favorable reservoirs in the tight sandstone is related to the secondary dissolution pores of minerals, including feldspar, and the rigid protective framework of terrigenous quartz. Quantitative research on the influencing factors of porosity in tight reservoirs is crucial for predicting the location of favorable tight sandstone gas reservoirs. Generally, multiple linear regression analysis can solve the quantitative dependency relationship between a dependent variable and multiple independent variables (Chen et al., 2019; Chen et al., 2021), quantitatively characterize the main influencing factors of porosity formation, and improve the prediction accuracy of porosity.

Based on the influence of mineral composition on porosity, this study uses the content of quartz (Q), feldspar (F), carbonate minerals (Cb), kaolinite (K), illite (I), chlorite (C), and rock fragments (R) as independent variables, and porosity as the dependent variable to establish a porosity prediction model using the SPSS software. The specific operation steps are described in the literature (Miao et al., 2012; Mei et al., 2011). Based on the compilation of the SPSS analysis results, a mineral prediction model affecting the porosity variation was developed as follows:

Y=11.23+0.04🞨Q+0.11🞨F-0.03🞨Cb+0.03🞨K-0.11🞨C-0.27🞨I-0.21🞨R.

The complex correlation coefficient of the model (0.95) is greater than the detection value (0.91), and the adjusted R2 is relatively large (0.86), indicating a good fitting effect of the model. In addition, the F-test regression equation model shows that the F-value (19.1) is greater than its examination threshold (14), further indicating that the established prediction model is robust. In addition, the residual error usually reflects the accuracy of the established model in predicting dependent variables. Generally, the smaller residual standard deviation (0.86) indicates that the established model has a good effect. Overall, the established prediction model has a certain geological significance and value.

In order to verify the prediction effect (reliability) of the model, each mineral composition tested in the NT1 well was substituted into the prediction model, and the prediction effect of the model was analyzed by comparing with the measured porosity. The predicted porosity of the model is basically consistent with the measured porosity (the average error is only 0.42%, Fig. 13). In addition, in statistics, determining whether the predicted value matches the measured value also requires determining the homogeneity of the sample. The paired samples t-test is usually used to identify whether the two groups of samples are from the same overall and to determine whether they are significantly different (Li., 2020; Chen et al., 2022). The significance probability P-value of the paired sample t-test between the model-predicted porosity and the measured porosity (0.52) is greater than 0.05, which indicates that the two groups of samples are from the same overall and comparable, and there is no significant difference between them at the 95% confidence intervals, that is, the model predicted porosity and the measured porosity basically match. In addition, the mineral content data of the tight sandstone reservoir in Well NT8 was selected as the sample data. Based on the established porosity prediction model, the mineral content data corresponding to the four samples were substituted into the model for porosity prediction. The results show that the results of the porosity prediction model still fit well with the measured porosity (Fig. 13) (the average error is only 0.26%).

##### 5.3.2 Exploration significance of the multiple linear regression porosity model

The evaluation and optimization of the sweet spot is the core of tight gas exploration and research, and is implemented throughout the exploration and development process. The pore structure evolution of tight reservoirs is of great significance for hydrocarbon charging mechanisms (Guo et al., 2018), which largely determines the location of hydrocarbon transport and accumulation. Porosity is a key parameter for evaluating the capacity of tight sandstone gas reservoirs, and as oil and gas exploration expands to deeper and newer blocks (Zeng et al., 2020), it is increasingly difficult to find relatively favorable reservoirs. Multiple linear regression models can be applied to predict and interpret the porosity of known mineral contents. It has some geological significance in predicting the distribution of sweet spot areas (intervals).

Based on the established multiple linear regression model, the porosity of wells NT4 and NT2 in the Jingle south sub-depression and well N7 in the Zhongzhuang steep slope belt were calculated, and it was found that the predicted porosity is higher in the northern part of the study area, especially in well NT4 (Fig. 14). The predicted porosity of the He8 member ranges from 3.1% to 12.8% (average = 7.5%), and the percentage of reservoirs with a porosity greater than 10% is about 25%. Although lower than the sandstone reservoirs in the He8 member of the Sulige area (the current porosity is about 9.3%; Bi et al., 2015), it is generally higher than that of the sandstone reservoirs in the He8 member of the Linxing-Shenfu area (current porosity is about 6.2%; Yang, 2021).

The Sulige gas field in the Ordos Basin is a typical tight sandstone gas field, with a cumulative proved geological natural gas reserve of 4×1012 m3 and an annual gas production of 2.5×1010 m3, accounting for over 25% of China's total natural gas production (Wang et al., 2023b). Among them, the He8 member is the main gas-bearing interval and it is mainly composed of medium-coarse-grained lithic sandstone and medium-coarse-grained lithic quartz sandstone, with a small amount of feldspathic lithic sandstone. Despite the compaction and cementation that increased the tightness of the sandstone reservoirs, dissolution during the mesodiagenetic stage increased the porosity by up to 12.3% (Table 2), resulting in the formation of high-quality sandstone reservoirs with an average porosity of 9.3% (Bi et al., 2015). One of the reasons for the formation of the high yield in the Sulige gas field is the significant effect of the porosity enhancement caused by dissolution (Wei et al., 2021). The Linxing-Shenfu area is located on the northeastern margin of the Ordos Basin, and has super-giant tight gas fields with proven reserves of over 100 billion cubic meters. The He8 member is the main gas-bearing interval of the gas field, with a lithology similar to that of the Ningwu South block, being mainly composed of medium-coarse-grained feldspathic lithic sandstone and medium-coarse-grained lithic sandstone (Zhu et al., 2022). The He8 member sandstone reservoir was mainly compacted and strongly cemented during burial, resulting in low porosity and limited dissolution, preventing the organic acid-rich fluids from fully entering the sandstone. The dissolution porosity only increased by 2.8%, and the current porosity is approximately 6.2% (Table 2). However, the successful development of a production capacity exceeding 15×108m3/a (Mi et al., 2021) indicates that tight sandstones with such dissolution intensity have exploration significance. Compared to the Linxing-Shenfu area, the northern part of the Ningwu South block has higher porosity with well-developed dissolution pores, including feldspar. Moreover, the interval with the high predicted porosity in the NT4 well displays good gas logging characteristics (Fig. 2), indicating that the He8 member sandstone reservoir in the northern Jingle south sub-depression may have considerable exploration and development prospects. Therefore, attention should be paid to the feldspar-rich intervals during the exploration and development of tight sandstone gas in the future.

1. **Conclusion**

(1) The He8 member sandstone reservoir underwent destructive diagenetic processes, including compaction and cementation, resulting in a porosity loss of 26.69% and 8.19%, respectively. Constructive diagenetic processes, including dissolution, increased the porosity by 3.54%. The reservoir is currently in the stage B of mesodiagenesis.

(2) The pore spaces of the He8 member sandstone are mainly composed of secondary pores and micropores within kaolinite aggregates. The rigid quartz framework and the feldspar grains' dissolution have improved the reservoir quality. Carbonate minerals have had a dual impact on the formation of pores spaces in the sandstone. The dissolution of kaolinite mineral grains is a contributor to porosity.

(3) The multiple linear regression model established based on the mineral contents of quartz, feldspar, carbonate minerals, kaolinite, chlorite, and rock fragments can better predict the distribution of reservoir porosity. The model predicts that the tight sandstone in the He8 member in the northern part of the Jingle south sub-depression has favorable prospects for hydrocarbon accumulation and exploration.