HIGH-EFFICIENCY ACCUMULATION PROCESS AND EXPLORATION POTENTIAL OF NATURAL GAS IN CHINA

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Abstract: In recent decade, some large gas fields, with recoverable reserve over 100 billion cubic meters, has been discovered during gas exploration activity in China, which promotes the rapid development of natural gas industry. Based on the analysis of geological feature, gas fields can be divided into two types: one is dominated by structural gas reservoir, where trap area is smaller, reservoir quality is good and thickness is large, and gas reserve abundance is above billions of m^3/km^2, which is known as large gas field with high abundance; whereas, the other is dominated by stratigraphic and lithologic gas reservoir, where gas-bearing area is quite large, reservoir quality is poor and thickness is small, and gas reserve abundance is less than 100 million m^3/km^2, which is known as large gas field with low abundance. The forming of these two types of large gas fields is related to the highly-effective accumulation of natural gas.Kela 2 gas field in Tarim Basin, the most typical large gas field with high abundance, had been formed in the thrust belt of foreland basin since Quaternary, where the Cretaceous sandstone reservoir was over 3000m away from Jurassic coal series source rocks, and Jurassic coal source rocks were rapidly buried below the depth of 6000m since 5Ma, which led to extreme high rate of organic matter maturation (△Ro%/△Ma). In other words, increased Ro% value per unit time was quite high and gas generating rate (Gv, $10^8 m^3/km^2 \cdot Ma$) was high as well. The highly effective gas generation process of source kitchen caused the effective gas accumulation volume of Kela 2 gas field to occupy over 20% of total gas generation volume in gas supply area, so as to ensure the highly effective accumulation process of source-reservoir-separated gas pool. Large gas fields with low abundance have been discovered in both Ordos Basin and Sichuan Basin. Sulige gas field in Ordos Basin is most typical, which is the stratigraphic-lithologic gas reservoir group developed under the gentle structural setting of cratonic basin hinterland. Permian sandstone is in close contact with Carboniferous coal series source rock, which underwent the pre-Cretaceous deep burial and post-Cretaceous overall uplift process. The burial period was the primary gas generating period of coal series source rock, and part of natural gas was expulsed from source rock in the volume flow mode and entered into reservoir for accumulation; natural gas absorbed in coal series strata was subject to desorption and expulsion, and entered the reservoir, re-charging and accumulating in the diffusion mode. Although such a complex hydrocarbon accumulation mode would last a longer period, it is favorable for large area accumulation and preservation of natural gas in low porosity & low permeability reservoir, and it is a type of highly effective gas accumulation as well. Thus, the potential of natural gas resources in gentle structural area and tight sandstone area has been significantly increased.

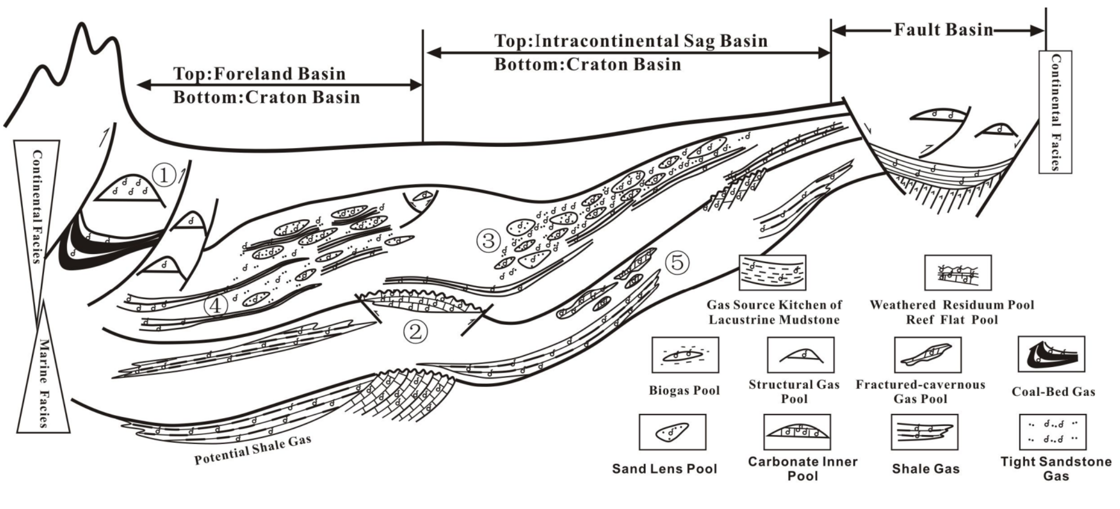
Keywords: Natural gas, gas source kitchen, highly effective accumulation, large gas field, reserve abundance, resource potential

1. Background

In recent decade, natural gas exploration & development in Chinese onshore basins has entered a rapid development phase. Annual increased proven reserves are above 500 billion cubic meters (bcm) from 2003, and annual natural gas production has increased from 50bcm in 2000 to nearly 100bcm in 2011 [1,2] . The rapid development of natural gas industry benefits from the discovery of a batch of large gas fields with proven gas reserve over hundreds of billions of cubic meters (Table 1), which are mainly distributed in three large-scale superposed basins in middle-west area, i.e. Tarim Basin, Ordos Basin and Sichuan Basin (Fig. 1). Paleozoic marine-facies cratonic basin was overlapped by Mesozoic and Cenozoic continental facies foreland & intra-continental depression basins and hereby the Chinese superposed basins were formed, where primary gas sources are oil cracked gas of marine facies basin and continental facies (including marine to continental transitional facies) coal-formed gas. Chinese scholars, represented by Academician Dai Jinxing, have made long-term research on Chinese large gas field forming condition [3-6]. As a conclusion, they proposed that the formation and distribution of large-medium scale gas fields were controlled by the gas-generating center (with gas-generating intensity over 2billion m^3/km^2) and its periphery, and the favorable conditions and accumulation characteristics for forming large-medium gas fields include: regional caprocks, high-quality reservoirs, large-scale paleo-uplifts, traps in deposit center of new tectonic movement, accumulation in low relief area, and late-stage accumulation. The common issues of natural gas accumulation under Chinese basin environment were basically answered and the discovery of large gas field can be guided effectively.

With the increasing amount of large gas field discovered, Chinese large gas fields can be divided into two types [7] distinctly: one is the large gas field with high reserves abundant, where recoverable reserve abundance is greater than 800 million m^3/km^2; the other is the large gas field with low abundance, where recoverable reserve abundance is less than 250 million m^3/km^2.

Large gas field with high abundance is dominated by large-scale structural gas reservoir and structural-lithologic gas reservoir, where reservoir physical property is good, porosity is commonly greater than 10%, permeability is greater than 1md, well-sorted sandstone reservoir or carbonate reef flat reservoir has large thickness and distributes continuously, and gas column height can reach hundreds of meters. Gas reservoirs have obvious gas-water contact and are mostly abnormal high-pressure gas reservoirs. The gas-bearing area of individual gas reservoir is limited (dozens to hundreds of km^2), whereas its controlled reserves scale is quite large (hundreds of billions of m^3) and reserve abundance is high, such as Kela 2 Gas field in Tarim Basin and Puguang Gas field in Sichuan Basin (Fig. 1).



①Kela-2 Gas Field in Tarim Basin;② Puguang Gas Field in Sichuan Basin;③Sulige Gas Field in Ordos Basin;
④Guang'an Gas Field in Sichuan Basin;⑤Tazhong Gas Field in Tarim Basin

Fig. 1 Distribution mode of large gas fields in Chinese Basins

Large gas fields with low abundance consist of multiple small-scale lithologic gas reservoirs in the cluster mode and distribute widely in Ordos Basin and Sichuan Basin. Gas-bearing area of the whole gas field is large (thousands to tens of thousands of km^2) and reserves scale is large (hundreds of billions to trillions of m^3) as well, whereas the reserve abundance is low. A large gas field usually consists of thousands of lithologic gas reservoirs with small individual scale and presents a gas reservoir group as a whole. Taking Sulige gas field in Ordos Basin as an example, the basic proven gas reserve is 2500 billion m^3 and the gas-bearing area is nearly 18000km^2, among which about 50-80 thousand individual gas reservoirs with gas column height of 2-6 m can be divided via clear sand body shape. Physical property of reservoir is poor as a whole (Fig. 2). Both conventional sandstone reservoir with porosity of over 10% and permeability of 0.01-10md and unconventional tight sandstone reservoir with porosity of less than 10% and permeability of less than 1md are included, and reservoir heterogeneity is strong. This type of large gas field is mostly formed within the structural gentle area above the large-scale cratonic basin[8-9].

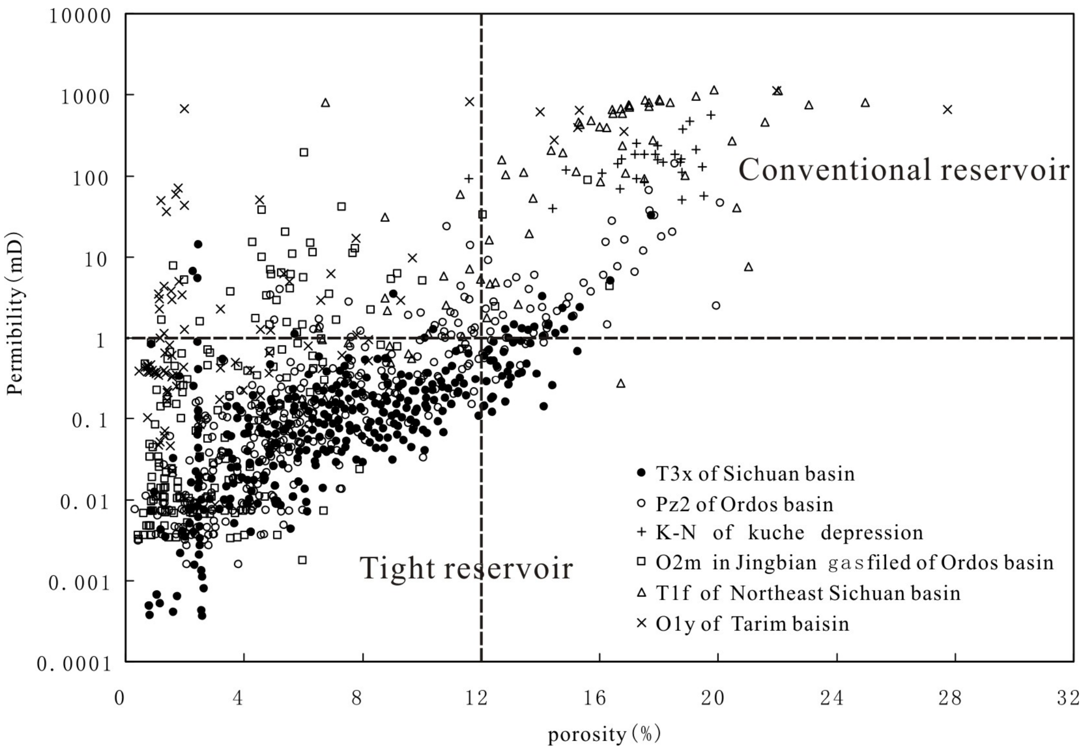


Fig. 2 Reservoir physical property parameters of Chinese large gas fields

These two types of large gas fields are quite different in both feature and structure, which must lead to the difference between thermal evolutional gas-generating process of gas source rocks and charging accumulation process of natural gas[10-13]. Thus, this paper mainly studies the control function of the evolution process of gas source kitchen and the charging accumulation process of natural gas on the formation of large gas fields, and reveals the highly effective accumulation process of natural gas under different geological conditions.

Table 1 Statistics of geological parameter characteristics for Chinese large gas fields

No.	Gas field name	Basin	Area (km^2)	Trap type	Gas in place ($\times10^2$ million m^3)	Technical recoverable reserves ($\times10^2$ million m^3)	Reserve abundance ($\times10^2$ million m^3/km^2)	Reserve abundance type	Reservoir characteristic				Natural gas origin	Gas reservoir forming phase
									Age	Lithology	Porosity（%）	Permeability（md）		
1	Puguang	Sichuan	126.6	Structural-lithologic	4121.73	2915.73	23	High	T1	Dolomite	6-8	0.1-3000	Oil cracked gas	K-N
2	Kela 2	Tarim	48.1	Structural	2840.29	2128.88	44.3	High	K、E	Sandstone	9-14	4.0-350	Coal-formed gas	N-Q
3	Dina 2	Tarim	125.31	Structural	1752.18	1138.92	9.1	High	N	Sandstone	8-15.2	0.5-216		N-Q
4	Sulige	Ordos	7969.95	Lithologic	11008.24	5656.5	0.7	Low	P	Sandstone	7-11	0.01-10		K-N
5	Daniudi	Ordos	1545.65	Lithologic	3926.75	1876.5	1.2	Low	C-P	Sandstone	5-11	0.001-10		K-N
6	Yulin	Ordos	1715.8	Lithologic	1807.5	1244.4	0.7	Low	C-P	Sandstone	5-11	0.01-10		K-N
7	Zizhou	Ordos	1189	Lithologic	1152	679.7	0.6	Low	C-P	Sandstone	4-9	0.01-10		K-N
8	Wushenqi	Ordos	872.5	Lithologic	1012.1	518.1	0.6	Low	C-P	Sandstone	3.5-14	0.01-10		K-N
9	Shenmu	Ordos	827.7	Lithologic	1012.1	518.1	0.6	Low	C-P	Sandstone	4-12	0.01-10		K-N
10	Guangan	Sichuan	578.9	Structural-lithologic	1355.6	610.01	1.1	Low	T3	Sandstone	6-13	0.001-10		K-N
11	Anyue	Sichuan	360.8	Lithologic	1171.19	527.03	1.5	Low	T3	Sandstone	6-14	0.001-14		K-N
12	Hechuan	Sichuan	1058.3	Lithologic-structural	2299.4	1034.7	1	Low	T3	Sandstone	7-10	0.001-50		K-N
13	Tazhong	Tarim	741.91	Structural-lithologic	3534.79	2163.97	2.9	Medium	O	Carbonatite	3-6	3.5-12	Oil cracked gas	E-Q

2. Objectives

(1) Possibility of high effective natural gas accumulation in foreland basin

Kela 2 gas field is situated on the second-row thrust fault anticlinal belt, north wing of Kuqa Depression, Tarim Basin (Fig. 3). The area of trap at top Paleogene of Kela 2 structure is 48.1km^2, the closure height is 455m, and it is a long axis anticline. The proven gas reserve is 284 billion m^3, gas layer thickness reaches 448m, and the trap is fully filled.

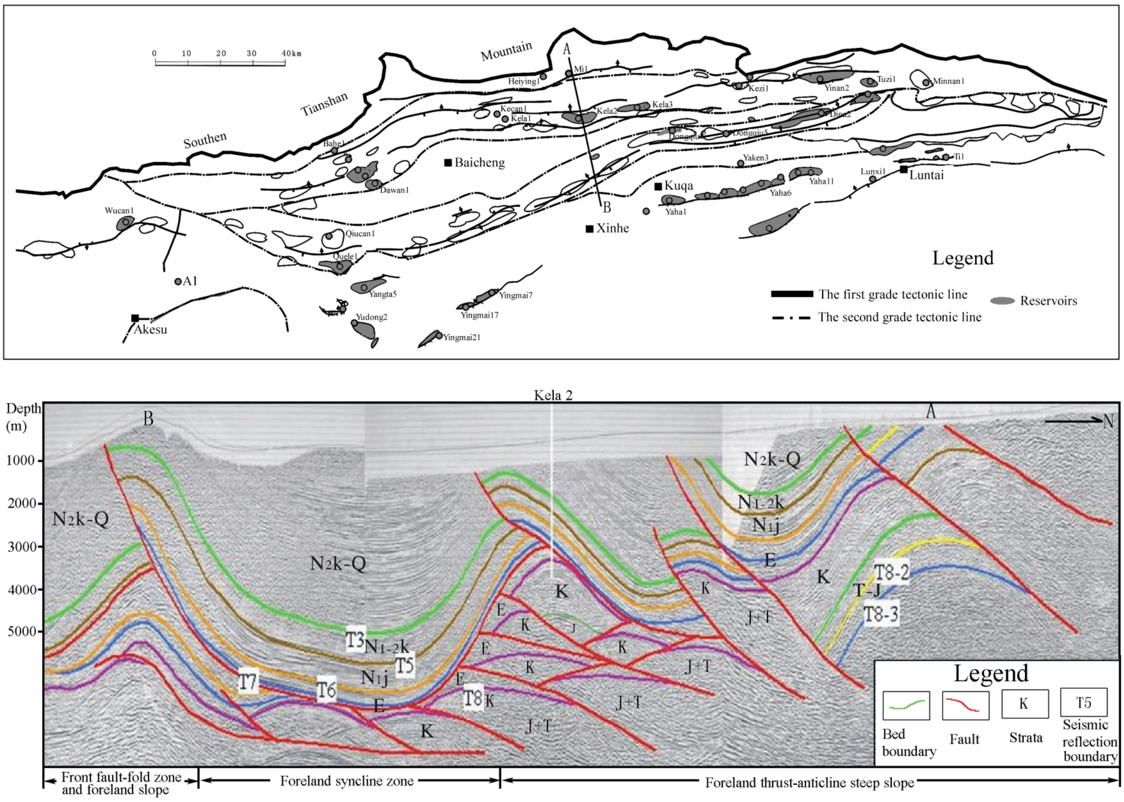


Fig. 3 Structural unit division and hydrocarbon reservoir distribution in Kuqa Depression

Mesozoic and Cenozoic deposition in Kuqa Depression includes the entire depositional sequence from Triassic-Quaternary system, among which Middle Upper Triassic-Middle Lower Jurassic series is the limnetic facies coal series under the humid climate and is the proven effective gas source rock in Kuqa Depression. Cretaceous deposit is an overwater proluvial facies-fluvial facies-dominated sedimentary assemblage formed in relatively blocked and dry environment and is a set of strata dominated by reservoir rock development. Paleogene and Neogene deposit is a blocked salty lagoonal facies sedimentary assemblage formed in dry climate, where quite thick gypsum rock member was developed, and plastic flow occurred in the later-stage deformation, with significant control for the shallow layer structural deformation.

Rapid subsidence at late stage is a typical characteristic of strata charging in Kuqa Depression since Neogene (Fig. 4). By the end of Paleogene, affected by the collision between Indian plate and Qinghai-Tibet plate, northern Tarim basin underwent intracontinental subduction underneath the Tianshan orogenic belt, Tianshan Mountain uplifted rapidly, Kuqa Depression was formed at the mountain front, and continental-facies red sedimentary formation with thickness of 6000m were received due to the rapid deposition in dry environment. In the center of depression, the sedimentary thickness of Meso-cenozoic is over 11,000m and that of Neogene is up to 4,500m, among which, the sedimentary thickness of Pliocene Kuqa Formation exceeds 2,000m and the maximum deposition rate reaches

1,300m/Ma. The deposition rates in various stages of Mesozoic are lower, which commonly vary from 20m/Ma to 40m/Ma (Table 2).

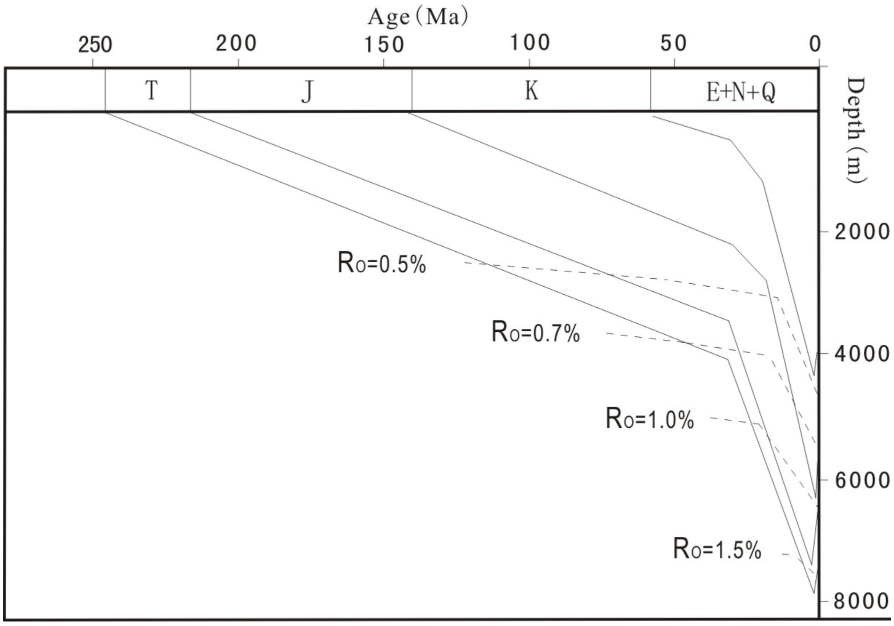


Fig. 4 Burial history of Kela 2 gas reservoir

Table 2 Deposition rate in Kuqa Depression

Geologic age		Stratum thickness (m)	Duration (Ma)	Deposition rate (m/Ma)
Cenozoic	Neogene	4500	19（24-5）	240
	Paleogene	750	41 (65-24)	18
Mesozoic	Early Cretaceous	1340	39 (135-96)	34
	Jurassic	2500	73 (208-135)	34
	Triassic	3300	42 (250-208)	78

Late-stage rapid subsidence caused highly effective gas accumulation, which may be reflected in two aspects: one is that Jurassic coal series source rocks have large accumulative gas generating volume and have experienced a rapid gas-generating process under the effect of later-stage rapid burial, which could lead to highly effective gas accumulation; the other is that the huge residual pressure difference is generated between gas source kitchen and reservoir, which becomes the strong driving force for migration of natural gas to traps[14-18].

(2) Possibility of highly effective gas accumulation in hinterland of cratonic basin

Sulige gas field is situated to the northwestern part of Ordos Basin and is the largest gas field discovered in recent years. By the end of 2010, the proven gas reserve has exceeded 1 trillion m^3 and proven gas-bearing area is nearly 8,000km^2. This gas field is distributed in the hinterland gentle slope of cratonic basin, where faults were not developed. The pay zone is Permian Shihezi-8 member and Shanxi-1 member, and the gas layer with average thickness of 8~20m is thinner. The whole gas field is a lithologic gas reservoir group that consists of tens of thousands of sand bodies with small individual scale (Fig. 5 and 6). Porosity of reservoir varies from 2% to 10% and the maximum value reaches 18%; whereas the permeability varies from 0.01 to 0.5mD, which is a typical low porosity and low permeability reservoir. Gas source primarily comes from coal series of Carboniferous and Permian Taiyuan Formation and Shanxi Formation[19-20]. This coal series gas source rocks are widely distributed over the whole area and the distribution of thickness is stable.

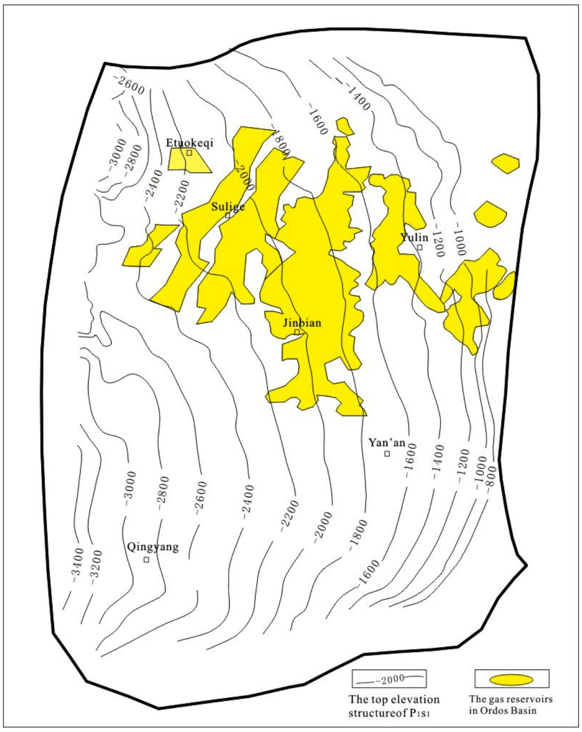


Fig. 5 Distribution of Upper Paleozoic slope structure and gas reservoir in Ordos Basin

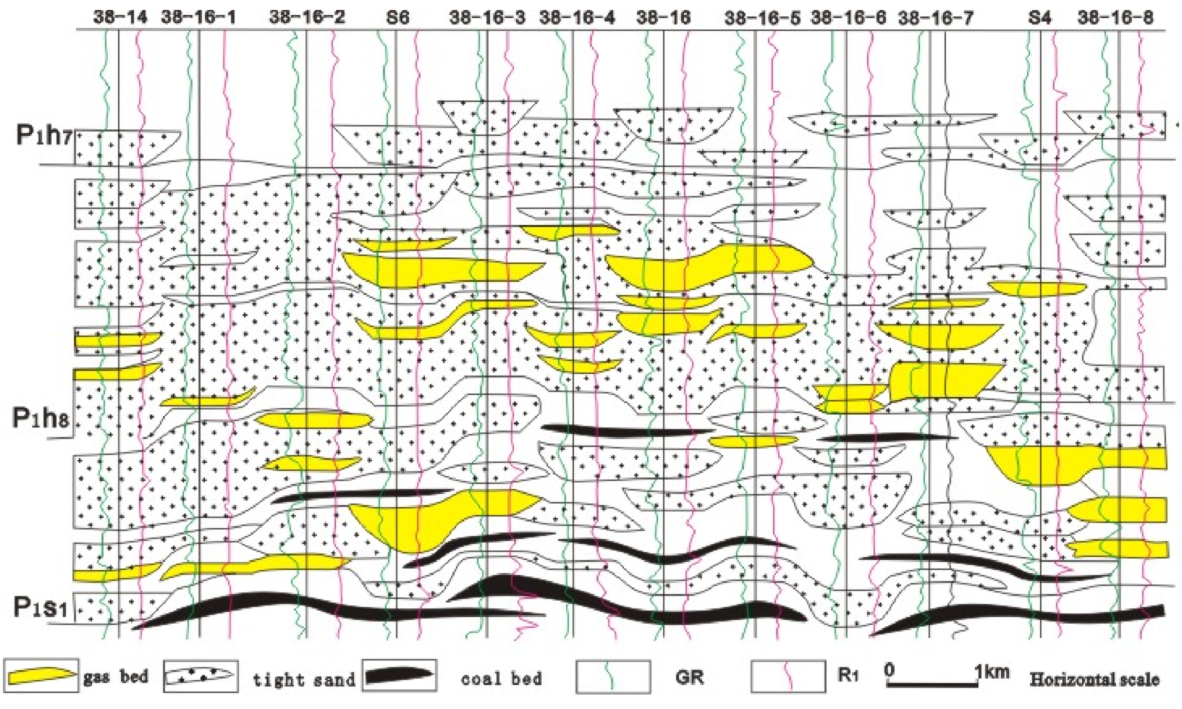


Fig. 6 Gas reservoir profile map of Sulige Gas field, Ordos Basin

Ordos Basin is one of the significant cratonic basins in middle-west of China in Middle Paleozoic, where the Upper Paleozoic geomorphology and geology of middle slope part are characterized by: (1) large area: slope is about 260km wide from east to west and about 500km long from north to south, the area is up to 130000km^2, which occupies 46.4% of the whole basin area; (2) monotonous structural feature and gentle dip: the dip usually varies from 1° to 2°, the maximum value is 3°, and local structure is not developed.

Under the stable and gentle structural setting, the highly-effective gas accumulation process is controlled by three favorable conditions: one is that coal series source rock is in large-area close contact with reservoir and presents the assemblage mode of "lower-generation and upper-preservation” so that natural gas possesses the favorable accumulation condition of near-source “planar” hydrocarbon supply (Fig. 7); the second is that the scale of tight individual sand body reservoir is small and its distribution is limited, whereas multiple individual sand bodies developed spatially in the mode of “planar-overlap and vertical-superposition”, forming large-scale reservoir, which is favorable for large-scale accumulation of natural gas; the third is that the basin has gone through the early-stage deep burial and late-stage large-scale uplift, and possesses two accumulation ways: volume flow charging and diffusion flow charging. Thus, the accumulation efficiency is significantly increased.

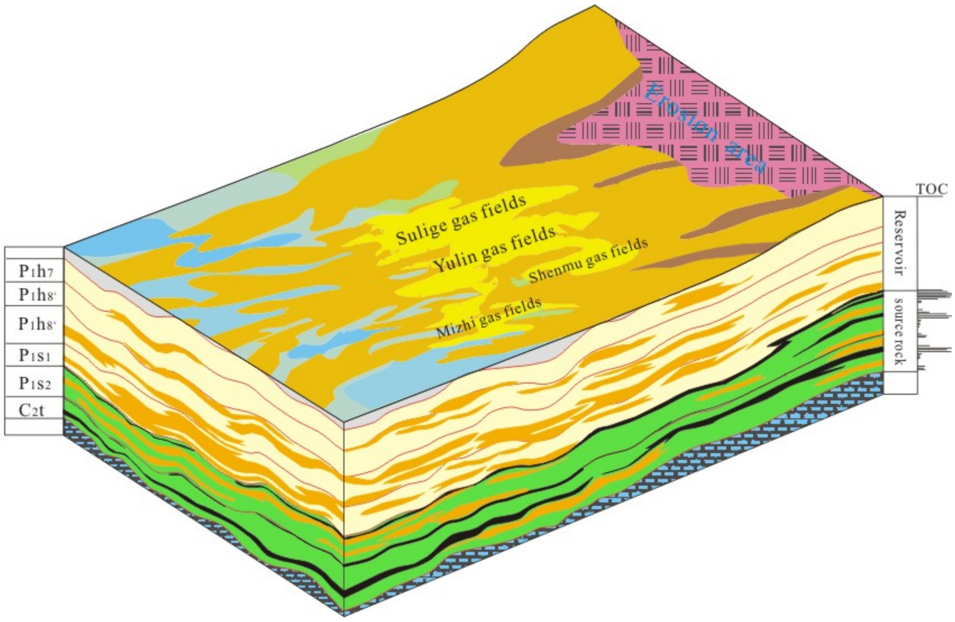


Fig. 7 Structural map of source-reservoir in Ordos Basin

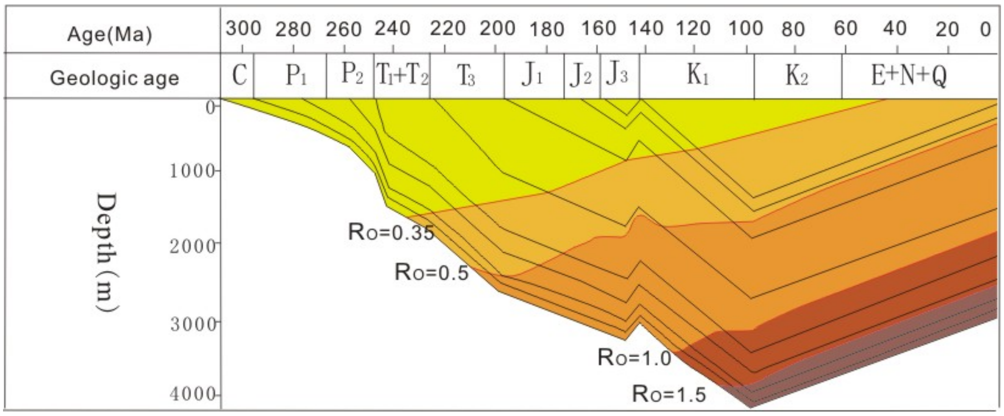


Fig. 8 Burial history of Sulige Gas field

3. Solutions

(1) Geological demonstration on highly-effective gas accumulation process in foreland basin

A. Highly effective gas-generating process of gas source kitchen and reservoir control function

The distribution area of coal series source rocks from Triassic to Jurassic system in Kuqa Depression varies from 12,000 km^2 to 14,000 km^2, and the maximum accumulative thickness is about 1,000m. Organic macerals are dominated by vitrinite (mostly more than 60%), followed by inertinite (10-25%) and few liptinite (mostly less than 10%). Liptinite is dominated by exinite, with quite few apropelinite, kerogen is dominated by Type Ⅲ, and it is a set of gas generating-dominated source rock. The average gas-generating intensity of Triassic and Jurassic source rocks is above 2 billion m^3/km^2 in depression and the gas-generating intensity of such source rocks is above 4 billion m^3/km^2 in hinterland of depression. A high-quality gas source kitchen has been formed, and all the large gas fields discovered are distributed within the high gas-generating center of this set of high-quality gas source kitchen.

Accumulative gas-generating intensity is utilized to reflect that the total gas-generating volume of Triassic and Jurassic system in Kuqa Depression is great, and the material support for forming large-medium scale gas field is available. From the gas-generating process of source rock, this set of hydrocarbon source rock still has another prominent characteristic: affected by late-stage rapid burial, the period for generating large amount of gas is quite short and gas supply efficiency is high.

Geothermal gradient of Kuqa Depression is 3.1℃/100m in Mesozoic, and has decreased from 2.8℃/100m to present 2.5℃/100m since Paleogene. In addition, the overall Cenozoic thickness in depression is not big enough, therefore gas source rock had kept at immature period before Neogene and R_o is less than 0.6%. Over 5,000m of strata has been accumulated rapidly by intense subsidence of depression since Neocene (23Ma), particularly, the strata thickness that has been accumulated since Pliocene (5Ma) exceeds 3500m, which leads to quick burial of source rocks below 6,000-7,000m. As shown in the source rock maturity evolution curve of Top Lower Jurassic stimulated with artificial points for central Baicheng Depression, Jurassic gas source rock entered the oil generation threshold (Ro=0.6%) no later than 15Ma and entered the oil generation peak (Ro=1.0%) by 5Ma, and Ro reaches 2.1% at present. Ro value increased from 1.0% to 2.1% and the primary gas generation process completed during the short period of 5Ma. Jurassic source rocks are characterized by rapid gas generation in short period besides large overall gas-generating volume, therefore it can be called highly effective gas source kitchen. It is certain that gas source kitchen possesses high gas supply efficiency, and it is favorable for forming highly effective gas reservoir within its control range. By using the increment △Ro of Jurassic hydrocarbon source rock Ro (%)increased over time, we can reflect the gas yield efficiency in primary gas generation period (Ro＝0.8%～2.0%) after source rock entered the hydrocarbon generation threshold, to characterize the distribution of highly effective gas source kitchen, and its interior and periphery is the favorable position for discovering large gas fields with high abundance (Fig. 9).

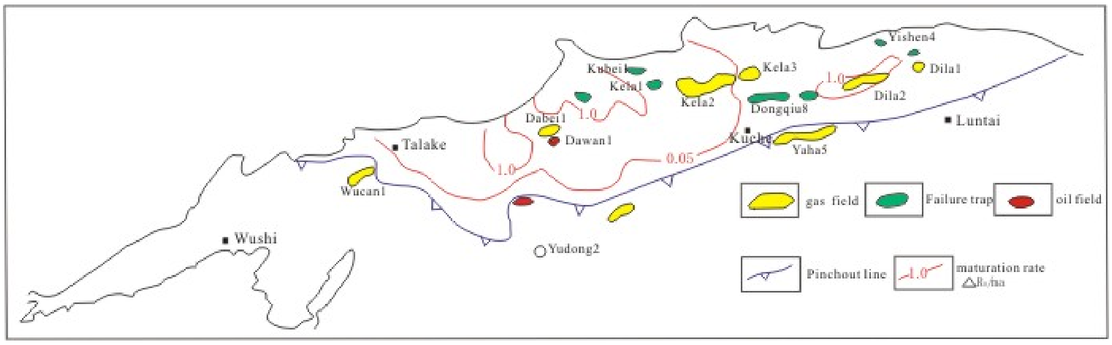


Fig. 9 Gas source rock maturation rate △Ro (%/Ma) isoline of Kuqa Depression since 5Ma (>0.05 means highly effective gas source kitchen)

B. Reservoir control function of residual pressure difference between source and reservoir

Furthermore, the highly effective gas accumulation process is also controlled by accumulation dynamics, dominant migration and conduction system, and good caprock condition. There are multiple dominant migration paths cutting the source rocks and leading to traps inside the thrust nappe in the forming period of Kela 2 gas reservoir, and the thick gypsum mudstone plays a good sealing and protecting role in gas accumulation and late-stage preservation. From the origin, whether the strong driving force for charging is available should depend on the effect of various geologic stresses upon fluids in accumulation period. In addition, the strong geologic tectonic movement, such as the structural deformation formed by Cenozoic extrusion nappe structure, may generate additional force for directional and accelerated migration of subsurface fluids. Overpressure could be generated during the quick hydrocarbon generation process of Jurassic source rock since 5Ma, which could induce the acting force of fluid pressurization in source rock to generate a great residual pressure difference, i.e. the difference between residual hydrocarbon supply pressure of gas source kitchen and residual pore fluid pressure of closed reservoir in the critical moment of gas accumulation is the direct driving force for highly effective gas migration.

Research reveals that, the abnormal formation pressure in Kuqa Depression is jointly controlled by multiple factors such as disequilibrium compaction, tectonic compression, fluid charging, sealing strata performance, and so on[21-25]. Through the establishment of overpressure equation with the origin meaning, necessary parameters were acquired with the multivariate statistics method, the abnormal formation development history of Kuqa Depression was restored, and then the pressure evolution from Jurassic source rock maturation period to now was restored. And the reservoir pressure in accumulation period can be determined via the combination of multiple methods such as fluid inclusion analysis, under-compaction research, and so on. Reservoir fluid pressure was basically under the normal status during the accumulation period of Kela 2 gas reservoir, and its source-reservoir residual pressure difference was up to 45Ma (Fig. 10), which offered the strong driving force for gas charging from source kitchens to traps. Through correlation of the average residual pressure difference and buoyancy of Kuqa Depression in accumulation period of primary gas reservoir, we can see that, the average residual pressure difference gradient for the structures of various reservoirs is greater than 0.03MPa/m, whereas the buoyancy gradient value is less than 0.008MPa/m. It is clear that residual pressure difference and residual pressure gradient are higher than buoyancy and buoyancy gradient, and the difference between the gradients would be an order of magnitude, which indicates that source-reservoir residual pressure difference is the primary driving force for highly-effective gas migration and accumulation.

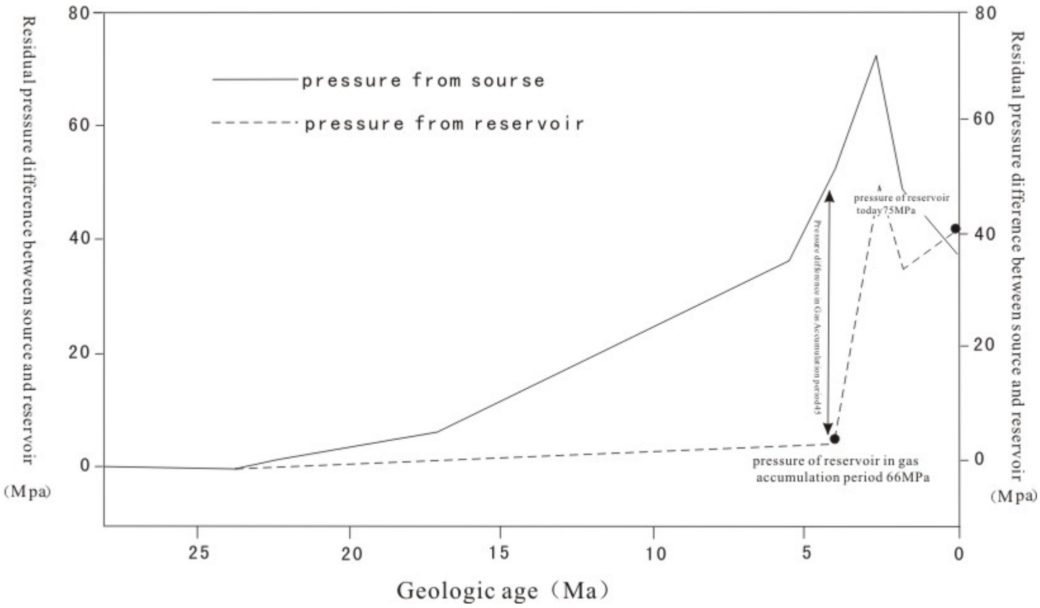


Fig. 10 Source-reservoir residual pressure difference in Kela 2 gas field in accumulation period

(2) Geological demonstration on highly effective gas accumulation process in

hinterland of cratonic basin

A. Reservoir has low porosity, low permeability and great lateral variation under the gentle structural setting, which is favorable for forming large-scale “gas reservoir group”

Large gas fields with low abundance were formed in the intracontinental depression under the large-scale cratonic background, and are the “reservoir body groups” remained from the constructive and destructive diagenesis of sedimentary sand bodies formed under the control of gentle topography and inherited water system, where reservoir is dominated by low porosity and low permeability, and sweet points with relatively high porosity and high permeability were developed locally. Sandstone reservoirs in Sulige Gas field, Ordos Basin mainly consist of tight sandstone and conventional sandstone reservoirs, where tight sandstone approximately occupies 75% and tight sandstone with the permeability of 1~0.1md approximately occupies 62%. Porosity varies from 5% to 13 % with the average value of 8.5%, mean value of pore throat diameter is about 0.1～0.5μm, and it belongs to micro-pore throat texture. The ultra tight reservoir with the permeability of less than 0.1md occupies some 32%, the average porosity varies from 4% to 7% with the average value of 5.7%, the mean value of pore throat diameter is less than 0.1μm, and it belongs to nanoscale pore throat texture. Conventional reservoir with the permeability of above 1md occupies some 25%, its average porosity is greater than 13%, the mean value of pore throat diameter is usually greater than 0.5μm, and it is characterized by large pore throat texture. For large-scale reservoir body formed under the gentle structural setting, both the physical property and internal structure present the strong variation in three-dimensional space, which leads to the cluster development and distribution of stratigraphic-lithologic traps. These traps include the lithologic traps formed by original deposition, physical property traps formed by diagenesis, and the stratigraphic traps formed by epigenesist between fracture-cavity bodies and surrounding rocks. These independently–semi-independently distributed traps commonly appear in cluster mode, and the “gas reservoir group” would be formed in case of accumulation. Although the individual body is limited, whereas the gas reservoir group consists of thousands of reservoirs would have great scale and large distribution area (several or tens of thousands of kilometers). But the gas-bearing abundance of gas reservoir is lower.

Low abundance gas reservoir is mainly characterized by gas-bearing in tight reservoir and gas enrichment in sweet point. Sweet points have relatively higher gas saturation, and meanwhile widely distributed tight sandstone commonly bears gas as well. The research results on porosity, permeability and gas saturation of tight sandstone and sweet point in 116 wells of Sulige Gas field reveal that, gas saturation of Upper Paleozoic sweet point in Sulige Gas field is higher than that of tight sandstone. Sweet points in He-8 member have higher gas saturation, which is mainly 60%~70% with the average value of 59.03%. Tight sandstone has lower gas saturation, which is mainly 40%~50% with the average value of 46.40%; reservoir of Shan-1 member has the similar distribution characteristic of gas saturation with He-8 member, whereas it is a bit higher than He-8 member as a whole. The average gas saturation of sweet points is 62.59%, and for tight sandstone it is 46.04%. Gas-water differentiation is poor in tight reservoir, gas saturation of sweet point is 40%-70%, and for tight sandstone it is 30%-60%.

Upper Paleozoic structure in Sulige gas field, Ordos Basin is gentle and presents a monocline where the north is higher than the south and the dip is 1～3º. Gas layers in Sulige Gas field are generally 5~15m thick, individual gas-bearing sand body is commonly 1,000~2,500m long and 100~250m wide, and maximum buoyancy generated by gas column height is 0.15MPa. Tight sandstone with worse physical properties, as the direct caprock, provided sealing for Sulige Gas field. Its drainage pressure is greater than 1.2MPa through the experimental test, and therefore the drainage pressure difference between gas layer and caprock is greater than 0.5Mpa. On that basis, buoyancy generated by gas column is not enough to break through the caprock so that gas reservoir can be preserved. Therefore, large area gas accumulation could be formed within the whole basin, even without quite thick gypsum like that in Kela 2 high-abundance large gas field acting as caprock (Fig. 11).

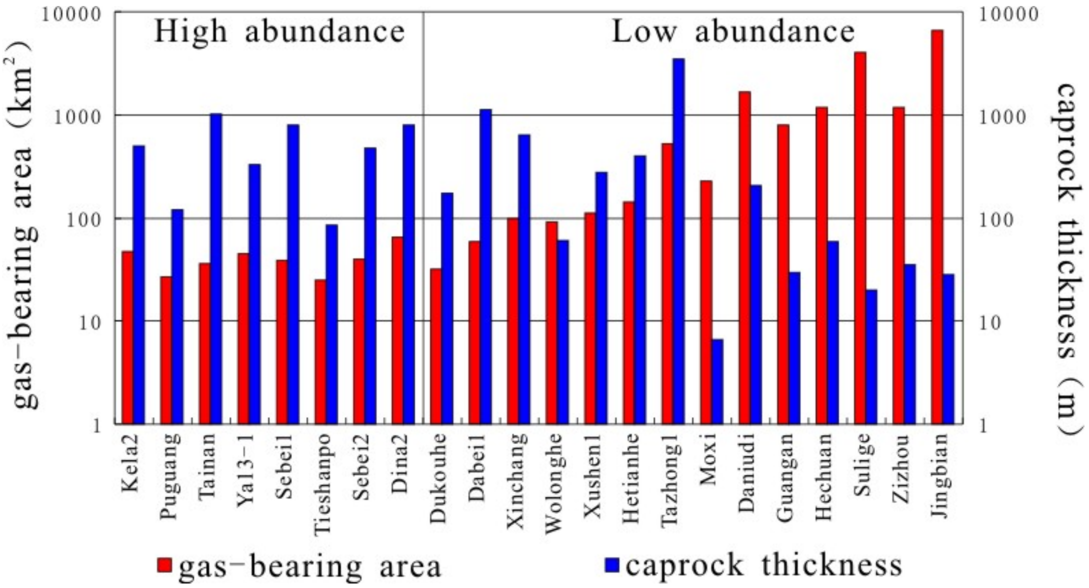


Fig. 11 Statistics relation between gas-bearing area and direct caprock thickness of Chinese large gas fields

B. Low abundance gas reservoir forming process has two types of charging modes, i.e. volume flow charging driven by residual pressure difference and diffusion flow driven by concentration difference so that the sufficiency of gas source is assured

Low abundance gas reservoir is mainly tight reservoir with low porosity and low permeability. Affected by high expulsion pressure, natural gas generated by source rock cannot charge into reservoir and migrate in reservoir under the buoyancy freely. Actual tight reservoir core charging experiment reveals that, natural gas must possess a certain start-up pressure so as to charge into reservoir and migrate in reservoir. During the geological history process, the abnormal high pressure developed in source rock is the necessary condition for natural gas charging into tight reservoir. In case that overpressure of source rock exceeds the displacement pressure of reservoir, natural gas is able to charge into tight reservoir and migrate in reservoir in volume flow mode, which means the volume flow charging and migration driven by residual pressure difference is the primary natural gas charging mode during the highly effective accumulation process of low abundance gas reservoir in strata burial stage.

Tight reservoir possesses higher displacement pressure, and the evolution of tight reservoir displacement pressure in geological history was restored via quantitative diagenetic history research. Based on mercury injection data of 190 Upper Paleozoic samples from Ordos Basin, relation between reservoir porosity and displacement pressure has been established. Reservoir displacement pressure has better exponential relation with porosity, and reservoir displacement pressure presents exponential decreasing with the increasing of porosity. Thus the variation of natural gas charging into reservoir and migrating in reservoir (displacement pressure) in geologic history period can be restored on the basis of porosity evolution research.

Critical condition of volume flow charging was determined by the natural gas charging experiment with actual tight reservoir core. 12 sandstone samples with permeability of （0.0043～1.37）$\times 10^{-3} \mu m^2$ were selected and adopted to conduct the methane charging experiment under different pressure gradient conditions. It is revealed by experiment that, a certain start-up pressure gradient must be available for the occurrence of volume flow flowing in low porosity and low permeability core. Start-up pressure gradient presents clear exponential relation with physical property. In case that permeability is $0.1\times10^{-3}\mu m^2$, minimum laboratory start-up pressure gradient is 0.1MPa/cm, and start-up pressure gradient under geological condition is some 5MPa/100m via similarity analysis; in case that permeability reaches $1\times10^{-3}\mu m^2$, minimum laboratory start-up pressure gradient decreases to some 0.02MPa/cm, which equals to subsurface pressure gradient of 0.25MPa/100m.

Buoyancy gradient induced by gas-water density difference is （0.023-4.9）$\times10^3$Pa/m, which is much smaller than start-up pressure gradient for volume flow flowing in low porosity and low permeability reservoir. Residual formation pressure gradient must exceed its start-up pressure gradient in case of volume flow charging and flowing under the strata condition.

Fluid inclusion pressure testing and compaction analysis reveal the condition for the occurrence of volume flow charging in geologic history. There are multiple pressurization mechanisms in different stages of basin development, most of which occur in the deep burial stage of strata. Mudstone (hydrocarbon source rock, in particular) in depositional layers is the primary layer for abnormal pressure development, and sandstone is the main pressure relief layer, where a residual source-reservoir pressure difference pointing from source to reservoir is usually formed, which is the primary driving force for natural gas charging from source rock towards reservoir.

Fluid inclusion pressure testing has confirmed the existence of obvious overpressure phenomenon in deep burial period of Upper Paleozoic formation in Ordos Basin. Maximum paleo-pressure coefficient of Shanxi Formation reaches some 1.4 and main peak range is from 1.2 to 1.3; Shihezi Formation is dominated by normal pressure, maximum paleo-pressure coefficient is 1.1, and main frequency range is from 1.0 to 1.1. During the maximum buried depth stage of strata, residual pressure difference of at least 2-3Mpa occurs between Shanxi Formation source rock and sand body with the occurrence of source rock gas-generating peak. The existence of this residual pressure difference must lead to migration of natural gas generated by source rock towards the reservoir driven by overpressure, which means overpressure charging has occurred (Fig. 12).

Based on mudstone compaction curve, fluid inclusion was used to calculate the pressure calibration at the meantime, and basin simulation technique was utilized to restore the pressure evolution history of source rock and reservoir in Sulige Gas field. Source rocks and reservoirs in Sulige gas field are characterized by “high residual pressure and low residual pressure difference” ——source rock and reservoir have higher residual pressure, which is commonly greater than 15MPa, whereas residual source-reservoir pressure difference is lower, which is commonly less than 3MPa. The existence of residual source-reservoir pressure difference will lead to large scale volume flow charging of natural gas within the research area. Volume flow charging is the primary mode of natural gas charging in the deep burial stage.

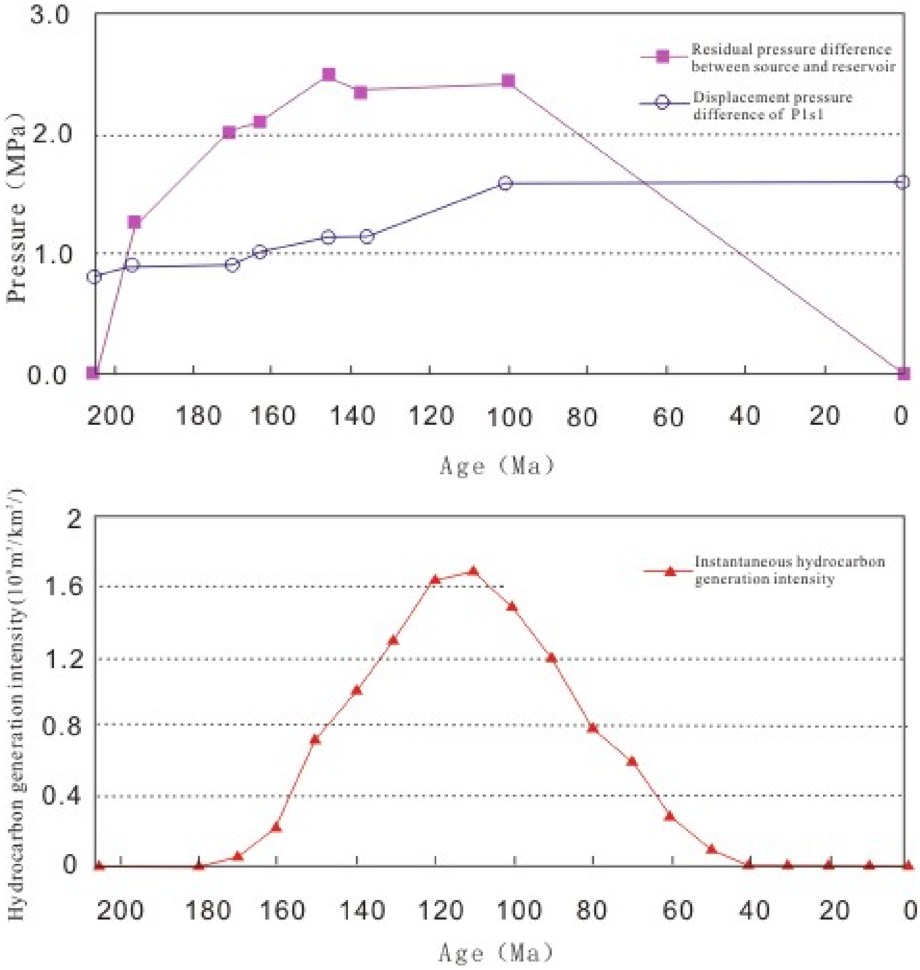


Fig. 12 Generation and evolution of residual source-reservoir pressure difference in Sulige Gas field

Diffusion is a material transfer mode and often refers to a material transfer process that a certain material is subject to molecular motion from high concentration area to low one spontaneously under the concentration gradient and achieves the concentration balance. Diffusion would occur as long as concentration gradient exists[26-27].

In previous cognition, diffusion is commonly considered as one of the main function to cause damage to gas reservoir. However, the understanding for contribution of diffusion to gas accumulation under specific condition is insufficient, and the understanding of the effect of diffusion charging to the large-scale accumulation efficiency of medium-low abundance gas reservoirs, in particular, is insufficient[28-31].

Highly effective accumulation in Sulige Gas field primarily occurs under the geologic condition of “widely covered” source-reservoir contact. Natural gas during the accumulation is dominated by primary migration and short-distance vertical secondary migration, and lateral secondary migration is unclear. This special accumulation condition ensures that the role of diffusion in large-scale accumulation of medium-low abundance gas reservoir is quite different from diffusion in conventional gas reservoir accumulation. In burial stage of strata, obvious overpressure, in particular, is developed in source rocks, the efficiency of volume flow charging efficiency is obviously greater than that of diffusion charging, and thus the contribution of diffusion charging is unobvious so that it is often ignored. However, volume flow charging tends to stop during the strata uplifting stage due to the decreasing or disappearing of residual source-reservoir pressure difference, diffusion charging condition still remains at this time, and diffusion becomes the main route for natural gas charging. The occurrence of large-scale accumulation in gas-bearing basin during the uplifting stage is a significant characteristic of highly-effective accumulation of low abundance gas reservoir. And diffusion accumulation during the uplifting process is reflected in the following two factors: one is that uplifting offloading leads to desorption and expansion of natural gas inside source kitchen, increasing the amount of free gas and providing driving force for effective gas displacement; the other is that the uplifting process presents the large-area overall uplifting of sedimentary basin so that the hydrocarbon expulsion of gas source kitchen has scale effect, therefore the accumulation range is large.

Sufficient gas source for diffusion accumulation can be provided during the uplifting. The mechanism is that, under the large-scale uplifting and erosion effect, the overlying pressure of deep strata is reduced (i.e. offloading) and the temperature and pressure dropping occurs in strata. Volume of gas absorbed in source rock pores may have greater expansion during the uplifting compared to volume of rock framework, which can become the significant driving force for gas discharging from source rock, lead to vast discharging of absorbed gas, increase the gas concentration inside the source rock, and provide the driving force for diffusion migration to reservoir. Based on the calculation with gas state equation, by the end of Early Cretaceous, the paleo-strata pressure of Permian Shihezi Formation in Sulige Basin is some 48~53MPa, 32～35MPa after temperature dropping, and 29~30MPa at present. Without considering natural gas loss or supplement, pressure reduction in Sulige area due to temperature dropping can reach 30%~35%.

Based on geologic analysis on Upper Paleozoic gas reservoir in Ordos Basin, a diffusion-seepage coupling model has been established, and numerical simulation has been conducted for volume flow charging and diffusion flow charging of Upper Paleozoic low abundance gas reservoir in Ordos Basin and its diffusion and loss process. Simulation results reveal that, gas volume flow charging primarily occurred in burial stage of basin, and the maximum volume flow charging rate reached $13\times10^6 m^3/(km^2\cdot Ma)$ by the maximum hydrocarbon generating stage in Early Cretaceous. Natural gas diffusion flow charging mainly occurred in the uplifting stage of basin, and maximum charging rate is $18\times10^6 m^3/(km^2\cdot Ma)$ (Fig. 13).

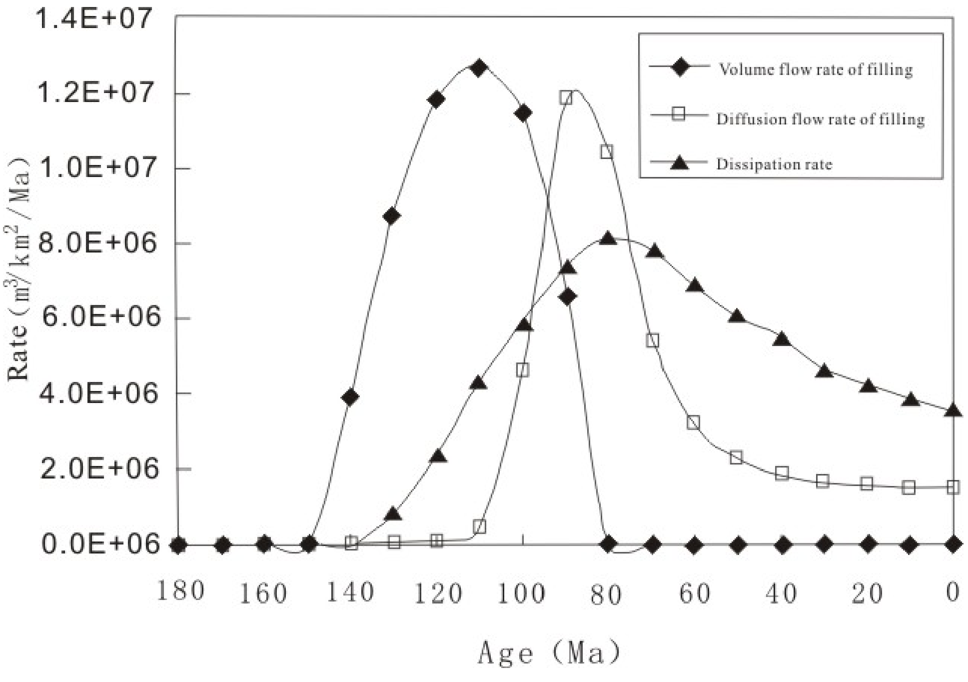


Fig. 13 Gas charging and loss rate evolution of Upper Paleozoic in Well Su-7, Sulige Gas field

The overall basin simulation results reveal that, natural gas volume flow charging amount is about 180 trillion m^3 and diffusion flow charging amount is about 60 trillion m^3 in strata burial stage; whereas natural gas volume flow charging amount is less than 10 trillion m^3 and diffusion flow charging amount approaches 70 trillion m^3 in overall formation uplifting stage, which indicates that the primary mechanism for natural gas charging is diffusion flow charging in strata uplifting stage. During the whole geologic history, natural gas volume flow charging amount is 190 trillion and natural gas diffusion flow charging amount is 130 trillion m^3, whereas the natural gas loss amount is 205 trillion m^3 during this stage, volume flow charging amount is not sufficient enough to meet the diffusion loss of natural gas. Therefore, natural gas diffusion charging has made up for the diffusion loss of natural gas effectively, and made positive contribution for highly effective accumulation and preservation of large gas fields with low abundance.

4. Results

(1) For the formation of Kela2 large gas field with high abundance, late-stage rapid subsidence is the key factor for highly-effective gas accumulation besides the common advantageous conditions such as source, reservoir, caprock, migration, trap and preservation. One is that Jurassic coal series source rock has accumulated large amount of gas and has gone through a rapid gas-generating process by late-stage rapid burial, which leads to quite high accumulation efficiency; the other is that great residual pressure difference is generated between gas source kitchen and reservoir during the rapid gas generation process, which becomes the strong driving force for natural gas migrating towards traps.

(2) Sulige large gas field with low abundance has no good accumulation conditions such as reservoir, trap and caprock, however it still featured by highly effective accumulation. This is mainly controlled by three distinctiveness: one is that hydrocarbon source rock presents large-area close contact with reservoir within the whole basin scope, which ensures the near source accumulation of natural gas; the second is that reservoir physical property is worse as a whole, “cluster” accumulation of numerous lithologic bodies in the environment with strong lateral lithologic variation could reduce the requirement for caprock and ensure the accumulation scale within the larger area; the third is that basin has gone through the overall deep burial and uplift, volume flow charging and diffusion flow charging accumulation has occurred respectively, and the sufficiency of gas source is assured.

5. Conclusions

(1) Natural gas resources are abundant in superposed basins in mid-western China. A batch of large gas fields has been discovered in recent years and have become the primary contributor for reserve and production growth. More gas fields will be discovered in the future natural gas exploration.

(2) Chinese large gas field can be divided into two types: one is the large gas field with high abundance, which is featured by excellent accumulation conditions, but less gas amount and big discovery difficulty; the other is large gas field with low abundance, where the formation is decided by continental facies basins widely distributed in China, the reservoir physical property is poor, and the gas-bearing property varies greatly. The scale is large once it has been formed. It is the main part of Chinese natural gas resources. Although the exploration & development is difficult, effective development can be achieved with the advancement of techniques. It is expected that the future exploration & development of large gas fields will rely on this type.

(3) Research on the highly effective accumulation process of these two types of large gas fields is very useful for evaluation and potential analysis of natural gas resources, especially for the formation of large gas field with low abundance. Advantages for forming large gas field are available at regions that are previously considered to have poor gas reservoir forming conditions, such as structural lows, structural uplift area, poor reservoir and caprock areas, and so on. Resources potential in these regions have been significantly enhanced, and these

regions have become the potential new domain for natural gas exploration.

References:

[1] Dai Jinxing. Major advancement of coal-formed gas exploration in the last 30 years in China. Petroleum Exploration and Development [J], 2009, 36(3), 264～279.

[2] Dai Jinxing, Huang Shipeng, Liu Yan et al. Major advancement of natural gas exploration & development in the last 60 years in China. Oil and Gas Geology [J]，2010，31(6),689-698.

[3] Dai Jinxing, Xia Xinyu, Hong Feng. Natural gas geology accelerates the growth of natural gas reserves in large scale in China. Xinjiang Petroleum Geology [J]. 2002，23 (5)：357～365.

[4] Dai Jingxing, Strengthen the natural gas geology research and explore more large gas fields. Natural Gas Geoscience [J], 2003, 14(1), 1～14.

[5] Dai Jingxing, Chen Jianfa, Zhong Ningning et al. Chinese large gas fields and gas source [M]. Science Press, Beijing, 2003.

[6] Dai Jinxing, Wei Yanzhao, Zhao Jingzhou. Important role of late-stage accumulation to the formation of large gas field. Geology in China [J], 2003, 30 (1), 10~17.

[7] Zhao Wenzhi, Liu Wenhui et al. Basic research on formation & distribution of high effective gas reservoir and economic development of condensate and low effective gas reservoir [M], Science Press, Beijing, 2008.

[8] Maxinhua. Discussion on characteristics and reservoiring mechanism of deep basin gas in Upper Paleozoic in Ordos basin. Oil and gas geology, 2005, 26(2): 230-236.

[9] Zhang L P, Bai G P, Luo X Ret al. Diagenetic history of tight sandstones and gas entrapment in the Yulin Gas Field in the central area of the Ordos Basin, China. Marine and Petroleum Geology, 2009, 26(6): 974-989.

[10] Law B E, Pollastro R M, Keighin C W. Geologic characterization of low-permeability gas reservoirs in selected wells, Greater Green River Basin, Wyoming, Colorado, and Utah. Geology of tight gas reservoirs: AAPG Studies in Geology, 1986, 24: 253-269.

[11] Spencer C W. Review of characteristics of low-permeability gas reservoirs in western united states. AAPG Bulletin, 1989, 37(5): 613-629.

[12] Spencer C W, Mast R F. Geology of tight gas reservoirs. Tulsa: AAPG, 1986.

[13] Law B E. Basin-centered gas systems. AAPG Bulletin, 2002, 86(11): 1891.

[14] Law B E, Dickinson W W. Conceptual model for origin of abnormally pressured gas accumulations in low-permeability reservoirs. AAPG Bulletin, 1985, 69(8): 1295-1304.

[15] Spencer C W. Hydrocarbon generation as a mechanism for overpressuring in Rocky Mountain region. AAPG Bulletin, 1987, 71(4): 368-388.

[16] Warner E M. Structural geology and pressure compartmentalization of Jonah field, Sublette County, Wyoming//Slatt R M ed. Compartmentalized reservoirs in Rocky Mountain basins: Rocky Mountain Association of Geologists, 1998: 29-46.

[17] Warner E M. Structural geology and pressure compartmentalization of Jonah field based on 3-D seismic data and subsurface geology. Sublette County, Wyoming: The Mountain Geologist, 2000, 37(1): 15-30.

[18] Shanley K W, Cluff R M, Robinson J W. Factors controlling prolific gas production from low-permeability sandstone reservoirs Implications for resource assessment, prospect development, and risk analysis. AAPG Bulletin, 2004, 88(8): 1083-1121.

[19] Zhu Xiaomin，Sun chao，Liu chenlin, et al. enesis and fluid. Reservoir diagenesis and fluid-rock interaction simulation of the Sulige gas field in the Ordos basin. Geology in china, 2007, 34(2): 276-282.

[20] Zhang Wenzheng，Yang Hua，Xie liqin, et al. Secondary porosity form ation of Upper Paleozoic low porosity—permeability coal-formed gas reservoirs，Ordos Basin：Simulation on dissolution of anorthite and dark—c0l0red femic minerals in acetic acid solution. Petroleum exploration and development, 2009, 36(3): 383-391.

[21] Chen S P, Tang L J, Jin Z J, et al. Thrust and fold tectonics and the role of evaporites in deformation in the Western Kuqa Foreland of Tarim Basin, Northwest China.Mar Petrol Geol, 2004, 21: 1027—1042
[22] Zhao W Z, Zhang S C,Wang F Y, et al. Gas systems in the Kuche Depression of the Tarim Basin: Source rock distributions, generation kinetics and gas accumulation history. Org Geochem, 2005, 36: 1583—1601
[23] Liang D G, Zhang Shuichang, Chen Jianping, et al. Organic geochemistry of oil and gas in the Kuqa depression, Tarim Basin, NW China. Org Geochem, 2003, 34: 873—888
[24] Liu guangdi,Sun mingliang, Lvyanfang， et al. evaluation of gas reservoir formation efficiency in Kuche depression. SCIENCE IN CHINA (EARTH SCIENCES)，2008,38（supplement）：103-110.
[25] LIU Quanyou，ZHANG Tongwei，JIN Zhijun，et al. Kinetic Model of Gaseous Alkanes Formed from Coal in a Confined System and Its Application to Gas Filling History in Kuqa Depression,Tarim Basin,Northwest China. Acta Geologica Sinica，2011, 85(4): 911-922.
[26] Hao shisheng. Natural gas reservoir formation and reservation. Beijing: Petroleun industry press, 1995.
[27] Leythaeuser D, Schaefer R G, Yukler A. Role of diffusion in primary migration of hydrocarbons. AAPG Bulletin, 1982, 66(4): 408-429.
[28] Zhang T W, Krooss B M. experimental investigation on the carbon isotope fractionation of methane during gas migration by diffusion through sedimentary rocks at elevated temperature and pressure. Geochimica et Cosmochimica Acta, 2001, 65(16): 2723-2742.
[29] Krooss B M, Leythaeuser D, Schaefer R G. The quantification of diffusive hydrocarbon losses through cap rocks of natural gas reservoirs-a reevaluation. AAPG Bulletin, 1992, 76(3): 403-406.
[30] Schlomer S, Krooss B M. Molecular transport of methane, ethane and nitrogen and the influence of diffusion on the chemical and isotopic composition of natural gas accumulations. Geofluids, 2004, 4: 81-108.
[31] Nelson J S, Simmons E C. the quantificaton of diffusive hydrocarbon losses through cap rocks of natural gas reservoirs-a reevaluation, discussion. AAPG Bulletin, 1992, 76(11): 1839-1841.