Geological Conditions for Upper Paleozoic Shale Gas Enrichment in the Ordos Basin, China*

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Abstract

The Ordos Basin is one of the largest basins in terms of natural gas resources. It is demonstrated that dark shales rich in organic matters are highly developed in Carboniferous, Permian, and Triassic horizons. Among them the Carboniferous-Permian shales are most excellent and are even better in shale gas potential than many marine Paleozoic shales in south China. Those conditions include:

1. Extensive distribution of dark shales. The Carboniferous-Permian shales, occur in the Benxi, Taiyuan, and Shanxi Formations, are nearly basin-wide. Their thickness ranges from 30 m to 300 m, with thickest deposition occurring in the western part of the basin and thinnest in the east.

2. High content of organic matter and appropriate thermal maturity. Deposited in marine to continental coal-bearing settings, the shales are rich in organic matter and their TOC ranges from 2.25% to 3.33%, bitumen “A” from 0.037% to 0.12%, and HC from 163.76 to 361.6 ppm. Their kerogens are dominated by type III and thus are favorable for gas generation. Thermal maturity is mostly in the range of 1.0 to 2.8% Ro, with most parts of the basin reaching thermal maturity greater than 1. 3% Ro.

3. Unique preserving condition. Owing to three factors, preserving condition for shale gas enrichment is extraordinary and unparallel compared with other regions in China, particularly for south China shales.

4. Medium to shallow burial depth. The upper Paleozoic shales are buried shallow in the east and modest in the west part of the basin. With respect to the buried depth on the bottom of Shanxi Formation, it is less than 2800 m in the east part, with a minimum depth of about 2300 m in the eastern margin.

5. Abundant resources of natural gas and co-existence of shale gas with tight gas and coalbed methane. The Ordos Basin is confirmed being extremely abundant in natural gas and most of the gas resources are unconventional, of which tight gas, coalbed methane as well as possibly shale gas are all of great potential. These unconventional gases are co-existed and interbedded so closely in the Carboniferous-Permian strata that they can be explored and exploited simultaneously.

Selected Reference

Zhang, Z., X. Yuan, Y. Chen, X. Tian, R. Kind, X. Li, and J. Teng, 2010, Seismic signature of the collision between the east Tibetan escape flow and the Sichuan Basin: Earth and Planetary Science Letters, v. 292, p. 254-264.

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1. Introduction

Inspired by the huge success of shale gas exploration and development in North America, investigation of shale gas resources have been kicked off in China recently and the interest of being involved in the activity is rapidly increasing. But current studies and other pilot exploration work are almost all focused on the marine shales in south China, leaving their non-marine counterparts in north China including the Ordos Basin being nearly neglected.

Nevertheless, our work shows that black shales rich in organic matters are highly developed in the Ordos Basin and Carboniferous, Permian and Triassic are their main occurring horizons. Among them the Carboniferous-Permian shales are the most potential and are even more advantageous than many marine Paleozoic shales in south China in terms of basic conditions for shale gas accumulation.

2. Geological Conditions of Shale Gas in the Ordos Basin

Preliminary investigation suggests that 6 factors make the Ordos Basin extremely favorable for gas accumulation in Upper Paleozoic shales. They are:

2.1 Widespread Distribution of Shales

2.2 High Content and Gas-prone Type of Organic Matter

2.3 Medium to Shallow Burial and Medium to High Thermal Maturity

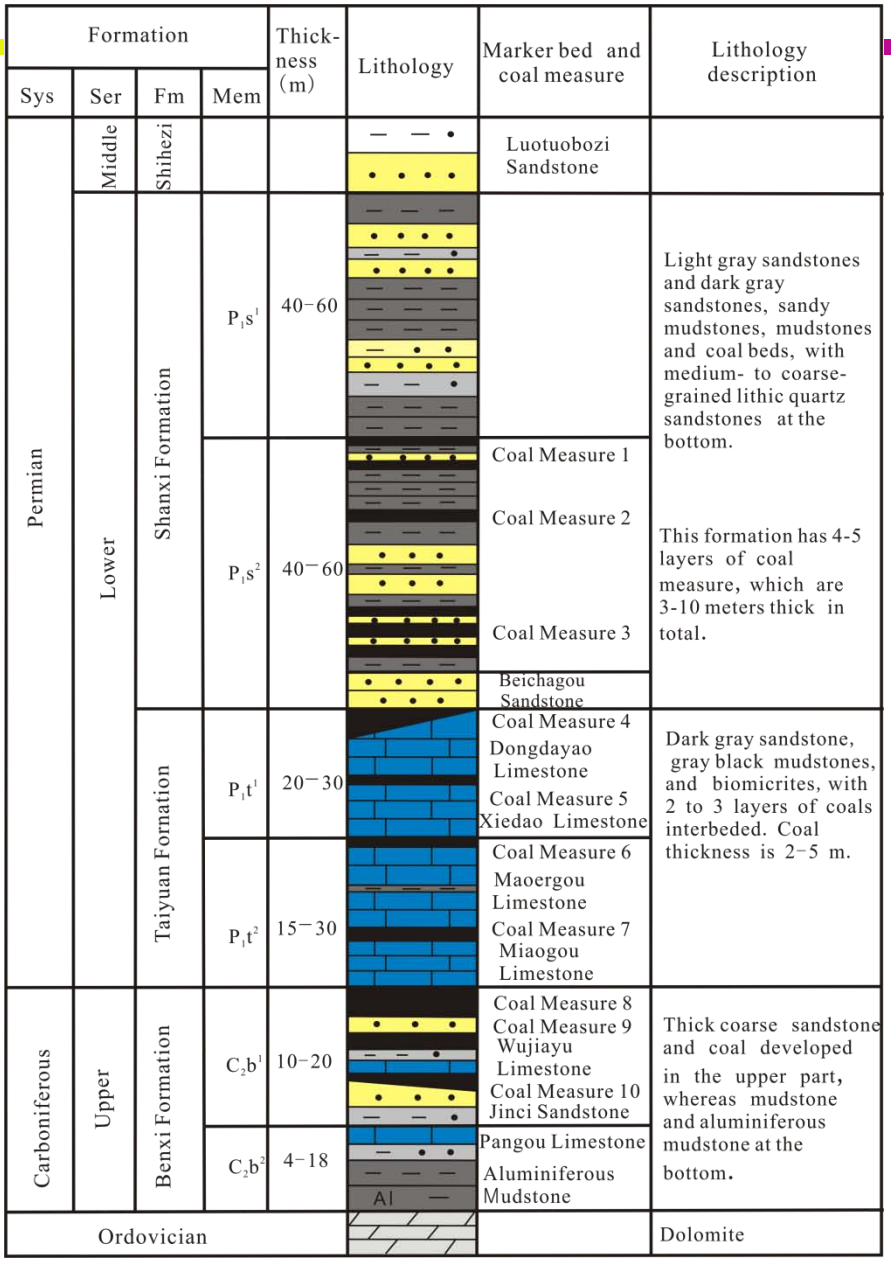
2.4 Various Reservoir Conditions and Strong Heterogeneity

2.5 Excellent Condition of Preservation

2.6 Abundant Natural Gas Resources and Co-existence of Tight gas, Coalbed Methane and Shale Gas

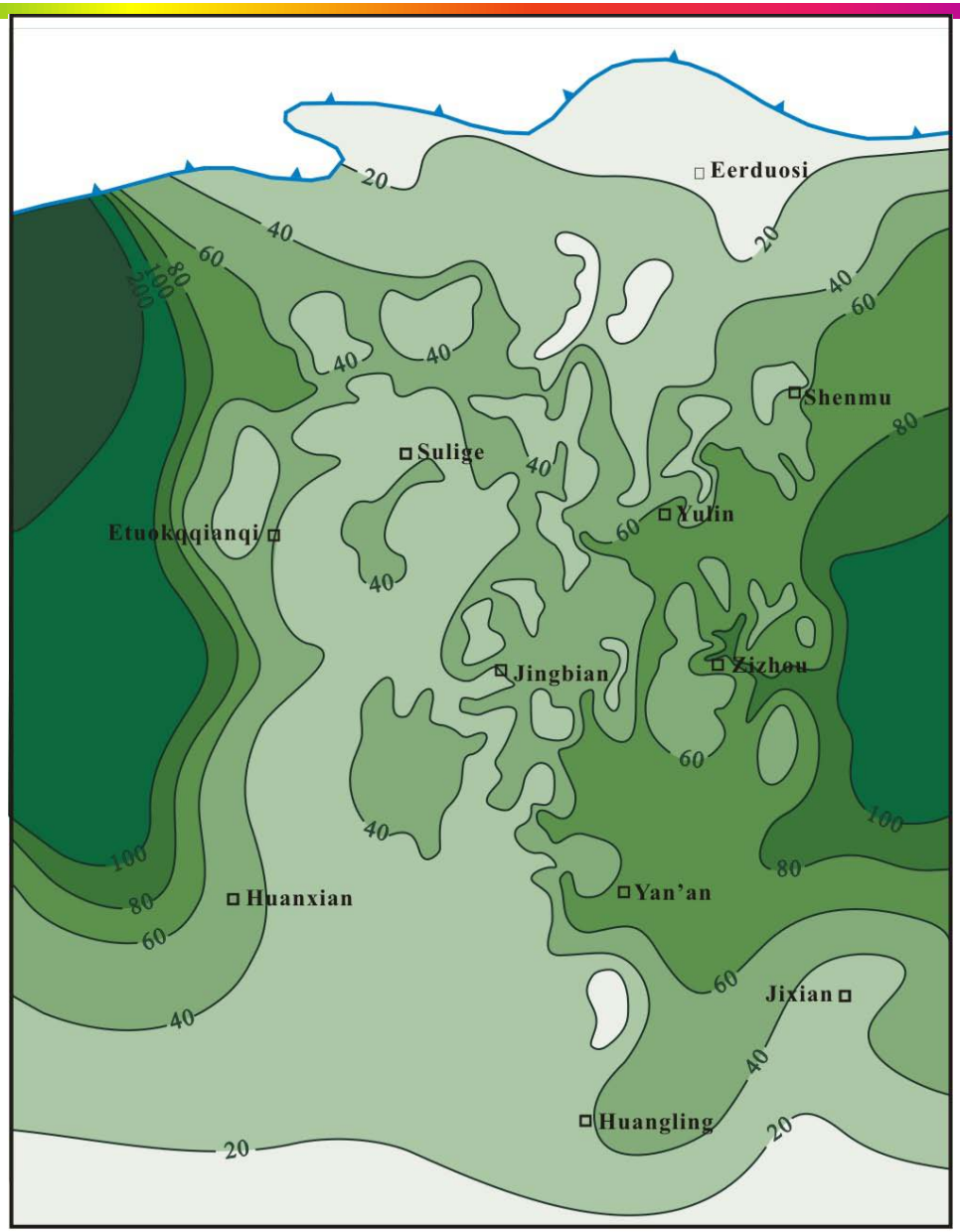
2.1 Distribution of Black shales

The Carboniferous-Permian black shales, occurred in the Benxi, Taiyuan and Shanxi formations, are nearly basin-wide. Their thickness mostly ranges from 30m to 100m and increases from the central part toward both east and west direction, with maximum thickness occurred in the west margin of the basin, Thickness of single shale bed is commonly 30-40m and even greater if coals interbedded with the shales are taken into consideration together.



2.1 Distribution of Black shales

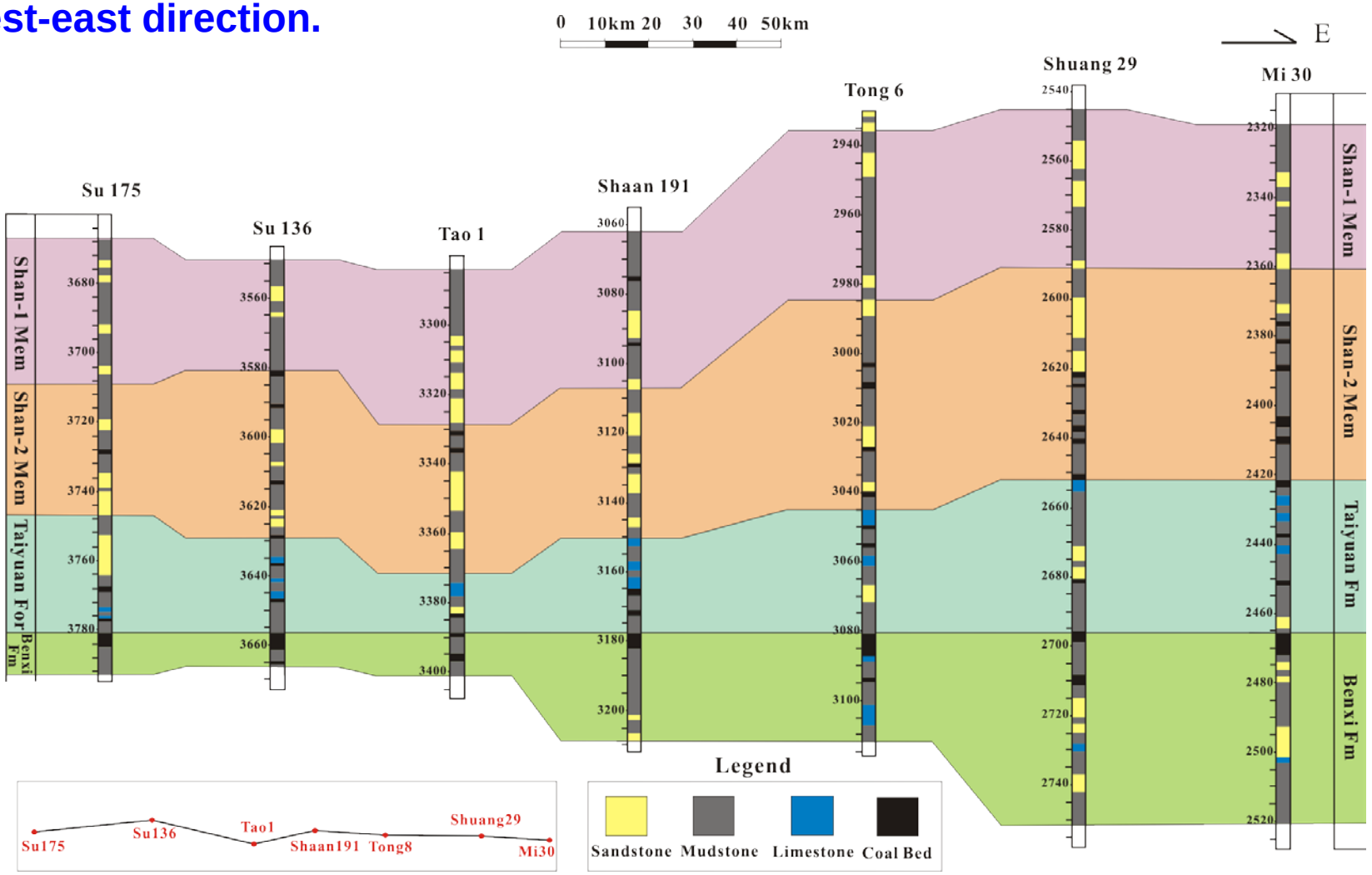
From the isopach of Upper Paleozoic black shales we compiled based on 840 wells, it can be observed that black shales are widely deposited across the basin and thicken from the central part toward both east and west flanks of the basin.



Isopach of black shales in the Upper Paleozoic formations of the Ordos Basin

2.1 Distribution of Black shales

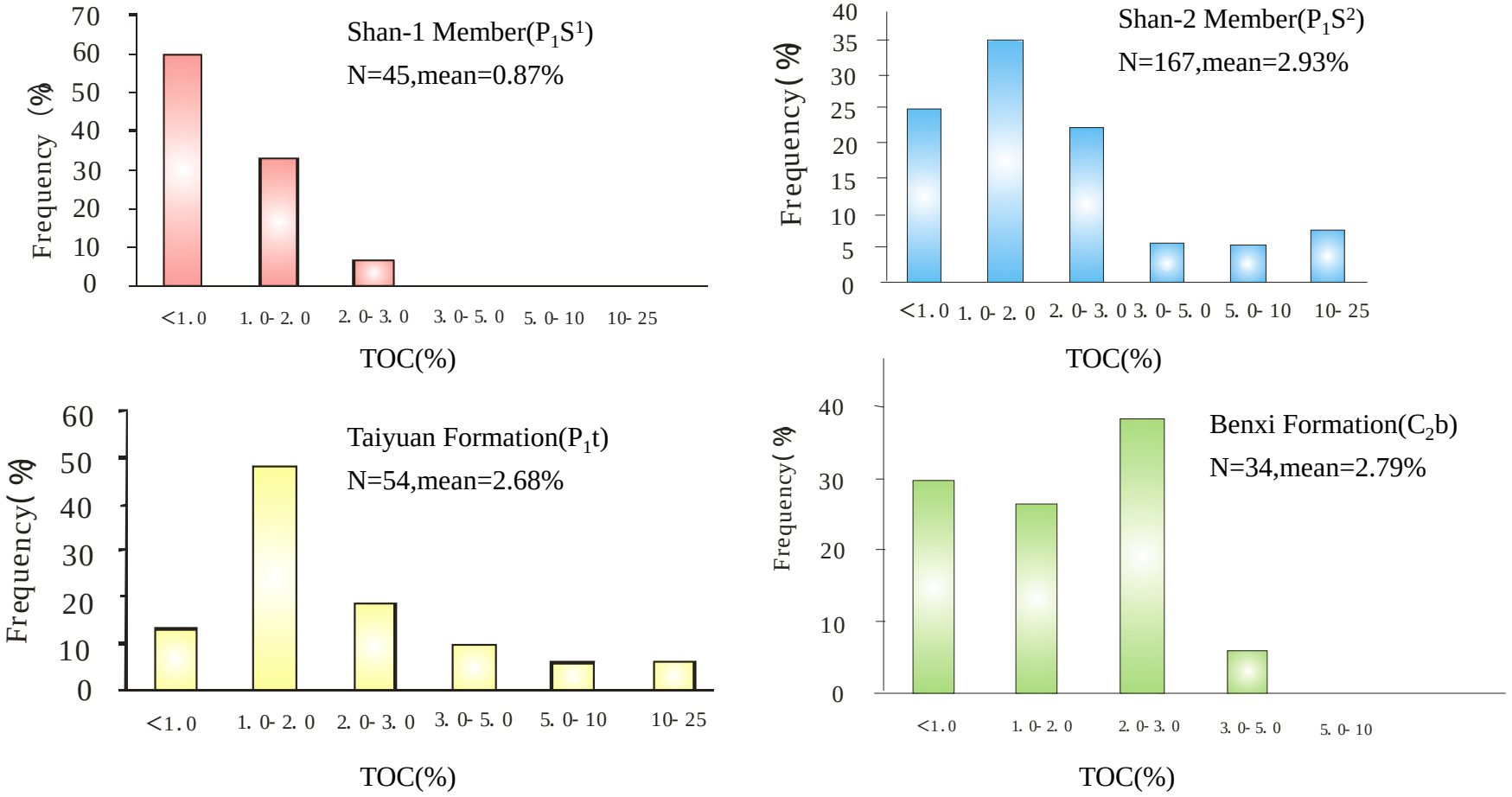
The thickening of black shales is mostly due to that of the Benxi Formation, which can be observed clearly from the stratigraphic correlation profile of west-east direction.



A west-east profile showing occurrence of black shales and coals in Upper Paleozoic formations of the Ordos Basin

2.2 Abundance and type of Organic Matter

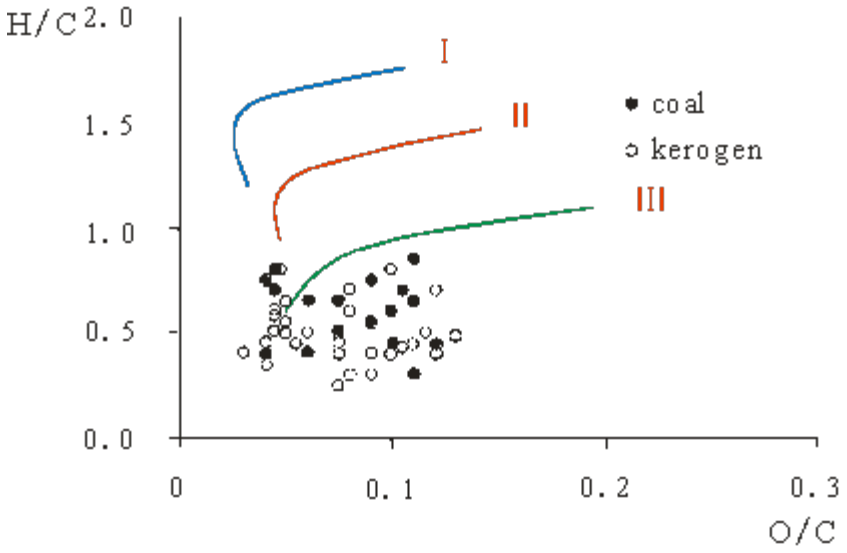
The black shales are rich in organic matter, especially those from Benxi, Taiyuan and Shan-2 Member of Shanxi Formation. The mean TOC of those shales ranges from 2.68% to 2.93%. But no abundant organic matter is observed in the Shan-1 black shales, the mean TOC of which is only 0.87%.



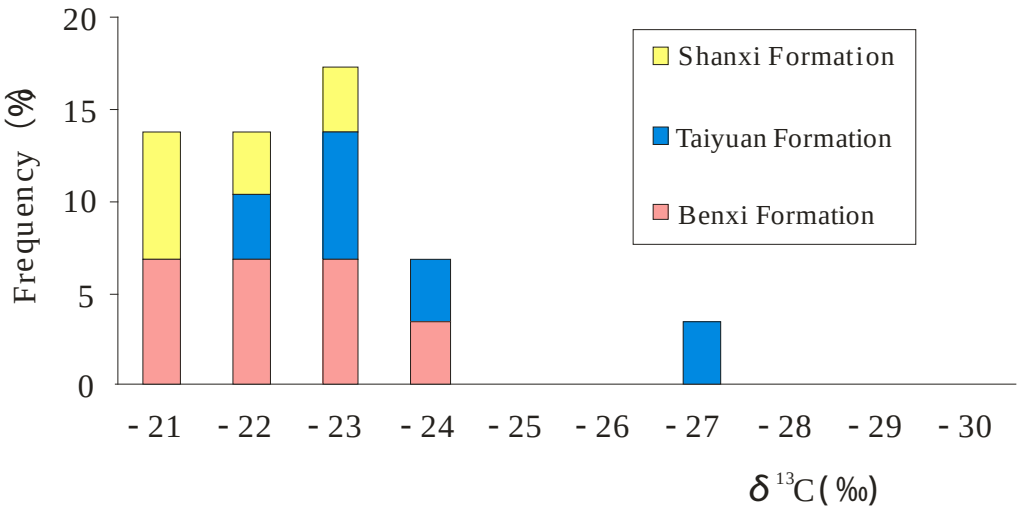
Frequency distribution for TOC of Upper Paleozoic shales

2.2 Abundance and type of Organic Matter

The organic matter is primarily type Ⅲ, which is favorable for gas generation and therefore a fundamental basis for shale gas accumulation.



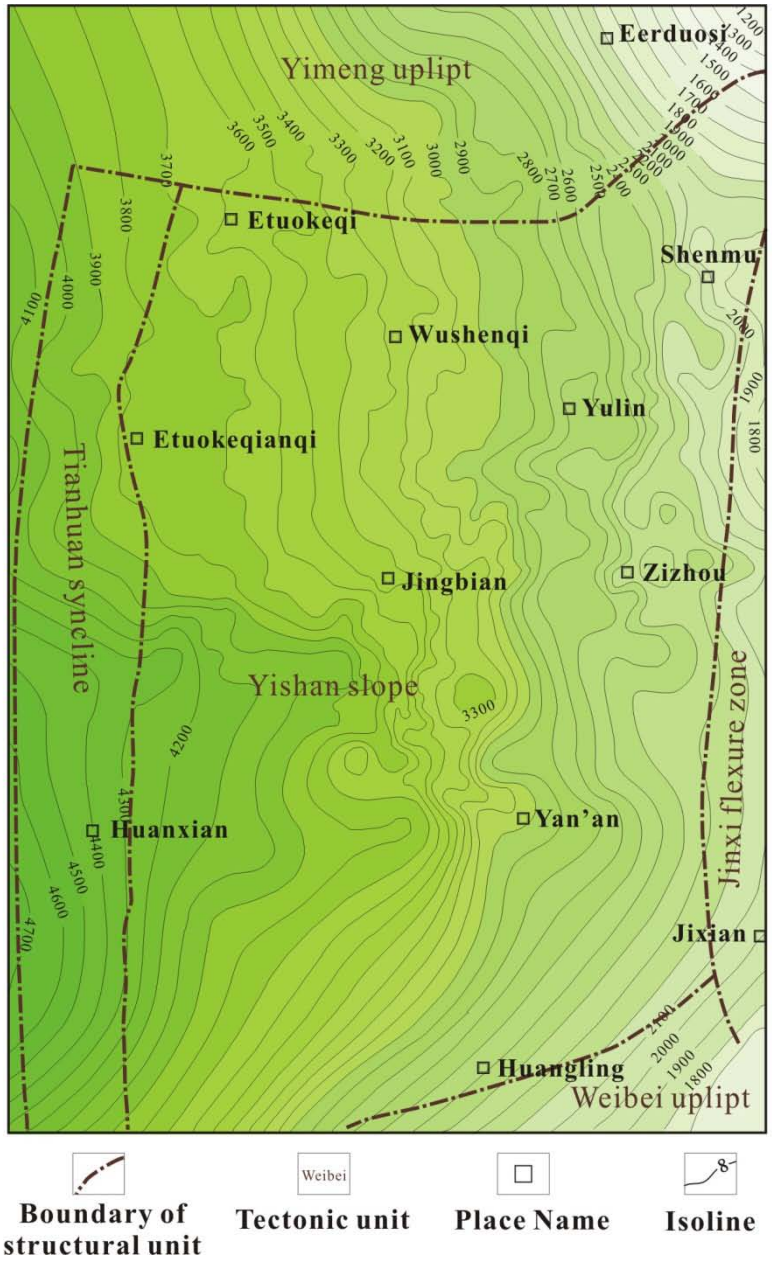
Composition of elements for shale kerogen and coals of Upper Paleozoic



Frequency distribution for $\delta^{13}C$ of kerogens from Upper Paleozoic shales

2.3 Burial Depth and Thermal Maturity

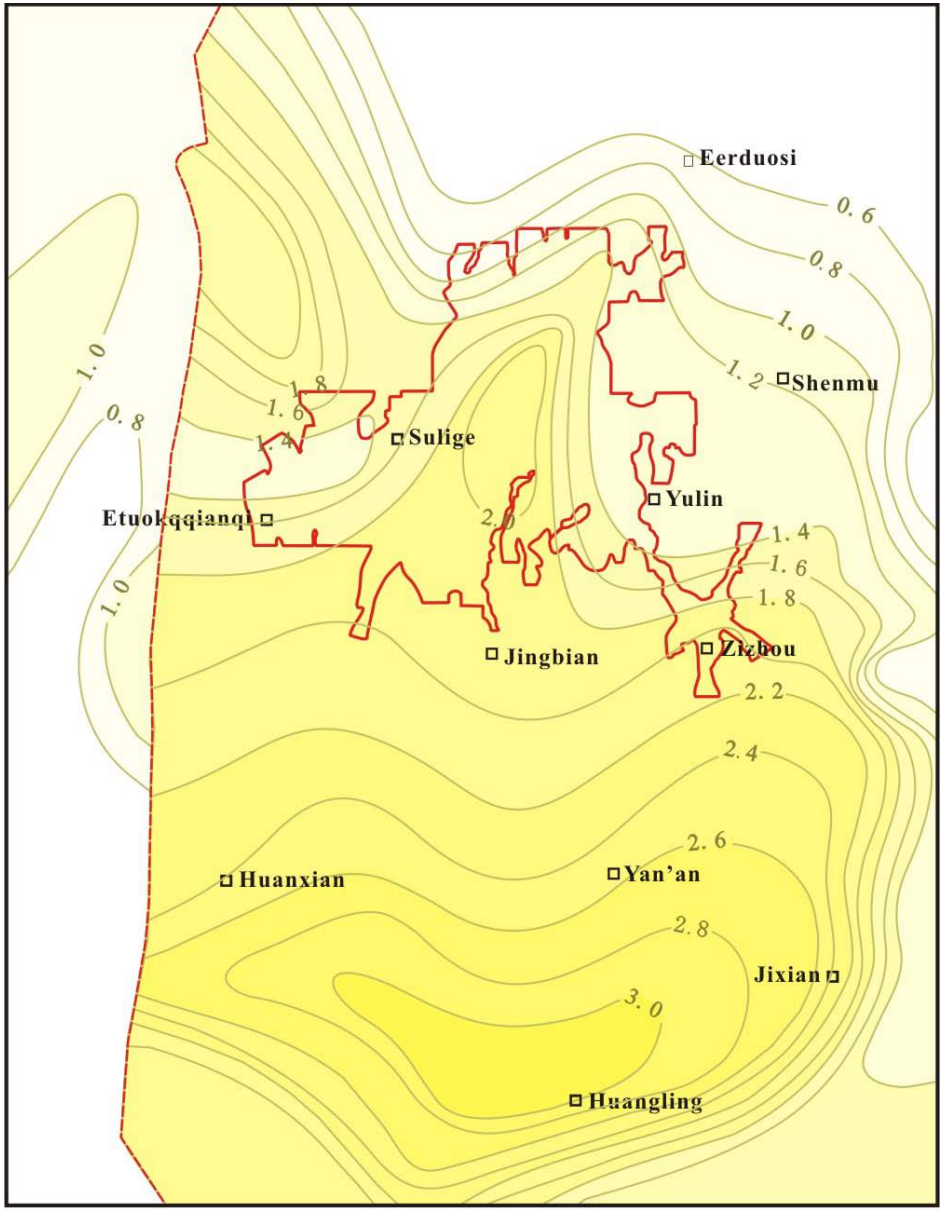
The Upper Paleozoic shales are buried shallow to medium in depth, with eastern part of the basin being shallow and west margin medium in burial. With respect to the buried depth of the bottom of Shanxi Formation, it is observed to be less than 2800m in the east part, with a minimum depth of about 2300 m in the eastern margin, and to vary from 2800 m to 3800 m in the central part, whereas in the Tianhuan Depression it is buried more than 3800m in depth. As a consequence, the search for shale gas should be focused on the east part of the basin at first.



Map showing the burial depth of the bottom of Shanxi Formation in the Ordos Basin

2.3 Burial Depth and Thermal Maturity

Thermal maturity is also favorable and mostly in the range of 1.0 to 2.8% Ro. The highest Ro locates in the southern part, where Ro is as high as 3.0% or more. From there thermal maturity decreases toward north and east and west flanks of the basin. But most part of the basin has reached thermal maturity greater than 1. 3 % Ro.

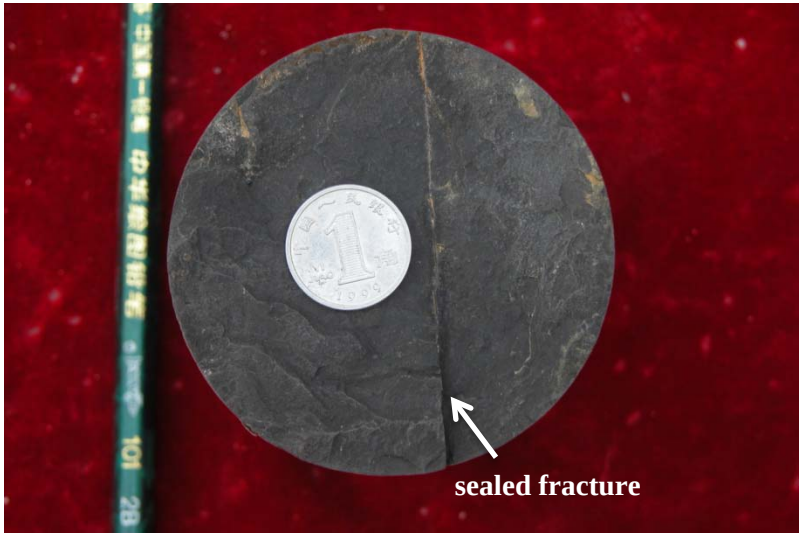


Distribution of Ro of Upper Paleozoic source rocks (Changqing Oilfield, 2010)

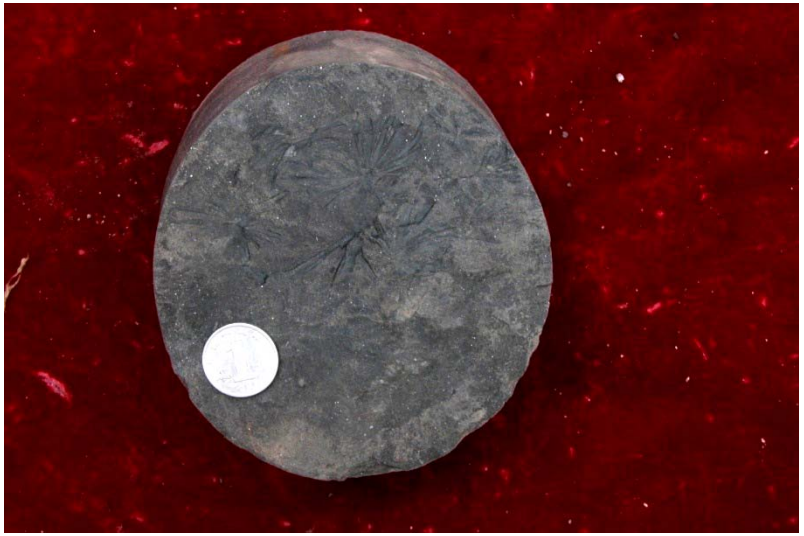
2.4 Reservoir Condition

Mi 10: Shaanxi Fm, 2278.4m. Dark mud with carbonized plant

Shen 12: Shaanxi Fm, 2507.8m. Shale with carbonized plant



Zhou 5: Shaanxi Fm, 2385.2m. Dark mud with sealed fracture

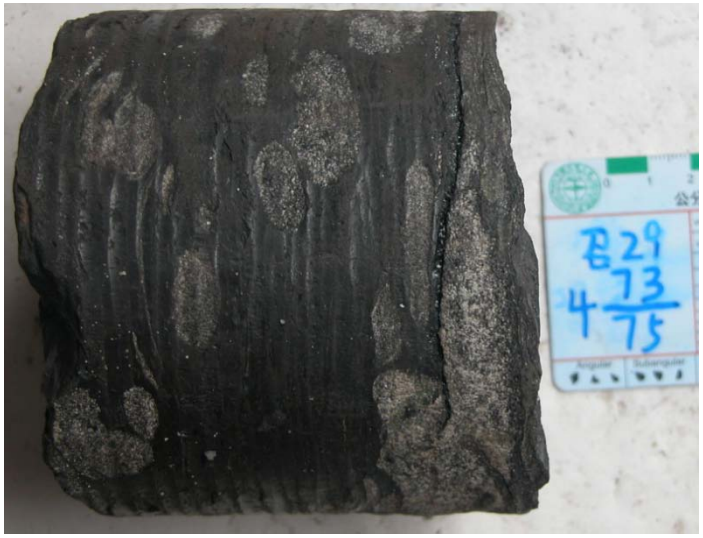


Yu 82: Shaanxi Fm, 2732.8m. Shale with carbonized plant

2.4 Reservoir Condition

Su 61: Shaanxi FM, 3703.8m. Shale with coal line

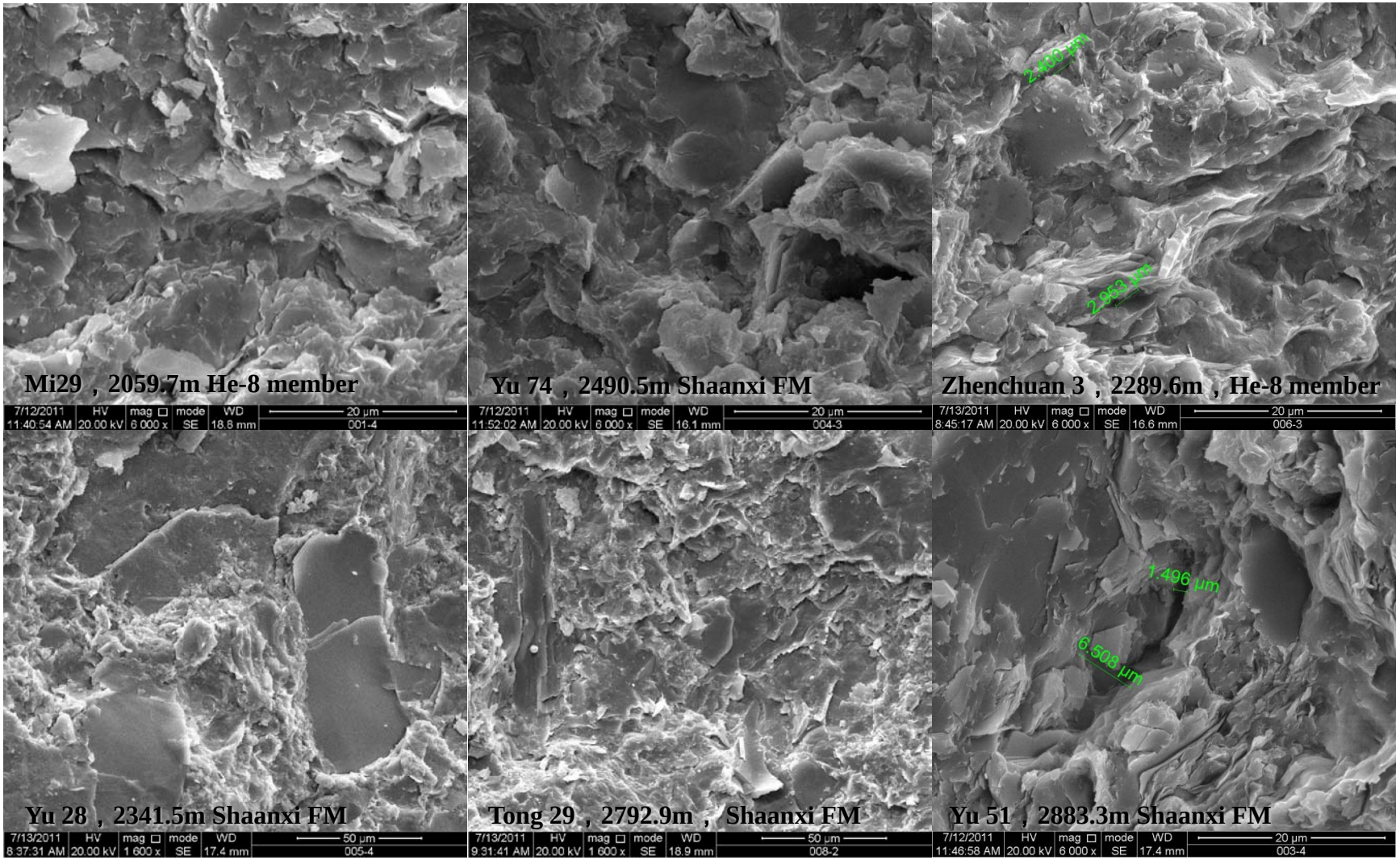
Su 53: Taiyuan FM, 3377.2m. Shale with carbonized plant



2.4 Reservoir Condition

Well	Depth/m	Horizon	Lithology	Clay mineral %	Quartz %	Feldspar %	Calcite %	Pyrite %
Mi-29	2059.7	He-8	black shale	43.9	56.1			
Shuang-11	2246.5	He-8	black shale	61.3	36.7			2.0
Yu-51	2883.3	He-8	black shale	64.9	35.1			
Yu-74	2490.51	He-8	black shale	59.1	40.9			
Yu-28	2341.45	He-8	black shale	65.9	32.9		1.2	
Zhenchuan-3	2289.6	He-8	black shale	45.9	51.6	0.9	1.6	
Tai-4	2671.01	He-8	black shale	71.2	28.8			
Tong-29	2792.9	He-8	black shale	54.2	45.0	0.8		
Yan-288	2603.4	He-8	black shale	65.2	30.7			1.4
Yan-272	2555.1	He-8	black shale	71.8	28.2			
Yan-272	2587.6	He-8	black shale	66.5	33.5			
Shi-209	2632.93	Shan-1	black shale	73.1	26.9			
Yan-288	2683.7	Shan-1	black shale	72.4	27.6			
Shi-7	2565.1	Shan-2	black shale	75.9	24.1			
Shi-209	2696.55	Shan-2	black shale	76.1	23.9			
Yan-272	2745.2	Benxi	black shale	79.1	4.2			16.7
Shi-8	2688.5	Benxi	black shale	95.3	0.9	2.7		1.1

2.4 Reservoir Condition



The pore configuration of Upper Paleozoic Shales shows slightly developed microporosity revealed by SEM.

2.4 Reservoir Condition

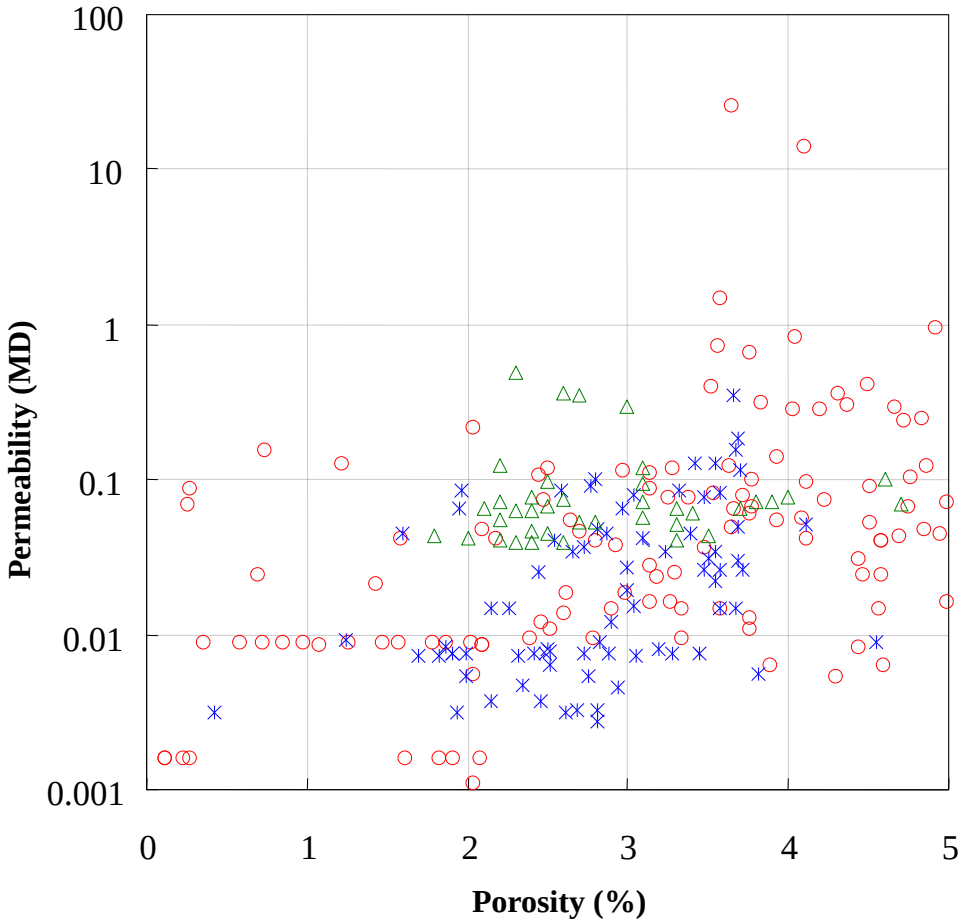
Tests of hundreds of samples reveal that porosity and permeability of Upper Paleozoic shales varies greatly in a given region, showing the shales are highly heterogeneous at local scale. The average values of the the Yulin, Sulige and Yanchang regions, however, remain relatively consistent, suggesting the shales are regionally homogeneous to some extent at basin scale.

Porosity and permeability of Upper Paleozoic shales from the Ordos Basin

Region	Number of samples	Porosity (%)			Permeabilty (mD)		
		Max.	Min.	Mean	Max.	Min.	Mean
Yulin	140	0.29	5.08	2.98	0.001	26.358	0.093
Sulige	118	0.43	4.55	2.58	0.001	4.670	0.076
Yanchang	125	0.98	5.06	2.96	0.01	1.48	0.079

2.4 Reservoir Condition

From the cross plot of porosity and permeability, it can be seen that relation between them is basically positive, but the correlation is not high, showing strong heterogeneity exists in the Upper Paleozoic shales.



Cross plot of porosity and permeability of Upper Paleozoic shales from the Ordos Basin

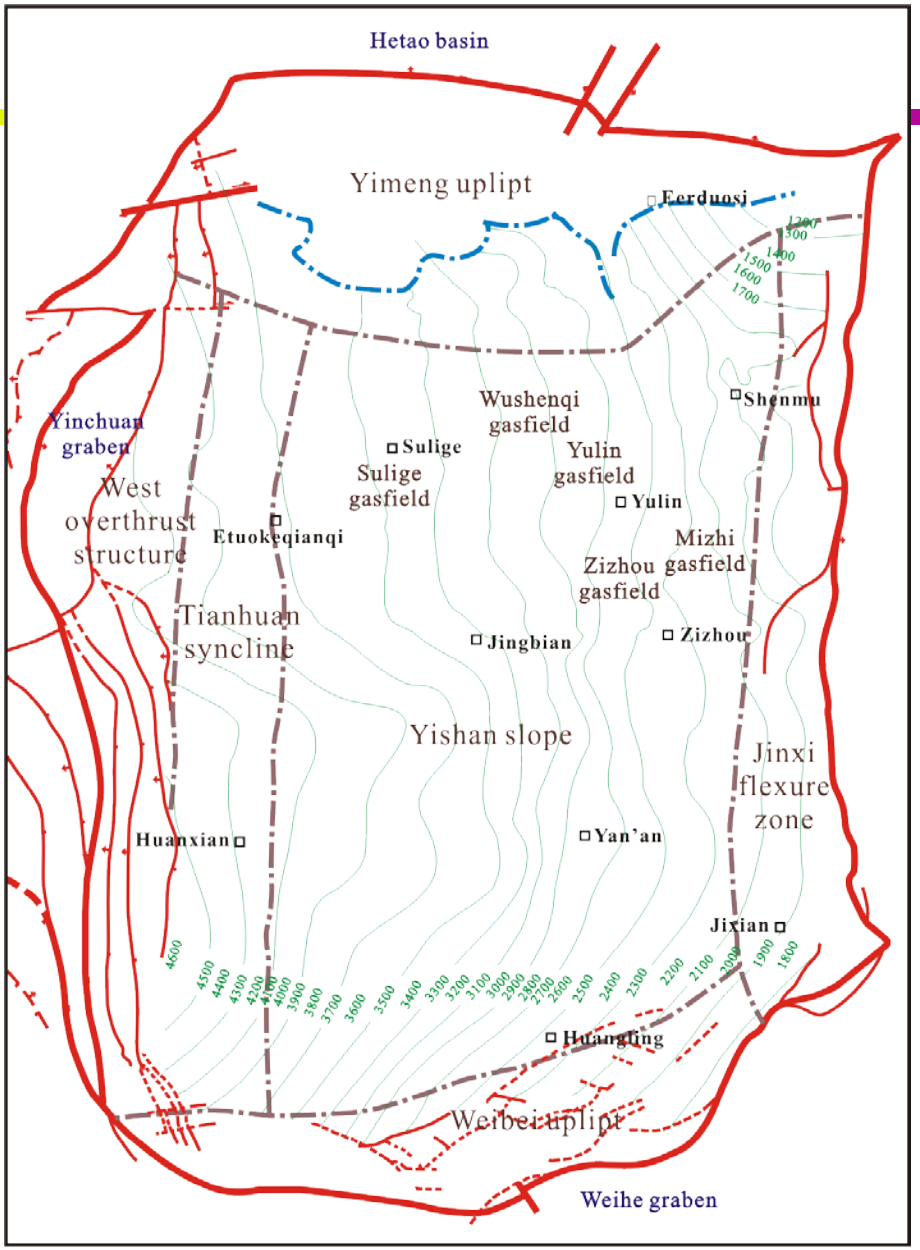
2.5 Condition of Preservation

Owing to three factors, preserving condition for shale gas enrichment is extraordinary .

□The Ordos Basin is the most stable block in China in terms of tectonic movement, and its principal part displays a simple westward-dipping monocline without folds and faults developed.

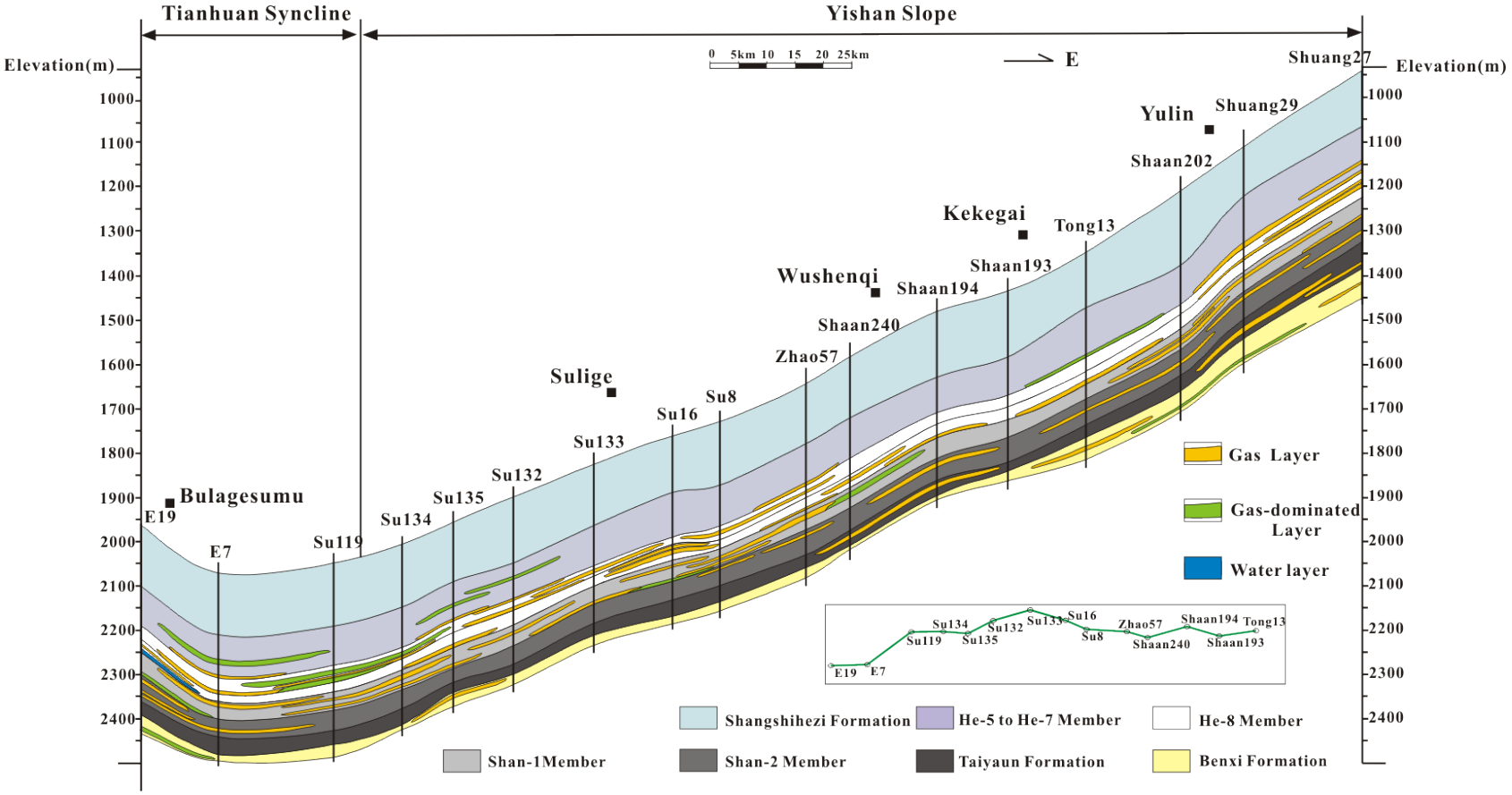
□ Cap rocks are also developed in the Upper Paleozoic shale-bearing formations, with thickness in the Shangshihezi Formation being more than 80m.

□ Rocks overlying and underlying the shales are either tight sands or coal beds, which can serve as excellent top seals and bottom seals for shale gas abundance.



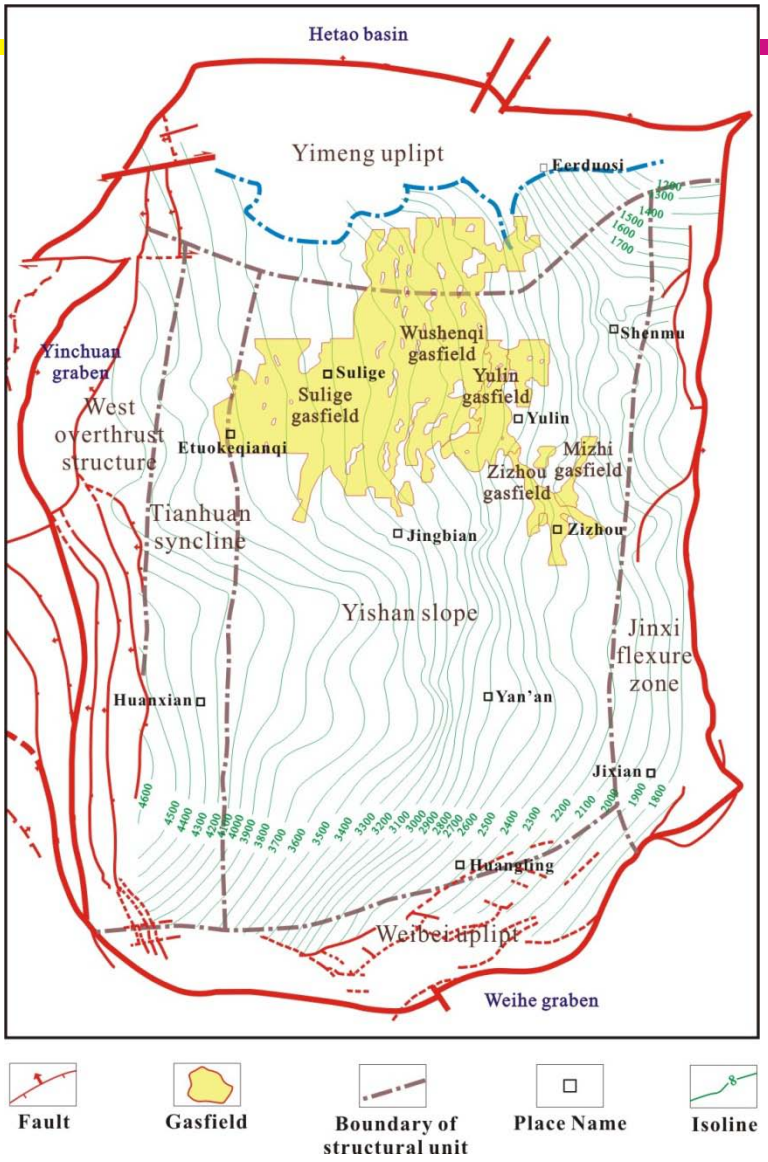
Contour map showing structure of the bottom of Upper Paleozoic, the Ordos Basin

2.5 Condition of Preservation



2.6 Co-existence of Shale Gas, Coalbed Methane and Tight Gas

The Ordos Basin is demonstrated to be one of the most abundant basins in China in natural gas resources. According to the recent resource evaluation, the basin hosts $10.7\times10^{12}m^3$ gas of prospective resource, most of which are tight gas. By 2010, 5 giant tight gas fields, namely the Sulige, Wushenqi, Yulin, Zizhou, and Daniudi, from Carboniferous and Permian with proved reserves of more than $1000\times10^{8}m^3$ each have been discovered, of which the Sulige is the largest in China and $1.10\times10^{12}m^3$ proved reserves of tight gas have been found out in this field. In 2010, over $100\times10^{8}m^3$ gas was produced from the Sulige.



Distribution of large tight gas fields of Upper Paleozoic in the Ordos Basin

2.6 Co-existence of Shale Gas, Coalbed Methane and Tight Gas

Besides, Coalbed methane is also abundant in the Ordos Basin. The resource in place and technically recoverable resource of coaled methane in Upper Paleozoic are estimated to be $3.27\times10^{12}m^3$ and $1.15\times10^{12}m^3$, respectively (Zhang et al., 2010), which is probably a conservative estimate.

In conclusion, tight gas, coalbed methane and, presumably, shale gas as well are all abundant in the Ordos Basin so that the basin can be regarded as a "museum" of unconventional gas resources. Since those three kinds of unconventional gases are associated in the Upper Paleozoic formations, they can be co-developed to achieve maximum economic benefit, which is an other favorable factor for shale gas exploration and exploitation in the Ordos Basin.

3. Comparison with Shale gas from South China

3.1 Common characters

Black shales are widespread and rich in organic matter .

3.2 Difference

- Black shales in south China are mostly marine deposition and their organic matter is commonly type Ⅰ and type Ⅱ. In the Ordos Basin, however, black shales of either Upper Paleozoic or Mesozoic are all terrestrial sediments and the organic matter of Upper Paleozoic shales is primarily type Ⅲ.
- Thermal maturity of the marine shales in south China is generally too high and reaches over-maturity in most part of the region, where Ro is widely greater than 2%. But in the Ordos Basin, the Upper Paleozoic shales remains at the stage of medium to high maturity, which is believed to be more favorable for shale gas enrichment.

3. Comparison with Shale gas from South China

- **Shales in south China Paleozoic formations have suffered strong tectonic movement and structurally deformation so that the preservation condition for shale gas accumulation is supposed to be unfavorable. On the contrary, the Ordos Basin is distinguished by rather stable tectonic movement and unparallel preservation condition for hydrocarbon accumulation, which is surely an other advantageous factor for shale gas accumulation.**

From the above analysis, it can be concluded that conditions for shale gas accumulation in Upper Paleozoic of the Ordos Basin are excellent. Consequently, shale has investigation and exploration should be paid more attention henceforth.

4. Conclusion and Proposals

- **Upper Paleozoic black shales in the Ordos Basin are mostly deposition of terrestrial facies. They are extraordinarily favorable for shale gas exploration due to their widespread distribution, high content of organic matter, medium to high thermal maturity, excellent preservation as well as appropriate burial depth.**
- **The Ordos Basin hosts an unusually large amount of unconventional natural gas resources including tight sand gas, coalbed methane and presumably shale gas. Owing to close association with other two categories of unconventional gas in the Upper Paleozoic, shale gas exploration and development can be taken into consideration when to explore for and develop tight gas and coalbed methane therein to make the profit maximization.**

4. Conclusion and Proposals

- Up to now, activities of shale gas exploration and development , whether in North America or in South China, have been largely focused on marine formations characterized by type Ⅰ and type Ⅱ organic matter. The criteria used for shale gas evaluation are also principally derived from those of marine shales in North American. But black shales in Upper Paleozoic formations of the Ordos Basin are widely terrestrial deposition and rich in organic matter of type Ⅲ. For this type of shales, little study has been done on their condition and mechanism of accumulation and no mature standards can be applied to the evaluation of resources and selection of exploration target. Thus, we suggest to strengthen the research work on accumulation conditions and evaluation criteria for shale gas of terrestrial origin to help promote shale gas exploration and development in the terrestrial basins like the Ordos Basin.

5. Acknowlegement

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- Petrochina Research Institute of Petroleum Exploration and Development.
- Research Institute of Exploration and Development, Changqing Oilfield Company, Petrochina.
- Co-authors: Cao, Bai, and Fan.