

# Accumulation of unconventional petroleum resources and their coexistence characteristics in Chang7 shale formations of Ordos Basin in central China

Jingwei CUI (✉)<sup>1,2</sup>, Rukai ZHU<sup>1</sup>, Zhiguo MAO<sup>1</sup>, Shixiang LI<sup>3</sup>

<sup>1</sup> Research Institute of Petroleum Exploration and Development, PetroChina, Beijing 100083, China

<sup>2</sup> Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Mineral, Shandong University of Science and Technology, Qingdao 266590, China

<sup>3</sup> Changqing Oilfield Research Institute of Petroleum Exploration and Development, CNPC, Xi'an 710018, China

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**Abstract** The Ordos Basin is the largest oil and gas producing basin in China, where tight oil, shale gas, oil shale, and other unconventional oil and gas resources have been found in the Chang7 subsection of the Triassic Yanchang Formation. However, the mechanism of formation and the distribution of unconventional oil and gas resources in the shale layers have not been systematically investigated until now. According to the type of unconventional oil and gas resources, main controlling factors, and the maturity, depth and abundance of organic matters, the shale oil and gas resources from Chang7 region are divided into five zones that include an outcrop-shallow oil shale zone, a middle-matured and medium-burial shale oil zone, a medium-matured and medium-burial in situ conversion process (ICP) shale oil zone, a high-maturity and deep-burial shale gas zone, and an adjacent-interbedded tight sandstone oil zone. By the distribution of resources, orderly evolution of oil and gas resources and coexistences in lacustrine shale formations have been put forward, and also a strategy of integrated exploration and development of resources in the shale formations is proposed. Overall, the outcome of this study may guide on the effective utilization of unconventional oil and gas resources in other shale formations.

**Keywords** shale formation, oil and gas resources, orderly accumulation and coexistence, integrated exploration and development

## 1 Introduction

Unconventional oil and gas resources from shale formations are under the spotlight of petroleum exploration and development globally. There are eight large shale gas production areas which include Marcellus, Haynesville, Eagle ford, Fayetteville, Barnett, Woodford, Utica, and Bakken (yearly production of more than  $172 \times 10^8 \text{ m}^3$ ), and four big tight oil production areas which include Eagle ford, Bakken, Wolfcamp, and Niobrara (yearly production of more than  $2000 \times 10^4$  tons) in shale plays in Northern America. Because of increasing production in the areas as mentioned above, the production from conventional oil fields which include the Permian Basin, West Gulf of Mexico and East Texas Basin in the US have gone up again after reduction (Jarvie, 2012; Cui et al., 2012; Charlez, 2014). Although the production of tight oil reduced in 2016, it still accounted for 47% of US crude oil production, and the shale gas accounted for 57% of US natural gas production. After 10 years of exploration in China, breakthroughs have been made in the production of shale gas from Wufeng Formation-Longmaxi Formation in the Sichuan Basin and Chang7 formation in the Ordos Basin, and the tight oil and shale oil in the Ordos Basin. The production of shale gas is about  $75 \times 10^8 \text{ m}^3$  and tight oil and shale oil are beyond  $100 \times 10^4$  tons per year.

As the second largest oil and gas basin in China, the Ordos Basin is rich in unconventional oil and gas resources. The Changqing Oilfield has become the largest oil and gas field in China, and more than 50 million tons of oil and gas equivalent have been achieved consecutively for five years since 2013. Currently, the research on unconventional oil and gas resources mainly include about the formation of organic shale in fine sedimentary facies,

the description of pores and throats in the tight reservoirs in characterizing unconventional reservoirs, and optimizing the selection of sweet spots in the unconventional petroleum resources (Zou et al., 2009, 2015; Zou et al., 2013; Cui, 2015; Yuan et al., 2015). However, a systematic study about unconventional petroleum resources in Chang7 shale systems has not been attempted till now. The theory of petroleum system is from source to trap, whereas the hydrocarbon accumulation system is from trap to source and then to trap. The above two important theories are for conventional petroleum, both of which consider the source rock, reservoir, seal, trap, accumulation model, and the spatial-temporal matching relation of these elements (Zhao et al., 2002; Liu, 2008; Liu et al., 2008; Zou et al., 2014). So, the relationship between geological evolution and spatial distribution of unconventional petroleum resources should be systematically examined in shale formations.

Tight oil, tight gas, shale gas, and shale oil all belong to large-scale resources of continuous accumulation (Schmoker, 1996). Tight oil and gas are accumulations in the tight reservoirs that are adjacent to shale formations. Shale oil has both broad and narrow meanings. In the narrow sense, it refers to the mature oil bearing in the shale. In a broad sense, it includes tight oil and shale oil and gas (Bustin, 2012; Jarvie, 2012; Cui et al., 2015). It should be noted that, in essence, the shale-hosted oil is the mature oil in the oil-bearing shale which is different from unmaturing oil shale and synthetic shale oil. Oil shale is a solid consisting of combustible organic minerals with a high content of ash and can provide shale oil by subjecting to dry distillation at low temperature. The oil-bearing content of oil shale is more than 3.5%, and its content of organic matter is high. Its composition includes sapropel, humus, and their mixture, and the calorific value is more than 4187 J/g (Liu and Liu, 2005). However, a continuous accumulation does not include all oil and gas resources in the shale systems, such as oil shale and fractured mudstone reservoir. Therefore, the studies on whether the distribution of different oil and gas resources in the shale systems are as orderly as conventional oil and gas resources are of utmost importance. Also, shale oil, tight oil, and fractured oil cannot be precisely distinguished from each other. On this context, this study has two objectives: first, to investigate the relationship of unconventional petroleum resources in shale formations; second, to provide the geological basis for the development of unconventional petroleum resources in the Ordos basin.

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## 2 Geological settings

The Ordos Basin, the second largest sedimentary basin in China covers an area of  $25 \times 10^4$  km<sup>2</sup>. This is a typical superimposed basin which was an alternating marine–terrestrial cratonic basin in the Paleozoic period, and then

a continental lake basin in the Mesozoic period. This basin is located near the Luliang Mountains on the east, the Qinling Mountains on the south, the Liupan and Helan Mountains on the west, and borders the Daqing Mountains in the north (Fig. 1). The Triassic deposition has changed from the Carboniferous–Permian marine–continental transitional facies into continental facies, and the Yanchang Formation is generally in the greater lake basin period. The oil formations are divided into ten types: Chang1 to Chang10. Chang7 oil formation represents the greatest lake flooding period of the basin, where the sedimentary system is dominated by to semi-deep lacustrine facies and a large area of high-quality source rock is developed in the south of the Ordos Basin (Fig. 1). The primary source rock of the Mesozoic oil-bearing system is Chang7 shale (Yang et al., 2016). The extensive presence and high-efficiency hydrocarbon expulsion of the Chang7 source rocks have accounted for a number of oil layers (Chang4 + 5, Chang6, Chang8, and Chang9) for the commercial oil flow in the Ordos Basin, and the recent reports indicate that the petroleum resources exceeding 12.8 billion tons (Zhang et al., 2006; Deng et al., 2009; Fu et al., 2013).

Stimulated by the North American shale gas revolution, in the exploration and research an organic-rich Chang7 shale is also considered (Miller et al., 2008; Clarkson et al., 2012; Donovan et al., 2012; Jarvie, 2012; Yang et al., 2013; Zou et al., 2013; Cui, 2015; Zhang et al., 2015). As of now, unconventional petroleum in Chang7 is recovered from horizontal wells through the stimulation of water fracturing. The first larger tight oil field in China (Xin'anbian Oilfield) was discovered in the central Basin. A breakthrough has been made to the exploration of lacustrine shale gas in the Ordos basin. During April 2011, in Well LP 177, Chang7 shale was successfully fractured, tested, and was declared as the first lacustrine shale gas well in China (Wang et al., 2012). In addition, the South-eastern Ordos Basin, especially the Tongchuan area, is a famous oil shale province where many efforts have been made to the sedimentary environment, the genesis, distribution, and properties of reservoir as well as in the evaluation of resources (Lu et al., 2006; Zhang et al., 2006; Ren, 2008; Li et al., 2009; Zhang, 2010; Chang et al., 2012).

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## 3 Samples and experiments

The geochemical analysis was carried out on 1000 Chang7 shale samples in the Ordos basin. The locations of sampling wells are shown in Fig. 1. Total organic carbon content (TOC) and sulfur content (S) analyses were carried out using the popular Leco CS 230 Carbon Sulfur Instrument following the national standard GB/T 19145–2003. In the first step, a sample powder of about 10 mg was placed in a porous porcelain crucible which was heated at 1000°C in a Muffle furnace for 2 h. In the second step, a

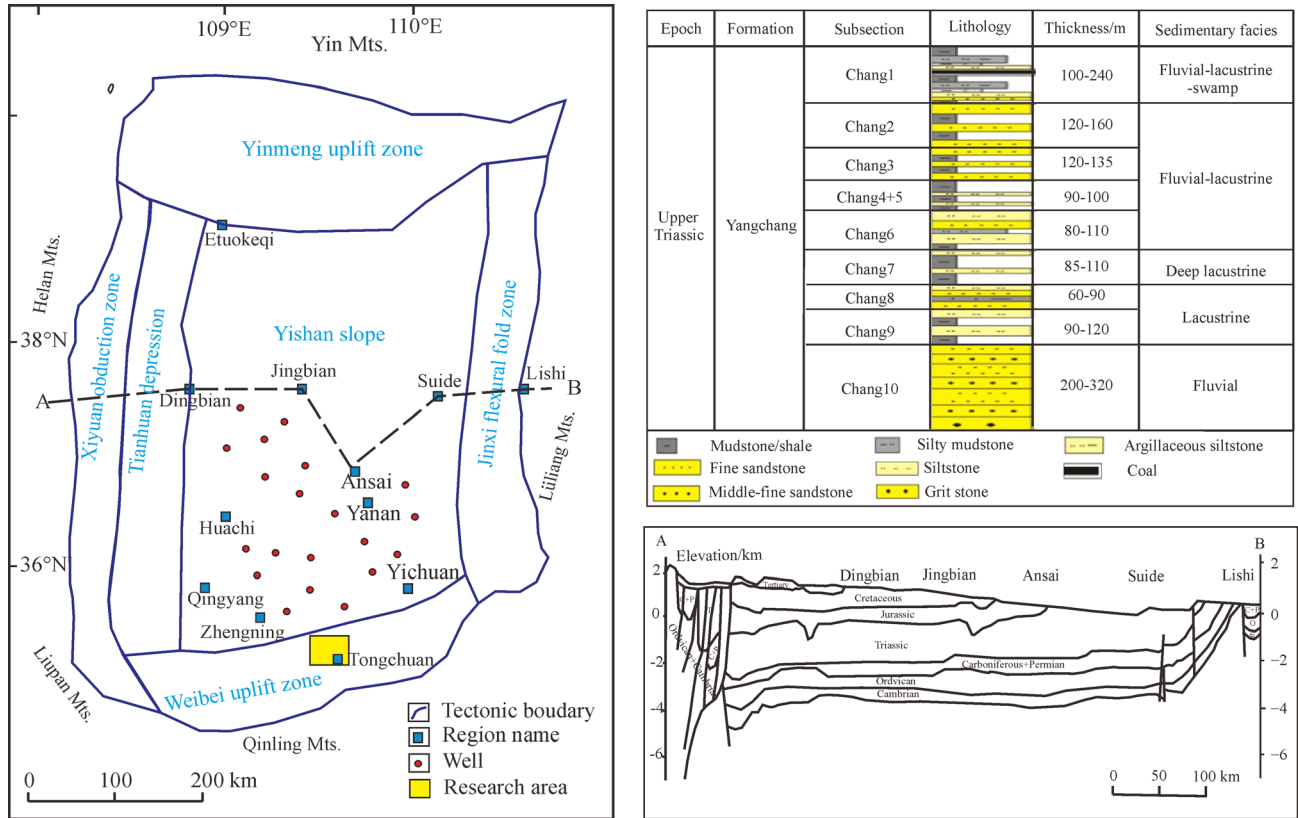


Fig. 1 The setting and tectonic units of the Ordos Basin

sufficient amount of 12.5% HCl was added and heated using an electrothermal plate at 60°C for 2 h until the completion of the reaction. In the third step, the crucible was kept into the filter vessel and rinsed after every 30 to 60 min for three days. Whereas, in the fourth step the crucible was dried at 60°C in a furnace and organic carbon and sulfur content were determined after cooling. Based on the analyzed results of core samples in different areas of the basin, combined with ΔLogR method, the distribution of Chang7 shale was characterized.

Analysis of the pyrolysis of rock was performed at the Petroleum Geochemistry Key Laboratory in China following the national standard GB/T 18602-2012. In the first step, a shale powder sample of 30–50 mg was accurately weighed and placed in the Rock-Eval 6 crucible for pyrolysis; Second, shale heating was divided into two stages: techniques of rock pyrolysis and parameters which are according to the standard processes followed by Peters and Cassa (1994). The measured parameters include hydrocarbon content (S<sub>1</sub>, mg of HC/g of rock), hydrocarbon-generating potential (S<sub>2</sub>, mg of HC/g of rock) and the maximum pyrolysis temperature (T<sub>max</sub>, °C). The parameters of hydrocarbon source rock include hydrogen index (HI), oxygen index (OI) and yield (PI).

Vitrinite reflectance (Ro) is the only internationally comparable indicator of the maturity of organic matter,

which can objectively reflect the maturity of the organic matter of most of the source rocks since the late Paleozoic. In fact, due to the uncommon or even rare occurrence of vitrinite in shale samples, we have therefore used Ro results on samples from nearby wells in which vitrinite was recognized and measured with more confidence, the number of measurements on any sample should be more than 25 (Hackley et al., 2015; Wang et al., 2015). The Ro analysis was completed in the Key Petroleum Geochemical Laboratory in China using RENISHAW in via laser Raman spectrometer equipped with an Ar<sup>+</sup> laser (488 nm) excitation and Leica DLMP polarizing microscope. The followed analytical steps are following the national standard GB/T 6948-2008.

Analysis on Shale Rock Properties (SRP) was performed in Weatherford International Laboratories to determine a range of petrophysical properties that include bulk density, crushed density, grain density, porosity, fluid saturation, and matrix permeability. The properties were used to calibrate open-hole log interpretation and to compute the volume of gas stored by compression in the gas-filled pores. The grain and the extracted fluid volumes were used to compute the total pore volume and total porosity of the sample. The fluid saturation was computed by dividing the extracted fluid volumes by the sample pore volume.

## 4 Results

Organic geochemical analysis of Chang7 shale in the Ordos basin shows a higher organic abundance (TOC > 2%), pyrolysis hydrocarbon potential of  $S_1 + S_2 > 6\%$ , chloroform asphalt A content exceeding 0.1000%, and the total hydrocarbon content > 500 ppm (Fig. 2). The abundance of organic matter of shale is high (more than 70%) which may be due to the high quality of the source rock of hydrocarbon. The organic petrological analysis shows primary amorphous humus and exinite groups, belonging to type I-II<sub>1</sub> kerogen (Fig. 3). The Ro shows in the mature to the highly mature stage, and in the oil window (Fig. 4). Two types of hydrocarbon source rocks, dark mudstone, and shale are developed in the Chang7 formation of the Ordos basin. Both of them have significant differences in the abundance of the total organic carbon content, hydrocarbon potential, and other geochemical parameters, as well as in the microscopic layer, mineral composition and distribution range. It can be understood that shale development lamination is prone to cracking, total organic carbon content over 6%, organic matter is distributed along the layer, chloroform extraction components are mostly aromatic hydrocarbons, and quartz content is low, with an average of 12.5%. Mudstone is generally undeveloped lamination, and total organic carbon content less 6%, organic matter is dispersed distribution, chloroform extraction group components are mostly saturated hydrocarbons, and quartz content is

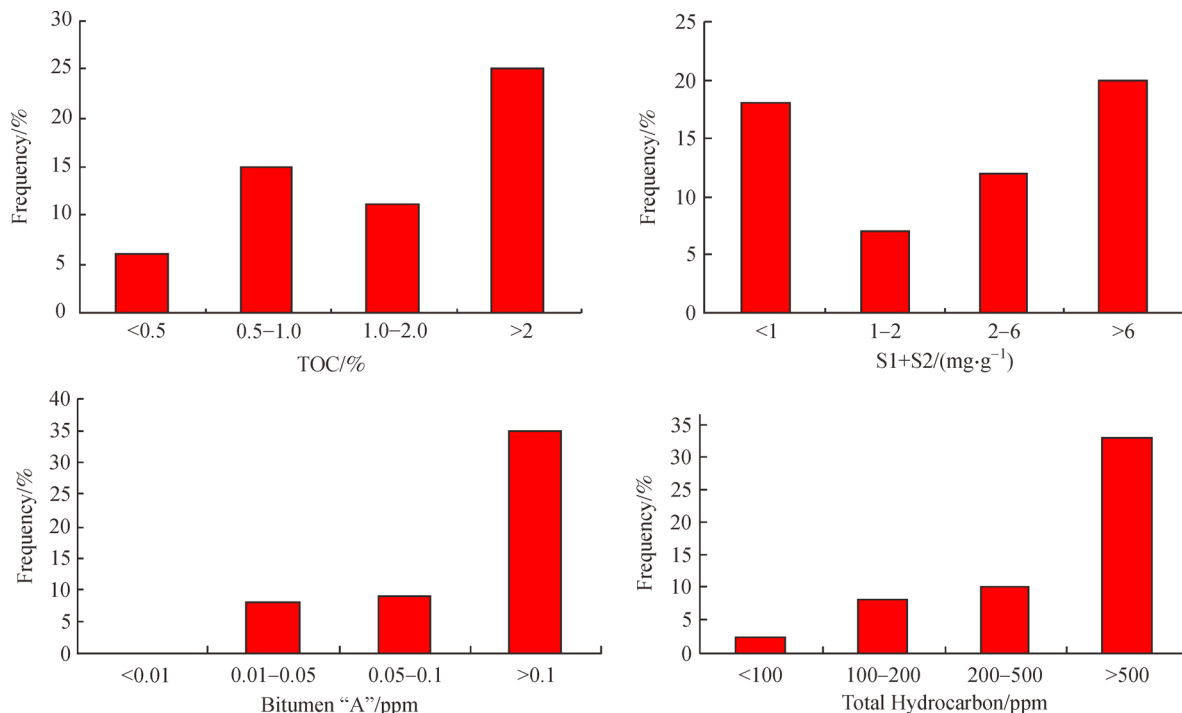
higher, with an average of 21.5%. Mudstone and shale have complementary characteristics in distribution (Lin et al., 2017).

According to the total organic carbon content (TOC) of mudstone in 8 wells of the Ordos Basin, the calculation formula for the TOC is established using the constrained  $\Delta\text{LogR}$  method:

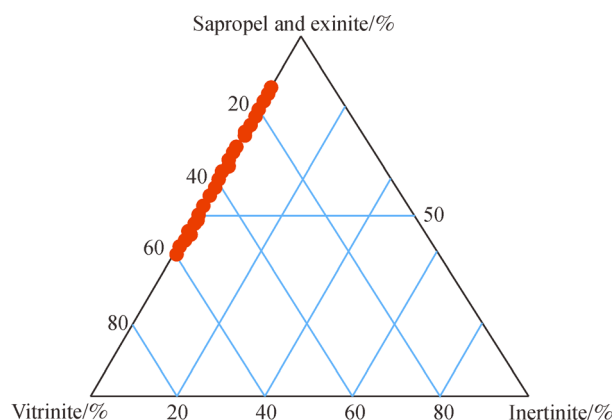
$$\Delta\text{LogR} = \log\left(\frac{Rt}{Rt_{\text{baseline}}}\right) - 0.02(\Delta t - \Delta t_{\text{baseline}}).$$

Among them,  $Rt$  is the resistivity log value,  $\Delta t$  is the acoustic time difference log value,  $Rt$  baseline and  $\Delta t$  baseline are the baseline, that is, the reading of the coincidence period and LOM is the heat change index of organic matter, reflecting the maturity of organic matter. Using the  $\Delta\text{LogR}$  method the distribution area of dark mudstone ( $2\% < \text{TOC} < 6\%$ ) and oil shale ( $\text{TOC} > 6\%$ ) were obtained.

The methods developed from the gas research institute, referred to as GRI methods, were recommended for the analysis of tight shale. GRI results of Chang7 formation show that the porosity of Chang7 formation is 4%–6% and the oil saturation is 12.9%–54%. Most of them are comparable with pyrolysis  $S_1$  (Table 1).  $S_1$  versus TOC suggested there exists a TOC valve. When TOC below 6%,  $S_1$  increases positive correlation with the TOC increase; when  $\text{TOC} > 6\%$ , the  $S_1$  almost the same as the TOC increase. However, the free hydrocarbons index  $S_1/\text{TOC}$  is a negative correlation with the TOC (Fig. 5). Studies have



**Fig. 2** Histogram of total organic carbon (TOC), hydrocarbon potential, bitumen "A" (extracted using chloroform), and total hydrocarbons (amounts of saturated and aromatic composition in bitumen "A").



**Fig. 3** Organic maceral Composition of Shale in Chang7 subsection.

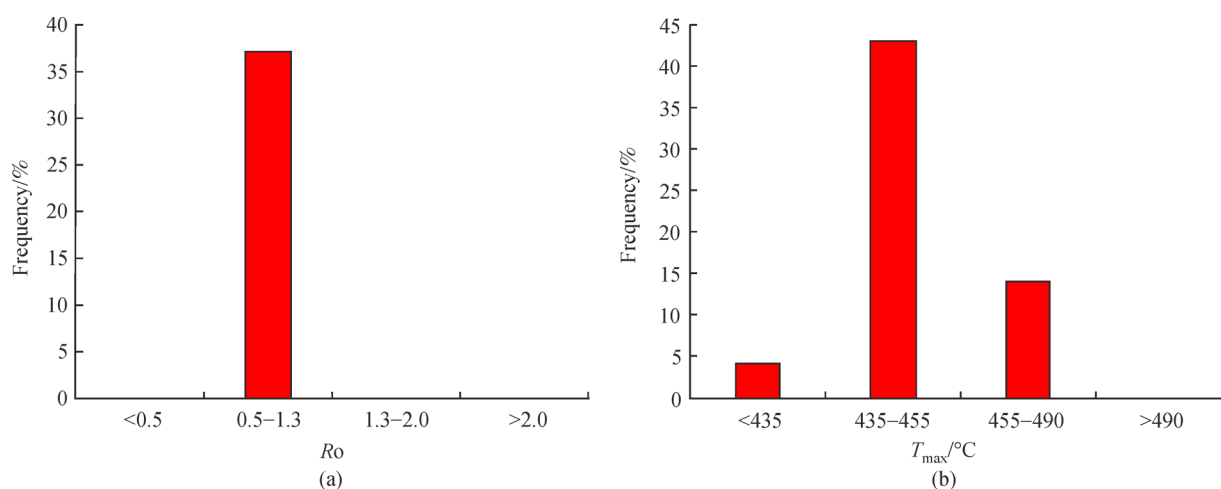
shown that when  $\text{TOC} > 6\%$ , organic matter forms networks, pores are not easily preserved and the corresponding pyrolysis of hydrocarbon  $S_1$  becomes lower, which are supported by pore studies (Stainforth, 2009; Milliken et al., 2013). It has been observed from

these studies that when Marcellus shale was found to be less than 5.5% of total organic carbon, the porosity was proportional to organic carbon, and the growth was not significant or constant when it is greater than 5.5%. So, the fractured shale oil should be concentrated in the dark mudstone area rather than in the oil shale area in Chang7 formation (Cui, 2015). The potential on the pyrolysis of hydrocarbon is positively correlated with TOC, which was mainly distributed in the developed area of shale so that the area is suited for in situ conversion process (ICP).

## 5 Discussion

### 5.1 Category of unconventional petroleum resources in the Chang7 formation

In this study, based on the understanding of the process of accumulation, occurrence, location, resource category, and development of technology, unconventional resources are described by taking typical examples in China. Chang7 formation includes tight oil, shale oil, shale gas, and oil



**Fig. 4** Frequency distribution of  $R_o$  (a) and  $T_{\max}$  (b) in Chang7 shale.

**Table 1** Comparison of typical Chang7 shale SPR Dean-star method with pyrolysis value

Well No.	Depth /m	Oil Saturation /%	Water Saturation /%	Gas porosity /%	Porosity /%	Oil amount $/(mg \cdot g^{-1})$	$S_1$ $/(mg \cdot g^{-1})$	TOC /%
1	3066.80	50.29	47.6	2.1	5.05	8.27	5.81	3.82
2	3057.20	52.29	42.3	5.4	4.64	7.83	4.83	3.01
3	2995.50	51.83	43.5	4.7	4.68	8.03	6.50	4.01
4	2989.80	53.98	43.4	2.6	4.11	7.32	5.79	3.64
5	2988.80	46.51	48.8	4.7	4.33	6.56	4.23	2.61
6	2980.80	49.11	45.0	5.9	4.60	7.60	6.84	3.94
7	2979.40	53.25	41.4	5.4	4.48	7.61	4.93	3.42
8	2976.30	34.12	45.4	20.5	5.37	5.74	2.93	1.39
9	2213.60	46.46	49.0	4.5	5.30	8.31	5.38	3.80
10	2489.60	12.90	69.9	17.2	4.23	2.16	2.54	16.12

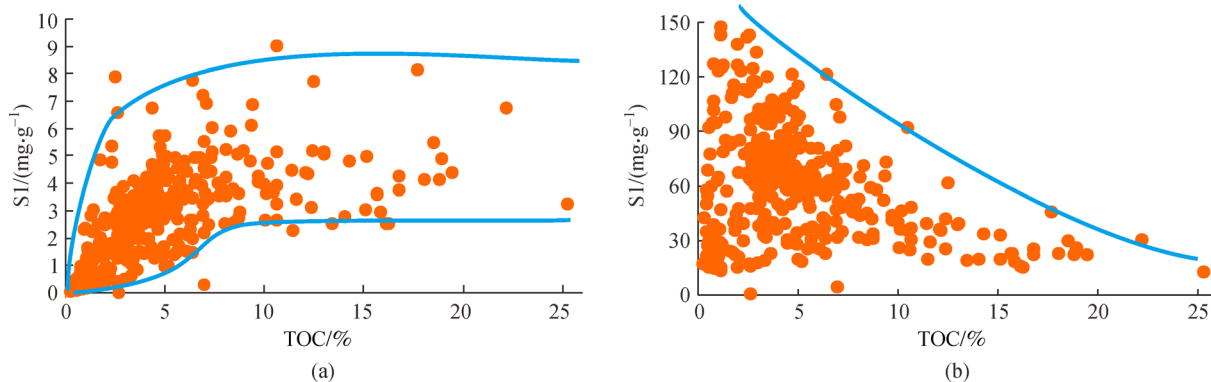


Fig. 5  $S_1$  versus TOC correlation. (a)  $S_1$  per rock samples; (b)  $S_1$  per TOC.

shale, all of which have been verified (Yang et al., 2010; Wang et al., 2012; Yang et al., 2013). The typical fractured shale reservoir is Ha14 Well in the Songliao Basin, and there are no reports of fractured mudstone reservoirs in the Chang7 formation (Curtis, 2002; Xu, 2003). Horizontal wells and hydraulic fractures are widely used in the exploration of tight oil, and a significant breakthrough has been made in the Chang7 formation (Yang et al., 2013). The oil shale which has a  $R_o < 0.6\%$  can be heated to generate shale oil, especially in the Tongchuan and Binxian areas in the south of the Basin where oil shale is developed with a high oil content (Cui et al., 2019).

According to conventional petrology theory and kerogen hydrocarbon generation theory, second migration is necessary for conventional structural reservoirs, lithological reservoirs, as well as stratigraphic reservoirs, all of which are conventional petroleum resources and are outside the source system. Tight oil, shale oil, and shale gas is accumulated in or adjacent to the source rocks, which only experience primary migration and belong to unconventional petroleum resources. Oil shale under heating and distillation can generate human-made shale oil, which is an *in situ* cracked unconventional petroleum resource belonging to kerogen system (Fig. 6).

## 5.2 Orderly accumulation and coexistence of Chang7 unconventional resources and the technology development

The unconventional resources in Chang7 formations include oil shale, shale oil, tight oil, and shale gas. The tight oil is mainly located in the east-north of the basin which developed delta-front sandstones and in the west-south of the basin where gravity flow is the main sedimentary facies. The tight oil resources are about  $9 \times 10^8$  tons, and the recoverable resources are more than 0.3 billion tons (Yang et al., 2013; Cui et al., 2016). In the deep lake area, there are vast volumes of thick, dark, lacustrine, muddy sediments which are mainly dark to gray and gray to black carbonaceous shale, gray-black shale, and oil shale. The lacustrine shale is thick in the west and south and thin in the east and north.

After analyzing ten representative samples about the oil content and porosity, the central controlling factors on the sweet spots in the fractured and ICP (*in situ* conversion process) shale oil areas have been determined. If the  $TOC > 6\%$ , the shale would be a desirable area of shale oil owing to a high-efficiency kerogen network for the expulsion of hydrocarbon, whereas if the  $R_o$  is below 1.0 the ICP shale is good. The shale with a TOC of 6% and a middle  $R_o$  (0.75%–0.9%) is good for the exploration of shale oil. All these conclusions have been confirmed from the drilling data (Cui, 2015; Yang et al., 2016). The area with a high-maturity shale ( $R_o > 1\%$ ) can be a promising place for the exploration of shale gas. The condition of the accumulation of tight oil is that thick sandstone with relatively high porosity and permeability is close enough to the mature source rocks.

The petroleum resources in the Chang7 shale formation are orderly and spatially coexist. In terms of burial depth, TOC, and maturity, the unconventional petroleum resources can be subdivided into five zones which include an outcrop-shallow oil shale zone with low maturity, a fractured shale oil zone ( $TOC < 6\%$ ) with a middle burial and maturity, an ICP shale oil zone ( $TOC > 6\%$ ) with a middle burial and maturity, a shale gas zone with a high maturity and deep burial, and a tight sandstone oil zone adjacent to the shale with a high maturity and deep burial (Fig. 7). Figure 8 demonstrates the proposed specific technologies based on unconventional petroleum resources.

Outcrop-shallow oil shale zone: the resources are located in the outcrop and shallow layers with shallow burial (less than 1000 m), low matured ( $R_o < 0.8\%$ ) and high oil content ( $> 3.5\%$ ) (Fig. 7(a)). The oil shale can be developed by open pits which are widely used in Estonia, Brazil, and China. In addition to the furnace process followed in China, the PetroSix process used by the Brazil Oil Company, the Kiviter, Galoter and Albert Taciuk processes in Estonia, the most globally advanced one is the EcoShale process. This process combines the surface with underground conditions. Oil shale is crushed above the ground and then buried and heated by steam underground








Petroleum category	Petroleum system	Occurrence	Schematic	Reservoir type	Foreign sample	Domestic sample	Recovery method
Conventional oil and gas	System outside the source rock	free state		structural reservoir	Western Siberia Urengoy	Song-liao Basin Daqing placanticline	Vertical well
		free state		lithologic reservoir	Appalachian hundreds inch sandstone	Ordos Basin Chang8	vertical well
		free state		stratigraphic reservoirs	Alaska Prudhoe Bay	middle and north area of the Tarim Basin	vertical well
unconventional oil and gas	system within the source rock	free state		fracture reservoir	Siberia Sam Oilfield	Songliao Basin qingshankou shale Ha No.14 well	vertical well
		free state plus absorption		tight oil and gas	Williston Basin Bakken shale	sweet point in the shale of Lucaogaou formation in Junggar Basin	horizontal well with hydrate fracture
		absorption		shale oil and shale gas	Fort Worth Barnett shale	Ordos Basin Chang7 Sichuan Basin Longmaxi shale	horizontal well with hydrate fracture horizontal well with heating
	kerogen system	pre-cracking state		man-made shale oil	Green River shale	Maoming shale Fushun shale	heating transforming on the surface

Fig. 6 The category, characteristics, occurrence and development technology of petroleum resources.

at 370°C, but this process has not been put into commercial application.

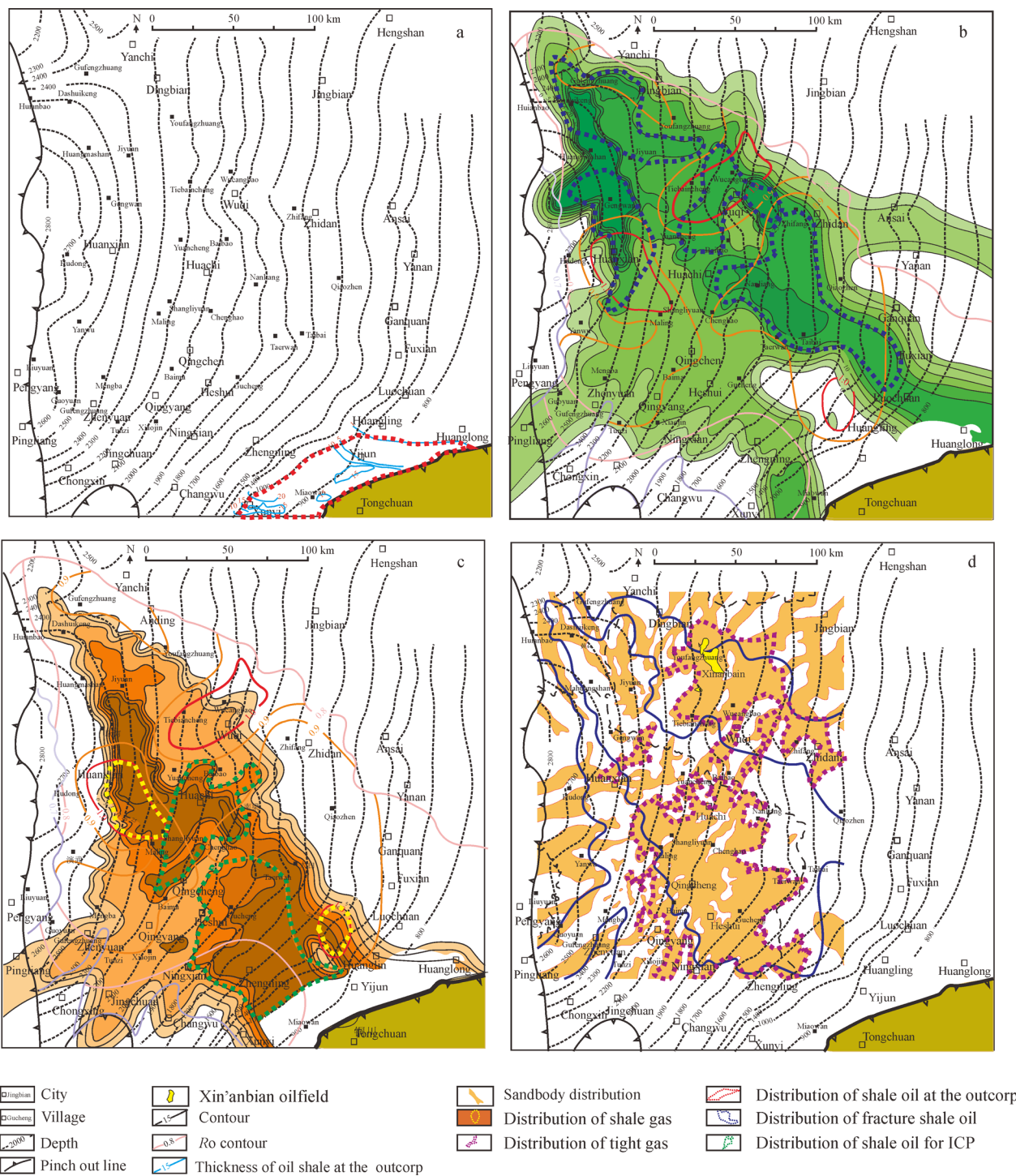
Fractured shale oil zone with middle burial and maturity: The TOC of the shale is in between 2% and 6%, the buried depth is in between 1500 and 2500 m, and the  $R_o$  is greater than 0.9% (Fig. 7(b)). The shale that matches with the above conditions can be developed after stimulation with fracturing. This type of technology is widely used in domestic and overseas fields.

ICP shale oil zone with middle burial and maturity: The ICP shale oil has a higher organic content ( $TOC > 6\%$ ), moderate maturity ( $R_o < 0.9\%$ ) and middle burial from 1000 to 2200 m. Currently, Shell oil company is playing the leading role in developing ICP shale oil. Apart from ICP, companies such as ExxonMobil, AMSO, IEI, are trying to find out new technologies to develop such oil shale. The disadvantages of the ICP technique are that the heating period is too long, the energy consumption is very high, and development needs seal layers. The advantage of ICP is that the product is light oil which is abundant in gas at a relatively low temperature and is convenient for subsequent disposal.

Shale gas zone with high maturity and deep burial: The shale-hosted gas is in much deeper layers, the maturity is beyond 1.0%, and TOC is more than 6%. Two Chang7 shale zones in the Ordos Basin are at 1400 m and 2200–2500 m, respectively (yellow dotted line in Fig. 7(c)). Currently, shale-hosted gas in organic shale is developed through large-scale horizontal wells and volume fracturing technology.

Tight sandstone oil zone adjacent to the shale with high maturity and deep burial: this type of resource is distributed in large-scale sandstones which are vertically adjacent to organic-rich shale ( $R_o > 0.8\%$ ). The Xin'anbian tight oilfield has been found out in this area, and there are many higher production wells in the Longdong area which have been constructed with a tight oil field for hundred million tons of oil (the purple dotted line in Fig. 7(d)). Large-scale horizontal wells and volume fracturing technology have been widely applied in these areas.

Besides the tight sandstone oil which is adjacent to the shale, the unconventional petroleum resources in the shale formations can be classified by the depth, maturity, and



**Fig. 7** Orderly accumulation and coexistence of oil and gas resources in shale formations in Chang7 subsection, Ordos Basin.

TOC of the shale, and are developed by surface and underground processes (Fig. 8).

### 5.3 Orderly evolution and coexistence of petroleum resources in shale formations

The evolution of oil and gas is orderly, and the resources

are coexisting in the shale formations. This indicates that the process from hydrocarbon generation and expulsion, residual hydrocarbon, to the change of reservoir space with increasing burial is orderly during thermal evolution of organic matter (Tissot and Welte, 1978; Curtis et al., 2012; Fishman et al., 2012; Zou et al., 2014). The type of petroleum occurrence, the content of hydrocarbon genera-

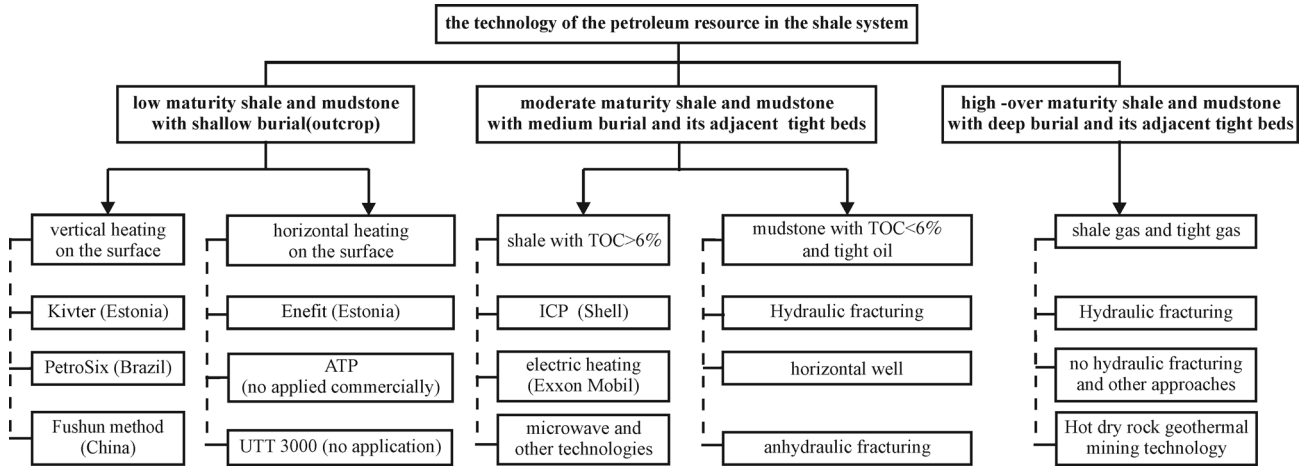
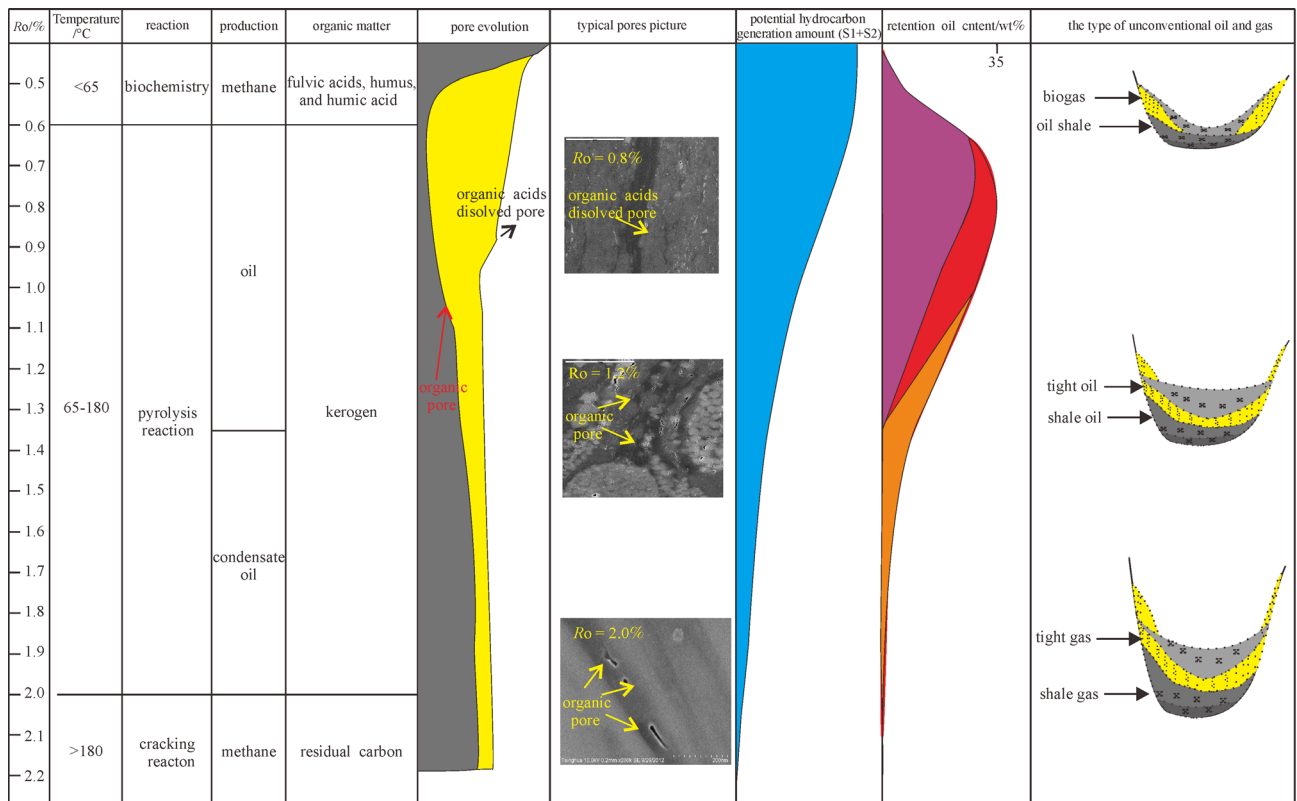


Fig. 8 Specific technology for petroleum resources in shale formations.

tion, the content of residual hydrocarbon, and the composition of oil and gas evolved orderly under the control of thermal evolution (time). The petroleum resources are biogas and oil shale during the low-maturity stage, and shale oil and tight oil during the high-maturity stage, and tight gas and shale gas during the over-maturity stage (Fig. 9).

In this study, resources orderly evolution and coex-

istence (ROEC) is proposed in the shale formations. ROEC includes five orderly aspects: time evolution, generation sequence, accumulation mechanism, spatial distribution, and exploration strategy. Whether terrestrial, lacustrine, or marine, the petroleum resources in the shale formations evolve orderly. The types of unconventional petroleum resources depend on the maturity of the organic matter in the shale formations under the control of regional tectonic



\* according to the experiment results of Chang7 shale

Fig. 9 Orderly evolution of unconventional petroleum resources in shale formations.

movements and the difference in thermal evolutions (Liu et al., 2014). The first step in the assessment of the type and potential of the unconventional petroleum resource in the shale system is to appraise the thermal evolution stage of the shale. For the Eagle ford shale in the U.S, for example, the exploration of shale gas and shale oil largely depends on the maturity of the shale (Cui et al., 2015).

The origins of organic and non-organic reservoir space are interrelated and evolved orderly, all the processes of which are under the control of pressure, inorganic, and organic reactions in the generation of hydrocarbon, and diagenesis. In the mature stage, the reservoir space becomes less because of compaction and diagenesis, and the unconventional petroleum resources are tight oil and shale oil migrating at an abnormal pressure from the generation of hydrocarbon. At the highly to over mature stage, the reservoir space would be enlarged because of the generation of organic pores, and the unconventional petroleum resources are shale gas which accumulates in the original places.

In terms of space, oil shale is located at the edge of the Basin, tight oil and tight shale are located at the middle-deep slope, and shale gas is found to be in deep. In terms of exploration strategy, the theory of orderly accumulation of unconventional petroleum resources lead us to prospect in the basin center, and the theory of orderly accumulation of oil and gas in shale formations leads us to explore in the source rock in the basin center.

The spatial coexistence of unconventional petroleum resources in shale formations is under the control of sedimentary construction. The types of oil and gas depending on the maturity of source rock, the number of resources on the content of organic matter, petroleum occurrences on the type of organic matter, and the types of unconventional petroleum resources in the sedimentary construction. The connotation of the spatial coexistence of

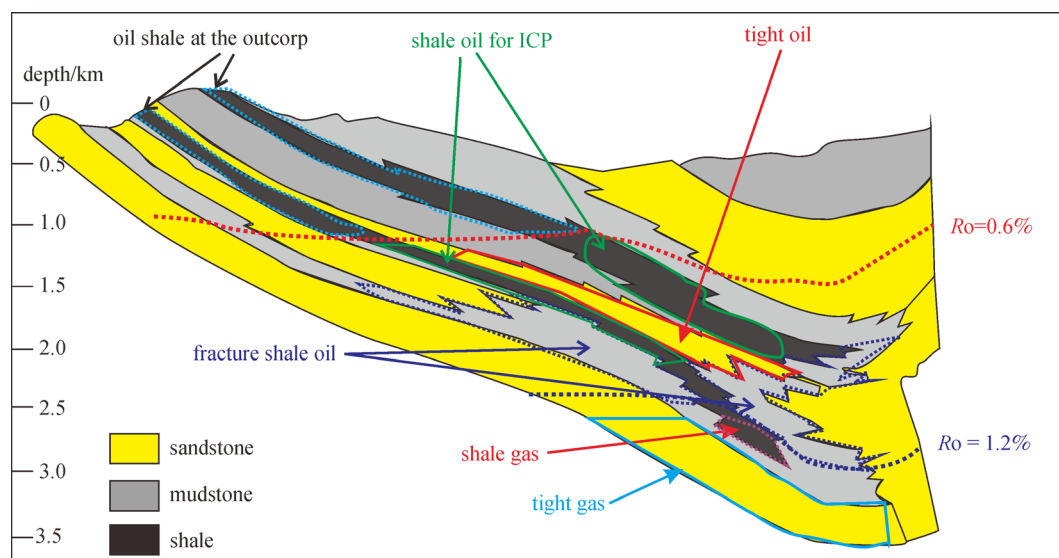
unconventional petroleum resources in shale formations is the relationship of distribution between different petroleum resources (Fig. 10).

It can be revealed from the coexistence of petroleum resources in shale formations is that there are sweet spots and heterogeneity in the unconventional petroleum resources. The location of coexistence depends on the conditions of formation and significant controlling factors. Based on the generation of hydrocarbon, residence, and migration mechanisms, the types, differences, main controlling factors, and enrichment of petroleum resources can be explained (Zou et al., 2013; Cui et al., 2015; Yang et al. 2016) (Table 2). It is of great importance for the evaluation and selection of sweet spots and taking specific measures for different petroleum resources in the exploration of petroleum resources in shale formations.

#### 5.4 Integrated exploration and development of petroleum resources in shale formations

Following the understanding of ROEC in shale formations, the exploration and development of unconventional petroleum resources are undergoing based on the characteristics of unconventional petroleum resources, especially the shale formations with a strong lateral heterogeneity in maturity and vertical complex sedimentary construction. The significance of integrated exploration and development is that the petroleum resources in different zones in the same formation should be investigated, evaluated, and explored as a unit, and 3D exploration, integral evaluation, and collaborative development should be conducted to the petroleum resources in different formations (Fig. 11).

The micro-fractures and permeable reservoirs in shale formations are favorable zones for the exploration of unconventional petroleum resources and sweet spots with a



**Fig. 10** Spatial coexistence of unconventional petroleum resources in shale formations.

**Table 2** Forming conditions and sweet spots of petroleum resources in shale formations

Resource type	Forming conditions and main controlling factors	Accumulation mechanism	Sweet spot	Specific technology
Oil shale	Oil shale formed in high-productivity lake bay, deep lake or uplifting shelf where it's anoxic and deep burial and thermal anomaly didn't occur, and controlled by high productivity, reducing environment and low maturity	Shale with high organic matter and low maturity; in-situ resource.	Zones with low maturity, shallow burial, high organic matter and high oil content	Semi-subsurface production Open-pit mining and heating with Cyclotron furnace
Fractured shale oil	Shale oil formed in fracture development zone in mature shales; and controlled by structure, stress releasing zone and mature source rock.	Fractures constitute main reservoir space. Shale oil accumulates adjacent to source rocks	The zone with structural fractures in mature shale	Fracture forecast technology FMI Geostress analysis
Shale oil	Tight layers are adjacent to source rock. The quality of shale oil is controlled by migration distance and maturity. Maturity, TOC and porosity are controlling factors	Pores in minerals and organic matter. Shale oil is residual in source rocks	Moderate-maturity shale thick and with high brittle minerals	Hydraulic fracturing for dark shale and ICP for the shale with high TOC
Tight oil	Tight layers with relatively developed fractures and high porosity and permeability are near source rocks during oil generation. Porosity and source-reservoir matching relationship are controlling factories	Intergranular, intragranular and solution pore sand fractures in inorganic minerals; near-source-rock accumulation	The zone with relatively high porosity and permeability, large thickness and high brittle mineral content	Horizontal wells, volume fracturing and water free fracturing
Shale gas	Pores in minerals coexist with pores in organic matters, and micro-fractures are developed in the shale with high organic matter. High organic abundance, porosity and mineral composition are controlling factors.	Organic pores, intergranular, intragranular and solution pores and fractures in inorganic minerals; near-source-rock accumulation	The zone with relatively high porosity and permeability, large thickness and high brittle mineral content	Horizontal wells, volume fracturing and water free fracturing
Tight gas	Tight layers with relatively developed fractures and high porosity and permeability are near source rocks during oil generation. Porosity and source-reservoir matching relationship are controlling factories	Intergranular, intragranular and solution pores and fractures in inorganic minerals; near-source-rock accumulation	The zone with relatively high porosity and permeability, large thickness and high brittle mineral content	Horizontal wells, volume fracturing and water free fracturing

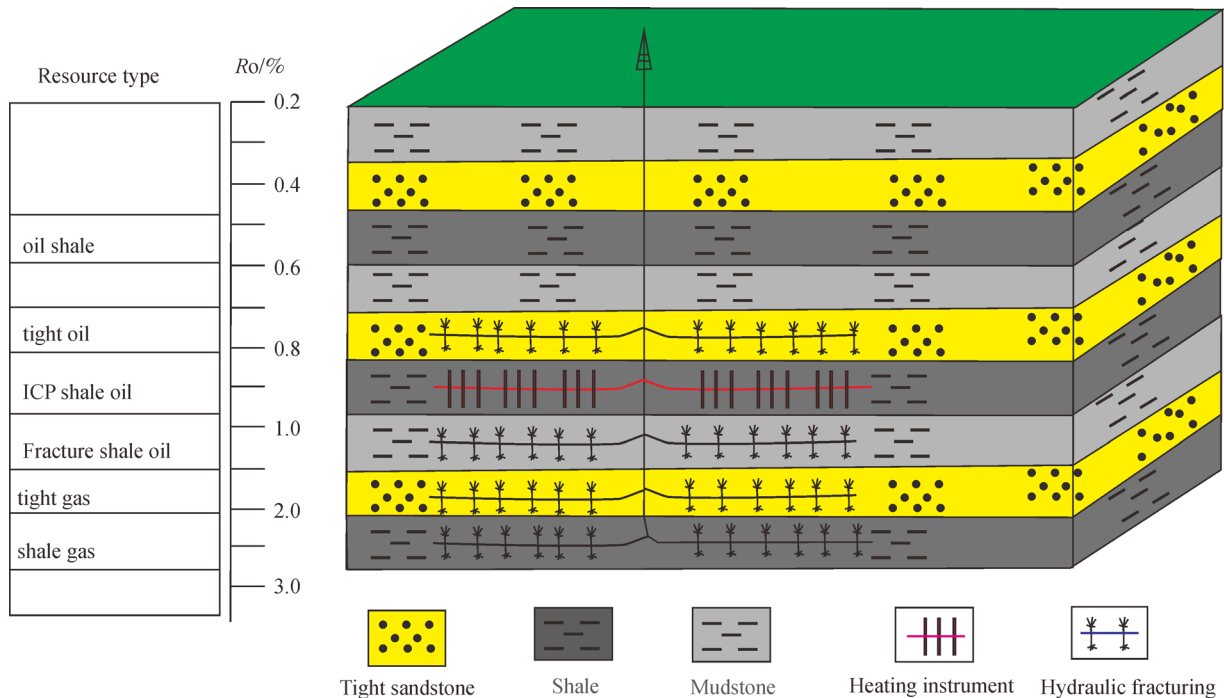
distribution of unconventional petroleum resources. These fields should be paid special attention. To develop sweet spots, ICP technology can be used to convert the kerogen in the shale into human-made shale oil which can flow in the micro-fractures and permeable reservoirs. Besides shale oil, the products also include gas and light hydrocarbon. They can decrease the viscosity of tight oil, and accordingly, the recovery of tight oil can be increased by converting the kerogen with the lowest maturity into a hydrocarbon. When applying ICP technology, a "kerogen revolution" should be carried out to extract as much as possible petroleum resources from it, while improving other unconventional petroleum resources in shale formations through integrated and collaborative exploration and development.

## 6 Conclusions

Unconventional petroleum resources in Chang7 formations are described based on the understanding toward

history, occurrence, the location of accumulation, resource type, and the developments made in technology. According to the key controlling factors and parameters for selecting the sweet spots, the Chang7 shale in the Ordos basin was analyzed. Then, in terms of maturity, burial and TOC, the petroleum resources in the Chang7 shale are divided into an outcrop-shallow oil shale zone, a fractured shale oil zone with middle maturity and burial, an ICP shale oil zone with middle maturity and burial, a shale gas with a high maturity and deep burial, and an adjacent or interbedded tight sandstone oil zone, and finally specific ICP development technologies have been proposed.

The idea of orderly evolution and coexistence states that the maturity of source rock controls the orderly evolution, and the sedimentary construction controls the coexistence of unconventional petroleum resources in shale formations. Based on the resources of orderly evolution and coexistence, the characteristics of unconventional petroleum resources in shale formations are analyzed, and an integrated exploration and development strategy has been proposed, especially for the shale formations with laterally



**Fig. 11** Schematic of integrated exploration of unconventional petroleum resources in shale formations.

heterogeneous maturity and vertically complex sedimentary construction. This study indicates that the petroleum resources in different zones in the same formation should be studied, evaluated, and explored as a unit, and those in different formations should be explored in a 3D and evaluated in an integrated way and developed in a collaborative means.

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