Geological Controls on High Production of Tight Sandstone Gas in Linxing Block, Eastern Ordos Basin, China

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Abstract: Tight sandstone gas in the Linxing Block, eastern Ordos Basin, has been successfully exploited. The high performance is mainly a result of the special geological conditions. The key geological controls for high production have been discussed on the basis of seismic data, field observation, sample features, mercury porosimetry, mechanical properties, and basin modeling. Firstly, the coal measures have good gas generation potential, not only because of the existence of coalbeds and organic-rich shales, but also because coal laminae and microbial mats in the shales significantly increase their total organic carbon (TOC) contents. Secondly, except for the uplifted zone of the Zijinshan complex and the eastern fault zone, large faults develop in the Carboniferous sequence, ensuring the sealing capacity of cap rock. Small fractures generally concentrated in the sandstones rather than the mudstones. Thirdly, gas accumulation in the Linxing Block was controlled by the tectonic, burial and thermal histories. Gas accumulation in the Linxing Block started in the Late Triassic, followed by three short pauses of thermal maturation caused by relatively small uplifts; the maximum hydrocarbon generation period is the Early Cetaceous as a combined result of regional and magmatic thermal metamorphisms. Field profiles show abundant fractures in sandstone beds but rare fractures in mudstone beds. Mechanical properties, determined by lithostratigraphy, confine the fractures in the sandstones, increasing the permeability of sandstone reservoirs and retaining the sealing capacity of the mudstone cap rocks. The modern ground stress conditions favor the opening of predominant natural fractures in the NNW–SSE and N–S directions. These conclusions are useful for exploring the potential tight sandstone gas field.

Key words: tight sandstone gas, structure, fracture, basin evolution, Ordos Basin

I Introduction

The Ordos Basin is a large superimposed basin with an area of 250,000 km2 in central China (Zhang et al., 2009). The upper Paleozoic petroleum system covers almost the entire basin (Xiao et al., 2005), including tight sandstone gas, coalbed methane, and shale gas (Zhu et al., 2009; Wei et al., 2010; Li and Zhang, 2013; Yao et al., 2013; Bao et al., 2016; Xiong et al., 2016; Li J et al., 2017; Han H et al., 2018; Zou et al., 2018). Tight sandstone gas plays an important role in unconventional natural gas exploration and exploitation worldwide. Many large tight sandstone gas fields, including Sulige, Daniudi, Zizhou, Shenmu, and Mizhi, have been discovered in the upper Paleozoic strata in the Ordos Basin. The Linxing Block has also been assessed as having a proven tight sandstone gas reserve of 1.01 billion m3. The sandstone layers in the Taiyuan and Shanxi Formations are part of the tight sandstone gas reservoirs in the Linxing Block (Ning et al., 2016). According to the data from China United Coalbed Methane Co Ltd., four of the five wells, which only recover the second section of the Taiyuan Formation, have average daily gas production of more than 10,000 m3/d. The accumulation of tight sandstone gas in the Ordos Basin has been studied from the aspects of sedimentary framework, tectonic events, diagenetic evolution of sandstone, reservoir properties, and gas origin and migration (Xiao et al., 2005; Yang et al., 2005, 2015; Yang H et al., 2008; Zhang et al., 2009; Zou et al., 2012; Zhao et al., 2014). Coal measures (and marine carbonates) are dominant source rocks (Dai et al., 2005; Xiao et al., 2005; Guo et al., 2014). The sandstone layers in the lower Permian System and the thick mudstone layers in the upper Permian strata make up a reservoir-sealing association (Xiao et al., 2005). Dissolution porosity may be as important as residual intergranular porosity for the...
tight sandstones (Zhang et al., 2009; Zou et al., 2012; Liu et al., 2016; Fan et al., 2017). Because tight sandstone reservoirs are characterized by poor petrophysical properties and fine pore structure with strong heterogeneity (Zou et al., 2012), recently, conventional and advanced experiment methods, such as thin section observation, cathode luminescence, scanning electron microscopy, mercury porosimetry, nuclear magnetic resonance, and micro/nano-computed tomography, have been used to study the reservoir properties of tight sandstone (Wu et al., 2018).

Based on our experience and understanding of tight sandstone reservoirs in the Linxing Block, several geological conditions benefit the accumulation and high production of natural gas. We combined stratigraphic structure, experiment data, and basin modeling to discuss the key geological problems, including gas sources, sealing capacity, tectonic evolution, and fracture development.

2 Geological Settings

The Ordos Basin is located in central China (Fig. 1a). Tectonically, it can be divided into six structural units, including the Yimeng Uplift, the Weibei Uplift, the Jinxin Fold Belt, the Shanbei Slope, the Tianhuan Depression, and the Jinxin Fold Belt (Fig. 1b). The basin is a huge asymmetric syncline with a gentle dip of 0.5°–1.0° toward the east and north and a slightly steeper dip of 2°–3° toward the west and south (Xiao et al., 2005). The Taiyuan-Shanxi Formations of the Carboniferous-Permian System in the Eastern Ordos Basin were deposited in a marine-continental transitional environment, including lagoon, tidal, barrier bar, and delta front (Li Y et al., 2015; Shen et al., 2017). These strata develop frequently interbedded mudstone, sandstone, and coal, as well as limestone (Fig. 2).

The Linxing Block is situated in the Jinxin Fold Belt. In the middle–late Proterozoic and Paleozoic, the Jinxin Fold Belt rose and suffered weathering and denudation. During the middle–late Cambrian, early Ordovician, late Carboniferous, and early Permian, the region received thin deposits associated with a marine or marine–continental environment. From the late Jurassic to early Cretaceous, the Yanshanian Movement caused the rise of the Lvliang Mountain, compressing the eastern Ordos Basin and forming the Jinxin Fold Belt in a north–south direction. The Lishi strike-slip fault between the Jinxin Fold Belt and Lvliang Mountain controlled the structural deformation of the region. The strata in the western part of the Jinxin Fold Belt are broad and gentle, while the formations in the eastern part are steep and were strongly reconstructed with a series of northeastward fractures. Multiphase magmatic activities during the Yanshanian Period also formed the Zijinshan alkali complex, situated in the middle area of the Jinxin Fold Belt.

Zircon dating indicates that the major period of magmatic activity was the early Cretaceous. The period is consistent with the tectonic-thermal activity in the whole of North China. Such activity uplifted the eastern Ordos Basin regionally and formed the Zijinshan complex (Yang X K et al., 2008). Said complex emplaced into the Triassic stratum and the underlayer formations, with an exposed area of 23.3 km². The complex comprises both intrusive and extrusive rocks. The Zijinshan complex not only uplifted the strata but also enhanced the thermal maturity.
of the organic matter (OM) around it. The vitrinite reflectance of OM in the Linxing Block generally increases westward because of the increase in depth, except for the high mature region around the Zijinshan complex (Fig. 1c).

The Taiyuan-Shanxi sequences are rich in OM, especially for coal and mudstone. The Taiyuan Formation comprises four to eight coalbeds with a total thickness of 8–18 m, and the Shanxi Formation contains five coalbeds with a total thickness of 4–14 m. No. 8 (+9+10) and No. 5 (+3+4) coalbeds are regional (or local) workable coalbeds (Li et al., 2016). Mudstone thickness in the Shanxi Formation ranges from 10–50 m; in the Taiyuan Formation, it is in the range of 20–80 m (Li et al., 2016).

### 3 Samples and Methods

Seismic profiles in the Linxing Block, provided by China United Coalbed Methane Corporation, were used to determine the stratum distribution and structures. Typical field profiles of Carboniferous–Permian outcrops to the east of the Linxing Block were studied. Current flood ditches provide good field profiles. Stratigraphic assemblage and joint development were recorded. A total of 518 fractures within the Taiyuan and Shanxi Formations were measured along eight field profiles. Strike direction, dip angle, and dip azimuth were documented.

In all, 20 mudstone and five sandstone samples were used in the work. The mudstones were collected from fresh coalfaces and drilling faces of the seven coal mines, and the sandstone samples were taken from drilling cores in the Linxing Block. All samples belong to the Taiyuan and Shanxi Formations.

Quantification of total organic carbon (TOC) and mineral compositions was performed for all the

<table>
<thead>
<tr>
<th>Strata</th>
<th>GR API</th>
<th>SP MV</th>
<th>CAL(IN)</th>
<th>DT24(us/ft)</th>
<th>ZDEN(g/cm³)</th>
<th>Depth (m)</th>
<th>Lithology</th>
<th>Facies</th>
<th>Subfacies</th>
<th>Microfacies</th>
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<td>T.</td>
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<td>120</td>
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<td>140</td>
<td>1,3</td>
<td>1700</td>
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<td>Distributary bay</td>
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<td>180</td>
<td>16</td>
<td>40</td>
<td>3</td>
<td>1750</td>
<td>Delta front</td>
<td>Distributary bay</td>
<td>Underwater distributary river</td>
<td></td>
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<td>C.</td>
<td>300</td>
<td>120</td>
<td>16</td>
<td>140</td>
<td>1,3</td>
<td>1800</td>
<td>Delta front</td>
<td>Distributary bay</td>
<td>Peat swamp</td>
<td>Mud flat</td>
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<td>O.</td>
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<td>120</td>
<td>16</td>
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<td>1,3</td>
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<td>Delta front</td>
<td>Distributary bay</td>
<td>Underwater distributary river</td>
<td>Mud flat</td>
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![Fig. 2. Stratigraphy and sedimentary environment of the Benxi to Shanxi Formations, modified from Shen et al. (2017).](image)
mudstones. TOC of the mudstones was measured with a Leco CS230 Carbon/Sulfur analyzer after removing carbonates by soaking in a heated hydrochloric acid solution. The procedure followed the Chinese National Standard GB/T 19145-2003. Mineral composition was measured by X-ray diffractometry (XRD). Both bulk mudstone samples and their clay fractions were detected by a D/max-2500 X-ray diffractometer. XRD patterns were recorded from 2°–45°(2θ) at the speed of 2°(2θ) per minute and the step width of 0.02°(2θ).

Based on the TOC and mineral analysis, five mudstone samples (without coal laminae) and the five sandstone samples were selected for mercury porosimetry and uniaxial compression experiments. The outgassing procedure, which preceded the experiments, was performed by a vacuum drying system under 110°C for 12 hours. The maximum incremental mercury pressure of the mudstones was 227 MPa, while that of the sandstones was 100 MPa. Mercury pressure can be converted to pore diameter. A lower pressure was used for the sandstones because they contained small pores < 10 nm. Washburn’s equation is commonly used to calculate pore diameters based on the hypothesis of cylindrical pores (Washburn, 1921). The parameters assume a contact angle of 141° between the mercury and the pore surface and a surface tension of 0.485 N/m (Rexer et al., 2014; Yao and Liu, 2012).

$$p = \frac{4\gamma \cos \theta}{d}$$

where the $p$ is mercury pressure, MPa, and $d$ is pore diameter, nm.

Uniaxial compression was performed on cylinders of the five mudstone and five sandstone samples. Cylinders with a diameter of 25 mm and a height of ~50 mm were cored for each sample. The lengths and diameters of the cylinders were measured using a Vernier caliper with an accuracy of 0.001 mm. A constant axial displacement ratio of 0.07 mm/min was used in the loading process until sample failure. Uniaxial compressive strength was recorded, and elastic module and Poisson’s ratio were calculated.

4 Results
4.1 Structures in seismic sections and natural fractures in outcrops

The formation occurrence is relatively stable with a gentle dip of 5°–10° toward the west, except for the region around the Zijinshan complex (Fig. 1c). Large faults are mainly located in the eastern fault zone and around the Zijinshan complex (Fig. 3a). Large faults can be identified from the seismic sections. Seismic sections in Fig. 3b and 3c clearly show that large faults are mainly in the Ordovician and usually do not cut through the roof of the Ordovician. The Carboniferous-Permian strata are stable and continuous, and rare large faults exist within them. The Zijinshan complex uplifted the strata in the southern research areas and produced plenty of faults, disrupting the stratum continuity. As a result of the karst landform in the Ordovician, collapsed columns exist, causing the downward collapse of upper strata. However, the collapses usually do not extend to Carboniferous systems.

Field profiles of outcrops provide higher resolution than seismic sections. Sandstone beds are mostly interbedded with mudstone beds, with thickness ranging from several millimeters to more than 10 meters. High angle fractures (or joints) are frequently developed in either thick or thin
sandstone and limestone beds but are rare in mudstone beds (Fig. 4a–c). Limestone comprises more regular fractures such as orthogonal joint systems (Fig. 4d and e). Jiang et al. (2013) also reported that six trends of joint sets form three groups of orthogonal joint systems in the southeastern Ordos Basin. Some mudstones occur as shale as a result of exposure and weathering, forming bed-parallel fractures (Fig. 4f). Stronger weathering can produce thin, papery shales (Fig. 4g).

Statistics of the fractures within the Taiyuan and Shanxi Formations in the Linxing Block are shown in Fig. 5. According to Fig. 5a, the most predominant fractures are in the NNW–SSE direction. The NNW–SSE fractures and ~W–E fractures make up conjugate shear fracture sets, which indicate a NW–SE compressive stress. Most fractures are high-angle fractures (Fig. 5b).

4.2 Sample features and optical microscopic images

The mudstones generally appear dark to black, indicating high TOC contents. Some of the samples contain extremely thin coal laminae, mostly with a thickness of 0.2–0.5 mm (Fig. 6a). TOC contents of the coal-laminae-bearing mudstones range from 15.55%–22.18%, with an average value of 19.36%, while those of the other mudstones are in the range of 1.11%–9.79%, with an average value of 4.68% (Table 1). Besides coal laminae, extensive microbial mats, which also significantly increase TOC contents, can be identified from optical microscopic observation of some thin sections (Fig. 6b). Sandstone in the coal measures may also contain OM, which occurs as fossil fragments of plants, thin coal laminae, or dispersive coal debris (Fig. 6c–f). The cyclically liner-distributed OM may be formed from in-situ microbial mats or terrestrial plant debris. Fragments of plants, such as Cordaites and Pecopteris, are common in both mudstone and sandstone (Fig. 6f).

Most of the samples are composed of clay minerals and quartz and contain a little K-feldspar, plagioclase, calcite, dolomite, siderite, and pyrite, as well as heavy minerals. Kaolinite accounts for the majority of clay minerals. The compositions of major minerals and clay minerals are shown in Fig. 7. High kaolinite (clay) content of the carboniferous–Permian mudstone was also reported by Xiong et al. (2017). The mineral compositions are distinct from those of marine shales, which commonly have more carbonate, quartz, and illite (Bu et al., 2015; Lyu et al., 2018). Besides, five tonsteins with kaolinite content greater than 90% were identified. Tonsteins are formed by diageneric alteration of volcanic ash, which falls in an acidic and low-salinity environment (Spears, 2012). The tonsteins act as the floor of No. 8 coalbeds.

4.3 Mercury porosimetry

Mercury porosimetry was applied on five mudstone and five sandstone samples. The cumulative intrusion volume of mercury was plotted with mercury pressure, as in Fig. 8. According to the final accumulative intrusion values, the porosity of the mudstones was much smaller than that of the sandstones. According to Washburn’s equation, pore diameters are negatively correlated with mercury pressure. The vertical dash line is located at the pressure corresponding to the pore diameter of 50 nm. According to the slope of the curves, most of the pores of sandstones were larger than 50 nm, while the mudstones were dominated by pores less than 50 nm. These results agree with those of previous studies (Ross and Bustin, 2007; Nelson, 2009; Chalmers et al., 2012; Pan et al., 2017).  

4.4 Mechanical properties

Uniaxial compression was performed to measure the mechanical properties. Based on the difference and anisotropy of the samples, the mechanical parameters of either the mudstones or the sandstones were relatively discrete. However, compared with the sandstones, the mudstones have lower compressive strength, as well as lower elasticity modulus and Poisson’s ratio (Fig. 9), which is in agreement with Meng and Pan (2007). The mechanical properties control their behaviors under stress.

5 Discussion

5.1 Source rocks and gas generation conditions

OM hosted in the sequence generates natural gas during thermal maturation. Based on stable isotope carbon compositions, the Carboniferous–Permian coal measures (and carbonate) are the dominant tight sandstone gas origin in the Ordos Basin (Dai et al., 2005; Han W et al., 2018). The high gas contents is caused by the abundant OM within the sequence, not only in coalbeds but also within mudstone and sandstone. The samples’ morphology, thin section observation, and quantitative analysis demonstrate the high TOC contents in the mudstones and some sandstones. The dark and black color of the mudstones indicates high TOC content (ranging from 1.11%–22.18%). Thin coal laminae and plant debris in the mudstones and sandstones significantly increase their TOC and hydrocarbon potential as well as gas adsorption capacity (Gao et al., 2013). In addition, extensive microbial mats, which can be observed from thin sections, also increase the TOC contents of mudstones (Fig. 6b). OM in sandstone consists mainly of terrigenous materials, including higher plants and swamp vegetation, and are primarily type III kerogen (Fig. 6c). Artmann et al. (2003) reported that a low-order sandstone stream in Weidlingbach, Lower Austria contained seasonal dynamics of algal biomass and allochthonous input of coarse particulate OM. The OM-bearing sandstone should be originally deposited from this type of sandstone stream. Because type III kerogen mainly generates gas rather than oil, the internal gas-prone OM partly turns the sandstones into source rocks. Due to the short distance of gas migration, OM in sandstones and their adjacent mudstones may be more efficient in charging sandstone reservoirs.

Tight sandstone gas in some gas fields was thought to

### Table 1 TOC contents of conventional mudstones and coal-laminae-intercalated mudstones

<table>
<thead>
<tr>
<th>Sample type</th>
<th>TOC contents (%)</th>
<th>Samples numbers</th>
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<tbody>
<tr>
<td>Dark to black mudstone</td>
<td>1.11–9.79 (average 4.68)</td>
<td>15</td>
</tr>
<tr>
<td>Coal-laminae-bearing</td>
<td>15.55–22.18 (average 19.36)</td>
<td>5</td>
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Fig. 4. (a) The profile for thick sandstone and mudstone beds of the Shanxi Formations; (b) The profile for interbedded thin sandstone and mudstone beds of the Shanxi Formations; (c) The profile for thick limestone and mudstone beds in the Taiyuan Formations; (d) Limestone cut by orthometric fractures; (e) Horizontal view of (d) shows regularly orthometric fractures; (f) Horizontal fractures in black shale of the Shanxi Formation; (g) Strongly weathered shale of the Taiyuan Formation.
partly originate from carbonate because stable carbon isotope compositions indicate a coal-derived gas mixed with an amount of oil-derived gas (Dai et al., 2005; Han W et al., 2018). However, because the sediments were deposited in a marine–continental transitional environment, a certain amount of OM in mudstone was sourced from marine aquatic-derived OM (Li Q et al., 2017; Qi et al., 2019a, 2019b). As such, we believe that the oil-derived gas may partly originate from these transitional mudstones. Moreover, the magmatic thermal events, especially around the Zijinshan complex, increase the thermal maturity to more than 2.0%, accelerating the gas generation (Gu et al., 2016).

5.2 Reservoir and mudstone cap rocks

In the Late Carboniferous to Early Permian, the study area was influenced by sea-level variations, forming cyclothems. Cyclothems are alternating stratigraphic sequences of marine and non-marine sediments and are bonded by marine flooding surfaces and coalbeds (Hampson et al., 1999). The multicycle sequence framework controls the formation of multi-superposed gas (or fluid) systems with independent pressure systems (Qin et al., 2016). Thick mudstone layers with relatively low
porosity and permeability can act as the cap rock for the sandstone reservoirs. Yang et al. (2005) also thought that stratigraphic variations in the Ordos Basin provide the principal traps based on its stable tectonic setting. Regional reservoir-sealing associations in the Ordos Basin have been proposed (Xiao et al., 2005; Yang et al., 2005). Furthermore, four layers of widely distributed siderite-bearing mudstone divide the gas systems because such mudstone is characterized by low porosity, low permeability, and high breakthrough pressure (Shen et al., 2017). However, the sealing capacity of the mudstone cap rocks has not been studied in detail. Herein, we discuss the controlling factors of the sealing capacity from two aspects: 1) the effects of faults and 2) pore structures.

According to the effects of the Zijinshan complex on formation occurrence, Cao et al. (2018) divided the Linxing Block into three structural units: central uplifted zone, annular folded zone and uniclinal structural zone (Fig. 3a). In the central uplifted zone, multiphase magmatic emplacements uplifted the strata and generated many large faults to connect the surface, breaking the stratigraphic continuity. The annular folded zone developed much smaller fractures which did not lead to remarkable loss of natural gas. The uniclinal structural zone also lack large faults except for the eastern fault zone (Fig. 3a). The sealing capacity of the cap rocks is strongly affected by large faults. The seismic profiles show that many large faults exist in the Ordovician and usually do not cut through the top of the Ordovician. The collapse columns were developed locally and also had little influence on the Carboniferous strata. Overall, except for the central uplifted zone and the eastern fault zone, the carboniferous and upper strata in the research area generally developed rare large faults, and are suitable for sealing.

Mercury porosimetry was used to evaluate the pore structures of the mudstones and sandstones (Fig. 8). According to the maximum intrusive volume, the mudstones commonly have much lower porosity than the sandstones. The pore diameters in the mudstones are mainly less than 50 nm, while those in the sandstones are mainly more than 50 nm. The weak pore structures of the mudstones indicate that they can be a good sealing for the sandstones. The weak pore structures of the mudstones are a result of the mineral compositions and the OM. On one hand, mudstones in transitional and coal-bearing strata generally have high kaolinite contents (Dill, 2016), and kaolinite decreases the volume of pores > 5 nm (Qi et al., 2019b). On the other hand, although OM in marine shales was reported to accommodate pore networks (Modica and Lapierre, 2012; Cardott et al., 2015), organic pores in the
transitional mudstones are relatively small (mainly < 5nm) and do not contribute significantly to porosity and permeability (Qi et al., 2019b).

5.3 Basin evolution and gas accumulation

The burial, thermal and maturation histories of Well X were modeled using PetroMod 1D software and is shown in Fig. 10a, b. Well X is located in the central part of the Linxing Block (Fig. 1c), which was moderately affected by the thermal effect of the Zijinshan complex. Stratigraphic continuity indicates a continued sedimentation before the Late Triassic. In the middle Triassic, the OM entered the oil window. According to Chen et al. (2006), small uplifts took place at the end of the Triassic, the end of the Early Jurassic, and the end of the Late Jurassic. The small uplifts led to short pauses of thermal maturation. In the Early Cretaceous, the deep-burial thermal metamorphism restarted as a result of

Fig. 9. Box plots of uniaxial compressive strength, elasticity modulus and Poisson’s ratio of the mudstones and sandstones.

Fig. 10. (a) Burial history of the Linxing Block; (b) thermal and maturation histories of the Linxing Block

The figures also indicate how the tectonic, burial and thermal histories control on reservoir formation.
increasing burial depth. In the same period, the major Zijinshan magmatic intrusion occurred in 125–138 Ma (Ren et al., 2007; Xiao et al., 2007; Yang et al., 2010; Chen et al., 2012). The maturity of OM increased rapidly in the Early Cretaceous as a combined result of regional and magmatic thermal metamorphisms. The OM in the Taiyuan and Shanxi Formations reached the gas window and maximum hydrocarbon yields. The last, and most major, uplift began in the Late Cretaceous, and the thermal maturation also stopped at that time.

Fig. 10 also shows how tectonic, burial and thermal histories controlled the gas occurrence in the sandstone reservoirs in the Linxing Block. The Linxing Block has experienced several important tectonic evolutions. In the early depositing period, the evolution of the research area consisted with the Ordos Basin; while after the end of Triassic, it was more related to the orogenic belt on the east. During Late Permian times, the Paleo–Asian Ocean closed as a result of the collision between the North China Block and the Siberia Plate (Eizenhöfer et al., 2014; Li D et al., 2015). The Ordos Basin was then transformed into a large intracratonic basin under an N–S compressive condition. The compressive stress came from collisional amalgamation between the North and South China Blocks (Wan et al., 2002; Wang et al., 2006; Darby and Ritts, 2007). Tectonic events controlled the deposition and erosion processes (Yu et al., 2018). In the middle Triassic, the source rocks entered into the oil window due to the fast deposition and gas began to accumulated. In the Jurassic (also Early Yanshanian), the subduction of the Pacific Plate beneath the Eurasian Plate induced an NW–SE compressive stress. The Yanshanian movement is generally considered to have strongly affected the Ordos Basin and North China. Many high-angle fractures were generated in the sandstones (Fig. 5) and accelerated the gas migration from the source rocks to the sandstones. According to the burial history, the research area suffered three periods of uplift from the end of Triassic to the end of Triassic, which led to the slow thermal maturation of OM. Since the Early Cretaceous (also Late Yanshanian), the Eastern Eurasia continent has entered into an extensional regime (Ren et al., 2002; Darby and Ritts, 2007). The research area deposited and magmatic hydrothermal fluids upwelled, forming the Zijinshan alkali complex. Thermal effects of increasing depth and magmatic intrusions caused the strongly thermal maturation of OM in the early Cretaceous, which is the major period of gas accumulation. Due to the far-field effects of the collision between the Indian and Eurasian plates since the late Cretaceous, the region has experienced a long period of uplift and erosion, under a NE–SW stress field (Wan et al., 2002; Wang et al., 2010). Some gas escaped during the last period, but most were retained, forming the unconventional natural gas reservoir.

5.4 Fracture development and mechanical properties
5.4.1 Lithostratigraphic controls on fracture distribution

Interbedded mudstone and sandstone (or limestone) layers do not only form stratigraphic–lithologic reservoir–sealing associations but also confine natural and hydraulic fractures within sandstone beds. Field observations show that high-angle fractures commonly run through the sandstone (or limestone) beds but terminate at the interfaces of mudstone beds. Cilona et al. (2016) and Ju et al. (2015) also reported well-connected fracture networks in sandstones and low hydraulic conductivity in shales in alternating sandstone and shale sequences. Strong vertical connectivity across shales only occurs in faults and large sheared fractures, but large faults or fractures are rare in our research area. The mudstone in outcrop shows abundant papery lamination, but the bed-parallel fractures are thought to be induced by weathering and are not pre-existing fractures underground. Stress reduction and weathering of outcrop shales easily generate bedding-parallel fractures (Gale et al., 2014). The differential distribution of fractures not only ensures the sealing capacity of mudstone caprock but also increases the hydraulic conductivity of sandstone reservoirs.

5.4.2 Mechanical principles of the differential fracture developments

Fracture development is controlled by mechanical properties and stress environment. Sandstone mainly releases the stress by brittle fractures while mudstones do so by both brittle fractures and plastic deformation (Ju et al., 2018; Zhu et al., 2018). The mudstones, especially the clay-rich varieties in the Taiyuan and Shanxi Formations, have a higher Poisson’s Ratio than sandstone (Fig. 9). High minimum horizontal stress can be expressed by equation (2) according to Zhang Y and Zhang J (2017). A high Poisson’s Ratio is associated with high minimum horizontal stress under formation condition:

$$\sigma_h = \left(\frac{\nu}{1-\nu}\right)(\sigma_v - \alpha p) + \alpha p + \frac{c}{1-\nu}$$  

Where $\nu$ is Poisson’s ratio, $\sigma_v$ is vertical stress, $\alpha$ is Biot’s effective stress coefficient, $p$ is pore pressure, and $c$ is minimum stress coefficient, which can be obtained by calibrating in-situ measured data.

Fracture networks are extremely important in the development of unconventional natural gas. The mechanical stratigraphy controls the natural fracture development (McGinnis et al., 2017). The schematic diagram indicates that mudstone beds have much higher minimum horizontal stress than the adjacent sandstone beds (Fig. 11). High minimum horizontal stress is an effective barrier that prevents fracture initiation and propagation. Thus the fractures, both natural and hydraulic, tend to terminate at the mudstone beds. Fractures from hydraulic fracturing also preferentially propagate within sandstone beds in an alternating sandstone and mudstone sequence to attain a larger fracturing radius (Zhang Y and Zhang J, 2017; Zhang et al., 2018).

5.4.3 Opening of natural fractures

The hydraulic conductivity of reservoirs depends strongly on whether the fractures are open or closed. Open fractures (< 3 km depth) are necessarily aligned with maximum horizontal stress because fractures that are
Fig. 11. Schematic diagram of ground stress distribution within an alternating sandstone and mudstone sequence, from Zhang et al. (2018), with permission from Elsevier. $\sigma_h$, $\sigma_v$ and $\sigma_t$ represent minimum horizontal principle stress, maximum horizontal principle stress and vertical stress, respectively.

oriented parallel or nearly parallel to modern-day maximum horizontal compressive stress have the lowest normal stresses across them (Laubach et al., 2004; Queen and Rizer, 1990). According to borehole breakouts and drilling-induced fractures (DIFs) in image logging, present-day principal stress in the Linxing Block was oriented to the N–S direction with the azimuth ranging from 86.9°–106.5° (Ju et al., 2017).

Because of the tectonic evolution, the Linxing Block has undergone several transitions of stress fields, from the N–S compressive stress in Permian and Triassic times to the NW–SE compressive stress in the Early Yanshanian, to the extensive conditions in the Late Yanshanian, and then to the final NE–SW compressive stress in the Himalayan Period (Fig. 10a). Different fracture sets were developed by different stress fields, forming a complex fracture system. The Yanshanian Movement was found to have mostly reconstructed the eastern Ordos Basin and to have created most of its fractures. The statistics of fractures indicate that the most predominant fractures are in the ~NNW–SSE and ~E–W directions, forming conjugate shear fracture sets (Fig. 5). The fracture sets also support an NW–SSE squeezing origin from the Yanshanian Movement. The modern principle stress is in the N–S directions, which are parallel or nearly parallel to the predominant fractures in the NNW–SSE and N–S directions. The situation favors the opening of these fractures, increasing the hydraulic connectivity.

Overall, the mechanical properties, which are essentially determined by lithostratigraphy, confine the fractures in the sandstones, increasing the permeability of sandstone reservoirs and retaining the sealing capacity of the mudstone caprocks. Both natural fracture propagation and hydraulic fracturing follow this rule. The predominant natural fractures in ~NNW–SSE and ~E–W are likely to be open under modern ground stress conditions.

6 Conclusions

The geological conditions in the Linxing Block are suitable for natural gas generation and retention, as well as the development of high-permeability reservoirs.

(1) The coal measures are rich in OM. Besides coals and shales, the coal laminae in mudstones and the OM in sandstones also serve as gas sources and contribute a great deal to gas generation.

(2) Expect for the central uplift zone and the eastern fault zone, the Taiyuan and Shanxi Formations lack large faults, ensuring that the mudstone beds have good sealing capacity. The sandstone and mudstone combination forms reservoir-sealing associations.

(3) Gas accumulation is controlled by tectonic, burial and thermal histories. Gas accumulation in the Linxing Block started in the Late Triassic, followed by three short pauses of thermal maturation as a result of the relatively small uplifts; the maximum hydrocarbon generation period is the Early Cetaceous as a combined result of regional and magmatic thermal metamorphisms. Fractures developed by the Yanshanian Movement remarkably accelerated the gas migration from the source rocks to the reservoirs.

(4) Within a sequence of alternating sandstone and mudstone layers, fractures tend to develop in the sandstone layers due to the mechanical differences between the sandstone and the mudstone. The modern-day stress direction favors the opening of the predominant natural fractures in the NNW–SSE and N–S directions.

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References


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