PETROLEUM EXPLORATION AND DEVELOPMENT
Volume 36, Issue 6, December 2009
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: PETROL. EXPLOR. DEVELOP., 2009, 36(6): 669–682.

RESEARCH PAPER

Global importance of "continuous" petroleum reservoirs: Accumulation, distribution and evaluation

Zou Caineng[1, 2,*], Tao Shizhen[1], Yuan Xuanjun[1], Zhu Rukai[1], Dong Dazhong[1], Li Wei[1], Wang Lan[1], Gao Xiaohui[1], Gong Yanjie[1], Jia Jinhua[1], Hou Lianhua[1], Zhang Guangya[1], Li Jianzhong[1], Xu Chunchun[3], Yang Hua[4]

1. PetroChina Research Institute of Petroleum Exploration and Development, Beijing 100083, China;
2. State Key Laboratory of Enhanced Oil Recovery, RIPED, PetroChina, Beijing 100083, China;
3. PetroChina Southwest Oil & Gas Field Company, Chengdu 610051, China;
4. PetroChina Changqing Oilfield Company,Xi'an 710018, China

Abstract: Based on distribution of oil and gas in the world, the connotation and characteristics of "continuous" petroleum reservoirs are elaborated in this paper. "Continuous" petroleum reservoirs refer to unconventional trap reservoirs existing in a large-scale unconventional reservoir system, and the distribution of oil and gas is continuous. The main geological characteristics of "continuous" petroleum reservoirs are as follows: located in the center and slope of a basin, large-scale distribution and rich locally; mainly of large-scale unconventional reservoirs; traps have no clear boundaries; mainly of self-generating and self-preserving; mainly of primary migration; accumulated by diffusion and buoyancy is limited; non-Darcy flow; poor oil-water differentiation and different saturation; oil, water and gas coexist and have no common interface and pressure system; resources abundance is low and reserves are calculated by well-control region; the mining technologies are special and tailored techniques are required. In this paper are discussed the cause of deep-water "sandy debris flow" and a few examples on "continuous" reservoirs, the shallow-water delta low or ultra-low porosity and permeability reservoirs, coal-bed methane and shale-cracked reservoirs and so on.

Key words: "continuous" petroleum reservoirs; unconventional trap reservoir; sandy debris flow; FORSPAN resources assessment model.

The naissance and development of petroleum geology experiences the process of "hydrocarbon seep" phenomenon → "anticline" theory → "trap" theory. The field of exploration and development increasingly broadens, from focus on structural reservoir to emphasis on both structural and stratigraphic-lithologic reservoirs, from conventional petroleum resource to unconventional resource, from conventional single trap reservoir to unconventional "continuous" trap reservoir. According to statistics, global gas production from "continuous" gas reservoir in 2007 was up to 5000×10^8 m^3 accounting for 1/6 of total gas production, among which the production of "continuous" tight sandstone gas, coal-bed methane and shale gas were about 3900×10^8 m^3, 600×10^8 m^3 and 450×10^8 m^3 respectively[1-4]. Therefore, the exploration and development of "continuous" petroleum resource and research into "continuous" reservoir play an important role in the sustainable development of petroleum resources.

The "continuous" reservoir is different from the "unconventional" reservoir. The "unconventional" reservoir highlights some special classification standards, such as maximum matrix permeability limit, application of unconventional special technologies and development difficulties (polar region or ultra deep waters, oil sand). The "unconventional" reservoir is a broad and ambiguous concept, as the above standards change with the advancement of petroleum industry and have strong subjectivity; while the "continuous" reservoir is a scientific and normative concept, which can better reflect the hydrocarbon forming mechanism, accumulation conditions, distribution characteristics and technical methods. Based on extensive investigation and in-depth research, this paper systematically describes the forming background, geologic characteristics, accumulation mechanism, exploration potential and evaluation method of the "continuous" reservoir.

1 "Continuous" reservoir concept and classification

1.1 Research history of "continuous" reservoir

Received date: 18 June 2009; **Revised date:** 10 August 2009.
* **Corresponding author.** E-mail: zcn@petrochina.com.cn
Foundation item: Supported by the National Program of Large Gas Field and Coalbed Gas Production, China (20082X05001).

Table 1 Research progress of "continuous" reservoirs at home and abroad

Type	Serial No.	Concept	Author	Year	Target areas
Research progress in China	1	Natural gas hydrate	He Chengzu	1982	Seabed and permanent frozen soil layer
	2	CBM (coal-bed methane)	Dai Jinxing	1986	14 coal mines and 3 CBM middle-deep wells in China
	3	Tight gas sands	Xu Huazheng	1991	Dongpu Sag
	4	Deep basin gas	Jin Zhijun, Zhang Jinchuan et al.	1996	Taibei Sag in Tuha Basin
	5	Source-contacting gas	Zhang Jinchuan	2003	Ordos, Tuha and Sichuan basins
	6	Shale gas	Zhang Jinchuan	2003	Shuixigou group in Turpan Depression, Tuha Basin
	7	Deep basin oil	Hou Qijun	2005	Songliao Basin (south)
	8	Syncline oil	Wu Heyong	2006	Songliao Basin (north)
	9	Continuous reservoir	Zou Caineng	2009	Relevant hydrocarbon provinces in China
Overseas research progress	1	Oil seep discovery	Drake		Titusville, Pennsylvania
	2	"Open" reservoir	Wilson	1859	Undetermined, may exist with potential
	3	CBM	C Joseph	1934	San Juan Basin in America
	4	Natural gas hydrate	D L Katz	1967	Simpson Cape and Prudhoe Bay gas fields
	5	Deep basin gas	J A Master	1971	Ermuwats deep basin gasfield in Canadian Alberta Basin
	6	Tight gas	B E Law	1976	American western basins
	7	Basin center gas	Rose	1979	American Raton Basin
	8	Continuous accumulation	J W Schmoker	1986	American petroleum resource assessment zone
	9	Shale gas	A Tyler	1995	American petroleum resource assessment zone

The "continuous" gas reservoir characteristics were noticed abroad long ago (Table 1). The earliest recognized "continuous" gas reservoir, as a kind of tight sandstone gas reservoir, was discovered in the American San Juan Basin in 1927 and put into production in the early 1950s when it was called hidden gas pool. In 1976, the Ermuwats giant deep basin gas reservoir was discovered in Alberta Basin of western Canada. In 1986, Rose et al. firstly proposed the term of "Basin Center Gas" during the research into Raton Basin[5]. Since 1990s, concepts of deep bed gas and deep gas have occurred in China. In 1995, USGS (U.S. Geological Survey) proposed the concept of "continuous" hydrocarbon accumulation [6, 7] and stressed the continuous gas reservoir was a large reservoir weakly affected by water column, where no direct relation exists between gas accumulation and water buoyancy on gas; and such reservoir was not constituted by the dispersed and countable gasfield group delineated by the downdip gas-water contact. In 2003, Zhang Jinchuan of China proposed the concept of "source-contacting" gas. USGS proposed six kinds of unconventional gas in 2006: (1) deep gas, (2) shale gas, (3) tight gas sands, (4) coal-bed methane, (5) shallow microbial gas sands [8-11], (6) natural gas hydrate /methane clathrate, which are generally called continuous gas.

1.2 Connotation of "continuous" reservoir

In 1934, Wilson proposed and predicted there were two kinds of reservoir: "closed" and "open", but the "open" reservoir has no industrial value. In 2005, Schmoker proposed that the continuous accumulation is the oil and gas accumulation with giant storing space and ambiguous boundary, whose existence doesn't rely on water column pressure[1]. Conventional trap reservoir refers to single closed-trap hydrocarbon accumulation, with clear trap boundary, as well as common interface and pressure system. The essential difference between "continuous" reservoir and conventional trap reservoir is whether the trap boundary is clear, whether the range is stable, and whether there is common oil-gas-water interface and pressure system; that is to say, the former is "invisible" or "subtle" trap and appears as a large scale reservoir, the latter is "visible" or "obvious" trap with a clear trap boundary. Some scholars consider oil and gas in the entire accumulations (tight sand, coal rock, mud shale and permanent frozen soil layer etc.) as a giant single reservoir [1].

The basic connotation of the "continuous" reservoir in this study is: the unconventional trap reservoir with continuous oil-gas distribution in a large-scale unconventional reservoir system, which has essential difference from traditional single closed-trap reservoir (Table 2), and can be also called as unconventional trap reservoir. "Continuous" type highlights the continuous or almost continuous distribution of oil and gas; "reservoir" refers to the oil and gas accumulating place in the unconventional reservoir system, with no clear trap limit, no common oil-gas-water interface and pressure system, big difference in hydrocarbon saturation, and co-existence of oil-gas-water phases, which is remarkably different from the forming mechanism, distribution characteristics and technical method of conventional trap reservoir.

1.3 "Continuous" reservoir classification

Previous researches pointed out unconventional oil and gas included tight oil and gas sand, oil sand, CBM, shale oil-gas and gas hydrate [2-4] according to the field and type involved in the exploration discovery. At present, there is no classification scheme of "continuous" reservoir proposed at home and abroad. According to the trap/reservoir substantial characteristics of "continuous" reservoir, the paper proposed several classification schemes (Table 3).

2 Basic characteristics and accumulation mechanism of "continuous" reservoir

2.1 Basic characteristics

The essential characteristics of "continuous" reservoir are the development in the unconventional reservoir system with ambiguous trap boundary and large range; and there is no common oil-gas-water interface and pressure system. It can be regarded as non-trap, unconventional trap and non closed trap or "invisible" or "subtle" trap. The basic characteristics are as follows:

Table 2　Major difference between “continuous” reservoir and conventional reservoir

Reservoir type	Distribution characteristics	Reservoir characteristics	Source-reservoir characteristics	Trap characteristics	Migration way	Accumulation	Flow characteristics	Fluid characteristics	Resource characteristics	Developing techniques
“Continuous”	Large-area “continuous” distribution at basin center and slope, local accumulation	Mainly large-scale unconventional reservoir	Mainly self generation and self reservoir	Non-closed trap without clear boundary	Mostly primary migration	Mainly by dispersion, buoyancy limited	Non-Darcy flow	Poor fluid differentiation, large saturation difference, co-existence of oil, gas, water and dry layer, no common oil-gas-water interface and pressure system	Low abundance, reserve calculation as per well control block	Special developing technique, pertinent technique required
Conventional trap	Relatively independent trap, non-continuous distribution	Conventional reservoir	Multiple source-reservoir relations	Conventional closed trap with clear boundary	Secondary migration	By buoyancy	Darcy flow	Upper oil(gas) lower water, clear interface	Reserve calculation as per trap factors	Mainly conventional technology, easy development

Table 3　“Continuous” reservoir classification

Serial No.	Classification basis		Major types
1	Reservoir rock type		Low-ultra low porosity and permeability (tight) sandstone reservoir, shale reservoir, carbonate rock reservoir with connected pores and fractures, volcanic rock pore-fracture reservoir and CBM reservoir etc.
2	Hydrocarbon origin		Reservoir of thermal origin, biogenetic origin and compound origin
3	Source-reservoir-seal assemblage	Source-reservoir assembly	Self-generating and self-preserving reservoir (CBM, shale oil gas etc.), non -generating and self-preserving reservoir (tight sandstone oil and gas etc.)
		Hydrocarbon source	Authigenic (CBM and shale oil & gas etc.) and allogenic reservoirs (tight sandstone oil & gas etc.)
4	Hydrocarbon occurrence		Absorbing type, free type and compound type
5	Continuity characteristics		Continuous reservoir of accumulation progress, space and development process

(1) Main types: low-ultra low porosity and permeability (tight) sandstone reservoir, carbonate rock pore-fracture-cavity reservoir, volcanic rock pore-fracture reservoir, CBM, shale oil & gas, deep basin reservoir, shallow microbial gas and gas hydrate etc (Fig. 1). According to the connotation and essential characteristics of “continuous” reservoir, the extension of “continuous” reservoir is incompletely consistent with the unconventional reservoir, including most unconventional and a few conventional reservoirs, as well as new types and fields at the present recognition blind area, but not all the unconventional oil and gas belongs to continuous reservoir, such as oil sand. “Continuous” reservoir highlights “invisible” or “subtle” trap and large-scale disperse distribution, including the reservoirs controlled by diagenesis and hydrodynamic action or those distributing in volcanic rock fracture and internal weathering crust, which also have “continuous” characteristics.

(2) Source rock characteristics: coal-measure or non coal-measure source rock of large-scale distribution shows integrated source and reservoir or close contact of source and reservoir, and the hydrocarbon expels inside or near the source rock. Good and rich source rock is the material basis of tight sandstone reservoir. For example, the upper Paleozoic Formation in the Sulige area in Ordos Basin and Xujiahe Formation in the central Sichuan Basin develop source rocks featuring high organic abundance, good type, and medium-high maturity. The coal measure can constantly generate gas that provides material basis for the development of sandstone giant gas provinces (zones) with low porosity and permeability [12-15].

(3) Reservoir characteristics: All types of “continuous” reservoir distrib ute in a large range with porosity usually less than 10%, permeability $10^{-9}\times10^{-3}$-1×10^{-3} μm^2 with some micro-fractures. According to the porosity and permeability parameter classification, China’s low and ultra-low porosity and permeability sandstone gas belongs to tight sandstone gas. In the Ordos Basin, the Carboniferous-Permian Formation is composed of large-scale deltaic systems in the Sulige area (Fig. 2). In the He_8 Member, average porosity and permeability values are 9.6% and 1.01×10^{-3} μm^2, respectively. In the $Shan_1$ Member, these values are 7.6% and 0.60×10^{-3} μm^2. According to the statistics on over 40,000 analysis samples in Xujiahe Formation throughout Sichuan Basin, the average porosity and permeability is 5.22% and 0.253×10^{-3} μm^2 respectively. The shale reservoir generally takes on the physical properties of low or ultra low porosity and permeability; porosity is generally 4%-6%, permeability is generally less than 0.0001×10^{-3} μm^2. The shale reservoir permeability at faulted zone or facture developing zone improves greatly, porosity occasionally exceeds 10%,

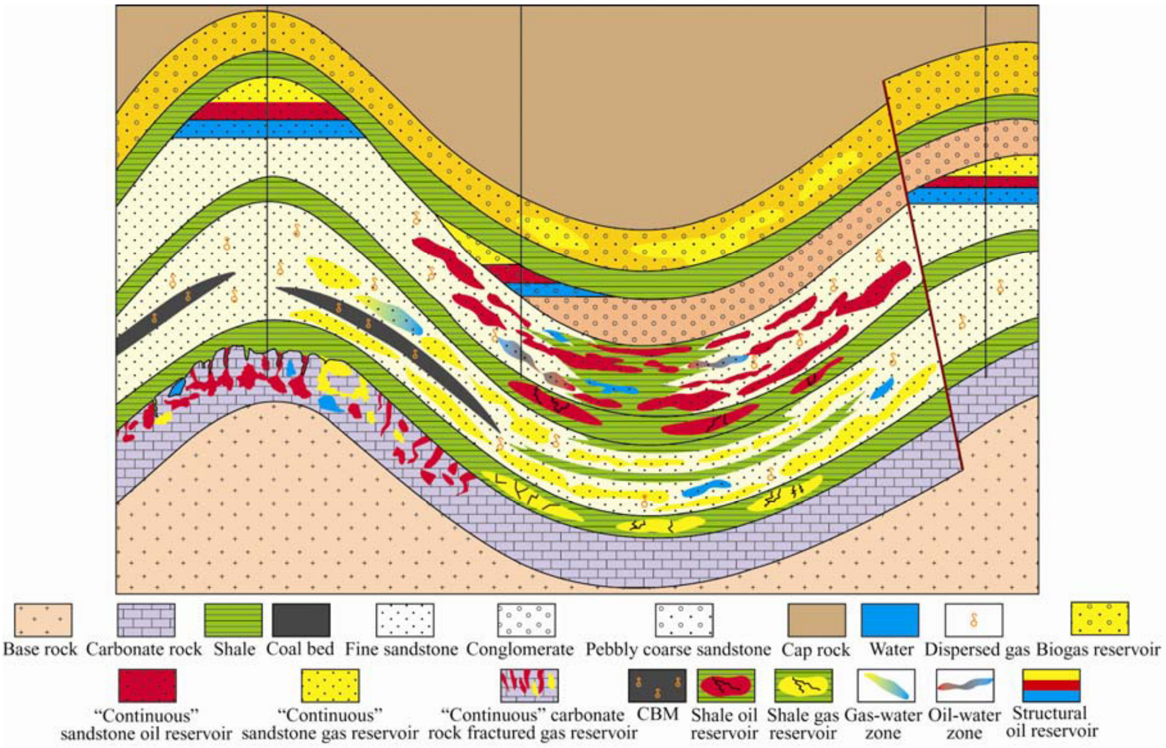

Fig. 1 Continuous reservoir distributing model of different types in the formation[12]

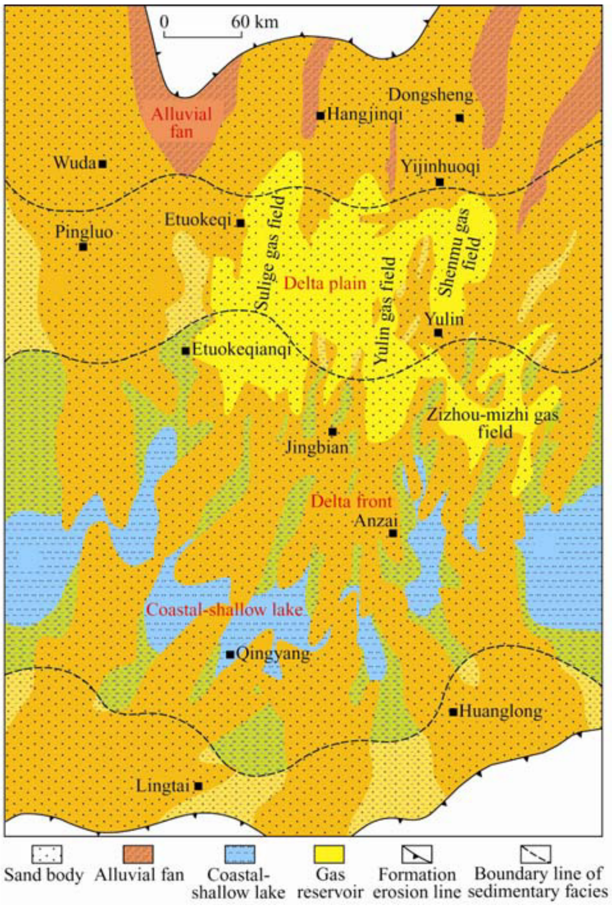

Fig. 2 Sedimentary facies and upper Paleozoic gas reservoir distribution of Permian H_8 in Ordos Basin

permeability is about 1×10^{-3} μm^2, but the general porosity and permeability is low.

(4) Trap characteristics: as unconventional trap reservoir, there is no clear trap and seal with fixed boundary, namely "invisible" or "subtle" trap. A large-scale continuous geological body with hydrocarbon accumulation is a hydrocarbon accumulation system, and the reserve calculation mainly depends on the well control block area. For example, as to Carboniferous Barnett shale gas reservoir of American Fort Worth Basin, the gas-bearing area is up to 1.6×10^4 km^2, in 2007 the recoverable reserve was about 7 500×10^8 m^3, and the annual production was 315×10^8 m^3. Carboniferous Barnett shale is both source rock and reservoir, but the gas reservoir of this type doesn't possess the conventional trap, and the natural gas distribution shows "continuous" accumulation. Wide regions in South China, such as Cambrian and Silurian marine formations in Sichuan Basin, develop rich shale gas resource with great exploration potential, which should be attached importance to.

(5) Accumulation characteristics: the effect of regional hydrodynamic force is small, and the accumulation mainly depends on dispersion since buoyancy is limited. Under low permeability and flow rate, the accumulation shows non-Darcy flow characteristics with poor differentiation of oil, gas and water, but the hydrocarbon migration in "sweet point" area is mainly controlled by buoyancy. The accumulating force is the discharge pressure in source rock, controlled by hydrocarbon generation pressure rise, poor compaction and structural stress; and the accumulating resistance is capillary pressure, both of which control the oil and gas boundary or range (Fig. 3). Large reservoir with low porosity and permeability mostly shows co-existence of oil, gas, water and dry layer, as continuous phase with complex distribution and without clear oil-gas -water interface; and the hydrocarbon saturation difference is great.

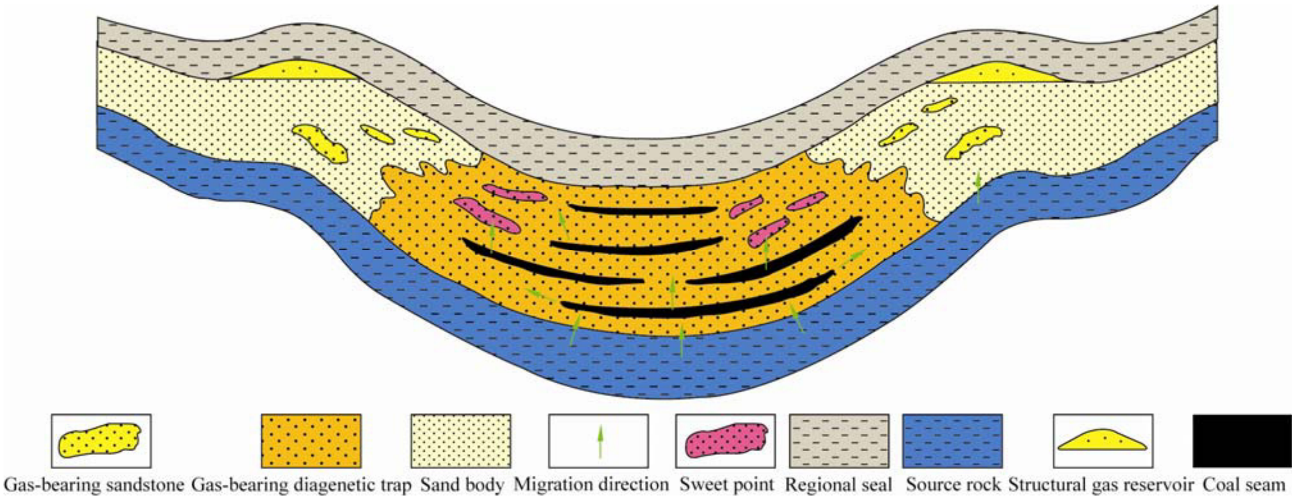

Fig.3 Accumulation mechanism model of tight sandstone gas reservoir

(6) Migration and accumulation characteristics: the "continuous" oil and gas migration distance is generally short, the effect of water column pressure and buoyancy is very limited in the migration and accumulation, and the primary migration is dominant. Especially for CBM and shale oil-gas, "source-reservoir-accumulation-seal" is an integrated system; there is almost no secondary migration, and the primary migration is not sufficient, the hydrocarbon is stored upon generated; while tight sand oil and gas shows secondary migration to some extent, among which dispersion is a major way of natural gas migration in the tight formation; for example, Xujiahe Formation in Sichuan Basin contains a large area of gas and some water. The development practice in Daqing, Changqing and Sichuan oilfields demonstrate that flow characteristics of low permeability reservoir are mainly non-Darcy flow; the driving force should be additionally applied to make the fluid flow, i.e., the fluid flow in the low permeability reservoir exists activating pressure gradient that enhances the additional flow resistance of fluid flow, thus special development technology should be adopted. As to CBM and shale gas, the natural gas is accumulated in the coal bed or shale in a way of absorption, which is substantially different from the migration and accumulation of conventional natural gas.

(7) Distribution characteristics: large area dispersed oil and gas (Fig. 4) shows the existence of "sweet point" and rich accumulation zone that directly contacts the source area; there is no water or less water in the lower reservoir or in the downdipping position, and the oil-gas-water relations are complicated, there is no common gas-oil-water interface and pressure system; the reserve scale is large and high production enriching block develops. For example, at the fracture or cleating belt, the CBM is under dehydration and degassing action and releases a lot of natural gas especially when the formation pressure declines, which determines the accumulation of natural gas. The cavity connecting carbonate rock and dissolved facies or fracture belt of tight sandstone are also oil and gas enriching area. Therefore, "continuous" reservoir also develops normal reservoir and favorable area controlled by "sweet point", which is the key object for the preferential development of "continuous" reservoir, "preferentially rich and then poor reservoir", but ultimately overall development should be carried out. "Continuous" reservoir distributes in the slope area or syncline area, which challenges the concept of oil and gas distribution controlled by conventional secondary structural belt and effectively extends the exploration range to the whole basin. The oil and gas is characterized by large area distribution and uneven abundance. For example, the capillary pressure sealing in the tight sandstone has dual flow mechanisms of Darcy and Non-Darcy, and the accumulation process takes on the dynamic mechanism of "overall advancing and blanket accumulation". The reservoir shows poor physical property and complicated oil-gas-water relations when it is controlled by capillary pressure. In this type of reservoir, water may occur in structural highs, and oil may occur in structural lows. Therefore, it is necessary to fully understand the complexity of oil-gas-water distribution.

(8) Development techniques: the development is very difficult with conventional technology, and pertinent technologies should be employed, such as artificial stimulation, large amounts of drilling, multilateral drilling or horizontal drilling, the single well production is generally low but relatively stable. For the natural gas development, the dispersed gas can be placed constantly and provide gas source with a long development life, which shows dynamic "continuity" in the development process. The core exploration and development technologies should be developed aiming at the "continuous" reservoir, such as resource and reserve evaluation method, pre-stack seismic reservoir and fluid saturation prediction, as well as borehole stimulation. The low permeability sandstone reservoir in China is generally characterized by "three lows and one large", namely low porosity and permeability, low abundance, low production and large area distribution. Usually the special techniques, such as reservoir protection, and stimulation, are employed. CBM and shale gas are similar; for example, American Barnett shale gas reservoir is characterized by low single well production

(0.1×10^4-1×10^4 m^3/d) and long production period (30-50 a), the horizontal well and sectional fracturing are needed to realize economical and effective development.

2.2 Accumulation mechanism

The "continuous" reservoir is characterized by (1) special-accumulation environment, (2) continuous-accumulation process, (3) continuous-accumulation space, and continuous-development process.

2.2.1 Special accumulation environment

The current major "continuous" reservoirs show particularity in the aspects of basin structural background, reservoir property, source-reservoir-seal assemblage, environmental physical and chemical conditions, and oil-gas migration: (1) "continuous" reservoir develops at the basin center and slope in the environment of special thermodynamic field, pressure field and fluid field. For example: the environment of deep oil and gas is under the deep high temperature and high pressure; the processes of hydrocarbon generation, accumulation and development all need special conditions. (2) The laminar and sheet distribution of reservoir with poor physical property determines complicated flow mechanism, low reserve abundance and large development difficulty. For example, shale is traditionally considered to have no reservoir characteristics and is difficult to develop. The shale oil and gas attaches at the surface of organic matter of shale and enriches at the fracture developing belt, the overall reserve abundance is low, but the scale and potential is large. The tight sandstone oil gas is stored in large area of low porosity and permeability reservoir, the production with traditional development means is very low. (3) Source- reservoir-seal assemblage has some unique features, or source reservoir integration (CBM, shale oil gas) or source and reservoir contacting (tight sandstone oil and gas), which presents "sandwich" configuration. The CBM reservoir—— coal bed is a special reservoir as dual media of low permeability and deformation. (4) Environmental, biological, physical and chemical conditions are special, including environmental temperature and pressure conditions and biophysical-chemical effects. For example: shallow microbial gas is generated from micro organisms in a very harsh environment [16, 17], in which the gas hydrates occur mainly at seabed or on land with permanent frozen layer.

2.2.2 Continuous accumulation process

The continuous accumulation process can be understood as the accumulation (supply and escape) is a continuous dynamic balance process, and the accumulation is relatively continuous. Coal measure source rock is "all-weather" gas source rock with long gas generation time, Ro value is 0.6%-6.0%, and it is a typical source rock with continuous hydrocarbon generation. The continuous hydrocarbon generation provides material basis and precondition for constant accumulation. Shale oil gas, CBM and tight sand gas from coal measure show obvious "continuous" accumulation. The other continuous gas accumulation also shows continuity, such as shallow microbial gas and gas hydrate. The shallow microbial gas accumulation is a constant balance of supply and escape; as long as there is suitable conditions and sufficient resource, the microbial gas generation will continue; and the shallow sand microbial gas source is not only shallow microbial gas but also the CBM migrating from the deep area through "gas chimney". Gas hydrate has the similar characteristics, with its forming model established in the lab. With the basic conditions and sufficient methane and water source, gas hydrate will be formed continuously.

2.2.3 Continuous spatial distribution

Continuous or quasi-continuous spatial distribution of accumulation is the fundamental characteristic of "continuous" reservoir. Integrated source and reservoir or large range continuous reservoir, and invisible or subtle trap determines the large area and continuous distributing oil and gas province; the formation generally contains oil and gas; the reservoir boundary is unobvious or difficult to confirm and great oil and gas provinces are easy to develop. The most typical "continuous" reservoir is low-ultra low porosity and permeability or tight sand oil and gas, and the deep basin gas in the domestic research actually belongs to tight sand gas. The tight sand gas shows the spatial continuous characteristics: (1) gas reservoir distributes continuously in a large area; sandstone generally contains gas and gas saturation is uneven; (2) there is lack of gas-water contact and edge-bottom water, and the reservoir boundary is unclear. As a continuous gas, shale gas has greater continuity [18, 19]. The shale gas is generated from and stored in shale. Shale gas is stored in the pore and fractures between the shale rock grains or adsorb on the surface of organic matter of shale, and there is no clear trap boundary and gas-water interface. CBM adsorbs in the very particular reservoir——underground coal bed whose trap boundary delineation is more difficult. As to the reservoir at basin center and slope with source-reservoir contacting, the spatial distribution also shows "continuity", such as the Continuous reservoir distribution of Triassic in Ordos Basin (Fig. 4). The continuous accumulation space distribution is a primary characteristic, phenomenon and mark of "continuous" reservoir.

2.2.4 Continuous development process

"Continuous" reservoir, especially "continuous" gas reservoir, is usually characterized by continuous gas production and supply, low production and stable productivity; large resource amount, but low recovery rate, and the reservoir needs artificial stimulation. The "continuous" reservoir, without geologic feature for continuous development, depends on the continuous accumulation of the low-abundance free-gas, adsorbed gas and dispersed gas characteristics for continuous development. Taking shale gas as an example, according to the statistics on the American shale gas well, the production period of shale gas well is long, and annual decline rate is less

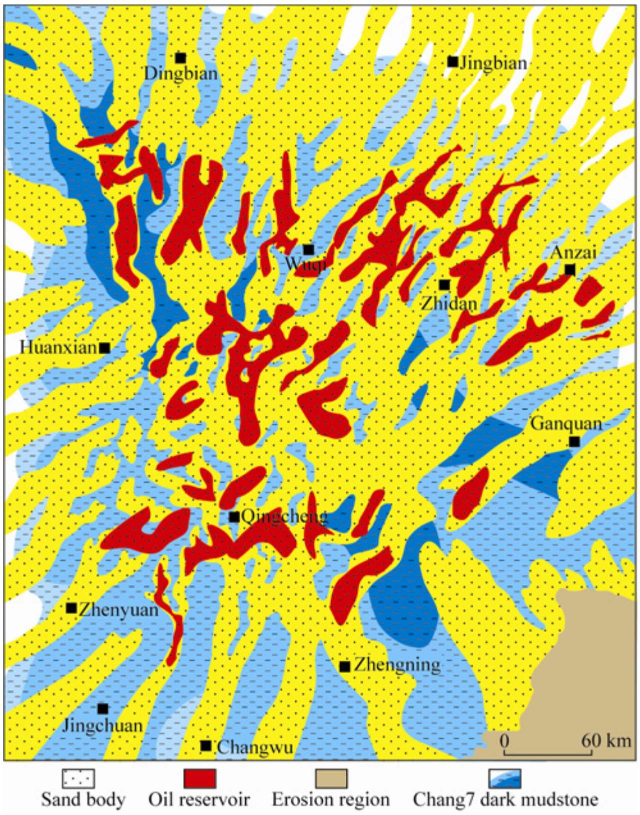

Fig. 4 Continuous reservoir distribution of Yanchang Formation in Ordos Basin

than 5%, usually 2%-3%. When the fractured shale gas reservoir is put into production, the free gas in the fracture and matrix pore is firstly discharged. With the decline of formation pressure, the absorbing gas on the rock surface begins to desorb and enters the fracture system through dispersion, and the shale gas in the fracture enters the well bottom and is recovered to ground. The free gas flow rate is fast, the dispersion rate of the absorbing gas is slow with low production, but the decline rate after stable production is low, the production cycle is relatively long, and the life of general shale gasfield is 30-50 a. The latest data[20] from USGS show that the development life of Barnett shale gasfield is up to 80-100 a. And the tight sand gas is also characterized by continuous production process [21, 22].

3 Major types and control factors, and distribution characteristics

The unconventional reservoir carrier——low-ultra low porosity and permeability (tight) reservoir distributes continuously in a large area, which is the precondition and fundamental reason of "continuous" reservoir. The theoretical basis of "continuous" reservoir of low-ultra low porosity and permeability (tight) sand is as follows: in macroscopic view, sands are distributed largely and continuously; whereas in microscopic view, such sands, though with internal heterogeneity, has no clear and fixed single trap boundary. The reservoir configuration of coal gas, shale gas and gas hydrate, which is similar to tight sand gas, has no single trap with clear and fixed boundary but consists of heterogeneous ambiguous dynamic trap. The difference is that the low—ultra low porosity and permeability (tight) sand oil and gas shows "separate source from reservoir, source connecting with accumulation", while coal gas and shale oil-gas shows "source-reservoir-accumulation integration". The large-area low permeability sandstone reservoir, carbonate rock reservoir with connected fractures and cavities, shale and volcanic rock pore-fracture reservoir discovered in China all show "continuity" to some extent.

3.1 "Continuous" sand gas

Carboniferous-Permian in Ordos Basin and Triassic Xujiahe Formation in Sichuan Basin are of large-scale shallow delta facies (Figs. 5 and 6); the large area source rock expels hydrocarbon as laminar evaporation, and large-scale low—ultra low porosity permeability sand is distributed continuously and characterized by lower-generating & upper-preserving, or "sandwich-type" source-reservoir-seal assemblage; thus forming the large-area "continuous" gas province (zone) under gentle background [12-15].

3.1.1 Characteristics of low—ultra low porosity permeability sand (tight) gas reservoir

The low—ultra low porosity permeability sand (tight) gas reservoir shows poor physical property (porosity less than 10%, permeability $10^{-9}\times10^{-3}$-1×10^{-3} μm^2); the general migration distance is short, sandstone is interbedded with mudstone and source connects reservoir; there is no clear trap and direct seal, and the reservoir is inside the middle-late diagenesis system, but the overlying regional seal is good with weak tectonic movement and good conservation conditions; and the reservoir distributes at the basin center and slope with complicated gas-water contact and distribution.

3.1.2 Low—ultra low porosity permeability sand (tight) reservoir-forming mechanism

The accumulation in this sand follows the migration principle of "piston", that is, "laminar" gas migration shows large area contact between tight oil-gas zone and gas source rock. The primary migration is dominant due to buoyancy limited, which is substantially different from the displacing accumulation model of conventional gas reservoir by buoyancy force. As to the heterogeneous connected sands in the central Sichuan Basin, the combination of gas reservoir dissection example and simulating experiment reveals the accumulating mechanism of low porosity and permeability sand gas reservoir of different types (Fig. 7).

The connected sands directly contact the coal measure source rock in great Sulige of Ordos Basin, so the natural gas accumulation is a continuous filling process. From Triassic to Neogene, gas generation, expulsion and accumulation always exist, which shows continuous accumulating process. Because Xujiahe Formation source rock and reservoir are distributed alternately in a large range with a gentle occurrence, the large area and low abundance "continuous" or quasi-continuous great gas province (zone) is developed.

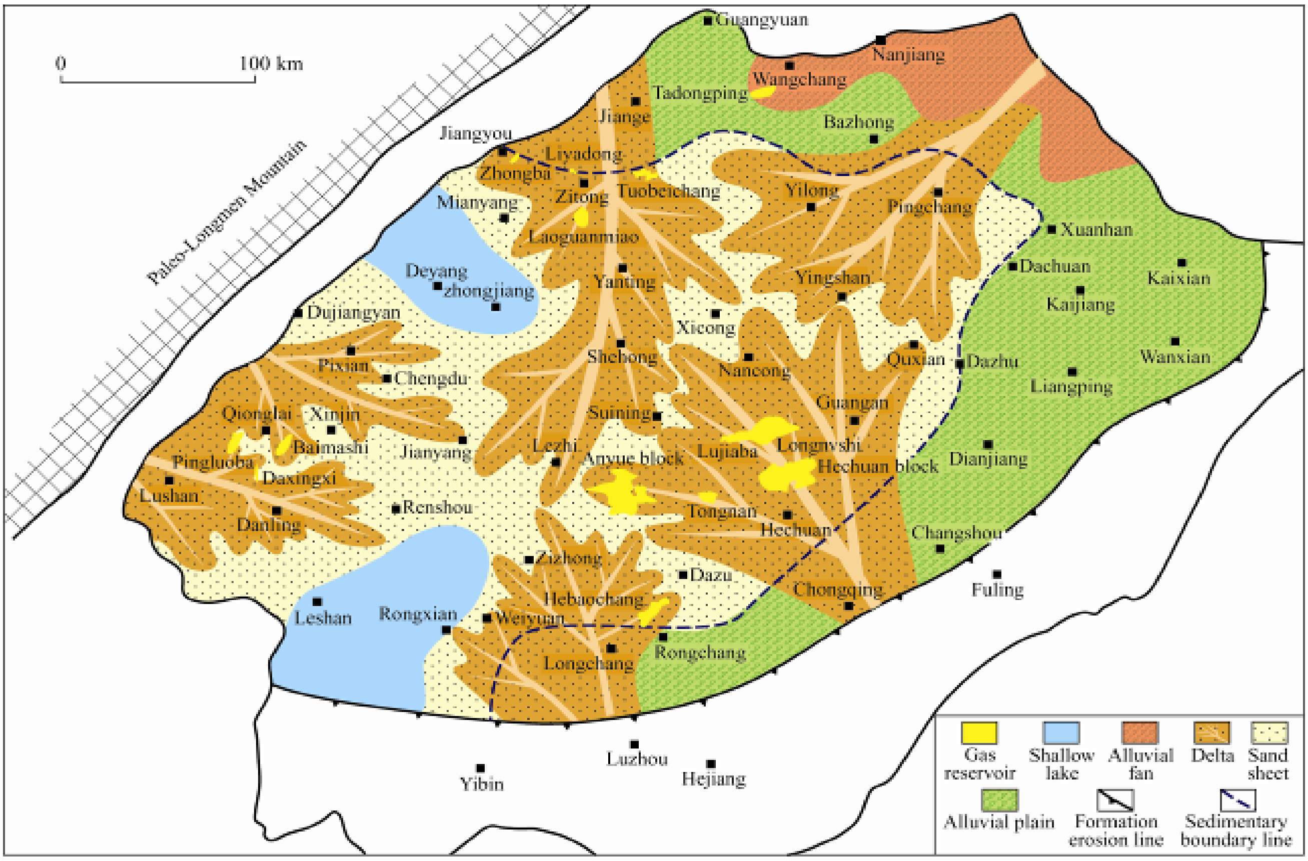

Fig. 5 Sedimentary facies of Upper Triassic Xujiahe2 Member in Sichuan Basin

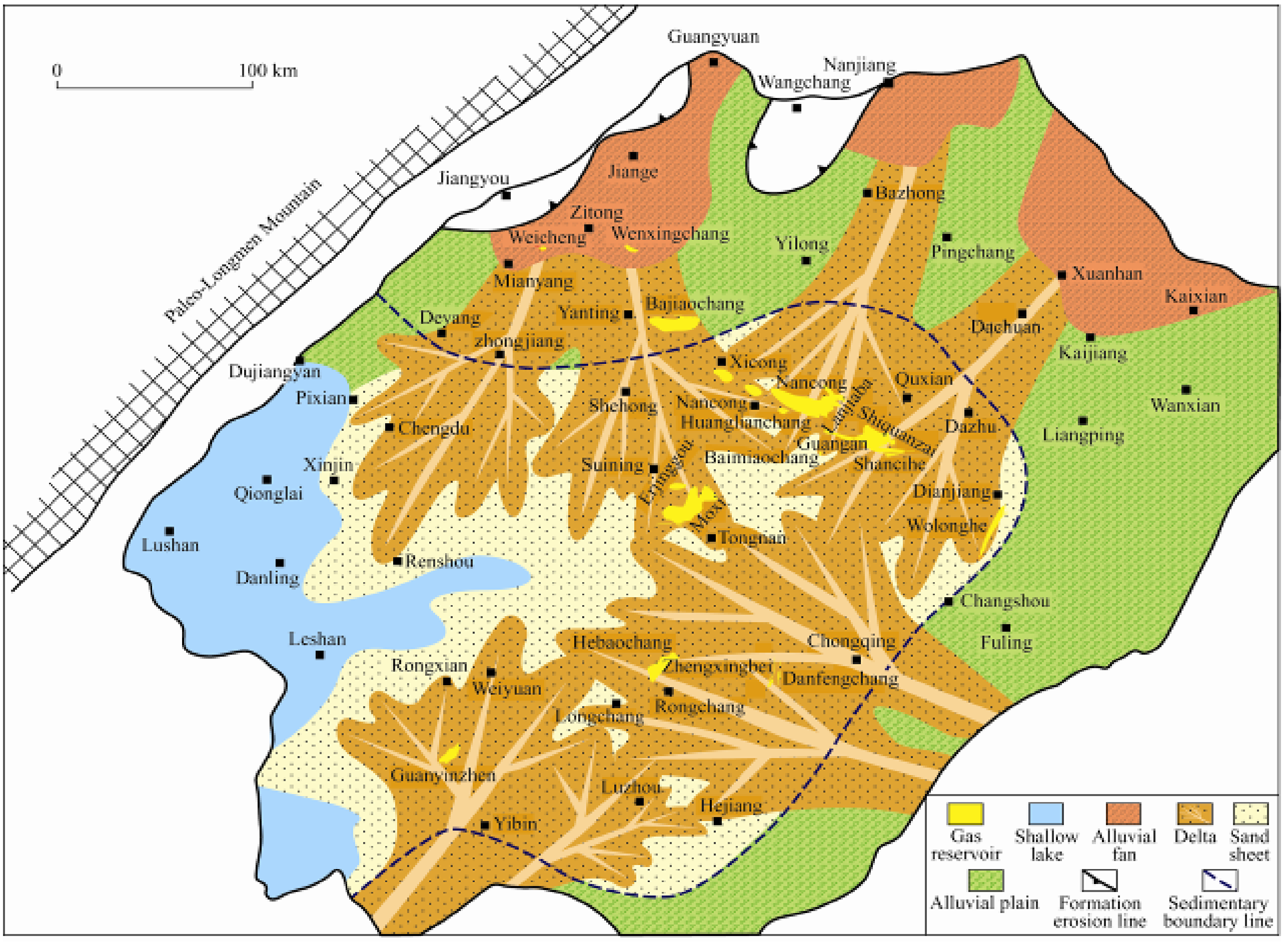

Fig. 6 Sedimentary facies of Upper Triassic Xujiahe4 Member in Sichuan Basin

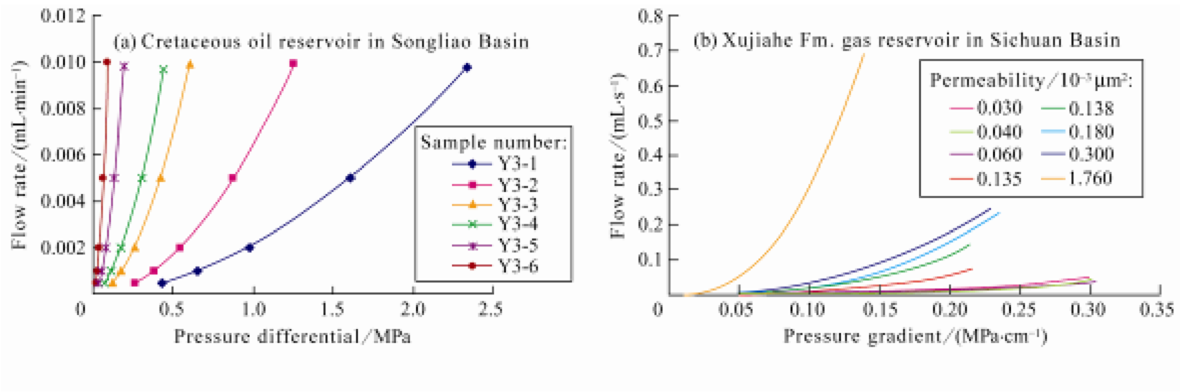

Fig. 7 Non-Darcy flow characteristics of low porosity permeability sandstone

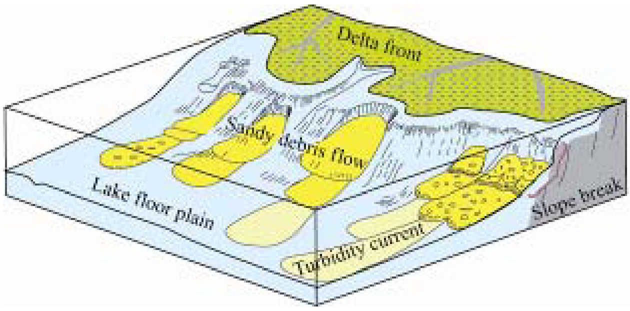

Fig. 8 Sandy debris depositional model for Chang6 Formation in Baibao area

3.1.3 Rich accumulation factors of low—ultra low porosity permeability sand (tight) reservoir

Favorable diagenetic facies, fault and local structure are the major factors for “continuous” gas accumulation, the favorable diagenetic facies in Xujiahe Formation in Sichuan Basin is medium-coarse dissolved sandstone, and the faults are developed in NNE and EW directions in different blocks. On the slope featured by higher in west than east, local structures, such as Guang’an structure, are developed into rich gas play of hundred billion cubic meters grade.

In summary, the “continuous” reservoirs should meet the following two conditions: (1) a large volume of source rock with sufficient laminar gas supply and high supply rate, and (2) a large volume of low—ultra low porosity permeability (tight) connected sand.

3.2 “Continuous” sandstone reservoir

Large-scale open-flow shallow delta provides conditions for large-scale reservoir system. The middle-deep reservoir in Songliao Basin and Triassic large-area continuous oil province (zone) in Ordos Basin mainly take on laminar source rock and large-area overlapped & connected sands, to develop into “continuous” reservoir. The thick sandy debris flow in the lake basin center was ignored by previous exploration and research to great extent; instead it was misunderstood as turbidite. The reason is that turbidite becomes a dominant factor in the thought, Shanmugam and Zimbrick modified the classification of deepwater gravity flow and added sandy and argillaceous debris flow [23].

Chang6 oil layer group in Baibao area in Ordos Basin develops a large set of deepwater sandy debris flow (Fig. 8). The sandstone observes two kinds of rock in the debris flow: pure massive sandstone and mud-gravel packsand. The normally-graded turbidite is underdeveloped, and the massive oil-bearing sandstone is the major reservoir with lateral continuity and large cumulative vertical thickness.

Based on the outcrop and core observation as well as logging parameter analysis, the gravity depositional model of deepwater “sandy debris flow” at depression lake basin center was established, represented by Chang6 Formation in Ordos Basin. Such a model points out that slope break of delta front is the major place of sandy debris flow distribution. The experimental research shows that Chang6 Formation in Baibao area developed sandy debris flow as banded distribution at the delta front ring end, which is characterized by wide distribution, large thickness and good physical property. And the prospective exploration area is about more than 4 000 km^2. The lake basin center can develop large-scale sandy debris flow due to collapse at the middle-lower slope or slope break, but the turbidite as fan-like distribution is less. Large-scale “sandy debris flow” is also discovered in many lake basin centers, such as Songliao Basin. The sands distribute continuously and can easily develop “continuous” or quasi-continuous reservoir. This new recognition broadens the oil exploration field at the lake basin center.

3.3 CBM

CBM is a kind of self-generating and self-preserving unconventional natural gas generating from coal bed and accumulating in coal bed, and mainly comprises of methane (content over 95%), less heavy hydrocarbons (mostly ethane and propane) and nitrogen and carbon dioxide. CBM shows integrated gas source and reservoir, accompanied source and reservoir, and unclear trap boundaries. Coal rock not only generates hydrocarbon continuously but also shows “continuous” characteristics of migration, enrichment, accumulation, distribution and development as typical “continuous” gas reservoir.

CBM reservoir contains a group of perpendicular faults called “cleat” perpendicular to coal bed, which provides major channel for fluid flow. The major factors controlling CBM content include coal bed thickness, coal component, absorption gas content and gas component. Coal component refers to the number and type of organic component that will greatly affect the number of absorption gas. The CBM gas content changes dramatically and is the function of coal component, thermal maturity, burial and rising history, migration heat increase or organic gas increase etc. In a word, CBM mainly absorbs the surface of coal grain, and some CBM contains trace free gas and dissolved gas in the coal cleat and fractures. The CBM heat is above 33 494.4 J/m^3 (8 000 kal/m^3) [24-27].

CBM conservation has obvious zoning property. CBM reservoir is not formed in-situ, contemporaneously or once; through coalification in the coal measures and under overlying deposition, faulting and hydrodynamic force, several zones with internal links are developed. In light of the CBM δ13C1 value, non-hydrocarbon content, methane content and development characteristics, four zones (Table 4) are usually divided from basin margin to hinterland usually: oxidation dissipating zone, biodegradation zone, saturation absorbing zone and low desorbing zone, among which saturation absorbing zone is characterized by large amount of gas, high absorbing saturation, medium burial depth, good physical property, and high single-gas-well production due to good caprock conditions and confined water sealing; thus this zone is the primary target for CBM exploration.

In the CBM exploration, the medium-high order coal should explore the saturation absorbing zone with regional thermal metamorphism, cleat development and confined water sealing; for the low order coal, the high permeability area with thick coal bed, deep basin shallow bed and good sealing conditions should be found.

3.4 Mud shale "continuous" reservoir

Mud shale fracture system refers to the reservoir with the major storage space of microfissure and fracture in the rock combination of mudstone and shale, which is a special "continuous" "self-generating and self-preserving" fractured-reservoir, including mud shale oil and gas. At present most domestic discovered fractured reservoir of argillaceous rock distributes in the source rock of dark mudstone and shale, and usually contains rich organic matter, calcium or silica minerals. The organic carbon abundance is usually 1.0%-20% with many organic matter types and the Ro is mostly 0.5%-1.3%. The mud shale fractured reservoir is similar to shale gas as a typical "continuous" reservoir through continuous fracturing network system.

Mud shale fractured reservoir develops in special geologic environment with corresponding accumulation conditions: (1) good source rocks; (2) fractured reservoir; (3) good sealing of network fracture in the thick mud shale. The mud shale fractured gas reservoir mainly develops in high-over mature mud shale source rocks. Shale gas is discovered both home and abroad. Barnett shale gas in American Fort Worth Basin contains organic carbon content of 4.5%, Ro value of 1.0%-1.3%, reserve abundance of 3.28 × 108-4.37 × 108 m^3/km^2 with good economic benefit (Table 5). Shale gas in China is mainly discovered in Sichuan Basin. For example, Jiulaodong Formation shale gas in southwestern Sichuan contains carbon content of 0.44%-2.70%, Ro value of 1.83%-3.23%, reserve abundance of 0.87 × 108-5.79 × 108 m^3/km^2 (Table 5), the burial depth is relatively large and about 3 200-5 000 m, the resource potential is large as "continuous" distribution.

The above mainly discusses the "continuous" clastic reservoir; among which carbonate rock and volcanic rock reservoir also belongs to "continuous" reservoir, but the precondition is that the oil and gas is conserved in the network space constituted by continuous large-area fractures and cavities. The carbonate rock has no clear trap boundary of pore, cavity and fracture, is difficult for trap description, consists of continuous and quasi-continuous reservoir space with less continuity than tight sand gas, but also shows "continuous" oil and gas characteristics. The "continuous" or "quasi- continuous" reservoir space (such as pore, cavity and fracture) developed from faulting, fracturing and secondary leaching plays a key controlling role on the development and distribution of carbonate rock network system, for example, carbonate rock gas fields in Lunnan Oilfield in Tarim Basin, Tahe Oilfield and central Ordos Basin. The network reservoir developing in some volcanic rock fracturing system also shows the "continuous" reservoir characteristics. The fracture development degree is an important condition for the forming of volcanic rock "continuous" reservoir, e.g., the continuous reservoir of Carboniferous large-area weathering crust in the northwestern margin of Junggar Basin.

4 Resource evaluation methods

Resource evaluation method of "continuous" reservoir is completely different from conventional reservoirs. The FORSPAN model of "continuous" reservoir resource evaluation method proposed by USGS is firstly employed in the American hydrocarbon resource evaluation in 1995 by USGS, which is worth research and attention. FORSPAN provides an evaluation strategy of potential reserve increase in the coming 30 a and highlights that the reservoir comprises of a series of hydrocarbon-filling units. The production data of such units is the basis to predict the potential reserve increase, which can be used to obtain the information about oil & gas in space and "recovery ratio", which is greatly different from conventional resource evaluation methods.

This evaluation method considers that the continuous reservoir is an aggregate constituted by hydrocarbon-filling units[1]. Each unit has certain gas production, but the production development index (including economic profit) is different in different units.

These units include three types: (1) unit proved by drilling; (2) unit unproved; (3) unit unproved but with potential reserve increase. Under many circumstances, the distribution area with one or many "sweet points" is very clear before evaluation where the production data is relatively complete, but the unproved unit with potential reserve increase usually distributes near sweet point.

The resource evaluation procedure and workflow with

Table 4 CBM origin zoning characteristics in the medium-high rank

Origin zoning	Structural location	Coal bed depth/m	CBM conservation conditions and gas-bearing characteristics	CBM storage	Hydrodynamics	CBM component		$\delta^{13}C_1$/‰	Fluid draining of pilot well	Typical area
						Hydrocarbon/%	Non-hydro carbon/%			
Oxidation dissipating zone	Near coal erosion	<200	Serious coal corrosion, poor sealing, in open-half open environment, low gas content	Mainly dissolved gas in water	Surface flow-drainage	<75	>25	—70-—55	Water, air or no air	Fugu-Lishi in eastern slope of Ordos Basin, Chengzhuang in southern slope of Qinshui Basin
Biodegradation zone	Slope updipping	200-500	Poor sealing and low gas content	Dissolved-absorbing type	Weak surface flow	75-95	5-25	—65-—50	Quick decline of daily gas production, large water production and small gas production of gas well	:iulin-Mengmen in eastern slope of Ordos basin, south to Panzhuang in southern slope of Qinshui Basin
Saturation absorbing zone	Central slope	500-1 200	Developed coal cleat with good physical property, high gas content and absorbing saturation in retention region with good sealing, high desorbing rate	Absorbing -free type	Weak surface flow-retention	>95	<5	—50-—30	Initial small gas large water production, middle-late large gas small water production	Daning-Jixian in eastern slope of Ordos Basin, Chengzhuang-Fanzhuang in southern slope of Qinshui Basin
Low desorbing zone	Hinterland and slope deep	>1 200	Mainly micro pore, poor physical property, high gas content, low desorbing rate	Absorbing type	Retention	90-95	5-10	<—45	Small gas well production	Yulin-Yanchuan in eastern slope of Ordos Basin, Hinterland in Qinshui Basin

Table 5 Shale gas abundance comparison between China Sichuan Basin and American basins

Country	Basin	Shale system name	Shale time	Net shale thickness/m	*TOC*/%	R_o/%	Reserve abundance/(10^8 m^3· km^{-2})
America	Michigan	Antrim	Devonian	21-36	0.30-2.40	0.40-0.60	0.66-1.64
	Appalachian	Ohio	Devonian	9-30	0.00-4.70	0.40-1.30	0.55-1.09
	Illinois	New Albany	Devonian	15-30	1.00-2.50	0.40-1.00	0.76-1.09
	Fort Worth	Barnett	Mississippi	300-500	4.50	1.00-1.30	3.28-4.37
	San Juan	Lewis	Cretaceous	60-90	0.45-2.50	1.60-1.88	0.87-5.46
China	Sichuan		Jiulaodong	220-350	0.44-2.70	1.83-3.23	0.87-5.79

FORSPAN model is as follows: firstly divide a continuous reservoir into several valuation units as the basic evaluation unit, and through the evaluation on each unit, select the estimated EUR value of each unit; then evaluate the geologic risk and development risk, and predict the number and EUR of unproved units of potential reserve increase in the coming 30 a; and finally predict the distribution of potential reserve increase.

FORSPAN model uses ACCESS calculation method (an electronic worksheet computing system with probability function as mathematic computation basis and with evaluation unit as calculation unit) to evaluate the "continuous" reservoir, and the evaluation workflow includes the following 8 procedures [1]:

(1) The "continuous" reservoir to be evaluated is divided into several evaluation units-hydrocarbon-filling units, among which the potential reserve increase without drilling proof is the direct target to be concerned in FORSPAN model.

(2) As to each evaluation unit, the EUR takes a low limit, and the hydrocarbon at low limit is not included in the reserve calculation in the prediction years.

(3) Geologic risk assessment: there should be at least one evaluation unit with sufficient reservoirs, hydrocarbon-filling time and charging quantity, and EUR larger than corresponding low limit.

(4) Development risk assessment: there should be some evaluation unit which can produce oil and gas in the coming 30 a.

(5) Calculate the probability distribution of undrilled unit number with potential reserve increase in the coming 30 a, following 3 steps [1]:

At first, calculate the undrilled unit ratio T with potential reserve increase in the evaluation area [1].

$$\mu_T = \mu_R \mu_S \ / \ 100 \tag{1}$$

$$\sigma_T = \sqrt{\mu_R^2 \sigma_S^2 + \mu_S^2 \sigma_R^2 + \sigma_R^2 \sigma_S^2} \Big/ 100 \tag{2}$$

among which, R is the undrilled unit ratio in the evaluation area, S is unit ratio with potential reserve increase in the evaluation area, μ is mean, and σ is standard error. The average and variance of the two values is figured out by probability density function with sampling statistics, and usually the triangle and censored logarithm distribution based on median is adopted.

Then, calculate the undrilled unit coverage W [1] with potential reserve increase in the evaluation area with T.

$$\mu_W = \mu_T \mu_U / 100 \tag{3}$$

$$\sigma_W = (1/100)\sqrt{\mu_T^2 \sigma_U^2 + \mu_U^2 \sigma_T^2 + \sigma_T^2 \sigma_U^2} \tag{4}$$

Where, *U* is evaluation area coverage, whose mean and variance adopts probability density function.

At last, calculate the undrilled unit number *N*[1] with potential reserve increase in the evaluation area with *W*.

.

$$W = \sum_{i=1}^{N} V_i \quad (5)$$

$$\mu_N = \mu_W / \mu_V \quad (6)$$

$$\sigma_N = \sqrt{(\sigma_W^2 - \mu_N \sigma_V^2) / \mu_V^2} \quad (7)$$

Where, V_i is the undrilled unit coverage with potential reserve increase, whose mean and variance can be figured out with probability density function.

(6) Calculate the EUR probability distribution of undrilled unit with potential reserve increase in the coming 30 a: input the reservoir parameters of undrilled units for EUR calculation into simulation database of drilled unit dynamic parameter, then the EUR probability is calculated from simulation.

(7) The ultimate recoverable reserve of petroleum by-product or joint-product can be predicted. The gas/oil ratio and condensate oil/gas ratio are evaluated with the oil as major unit; the oil-water/gas ratio is evaluated with gas as major unit.

(8) Ultimately calculate the potential reserve increase Y and by-product or joint-product reserve [1] in the evaluated unit through the following computation.

$$Y = \sum_{i=1}^{N} X_i \quad (8)$$

Where, Xi is the potential reserve increase in a single evaluation unit. Because potential reserve increase Y is a probability distribution sequence; thus some key data [1] to limit Y should be calculated [1]:

$$\mu_Y = \mu_X \mu_N \quad (9)$$

$$\sigma_Y = \sqrt{\mu_N \sigma_X^2 + \mu_X^2 \sigma_N^2} \quad (10)$$

$$\mathrm{Min}\,(Y) = \mathrm{Min}\,(N)\,\mathrm{Min}\,(X) \quad (11)$$

$$\mathrm{Max}\,(Y) = \mathrm{Max}\,(N)\,\mathrm{Max}\,(X) \quad (12)$$

This prediction model should be paid enough attention to.

5 Exploration and development technologies

The special hydrocarbon distribution rule of "continuous" reservoir puts forward higher requirements on E&D technologies. And in many aspects, such as seismic response and logging judgment of favorable reservoir distribution, drilling and formation test means, reservoir stimulation methods, development evaluation, well pattern, EOR, and matching techniques etc., the "continuous" reservoir is different from the conventional reservoirs and needs pertinent technologies for development.

5.1 Geologic evaluation technology of "continuous" reservoir

5.1.1 Industrial application technology of sequence stratigraphy

The industrial application of sequence stratigraphy has "six procedures": (1) sedimentary background survey; (2) sequence division and correlation; (3) closure tracing within sequence boundary; (4) integrated analysis on sedimentary facies; (5) sequence boundary constrained seismic reservoir prediction; (6) accumulation rule and target evaluation.

Under the constraint of high resolution sequence framework, by tracing closure within sequence boundary, all kinds of new technologies, such as reservoir inversion, isotime slice, seismic waveform classification, 3D visualization interpretation, are used in sequence analysis, to compile a series of sandstone thickness map and sandstone content contour map, and improve the precision of sandstone prediction. This procedure can predict remarkable lithologic traps and unconventional large-area lithologic reservoir bodies.

5.1.2 Diagenetic facies quantitative evaluation technology

"Continuous" reservoir generally shows poor physical property and needs diagenetic facies reservoir space evaluation. The favorable reservoir distribution is mainly predicted according to seismic, drilling and outcrop data. The major procedures are: (1) sedimentary and diagenetic background analysis, to confirm the macroscopic distribution rule and major control factors of diagenetic facies and compile depositional system or facies (subfacies/microfacies) distribution map, rock type chart and ancient-present fluid physicochemical composition chart; (2) core and thin section analysis, to confirm the diagenetic facies type and compile the single well diagenetic facies column and well-tie diagenetic facies distribution diagram; (3) logging and seismic facies prediction, to confirm the lithology and porosity-permeability distribution in non-coring wells or non-well areas, and compile the porosity and permeability map/section and diagenetic facies type prediction; (4) composite analysis of diagenetic facies, to compile diagenetic facies map/section and predict distribution of favorable reservoirs and sweet points.

As to low porosity and permeability reservoir, such as Xujiahe Formation in Sichuan Basin, Yanchang, Shihezi and Shanxi formations in Ordos Basin, one of key questions containing exploration is strong reservoir heterogeneity, and the favorable reservoir and rich accumulation of hydrocarbon is obviously controlled by dilatancy diagenetic facies. For example, aimed at deposition and reservoir characteristics of Xujiahe Formation in Sichuan Basin, the quantitative descriptions of diagenetic facies, such as compaction ratio, cementation ratio and dissolution ratio, are applied to quantitatively classify the diagenetic facies into 8 subfacies and 20 microfacies. The relative data, such as Ro, formation water salinity and pH, are applied to analyze the origin of diagenetic facies. Through extraction of typical logging parameters (such as element logging, GR logging and density logging) and seismic attribute parameters, the favorable diagenetic facies are predicted.

5.2 Seismic prediction technology of "continuous" reservoir

The seismic prediction technology of "continuous" reservoir widely applied today includes high resolution full digital 2D, high resolution 3D, multi-component and high-density seismic survey; through pre-stack processing and pre-stack reservoir fluid prediction, the E&D efficiency is greatly improved; thus it is one of core technologies.

The full 2D seismic survey is mainly carried out in Ordos Basin, the effective band is up to 4-110 Hz, and the apparent main frequency of the target formation is above 45 Hz. Through seismic reservoir prediction and gas detection, the "continuous" gas reservoir and gas-bearing sandstone distribution can be effectively identified. The high resolution 2D survey in Xujiahe Formation in Sichuan Basin shows high pre-stack gas detection success rate and the accordance rate is above 75%.

As to the carbonate rock fracturing system, such as Lunnan in Tarim Basin, fracture distribution is performed on the basis of the high resolution 3D seismic volume, the carved fracture and cavity distribution and the seismic slice, to direct E&D deployment.

5.3 "Continuous" reservoir development technologies

"Continuous" reservoir is mainly characterized by low-ultra and low porosity and permeability and large development difficulty; and the conventional technology requires fracturing technology; the horizontal and multilateral drilling technologies are mainly adopted to increase single well production. At present, the drilling, fracturing and well pattern technologies are developed aimed at the low permeability sandstone reservoir. And the above key technologies observe obvious application effect in large-area "continuous" reservoir exploration in PetroChina.

6 Resource potential and research meanings

The resource scale of "continuous" reservoir is very large and possibly exceeds the presently recognized hydrocarbon resources, which has attracted close attention of the geologists and E&D experts at home and abroad, and the resource has become the major point of global theoretical and technical research and the key domain for the replacement of future E&D. China's "continuous" reservoir exploration and development mainly includes low permeability sandstone reservoir, fractured carbonate rock reservoir and volcanic rock reservoir; up to the end of 2008, the cumulative proved oil & gas in place of such reservoir accounts for 47% and 56% of the national total respectively, which shows a great exploration potential.

6.1 Potential prospect of global "continuous" petroleum exploration

According to statistics of Brown A data [28], the world "continuous" gas resource is 800×1012-6 521×1012 m^3, which is about 2-15 times of conventional gas resource (436×1012 m^3). The "continuous" gas accounts for a considerable proportion in the world major gas-producing countries, among which 43% gas production in America is continuous gas, in China the proportion is also above 40%, and the production is still rising year by year [29-33]. The world "continuous" petroleum resource is 2-3 times of conventional petroleum resource.

6.2 "Continuous" petroleum resource potential in China

The "continuous" petroleum resource potential is huge in China. Fuyang oil zone in deep Songliao Basin, great gas province in Xujiahe Formation of Sichuan Basin, connective and fractured carbonate rock reservoir in Tarim Basin and volcanic rock reservoir in Songliao Basin and Junggar Basin under current E&D have become a significant area of China's petroleum reserve increase. Meanwhile, the tight sand gas in J+K formations in deep Songliao Basin, S formation in Tarim Basin and C formation in Junggar Basin has a great potential. The CBM resource in China is rich, and the CBM resource with the burial depth of less than 2 000 m is about 36.81×1012 m^3. According to initial evaluation, the shale gas resource in Sichuan Basin is more than one trillion cubic meters.

"Continuous" reservoir exploration and development in China should be divided into steps: tangible area includes low-ultra low porosity and permeability sand oil and gas in Ordos Basin, low porosity and permeability oil in Songliao Basin, low-ultra low porosity and permeability sand gas in Xujiahe Formation of Sichuan Basin, and Qingxi shale gas in Sichuan Basin etc.; the replacing area includes CBM, tight sand gas in deep Songliao, Bohai Bay, Tarim and Junggar basins and shale gas in Sichuan Basin etc.; potential area includes gas hydrate in south China sea etc. The potential of "continuous" reservoir is huge.

6.3 Meanings of "continuous" reservoir research

Due to large area and large scale of "continuous" reservoir, the "continuous" reservoir research has important meanings: (1) "continuous" reservoir distributes in a large area but with great oil saturation difference. The pertinent technologies should be carried out, such as resource evaluation, reservoir and fluid detection, stimulation and EOR etc; (2) in "continuous" reservoir, oil, gas, water and dry layer often co-exist, both high-production and low-production wells exist, and, the actual dry well is very few; it is required to adhere to the principle of "overall research, overall deployment and overall evaluation" without fear of penetrating dry wells or water layers; (3) "continuous" reservoir has the geologic conditions to form great oil and gas province (zone) with a large reserve scale; the requirement of research into the spatial boundary and three-order reserve scale of oil and gas province is favorable for development and pipeline construction. (4) The "continuous" reservoir resource regarded as no industrial value currently, especially some "continuous" gas reservoirs, possibly has development value in the future along with technical advancement and oil price rise. For example, as to continuous sandstone great oil and gas provinces in Ordos Basin, the continuous distribution range both exceeds 2×104 km^2, at present the lower limit of permeability of hydrocarbon reserve calculation and development is 0.1×10-3 μm^2; after further advancement of development technology, the lower limit of permeability of hydrocarbon reserve calculation and development may decline, and the gas reservoir with permeability far less than 0.1×10-3 μm^2 can probably develop efficiently. Because of the world's growing need for petroleum energy, it is imperative to strengthen the basic research on and to develop efficient methods of extracting petroleum from the "continuous" reservoirs.

7 Conclusions

The substantial difference between "continuous" reservoir and conventional reservoir is hydrocarbon accumulation way and conservation condition. The conventional reservoir connotation is based on single trap conception, that is to say, trap is the smallest unit of hydrocarbon accumulation. The "continuous" reservoir distributes in the large-range and connected reservoir system and can easily form "continuous" great oil and gas province (zone).

All kinds of "continuous" reservoir has two key marks: pervasive large-scale unconventional reservoir system with oil and gas, short of clear trap boundary; poor fluid differentiation, no common oil-water interface and pressure system, great hydrocarbon saturation difference, easy co-existence of oil-gas-water phases etc.

"Continuous" reservoir in China has many types and a great resource potential, including low-ultra low porosity and permeability (tight) sand oil and gas, CBM, shale oil and gas and gas hydrate, which distributes in a large area in Ordos, Sichuan, Tarim basins, with large discovered reserves and large remaining resource potential.

The depression lake basin center "sandy debris flow" represented by Chang6 Formation in Ordos Basin is "continuous" reservoir, the lower slope break at delta front is the major place for sandy debris flow distribution; in many lake basin centers, such as in Songliao Basin, large-scale "sandy debris flow" was discovered, which broadens the oil exploration area in the lake basin center.

"Continuous" reservoir research is favorable for speeding up the confirmation of spatial distribution boundary and reserve scale of low porosity and permeability great oil-gas province; favorable for overall research, overall deployment and overall evaluation; and favorable for new theoretical and technology breakthrough and preparation.

Acknowledgement

The authors thank Dr. G. Shanmugam for his valuable comments on this paper.

References

[1] Schmoker J W. U.S. Geological Survey assessment concepts for continuous petroleum accumulations. http: //certmapper.cr.usgs. gov / data / noga00 / natl / text / CH_13.pdf, 2005.

[2] Jia Chengzao, Zhao Zhengzhang, Du Jinhu, et al. PetroChina key exploration domains: Geological cognition, core technology, exploration effect and exploration direction. Petroleum Exploration and Development, 2008, 35 (4): 385-396.

[3] Zhao Wenzhi, Hu Suyun, Dong Dazhong, et al. Petroleum exploration progresses during the 10th Five-Year Plan and key exploration domains for the future in China. Petroleum Exploration and Development, 2007, 34(5): 513-520.

[4] Dai Jinxing. Potential areas for coal-formed gas exploration in China. Petroleum Exploration and Development, 2007, 34 (6): 641-645, 663.

[5] Law B E. Basin-centered gas systems. AAPG Bulletin, 2002, 86 (11): 1891-1919.

[6] Gautier D L, Mast R F. US geological survey methodology for the 1995 national assessment. AAPG Bulletin, 1995, 78 (1): 1-10.

[7] Schmoker J W. National assessment report of USA oil and gas resources. Reston: USGS, 1995.

[8] Garcia-Garcia A, Orange D, Lorenson T, et al. Reply to comments by Mastalerz V on "Shallow gas off the Rhone prodelta, Gulf of Lions" Marine Geology 234 (215-231). Marine Geology, 2008, 248 (1-2): 118-121.

[9] Orange D, Garcia-Garcia A, Lorenson T, et al. Shallow gas and flood deposition on the Po Delta. Marine Geology, 2005, 222-223: 159-177.

[10] Garcia-Garcia A, Orange D, Lorenson T, et al. Shallow gas off the Rhone prodelta, Gulf of Lions. Marine Geology, 2006, 234 (1/4): 215-231.

[11] Shurr G W, Ridgley J L. Unconventional shallow biogenic gas systems. AAPG Bulletin, 2002, 86 (11): 1939-1969.

[12] Zou Caineng, Tao Shizhen, Zhu Rukai, et al. Formation and distribution of "continuous" gas reservoirs and their giant gas province: A case from the Upper Triassic Xujiahe Formation giant gas province, Sichuan Basin. Petroleum Exploration and Development, 2009, 36 (3): 307-319.

[13] Dai Jinxing, Zou Caineng, Tao Shizhen, et al. Formation conditions and main controlling factors of large gas fields in China. Natural Gas Geoscience, 2007, 18 (4): 473-484

[14] Dai Jinxing, Ni Yunyan, Zhou Qinghua, et al. Significances of studies on natural gas geology and geochemistry for natural gas industry in China. Petroleum Exploration and Development, 2008, 35 (5): 513-525.

[15] Zou Caineng, Tao Shizhen, Yuan Xuanjun, et al. The formation conditions and distribution characteristics of continuous petroleum accumulations. Acta Petrolei Sinica, 2009, 30 (3): 324-331.

[16] Collett T S. Energy resource potential of natural gas hydrates. AAPG Bulletin, 2002, 86 (11): 1971-1992.

[17] Dai Jianchun, Niranjan B, Diana G, et al. Exploration for gas hydrates in the deepwater, northern Gulf of Mexico: Part II, Model validation by drilling. Marine and Petroleum Geology, 2008, 25 (9): 845-859.

[15] Zhang Jinchuan, Xu Bo, Nie Haikuan, et al. Exploration potential of shale gas resources in China. Natural Gas Industry, 2008, 28 (6): 136-140.

[19] Li Xinjing, Hu Suyun, Cheng Keming. Suggestions from the development of fractured shale gas in North America. Petroleum Exploration and Development, 2007, 34 (4): 392-400.

[20] Bowker K A. Barnett Shale gas production, Fort Worth Basin: Issues and discussion. AAPG Bulletin, 2007, 91 (4): 523-533.

[21] Hill R G, Zhang Etuan, Katz B J, et al. Modeling of gas generation from the Barnett Shale, Fort Worth Basin, Texas. AAPG Bulletin, 2007, 91 (4): 501-521.

[22] Shanley K W, Cluff R M, Robinson J W. Factors controlling prolific gas production from low-permeability sandstone reservoirs. AAPG Bulletin, 2004, 88 (8): 1083-1121.

[23] Shanmugam G, Zimbrick G. Sandy slump and sandy debris flow facies in the Pliocene and Plaistocene of the Gulf of Mexico: Implications for submarine fan models. Proceedings of American Association of Petroleum Geologists International Congress and Exhibition, Caracas, Venezuela. Tulsa: AAPG, 1996. A45.

[24] Eaton S R. Coalbed gas frontier being tapped. Explorer, 2006, 12: 20-24.

[25] Kvenvolden K. Methane hydrates and global climate. Global Biochemical Cysles, 1988, 2: 221-229.

[26] He Guomao, Zhang Feng, Wang Wenxia. Analysis on characteristics and favorable forming conditions of volcanic reservoirs in Santanghu Basin. Tuha Oil & Gas, 2004, 9 (4): 309-312.

[27] Zou Caineng, Zhao Wenzhi, Jia Chengzao, et al. Formation and distribution of volcanic hydrocarbon reservoirs in sedimentary basins of China. Petroleum Exploration and Development, 2008, 35 (3): 257-271.

[28] Brown A. Evaluation of possible gas microseepage mechanisms. AAPG Bulletin, 2000, 84 (11): 1775-1789.

[29] Mohr S H, Evans G M. Model proposed for world conventional, unconventional gas. Oil & Gas Journal, 2007, 105 (47): 46-50.

[30] Curtis J B, Montgomery S L. Recoverable natural gas resource of the United States: Summary of recent estimates. AAPG Bulletin, 2002, 86 (10): 1671-1678.

[31] Schmoker J W. Resource-assessment perspectives for unconventional gas systems. AAPG Bulletin, 2002, 86 (11): 1993-1999.

[32] Nick S. Study: US unconventional gas resources underestimated. Oil & Gas Journal, 2008, 106 (29): 30-31.

[33] Petzet G A. UGI: Unconventional gas wealth seen in world's basins. Oil & Gas Journal, 2008, 106 (37): 38-39.