Geological Features and Exploration for Tight Sand Gas, Shale Gas and Other Unconventional Oil/Gas Resources in China*

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Abstract

Petroleum exploration and development in China has extended rapidly from the conventional oil/gas resource to the unconventional oil/gas resource, which has large exploration potential. In China, there are various types of unconventional oil/gas resources, covering a large area. Especially, the exploration domains of shale gas and tight sand gas are very broad (Figure 1). The resource types, geological features and evaluation methods of unconventional petroleum resources are quite different from those of conventional ones; thus, it is necessary to set up theories of unconventional petroleum geology and develop pertinent technologies for exploration and development.

It is generally thought that the conventional oil and gas resources are those within reservoirs with air permeability over 1mD, accounting for 20% of the total resources; The oil and gas within reservoirs with air permeability less than 1mD are unconventional oil and gas resources which account for 80% of the total resources (Figure 2). Unconventional oil/gas plays refer to oil/gas accumulations whose oil/gas and water distribution are not controlled by obvious trap, with oil/gas accumulated in tight unconventional reservoir systems. They are difficult to produce with conventional technologies, but they can be exploited by applying pertinent technologies for industrial production. According to oil/gas accumulation patterns, they can be divided into continuous, transitional and discontinuous types. “Continuous” oil/gas is the major type of unconventional oil/gas resources, including tight sand gas, shale gas, part of the tight sand oil, coalbed methane, bio-methane gas and gas hydrates. Chinese examples are the Upper Paleozoic tight sand gas in Sulige gas field in Ordos Basin, the Lower Cambrian - Lower Silurian shale gas in Sichuan Basin, the Middle Mesozoic Yanchang Formation tight sand oil in Ordos Basin. ”Transitional” oil/gas includes part of the tight sand oil, oil sands, part of the fracture-vug carbonate and volcanic reservoirs; e.g., some fracture-vug carbonate reservoirs in Tarim Basin and deep volcanic reservoirs in Songliao Basin. “Discontinuous” oil/gas includes heavy oil and tar sands; e.g., the oil sands in Fengcheng area on northwest margin of Junggar Basin.

In China, there are not only various type of continuous gas plays, but also continuous oil plays with a wide distribution; e.g. tight sand oil (Songliao, Ordos basins), shale oil (Jurassic formation in the middle Sichuan Basin). The middle-shallow Cretaceous formation in Songliao Basin is characterized by laminar source rock overlapped and connected with large-area sands, forming “continuous” oil play in the sag center, with distribution area over 4×10^4 km^2.

Unconventional oil/gas plays have the following essential characteristics: large-scale distribution in the basin center and slopes; developed in unconventional reservoirs without clear trap boundary and seal rock; having no uniform oil/water or gas/water contacts and pressure system; diverse oil/gas saturation, and coexistence of multi-phases of oil/gas and water. They are mainly controlled by factors of pore throat diameter, porosity, permeability, residual organic-matter content of source rock, degree of thermal evolution, and the pressure difference between source rock and reservoir. In general, pore throat radius less than 1μm, porosity lower than 10%, permeability lower than 1×10^{-3} μm^2, TOC over 1%, R_o over 0.7%, pressure difference between source rock and reservoir higher than 10MPa are favorable geologic conditions for forming unconventional oil/gas plays. The porosity and permeability of unconventional oil/gas plays is shown to be quite low (Table 1). The pore throats are nm-μm; thus, the shale gas plays are liable to be saturated (Figure 3). In shale reservoirs, the pore space includes some micropores after the gas generation from original organic matter and micro-fractures formed by tectonic and diagenetic action; pore throat diameters are generally 0.005-0.100 μm (Figure 4A-D). In tight sandstone, the pore space mostly includes micropores between quartz crystals, vugs on the crystal surface, intercrystalline pores between the authigenic clay minerals, interlayer cracks, etc.(Figure 4E-J).

Special evaluation and production technologies are needed for unconventional oil/gas exploration and development. Currently, USGS has proposed the FORSPAN model evaluation method. Based on the resource spatial prediction of the Upper Triassic Xujiahe “continuous” tight sand gas field in central Sichuan Basin, we have developed software BASIMS2009, which can effectively forecast the unconventional oil/gas resources. The accumulation and distribution simulation process includes geological modeling, unconventional accumulation power balance equation and accumulation volume calculation. The unconventional oil/gas resources need matching “mining” techniques, such as pre-stack seismic reservoir prediction, stimulation, such as horizontal drilling and coiled tubing fracturing, pilot test, etc.

China’s unconventional oil/gas resources are abundant, but with low rate of exploration, but they are the strategic targets for rapid increase. The exploration of tight sand gas in China will target the Paleozoic marine tight sand gas and the Mesozoic-Cenozoic terrestrial tight sand gas. Most tight sand gas is associated with coal seams, with reservoirs close to the source rocks, which cover a large area. The Paleozoic marine tight sand gas can be represented by the Silurian formation on the Tarim Platform, the Carboniferous-Permian formation on the North China Platform, the Devonian-Silurian formation on the Yangtz Platform and the Carboniferous-Permian formation in northwest China, covering a total area of 260×10^4 km^2, with cumulative sandstone thickness of 500-2700 m. Proved recoverable reserves of Upper Paleozoic tight sand gas in Ordos Basin reaches $1.5\text{-}2\times10^{12}$ m^3, and proved recoverable reserves of Upper Triassic Xujiahe Formation tight sand gas in Sichuan Basin are $0.5\text{-}1\times10^{12}$ m^3. Mesozoic and Cenozoic terrestrial tight sand gas covers most of the major sedimentary basins in China, such as the Ordos, Sichuan, Tarim, Junggar, Qaidam, Songliao, Bohai Bay and Tuha basins, with prospective resources over

30×10^{12} m^3. In China, there are both marine and terrestrial shale gas resources, mainly in three marine areas and five terrestrial basins. The three marine areas include the Paleozoic marine shale on the Yangtz Platform, the Paleozoic marine shale on the North China Platform-Gansu Corridor and the Cambrian-Ordovician marine shale in the Tarim basin; The five terrestrial basins include the Cretaceous formation in the Songliao Basin, the Paleogene formation in the Bohai Bay Basin, the Upper Triassic formation in the Shanganning Basin, the Carboniferous-Jurassic formation in the Junggar Basin and the Middle-Lower Jurassic formation in the Tuha Basin. Table 2 indicates that the favorable exploration area of shale gas is about 83×10^4-120×10^4 km^2 and the preliminary prospective resource is about 80×10^{12}-100×10^{12} m^3. Major gas hydrate discoveries have been made in South China Sea and the Tibetan Plateau tundra area. The prospective gas hydrate resources discovered in the northern slope of South China Sea and the Tibetan Plateau recently were estimated to be about 500×10^8 t oil equivalent.

Unconventional oil/gas resources should be explored in several phases in China. Tight sand oil/gas, some carbonate and volcanic vuggy oil/gas, coalbed methane and biogas, which account for 50% of national total reserves and production, are practical areas for reserve and production enhancement. Shale gas is experiencing breakthrough and rapid development; gas hydrates are the strategic alternative area for future exploration.

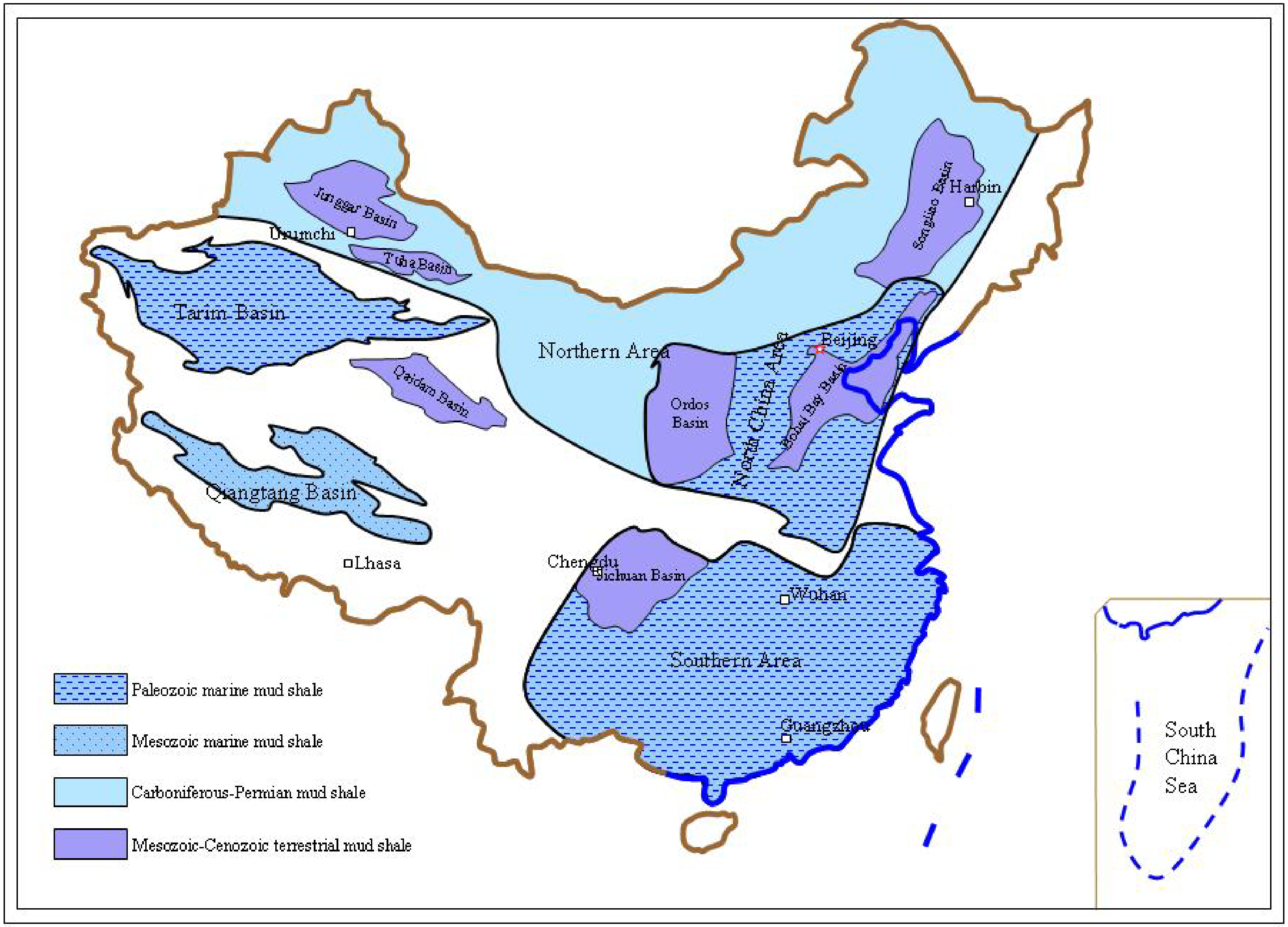

Figure 1. Areal distribution of shale gas potential in onshore China.

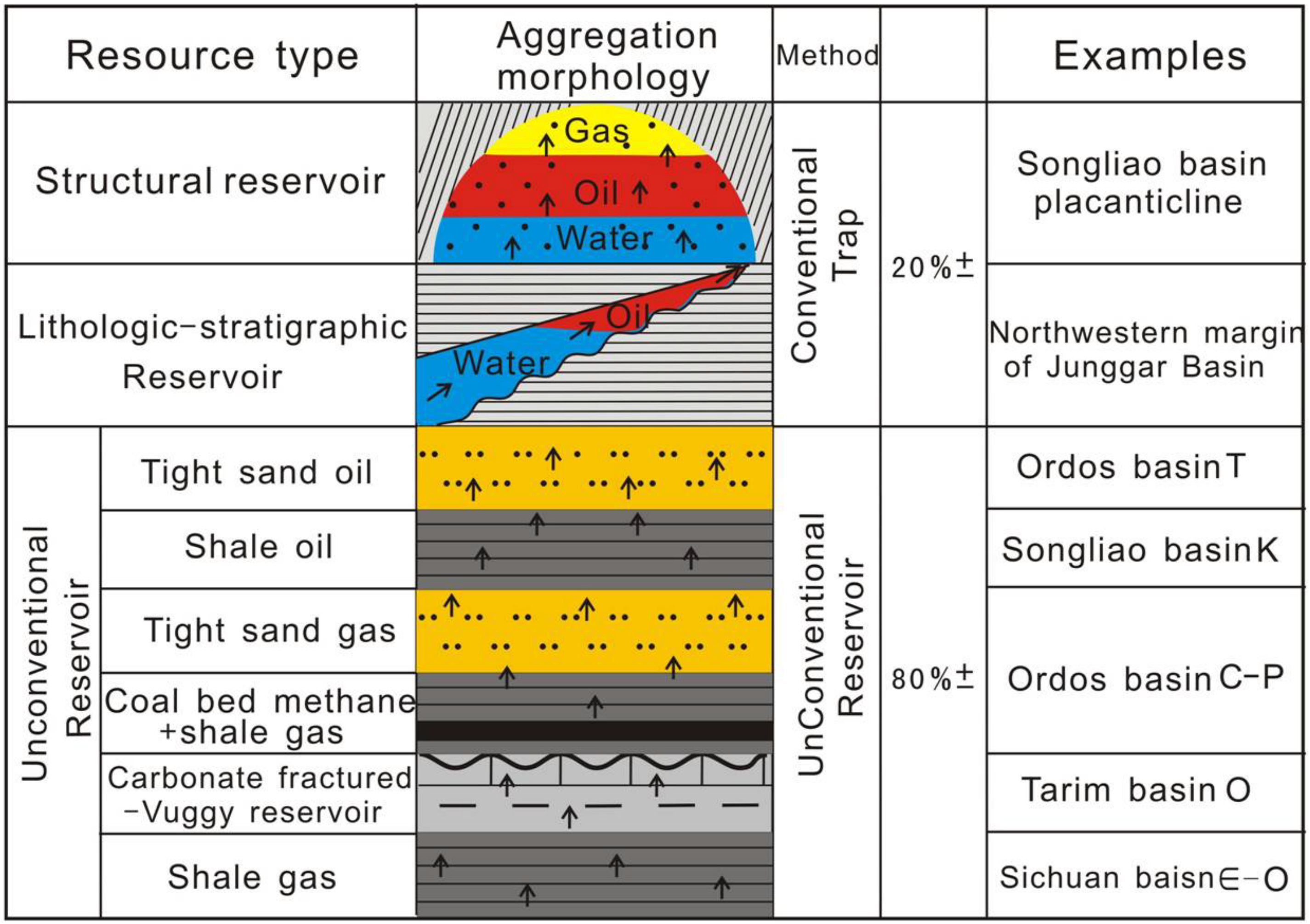

Figure 2. Type and development of oil/gas resources.

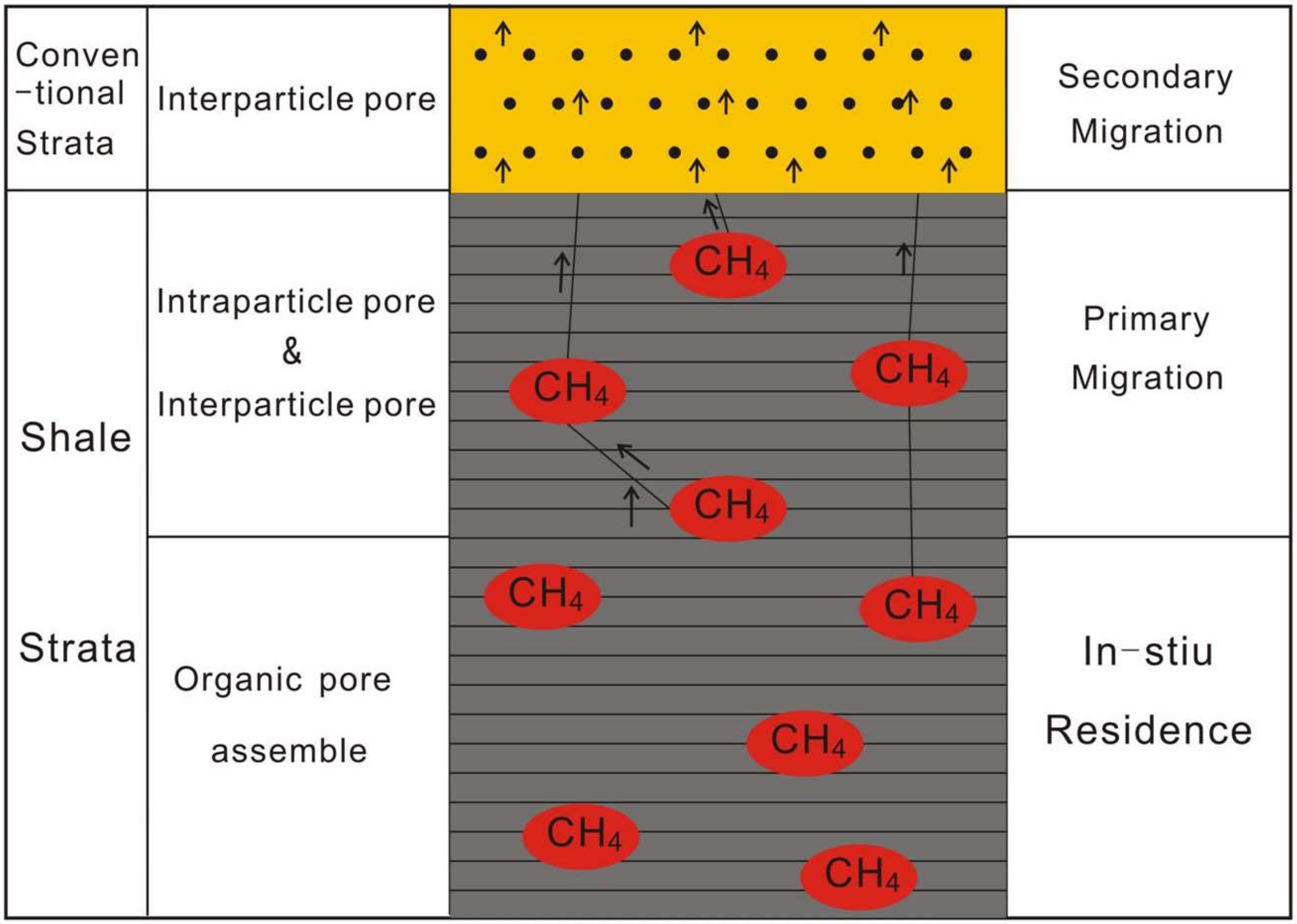

Figure 3. Shale gas formation mechanism and saturated reservoir pattern.

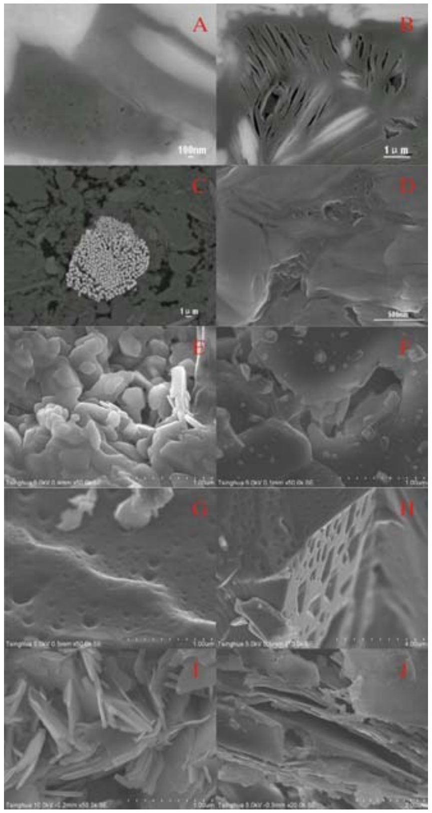

Figure 4. Field emission scanning electron micrograph in shales and tight sandstones in China. A. Well Wei 201--angular micropores and nanopores in rich organic matter from Longmaxi black shale (S_1l) of Sichuan Basin; B. Well Wei 201-- angular micropores and nanopores in rich organic matter from Longmaxi black shale (S_1l) of Sichuan Basin; C. Well Wei 201--pyrite framboid containing intercrystalline micropores and nanopores in Longmaxi black shale (S_1l) of Sichuan Basin; D. Well Wei 201--subrounded nanopores in organic matter from Longmaxi black shale (S_1l) of Sichuan Basin; E.Well Z60, 2991.1m--dissolved pore-inter-granular pores in authigenic microcrystal quartz in Upper Paleozoic(P_1s_1) tight quartz sandstone in Ordos Basin, FESEM×50K; F. Well S315, 3745.7m--intergranular micropores in Upper Paleozoic(P_1h_8) tight quartz sandstone in Ordos Basin, FESEM×50K; G. Well S113, 4305.98m--micro-pits in the surface of the quartz grain in Upper Paleozoic(P_1h_8) tight quartz sandstone in Ordos Basin, FESEM×50K; H. Well S113, 4305.98m--micro-pits in the surface of the quartz grain in Upper Paleozoic(P_1h_8) tight quartz sandstone in Ordos Basin, FESEM×30K; I. Well Z69, 2801.88m--intercrystalline micropores in the leaf-shaped chlorite in Upper Paleozoic(P_1h_8) tight lithic quartz sandstone in Ordos Basin, FESEM×50K; J. Well T37, 2648.03m, P1s1--lithic quartz sandstone, 0.156mD, 6.5%, interlayer gaps in authigenic illite crystal in Upper Paleozoic(P_1s_1) tight lithic quartz sandstone in Ordos Basin, FESEM×20K.

Item	Sulige Gasfield	Wushenqi Gasfield	Yulin Gasfield	Zizhou Gasfield
Reservoir	Permian $Shan_1$ and He_8	Permian He_8	Permian $Shan_2$	Permian $Shan_2$
Gas zone thickness/m	8.2	8	8.9	8.5
Porosity/%	9.8	10.4	6.5	6.4
Permeability/(10^{-3} μm^2)	0.774	0.629	2.05	1.78
Reserve abundance/($10^8 m^3/km^2$)	1.1	0.6-1.2	0.6-1.2	0.81
Pressure coefficient	<1, average 0.87	<1, average 0.85	0.93-0.98	<0.1, average 0.95
Reservoir depth/m	3250-3390	3000-3300	2600-3100	2100-2600
Production after fracturing/(10^8 m^3/d)	1-2	1-2	5	1-2

Table 1 Characteristics of Upper Paleozoic tight sandstone gas field in Ordos Basin.

Area or Basin	Formation age	Gas bearing area/$10^4 km^2$	Thickness/m	TOC/%	R_O/%	prospective resource/$10^{12} m^3$	Oil or gas display
Yangtz area	Z-J	30-50	200-300	1.0-23.49	2.0-4.0	33-76	Gas display, commercial gas production
North China area	O, C-P	20-25	50-180	1.0-7.0	1.5-2.5	22-38	Gas display
Tarim Basin	Є-O	13-15	50-100	2.0-3.0	O:0.9-2.4	14-22.8	Gas display
Songliao Basin	C-P,K	7-10	180-200	0.5-4.57	0.9-2.0	5.9-10.5	Oil and gas display
Bohai Bay Basin	Ek-s	5-7	30-50	1.5-5.0	1.0-2.6	4.3-7.4	Oil and gas display
Ordos Basin	C-P, T3	4-5	20-50	2.0-22.21	0.8-1.3	3.4-5.3	Gas display
Junggar Basin	C-J	3-5	150-250	0.47-18.47	1.2-2.3	2.6-5.3	Gas display, low gas production
Tuha Basin	C-J	0.8-1.0	150-200	1.58-25.73	0.8-2.0	0.7-1.1	Gas display, low gas production
Shale gas prospective resource in China add up to:						$86\text{-}166\times10^{12} m^3$	

Table 2. Prediction of shale gas resources in China.