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PII: S0012-8252(13)00138-4
DOI: doi: 10.1016/j.earscirev.2013.08.006
Reference: EARTH 1888

To appear in: *Earth Science Reviews*

Received date: 22 June 2011
Accepted date: 10 August 2013

Continuous Hydrocarbon Accumulation over a Large Area as a Distinguishing Characteristic of Unconventional Petroleum: The Ordos Basin, North-Central China

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ABSTRACT

Global petroleum exploration is currently undergoing a strategic shift from conventional to unconventional hydrocarbon resources. Unconventional hydrocarbons in tight reservoirs show characteristics distinct from those of conventional hydrocarbon sources hosted in structural and stratigraphic traps. The characteristic features include the following: a hydrocarbon source and reservoir coexist; porosity and permeability are ultra-low; nano-pore throats are widely distributed; hydrocarbon-bearing reservoir bodies are continuously distributed; there is no obvious trap boundary; buoyancy and hydrodynamics have only a minor effect, and Darcy's law does not apply; phase separation is poor; there is no uniform oil-gas-water interface or pressure system; and oil or gas saturation varies. Examples of unconventional hydrocarbon accumulations are the Mesozoic tight sandstone oil province and the Upper Paleozoic tight sandstone gas province in the Ordos Basin, north-central China. Generally, continuous hydrocarbon accumulation over a large area is a distinguishing characteristic of unconventional hydrocarbon sources. Because of the great potential of unconventional petroleum resources, it is believed that research on such resources will be at the forefront of the future development of petroleum geology.

Keywords:

unconventional petroleum resources

continuous hydrocarbon accumulation

petroleum geology

tight reservoir

Ordos Basin

Contents:

1. Introduction

Oil and gas are necessities and represent strategic resources within modern society. As a branch of mineral geology, petroleum (oil and gas) geology is a comprehensive applied science that guides petroleum exploration and recovery. It aims to explain the generation, migration, accumulation and distribution of petroleum in the near-surface strata of the earth's crust. Petroleum geology has been substantially developed within the modern oil and gas exploration and exploitation industry, leading to the development of many classic petroleum geology theories. A short review of the development of petroleum geology is provided below.

White (1885) proposed the anticlinal theory, in which the anticline is believed to control hydrocarbon accumulation. The prospecting techniques outlined by White (1885) were quickly accepted by petroleum exploration companies. In 1917, the American Association of Petroleum Geologists (AAPG) was founded and published their periodical *AAPG Bulletin*, in which Emmons (1921) subsequently published "Geology of Petroleum", thus heralding the birth of petroleum geology as an independent subject.

In the 1930s, after the discovery of the giant East Texas stratigraphic pool, geologists began to realize that the application of the anticlinal theory could not solve all problems in petroleum geology. McCollough (1934) presented the "trap theory", which was a milestone in the development of conventional petroleum geological theory. Pan (1941) subsequently proposed the theory of nonmarine origin petroleum. Hubbert (1953) introduced the concept of hydrodynamics into petroleum geology, and the trap theory was refined in the publications of Levorsen (1956; 1967). During the peak phase of global conventional petroleum exploration and exploitation (1960–1970s), the theory of plate tectonics (Wilson, 1963; Le Pichon, 1968; Morgan, 1968; McKenzie, 1969) was applied to the research of sedimentary basin formation and classification, as well as petroleum accumulation and occurrence. In the 1970–1980s, the theories of seismic stratigraphy and sequence stratigraphy were developed (Vail et al., 1977; Haq et al., 1987; Van Wagoner et al., 1987; Galloway, 1989; Van Wagoner, 1995; Cross and Lessenger, 1998), as were the theories of organic origin and catagenesis of kerogen, to better explain petroleum formation (Tissot and Welte, 1978; Hunt, 1979). Since the 1970s, petroleum migration has become an important research field (Berg, 1975; Magara, 1978; Schowalter, 1979; Roberts and Cordell, 1980; Davis, 1987; England et al., 1987; Hunt, 1990). In the 1990s, sedimentary basin numerical-modeling technology (Lerche, 1990) and petroleum system theory (Magoon and Dow, 1994) were used to simulate hydrocarbon generation, migration and accumulation on a basin scale. Simultaneously, Peters and Moldowan (1993) published works promoting the development of petroleum geochemistry research, especially on the molecular scale.

In the last 20 years, unconventional resources, such as tight sandstone gas, coalbed methane, shale gas, heavy oil, and tar sands, have gradually aroused interest in the petroleum industry. Schmoker (1995) proposed the concept of "continuous-type petroleum accumulation", an important milestone in unconventional petroleum geology, which has since become a cutting-edge topic of research (Selley, 1998; Law and Curtis, 2002; Zou, 2012).

This brief review demonstrates that the development of global petroleum exploration and petroleum geology can be split into three main stages: structural pools, stratigraphic pools and unconventional continuous accumulations. There are two major theoretical breakthroughs and technical innovations that have been made. The first is the shift from structural pools, with their easily identifiable traps, to stratigraphic pools, with traps that are more difficult to identify; the second is the breakthrough from stratigraphic pools to unconventional continuous accumulations lacking well-defined boundaries. The goal now is to find such continuous hydrocarbon reservoirs.

According to the statistics of the International Energy Agency (IEA), the present size of global unconventional oil resources is up to 620 billion tons (IEA, 2010), approximately equal to that of conventional resources. The exploitation of global unconventional oil resources is increasing so dramatically that production in 2008 (IEA, 2008) was in excess of 60 Mt, nearly double the production reported in 2001. Global unconventional gas resources are estimated to be 3921 tcm, i.e., eight times the volume of conventional resources (IEA, 2010). The exploitation of unconventional gas resources is also increasing rapidly, accounting for 13% of total gas production (IEA, 2009). As a strategic field in future petroleum exploration, unconventional resources are more important in the global energy share and therefore warrant further research. In this paper, an introduction to unconventional petroleum geology is provided by comparing its distinguishing characteristics from those of conventional petroleum geology. A case study of the Ordos Basin, China, is presented as an example of continuous hydrocarbon accumulation.

2. Geological characteristics of conventional hydrocarbon accumulation in a trap

Conventional hydrocarbon accumulation is the key to traditional petroleum geology and usually refers to an individual hydrocarbon accumulation in a single trap with a uniform pressure system and oil-water contact. A trap is a reservoir rock capable of accumulating and retaining petroleum. If there is only oil (gas) in the trap, it is called an oil (gas) pool, whereas if there is both oil and gas, it is called a petroleum pool.

A conventional hydrocarbon accumulation is a three-dimensional(3D) geological entity with clear boundaries. The bulk of a pool can be described through defined parameters, e.g., seep point, altitude and area of entrapment. Other parameters can be used to calculate the reserves in a pool, e.g., volume height of oil or gas, oil- or gas-bearing boundaries and extent area, gas top and oil ring and pore space.

In conventional hydrocarbon accumulations, hydrocarbon migration and fluid flow follow Darcy's law. Based on hydrodynamics, a conventional hydrocarbon reservoir is located in a zone with low hydraulic potential energy. It is entrapped individually or sealed by a higher-potential zone or impermeable rock. This type of accumulation usually forms in millimeter (micrometer)-pore reservoir rock and is distributed in a discrete or clustered pattern. The characteristics of hydrodynamics in a conventional accumulation include the following: (1) applicability of Darcy's law; (2) clear oil-gas-water contact; and (3) obvious effects of gravitational segregation and buoyancy. Therefore, hydrocarbons are likely to accumulate in an individual trap.

The two examples of the Daqing Placanticline oil field in the Songliao Basin and the Kela-2 gas field in the Tarim Basin, both in China, are provided to demonstrate the geological characteristics of conventional hydrocarbon accumulation. The Daqing Placanticline oil field predominantly consists of seven anticline accumulations (Fig. 1A). The Lower Cretaceous sandstone reservoir has the following properties: trap area 1777.7 km^2, trap altitude ~200–250 m, thickness of the pay zone ~140–200 m and oil-water contact -1050 m. They are conventional reservoir rocks with a porosity of ~22–30%, permeability generally greater than $100x10^{-3}$ μm^2 and pore-throat size generally greater than 3 millimeters. In this accumulation, Darcy's law applies and a unified hydrostatic system exists (pressure coefficient of 1.05). Based on these parameters, the measurable oil reserves are up to $45.6x10^8$ t. The Kela-2 gas field is a gas accumulation in an anticline trap (Fig. 1B). The Cretaceous–Paleogene sandstone reservoir has the following properties: trap area 49.6 km^2, trap altitude 510 m, gas volume height ~400 m, thickness of gas pay zone 200 m and gas-water contact -2468

m. It is a conventional reservoir with porosity ~15–20%, permeability generally ~200–800×10^{-3} μm^2 and pore-throat size generally ~0.4–16 millimeters. Darcy's law also applies, and the pressure coefficient is 2.02. The measured reserves are up to 0.284 tcm.

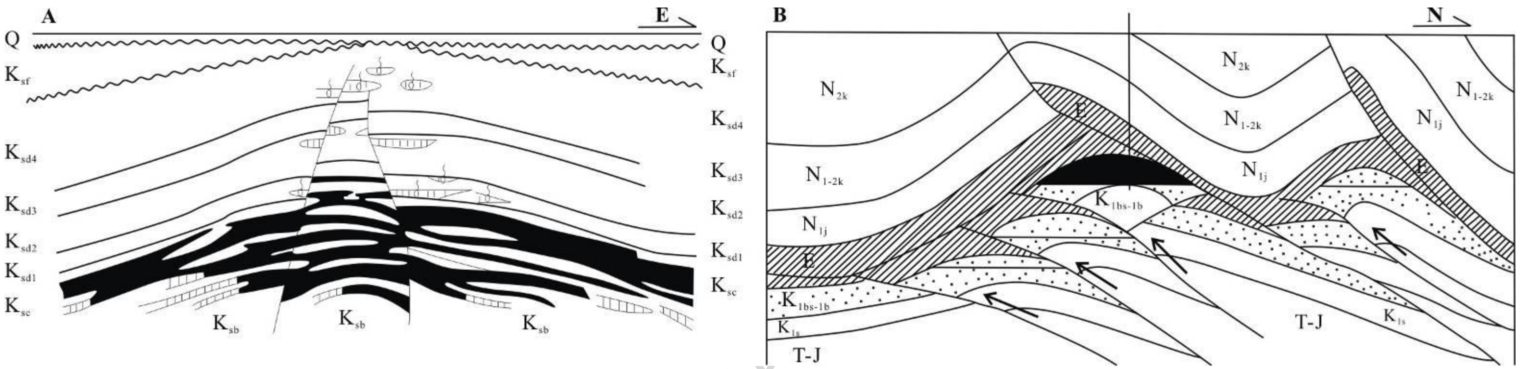

Fig. 1. Profiles of (A) the Daqing Placanticline oil field in the Songliao Basin of north-east China and (B) the Kela-2 gas field in the Tarim Basin of north-west China.

3. Geological characteristics for continuous hydrocarbon accumulation over a large area

Unconventional petroleum resources are continuously or quasi-continuously distributed hydrocarbon accumulations, which generally cannot be exploited through conventional methods and techniques, but they can be extracted economically using new technologies, e.g., improving reservoirs' permeability or fluid viscosity. An unconventional petroleum accumulation usually occupies a large volume, with low air permeability ($< 1\times10^{-3}$ μm^2) and low porosity (<10%).

Although unconventional petroleum resources aroused interest early on (Roen and Kepferle, 1993), they were not widely exploited by the exploration industry because of the preponderance of, poor reservoirs and the corresponding difficulty of exploration and exploitation. However, since the end of the 1970s, unconventional reserves, such as tight sandstone gas, coalbed methane and shale gas, have become the main additions to the growing reserves of petroleum. For instance, unconventional petroleum accounted for 13–72% of the increase in China's total reserves from 2000 to 2010 (Zou, 2012). Therefore, research on unconventional resources is gradually attracting attention from the petroleum industry (Masters, 1979; Spencer and Mast, 1986; Law and Curtis, 2002). Shanley et al. (2004) believed that the first clear description of an unconventional low-permeability gas province, in terms that are commonly associated with basin-centered systems, came from Masters (1979), who described the deep, gas-saturated Cretaceous sandstone reservoirs of western Alberta, the San Juan Basin in New Mexico and Wattenberg field in the Denver Basin of Colorado. In 1995, the U.S. Geological Survey (USGS) suggested the concept of "continuous-type petroleum accumulation" (Schmoker, 1995). The USGS emphasized that continuous gas accumulation is usually distributed over a large area, and there is no trap for the accumulation and buoyancy has a weak effect on hydrocarbon migration. Based on these concepts, the USGS appraised the available unconventional resources (Schmoker, 2002), leading to the exploration and recovery of unconventional petroleum resources in the US. Law and Curtis (2002) proposed the concept of unconventional petroleum systems. They believed that such systems are neither related to structural traps nor substantially affected by gravitational segregation, and they are regionally charged in large-scale oil-bearing plays. In 2007, four major petroleum associations (AAPG, Society of Petroleum Engineers (SPE), World Petroleum Council (WPC), Society of Petroleum Evaluation Engineers (SPEE)) defined the relevant concepts for unconventional petroleum resources in their report (WPC, 2007). A continuous-type deposit, nearly synonymous with unconventional resources, is pervasive throughout a large area and is not significantly affected by hydrodynamic effects. Such accumulations are deposits that include "basin-centered" gas, shale gas, gas hydrates and natural bitumen and oil shale accumulations. In this same report, technical problems and economic viability were also emphasized. Zou et al. (2009a; 2009b; 2010b; Zou, 2012; 2012; 2013) summarized Chinese petroleum exploration and developed the concept for continuous petroleum accumulation based on global unconventional petroleum geological research and exploration. A continuous petroleum accumulation is defined as an unconventional reservoir with continuous distributed hydrocarbons that make up a large proportion of an unconventional reservoir system.

Unconventional petroleum geology differs from traditional petroleum geology in terms of trap conditions, reservoir properties, combination of source and reservoir rocks, accumulation features, percolation mechanism, occurrence features, etc., (Zou et al., 2009a; Zou, 2012; Zou et al., 2012). The two are compared in Fig. 2, Fig. 3 and Table 1. In conventional hydrocarbon accumulations, hydrocarbons are generated in the source rock and migrate into the reservoir rock. After the second migration, driven by buoyancy, hydrocarbons finally accumulate in a structural or stratigraphic trap. Unconventional hydrocarbon accumulations are mainly retained within the source rock and are continuously distributed over a large area. Hydrocarbons only experience primary migration or short near-source secondary migration. Unconventional hydrocarbon accumulations usually have neither a clear boundary between trap and seal rock nor a uniform pressure system. In unconventional accumulations, fluid differentiation is poor and multiple phases of oil, gas and water coexist (Fig. 3).

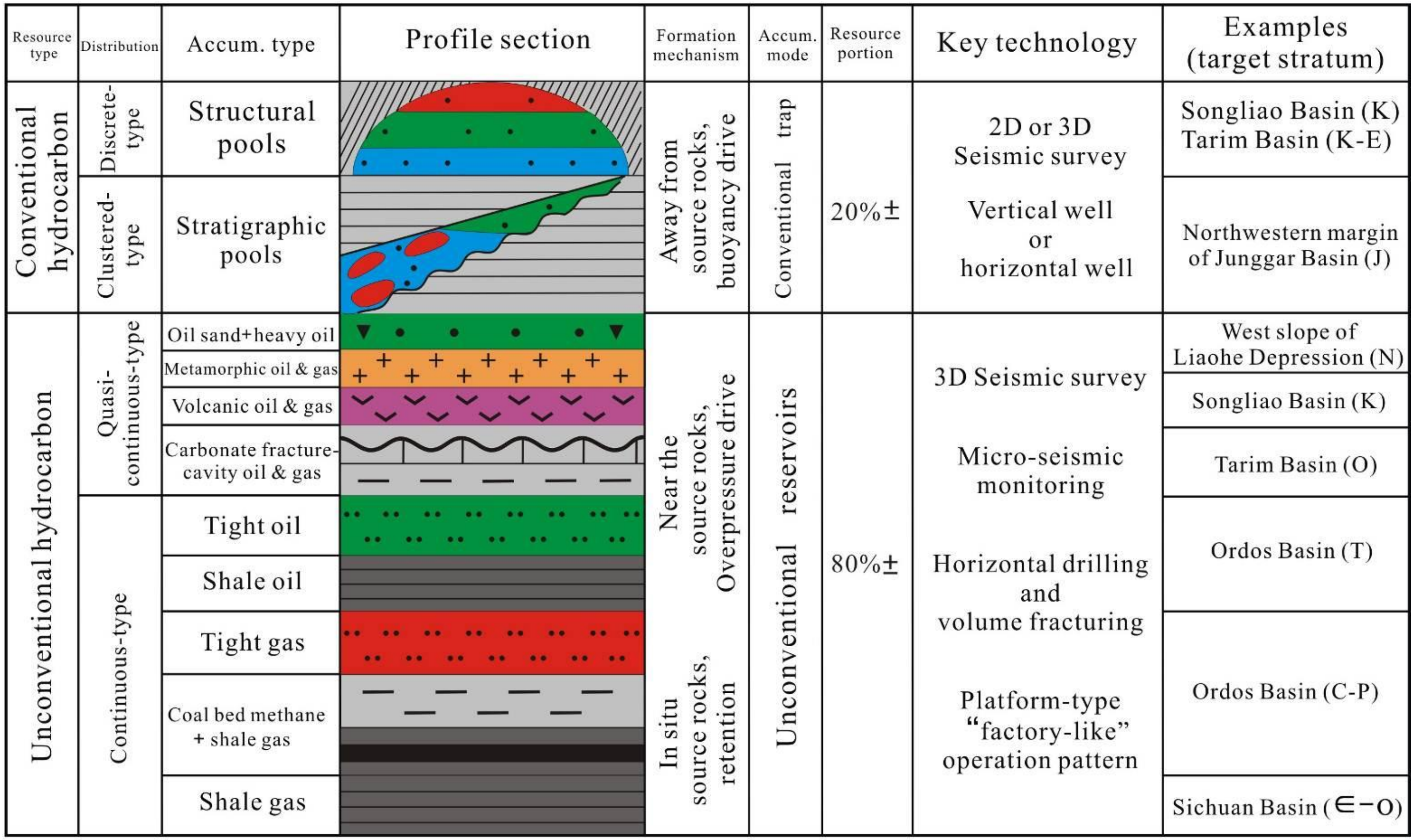

Fig. 2. Classification of conventional and unconventional hydrocarbons and their accumulation mechanisms.

Table 1. Comparison between unconventional and traditional petroleum geology.

Category Items	Unconventional Petroleum Geology	Traditional Petroleum Geology
Studied object	Unconventional hydrocarbon resources	Conventional hydrocarbon resources
Accumulation unit	Large-scale continuous reservoirs	Structural, stratigraphic and other combined traps
Reservoir	Unconventional tight reservoirs, with ultra-low porosity and permeability	Conventional reservoirs, with high porosity and permeability
Configuration of source rocks and reservoirs	As one or in contact with each other	Reservoirs may be far from source rocks
Trap	No obvious definition, open trap	Obvious definition, closed trap
Migration	Primary migration or secondary migration over short distance	Secondary migration over a long distance
Accumulation	Buoyancy is limited	Buoyancy is the main force
Percolation	Mainly non-Darcian percolation	Darcian percolation
Fluid relationship	No uniform fluid contacts or pressure systems, hydrocarbon saturation varies greatly	Uniform fluid contacts
Distribution	Widespread, continuous or quasi-continuous distribution at the basin center or slope	Discrete or clustered distribution
Resource assessment	Low resource abundance, and resource is based on well production	Resource is based on trap parameters
Technology	3D seismic survey, micro-seismic monitoring, horizontal well and volume fracturing, platform-type “factory-like” operation pattern	2D or 3D seismic survey, vertical well or horizontal well, conventional fracturing

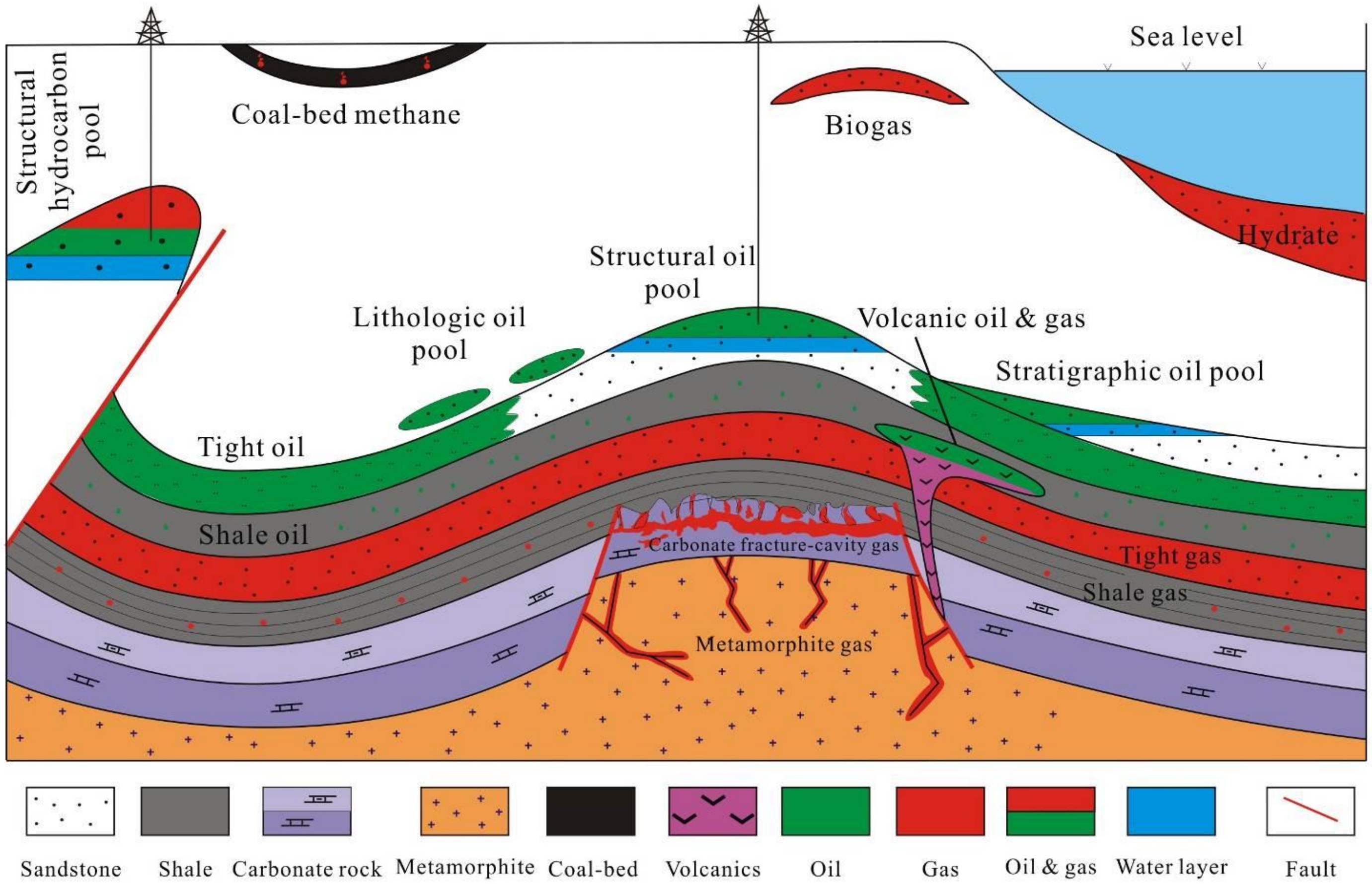

Fig. 3. Schematic section of the occurrence of conventional and unconventional hydrocarbon resources.

As shown in Fig. 4 and Fig. 3, unconventional hydrocarbon resources have continuous and quasi-continuous accumulations (Zou et al., 2009b; Zou et al., 2012). Continuous accumulations are the main type, which include tight sandstone gas, tight sandstone oil, coalbed methane, shale gas, shale oil, shallow biogas, gas hydrate, etc. (Zou and Tao, 2008; Zou et al., 2010a; Zou et al., 2012; Zou et al., 2013). Quasi-continuous accumulations are those in unconventional reservoirs, such as carbonate fracture-cavity reservoirs, volcanic reservoirs and metamorphic reservoirs (Zou, 2012).

The development of continuous hydrocarbon accumulation challenges the concepts of traditional petroleum geology (e.g., limitation of reservoir properties and "trap prospecting"). A continuous hydrocarbon accumulation has two critical features. First, there are hydrocarbon-bearing beds (self-sourcing and near-source reservoirs) continuously distributed over a large area, without a clear trap boundary. Second, the hydrocarbon accumulation is not driven by buoyancy and only weakly affected by hydrodynamics. The key factor giving rise to these two features is a pervasively distributed nanometer-pore-throat network. The diameters of the pore-throats are range from ~100–500 nm. The pore throats provide a connectivity function and thus affect the occurrence of continuous hydrocarbon accumulations. The key to exploring a pervasively continuous hydrocarbon accumulation is defining the reservoir range through advanced techniques such as 3D pre-stack seismic reservoir and fluid prediction techniques. With respect to development, methods such as micro-seismic monitoring, horizontal drilling and volume fracturing are adopted to artificially increase a reservoir's permeability (Fig. 2).

4. Continuous hydrocarbon accumulation in the Ordos Basin, China

In the previous section, the geological features of continuous hydrocarbon accumulation over a large area were summarized. For clarity, this section presents two examples of Mesozoic tight oil and Upper Paleozoic tight gas in the Ordos Basin, north-central China (the main geologic parameters of which are outlined in Table 2).

The Ordos Basin is located in north-central China and occupies an area of ~$25x10^4$ km^2. The Ordos Basin is structurally affiliated with the Northwest China Platform. The western flank is narrow and steep, whereas the eastern flank is wide and dips slightly. The slope gradient of the main part (i.e., the Yishan slope) is lower than 6 m/km (Fig. 4). There are abundant petroleum resources in the Ordos Basin, continuously distributed over a large area, such as the Mesozoic tight sandstone oil province in the south of the Yishan slope and the Upper Paleozoic tight sandstone gas province in the north of the Yishan slope (Fig. 4).

Table 2. Main geologic parameters of the Mesozoic oil province and the Upper Paleozoic gas province of the Ordos Basin, north-central China.

Field	Basin	Trap	Oil or gas bearing Area (km^2)	Reserves Richness	Single-well Production	Reservoir Lithology	Reservoir Properties			Initial pressure gradient (MPa/cm)	Pressure coefficient
							Porosity (%)	Air Permeability (mD)	Pore throat Radius (μm)		
Mesozoic oil province	Ordos	—	8100	15–20 $10^4 t/km^2$	2-3 t	sandstone	7–13	<0.1–1	0.06–0.8	–	0.6–1.0
Upper Paleozoic gas province	Ordos	—	3×10^4	1.1–1.3 $10^8 m^3/km^2$	2-4×10^4 m^3	sandstone	5.6–7.3	0.03–1	0.01–0.7	0.1–0.3	0.7–0.95

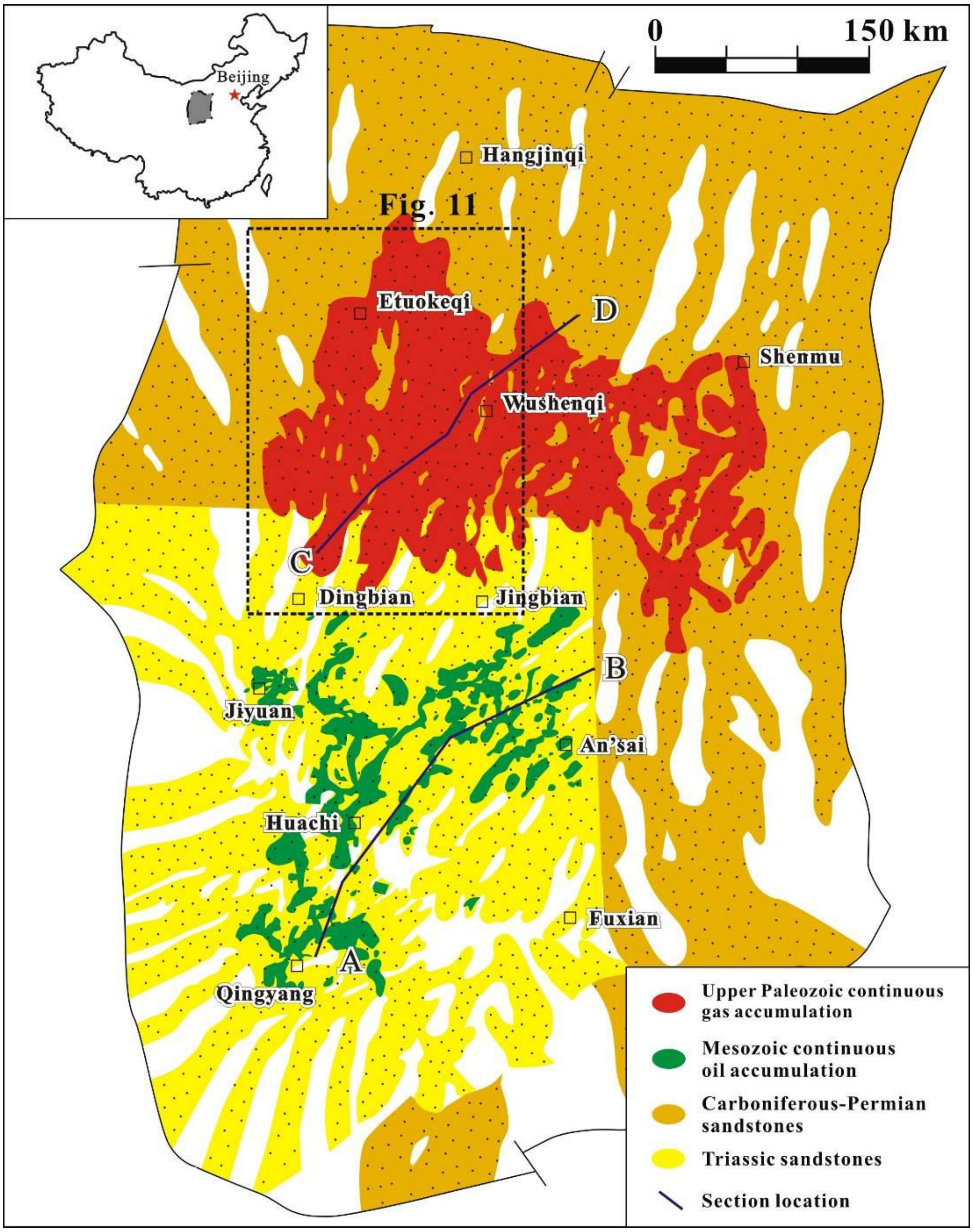

Fig. 4. Hydrocarbon occurrences in the Ordos Basin in plane view.

The sandstone reservoir is pervasive and continuous, and it spans a large area of the Ordos Basin. The main period of sedimentary deposition was the Upper Paleozoic and Mesozoic, when a sufficient supply of clastic material within a stable and gentle slope setting developed a well-established fluvial-deltaic sedimentary system. Within this setting, fluvial channels frequently changed course, and sand bodies were laterally interfingered with one another. These widely distributed sedimentary sandstones within the basin provide good potential for a large gas or oil reservoir. The Upper Paleozoic formation constitutes a set of typical unconventional tight sandstone reservoirs that show widespread, overlapping distribution in plane view. In the vertical column, sandstones of multiple horizons are superimposed, with the cumulative sandstone thickness typically between 30 m and 100 m and the ratio of sand to mud in the major gas layer being greater than 3:5. The sandstone reservoir is up to ~150–200 km long and extends lengthwise in the S–N direction (Fig. 4). The deltaic front sand and basin-center debris-flow sand of the Mesozoic Yanchang Member are pervasive. Multiple sandstones are also superimposed, with the cumulative sandstone ranging from 20–50 m thick and the ratio of sand to mud in the oil layer being greater than 1:1. The sandstone reservoir is ~100–120 km long and extends in the NE–SW direction (Fig. 4).

The contact part of the Upper Paleozoic and Mesozoic source and reservoir in the Ordos Basin is large in area, with oil and gas being distributed continuously in or near the source. There are two sets of Late Carboniferous and Early Permian coal-bearing formations in the transitional and deltaic front facies. The coal bed is cumulatively 6–15 m thick with a total organic content (TOC) above 70%. Dark mudstone is also distributed widely throughout the basin, with a thickness of ~30–50 m and TOC of ~2.0–3.0 %. The present thermal evolution degree R_o of coal-measure source rock is up to ~1.5–2.5 %. The wide coal source is in contact with large continuous sand bodies, with the contacted areas being ~18×10^4 km^2 in extent. Natural gas is mainly found within the coal source, while some is also located within the near-source tight reservoir rocks (Fig. 5). There are also multiple sets of Triassic lacustrine source rocks, among which the 7th Yanchang Formation (T_3y^7, the dark mudstone formed during the high-stand period of the lake) is the most important one. The dark mudstone is cumulatively ~25–35 m thick, with a TOC of ~5.0–15.0 % and type-I to type-II_1 kerogen. The present thermal evolution degree R_o is up to ~0.7–1.1 %. The areas in contact are up to 5×10^4 km^2 in extent, with oil and gas being distributed continuously over a large area and the source rocks sandwiched in between (Fig. 5).

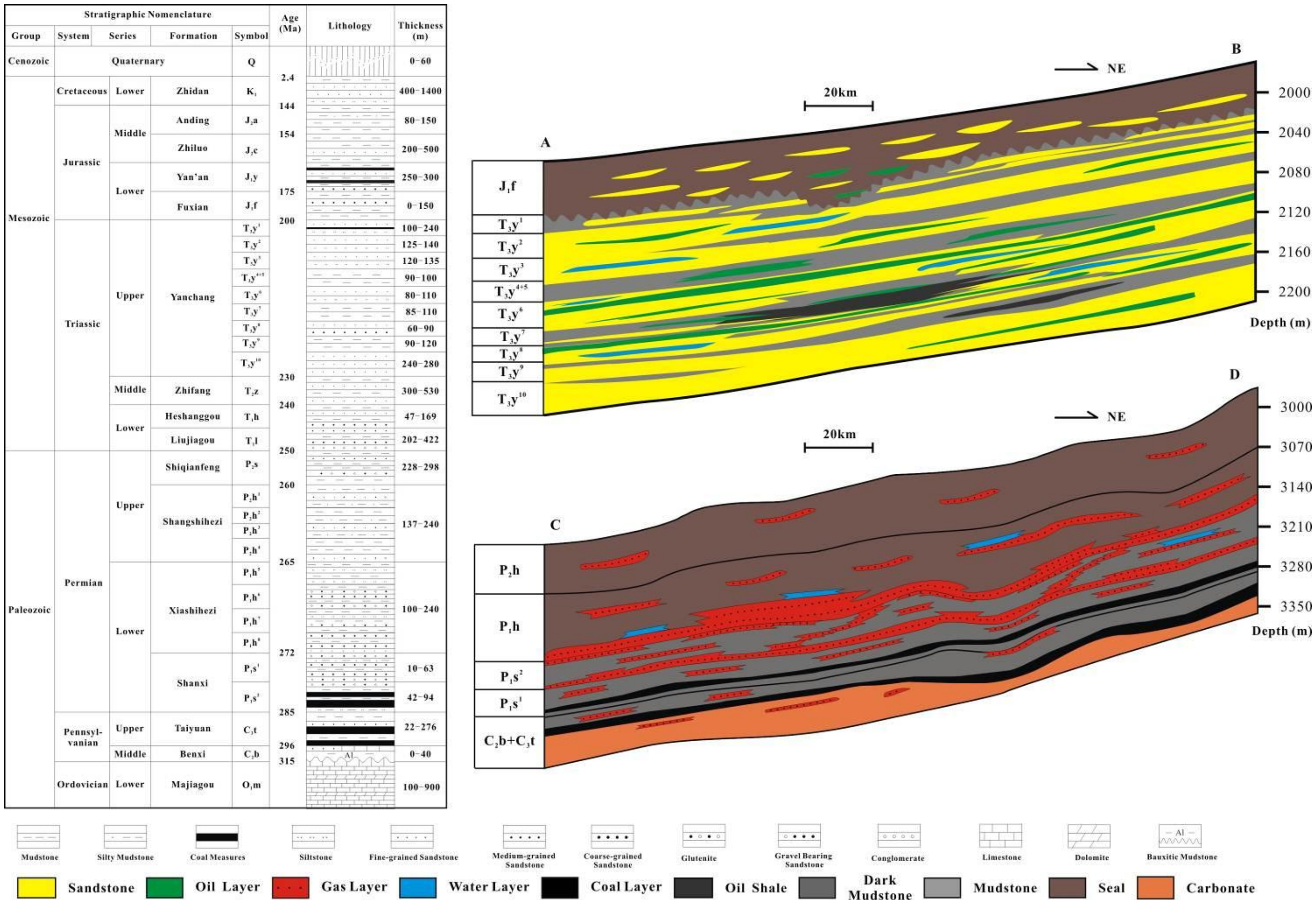

Fig. 5. Lithological column and hydrocarbon accumulation section within the Ordos Basin (the locations of sections AB and CD are shown in Fig. 4).

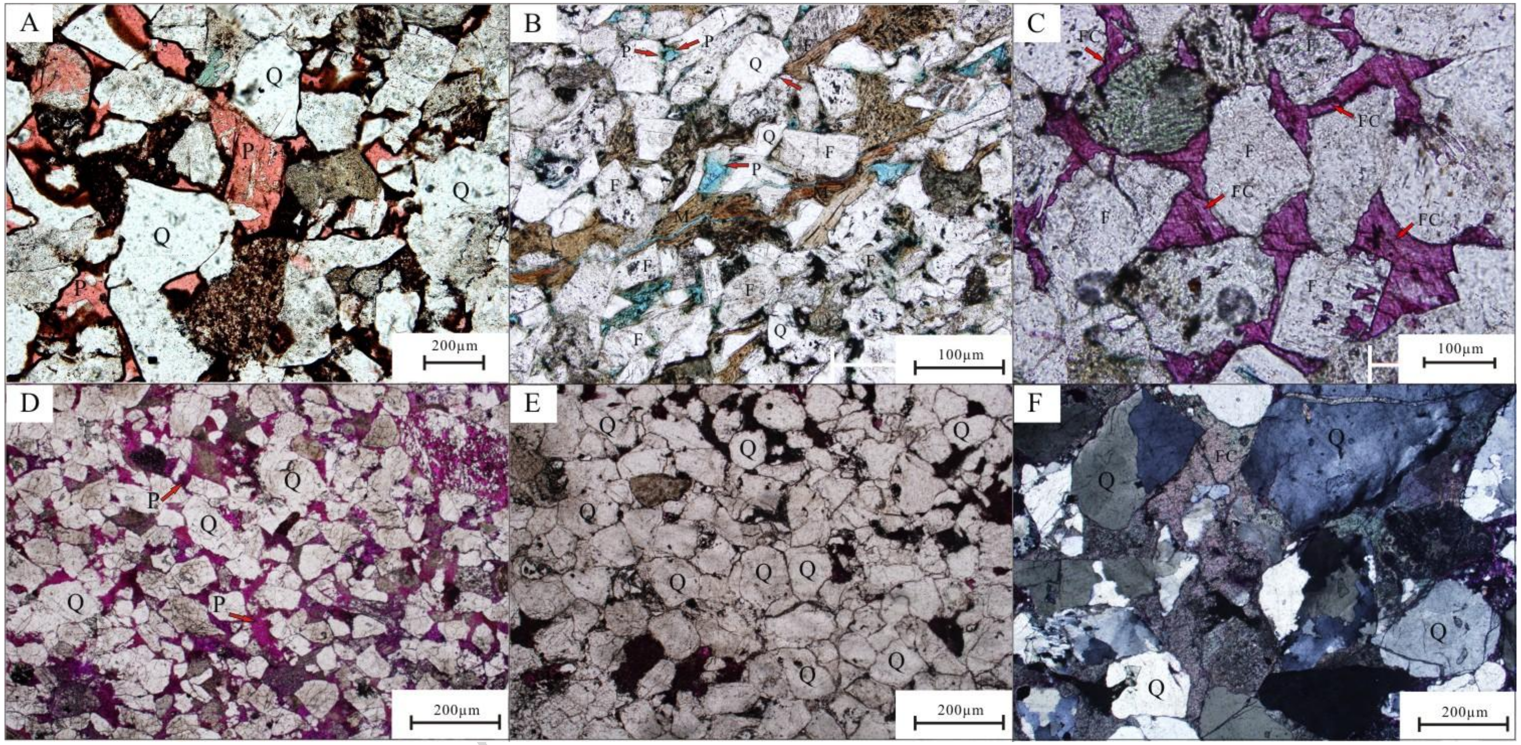

Fig. 6. Micrographs of thin sections of tight sand reservoir rocks in the Ordos Basin.

Notes: A. Bai-210 well, T_3y^6, 2042.5 m: pores resulting from dissolution of feldspar, and residual intergranular pores shown by red cast and mono-polarizer; B. Gao-48 well, T_3y^6, 1685.50 m: intensely compacted, the grains contact in a sutured pattern, and the dark micas are bent and dispersed around the less ductile grains (quartz and feldspar), with blue cast and mono-polarizer and without dye; C. Gao-48 well, T_3y^6, 1711.34 m: cemented by ferro-calcite, deposited in both the primary intergranular and secondary dissolution pore spaces, some remaining grain "ghost outlines" are visible, with blue cast and mono-polarizer, dyed by a mixture of alizarin and potassium ferricyanide; D. Z62 , P_1s^1, 2818.43 m: pores resulting from dissolution of feldspar and residual intergranular pores shown by amaranth cast and mono-polarizer; E. S99, 3433.02 m, P_1h^8, intensely compacted and silica-cemented, pores are not developed, amaranth cast thin section, mono-polarizer; F. S189, 3596.16 m, P_1h^8: carbonate cements fill all pore throats, dissolution pores are not developed, amaranth cast thin section, mono-polarizer. F=Feldspar, P=Pores, Q=Quartz, M=Micas, FC=Ferro-Calcite.

Both the Upper Paleozoic and Mesozoic formations in the Ordos Basin are fairly compacted sandstone reservoirs. The target zone in the Mesozoic oil province is mainly the Yanchang Formation, with its micrometer storage spaces being dominantly feldspar-, clast- and laumontite-dissolved secondary pores (Fig. 6A). The target in the Upper Paleozoic gas province is the Late Carboniferous and Early Permian formation, which has micrometer storage spaces predominantly composed of dissolved intra-granular and residual primary pores (Fig. 6D). These two sets of tight sandstone reservoirs experienced the processes of compaction, siliceous cementation and calcareous cementation during deep burial diagenesis, and the resulting micrometer porosity within these reservoirs is not well developed (Fig. 6B, C, E and F).

The tight sandstone reservoirs in the Ordos Basin have various types of nanometer pores. The tight sandstone of the Mesozoic Yanchang Formation typically has nanometer pores on the surface of grains, inter-crystalline pores of authigenic clay minerals, and fractures between layers. The pores of quartz are pits on the surface. The shapes of the pores are irregular, with pore diameters of ~200–400 nm (Fig. 7A). The pores on the surface of feldspar are triangular or sub-orbicular in shape, with pore diameters of ~70–200 nm (Fig. 7B). In the shale of the Yanchang Formation, there are also pores in the clay mineral matrix（Fig. 7C）and organic pores (Fig. 7D), with pore diameters of ~100–400 nm. The tight sandstone pores of the Upper Paleozoic formation are predominantly filled with clay and silica. The clay minerals may include inter-crystalline pores that developed within authigenic clay structure (Fig. 7E) and fractures between layers (Fig. 7F), with pore diameters of ~150–600 nm. The siliceous type includes connected fractures (Fig. 7G) and intergranular micro-pores (Fig. 7H), with pore diameters of ~100–400 nm.

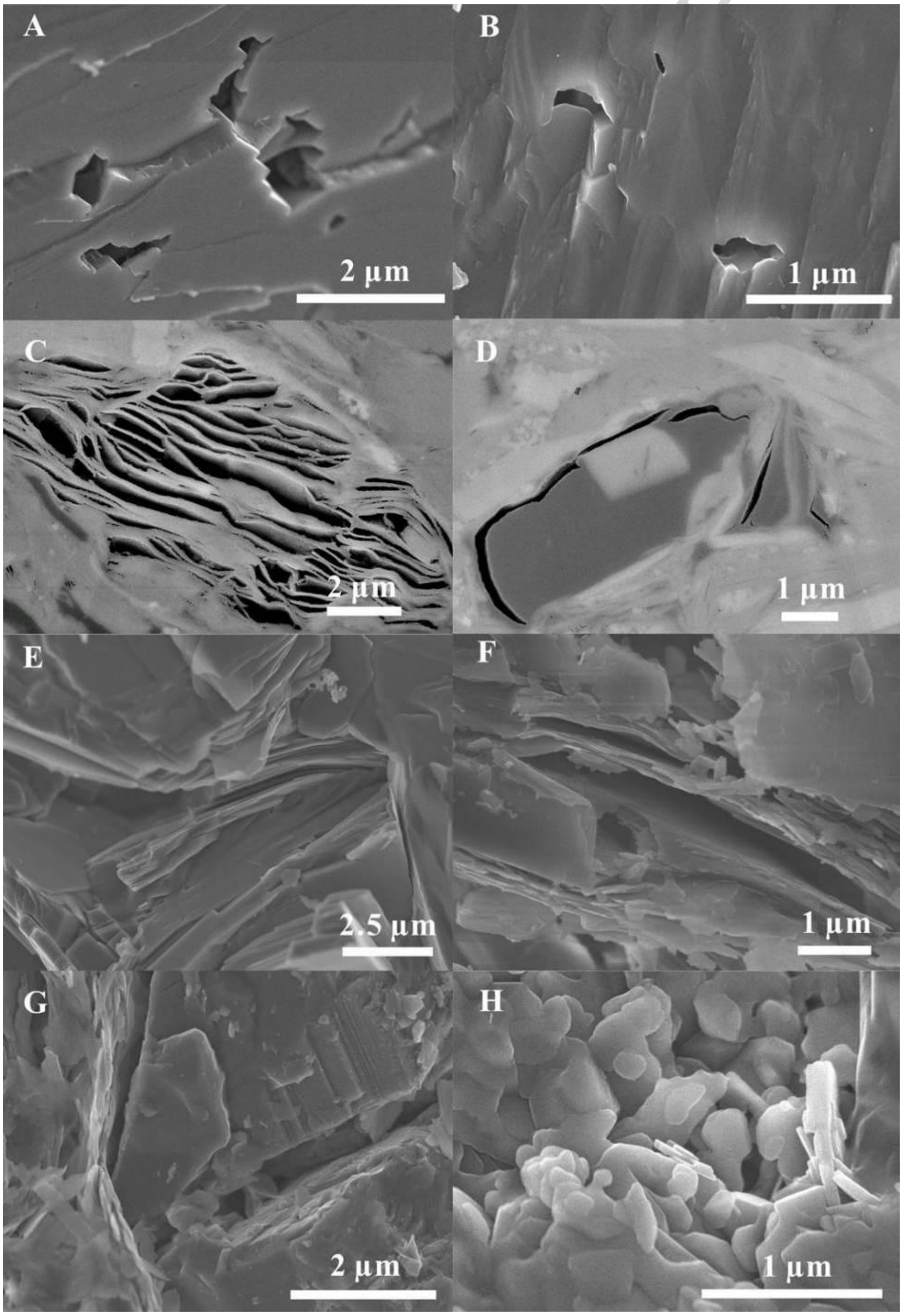

Fig. 7. Micrographs of the tight sandstone reservoir of the Ordos Basin obtained by field emission scanning electron microscopy.

Notes: A. Gao-46 well, T_3y^6, 1742.5 m: nanometer pores on the quartz; B. Yuan-190 well, T_3y^6, 1998.45 m: nanometer pores on the feldspar; C. Zhang-2 well, T_3y^{4+5}, 960 m: pores in the matrix of slate chloride; D. Bai-406 well, T_3y^7, 1976 m: organic pores; E. S-146 well, 3594.4 m, P_1s^1: inter-crystalline pores in the kaolinite; F. T-37 well, 2648.03 m, P_1s^1: fractures between the layers of illite; G. T-37 well, 2648.03 m, P_1s^1: connected pores between grains through silica overgrowths; H. Z-60 well, 2991.9 m, P_1s^1: inter-granular pores among the authigenic microlite silica.

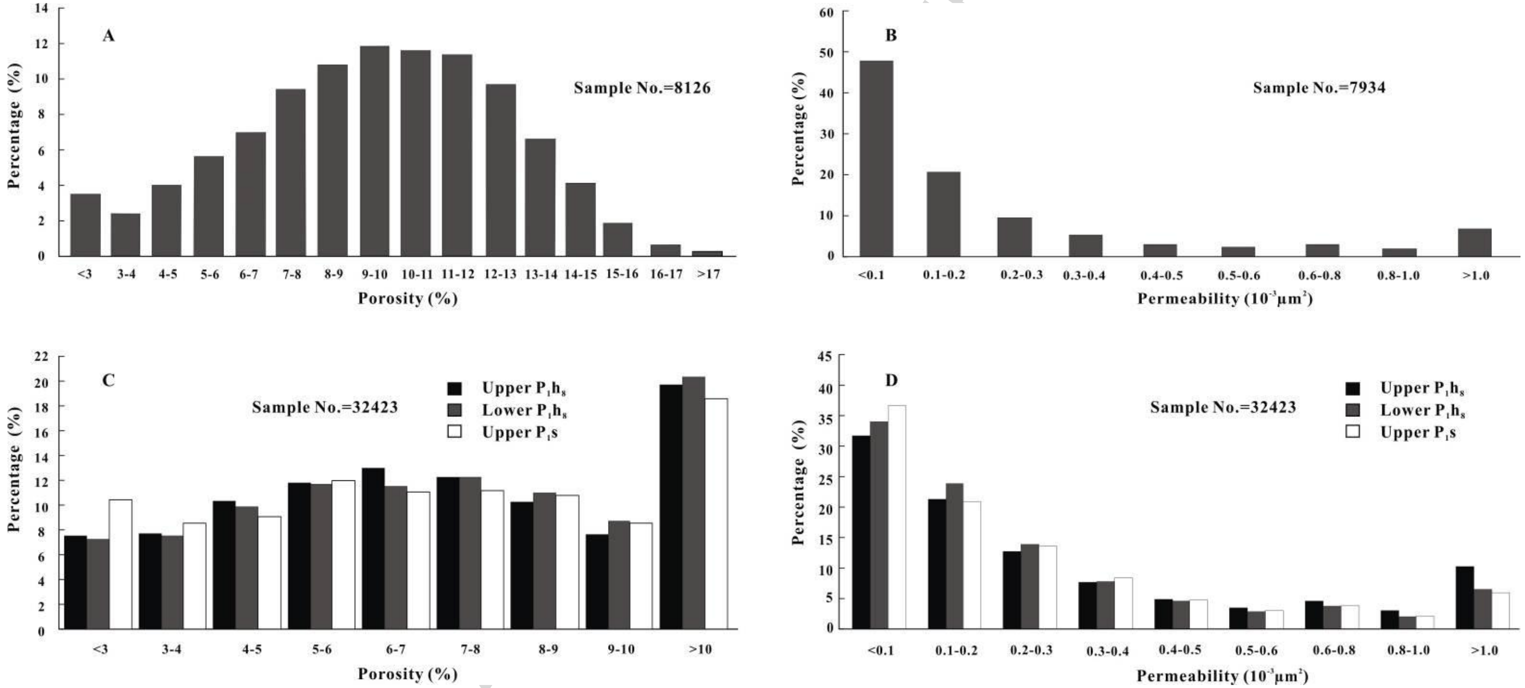

Fig. 8. Histograms of the properties of the tight sandstone reservoir in the Ordos Basin.

Notes: A. Porosity histogram for the tight sandstone reservoir of the Mesozoic Yanchang Formation. B. Permeability histogram for the tight sandstone reservoir of the Mesozoic Yanchang Formation. C. Porosity histogram for the tight sandstone reservoir of the Upper Paleozoic Formation. D. Permeability histogram for the tight sandstone reservoir of the Upper Paleozoic Formation.

The tight sandstone reservoir in the Ordos Basin is characterized by ultra-low porosity and ultra-low permeability. The porosity and permeability of the tight sandstone of the Mesozoic Yanchang Formation are distributed evenly, with porosity values less than 13% accounting for ~86.6 % (Fig. 8A) and a permeability of less than 0.5x10^{-3} μm^2 (0.4x10^{-3} μm^2, 0.3x10^{-3} μm^2) accounting for ~86.3 % (~83.3%, ~78.0%) (Fig. 8B). The porosity and permeability of the Upper Paleozoic tight sandstone is also distributed evenly, with porosity values less than 8 % accounting for 61.3 % (Fig. 8C), permeability of less than 0.5×10^{-3} μm^2 accounting for ~82.9 %; permeability of less than 0.5×10^{-3} μm^2 (0.3×10^{-3} μm^2) accounting for ~78.1 % (70.1 %); and permeability of less than 0.3×10^{-3} μm^2 accounting for ~70.1 % (Fig. 8D).

The storage space of the tight sand reservoir in the Ordos Basin is mainly characterized by pore-throat sizes on the scale of nanometers. Within the tight sandstonestone of the Mesozoic Yanchang Formation, 57.2% of the total pore throats have radii smaller than 0.1 μm (Fig. 9A). Within the tight sandstone of the Upper Paleozoic, 52.8% of the total pore throats have radii smaller than 0.1 μm, and 34.3% of the totals have radii between 0.1 and 1.0 μm (Fig. 9B).

The tight sandstones of the Ordos Basin follow both Darcian and non-Darcian percolation laws, with the latter being dominant. Non-Darcian percolation under a low permeability and low flow rate requires an additional driving force to initiate fluid flow, which means that the starting pressure gradient of the fluid in low-permeability reservoirs increases the additional fluid resistant force. The starting pressure gradient of the Upper Paleozoic tight sandstone is ~0.1–0.3 MPa/cm (Fig. 10).

The nanometer-sized pore throats of tight sandstone reservoirs causes very poor gravity separation of oil, gas and water. The bond-water saturation is high and in some cases ultra-high. The coexistence of oil, gas and water is common and is continuously distributed in complex patterns. There is no uniform pressure system or oil-gas-water contact surface. The oil- or gas-bearing saturation varies. As calculated from well-logging data, the gas-bearing saturation of the Upper Paleozoic tight sandstone varies from 30% to 80% (Fig. 11).

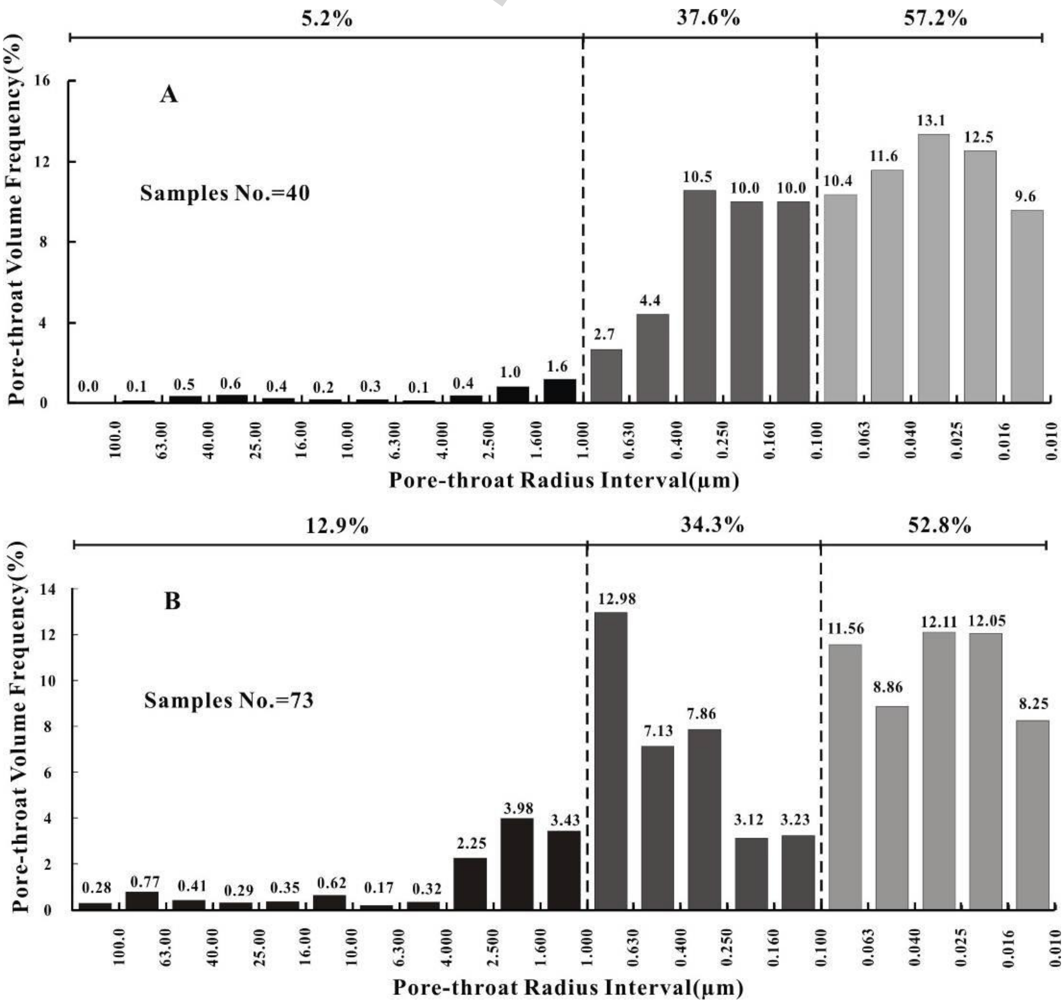

Fig. 9. Histograms of the pore-throat sizes of the tight sandstone reservoir in the

Ordos Basin.

Notes：A. Pore-throat histogram for the tight sandstone reservoir of the Mesozoic Yanchang Formation. B. Pore-throat histogram for the tight sandstone reservoir of the Upper Paleozoic Formation.

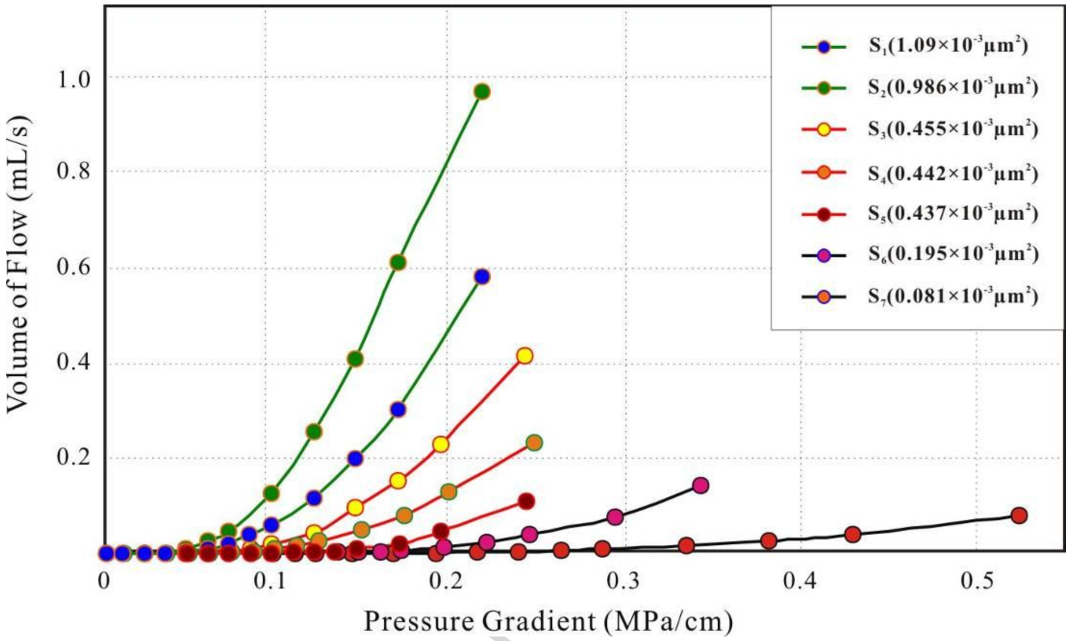

Fig. 10. Non-Darcian percolation features of the Upper Paleozoic tight sandstone reservoir of the Ordos Basin.

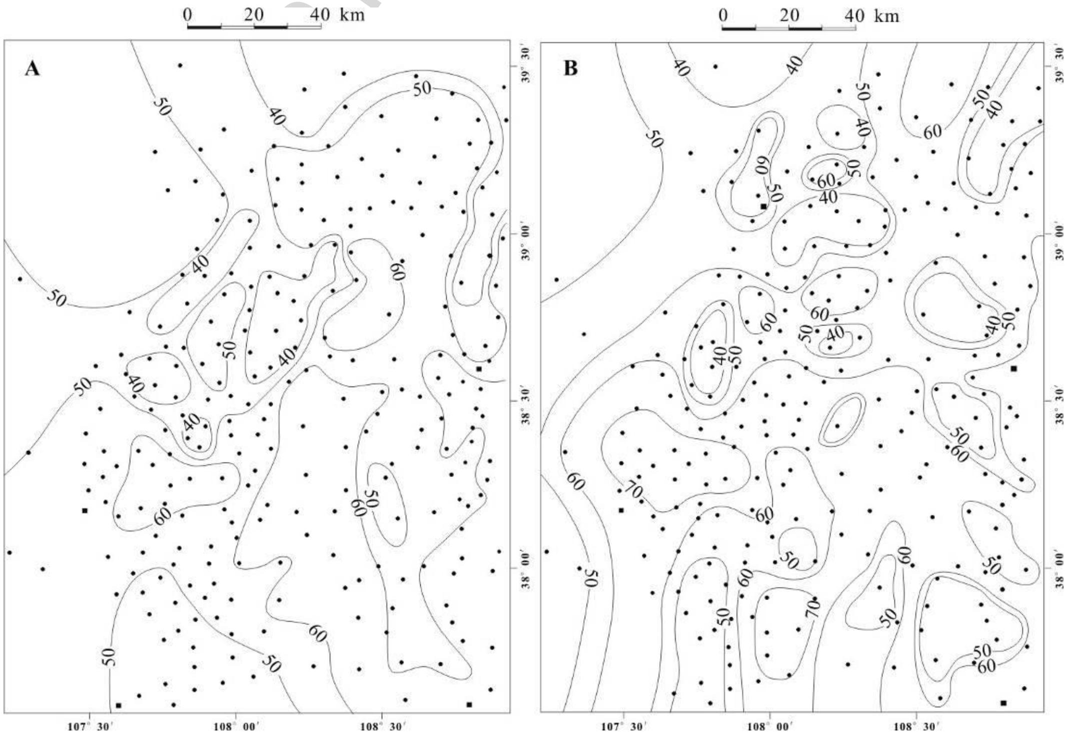

Fig. 11. Gas-bearing saturation distribution of the Upper Paleozoic tight sandstone reservoir of the Ordos Basin.

Notes：A. Gas-bearing saturation distribution of the P_1h^8 tight sandstone reservoir. B. Gas-bearing saturation distribution of the P_1s^1 tight sandstone reservoir. See Fig. 4. for the map location.

5. Conclusions and Significance

Unconventional hydrocarbons in tight reservoirs exhibit characteristics that are distinct from those of conventional hydrocarbons in structural and stratigraphic traps. Generally, unconventional hydrocarbons accumulate continuously, and conventional hydrocarbons accumulate locally. Unconventional hydrocarbons exhibit characteristic features: the hydrocarbon source and reservoir coexist; porosity and permeability are ultra-low; nanometer-sized-pore throats are widely distributed; hydrocarbon-bearing reservoir bodies are continuously distributed; there is no obvious trap boundary; buoyancy and hydrodynamics have only minor effects; Darcy's law does not apply; phase separation is poor, and there is no uniform oil-gas-water interface or pressure system; and oil or gas saturation varies. In summary, unconventional continuous hydrocarbon accumulation over a large area is the distinguishing characteristic of unconventional petroleum.

Unconventional hydrocarbon resources occupy the lower part of the energy triangle structure, accounting for a large volume, most likely 80% of all remaining hydrocarbon resources (Masters, 1979; Deming, 2001). The resources retained in source rocks (e.g., coalbed methane, shale gas and shale oil) account for ~50%. The other resources, which experienced primary migration or short-distance secondary migration and accumulated pervasively in unconventional continuous or quasi-continuous reservoirs, (e.g., tight sandstone, tight limestone, carbonate rock, igneous rock and metamorphic rock), account for ~30%. For example, unconventional hydrocarbon resources in China accounted for 75% of the total discovered hydrocarbon resources in 2010 (Zou, 2012). Although the reserves of unconventional hydrocarbon are enormous, economically, they are difficult to explore by conventional techniques. Therefore, unconventional petroleum geology and unconventional exploration techniques require further development. It would be advantageous to do additional monitoring of continuous hydrocarbon accumulations over large areas.

Acknowledgments

This work was supported by the Chinese Major National Scientific and Technological Program (Grant 2011ZX05001) and the PetroChina Major Scientific and Technological Program (Grant 2011B-03). This work could not have been achieved without the cooperation and support from the Research Institute of Exploration and Development and PetroChina ChangQing Oilfield Company. The authors also thank Prof. Zhongjian Qiu, Prof. Chengzao Jia, Prof. Jinxing Dai, Prof. Jianyi Hu, Prof. Wenzhi Zhao, Prof. Hua Yang, Prof. Jinhua Fu and other colleagues (Suyun Hu, Jianzhong Li, Jingli Yao, Tao Yang, Denghua Li, Dazhong Dong, Guosheng Zhang, Qiulin Guo, Xinjing Li, Lan Wang, Xiaohui Gao, Bin Bai and Jianwei Fan) for their generous help. The authors appreciate both Journal editors and anonymous reviewers for their precious time and useful suggestions.

References

Berg, R.R., 1975. Capillary pressures in stratigraphic traps. AAPG Bulletin, 59(6):

939-956.

Cross, T.A. and Lessenger, M.A., 1998. Sediment volume partitioning: rationale for stratigraphic model evaluation and high-resolution stratigraphic correlation. In: F.M. Gradstein, K.O. Sandvik and N.J. Milton (Editors), Sequence Stratigraphy-Concepts and Applications. Norwegian Petroleum Society (NPF), pp. 171-195.

Davis, R.W., 1987. Analysis of hydrodynamic factors in petroleum migration and entrapment. AAPG bulletin, 71(6): 643-649.

Deming, D., 2001. Oil: Are we running out? In: M.W. Downey, J.C. Threet and W.A. Morgan (Editors), Petroleum Provinces of the Twenty-first Century. AAPG, Tulsa, pp. 45-55.

Emmons, W.H., 1921. Geology of Petroleum. McGraw-Hill, New York, 610 pp.

England, W.A., Mackenzie, A.S., Mann, D.M. and Quigley, T.M., 1987. The movement and entrapment of petroleum fluids in the subsurface. Journal of the Geological Society, 144(2): 327-347.

Galloway, W.E., 1989. Genetic stratigraphic sequences in basin analysis I: Architecture and genesis of flooding-surface bounded depositional units. AAPG Bulletin, 73(2): 125-142.

Haq, B.U., Hardenbol, J. and Vail, P.R., 1987. Chronology of Fluctuating Sea Levels Since the Triassic. Science, 235(4793): 1156-1167.

Hubbert, M.K., 1953. Entrapment of petroleum under hydrodynamic conditions.

AAPG Bulletin, 37(8): 1954-2026.

Hunt, J.M., 1979. Petroleum geochemistry and geology. W. H. Freeman and Company, San Francisco, 743 pp.

Hunt, J.M., 1990. Generation and migration of petroleum from abnormally pressured fluid compartments. AAPG Bulletin, 74(1): 1-12.

IEA, 2008. World Energy Outlook, International Energy Agency (IEA), Paris, 569 pp.

IEA, 2009. World Energy Outlook, International Energy Agency (IEA), Paris, 696 pp.

IEA, 2010. World Energy Outlook, International Energy Agency (IEA), Paris, 731 pp.

Law, B.E. and Curtis, J.B., 2002. Introduction to Unconventional Petroleum Systems. AAPG Bulletin, 86(11): 1851-1852.

Le Pichon, X., 1968. Sea-floor spreading and continental drift. Journal of Geophysical Research, 73(12): 3661-3697.

Lerche, I., 1990. Basin analysis: quantitative methods, 1. Academic Press, San Diego, 589 pp.

Levorsen, A.I., 1956. Geology of petroleum (1st Edition). W. H. Freeman and Company, San Francisco, 703 pp.

Levorsen, A.I., 1967. Geology of petroleum (2nd Edition). W. H. Freeman and Company, San Francisco, 724 pp.

Magara, K. (Editor), 1978. Compaction and Fluid Migration Practical Petroleum Geology. Elsevier, 319 pp.

Magoon, L.B. and Dow, W.G., 1994. The petroleum system. In: L.B. Magoon and W.G.

Dow (Editors), The petroleum system-from source to trap. AAPG, Tulsa, pp. 2-24.

Masters, J.A., 1979. Deep Basin gas trap, western Canada. AAPG Bulletin, 63(2): 152-181.

McCollough, E.H., 1934. Structural influence on the accumulation of petroleum in California. In: W.E. Wrather and F.H. Lahee (Editors), Problems of petroleum geology. AAPG, Tulsa, pp. 735-760.

McKenzie, D.P., 1969. Speculations on the Consequences and Causes of Plate Motions. Geophysical Journal of the Royal Astronomical Society, 18(1): 1-32.

Morgan, W.J., 1968. Rises, trenches, great faults, and crustal blocks. Journal of Geophysical Research, 73(6): 1959-1982.

Pan, C.H., 1941. Nonmarine origin of petroleum in north Shensi, and the Cretaceous of Szechuan, China. AAPG Bulletin, 25(11): 2058-2068.

Peters, K.E. and Moldowan, J.M., 1993. Interpreting Molecular Fossils in Petroleum and Ancient Sediments. Prentice-Hall, New Jersey, 363 pp.

Roberts, W.H. and Cordell, R.J., 1980. Problems of petroleum migration. AAPG, Tulsa, 273 pp.

Roen, J.B. and Kepferle, R. C., 1993. Introductory review--Devonian and Mississippian black shales, eastern North American. In: J.B. Roen and R.C. Kepferle (Editors), Petroleum Geology of the Devonian and Mississippian Black Shale of Eastern North America. U.S. Geological Survey, pp. A1-A8.

Schmoker, J.W., 1995. Method for assessing continuous-type (unconventional) hydrocarbon accumulations. In: D. L. Gautier, G. L. Dolton, K. I. Takahashi and K. L. Varnes (Editors), National Assessment of United States Oil and Gas Resources - results, methodology, and supporting data. U.S. Geological Survey Digital Data Series DDS-30.

Schmoker, J.W., 2002. Resource-Assessment Perspectives for Unconventional Gas Systems. AAPG Bulletin, 86(11): 1993-1999.

Schowalter, T.T., 1979. Mechanics of secondary hydrocarbon migration and entrapment. AAPG Bulletin, 63(5): 723-760.

Selley, R.C., 1998. Elements of Petroleum Geology (2nd Edition). Academic Press, Waltham, 470 pp.

Shanley, K.W., Cluff, R.M. and Robinson, J.W., 2004. Factors controlling prolific gas production from low-permeability sandstone reservoirs: Implications for resource assessment, prospect development, and risk analysis. AAPG Bulletin, 88(8): 1083-1121.

Spencer, C.W. and Mast, R.F., 1986. Geology of tight gas reservoirs, AAPG Studies in Geology, New York, 305 pp.

Tissot, B.P. and Welte, D.H., 1978. Petroleum formation and occurrence. Springer-Verlag, Berlin, 699 pp.

Vail, P.R., Mitchum Jr., R.M., Todd, R.G., Widmier, J.M., Thompson III, S., Sangree, J.B., Bubb, J.N. and Hatlelid, W.G., 1977. Seismic stratigraphy and global changes of sea-level. In: C.E. Payton (Editor), Seismic Stratigraphy–Applications to

Hydrocarbon Exploration. AAPG, Tulsa, pp. 49-212.

Van Wagoner, J.C., 1995. Overview of sequence stratigraphy of foreland basin deposits: terminology, summary of papers, and glossary of sequence stratigraphy. In: J.C. Van Wagoner and G.T. Bertram (Editors), Sequence Stratigraphy of Foreland Basin Deposits: Outcrop and Subsurface Examples from the Cretaceous of North America. AAPG, Tulsa, pp. 9-21.

Van Wagoner, J.C., Mitchum, R.M., Posamentier, H.W. and Vail, P.R., 1987. An overview of sequence stratigraphy and key definitions. In: A.W. Bally (Editor), Atlas of Seismic Stratigraphy. AAPG, Tulsa, pp. 11-14.

White, I.C., 1885. The Geology of Natural Gas. Science, 125: 521-522.

Wilson, T.J., 1963. Hypothesis of Earth's Behaviour. Nature, 198(4884): 925-929.

WPC, 2007. Petroleum Resources Management system, Society of Petroleum Engineers (SPE), American Association of Petroleum Geologists (AAPG), World Petroleum Council (WPC), Society of Petroleum Evaluation Engineers (SPEE), 49 pp.

Zou, C.N., 2012. Unconventional petroleum geology. Elsevier, Beijing, 373 pp.

Zou, C.N., Dong, D.Z., Wang, S.J., Li, J.Z., Li, X.J., Wang, Y.M., Li, D.H. and Cheng, K.M., 2010a. Geological characteristics and resource potential of shale gas in China. Petroleum Exploration and Development, 37(6): 641-653.

Zou, C.N., Tao, S.Z., Yuan, X.J., Zhu, R.K., Dong, D.Z., Li, W., Wang, L., Gao, X.H., Gong, Y.J., Jia, J.H., Hou, L.H., Zhang, G.Y., Li, J.Z., Xu, C.C. and Yang, H., 2009a. Global importance of "continuous" petroleum reservoirs: Accumulation, distribution and evaluation. Petroleum Exploration and Development, 36(6): 669-682.

Zou, C.N. and Tao, S.Z., 2008. Geological characteristics of large gas provinces and large gas fields in China. Science in China Series D: Earth Sciences, 51(1): 14-35.

Zou, C.N., Tao, S.Z., Zhu, R.K., Yuan, X.J., Li, W., Zhang, G.Y., Zhang, X.X., Gao, X.H., Liu, L.H., Xu, C.C., Song, J.R. and Li, G.H., 2009b. Formation and distribution of "continuous" gas reservoirs nd their giant gas province: A case from the Upper riassic Xujiahe Formation giant gas province, Sichuan Basin. Petroleum Exploration and Development, 36(3): 307-319.

Zou, C.N., Yang, Z., Cui, J.W., Zhu, R.K., Hou, L.H., Tao, S.Z., Yuan, X.J., Wu, S.T., Lin, S.H., Wang, L., Bai, B. and Yao, J.L., 2013. Formation mechanism, geological characteristics and development strategy of nonmarine shale oil in China. Petroleum Exploration and Development, 40(1): 15-27.

Zou, C.N., Yang, Z., Tao, S.Z., Li, W., Wu, S.T., Hou, L.H., Zhu, R.K., Yuan, X.J., Wang, L., Gao, X.H., Jia, J.H. and Guo, Q.L., 2012. Nano-hydrocarbon and the accumulation in coexisting source and reservoir. Petroleum Exploration and Development, 39(1): 15-32.

Zou, C.N., Zhang, G.Y., Tao, S.Z., Hu, S.Y., Li, X.D., Li, J.Z., Dong, D.Z., Zhu, R.K., Yuan, X.J., Hou, L.H., Qu, H., Zhao, X., Jia, J.H., Gao, X.H., Guo, Q.L., Wang, L. and Li, X.J., 2010b. Geological features, major discoveries and unconventional petroleum geology in the global petroleum exploration. Petroleum Exploration and Development, 37(2): 129-145.