



A Volumetric Model for Evaluating Tight Sandstone Gas Reserves in the Permian Sulige Gas Field, Ordos Basin, Central China

CUI Mingming¹, FAN Aiping², WANG Zongxiu^{1,*}, GAO Wanli¹, LI Jinbu³ and LI Yijun³

¹ Key Laboratory of Shale oil and Gas Geological Survey, Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, China

² College of Geological Science & Engineering, Shandong University of Science and Technology, Qingdao 266590, Shandong, China

³ Institute of Exploration and Development, Changqing Oilfield Company, Petrochina, Xi'an 710069, Shaanxi, China

Abstract: To accurately measure and evaluate reserves is critical for ensuring successful production of unconventional oil and gas. This work proposes a volumetric model to evaluate the tight sandstone gas reserves of the Permian Sulige gas field in the Ordos Basin. The reserves can be determined by four major parameters of reservoir cutoffs, net pay, gas-bearing area and compression factor Z , which are controlled by reservoir characteristics and sedimentation. Well logging, seismic analysis, core analysis and gas testing, as well as thin section identification and SEM analysis were used to analyze the pore evolution and pore-throat structure. The porosity and permeability cutoffs are determined by distribution function curve, empirical statistics and intersection plot. Net pay and gas-bearing area are determined based on the cutoffs, gas testing and sand body distribution, and the compression factor Z is obtained by gas component. The results demonstrate that the reservoir in the Sulige gas field is characterized by ultralow porosity and permeability, and the cutoffs of porosity and permeability are 5% and $0.15 \times 10^{-3} \mu\text{m}^2$, respectively. The net pay and gas-bearing area are mainly affected by the sedimentary facies, sand body types and distribution. The gas component is dominated by methane which accounts for more than 90%, and the compression factor Z of H8 (P_2h_8) and S1 (P_{1S1}) are 0.98 and 0.985, respectively. The distributary channels stacked and overlapped, forming a wide and thick sand body with good developed intergranular pores and intercrystalline pores. The upper part of channel sand with good porosity and permeability can be sweet spot for gas exploration. The complete set of calculation systems proposed for tight gas reserve calculation has proved to be effective based on application and feedback. This model provides a new concept and consideration for reserve prediction and calculation in other areas.

Key words: tight sandstone reservoir, volumetric, gas reserve, Permian, Sulige gas field, Ordos Basin

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1 Introduction

With the growing demand for oil and gas, conventional oil and gas have become depleted (Zou et al., 2013; Yang et al., 2014a; Wang et al., 2017). Simultaneously, the continuous development of oil and gas exploration technology makes unconventional oil and gas exploitation possible (Zou et al., 2015, 2019). Especially the tight sandstone gas and shale gas have gradually become an important successor and focus of geologists (Montgomery, 1998; McLane et al., 2008; Soliman et al., 2008; Porter and Wildenschild, 2010; Mousavi and Bryant, 2012; Hughes, 2013; Fan et al., 2017; Yang et al., 2017a, 2018; He et al., 2018; Zhai et al., 2018). Many scholars have conducted intensive research on microscopic pore characteristics, reservoir property controlling factors, sedimentary facies and tight reservoir distribution (Islam, 2009; Ajdukiewicz

and Lander, 2010; Ozkan et al., 2011; Bai et al., 2013; Milliken and Curtis, 2016; Ran et al., 2016; Yang et al., 2017b). However, studies on the tight sandstone gas reserve in Sulige gas field are still relatively scarce. Oil and gas reserves are the basis for the development of the petroleum industry, even the national safety and development.

The evaluation accuracy may be impacted by the reservoir complexity and heterogeneities (Hamilton et al., 1998; Rui et al., 2011). Also geological factors and reservoir heterogeneity may influence the reserve growth (Dromgoole and Speers, 1997). Many simulations can be used to evaluate gas reservoir performance and reserve (Ou et al., 2016). Some experts used fuzzy evaluation method to evaluate shale gas reserve and proposed new methods and factors controlling the shale reserve quality (Atchley et al., 2006; Cao and Zhou, 2015; Zhao et al., 2015; Ou et al., 2016; Han et al., 2018). The water flooding reservoir evaluation was also investigated (Fan et

* Corresponding author. E-mail: wangzongxiu@sohu.com

al., 2014). Various researchers have evaluated shale gas reservoir, but to the tight oil and gas reservoirs, it's difficult to evaluate the reserves because of the technical difficulty and reservoir complexity (Hu et al., 2016; Wang et al., 2017). Most tight gas reservoir are characterized by ultralow porosity, ultralow permeability and strong heterogeneity, also the properties difference between effective and ineffective reservoirs is small. The tight gas reservoir characteristics increase the reserve estimation uncertainty and risk.

Reliable reserve evaluation must depend on a suitable evaluation method. An inclusive model provides important information for business decisions and predictions, but sufficient evidence is needed to categorize the full simulation (Abasov et al., 1997; Rietz and Usmani, 2009; Jones et al., 2016). The complex static data, production constraints, and real-time data should be integrated in the evaluation model. The analogy method is suitable for gathering data during the preliminary stage of exploitation, but with low accuracy. In the later stage of exploration and production, it is suitable to use the production decline method. This requires a large quantity of production data to fit the production decline law, but it decreases the accuracy caused by determination of decline rate. In most stages of gas field exploration, we can use the volumetric method. It relies on well logging, seismic analysis, core analysis, gas testing and some static data. Its accuracy is less affected by the reservoir's condition and individual statistical factors.

This work aims to: (1) use the volumetric method to determine the reserve parameters, analyze the reservoir properties cutoff, effective thickness (net pay), gas-bearing area and compression factor; (2) based on the analysis of reserve parameters, construct a calculation system and

provide reference and support for other tight sandstone gas reserve calculation; (3) clarify the distribution of the high quality reservoir and select the sweet spot for gas exploration.

2 Geological Settings

The Sulige gas field in the Ordos Basin is one of the biggest tight gas fields in China (Zou et al., 2013). The SX block is located northwest of the Yishan slope in the Ordos Basin, next to the Tianhuan depression (Fig. 1). The Ordos Basin is a gentle west dipping synclinal basin with a general gradient of 3–10 m/km. It is situated at the western part of the Sino-Korean Plate, as a walled basin (Carroll et al., 2010). It has been intensively studied for its important resources of gas (Paleozoic) (Yang et al., 2014b; Zou et al., 2018), oil (Mesozoic) (Zhang et al., 2013; Xie and Heller, 2013; Wang et al., 2017), coal (Paleozoic and Mesozoic), uranium (Mesozoic) (Mao et al., 2014), and metal deposits (Cao et al., 2017). Also the regional tectonic settings at different geological times have been documented in literature (Li et al., 2011, 2015; Qiu et al., 2014; Liu et al., 2015; Du et al., 2017; Sun and Dong, 2019a). Since the Late Cretaceous, the entire basin began to uplift. Its western flank is narrow and sharp while the eastern flank is wide and gentle (Yang et al., 2017). Its structural traps are not well developed but there are some NE-SW low nose structures of 10–20 m amplitude on the gentle syncline (Tang et al., 2006; Li et al., 2018).

The natural gas accumulation is weakly influenced by the nose structures but mainly controlled by the sand body distribution and the reservoir properties (Wang et al., 2017; Yang et al., 2017). The dark mudstone and coal-bearing strata of the Carboniferous Benxi Formation (C_2b)

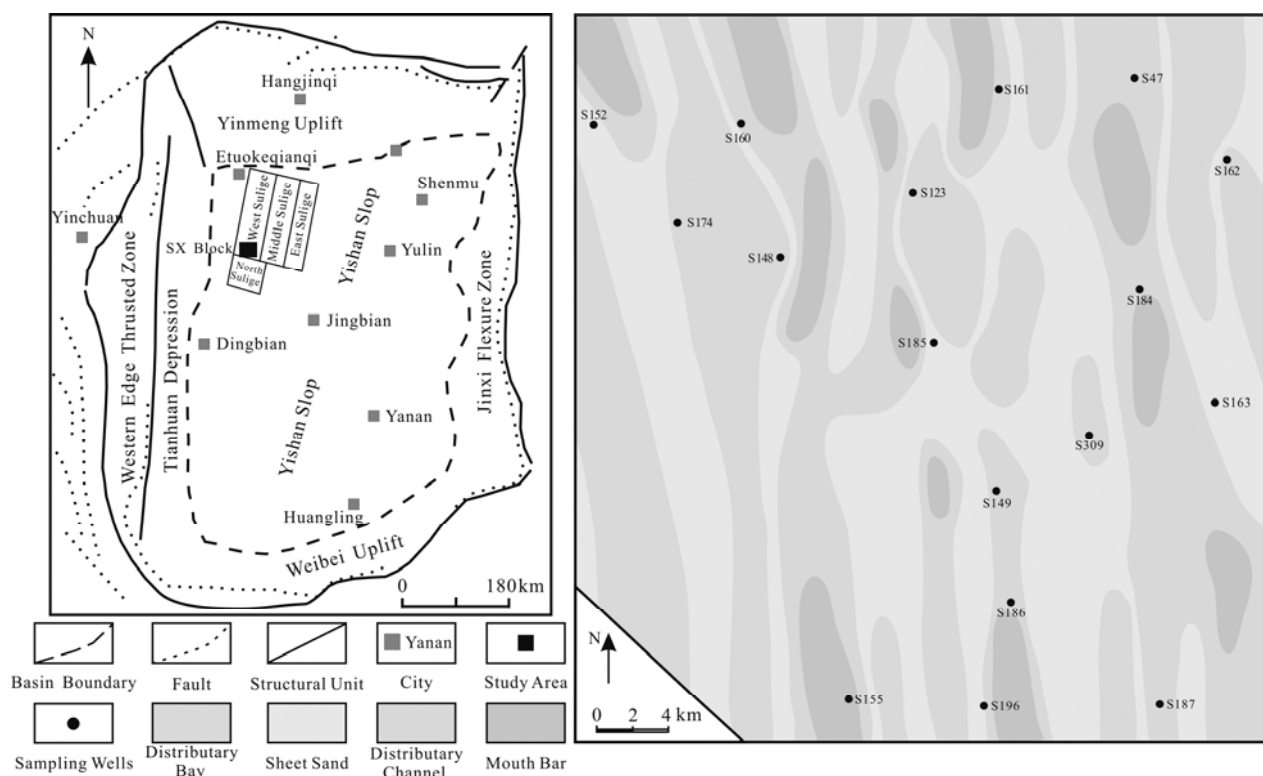


Fig. 1. Location and sedimentary microfacies of the study area.

and the Permian Taiyuan Formation (P_1t) are characterized by broad covered and continuous gas generation (Fig. 2). On the source rocks, a river-delta front deposits system developed; its distributary channel, point bar, and channel bar are the main reservoirs. S1 (P_{1S1}), the upper member of the Shanxi Formation, and H8 (P_{2h8}), the eighth member of the Shihezi Formation, are the main target member and can be 80–150 m thick. The gas generating layers can be subdivided into H_{8S}^1 , H_{8S}^2 , H_{8X}^1 , H_{8X}^2 , S_1^1 , S_1^2 , and S_1^3 . The sedimentary facies are braided river delta front, meandering river delta front and shallow lake, including submarine distributary channel, distributary bay, sheet sand, and mouth bar (Fig. 2). The distributary channel extends far along the NS direction and is distributed widely in the gently sloping background. The reservoir densified before its continuous gas accumulation.

3 Methods

Considering the reservoir characteristics of the Sulige gas field, we need determine the reservoir properties cutoff first. The difference in reservoir properties between effective and ineffective reservoirs is small, such a small difference makes it difficult to distinguish the effective thickness and gas-bearing area for other methods (Yang and Fan, 1998; Hu and Zhao, 2013; Liu et al., 2014). Hence, a volumetric case of SX block is adopted to discuss how to determine the tight gas reservoir parameters.

The four major parameters are gas-bearing area, effective thickness (net pay), porosity, and compression factor Z . The main process can be divided into two steps. (1) Evaluate the oil and gas reserves underground by calculating the total pore volume and gas saturation in the reservoir. (2) Based on the volume change after the gas was exploited, convert the volume underground to the volume ground, and then calculate the geological reserve. The gas reserve is calculated by the Equation (1):

$$G = 0.01Ah\phi S_{gi} \frac{T_{sc}P_i}{P_{sc}T_iZ_i} \tag{1}$$

Where G is the original geological reserve of natural gas, 10^8 m^3 ; A is the gas-bearing area, km^2 ; h is the average effective thickness, m; ϕ is the average effective porosity, decimal; S_{gi} is the average primary gas saturation, decimal; T_i is the average reservoir temperature, K; T_{sc} is the standard ground temperature, K; P_i is the standard ground pressure, MPa; and Z_i is the compression factor, dimensionless quantity.

The well logging, seismic, gas testing data, and production data are obtained from the Sulige gas field research center. In the study, a total of 211 sandstone samples and 124 thin sections are obtained from H8 and S1 reservoirs, which are all from 3450–3710 m depths of 46 wells (Fig. 1). The samples were investigated mainly by thin section identification, mercury injection, and SEM analysis. We used a Nikon COOL-PIX4500 microscope

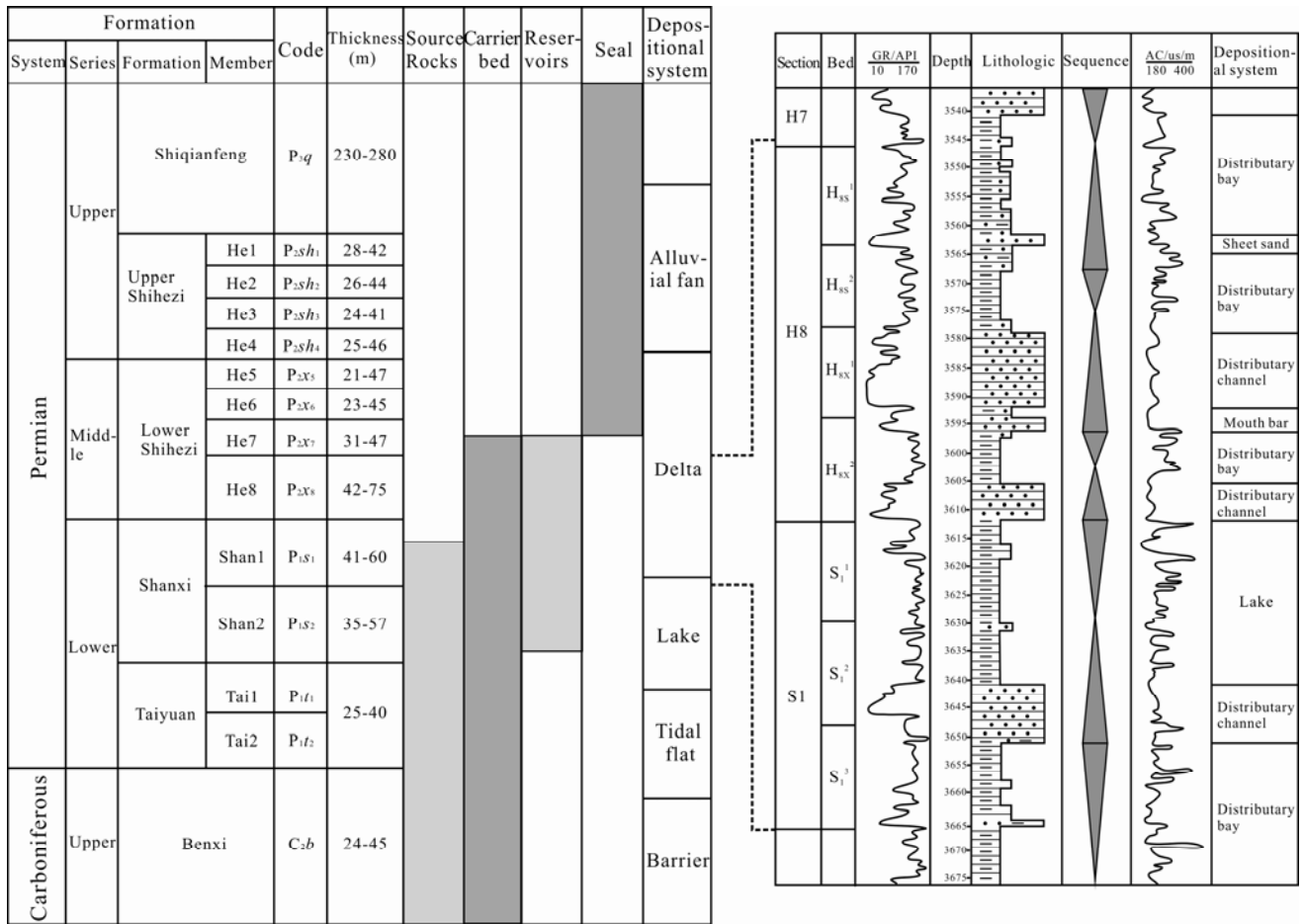


Fig. 2. Stratigraphic column of the Sulige gas field and the detail column of the study area (modified from Wang et al., 2017).

under polarized light and fluorescence to observe the grains and the pores to analyze the pore types and pore throat structure. The scanning electron microscope used to analyze the mineral forms and pore throat structures is a SYKY-2800B microscope. Its acceleration voltage is 0.13kV, with amplifications of $15\times$ to $250000\times$ and a resolution above 4.5 nm.

4 Data and Results

4.1 Reservoir properties

A conventional porosity test was performed on 211 core samples. The results show that the porosity of H_{8S} (H_{8S}^1 and H_{8S}^2) is 2.2%–14.6%, with an average of 7.2%, concentrated at 5%–12%. The permeability is 0.01 – $2.72\times 10^{-3}\mu m^2$, with an average of $0.485\times 10^{-3}\mu m^2$. The porosity of H_{8X} (H_{8X}^1 and H_{8X}^2) is 4%–13%, with an average of 7.4%, the permeability is 0.04 – $2.26\times 10^{-3}\mu m^2$, with an average of $0.371\times 10^{-3}\mu m^2$. The porosity of S1 is 3.1%–13.2%, with an average of 6.7%, concentrated at 3%–12%, and the permeability is 0.03 – $1.65\times 10^{-3}\mu m^2$, with an average of $0.377\times 10^{-3}\mu m^2$ (Table 1). The reservoir is characterized with ultralow porosity and permeability, and H8 is slightly better than S1. Thin section identification and SEM analysis show that the reservoir has undergone a strong diagenetic alteration. The favorable pores are mostly intergranular pores and dissolution pores; they account for 60%–80% of all the pores. Various throats develop in reservoirs, mainly the necking throat and lamellar throat (Fig. 3). The pore throat coordination number is generally 1–3, the displacement pressure is 0.3–2.7 MPa with an average of 1.4 MPa (Table 1). Mercury saturation is 23%–83% with an average of 72%. The reservoir is characterized by small pore throat, poor sorting, high displacement pressure, poor connectivity and small main contributed throat.

4.2 Determination of the reservoir property cutoffs

In the tight gas field, some reservoirs characterized by ultra-low porosity and permeability cannot allow gas to accumulate or flow (Zasadnyy and Lakhnyuk, 1978;

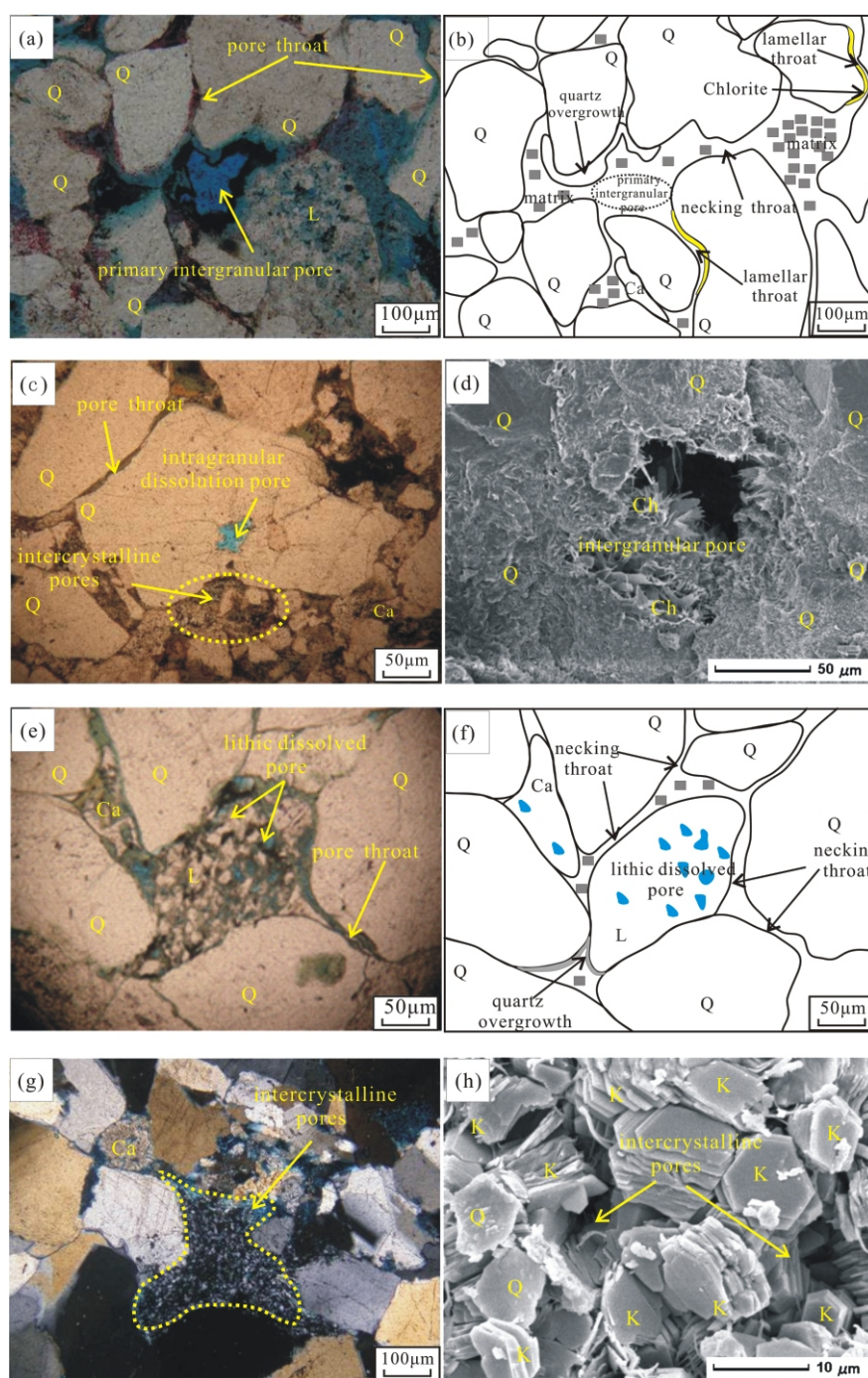


Fig. 3. Photomicrographs showing typical pore and pore throats observed in H8 reservoir.

(a) Intergranular pores among quartzes, pore throats connecting different pores; S315, 3754.13 m; (b) sketch of (a) showing different pore throats, including lamellar throat partly surrounded by chlorite rim, necking throat connecting different pores, and some pores that are filled with matrix; S315, 3754.13 m; (c) intragranular pores formed due to quartz dissolution, and some kaolinite intergranular pores formed among kaolinite particles; S334, 3619.2 m; (d) SEM images showing typical intergranular pores, some chlorite rim formed on the periphery of the quartz grains; S183, 3631.0 m; (e) lithic dissolved pores formed by dissolution; S47, 3586.43 m; (f) sketch of (e), quartz overgrowth blocking pores, necking throat connecting different pores; S47, 3586.43 m; (g) good development of kaolinite intergranular pores; S163, 3685.65 m; (h) SEM images kaolinite and its intergranular pores; S186, 3680.7 m. (Q= quartz; L= lithic fragment; Ca= carbonate cementation).

Honarpour and Mahmood, 1988). These reservoirs are not considered as the effective reservoirs. In other words, the accumulated gas should be produced economically under

current industrial technology. The reservoir property cutoffs are the limiting values of porosity and permeability that the reservoir can allow gas to accumulate and flow (Wan et al., 1999; Wang et al., 2007; Worthington, 2007; Cao et al., 2009; Li et al., 2011). Reservoirs above these cutoffs can be effective, while others are invalid. It's necessary to eliminate the invalid reservoirs below the cutoffs before calculating the reserves. The reservoir properties of H8 and S1 in SX block vary little, so the same cutoffs can be used in different members. The cutoffs can be determined by distribution function curve, empirical statistics, porosity-permeability intersection plotting, mercury injection curve, or capacity simulation experiments. All based on well logging data, mercury injection analysis and gas testing data.

4.2.1 Distribution function curve

In the curve we need count the number of effective reservoirs and invalid reservoirs in different periods of porosity and permeability. Effective reservoirs are reservoir intervals of gas layer, differential gas layer, and gas-bearing water layer. Invalid reservoirs are reservoir intervals interpreted as dry layers. In the same coordinate system, we plot the physical frequency distribution curves of effective and invalid reservoirs respectively. The corresponding values of the intersections of the two curves are the property cutoffs. In Fig.4 when the porosity is 5%–6%, the first intersection of two curves appears. In the range of 5%–6%, the reservoir intervals can be effective and invalid, so we set 5.5% as the porosity cutoff. Similarly, the permeability cutoff is set at $0.2 \times 10^{-3} \mu\text{m}^2$.

4.2.2 Empirical statistics

The empirical statistics is based on the porosity and permeability measured by Core Pore Master and well log interpretation. When the cumulative porosity and permeability loss accounts for 10% of the total accumulated, that porosity value is the cutoff. The eliminated reservoir intervals cannot accumulate enough gas to flow and are negligible. American energy companies usually adopt this method, the same to most Chinese oilfields. Porosity represents gas storage capacity of a reservoir and permeability represents the capacity allow gas to flow. The cumulative formulas are expressed as Equation (2):

$$Q_{\phi i} = \frac{\phi_i H_i}{\sum_{i=1}^n \phi_i H_i} \quad Q_{K_i} = \frac{K_i H_i}{\sum_{i=1}^n K_i H_i} \quad (2)$$

Where $Q_{\phi i}$ is the cumulated storage capacity, %; Q_{K_i} is the cumulated permeability capacity, %; H_i is the thickness of reservoir interval, m; ϕ_i is the porosity of each reservoir interval, %; and K_i is the permeability of each reservoir interval, $10^{-3} \mu\text{m}^2$.

The reservoir in the Sulige gas field is characterized by low porosity and low-ultralow permeability. We set the cumulative porosity and permeability loss cutoff at 20%, the accumulative storage capacity loss and cumulative infiltration capacity loss at 10%. In Fig. 5, when the porosity cutoff is set at 4%, the cumulative frequency loss is 15.5%, and the cumulative loss of reservoir capacity is 5.3%. When the porosity cutoff is set at 5%, the loss of frequency is 30%, and the cumulative loss of storage capacity is 14.4%. According to the principle mentioned above, 4.5% is chosen as the porosity cutoff. Similarly, the permeability cutoff is $0.15 \times 10^{-3} \mu\text{m}^2$.

4.2.3 Porosity-permeability intersection plotting

Compare the porosity and permeability of different gas testing results, the cutoffs can be roughly judged. The porosity and permeability of effective reservoirs should be better than the invalid reservoirs. In the porosity-permeability plot, the threshold values k_c and ϕ_c are defined by different regions (Fig. 6a). The reservoir intervals with high porosity and permeability in region B are gas layers, differential gas layer, gas-water layer, make them good reservoirs. Reservoir intervals with low porosity and permeability in region C cannot allow gas to accumulate nor flow, they are almost dry layers. Reservoir intervals with low porosity and high permeability in region A cannot accumulate tight gas although they can allow the gas to flow. Reservoir intervals with low permeability and high porosity in region D cannot allow gas to flow although they can accumulate tight gas. In the plot we determine 5% and $0.15 \times 10^{-3} \mu\text{m}^2$ as the porosity cutoff and permeability cutoff.

In addition, the fitting curve of porosity and permeability can be obviously divided into three parts (Fig. 6b): when porosity is below 5%, the corresponding permeability increases slowly with the increase of porosity. At this time the reservoir accumulate some gas but cannot allow the gas to flow easily, indicated that their pore-throat radius is below the minimum value and cause the invalid reservoirs. When the porosity is 5%–8%, permeability increases linearly with the increase of porosity. At this time the accumulate gas can flow easily, make them reservoirs with good exploitation value. The permeability increases dramatically with increasing porosity when it's above 8%. Now the reservoirs are

Table 1 Reservoir physical parameters in study area

Section	Porosity (%)	Permeability ($\times 10^{-3} \mu\text{m}^2$)	Saturation (%)	Displacement pressure (MPa)	Mercury saturation (%)
H _{8s}	2.2–14.6 7.2(66)	0.01–2.72 0.485(66)	25.8–61.5 47.1(31)	0.45–2.6	40–72
H _{8x}	4–13 7.4(71)	0.04–2.26 0.371(71)	21.9–62.4 45.1(66)	0.3–2.1	46–94
S1	3.1–13.2 6.7(69)	0.03–1.65 0.377(69)	14–57.7 36.8(57)	0.6–2.7	23–83

characterized by good porosity and permeability, make them better reservoir for exploitation.

Similarly the gas saturation cutoff can be determined by the fitting curve of porosity and gas saturation. According to the fitting formula, the gas saturation cutoff can be deduced.

Synthesizing the cutoffs above, we set the cutoffs of porosity, permeability, gas saturation at 5%, $0.15 \times 10^{-3} \mu\text{m}^2$ and 48%, respectively. The reservoir interval thickness varies a lot. To decrease the influence of reservoir complexity and heterogeneity, we use the weighted average as the effective porosity and permeability. The effective porosity and permeability of H8 and S1 are 8.34%, 7.58%, $0.46 \times 10^{-3} \mu\text{m}^2$ and $0.48 \times 10^{-3} \mu\text{m}^2$, respectively. The gas saturations are 54.7% and 62.3%, respectively.

4.3 Gas-bearing area

The gas-bearing area is the projection of the reservoir's effective gas-bearing area in the plane. It is controlled by the trap type, gas-water distribution and porosity-permeability distribution. Gas reservoirs in the Ordos

Basin are lithologically trapped reservoirs with simple structure and strong heterogeneity (Li et al., 2009; Liu et al., 2013; Guo et al., 2014; Zhu et al., 2015). The oil-gas systems are relatively simple. The reservoir distribution is controlled by different sand bodies. The main sand bodies are underwater distributary channel, mouth bar and sheet sand. They are mostly strip shaped and lens shaped (Fig. 7). Distributary channels migrate laterally in a horizontal direction and periodically superimposed vertically. They can be 8–30m thick and 2–5km wide, forming a wide range of large scale distribution of reservoirs. Their sandstones are quartz sandstone and lithic quartz sandstone with a certain number of intergranular pores and dissolved pores (Fig. 3). These sand bodies are almost the gas layers with good porosity and permeability. Cracks caused by fracturing and tectonic stress can provide a channel for hydrocarbon migration and improve reservoir permeability. These channel sands are the most favorable reservoir in the study area. The shore shallow lakes are characterized with the mudstone, which makes it an invalid reservoir. Therefore, to determine the gas-bearing

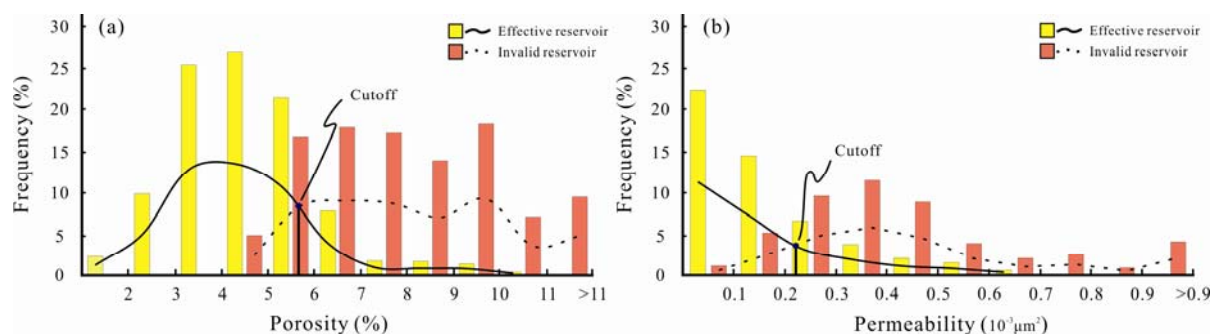


Fig. 4. Porosity and permeability distribution curve of effective and invalid reservoir.

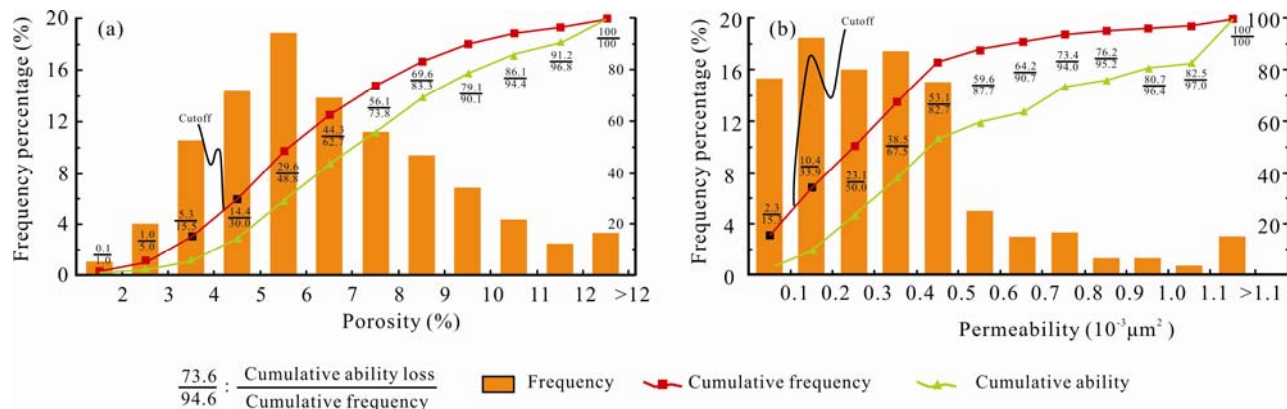


Fig. 5. Porosity and permeability distribution histogram and cumulative reservoir capacity loss.

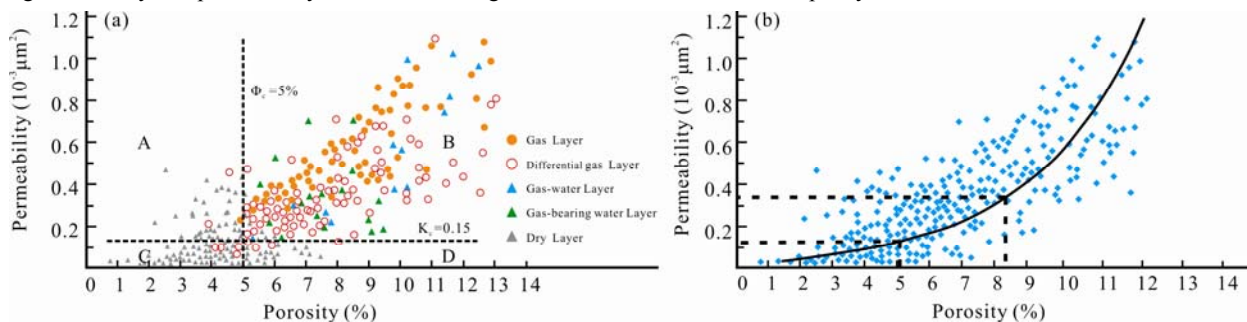


Fig. 6. Plot of porosity-permeability in study area.

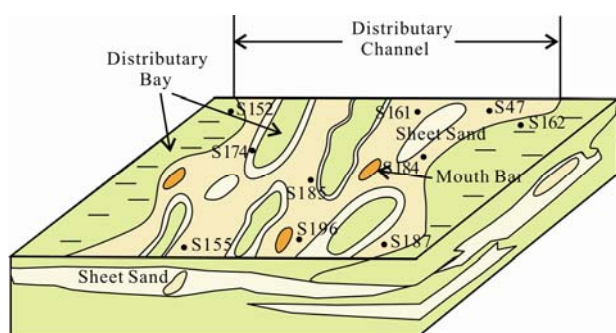


Fig. 7. Sand body model of SX block, Ordos Basin.

area, it's necessary to distinguish the gas-bearing boundary of different sand body first.

The sand bodies in H8 member collaged, overlapped and formed complex sand bodies, but the main sand body types are channel sand and bar sand. Based on the sand body type and sand thickness of production well, the approximate pinch-out position can be estimated. The channel sand bodies are generally strip shaped and extends long but narrow in a relatively lateral direction. The boundary of the reservoir is parallel to the short axis of sand body (Fig. 8). If a fault exists, the edge of a lithology mutation or a lithology interface should be the boundary. The mouth bar sand bodies are generally lenticular shaped and the lithology vary a lot around them. The boundary of the lens body is the gas reservoir boundary. The sheet sand is the generally thin sand body, which superimposed with each other, makes it difficult to find the lithology boundary. We can use the sedimentary facies distribution and zero coil boundary of effective thickness to determine the gas-bearing area. Mudstone and siltstone in the distributary bay and lake bay have no storage capacity and will not be considered.

In some area no drilling or production well exists, we can use seismic data, sedimentary facies distribution and the channel distribution to speculate the boundary. If this boundary cannot be determined, we can also extrapolate a certain distance according to the production well location. The interval of oil wells in the area is generally 200–500 m. The average width of lenticular sand bodies and strip sand bodies is 500–600 meters. In the case of absence of production wells we can extrapolate 200–300 m.

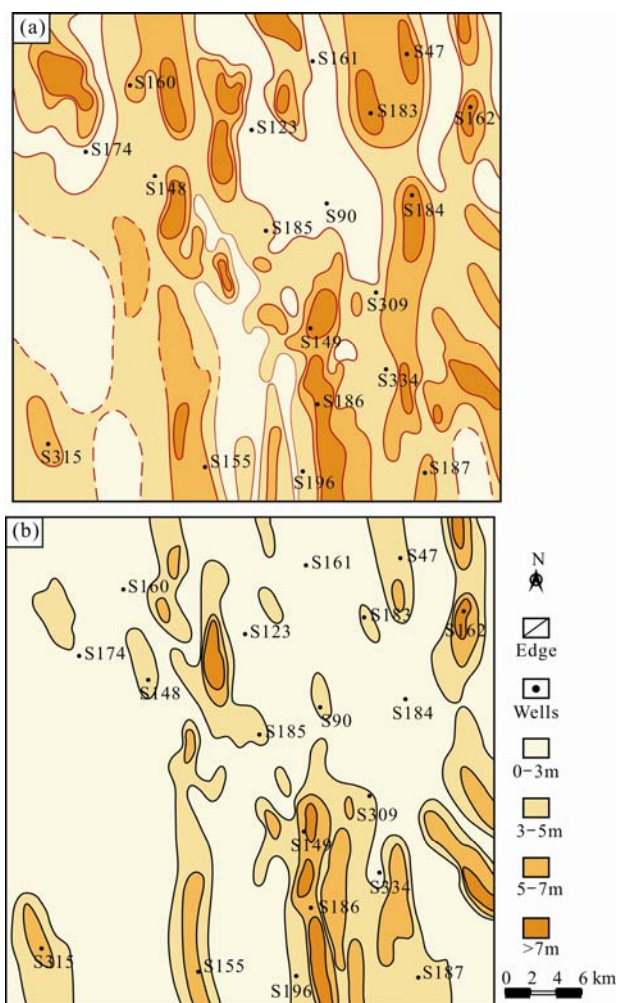


Fig. 8. Gas-bearing area and the reservoir thickness of H8 (a) and S1(b).

Reservoirs in H8 member are thick and widely distributed. Most sand bodies are 5–7 m thick, make them good layers for gas accumulation. Most sand bodies in S1 member are in center and southeast area and can be 3–6 m thick, make them common layers for gas accumulation (Fig. 8).

4.4 Reservoir effective thickness

The effective reservoir (net pay) may be defined as the

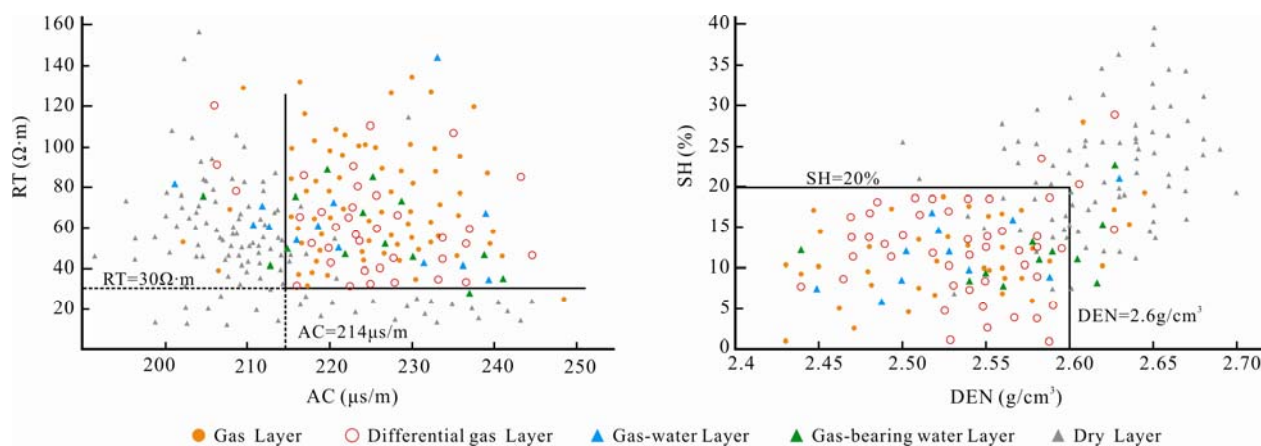


Fig. 9. Intersection plot of AC with RT and DEN with SH.

reservoir that contains sufficient porosity, permeability and hydrocarbons for economic exploitation (Bouffin and Jensen, 2010). In the reserve evaluation, the effective thickness refers to the gas bearing reservoir thicknesses that can produce gas economically. The reservoirs must satisfy two conditions: they must be gas reservoirs; they must be able to produce industrial gas streams under current economic and technological conditions (Li et al., 2007; Wang et al., 2012; Hu et al., 2013). The effective thickness of a single well is determined base on the property cutoffs and the lithology characteristics. The logging curves can give us the information to determine the reservoirs. The gas layers in study area are mainly coarse grained quartz sandstones with electrical characteristics of low SH and high AC (Fig. 9). Similar to the determination of property cutoffs, we use the intersection plot of different logging data based on different layers to determine the cutoffs. When $AC < 214 \mu\text{S/m}$, $RT < 30 \Omega\cdot\text{m}$, the layers are almost dry layer. When $AC > 214 \mu\text{S/m}$ and $RT > 30 \Omega\cdot\text{m}$, most of the layers are gas layer, differential layer, gas-water layer and gas-bearing water layer (Fig. 9). So we can set $214 \mu\text{S/m}$ and $30 \Omega\cdot\text{m}$ as the cutoffs of AC and RT. Similarly, we choose 2.6 g/cm^3 and 20% as the cutoffs of DEN and SH.

In addition, some small intervals exist in the reservoir. They are mainly discontinuous and thin intervals of argillaceous and silty sand with low permeability and high resistance to gas migration. These intervals should be eliminated when calculating the effective thickness of sandstone. The eliminated standard of these sandstones in Sulige gas field is 0.2 m (Table 2). When the sand is too thin, it is useless for gas extraction. In the Sulige gas field, the cutoff of sand thickness determined by the Sulige gas field research center is 0.4 m.

Consider the uneven well distribution in current development status, we use the weighted average of the area as the effective thickness of each small layer.

4.5 Compression factor Z

The tight gas composition was analyzed based on the test results in the SX block (Table 3). The composition is characterized by a high methane content of more than 90%, with heavy hydrocarbon (C_{2+}) content of $<10\%$. When the gas was exploited to ground, the volume expanded due to the temperature and pressure change. Compression factor Z is the volume deviation to measure the volume change. It's controlled by gas composition,

pressure, and temperature. We can qualify the factor Z by steps as following.

4.5.1 Calculate the apparent contrast temperature and pressure

$$T_{pr} = \frac{T}{T_{pc}} \quad P_{pr} = \frac{P}{P_{pc}} \quad (2)$$

$$T_{pc} = \sum y_i T_{ci} \quad P_{pc} = \sum y_i P_{ci} \quad (3)$$

Where T is the reservoir temperature, P is the reservoir pressure; T_{pr} is the apparent contrast temperature, P_{pr} is the apparent contrast pressure; T_{pc} is the pseudo critical temperature, sumproduct of each natural gas component y_i and its critical temperature T_{ci} ; and P_{pc} is the pseudo critical pressure, the sumproduct of each natural gas component y_i and its critical pressure P_{ci} .

Based on the gas composition and hydrostatic pressure data of each well, we get the factors we need (Table 4). The P_{pc} , T_{pc} of H8 and S1 are 4.76 MPa, 4.78 MPa, 199.60 K and 202.04 K, respectively. The average reservoir depth is 3635m and the pressure coefficient is 0.83–0.94, indicating a low pressure gas reservoir.

4.5.2 Obtain compression factor Z from Stein-Katz chart

There is a certain correspondence between factor Z and P_{pr} , T_{pr} (Fig. 10). If the P_{pr} and T_{pr} are obtained, we can deduce the factor Z by the Stein-Katz chart (Fig. 10). The compression factors Z of H8 and S1 are 0.98 and 0.985, respectively.

Finally the reserves of each layer can be calculated by Equation (1) and the complete set of calculation systems for tight gas reserve calculation is established.

5 Discussions

5.1 The validity and practicability of volumetric evaluation

The tight gas reserve can be estimated base on many methodologies, each with its associated uncertainty (Fig. 11). The common methods include volumetric, material balance analysis, reservoir simulation, analogy method, and decline curve analysis (Dodge, 1941; Worthington, 2007). Material balance analysis and reservoir simulation are based on the total materials and probability distribution curve. They are not accurate and lack the

Table 2 Standard of effective reservoir

Porosity (%)	Permeability ($\times 10^{-3} \mu\text{m}^2$)	Sg (%)	AC ($\mu\text{S/m}$)	SH (%)	DEN (g/cm^3)	RT ($\Omega\cdot\text{m}$)	Interlayer cutoff(m)	Sand thickness cutoff(m)
>5	>0.15	$>48\%$	>214	<20	<2.6	>30	0.2	0.4

Table 3 Gas composition in the SX block

Member	Depth (m)	Number	Gas composition (%)							Relative density
			CH_4	C_2H_6	C_3H_8	C_4H_{10}	N_2	CO_2	H_2S (mg/m^3)	
H8	3540–3630	142	Min	90.58	1.68	0.22	0.02	0.11	0.12	0.5662
			Max	95.1	3.76	0.888	0.68	1.72	4.29	0.649
			Ave	93.55	2.62	0.51	0.15	1.09	1.54	0.5789
			Min	91.76	2.98	0.5	0.004	0.75	1.01	0.5694
S1	3610–3680	126	Max	93.07	4.33	0.96	0.19	1.76	2.07	0.5858
			Ave	92.34	3.81	0.74	0.11	1.3	1.37	0.5795

Table 4 Contrast temperature and pressure in H8 and S1 member

Block	Member	Relative density	P_{pc} (MPa)	T_{pc} (K)	P (MPa)	T (K)	P_{pr}	T_{pr}
SX Block	H8	0.5789	4.76	199.60	28.90	392.75	6.07	1.97
	S1	0.5795	4.78	202.04	29.32	393.68	6.13	1.95

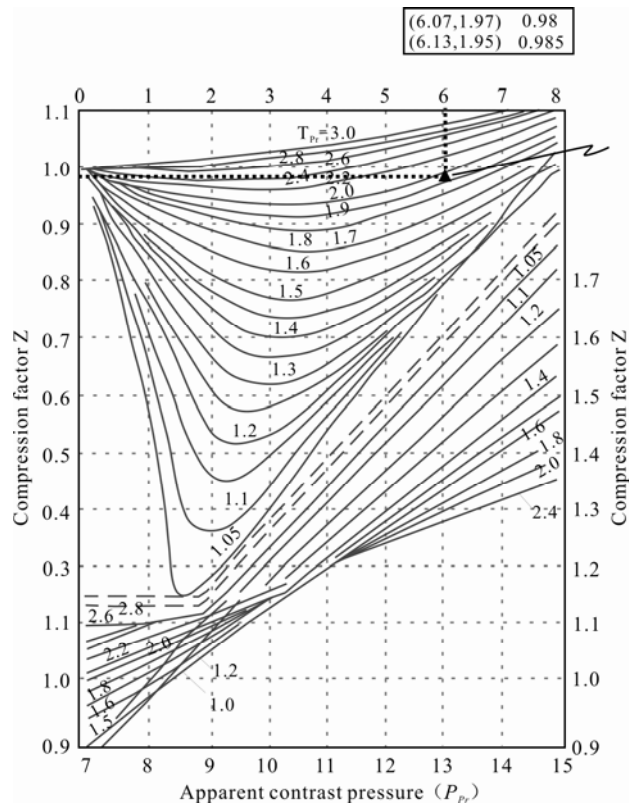


Fig. 10. Stein-Katz chart (modified from Yang and Fan, 1997).

consideration of porosity and permeability (Yang and Fan, 1998). The analogy method and decline-curve analysis are used in exploration stage and final stage of production, respectively. Different certifiers may obtain significantly different results for the same gas filed using the same database and method. This is because the elements in

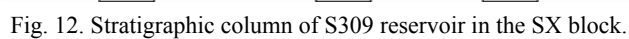
reserve evaluation are often subjective and cannot be determined certainly due to the reservoir complexity (Fan et al., 2014; Ou et al., 2016; Rui et al., 2011). The correct identification mitigates the influence of reservoir complexity, especially for the reservoirs characterized by ultralow porosity, permeability and strong heterogeneity. Therefore, the identification and determination of effective reservoir (net reservoir) and effective thickness (net pay) is particularly important. The reservoir cutoffs we proposed to identify net reservoir is of great significance. Compared with other reserve estimation, the complete set of volumetric model is detailed and logical which depends on the cutoffs, net reservoir, net pay, and compression factor Z . Compared with different evaluation results obtained from the Sulige gas field research center, the evaluation model in the SX block is proved to be effective and acceptable.

5.2 The sedimentary influence on net reservoir and net pay

The tight reservoir property is controlled by diagenesis, which has been recognized by many scholars (Ehrenberg et al., 2007; Xin et al., 2013; Zou et al., 2015; Huang et al., 2016; Liu et al., 2016; Yang et al., 2017). But the most important factor is sedimentation, which controls the thickness and distribution of sand body. the sand body is the basis for gas accumulation. The sedimentary environment of SX block is river delta front and shallow lake (Fig. 2). In the Permian period, the Ordos Basin is affected by the uplift of the North China platform. The abundant land-source debris from Alxa and Yinshan in the north were brought into the sedimentary center (Sun and Dong, 2019b), the braided channel migrated and stacked rapidly when they flow into the lake (Tian et al., 2011; Zhao et al., 2012). The high quality reservoirs are mainly concentrated in the channel sand body, which is

Estimation Approach	Life cycle				Main Fators	Range of Application
	Exploration	Appraisal	Development	Production		
Data Availability	Pre-well Data ←→		Well Data ←→	Production Data ←→	— —	— —
Analogy method	←→				reserve estimation of similar field	new reservoir to explore
Volumetric method	←			→	cutoffs, net reservoir, net pay, compression factor Z	tight gas reservoir ; simple trapped reservoir
Reservoir Simulation		←		→	probability distribution curve by statistic analysis	complex reservoir; low accuracy
Material Balance				←→	total materials	middle stage of production
Decline-Curve analysis				←→	predicted decline curve	final stage of production

Fig. 11. Different estimation approaches and their application.



characterized by wide and thick tight sandstones (Table 5). They can store 80% of all reserves. The bar sand bodies with small distributed and thin sand have fewer reserves. The reservoirs here are usually with lower porosity and permeability.

In detail, sedimentation controls the net reservoir and property, which lead to the difference of gas accumulation in the reservoir (Gao et al., 2003; Hammer et al., 2010; Bian et al., 2012; Guo et al., 2016). In Fig. 12, the distributary channel in 3650–3655 m of S309 is coarse quartz sandstones with some muddy gravel. We can recognize the trough cross-bedding and high angle fracture by core observation. The sandstone is characterized by good porosity, permeability, and gas saturation, makes it good reservoir that can allow the tight gas to accumulate and flow. The GR and RLLD curve are bell shaped and box shaped. On the contrary, the distributary channel in 3615–3625 m is also coarse quartz sandstones with good porosity, gas saturation, but low permeability. The tight gas accumulated in the sandstone cannot flow due to the low permeability, makes it a dry layer. The logging curves are toothed box shaped. The distributary channel in 3590–3600 m is differential gas layer and gas-bearing water layer, we can see an obvious scoured surface and gravel in the bottom sandstone (the second core photo). The sandstone on the top is characterized by good porosity, permeability, and gas saturation, makes it a differential gas layer. In the middle of the sandstone there is not enough gas accumulated to expel formation water due to the lower permeability, makes it a gas-bearing water layer. The reservoir in 3600–3603 m is mouth bar with medium funnel shaped RLLD and LLS curves. The sandstone is characterized by good porosity, gas saturation, and low

permeability, result in a difficult gas migration and dry layer.

5.3 The sweet spot for tight gas exploitation

As can be seen from the discussion above, the net reservoirs are mainly concentrated in the distributary channel, but the reservoir heterogeneity may cause the different distribution of tight gas. Many experts proposed that the gas accumulation can be influenced by hydrocarbon source rocks, tectonic movement, pore throat structure, mineral composition, and formation water (Li et al., 2009; Liu, 2015; Yang et al., 2017). In the SX block, most gas layers are in the top of distributary channel sand, while the gas-water layers, gas-bearing water layers and water layers are in the middle and bottom of the channel sand, respectively (Fig. 13). This may be caused by the lower hydrocarbon generation potential and reservoir complexity. The hydrocarbon intensity is $(12\text{--}28) \times 10^8 \text{ m}^3/\text{km}^2$, the tight gas cannot expel all the formation water, caused the gas-water mix (Meng et al., 2016; Cui et al., 2018). Also the different sand bodies stacked and formed overlapped complex sand body, with good porosity in the top and lower porosity and permeability in the bottom. The gas accumulation in mouth bar and sheet sand is not ideal, and some may cause a water production well. Therefore, the top part of the channel sand can be the sweet spot for gas exploitation.

6 Conclusions

(1) The SX block is a typical tight gas field characterized by ultralow porosity and permeability. Its porosity and permeability cutoffs are 5% and $0.15 \times 10^{-3} \mu\text{m}^2$ and the reservoir intervals above the cutoffs are net

Table 5 Reservoir parameters of different sedimentary facies in the SX block

Sedimentary facies	Area (km^2)	Net pay (m)	Porosity (%)	Permeability ($\times 10^{-3} \mu\text{m}^2$)	Gas saturation (%)
distributary channel	412.7	3–14	6.9–14.1	0.5–2.4	47–75
mouth bar	52.3	4–9	5.1–11.2	0.4–1.3	50–68
sheet sand	75.7	1–3	2.7–8.6	0.3–0.8	41–65

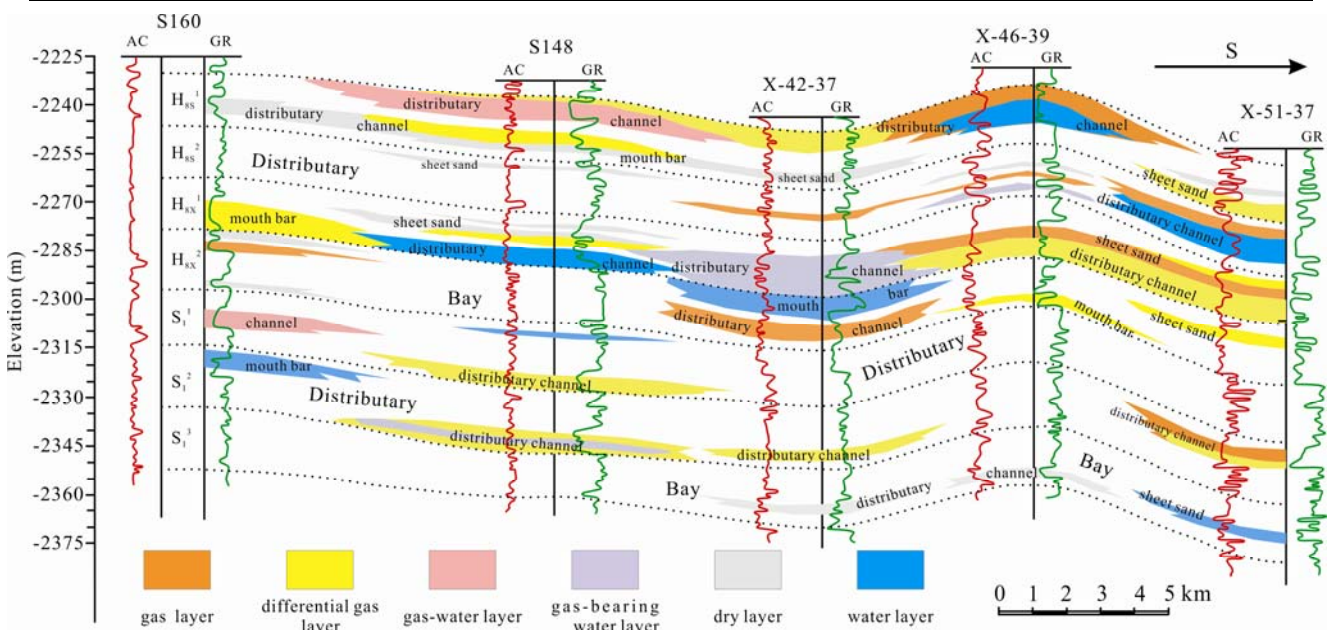


Fig. 13. Typical gas reservoir section in the SX block.

reservoirs. The gas-bearing area and net pay is determined base on the sand body type and distribution. The detailed volumetric model based on the four parameters provides a new concept and reference for reserve estimation.

(2) Sedimentation controls the distribution and thickness of sand body, caused a great reserve disparity in different sedimentary facies. The high quality net reservoirs are mainly concentrated in the channel sand, which are formed by stacked and overlapped sandstones. The mouth bar and sheet sand contain little reserve because of their lower porosity and the narrow and thin sand body.

(3) Reservoir heterogeneity may affect the gas accumulation in the same set of tight sand body, the gas layers are concentrated in the top of channel sand, while the water-bearing layer and water layer are in the middle and bottom of sand body. The top position of the channel sand can be the sweet spot for gas exploitation.

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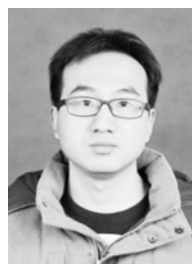
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About the first author



CUI Mingming, male; born in 1989 in Dezhou City, Shandong Province; graduated from Shandong University of Science and Technology; a Ph.D. candidate of Institute of Geomechanics, Chinese Academy of Geological Science. He is now interested in sedimentology and reservoir geology. Email: cuiiskd1988@163.com; phone: 13641277187.

About the corresponding author



WANG Zongxiu, male; born in 1959 in Dalian City, Liaoning Province; graduated from Institute of Geology, China Earthquake Administration; doctor; a senior engineer of Institute of Geomechanics, Chinese Academy of Geological Science. He is now interested in the study on structural modification and its influence on oil and gas conservation. Email: wangzongxiu@sohu.com; phone: 010-88815603.