Chinese Science Bulletin

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Springer

The controlling factors of oil and gas charging and accumulation of Puguang gas field in the Sichuan Basin

MA YongSheng[1†], CAI XunYu[1] & GUO TongLou[2]

[1] Exploration Company, SINOPEC, Beijing 100029, China;
[2] Exploration Company in Southern China, SINOPEC, Chengdu 610041, China

Combined with oil and gas transport and accumulation, structure-lithology evolution history, and with geochemistry and synthesizing geology methods, this paper studies the oil and gas discharge history of Puguang large scale gas field and the main controlling factors of oil accumulation. The natural gas in Puguang gas field is mainly coal-derived gas and oil-racked gas. The main hydrocarbon is Upper Permian coal mudstone and Lower Silurian mud shale with organic material. Puguang gas field has gone through discharge and adjustment 3 times, and it has favorable palaeostructure location, high quality dredge and effectively conserving conditions.

Puguang gas field, oil and gas charging, carbonate rock, main controlling factors of oil accumulation, Sichuan Basin

Puguang gas field in northeastern Sichuan Basin is the largest carbonate gas discovered in China, with highest abundance, deepest burial, best reservoir quality, thickest high quality reservoir, highest content of H_2S and the driest gas[1−4]. Because China marine carbonate is old and had gone through multicycle folding and reform, the oil distribution is complex[5−9], so the exploration step has been slow for a long time. The discovery of Puguang super scale gas field and deep high quality carbonate reservoir[2,3] shows the great exploration potential of Chinese marine carbonate and sets off the upsurge of exploration and study.

1 Petroleum geology characteristics of Puguang gas field

The Puguang gas field is located in the Huangjinkou tectonics, Shuangshimiao-Puguang tectonic zone, Xuanhan-Daxian district, northeastern Sichuan Basin (Figure 1(a) and (b)). It is a large structure-lithology composite gas pool with a confirmed gas enclosure area of approximately 50 km^2. The main gas payzones include dolomite reservoirs in the Lower Triassic Feixianguan formation and Upper Permian Changxing formation, developing along the platform edge, and belonging to oolitic dolomite reservoir[10−14]. The oolitic dolomite in Feixianguan formation and biothermal limestone in Changxing formation overlap laterally and connect with each other vertically, with wide aerial distribution. The burial depths of the gas reservoirs in the Feixianguan formation are relatively deep, over 5000 m. All of the six wells, Puguang 1, Puguang 2, Puguang 3, Puguang 4, Puguang 5, Puguang 6, drilled in the Puguang gas field produced high flows, approximately $(50-120)\times10^5$ m^3/d before acidification, and there are also wide distributed thick high quality reservoir, with some reaching 400 m, and also the proven gas reserves in the Puguang field had reached 3560.72×10^8 m^3, so it is the largest gas field in the Sichuan Basin. Luojiazhai, Dukouhe and Tieshanpo gas fields were also found in the east of Puguang gas field, and they are shallowly buried at about 3500−4500 m, and the gas accumulation and abundance are small compared with Puguang

Received December 20, 2006; accepted March 10, 2007
doi: 10.1007/s11434-007-6007-7
†Corresponding author (email: yongshma@sohu.com)
Supported by the National Key Basic Research and Development Program of China (Grant No. 2001CB209100)

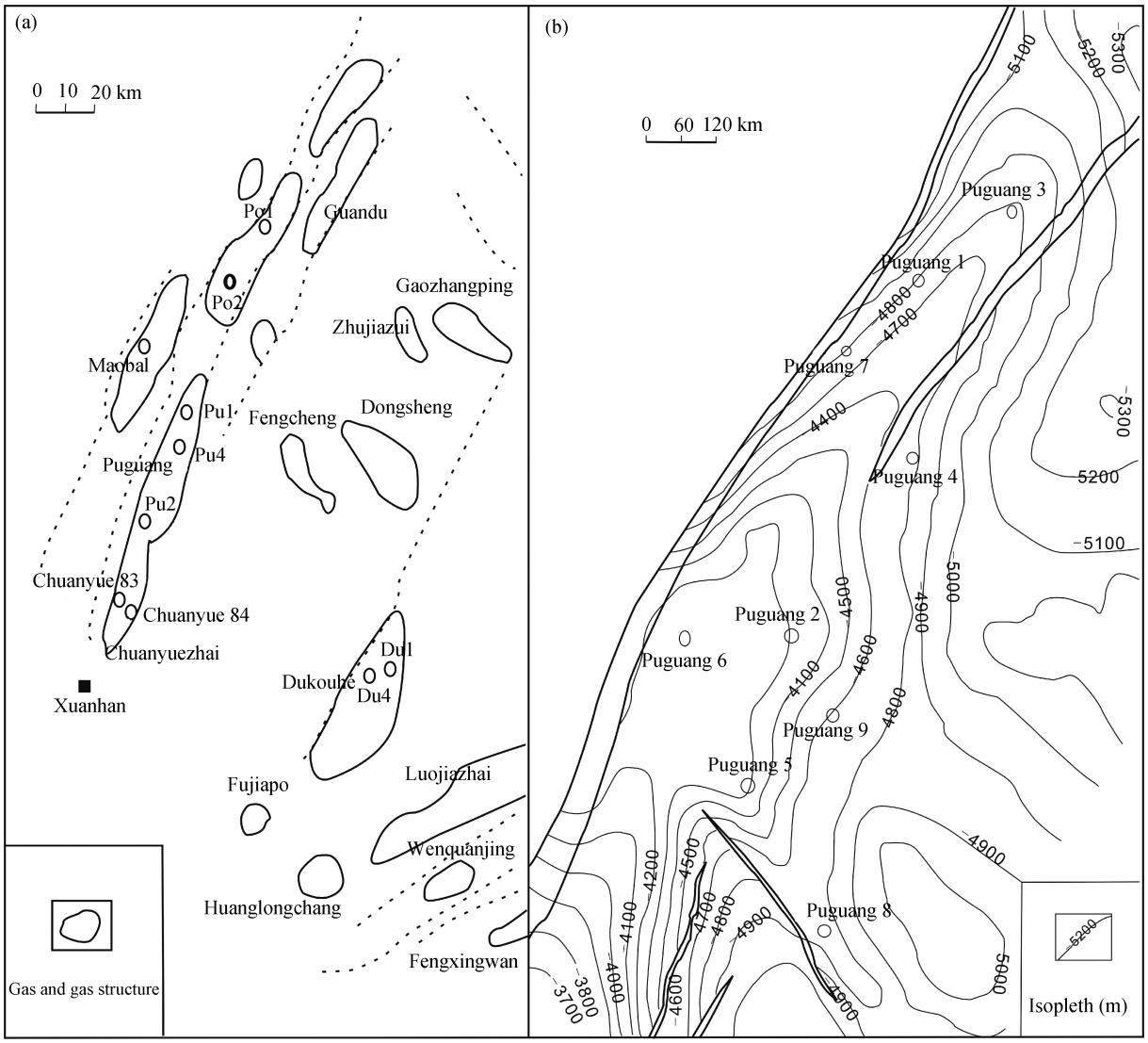

Figure 1 The location of Puguang gas field.

gas field. But they have the same petroleum geology characteristics[15]. The objective of this paper is to describe the oil and gas charging history and combine structure-lithology evolution history to study the main factors of oil and gas accumulation of the Puguang gas field on the basis of oil and gas transportation and accumulation, and through the oil and gas geochemistry and basin simulation analyses on geological setting to propose potential areas for future petroleum exploration in the northeastern Sichuan Basin.

2 The gas geochemistry characteristics of Puguang gas field

Natural gas produced from Puguang gas field are typically dry, with around 80% methane, less than 0.05% C_{2+} alkanes, and $C_1/(C_1-C_5)$ ratios greater than 0.995. These gases are rich in H_2S (14%—17%) and CO_2 (3%—10.5%), with similar chemical compositions for gases produced from the Feixianguan and Changxing formations (Table 1), for example, both of them have high content of H_2S, H_2S reaches 16% and CO_2 reaches 9% in Changxing formation and H_2S reaches 17% and CO_2 reaches 10% in Feixianguan formation, and also there are some nonhydrocarbon gases such as N_2, He and H (Table 1).

The $\delta^{13}C$ values of methane and ethane in these gases are within the range of –30.0‰ to –31.0‰ and –25.2‰ to –29.1‰ respectively, and the content of propane is small. So judging from the component of the $\delta^{13}C$ values of methane and ethane, we can see that Puguang gas

Table 1 The components and carbon isotope of natural gas of Puguang gas field

Well no.	Position	Well interval (m)	Component (%)								(C_1/C_{1+})	$\delta^{13}C$(‰)	
			CH_4	C_2H_6	C_3H_8	H_2S	CO_2	N_2	H_2	He		CH_4	C_2H_6
Puguang1	T_1f	5610	77.5	0.02	0	12.7	9.1	0.62	0.04	0.01	1		
Puguang 2	T_1f	5062	75.6	0.11	0	15.8	7.96	0.44	0.03	0.01	0.999	–31	–28.8
	T_1f	5027	80	0.06	0	14.7	2.55	0.46	2.19	0.01	0.999		
	T_1f	4958	74.3	0.22	0	17.2	7.9	0.42	0.01	0.01	0.997	–30.5	–29.1
	T_1f	4801	76.1	0.02	0	15.5	7.71	0.44	0.01	0.01	1	–30.9	–28.5
	P_2ch	5315	74.2	0.02	0.001	16.0	9.46				1	–30.6	–25.2
	P_2ch	5259	75	0.33	0.001	15.4	8.73	0.47	0.02	0.01	0.996	–30.1	–27.7
Puguang 4	T_1f	5770	73.8	0.03	0	17.1	8.47	0.59	0	0.02	1		
Puguang 6	T_1f	5044	74.7	0.03	0	14.1	10.5	0.65	0.06	0.01	1		
	P_2ch	5240	75.9	0.05	0	14.7	8.74	0.49	0.06	0.01	0.999		

is the oil-mixed gas and coal-derived gas[16−19]. The $\delta^{13}C$ values of ethane in Chuanyue 83 and Chuanyue 84 gas fields, beside Puguang gas field, are within the range of –29.21‰—–32.02‰, which show the characteristics of oil type gas. While the $\delta^{13}C$ values of ethane in Maobo gas field, north of Puguang gas field, is obviously heavy, –25.04‰ — –25.19‰, belonging to coal-derived gas. So from the $\delta^{13}C$ values of methane and ethane in these gases, we can deduce the conclusion that the natural gas has mixed origin.

Pyrobitumens can be extensively found in carbonate reservoir in all kinds of corrosion pores, dissolved fracture, limestone cave, crack, microcrack and suture, especially Fei 1 and Fei 2 reservoir strata. Pyrobitumens can be seen except on the top and base layers, which provides clear evidence for an early oil charge and subsequently thermal cracking at higher temperatures, and also confirms the contribution of oil type gas.

The H_2S gas is rich in the areas of carbonate and sulphate (containing gypse) sedimentation and there is H_2S in the Sichuan Basin[20−25]. The content of H_2S in the eastern Sichuan is tremendously different according to the statigraphy statistics. The content of H_2S in Carboniferous gas accumulation is less than 0.5%, while the content of H_2S of Feixianguan formation reaches 14%, and the Jialingjiang formation of lower Triassic and Permian is about 3%. The content of H_2S produced from the Feixianguan and Changxing formations is similar. So we can derive the conclusion that H_2S does not come from gas source rock, but from inside gas accumulation. There have been many discussions on the potential sources of H_2S in petroleum reservoirs[26−30], usually it is believed that H_2S generates from sulfate reduction, similar to the gas field with rich H_2S in other countries[31−36], and the reservoir is mainly carbonate and once went through high temperature.

3 The charging history of Puguang gas field

There are 3 suits of high quality source rocks in the northeastern Sichuan Basin[37], namely, the Lower Cambrian Jiulaodong formation (Є$_1$g), the Lower Silurian Longmaxi formation (S_1lm) and the Upper Permian Longtan formation (P_2l). Using basin modeling software and accumulation dynamics methods[38], and after modeling the generating history of Chuanyue 84 in Xuanhan area, northeast of Sichuan (Table 2), we found that Lower Cambrian hydrocarbon came into oil widow at Silurian, reached oil peak at the end of Middle Triassic and matured at Middle Jurassic. Silurian and Permian hydrocarbon reached oil widow at early and middle Early Triassic, reached oil peak at Early Jurassic, matured at late Middle Jurassic and early Late Jurassic and is mainly dry gas. From the evolution history of hydrocarbon and the sediment time of reservoir, the three suits of hydrocarbon were charged at Lower Triassic and the Silurian and Permian hydrocarbon should reach oil peak at Middle Jurassic. From the regional distribution of hydrocarbon, we found that Silurian and Permian hydrocarbon was mostly developed.

The reservoir inclusions mainly occurred in calcsparite, calcite arteries, and limestone quartz crystal and formed in the middle-late catagenesis time. After carrying out identification and making micro-measurement on temperature for the hydrocarbon fluid inclusions and the coexisting saline inclusions (Table 3), we have found that the organic inclusion homogenization temperature usually represented the lowest temperature when captured, that is the temperature of the hydrocarbon coming into reservoir, so the peak temperature represents the

Table 2 The simulation of generating hydrocarbon history of different strata in Xuanhan district

Section	Hydrocarbon strata	Hydrocarbon window	Oil peak	High maturity	Over maturity
Chuanyue 84 (Daxian-Zhihan)	$\in_1$g	S3	Late T_2	Early J_2	Middle J_2
	S_1lm	Early T_1	Early J_2	Early J_2	Late J_2
	P_2l	Middle T_1	Early J_2	Early J_2	Early J_3

Table 3 The fluid inclusion characteristics and oil and gas inclusion time of Puguang 2

Host mineral	Inclusion type	Color and shape	Homogenization temperature (℃)	Peak value (℃)	Freezing point (℃)	Salinity (%)	Capture depth (m)	Charging time
Early fracture calcite, granular calcite	liquid, solid	irregular light blue luminescence	100－120	110	–8.9－–9.4	12.86－13.30	3625	Late Indo-Chinese epoch-Early Yanshan Mountain
Late crystal stock calcite, calcite nerve limestone cave quartz	mainly liquid and solid, secondly liquid	rectangle, circular, ellipse and long ellipse	140－160	150	–3.3－–7.6	5.32－9.84	5292	Middle and Late Yanshan stage
Calcite nerve limestone cave quartz	mainly liquid and gas	long, circular, rectangle, irregular	170－210	190	–7.5－–8.0	11.10－11.70	6958	Xishan stage

fastigium of the oil migration. The saline inclusion homogenization temperature of Puguang 2 is wide, at the range of 96－215℃, and the homogenization temperature has two obvious dominant peaks and a second dominant peak, the temperature of the dominant peak is 100－120℃, averaging 110℃, the temperature of the second dominant peak is 140－160℃, averaging 150℃, and the third dominant peak is not obvious, at the range of 170－210℃. Combined with the inclusion phase state and salinity analysis under the microscope, three stages of hydrocarbon fluid should exist.

The first stage hydrocarbon inclusion mainly occurred in the early split calcite or granular calcsparite, and in liquid or solid state (bitumen inclusion). They have irregular shape and the homogenization temperature is at the range of 96－120℃, also the frequency value is high, and dominant peak is obvious, about 110℃, show- ing slight blue color with fluorescent light.

The second stage hydrocarbon inclusion mainly occurred in late crystal stock calcite, calcite arteries and limestone cave quartz crystal, and they are gas and oil biphase inclusions, showing rectangle, circular, ellipse and long ellipse shapes. And the homogenization temperature is at the range of 140－160℃. The frequency value is high, and dominant peak is obvious.

The third stage hydrocarbon inclusions mainly occurred in calcite arteries and limestone cave quartz crystal, and they are gas and oil biphase inclusions, showing circular, ellipse and long ellipse shapes. And the homogenization temperature is at the range of 170－210℃. The dominant peak is not obvious.

The salinity distribution characteristics of the inclusion also support the above idea. The mass fraction of NaCl of the first stage salinity inclusion is 12.9%－13.3%, and has centralized distribution. The mass fraction of NaCl of the second stage salinity inclusion is very wide, 5.32%—9.84%. The mass fraction of NaCl of the third stage salinity inclusion is 11.1%－11.7%.

Combining with the tectonic development history, the homogenization temperature and saline analysis, we conclude that there are at least 3 times of oil and gas charging. And the formation temperatures are 110℃±, 150℃± and 190℃ separately. On the basis of the above data, we usd the following formula to calculate burial depth:

$$H=(T_c-T_o)/G\times 100℃,$$

where T_c is the tested inclusion homogenization temperature, T_o is the temperature of the inclusion formation, where we take the normal year average temperature, 23℃, G is the paleogeothermal gradient, 2.4℃/100 m, H is the depth of the oil and gas accumulation. So we can see that the depth of the first transportation is 3625 m, that of the second one is 5292 m and that of the third one is 6958 m. Combined with the stata burial history of Puguang gas reservoir, we can estimate that the oil and gas inclusions occurred in Late Indo-Chinese epoch, Early Yanshan Mountain (T_3-J_1) and Xishan stages (Figure 2).

By synthesizing the above data, the gas accumulation history is got. From Late Indo-Chinese epoch to Early

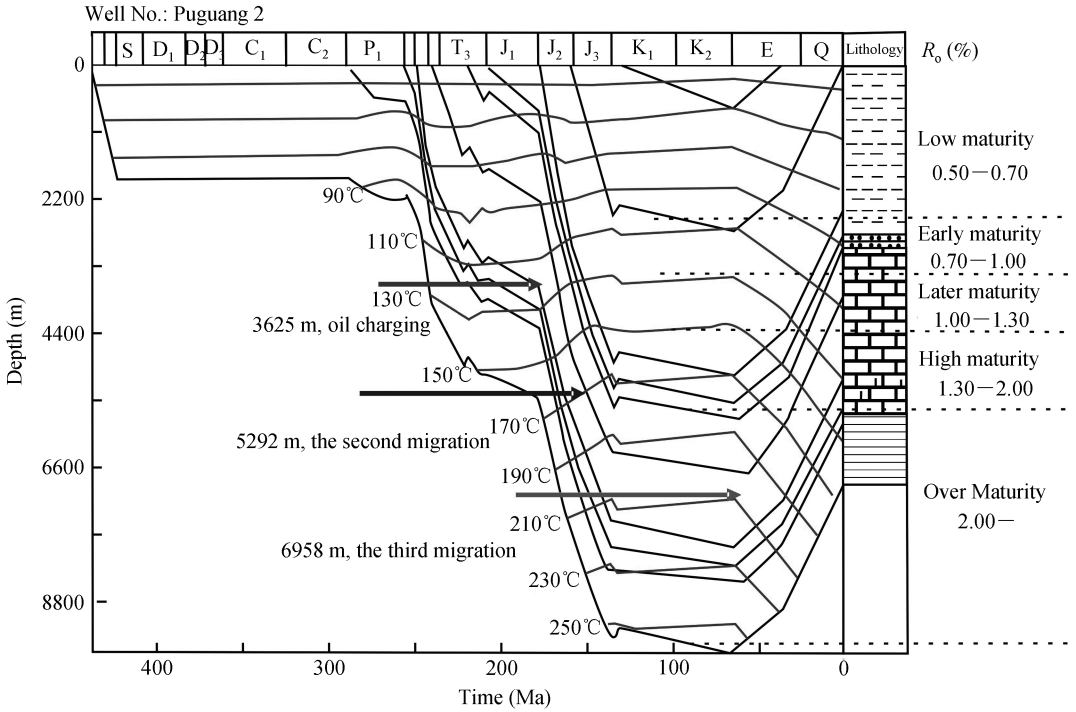

Figure 2 The accumulation history of Feixianguan gas field in Puguang.

Yanshan Mountain period, liquid hydrocarbon transported into paleo-oil accumulation, the liquid hydrocarbon came into gas hydrocarbon, crude oil cracked into gas and relic bitumen and there was the charging of coal-derived gas of Longtan formation of Permian at Middle Late Yanshan Mountain period. The modern structure-lithology complex gas reservoirs of mixed coal-derived gas and oil-cracked gas were formed at Xishan stage.

4 The main controlling factors of gas accumulation of Puguand gas field

(1) Palaeostructure is the important factor of controlling high quality reservoir and gas accumulation.

The Sichuan Basin has experienced polycyclic tectonic movement and deformation to form multiphase palaeostructure. This palaeostructure has important controlling function to the early accumulation. Puguang structure lies in the northwest upper slope of Kaijiang palaeohigh, which had a paleonose at the end of Middle Triassic and continued to develop until Early Yanshan stage. While it was the generating hydrocarbon peak time of Silurian and Permian, it is the profitable time for the early oil and gas accumulation.

The formation of large scale gas field needs good reservoir strata of good reservoir and permeability conditions. Changxing-Feixianguan formation is exposed shallows facies in the edge of tableland, which is favorable for the formation and development of reservoir and possesses the advantageous conditions of forming pores and holes of fresh water corrosion and mixing water dolomization[39 − 41]. The multiple corrosions are key factors to further optimize Puguang tectonic reservoir. The results of corrosion action are intercrystal pore, intracrystalline pore, intergranular pore, intragranular corrosion pores, foundry pore, and powder-fine dolomite with corrosion clastic texture (Figure 3). The corrosion pores, holes and seam promote the porosity and seepage of dolomite of Feixianguan formation, especially, the TSR process and the formed H_2S promote secondary porosity of deep carbonate reservoir[4,12,42], and also accelerate greatly the forming of large scale corrosion pores and holes. The formed intercrystal pore, intracrystalline pore, intergranular pore, intragranular corrosion pores, foundry pore are inner key factors of improving porosity and permeability of reservoir and the most important petrogenetic events.

The palaeostructure controls the early oil and gas accumulation, and the favorable tectonics controls the development of beneficial sedimentary facies. And the folding of the pores and holes reservoir and palaeostructure is the profitable area of searching for large

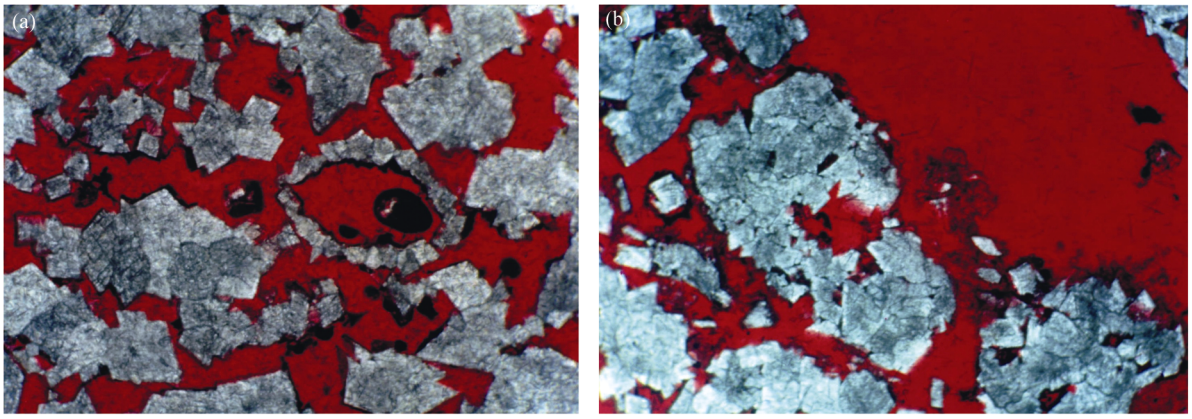

Figure 3 The microstructure characteristics of reservoir of Feixianguan formation in Puguang gas field (red cast represents pores and holes, and black cast represents reservoir bitumen). (a) 5090.70 m, remained macrocrystalline dolomite, porosity is 20.45%, permeability is 1816 md, intergranular corrosion porosity is 80%; (b) 5087.76 m, remained macrocrystalline dolomite, porosity is 16.5%, permeability is 864 md, and corrosion occurring the second time is strong.

scale gas field.

(2) The effective hydrocarbon and the deep cracking of old-oil reservoir are the most important factors of high production of Puguang gas field.

From the accumulation evolution history, the hydrocarbon of Silurian and Lower Permian began to mature at Late Indo-Chinese epoch and came into early mature stage at Early Yanshan Stage, and the hydrocarbon reached high mature stage and generated large amount of oil and gas at Middle Yanshan Stage. On the palaeohigh background, the structural trap turned into palaeo-oil accumulation, and the reserve was over 7.5×10^9 tons (the reserve of remained bitumen was 5×10^9 tons, 1 thousand kg bitumen resumes 1.5 oil). Bitumen can be found broadly in reservoir (Figure 3). The hydrocarbon reached over mature stage at Late Yanshan Stage. The present R_o is 2.5%—3.3%, so the hydrocarbon is already in middle and late over-mature stage. The oil generated earlier has been cracked into natural gas. The hydrocarbon with great depth and high organic abundance of Longtan formation developed fully in Puguang area. The two suits of hydrocarbon constitute the important material basis of the tremendous natural gas source of Puguang gas reservoir.

(3) The effective dredge is the key factor of transportation and gathering the natural gas of Puguang gas reservoir.

The reservoir lithology of Changxing-Feixianguan formation is a large suit of combination of grey-slight grey corrosion oolite dolomite and grey dolomite and limestone dolomite, mainly resided in oolite dolomite. The reservoir has great effective depth, good lateral distribution, good communication and is the chief channel of the parallel migration (Figure 4). Also the migration channel makes contributions to the connection of the lateral fault (Silurian-Permian), but this kind of abnormal fault did not cut the upper cap rock (Jianglingjiang formation, gypsum salt bed of Leikoupo formation). So the integrity of complex structural stratigraphic trap is a key factor to Puguang gas reservoir.

(4) The effective conserve conditions are the key factors of late adjustment and position of Puguang gas reservoir.

The gypsum salt fully developed in the second and fourth parts of Jialingjiang formation and the second part of Leikoupo formation and the gypsum salt has good plastic property, so under the structure press, it still has lateral continuance and good seal ability. According to the well drilling data, the gypsum remained relatively stable. The development of gypsum salt layers constitutes the integrated cap rock of Changxing-Feixianguan formation reservoir. There was formation water of $CaCl_2$ in northeastern Xuanhan-Daxian area, and rNa+/rCl-(0.77—0.91) and $rSO_4^{2-}\times102$/rCl-(0.45—1.28) are the lowest in the studied area, with perfect trapping condition, which constitute the safeguard against late accumulation of Puguang gas reservoir[43]. So the effective conserving condition is a key factor of controlling accumulation of natural gas of Puguang structure.

5 Conclusions

(1) Puguang gas field is the driest large scale gas field

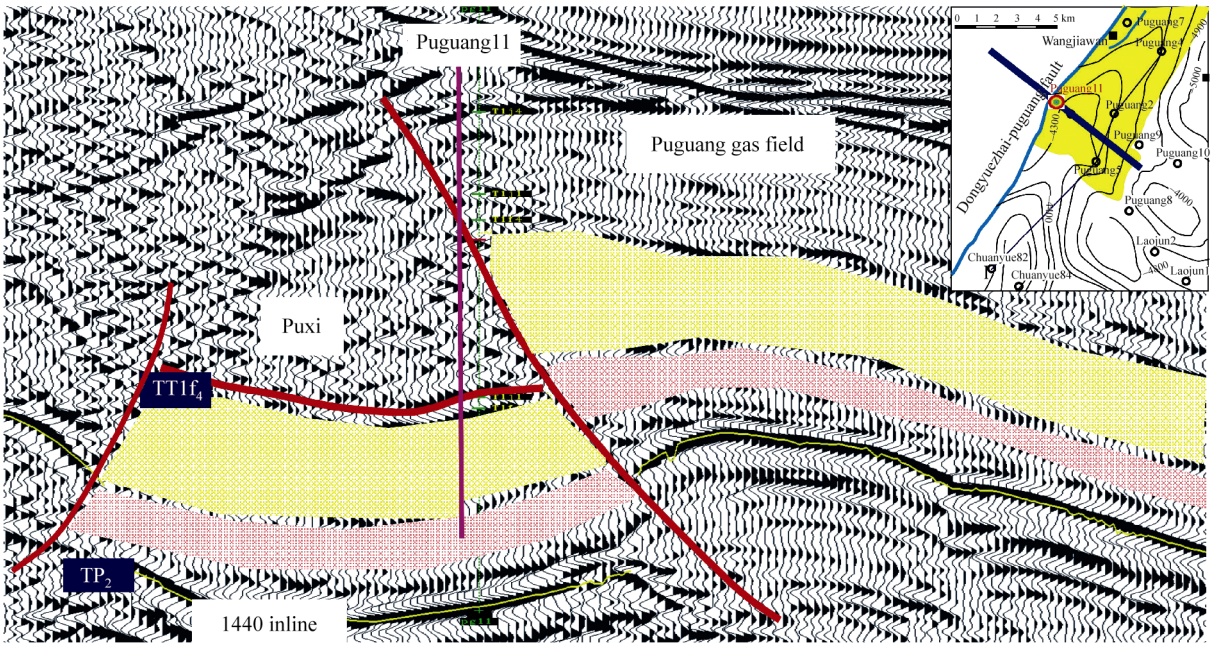

Figure 4 The composite dredge of relic oolite dolomite of the good fault and good connection.

with highest content of H_2S. The gas source is the coal-derived gas of Longtan formation of Upper Permian and oil-cracked gas of mud shale of Longmaxi formation of Lower Silurian.

(2) The charging history of Puguang gas field: At Late Indo-Chinese epoch-Early Yanshan stage, liquid hydrocarbon transported into paleo-oil accumulation, was deeply buried at Middle and Late Yanshan stage, and the liquid hydrocarbon cracked into gas and relic bitumen and there was the charging of coal-derived gas. The modern structure-lithology complex gas reservoirs of mixed coal-derived gas and oil cracked gas formed at Xishan stage.

(3) Favorable palaeostructure, valid hydrocarbon development, high quality dredge and effective conserve condition are the main controlling factors of Puguang large scale gas field.

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