Basic Contents, Geological Features and Evaluation Methods of Continuous Oil/Gas Plays in China

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USGS presented the concept "continuous-type petroleum accumulations" for purpose of resource assessment. And we have further studied the concepts, geological characteristics and evaluation techniques for continuous petroleum accumulations based on many cases in China basins.

1. Continuous petroleum accumulations are those oil or gas accumulations that exist in large spatial dimensional unconventional reservoir systems and are continuously distributed in "non-closed traps". "Continuous" stresses the continuous distribution of hydrocarbon in dimensions, and "petroleum accumulation" refers to the places where petroleum accumulated. Tight sandstone oil/gas, carbonate cavity reservoirs, coal-bed methane, shale oil, shale gas and gas hydrate all belong to category of continuous petroleum accumulations.

2. Geological characteristics: (1) large-scale continuous distribution, but local enrichment, (2) mainly unconventional reservoirs in large dimensions, (3) non-closed traps with indistinctly defined boundaries, large reservoir space, (4) in-source or near-source distribution, (5) no migration or mainly primary migration, (6) accumulated mainly by diffusion, limited role of buoyancy, (7) non-Darcy infiltration flow, (8) weak fluid differentiation, diverse oil or gas saturation, and complex distribution of oil, gas and water.

3. Techniques for continuous petroleum accumulations require more strict study and procedure than conventional accumulations in many aspects, such as seismic reflectance, logging identification, oil or gas test measurement, reservoir transformation, exploitation evaluation, recovery improvement, assorted techniques, and so on.

4. Exploration and exploitation areas in China: (1) Realistic areas: tight sand oil and gas with low /ultra-low porosity and permeability in Ordos Basin, Sichuan Basin, and Songliao Basin, oil and gas in carbonate cavity reservoirs in Tarim Basin, bacterial gas in Chaidamu Basin, and coal-bed methane. (2) Preparatory areas: shale gas in South China, tight gas in deep strata in Songliao Basin, Bohai Bay Basin, Tarim Basin, and Junggar Basin, and gas hydrate in South China Sea. Continuous petroleum accumulations have been one of the most important fields for theory and technology research and for the subsequent exploration and exploitation. By the end of 2008, the continuous oil accumulations and continuous gas accumulations reached 47% and 56% of the total geological reserves in China, respectively, and the exploration potential will be greater in future.

Introduction

It is generally believed 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 lower than 1mD are unconventional oil and gas resources which account for 80% of the total resources; These two resources' constitutional ratio is called 2:8 ratio. The theory and technology development of China's petroleum industry has experienced two major revolutions, the first one is from structural reservoir to lithologic-stratigraphic reservoir, and the second one is from lithologic-stratigraphic reservoir to unconventional continuous oil/gas plays. The current oil/gas exploration is focused on three areas: the first one is structural reservoir, mainly seeking for effective traps; the second one is lithologic-stratigraphic reservoir, mainly to characterize the closed reservoirs; the third one is unconventional oil/gas plays, mainly to predict the distribution of continuous oil/gas resources.

Unconventional Oil/Gas Plays

1. Basic contents and resources composition of unconventional oil/gas plays

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 the tight unconventional reservoir systems; they are difficult to produce with conventional technologies, but 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, which accumulated after primary migration and short-distance secondary migration, accounts for 40-50% of the total resources, including tight sand gas, shale gas, part of the tight sand oil, coalbed methane, bio-methane gas and gas hydrates (Fig. 1); “Transitional” oil/gas experienced middle-short-distance secondary migration, accounts for 20-30% of the total resources, including part of the tight sand oil, oil sands, part of the fracture-vug carbonate and volcanic reservoirs, etc.; “Discontinuous” oil/gas accumulated after middle-short-distance secondary migration, accounts for 10-20% of the total resources, which includes heavy oil and tar sands, etc.

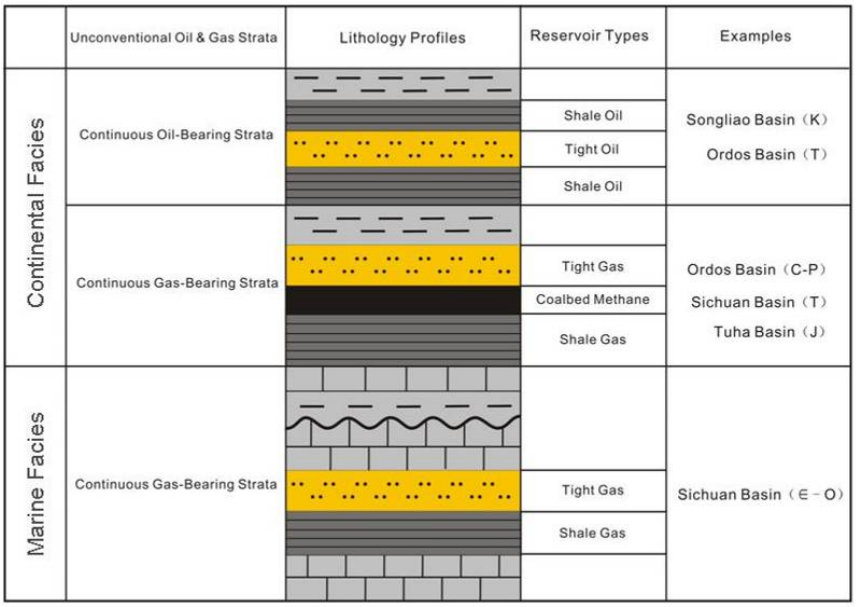

Fig. 1 Profile distribution patterns of China's unconventional "continuous" oil/gas plays

2. Geological features of continuous oil/gas plays

Continuous oil/gas plays have the following common characteristics: 1) large-scale “continuous” distribution but local enrichment in the basin center and slopes; 2) mainly accumulated in large-scale unconventional reservoirs with porosity lower than 10% and permeability lower than 1mD; 3) no obvious trap boundary, nor uniform oil/gas-water boundaries; 4) mainly self generation and self preservation, e.g., the nano-scale pore throats in Paleozoic shale of Sichuan Basin are still effective space for gas flow and accumulation (Fig. 2); 5) mostly primary migration and short-distance secondary migration; 6) mainly accumulated by diffusion, buoyancy is limited; 7) non-Darcy flow; 8) poor fluid differentiation, large oil/gas saturation differences, and coexistence of oil/gas and water; 9) low resources abundance, and reserves are calculated by well-control blocks; 10) special mining technologies are employed, such as pertinent technologies of horizontal wells and multi-level fracturing. For example, the Cretaceous deep tight sand gas of the Kelasu structure zone in the Kuqa Depression, Tarim Basin has large-area continuous distribution (Fig. 3), and the annual natural gas production of the middle-shallow Kela-2 structure gasfield reaches nearly 12 billion cubic meters. In recent years, large-scale tight sand gas has been found in the deep formation with depth of 6000-7500 m, with average porosity 5%, permeability 0.5mD, and tight gas sandstone thickness 60-150 m. For example, the daily natural gas output of Keshen-2 well (depth 6500-6700 m) is 46.6×10^4 m^3, the daily natural gas production of Keshen-5 well (depth 6666-6900 m) is 15×10^4 m^3, and Dabei-301 well (depth 6923-7065 m) is 23×10^4 m^3, the whole deep formations have made new discovery of tight sand gas.

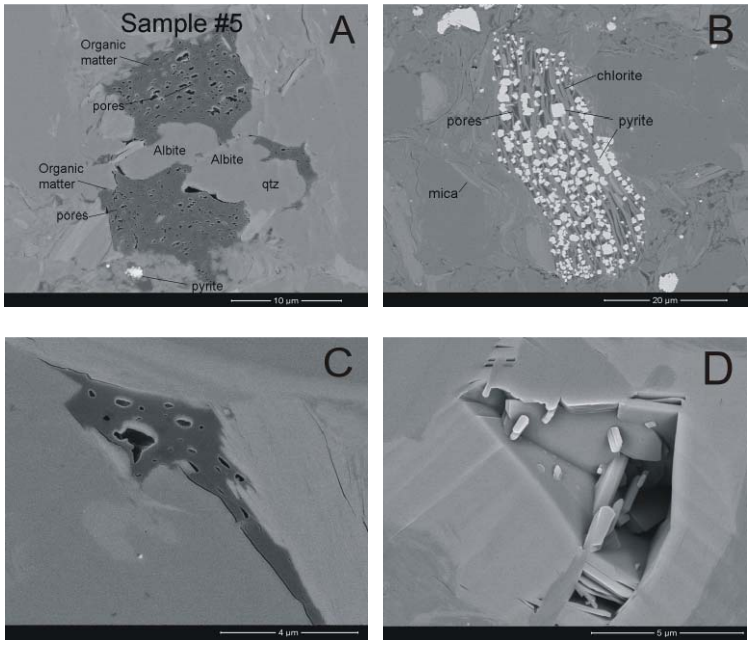

Fig. 2 SEM micrographs of pores in Permian, Silurian shale of Wei#201 Well in Sichuan Basin

A. Intra-pores in organic matter from Silurian Longmaxi formation shale of Sichuan Basin; B. Pore structure of Silurian Longmaxi formation shale from Sichuan Basin; C. Intra-nanopores in organic matter; D. Pore throats of Permian Longmaxi formation shale, Sichuan Basin.

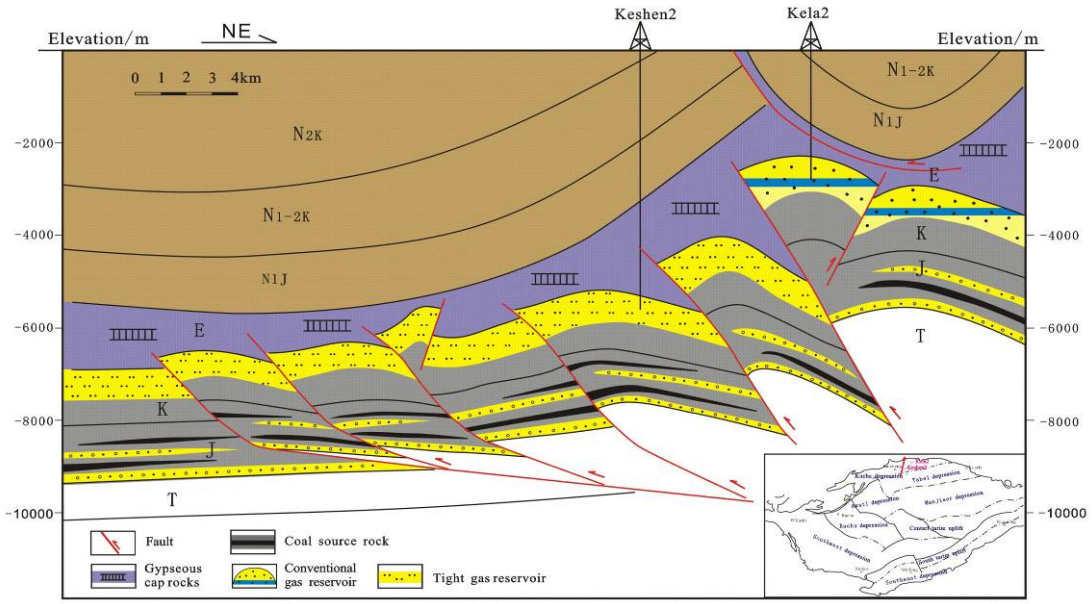

Fig. 3 Profile of continuous tight sand gas of deep Kelasu structure zone in Kuqa Depression, Tarim Basin

Obvious differences exist between different types of continuous oil/gas plays, such as tight sand gas, shale gas, tight sand oil, coalbed methane, bio-methane gas and gas hydrates, especially in the aspects of formation conditions and accumulation mechanism (Table 1).

Table 1 Differences between several major types of unconventional continuous oil/gas plays

SN	Characteristics	Shale gas	Coalbed methane	Shale oil	Tight oil	Tight gas
1	Distribution	near the basin subsidence-deposition Center	higher terrestrial plants -developed area	shale -developed area of furrow or slope	basin Center or slope	basin Center or slope
2	Porosity（%）	<4%-6%	mostly <10%	mostly <10%	mostly <10%	mostly <10%
3	Permeability（mD）	<0.001-2×10^{-3} mD	mostly <1 mD	mostly <1 mD	mostly <1 mD	mostly <1 mD
4	Source-reservoir	source-reservoir-cap is trinity, authigenic reservoir	source-reservoir-cap is trinity, authigenic reservoir	source-reservoir-cap is trinity, authigenic reservoir	source-reservoir contact directly or closely	source-reservoir contact directly or closely
5	Trap	no obvious trap boundary				
	Migration	no migration or short-distance primary migration in source rocks	no migration or short-distance primary migration in source rocks	no migration or short-distance primary migration in source rocks	primary migration and short-distance secondary migration	primary migration and short-distance secondary migration
6	Accumulation	dispersed distribution in shale, enrichment at the crack/cleat area	enrichment at the crack/cleat area	enrichment at the crack area	enrichment at the crack/dissolution area	enrichment at the crack/dissolution area
7	Flow	resolution, diffusion	mainly non-Darcy flow			
8	Fluid	mainly dry gas, adsorbed in kerogen, porosity, etc.	mainly adsorbed gas, and a small amount of free gas	mainly middle-low maturity petroleum	mainly middle-low maturity petroleum	large difference in gas saturation, mostly less than 60%
9	Resource	low resource abundance, and reserves are calculated by well-control blocks	low resource abundance, and reserves are calculated by well-control blocks	low resource abundance, and reserves are calculated by well-control blocks	low resource abundance, and reserves are calculated by well-control blocks	low resource abundance, and reserves are calculated by well-control blocks
10	Development technology	low output, low recovery, long production cycle, multi-stage fracturing and horizontal wells are required	low output，no natural production, long production cycle, fracturing and horizontal wells are required	low output, no or low natural production, fracturing are required	no or low natural production, fracturing are required	no or low natural production, fracturing are required
11	Typical cases	lower Paleozoic and Triassic shale gas in Sichuan Basin	CBM of Hancheng in Ordos Basin and Qinshui in Shanxi	shale oil of Jurassic in north Sichuan Basin and Triassic in Ordos Basin	tight sand oil of Yanchang formation in Ordos Basin and Cretaceous formation at basin center in Songliao Basin	tight sand gas of Sulige in Ordos Basin and Xujiahe formation in Sichuan Basin

Continuous oil resources, such as tight sand oil and shale oil are widely distributed in China. In recent years, great breakthrough has been made in tight sand oil exploration in Songliao and Ordos Basin, etc., and major discovery has been made in shale oil exploration in Cretaceous formation of Songliao Basin, Jurassic formation of Sichuan Basin and Tertiary formation of Bohai Bay Basin. Tight sand oil which has been found in Ordos Basin in China is very similar to that of Bakken formation of Williston Basin in North America. The Upper Triassic Yanchang formation in Ordos Basin can be divided into 9 members, of which the lower part Chang 7 member and Chang 9 member are shale layers rich in organic matter, with average thickness 15-50 m, burial depth 600-2600 m, Ro 0.7-1.3%. The Chang 7 and Chang 9 member are in the stage of

peak oil generation, and tight oil has been found in the tight sandstone between Chang 7 and Chang 9 member. In recent years, 187 wells drilled into Chang 7 member in the basin center have produced commercial oil flow, with average single well oil testing production of 8.6 t/d, average porosity of 10.2%, average permeability of 0.21mD, favorable oil-bearing area more than 30000 km^2, and the estimated OOIP of tight oil reaches 5-10×10^8 t. The middle-shallow Cretaceous tight formation in Songliao Basin is featured by laminar source rock overlapped and connected with large-area sands, with tight oil distribution area over 4×10^4 km^2. Meanwhile, the shale oil is also widely accumulated in Songliao Basin. Shale oil plays have been found in Lower Cretaceous Qingshankou formation and Nenjiang formation of the Gulong sag, Songliao Basin, and the mud shale of these two formations is rich in organic matter, with total thickness of 300-620 m; the kerogen type mainly includes type □and type II; Ro is 0.9% -1.8%; abnormal overpressure is developed. At the early stage, Da-4 well drilled into the mudstone of Qingshankou formation of Da'an structure produces oil 2.66 t/d; more than 50 wells have show of oil and gas; 4 wells produce a small amount of oil and gas (i.e. Gu-501 well, Ying-15 well, Ying-3 well, Da-111 well), and 5 wells produce commercial oil/gas flow (i.e. Ying-12 well, Ying-18 well, Ying-16 well, Gu-1 well, Da-4 well) (Table 2). The fractured-mudstone oil plays of Xinbei oilfield in south Songliao Basin have being mined for more than 10 years, with cumulative oil production more than 3×10^4 t.

Table 2 Basic characteristics of shale oil plays in China

Basin	Region	Formation	Kerogen Type	Ro (%)	Pressure coefficient	Cases
Bohai Bay	Liaohe depression	Shahejie formation	I	0.85-1.15	1.3-1.8	
Bohai Bay	Jiyang depression	Shahejie formation	I	0.77-1.32	1.53-1.8	Luo-18 well, Xinyishen-9 well
Bohai Bay	Dongpu sag	Shahejie formation	I-II_1	0.9-1.12	about 1.85	Wen-300 well
Songliao	Gulong sag	Qingshankou formation	I-II_1	>1.0	1.19-1.51	Ha-16 well, Ying-12 well
Qaidam	Mangya sag	Tertiary	II	0.51-0.82		Youquanzi oilfield, Nanyishan oilfield

3. Core technologies for continuous oil/gas exploration and development

The pertinent technologies for continuous oil/gas exploration and production mainly include: geologic evaluation technology of continuous oil/gas play (industrial application technology of sequence stratigraphy, diagenetic facies quantitative evaluation technology, resources and reserve evaluation method, resources spatial distribution prediction method), geophysical prediction technology of continuous oil/gas play (high-resolution and large-area seismic data acquisition technology, pre-stack seismic reservoir prediction technology, fracture-vug characterization technology of carbonate rock, gravitational-magnetic-electrical prediction technology of volcanic reservoir, fluid saturation prediction, etc.), and continuous oil/gas play development technologies (horizontal well and multi-lateral well technologies, stimulation technologies such as well bore reconstruction and coiled tubing fracturing, etc.).

4. Exploration potential of continuous oil/gas plays

Continuous oil/gas plays have become hot spot for domestic and overseas theory and technology research, and is one of future targets for exploration and development. According to statistics, the favorable exploration area of tight sand gas of onshore China's seven oil-bearing basins is 62×10^4 km^2, and the prospective resources is about 22×10^{12} m^3 (Table 3). There is great potential of tight sand gas in deep formations of J and K in Songliao Basin, formation of S in Tarim Basin, formation of J in Junggar and Tuha Basins, and formation of C-E of Bohai Bay Basin. The resource of coalbed methane is abundant in China. The resource of coalbed methane with burial depth less than 2000 m is about 36.81×10^{12} m^3. According to

preliminary evaluation, the prospective resources of shale gas in China are approximately 100×10^{12} m^3 (Table 4). There is also broad distribution of terrestrial oil-bearing argillaceous source rocks in China, with a huge potential of shale oil resources.

Table 3 Resources and distribution of tight sand gas in China

Basin	Basin area ($\times10^4$ km^2)	Exploration target	Exploration area ($\times10^4$ km^2)	Resources ($\times10^{12}$ m^3)
Ordos	25	C-P	18	8.4
Sichuan	18	T3x	6	3.2
Songliao	26	K1	5	1.8
Tuha	5.5	J	1.5	0.6
Bohai Bay	8.9	Es3-4	3	1
Tarim	56	S	24	4.5
Junggar	13.4	J	4.5	2.4

Table 4 Geological and geochemical parameters of terrestrial oil-bearing argillaceous source rocks in China

Basin	Formation age	TOC/%	Chloroform bitumen	Oil source rock
Junggar	P	2.0~10.0	0.072~0.338	1200~1500
Ordos	T_3	1.2~1.9	0.100~0.210	300~500
Songliao	K_1	2.2~2.4	0.100~0.250	400
Erlian	K_1/J_3	1.7~2.1	0.080~0.310	1300
Jiuquan	K_1	1.1~1.8	0.143~0.225	600
Tuha	J_1	0.47~3.5	0.017~0.081	300~500
West Liaohe	E_3	1.6~3.8	0.150~0.400	2000
Bohai Bay	E_3	1.3~2.3	0.145~0.349	3200
Huanghua	E_3	1.1~1.8	0.120~0.190	2000~2500
Jiyang	E_3	0.8~3.0	0.200~0.380	2400
Raoyang	E_3	0.1~4.6	0.190	1500
Zhongyuan	E_2E_3	1.0	0.134	2500
Dongtai of Subei	E_3	1.2~1.6	0.105	840
Nanxiang Biyang /Nanyang	E_3	1.4~1.8	0.138~0.217	800
Jianghan	E_2E_3	0.6~0.7	0.206~0.339	1500
Qaidam	N_1N_3	0.4~0.6	0.115	2500
Zhujiangkou	E_3	1.1~1.4	0.100~0.230	
Beibu Bay	E_3	1.7~2.2	0.230~0.310	900

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