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An analysis of the types and distribution characteristics of natural gas reservoirs in China

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Abstract: The natural gas reservoir beds of different areas in China can be divided into three kinds, clastic natural gas reservoir bed, carbonate natural gas reservoir bed and special natural gas reservoir bed. They have different combination patterns controlled by deposition, diagenesis and tectonism. Our analysis indicates that the natural gas reservoirs are mainly distributed in the Precambrian, Palaeozoic, Mesozoic, and Tertiary-Quaternary. Craton basin, foreland basin and intracontinental rift basin which contain most of natural gas in China have special geological features and favorable accumulation conditions, and will be important exploration areas in the future.

Key words: Natural gas, clastic reservoir, carbonate reservoir, gas-bearing basin, China

1 Introduction

In the 21st century, the natural gas industry in China has developed quickly, and has entered a stage of rapid increase of proven gas reserves (Zhang, 2004; Dai, 2005; Zeng et al, 2007a). Through the study on the Sichuan Basin, Ordos Basin, Tarim Basin, Qaidam Basin, Junggar Basin, and Songliao Basin, China has made great breakthroughs in natural gas discovery, which is attributed to the change of exploration concepts (Song and Liu, 2008a), the finding of several natural gas fields (Zhao et al, 2005; 2006a; 2006b; Li et al, 2006; 2007a; 2008; Song and Liu, 2008b), and the progress of Chinese natural gas geology and subtle reservoir exploration technology (Dai et al, 2005; Fu et al, 2004; Li et al, 2006; Song et al, 2004; Zhao et al, 2007a; 2007b; Zhu et al, 2007a; 2007b). In contrast to the development of natural gas exploration in foreign countries, the exploration for natural gas in China is still in the early stage. The average discovery degree of natural gas resources is only 10% (Li et al, 2005; 2008) and the degree of exploration is the same as the level of USA in the 1930s, namely, a period of fast increase of reserves. It is forecasted that the natural gas reserves of China will be increasing gradually (Jia et al, 2002; 2007; Jia and Chi, 2004; Li et al, 2007b). Besides the proven gas-bearing basins, some new target areas are determined (Zhao et al, 2006c; Men et al, 2006). Supported by the CNPC Innovation Foundation program of "Natural gas reservoir forecast based on the theory of petrophysics facies", the authors try to clarify the features of Chinese natural gas reservoirs and analyze the distribution of natural gas pools and their controlling factors, which are expected to guide future natural gas exploration.

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2 Types and characteristics of natural gas reservoir beds

2.1 Carbonate natural gas reservoir bed

Carbonate natural gas reservoir bed has become a very important gas-producing source. Its distribution area is 250 $\times 104 km^2$, accounting for 55% of the total sedimentary rock area. The thickness of formation from the late-Proterozoic to the Neozoic is about 27,000m, 41% of which is carbonate formation and amounts to 11,000m.

2.1.1 Types of combination of reservoir space

(1) Pore: The pores of carbonate gas reservoir are developed with wide pore throats. The matrix permeability is high. Commercial gas can be produced from pores and throats without the need of fracturing.

(2) Fracture-pore: Narrow throat of reservoir bed makes the permeability of matrix too low to produce commercial gas, but developed fractures can be the main seepage channel to produce commercial gas.

(3) Fracture-cave: The main reservoir space is limestone cave. Fractures are the main seepage channel.

(4) Fracture: Reservoir rock is tight. Fractures are the reservoir space and seepage channel.

2.1.2 Controlling factors

Tectonism is very important in all controlling factors of carbonate natural gas reservoirs, and it controls the deposition and diagenesis of reservoirs. Tectonism, deposition and diagenesis combine and then form the present reservoirs.

(1) Tectonism: It mainly includes the changes resulting from the earth crust movement, syndepositional palaeostructure and palaeogeomorphology, and tectonic movement itself.

(2) Deposition: It includes deposition environment,

change of relative sea level, aqueous medium salinity, climate, tidal energy and storm energy, which are important factors of forming carbonate natural gas reservoirs.

(3) Diagenesis: It can be divided into two circumstances. One is the factors that result in low porosity, including cementation, packing, compaction, pressure solution, dedolomitization, recrystallization; the other is the factors that result in high porosity, including dolomitization, denudation in contemporaneous time and hypergene time, and organic acid denudation in hydrocarbon-generating time.

2.2 Clastic natural gas reservoir bed

Clastic natural gas reservoirs in China are distributed in the Sichuan Basin, Ordos Basin, Tarim Basin, Bohai Bay Basin, Junggar Basin, Tuha Basin, and Yinggehai Basin. Gas-bearing layers are mainly the Permian, Triassic, Jurassic and Tertiary system, and the Carboniferous, Cretaceous and Quaternary system are next.

2.2.1 Types of combination of reservoir space

Clastic natural gas reservoir consists of primary pores, secondary pores and fractures. Therefore, it is usually divided into three kinds: pore (normal) clastic natural gas reservoir, fracture-pore (fine and tight) clastic natural gas reservoir, and fracture clastic natural gas reservoir. Their characteristics are similar to those of carbonate natural gas reservoir.

2.2.2 Controlling factors

The controlling factors of clastic natural gas reservoirs are greatly different from those of carbonate natural gas reservoirs. Although they are all restricted by tectonism, deposition and diagenesis, the former is influenced more by deposition and sedimentary facies. As the degree of compaction increases, the influence of diagenesis is more obvious. Fractures produced by tectonism intensify the heterogeneity of reservoir beds.

(1) Tectonism: Different structures determine different gas-bearing basins, palaeogeothermal gradients and rates of deposition, which have a great influence on the distribution of clastic natural gas reservoirs and the evolution of diagenesis. Different structures exist in different areas in China, so different types of gas-bearing basins are formed, such as eastern tensional fault basins, western compression foreland basins, and depression basins.

(2) Deposition: Deposition is the basis of forming clastic reservoirs, and it determines lithology and maturity of clastic rock. Usually, when maturity and degree of sorting of clastic rock are high, its porosity and permeability are also high and vice versa. Different depositional environments form different clastic depositional systems and constitute different sedimentary facies with different depositional characteristics. As a result, the distribution of clastic gas reservoirs is obviously controlled by sedimentary facies and microfacies.

(3) Diagenesis: Diagenesis of clastic gas reservoirs mainly includes compaction, pressure solution, cementation, denudation and metasomatism. The former three make physical properties of reservoir bed worse, but the later two make those better (Jiang et al, 2004; Yang et al, 2008). Besides, in the process of organic matter thermal evolution, formed organic acid that can dissolve in water easily made the pH value of formation water lower and induced denudation, such as feldspar denudation. Meanwhile, as cementation, denudation and metasomatism occurred in aqueous medium in the pore space, when oil and gas entered the pores, it displaced the water, and the above diagenetic actions were weakened. The porosity and permeability of the reservoir bed could thus be protected.

2.3 Special natural gas reservoir bed

Special natural gas reservoirs are composed of volcanic rock, metamorphic rock, argillaceous rock, and near surface loose deposits. They are different from carbonate reservoir bed and clastic reservoir bed in lithology, lithofacies, diagenesis, reservoir space, electric property, seismic property, and gas bearing property. In recent years, a few gas reservoirs have been found, and significant progress has been made in the exploration, so it is useful to intensify the study on special reservoirs.

2.3.1 Volcanic natural gas reservoir bed

Volcanic reservoirs are distributed widely in China (Lü et al, 2004; Zhao et al, 2008). They are found in the Bohai Bay Basin, Junggar Basin, Sichuan Basin, Erlian Basin, Subei Basin, and Sanshui Basin. Most of them are the Mesozoic and Cenozoic, and the rest are the Permian and Carboniferous. The reservoir space is composed of pore, limestone cave and fracture. The seepage channel is fractures of various kinds, which is different from usual clastic reservoir. Fractures of volcanic rock are well developed, but the types of origin are different. Fractures caused by primary crush structure are common, the next is secondary structure fracture caused by cryptoexplosion, and fracture caused by regional tectonism is rare.

In China, volcanic gas reservoir bed is fracture-pore type. Whether it can be a good gas reservoir bed is up to the degree of development of crush structure or fracture network. It is a necessary condition for forming a gas reservoir that the pores and caves are connected. Both primary fracture and secondary fracture have strong heterogeneity, which results in the heterogeneity of volcanic reservoir bed.

2.3.2 Metamorphic natural gas reservoir bed

The earliest reservoir of this type is metamorphic reservoir of the Silurian system in the Ya'er Gorge, Jiuxi Basin (discovered in 1959). In 1971, natural gas and condensate oil were found in the Western Sag of the Liaohe Depression. In the 1980s, commercial gas and oil were found in the Bohai Bay Basin. The above exploration achievements show that the exploration of metamorphic oil and gas reservoirs has good prospect in China.

Metamorphic reservoirs already found are distributed in the Liaohe Oilfield, Shengli Oilfield, Bohai Bay Oilfield in eastern China and Yumen Oilfield in western China. The reservoirs are formed in the Archaean and Proterozoic, but few in the Paleozoic. The types of rock are mainly migmatite and gneiss, the next is schist, phyllite and granulite. They are all migmatite, regional metamorphic rocks, and dynamometamorphic rocks.

2.3.3 Argillaceous natural gas reservoir bed

Argillaceous gas reservoir is few, but natural gas has been found in the Songliao Basin and western Sichuan foreland basin. The output of oil and gas in argillaceous reservoirs will

reduce rapidly when exploited, so it is not the best time to exploit argillaceous gas reservoir under the present economic and technical conditions. However, the gas in argillaceous gas reservoirs is a potential resource with the development of science and technology.

2.3.4 Near surface loose deposit natural gas reservoir bed

In recent years, natural gas reservoirs have been found in non-consolidated or weakly consolidated deposits of the Quaternary system, for example, shallow natural gas reservoir in loose deposits of the Quaternary system in Zhejiang province, and shallow natural gas reservoir in weakly consolidated deposit of the Quaternary system in the Qaidam Basin. The gas in loose deposits is of biological origin, or maybe comes from deep secondary gas. Because the deposit has good porosity and permeability, it is possible to form commercial reservoir as long as it is preserved well. Moreover, this kind of reservoir is distributed widely, and has shallow burial depth and low exploitation cost, so it is an important field of exploration in the future.

3 Distribution of natural gas layers

The distribution of Chinese onshore natural gas has the multi-layer characteristics, from the Precambrian, Palaeozoic, and Mesozoic to the Cenozoic.

3.1 Gas layers of Precambrian

Gas layers of the Precambrian include basal metamorphic layer and Sinian system gas layer. They are distributed in the Songliao Basin, Sichuan Basin and Tarim Basin. Xinglongtai gas field in the Archean erathem and Weiyuan gas field in the Sinian system have been found. Commercial gas of the Sinian system has been discovered in the Yakela structure, Tarim Basin.

3.2 Gas layers of Palaeozoic

Gas layers of the Palaeozoic erathem are distributed widely except in the Devonian system. The lower Palaeozoic refers to the Ordovician system and the Silurian system, and the Neopaleozoic refers to the Carboniferous system and the Permian system. At present, 18 gas fields are found, accounting for 26.15% of the total proved gas reserves in China.

The Tazhong-6 gas field of the Cambrian has been found in the Tarim Basin, and the Sulige gas field in the Ordovician system which is the biggest gas field has been found in the Changqing Oilfield, Ordos Basin. Only commercial gas of the Silurian system has been found in the sandstones of the Xiaoheba area in the Sichuan Basin.

The Carboniferous system and Permian system are rich in gas, and the Carboniferous system in eastern Sichuan is a good target for gas exploration. Twelve gas fields have been found, including Wubaiti, Wolonghe, Dachiganjing, Longmen, Shapingchang, Gaofengchang, Shuangjiaba, Fengjiawan, Yunhezhai, Xiangguosi, Puxi and Wenquanjing.

3.3 Gas layers of Mesozoic

Natural gas of the Mesozoic has an important role in Chinese gas reserves. At present, 23 gas fields are found in the Tarim Basin, Sichuan Basin, Junggar Basin and Songliao Basin, which account for 49.7% of the total proved gas reserves in China.

The Tarim Basin is the best area for gas fields of the Mesozoic erathem, such as the Kela 2 large gas field. In addition, the Yakela and Yudong gas fields of the Cretaceous system, the Yinan 2 large gas field of the Jurassic system, and the Jilake large gas field of the Triassic system are all in the Tarim Basin.

3.4 Gas layers of Cenozoic Tertiary-Quaternary

At present, 16 large and medium-sized gas fields of the onshore Cenozoic have been found in China. Thirteen gas fields are in the Tertiary system, and are distributed in the Tarim Basin, Qaidam Basin and Bohai Bay Basin. Other three gas fields of the Quaternary system are in the Qaidam Basin.

4 Distribution characteristics of natural gas pools and controlling factors

Continental plate movement of China formed several types of basins, including craton basins, foreland basins, intermontane and piedmont basins, and intracontinental rift basins in the process of long-term tectonic evolution. Craton basins, foreland basins and intracontinental rift basins are three favorable types of basins, where natural gas is widely distributed because of their special geological characteristics and favorable accumulation conditions.

4.1 Gas-bearing craton basin

Chinese craton basins were formed on the Tarim platform, North China platform and Yangtze platform of the Palaeozoic era. Natural gas exploration in the Tarim Basin, Sichuan Basin and Ordos Basin confirms powerfully that craton basin is an important field of natural gas exploration (Li et al, 2007c; Wang et al, 2007). Lower Paleozoic tectonic sedimentation evolution of the three craton basins have the similarity of developed palaeo-uplifts. However, upper Paleozoic tectonic sedimentation evolution in those basins have big differences, and different types of sedimentary systems were formed. Therefore, the reservoirs in the upper Paleozoic and lower Paleozoic become two major exploration fields of natural gas.

(1) Palaeo-uplift controls the distribution of gas reservoirs

Because of the development of unconformity and the effect of long-term weathering and leaching, the lower sequences in craton basins formed pore carbonate reservoir, pore-cave carbonate reservoir, pore-fracture carbonate reservoir and fracture carbonate reservoir. They become main distributions of large and medium-sized gas fields. Some famous gas fields are found in this field, including the giant gas field in the middle of the Ordos Basin, Weiyuan gas field in the Sichuan Basin, water-soluble gas field in the Tarim Basin, TZ-1 gas field, TZ-16 gas field and Yakela condensate gas field in the Tarim Basin (Lü et al, 2007).

(2) Structures of subtle trap in the upper sequence of craton basins provide favorable conditions for the distribution of large and medium-sized gas fields

Orogenic belt on basin margin was formed in the late stage of evolution in craton basin, so there was sufficient

supply from the provenance and the basins were in the stage of Pangea, forming the upper sequences which were dominated by continental deposits and deposits of transitional facies. In the upper sequences, there were developed many subtle traps of shelf-edge reefs, oolitic beaches, channel and frontal sand bodies of delta, sandstone and marine clastic limestone to create beneficial conditions for gas accumulation (Yang et al, 2006; 2008).

4.2 Gas-bearing foreland basin

(1) Many structure zones were developed in the foreland basin in the midwest of China

On the basis of craton tectonic evolution in the Paleozoic, six main foreland basins were formed in the midwest of China in the Cenozoic, including northwest margin of the Sichuan Basin, western margin of the Ordos Basin, Kuqa area of the Tarim Basin, the southwest Tarim Basin, northern margin of the Qaidam Basin, and southern margin of the Junggar Basin. Because of intense structural squeezing action in the late stage of evolution, thrust belt formed many traps, which were related to fault and folds and elongated mostly in a form of belt. For example, the thrust belt in the Kuqa area includes five structural belts, which are thrust-monocline belt in the northern margin, Kesangtuokai-Yiqikelike anticline belt, Baicheng pull-apart basin, Qiulitage anticline belt and Yingmai7-Yaha early foreland frontal uplifted and tenso-shear belt.

(2) Different sets of sandstone reservoirs were developed in the foreland basin with great difference in reservoir quality

In the Cretaceous Bashijiqike formation of the Kela-2 well in the Kuqa area, Tarim Basin, the sandstone thickness was 259.2m, porosity was between 10%-17%, and permeability generally was $(1\text{-}50)\times10^{-3}\mu m^2$ with a maximum of $1407.6\times10^{-3}\mu m^2$. However, sandstones of the Jurassic Penglaizhen Formation and the upper Triassic Xujiahe Formation in the west Sichuan Depression often showed lenticular distribution. The types of reservoir space are pore type, which is composed of residual intergranular pores (Zeng et al, 2007b) and fracture-pore type, which is composed of secondary solution pores and microcracks (Lü, 2005; Deng et al, 2008). The reservoirs are of ultra-low porosity and low permeability reservoirs. Porosity is 3%-5% and permeability is $0.01\times10^{-3}\mu m^2$-$0.1\times10^{-3}\mu m^2$.

(3) Four types of gas reservoirs were developed in foreland basin

Various gas reservoirs have been found in the foreland basins of China (Wang and Zhu, 1991; Yang, 2006), mainly including four types, which are extruding anticline coal-type condensate gas reservoir of Jurassic, tensional fault-block and faulted anticline secondary gas reservoir of the Jurassic-Triassic, fault-nose coal-based primary gas reservoir, and compound gas reservoir superimposed by gas reservoir of structural-litho-trap, coal-based primary gas reservoir of the Triassic, and secondary gas reservoir of the Jurassic.

4.3 Gas-bearing intracontinental rift basin

This type of basins includes mainly the Songliao Basin, Bohai Bay Basin, northern Jiangsu Basin and Jianghan Basin in China. Not only oil reservoirs are mainly found in rift basins, but also there are sufficient resources of gas. Large gas fields were developed in rift basins, which belong to an important type of basin for natural gas exploration.

Many favorable exploration zones of natural gas were developed in deep layers of rift basins in China. For example, in the deep layers of the Songliao Basin, there were mainly developed Xujiaweizi-Yingshan downfaulted area which lies in the east of Daqing Placantieline, the downfaulted area which lies in the west of central palaeo-uplift and Wangfu-Dehui downfaulted area in the southeast uplift. Favorable zones of natural gas exploration in deep layers of the Bohai Bay Basin are more numerous than those in the deep layers of the Songliao Basin, including the trap belt in metamorphic rock buried hill of the Archean, anticline structure of the middle to upper Proterozoic, compressed structural zones of the Paleozoic that was formed during the Indo-Yanshan epoch, fault structural zone that was formed during the Himalayan period, fault structural zone of the Mesozoic, deep fault structure of the lower Tertiary, and fan body belt of sandy conglomerate inside the sag. All of them are prospective zones. In the Huanghua Sag of the Bohai Bay Basin, a condensate gas field with in-place reserves up to $600\times10^8m^3$ has been found, implying that intracontinental rift basins have good prospects to develop large and middle-sized gas fields in China.

5 Conclusions

1) Gas reservoirs of China are diverse and widely distributed. Their distribution is characterized by multi-layer in the vertical direction, and could be divided into four types, gas-bearing reservoirs of the Precambrian system, gas-bearing reservoirs of the Palaeozoic erathem, gas-bearing reservoirs of the Mesozoic erathem, gas-bearing reservoirs of the Tertiary and Quaternary system.

2) In the plate movement in China, craton basins, foreland basins, intermontane and piedmont basins, and intracontinental rift basins were formed. It is demonstrated by our analysis that craton basin, foreland basin and intracontinental rift basin are favorable areas for natural gas exploration because of their special geological features and good accumulation conditions.

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