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A new classification system of lithic-rich tight sandstone and its application to diagnosis high-quality reservoirs

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Abstract:
Lithic-rich tight sandstone is one of the most enrichment lithofacies in the Sulige gas field. Clarifying the enrichment mechanism of high-quality lithic-rich tight sandstone is important to economic and efficient development of the tight gas reservoir. This paper introduces a new classification method, which is based on the origin of particles and interstitial materials and their control on reservoir pores growth. Lithic-rich tight sandstone can be subdivided into three types: sedimentary lithic sandstone, diagenetic lithic sandstone and event-type lithic sandstone. The genetic mechanism of a high-quality reservoir is studied by this new method. Research shows that the sedimentary lithic sandstone has high contents of plastic lithics, strong compaction effects of early diagenesis, large porosity reduction and almost no dissolution-induced porosity. The diagenetic lithic sandstone has high contents of rigid lithics and strong compaction effects. Organic acids promote alteration of a large amount of feldspars into kaolinite, while such sandstones are highly cemented. It is seen with moderate porosity reduction and moderate dissolution-attributed porosity growth. Event-type lithic sandstone also has high contents of rigid debris and strong compaction effects. Synsedimentary volcanic dust materials of subaerial deposition are altered into illite through smectite and illite-smectite mixed-layer clay under the effects of acids, which generate many pores and results in large dissolution-attributed porosity growth. Research shows that the sedimentary lithic sandstone has poor physical properties and is identified as the unfavorable reservoir; the diagenetic lithic sandstone having medium physical properties, as the relatively favorable reservoir; the event-type lithic sandstone having good physical properties, as the favorable reservoir. The research route and results have laid a solid geological foundation for better development of lithic-rich tight sandstone reservoirs.

1. Introduction

Sulige gas field in the Ordos Basin is the largest onshore gas field discovered in China. However, low porosity, low abundance, low permeability and strong heterogeneity make it hard to develop (Yang et al., 2008; Gao et al., 2019). Compared with the middle and western Sulige districts characterized by relatively more developed quartz sandstone (Wang et al., 2009, 2017), the reservoir sandstone in District East-II of the Sulige gas field is dominated by lithic sandstone, with pores mainly consisting of secondary pores and stronger heterogeneity (Yang et al., 2008; Liu et al., 2019). The key gas producing zone in this district is the He-8 Member of the Permian Shihezi Formation and Shan-1 Member of the Shanxi Formation (Ding et al., 2016; Hao et al., 2017). It is particularly crucial to explore the development law of "sweet-spot" reservoirs (Zhu et al., 2015). Since the source of sediments in the research area includes not only the quartz-rich provenance in the northwest but also the lithic-rich provenance in the northeast and the sedimentary environment is a braided river with obvious changes in hydrodynamics, the reservoir rocks show significant differences in composition characteristics and textures (Wang et al., 2018). In this paper, the reservoir of the He-8 Member

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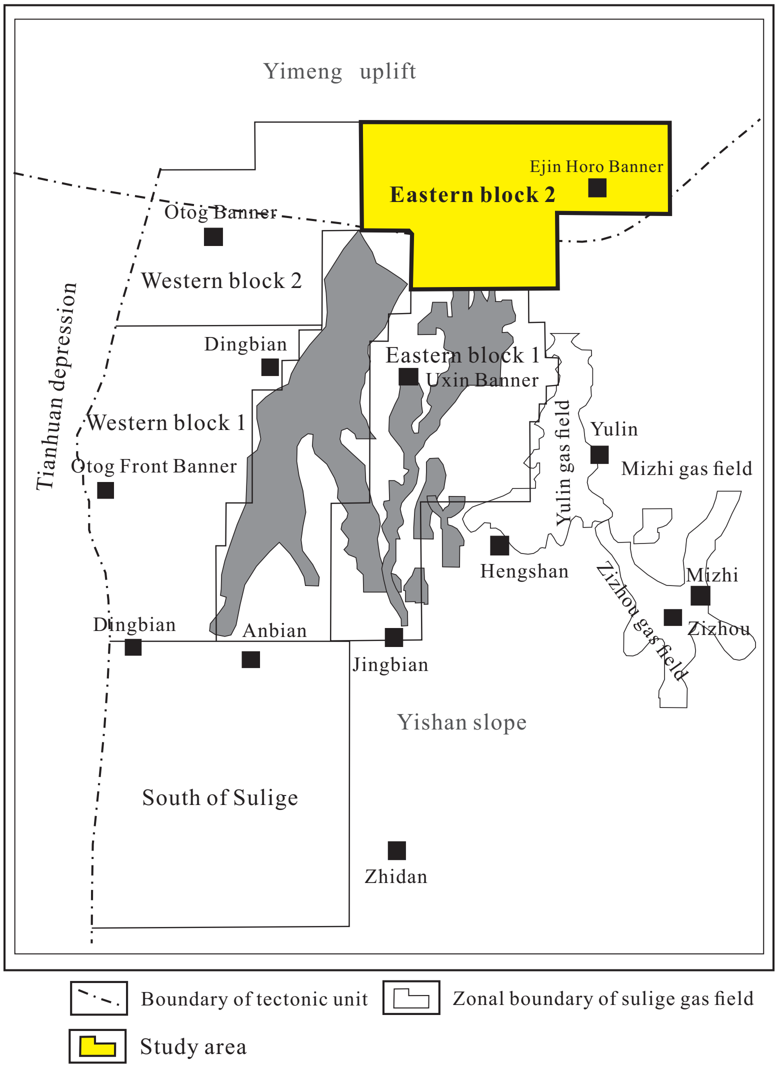

Fig. 1. Location of the district East-II of Sulige gas field.

in District East-II is taken as an example to study the reservoir characteristics of subdivided lithic sandstone types, from the perspective of origins (Liu et al., 2019).

2. Regional geological overview

District East-II of the Sulige gas field is located in Ordos City, starting from the Yishan Slope in the southern Ordos Basin and extending to the Yimeng Uplift in the north in Fig. 1. This district is generally manifested by deposition of marine-continental transitional continental clastic rocks. In terms of development of the Upper Paleozoic, the lower part is Carboniferous Benxi Formation and Taiyuan Formation, and the upper part is the Permian Shanxi, Shiqianfeng and Shihezi Formations. The He-8 Member of the Shihezi Formation is one of the key target layers in this district, which is mainly of braided river deposition. It features variable and complex colors. Brown (or variegated) mudstone is usually interbedded with greyish-green (or grey) mudstone. It can also be observed that thick grayish green (or gray) mudstone is mixed with colored mudstone. These indicate the high variability of water levels during sedimentation and that the water body mostly fluctuated between oxidizing and reducing environments. The flow rate of the sedimentary water body and the grain size and composition of sandstone vary greatly, presenting strong heterogeneity. Scour structures commonly develop at the base of the He-8 Member, and the scour surface undulated. Contact with the overlying and underlying strata is primarily represented by the abrupt change at the bottom and gradual change at the top. The lithology presents gradual upward fining from the bottom up, and is mainly medium-grained and fine-grained sandstones. The sedimentary bedding includes small-scale cross bedding and trough cross bedding, which change into ripple cross bedding and horizontal bedding at the top. He-8 Member generally presents positive rhythm, showing the characteristics of low-energy water flows with the water energy slowly decreasing. In local areas, large trough cross bedding, block-shaped bedding, wedge-shaped cross bedding, parallel and sheet-like cross bedding occur, showing the characteristics of high-energy water flow (Yang et al., 2008).

Research has confirmed that the composition of the Upper Paleozoic rock types in Ordos Basin is dominated by quartz sandstone, lithic sandstone and the transitional type between the two. Across the whole basin, sandstone is seen with relatively high contents of volcanic components, usually 5%-17% (Zhao et al., 2011), including clastic particles such as lithics, volcanic mud balls and crystal pyroclasts, dominated by volcanic ash. It is revealed that there were strong and frequent volcanic activities in the vicinity of the Ordos Basin during the Late Paleozoic (Wang et al., 2017).

3. Basic characteristics of the reservoir

3.1 Petrological characteristics

On the basis of statistics of 113 appraisal and exploration wells and thin-section analysis of 1215 sandstone samples in the research area, as per the conventional clastic sandstone classification system, sandstone in the area of interest can be divided into three types: lithic sandstone (dominant, 82.4%), lithic quartz sandstone (15.3%) and pure quartz sandstone (2.4%) (Fig. 2). The lithic type is dominated by metamorphic lithic fragments (accounting for 77.9%), followed by igneous lithic fragments (17.9%) and the least sedimentary lithic fragment (4.2%) (Fig. 3). In terms of grain sizes, clastic rocks are mainly medium-coarse sandstone, pebbly coarse sandstone and coarse sandstone, followed by fine sandstone and the lowest pebbly medium-grained sandstone and conglomerates. The average amount of interstitial materials is 17.68%, dominated by pyroclastic, hydromica, kaolinite and chlorite, followed by tuffaceous and carbonate minerals (dominated by calcite and ferrocalcite), with a little siderite. The pore types are characterized by "dominant secondary pores and subsidiary primary pores", which shows the secondary pores account for more than 90%, while the primary pores account for less than 10%. The porosity of the reservoir is 4%-14%, with permeability of (0.1-2)$\times 10^{-3}$ μm^2. To sum up, the reservoir is a typical lithic-rich tight sandstone reservoir (Aliyev et al., 2016).

3.2 Pore types

In accordance with the conventional and casting thin-section analysis results, the pore types of the He-8 Member in the research area are mainly lithic dissolved pores (Fig. 4(a)), accounting for 42.9% of the total surface porosity, followed by intercrystal pores (16.9%, Table 1, Fig. 4(b)), feldspar dissolved pores (15.3%, Table 1, Fig. 4(c)) and intergranular pores (mainly of kaolinite intercrystal pores, 13.0%, Table 1, Fig. 4(d)), as well as some less-common matrix dissolved pores (Fig. 4(e)) and intergranular dissolved pores (Fig. 4(f)).

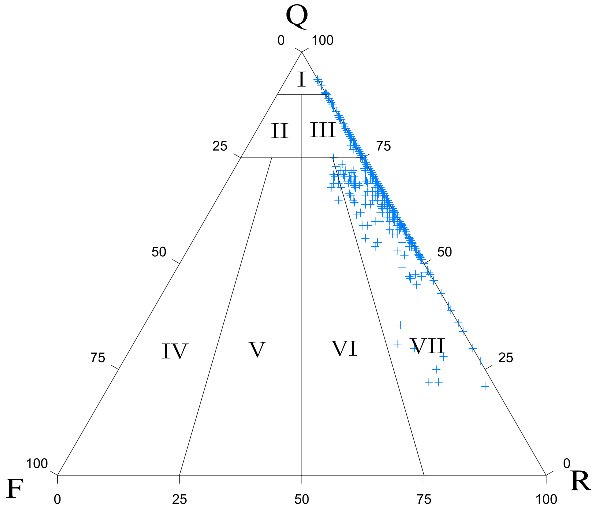

Fig. 2. Triangular diagram of sandstone composition in the research area. Q: Quartz; F: Feldspar; R: Feldspar; I: Quartz sandstone; II: Quartz sandstone; III: Lithic quartz sandstone; IV: Feldspathic sandstone; V: Lithic feldspar sandstone; VI: Feldspar lithic sandstone; VII: Feldspar lithic sandstone.

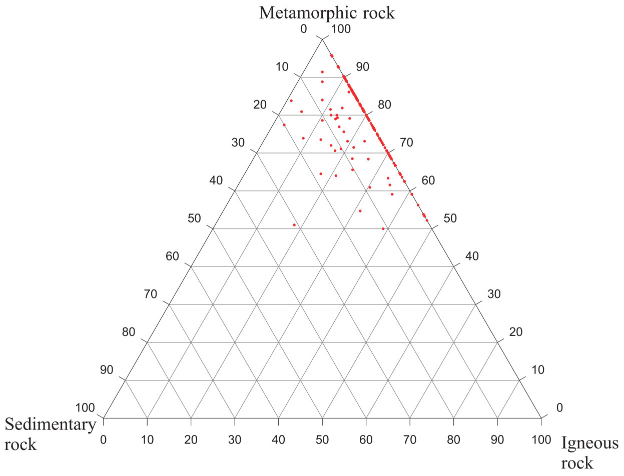

Fig. 3. Triangular diagram of lithic fragment classification for sandstone in the research area.

4. Diagenesis processes

4.1 Compaction

Compaction is the main factor that leads to reduction of primary porosity of reservoirs (Nguyen et al., 2014; Makeen et al., 2016), especially for the reservoir of the He-8 Member in the research area, mainly of lithic-rich sandstone and containing plastic volcanic dust, which results in compression resistance of the He-8 sandstone lower than those of quartz sandstone and lithic quartz sandstone. As the thickness of overlying strata increases, compaction became more and more intense, resulting in tight arrangement, displacement and redistribution of sandstone particles as well as plastic deformation of micas and plastic lithics, and consequently huge loss of primary intergranular pores (Stroker et al., 2013; Therkelsen, 2016) (Fig. 5(a)). Extensive studies on burial-induced modification of sandstone intergranular porosity show that when the burial depth <1500 m, the intergranular volume of sandstone decreases rapidly to 28% by redistribution of lithics, and moreover with the further increase of burial depth, the volume reduction slows down. When the burial depth reaches 2400 m, the intergranular volume decreases to 26%. Therefore, the compaction in the early diagenesis stage (depth <2500 m) is the main reason for large loss of sandstone primary porosity in this district.

Table 1. Statistics of pore types in the research area.

Stratigraphy	Percentages by pore type						Number of samples
	Lithic dissolved pores	Intercrystal pores	Feldspar dissolved pores	Intergranular pores	Matrix dissolved pores	Other types	
He-8	42.9	16.9	15.3	13	4.9	7	517

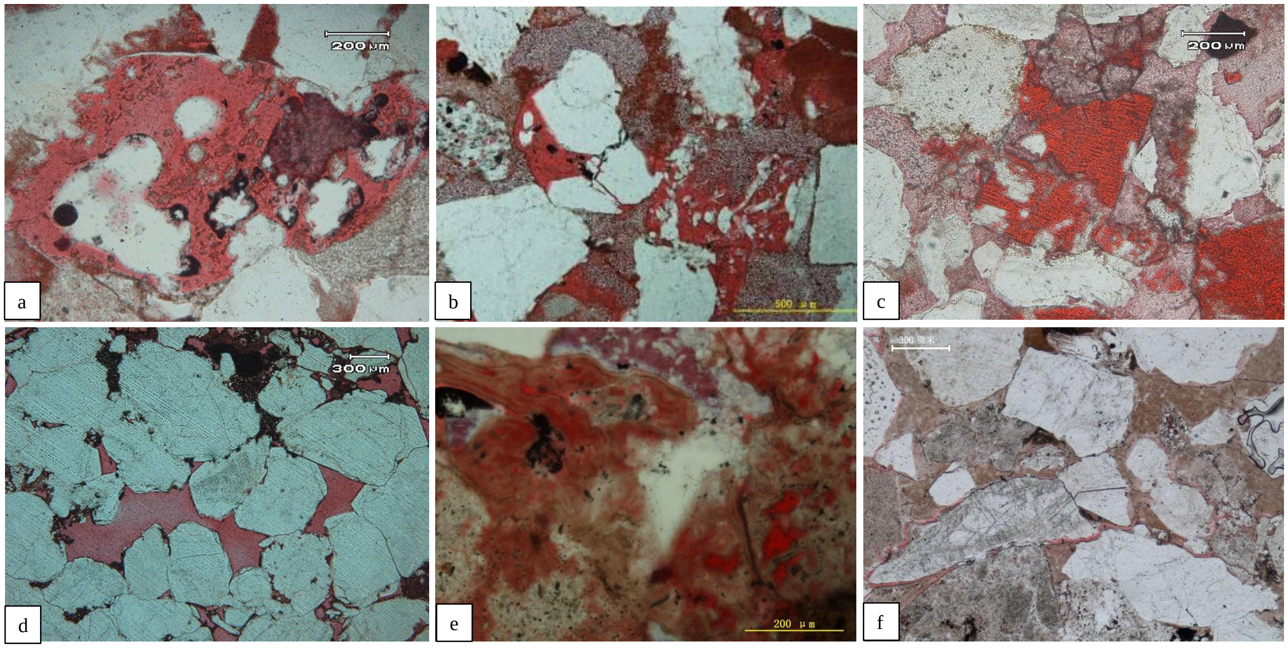

Fig. 4. Main pore types of the He-8 Member reservoir in the study area. (a) Lithic dissolved pores formed by dissolution of lithic particles, well 36, 2549.83 m; (b) Kaolinite intercrystalline pores, Zhao 68 well, 2903.46 m; (c) Feldspar dissolution pores, Zhao 52 well, 273.331 m; (d) Intergranular pores, Zhao 70 well, 2664.8 m; (e) Matrix dissolved pores (volcanic dust), Zhao 65 well, 2927.12 m; (f) Micro-cracks, Zhao 30 well, 3015.19 m.

4.2 Cementation

Siliceous cementation is mainly manifested as the secondary enlargement and recrystallization of quartz particles (Fig. 5(c)), with carbonate cementation mainly embodied as calcite cementation (Fig. 5(e)), and the clay mineral cementation mainly represented by hydromica (Fig. 5(b)) and chlorite membranes (Fig. 5(d)). Although the secondary enlargement edge of quartz occupies part of the pore space, it to some extent suppresses compaction and reduces pore loss. However, the idiomorphic authigenic quartz, produced by recrystallization, creates pores due to its coarse crystalline grains. Late cementation of calcite is often accompanied by metasomatism of quartz at some pore edges, kaolinite in the middle of pores. Calcite crystals formed by cementation have bright surfaces and complete crystal shapes (Rahman and Worden, 2016; Wüstefeld et al., 2017). Effects of later calcite cementation are minor, which once again compromise the pore structure. However, metasomatism (replacement) of volcanic materials by calcite occurs in early diagenesis. On the one hand, this early calcite metasomatic product hinders the hydration reaction inside rock at shallow depth and the late-stage dissolution by acid, thus sealing the rock. On the other hand, it impedes the early-stage charging of oil and gas into internal pores of rock. Although such calcite metasomatism of volcanic materials does not directly reduced sandstone porosity, it hinders improvement of sandstone porosity by constructive diagenesis processes such as dissolution. Calcite cementation generally occurs in late diagenesis. Once formed, calcite cement often experienced no dissolution from underground fluids and thus greatly reduce sandstone porosity. Hydromica, shown as irregular-shaped flaky and scaly aggregates, mostly occurs in the form of interstitial filling and tower bridge structures, and it also fills pores.

4.3 Metasomatism

Metasomatism of volcanic materials by calcite occurs in early diagenesis. On the one hand, this early calcite metasomatic product suppresses the hydration reaction inside rock buried at shallow depth and moreover the late-stage acid, and thus seals the rock (Mostafa et al., 2018; Busch et al., 2019). On the other hand, it impedes the early hydrocarbon charging into internal pores of the rock. Although such calcite metasomatism with volcanic materials does not directly reduce sandstone porosity, it impacts improvement of sandstone porosity contributed by constructive diagenesis processes such as dissolution. Calcite cementation generally occurs in late

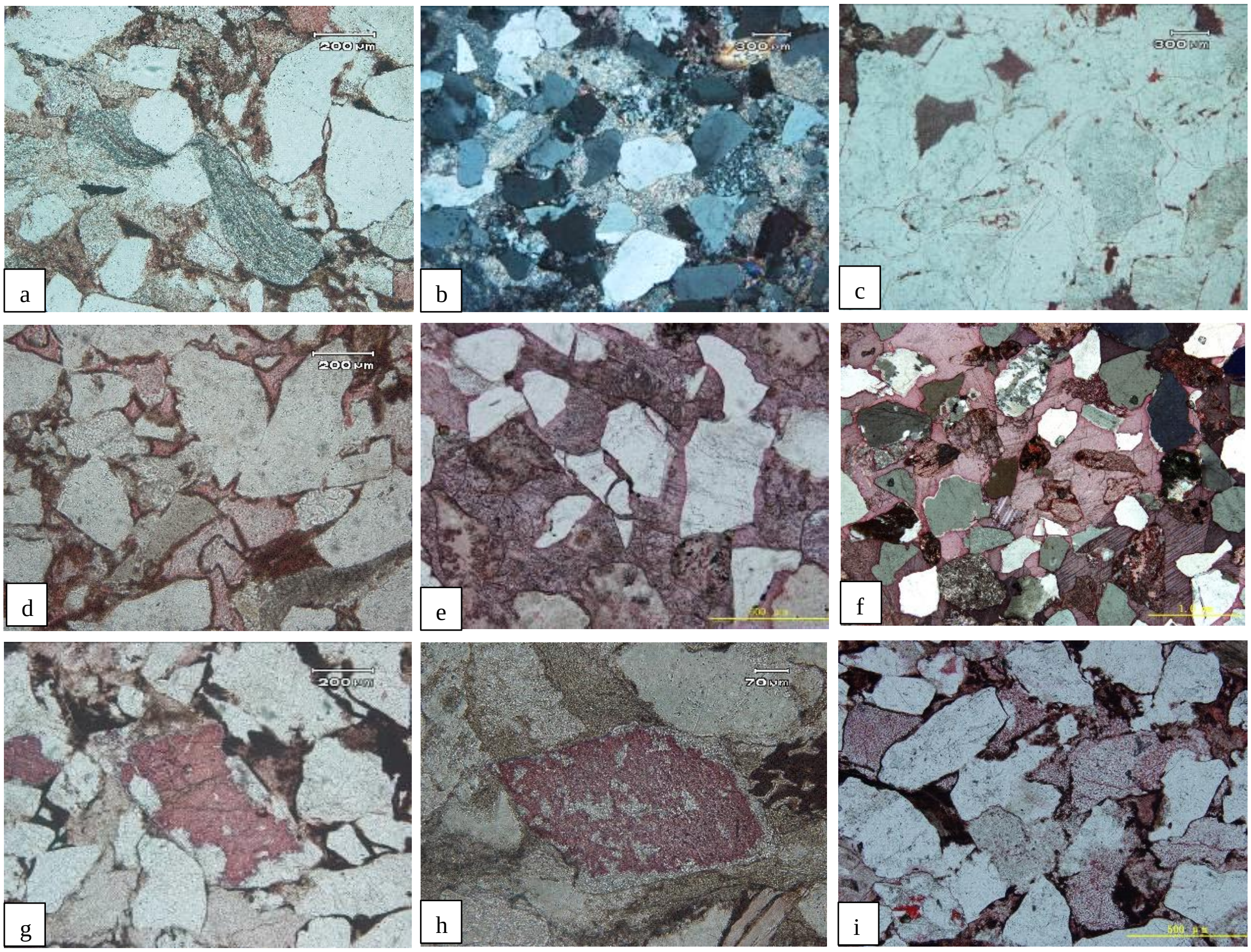

Fig. 5. Diagenesis types of He-8 member in the study area. (a) Phyllite deformation under pressure, well 32, 2702.93 m; (b) Hydromica cementing, Zhao 64 well, 2885.5 m; (c) Siliceous cement-quartz enlargement, Tong 32 well, 2739.56 m; (d) Chlorite cementation, Zhao 52 well, 2703.1 m; (e) Ferrocalcite cementation, Zhao 52 well, 2795.38 m; (f) Ferrocalcite cementation, Zhao 30 well, 2785.81 m; (g) Ferrocalcite metasomatic feldspar, Well 27, 2839.78 m; (h) Ferrocalcite metasomatic feldspar, Zhao 78, 2743.62 m; (i) Kaolinite metasomatic feldspar, Tong 30, 2832.16 m.

diagenesis. Once formed, calcite cements are in most cases exempt from dissolution by underground fluid and thus greatly reduce sandstone porosity (Pujol et al., 2018).

4.4 Dissolution

Dissolution in the research area mainly occurs in pyroclastic materials (Surarn et al., 2013), feldspar and matrix. Via dissolution, secondary pores such as lithic dissolved pores, feldspar dissolved pores and matrix dissolved pores are formed (Xiong et al., 2016). Among them, the intergranular dissolved pores and matrix dissolved pores formed by tuffaceous volcanic dust dissolution are important sources for the formation pores in the research area. Secondary pores formed by dissolution can increase porosity by 3%-5%, which is of great importance for such tight sandstone reservoirs.

4.5 Alteration

In the research area, alteration of feldspar particles into kaolinite (Fig. 4(b)) is critical, which is associated with the formation of kaolinite intercrystal pores. Kaolinite intercrystal pores are important reservoir space in the research area and provide a highly desirable condition for natural gas enrichment.

5. A new classification system for lithic-rich sandstone

Since the lithology of the research area is dominated by lithic sandstone, and the pores are dominated by secondary pores, the study of the formation mechanism of high-quality reservoirs of lithic-rich tight sandstone should start with the subdivided types of lithic sandstone and the development mechanism of secondary pores. However, the high proportion of the lithic sandstone (up to 82.4%) in this district makes it difficult to distinguish high-quality reservoirs from ordinary ones, using the research method for conventional lithic sandstone (in which lithic sandstone is investigated as a whole, with no rock type subdivision). Therefore, according to origins of lithics and interstitial materials as well as their control on reservoir pores, the lithic sandstone is subdivided into three

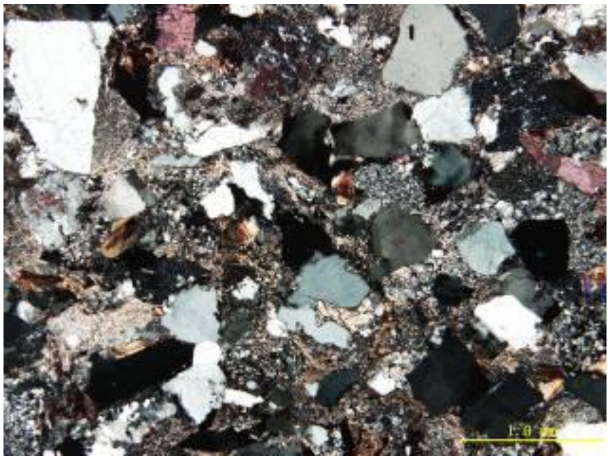

Fig. 6. Sedimentary lithic sandstone, Zhao 65, He-8.

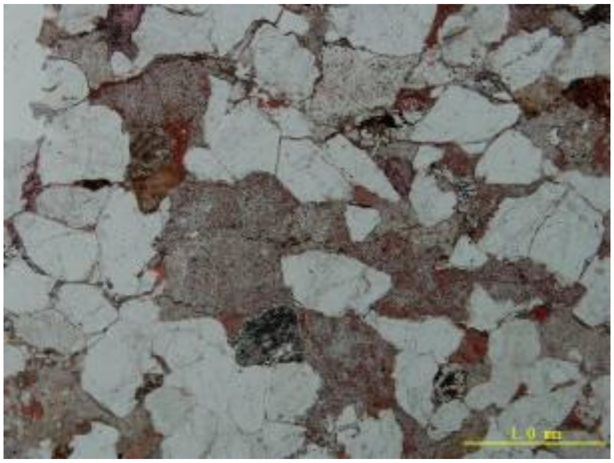

Fig. 7. Diagenetic lithic sandstone, Zhao 65, He-8.

types: sedimentary lithic sandstone, diagenetic lithic sandstone and event-type lithic sandstone.

The sedimentary lithic sandstone is formed by erosion and weathering of the parent rock, followed by water flow deposition. The lithology is mainly flexible lithic sandstone, and lithic fragments primarily include phyllite, mica and argillite. Due to the relatively low proportion of rigid particles, the rock cannot effectively resist mechanical compaction. Therefore, after deposition, the whole intergranular space is first filled with matrix. The lithics are usually seen with plastic deformation and water-absorption swelling, resulting in throats and pores plugged by pseudo-matrix. Intensive compaction has damaged many original pores, and the pore-throat structure is greatly obstructed (Fig. 6). The sandstone evolves into a pre-mature densification stage, which shadows the effects of the late diagenesis modification. Dissolution and other late modification activities are rarely found.

Diagenetic lithic sandstone refers to the lithic sandstone, of which feldspar and feldspathic lithics are converted into kaolinite minerals via dissolution alteration (Fig. 7). The initial cementation can inhibit compaction, which is beneficial to preserving the original pores of rock, and in the late stage, cements generates a considerable number of secondary pores through dissolution, which thus improve the reservoir physical property of such lithic sandstone (Mahmic et al., 2018). However, it should be noted that the undissolved part of produced cements tends to concentrate in pores, plugging throats and resulting deterioration of reservoir physical properties.

Event-type lithic sandstone refers to the tuffaceous sandstone formed by the synsedimentary neutral-acid volcanic materials in sandstone, which is called event-type lithic sandstone (Fig. 8). In many cases, these tuffaceous components improve the physical property of sandstone reservoirs: tuffaceous lithics, as the framework particles of sandstone, provide resistance to compaction during early diagenesis and increase the residual intergranular pores. In the late diagenesis stage, they provide parent materials for dissolution, which results in development of secondary pores and subsequent enhanced permeability of sandstone (Desbois et al., 2016; Tang et al., 2018). Synsedimentary volcanic dust materials of subaerial deposition massively transform into illite through the intermediate products of smectite and illite-smectite mixed layers, by alteration assisted with acid, which generates a large number of dissolved pores. At the same time, the tuffaceous matter at the edge of the secondary pore of sandstone to some extent inhibits the secondary enlargement of quartz, which helps preserving pores.

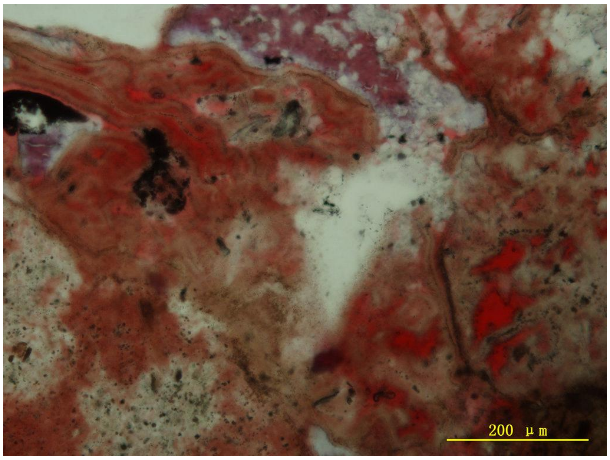

Fig. 8. Event-type lithic sandstone, Zhao 65, He-8.

Finally, statistics of contents (in percentages) of sedimentary lithics such as schist, phyllite, slate and siltstone are taken as indicators for sedimentary lithic sandstone; contents of kaolinite interstitial materials, for diagenetic lithic sandstone; contents of tuffaceous interstitial materials and volcanic materials such as pyroclasts, for event-type lithic sandstone. After data normalization, a ternary diagram of the three-phase indexes was plotted. The lithic-rich tight sandstone of the He-8 Member in this district is classified into the sedimentary type, diagenetic type, event type, and the transitional type among them (Fig. 9).

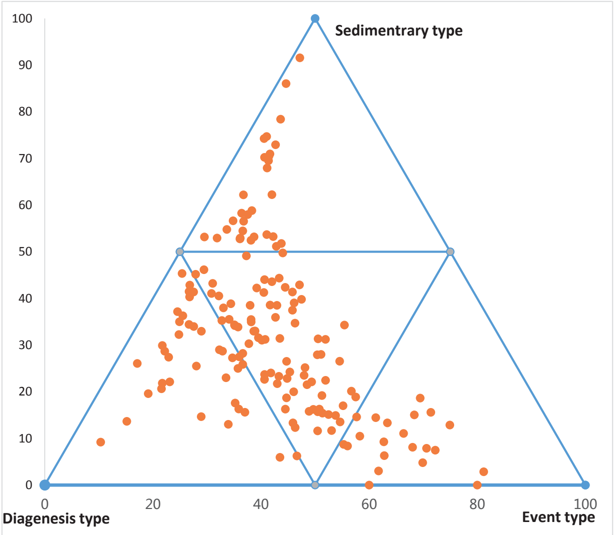

Fig. 9. Triangle diagram of debris sandstone classification.

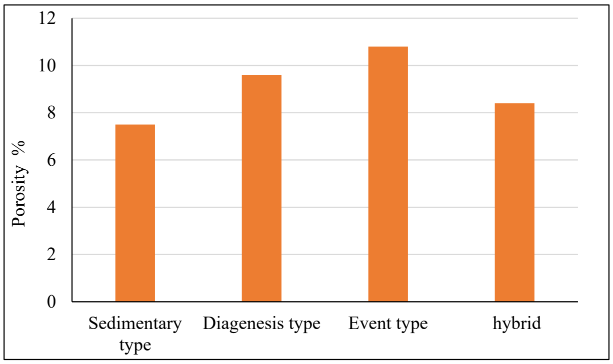

Fig. 10. Histogram of average porosity on various types of lithic sandstone.

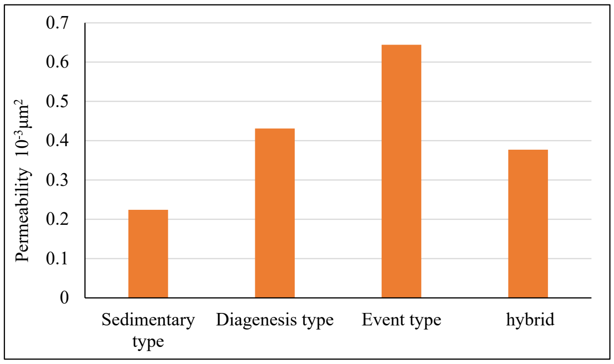

Fig. 11. Histogram of average permeability on various types of lithic sandstone.

6. Characteristics of various lithic sandstone reservoirs

6.1 Reservoir physical properties

The porosity of the lithic sandstone in the research area is generally lower than 13% (Fig. 10). The event-type lithic sandstone is rich in volcanic materials providing massive feldspar minerals, which are favorable for dissolution. Its porosity is the highest, generally ranging from 7% to 12%, averaging 10%. The second highest porosity is found in the diagenetic lithic sandstone. Due to the protection of primary pores by early chlorite cementation and late modification induced by dissolution (English et al., 2017; Kadkhodaie-Ilkhchi et al., 2019), some secondary pores have been formed, and the measured porosity is typically of 6%-11%, with an average of 9%. The sedimentary lithic sandstone has no dissolution-prone feldspar and is enriched with plastic lithics. Thus, it has low resistance to compaction, during which lithics plastically deform and thus huge loss of primary pores occurs, and the porosity is less than 8%.

In terms of permeability, these lithic sandstones are generally characterized by low to ultra-low permeability. For event-type lithic sandstone featuring a conventional low-permeability setting, dissolution modification improves not only porosity but also pore connectivity, which thus enhances permeability (Fu et al., 2015). Therefore, the permeability of event-type lithic sandstone is relatively high, generally less than 1×10^{-3} μm^2, with an average of about 0.6×10^{-3} μm^2. For diagenetic lithic sandstone presenting the initial chlorite rim cementation, pores to exist and yet pore-throat radii are reduced, with some pores and throats even plugged. Correspondingly, the permeability is of $(0.3\text{-}0.5)\times10^{-3}$ μm^2, averaging 0.46×10^{-3} μm^2. In terms of the sedimentary lithic sandstone, it is enriched with flexible particles that are mostly subjected to plastic deformation and have oriented arrangement. Such particles evolve into the pseudo-matrix after absorbing water and swelling, and plug pores and throats, causing serious damage to the pore-throat structure (Wang et al., 2019). Hence, the permeability of sedimentary lithic sandstone is less than 0.3×10^{-3} μm^2, with an average of only 0.15×10^{-3} μm^2 (Fig. 11).

6.2 Characteristics of the reservoir pore-throat structure

The key point when exploring the pore structure of the reservoir is to clarify the distribution and size of the pore throat. Nowadays, the size distribution of the pore throat is mainly determined by the mercury intrusion method (Schmitt et al., 2015; Zhang et al., 2019). Measurement results of tight sandstone in the study area show that the radius of pore throats is mostly low. The average radius distribution is in the range of 0.245-2.611 μm, and the median radius is in the range of 0.007-0.576 μm.

The strong heterogeneity of tight sandstone is embodied as higher displacement pressure and lower mercury withdrawal efficiency (Oluwadebi et al., 2019). The displacement pressures of the mercury intrusion tests for the three types of lithic sandstone are all greater than 0.5 MPa, especially for sedimentary lithic sandstone, which has a displacement pressure as high as 1.164 MPa due to the strong influence of compaction and lack of modification induced by later dissolution. Diagenetic lithic sandstone, with part of pores and throats plugged by chlorite rims, also presents a relatively

Table 2. Pore characteristics of the three types of lithic sandstone in the research area.

Type	Porosity (%)	Average pore radius (μm)	Permeability (10^{-3} μm^2)	Median radius (μm)	Throat mean value	Maximum mercury withdrawal efficiency (%)	Maximum mercury intrusion saturation (%)	Displacement pressure (MPa)
Event-type	11	0.482	0.589	0.204	9.862	36.11	84.82	0.5276
Diagenetic	7.3	0.303	0.357	0.026	10.963	45.44	79.76	0.7202
Sedimentary	4.9	0.227	0.207	0.014	9.519	36.56	67.39	1.164

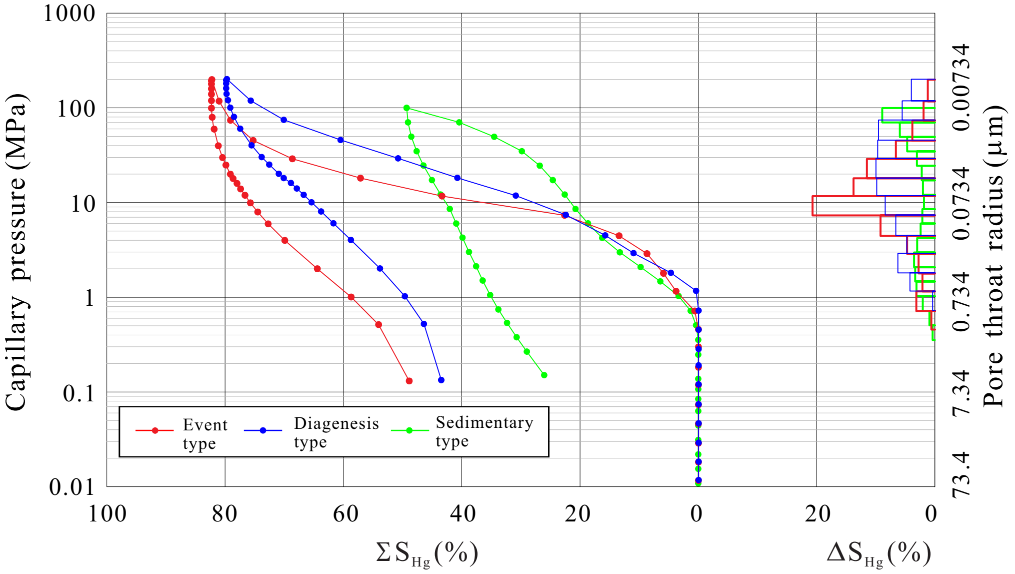

Fig. 12. Capillary pressure curves of three types of pore structures in the study area.

high displacement pressure (about 0.7 MPa). Among the three types, the event type has the best porosity, and still its maximum mercury withdrawal efficiency is below 50% (Table 2 and Fig. 12). The results show that the restraining ability of the pore-throat structure on non-wetting phase fluids' increases from the event type to the diagenetic type and at last the sedimentary type.

7. Formation mechanisms of high-quality reservoirs

The high-quality reservoirs in this study are defined as those with relatively better physical properties, given the overall low-porosity low-permeability reservoir setting in this district. Considering the refined division of lithic sandstone, it is believed that development of high-quality reservoirs in the He-8 Member in this district is mainly controlled by the following factors:

1) Development of various dissolved pores: a large number of dissolved pores to develop in the He-8 reservoir, which are dominated by secondary pores (mainly lithic, intercrystal and feldspar dissolved pores and intergranular pores). These dissolved pores, together with micropores among clay minerals such as kaolinite and illite, greatly increase pore space.
2) Favorable throat combination of clay minerals: especially, illite of the event-type lithic sandstone, extensively generated by alteration of volcanic dust materials through the intermediate smectite and illite-smectite mixed layer clays during diagenesis, and the smectite interbedding-kaolinite-chlorite clay mineral association of the diagenetic lithic sandstone formed during diagenesis, lead to the micropore-fine throat-micro throat assemblage, which endows the reservoir with relatively high permeability.
3) In the Taiyuan Formation and Shanxi Formation under the He-8 Member, a large number of thick coal seams are developed, which provide the fluids required for dissolution during burial evolution. These coal rakes, as the main source rocks in the study area, have strong hydrocarbon generation ability. The humic acid generated during the early diagenesis stage promotes the dissolution of medium-based plagioclase such as anorthite. In the diagenetic stage, a large amount of organic acid produced will promote the dissolution of feldspar again.

In other words, in the case that thermal evolution of thick coal beds provides sufficient acid fluids, the factors contributing to formation of high-quality lithic-rich sandstone reservoirs in the He-8 Member should be concluded as a certain quantity of rigid lithic fragment contents, certain compaction resistance during early diagenesis, and intensive dissolution during middle diagenesis (increasing porosity). Direct representation of high-quality reservoirs features development of secondary pores dominated by lithic, feldspar and matrix dissolved pores and kaolinite intercrystal pores, and the throat combination of micropore, fine throat and micro-throat, dominated by the micropores between clay minerals such as kaolinite and illite.

8. Conclusion

1) According to origins of lithics and interstitial materials as well as their control on reservoir pores, lithic sandstone is subdivided into the sedimentary lithic sandstone, diagenetic lithic sandstone, event-type lithic sandstone and transitional lithic sandstone.
2) For the sedimentary lithic sandstone with high contents of plastic lithics, the early diagenesis is regarded with strong compaction effects, which result in large porosity reduction, and moreover, such lithic sandstone barely has dissolved pores to compensate porosity. As for the diagenetic lithic sandstone with high contents of rigid lithics, the compaction effect is strong; extensive alteration of feldspar into kaolinite due to organic acid; the rock is highly cemented; middle porosity increase is observed. Finally, for the event-type lithic sandstone with high contents of rigid lithics, and which makes the reservoir has stronger ability to resist the compaction. And porosity growth attributed to dissolved pores is high, due to acid-assisted alteration of extensive synsedimentary volcanic dust materials of subaerial deposition into illite through intermediate smectite and illite-smectite mixed-layer clays and consequent generation of a large number of pores.
3) The sedimentary lithic sandstone has poor physical properties and is identified as the unfavorable reservoir; the diagenetic lithic sandstone having medium physical properties, identified as the relatively favorable reservoir; the event-type lithic sandstone having the best physical properties, defined as the favorable reserv In the research area, the direct manifestation of high-quality reservoirs is the development of secondary pores dominated by lithic dissolved pores, kaolinite intergranular pores, feldspar dissolved pores and matrix dissolved pores, and the throat combination of micropores-fine throats-micro throats, dominated by micropores among clay minerals such as kaolinite and illite.oir.
4)

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Conflict of interest

The authors declare no competing interest.

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