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REVIEWS

Heavy Oil and Oil Sands: Global Distribution and Resource Assessment

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Abstract: Global recoverable resources of heavy oil and oil sands have been assessed by CNPC using a geology-based assessment method combined with the traditional volumetric method, spatial interpolation method, parametric-probability method etc. The most favourable areas for exploration have been selected in accordance with a comprehensive scoring system. The results show: (1) For geological resources, CNPC estimate 991.18 billion tonnes of heavy oil and 501.26 billion tonnes of oil sands globally, of which technically recoverable resources of heavy oil and oil sands comprise 126.74 billion tonnes and 64.13 billion tonnes respectively. More than 80% of the resources occur within Tertiary and Cretaceous reservoirs distributed across 69 heavy oil basins and 32 oil sands basins. 99% of recoverable resources of heavy oil and oil sands occur within foreland basins, passive continental-margin basins and cratonic basins. (2) Since residual hydrocarbon resources remain following large-scale hydrocarbon migration and destruction, heavy oil and oil sands are characterized most commonly by late hydrocarbon accumulation, the same basin types and source-reservoir conditions as for conventional hydrocarbon resources, shallow burial depth and stratabound reservoirs. (3) Three accumulation models are recognised, depending on basin type: degradation along slope; destruction by uplift; and migration along faults. (4) In addition to mature exploration regions such as Canada and Venezuela, the Volga-Ural Basin and the Pre-Caspian Basin are less well-explored and have good potential for oil-sand discoveries, and it is predicted that the Middle East will be an important region for heavy oil development.

Key words: heavy oil, oil sands, residual hydrocarbons, global resource assessment

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1 Introduction

CNPC has completed its latest round of global oil-and-gas resource assessment by the end of 2016. 85 assessment units were considered within 69 heavy oil basins in 37 countries. These included oil-sand resources, which were assessed in 35 assessment units covering 32 basins in 16 countries, not including the provinces within China (Fig. 1). This represents a complete reassessment of global heavy oil resources, following the previous assessment undertaken in 2011. However, not all areas potentially rich in heavy oil and oil sands were assessed. According to the assessment results, global in-place resources of heavy oil and oil sands in known accumulations comprise 991.18 billion tonnes and 501.26 billion tonnes respectively, while global recoverable resources of heavy oil and oil sands are estimated at 126.74 billion tonnes and 64.13 billion tonnes respectively.

There is no uniform standard for defining heavy oil and oil sands. For the assessment described in this article we have classified heavy oil and oil sands into three types: (1) heavy crude oil: any liquid petroleum with an API gravity below 20°; (2) extra-heavy oil: crude oil having a gravity of less than 10° and a reservoir viscosity of no more than 10,000 centipoises; (3) oil sand: following the World Energy Council (WEC) definition we classify natural oil sands as "those containing oil having a viscosity greater than 10,000 centipoise under reservoir conditions and an API gravity of less than 10° API". In accordance with the definitions of the U.S. Department of Energy, USGS and others (Meyer, 1991; Richard et al., 2003; USGS, 2006; Hinkle, 2006; Attanasi et al., 2010; Zou Caineng, 2015), extra-heavy oil and oil sands can initially be distinguished by whether the oil is solid-state.

2 Exploration and Development Status

The major areas of heavy oil and oil-sand production globally are in the Americas. Canada is the only country in the world that has achieved large-scale commercial development of oil sands, and China also produces a small amount of oil from oil sands. According to statistics from the Canada Alberta Energy Resources Conservation Board (ERCB) and the Canada Association of Petroleum Producers (CAPP), oil-sand production in Canada was 205.4 kt /day in 2010, 219.1 kt/day in 2011, 232.9 kt/day in 2012, and 246.57 kt/day in 2013. Despite a low oil price

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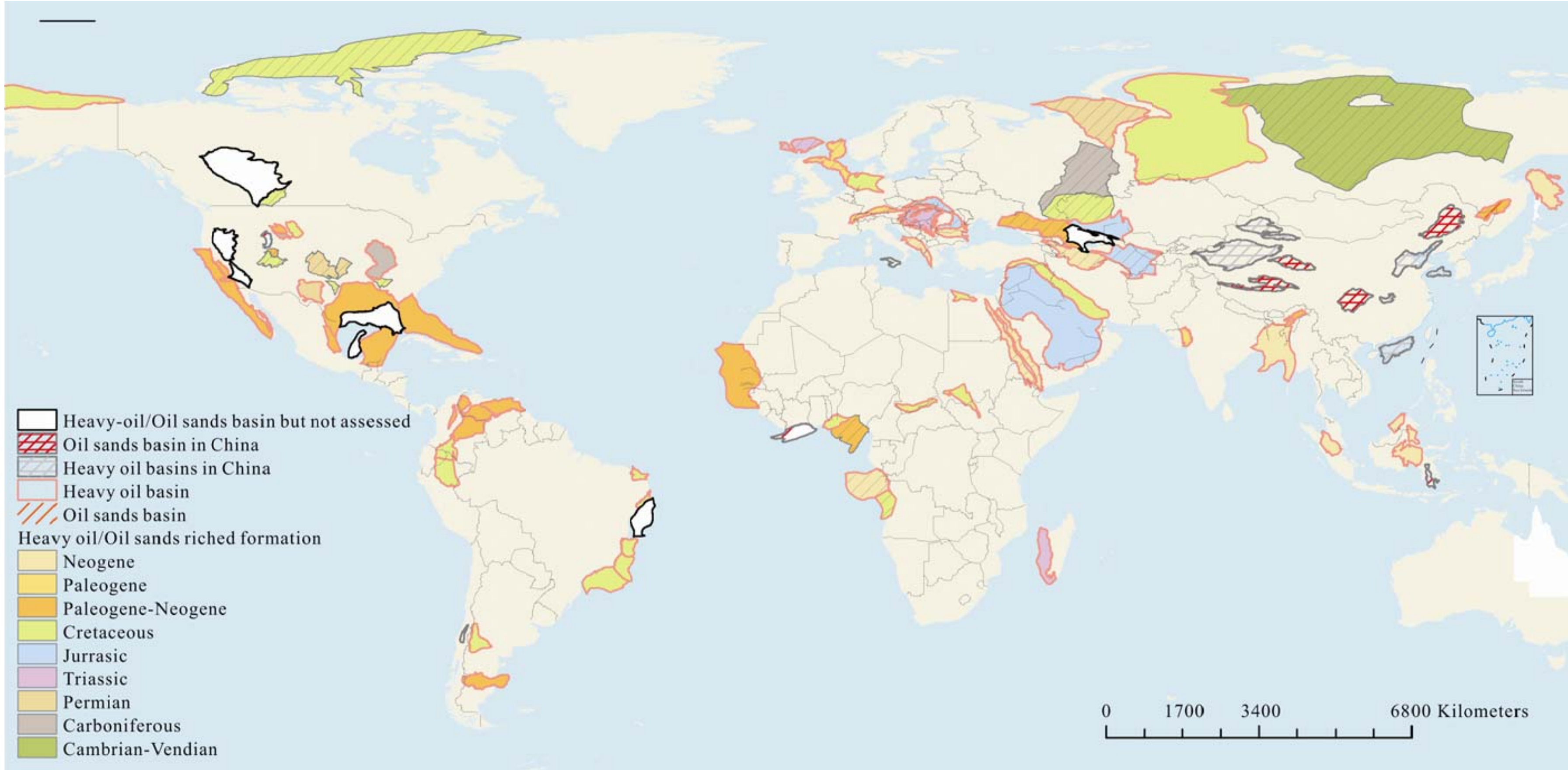

Fig. 1. Global distribution of heavy oil and oil-sand resources.

Note: Data compiled from USGS, 2006; Meyer, 2007; Suter, 2007; Chi Yaao, 2015; Zhang Guanyga, 2012; Tong Xiaoguang; 2014; Li Yan, 2017) (China basemap after China National Bureau of Surveying and Mapping Geographical Information).

in 2014-2015, oil-sand production in Canada increased to 332.97 kt/day in 2015, and reached almost 328.76 kt/day in 2016. The Alberta Energy Regulator predicted that oil-sand production in Canada would be 726 kt/day in 2035 (Statista website). Hart Energy predicted that it would reach 872.19 kt/day in 2035 (including modified heavy oil) (Hart Energy, 2013).

Venezuela is the chief producer of extra-heavy oil. Although Venezuela's Orinoco belt has the largest heavy oil reserves in the world (Pierre,2006), owing to nationalization of oil and gas resources in Venezuela since 2006, most of the profits of the Venezuelan Petroleum Co. (PDVSA) have been applied to social costs, leading to a decrease in oil and gas investment by PDVSA. Moreover, foreign oil companies have also reduced their investment in Venezuela, so that its oil production has dropped significantly in the past few years. PDVSA predicted at the beginning of 2012 that heavy oil production would be 172.6 kt/day in that year.

Mexico and Brazil have the highest heavy crude oil production. Mexico is the major producer in North America, where production was 216.43 kt /day in 2012, slightly lower than in 2011. Almost two-thirds of oil produced in the offshore Gulf of Mexico is heavy oil, chiefly from its NE Mexico sector. Three-quarters of its crude oil is exported to the USA, with light oil consumed domestically. The Campos Basin deep-water fields produce almost all of the heavy oil in Brazil, mainly from post-salt formations. However, with the deepening of sub-salt oil-and-gas exploration, some heavy crude oil reservoirs have been discovered, such as Iguacu Mirim (20°API) (Xie Yinfu et al., 2012). The USA has huge extra-heavy oil and heavy crude oil resources in California, Alaska and elsewhere, although only a few such oilfields are producing, in California, Texas, Wyoming and Mississippi, and most heavy crude-oil resources have not yet been developed. The USA has much lower production of oil sands/extra-heavy oil (0.38 kt/day), and produces chiefly heavy crude oil. For instance, California produced 90.4 kt/day of heavy crude oil in 1996, and 58.7 kt/day in 2012. China, Venezuela and Angola, also produce some heavy crude oil. Although abundant in heavy oil resources, Middle Eastern countries still have sufficient conventional oil and gas resources, and have not begun to explore and develop heavy oil resources at a large-scale; only preliminary and limited attempts have been made to explore for heavy oil resources in certain specific areas.

Although resources are generally large and well-defined, oil recovery rates using primary and secondary recovery techniques are low. Such techniques involve either letting the wells produce without pressure maintenance (primary), or injecting water or gas to maintain pressure and sweep extra oil to the wellbores where it can be produced (secondary). Primary production techniques result in recovery rates varying from 5% to 10% of OOIP; secondary techniques recover 10% to 20% of OOIP utilizing water and/or gas injection (Gray,1994). In rare cases, higher recovery rates can be achieved; Mexico's Canterell field, for example, has achieved relatively high recovery rates using nitrogen injection. However, most fields require some type of enhanced oil recovery (EOR) process to recover more than a small fraction of the OOIP. Steam injection can recover as much as 70% of the OOIP, though it requires large numbers of closely-spaced wells to achieve such high recoveries. In Canada, a technique called steam assisted gravity drainage (SAGD) is commonly used nowadays. An older steam-injection technique called cyclic steam stimulation (CSS) is also used and works well in certain reservoirs. In-situ combustion techniques, such as the toe-to-heel injection process developed in Canada, have been difficult to implement, but some commercial-scale projects are ongoing in Kazakhstan and Romania, with small projects in the United States. Other EOR processes that have been effective for heavy crude oil and some types of extra-heavy oil include polymer injection and immiscible gas injection. Heavy oil in deep reservoirs or offshore presents a different set of challenges. Steam injection is not effective because of excessive heat loss in the wellbore. Most offshore heavy oil fields are developed using horizontal or multilateral wells, and the oil is pumped to the surface using high-powered electric submersible pumps. Water and/or gas injection is used for pressure maintenance. Even so, recovery factors are low, and the fields tend to decline at high rates, averaging 20% per year. Newer technologies, such as thermal Dynamic Stripping (ET-DSP™), N-Solv™ (N-Solv Corporation), Toe-to Heel-Air Injection (THAI) and others have not yet been widely used in commercial projects, although they are allowing heavy oil and oil sands to be produced at lower cost and with reduced impact on the environment. EOR techniques such as polymer or solvent injection could be effective if the economics would support these high-cost techniques. Technology is constantly evolving and improving, as conventional light-oil supplies become less abundant, unconventional sources will supply a greater share of the world's liquid hydrocarbon supplies (Hu Wenrui,2013; Zou Cainneng, 2014) (Fig. 2).

3 Methodology

The methodology adopted during this assessment exercise included undertaking a complete geological-framework description for each oil accumulation, based mainly on data from IHS, Hart Energy, Woodmac and Blackbourn databases in addition to published literature, supplemented by primary data from CNPC working blocks. In this study, 120 assessment units were defined and assessed for recoverable oil resources. The exploration and discovery history was critical in determining the size of geological resources in each unit. In addition to geological analysis, the methods used in this evaluation included traditional volumetric methods and an improved volumetric method based on GIS systems, including a GIS spatial-graph interpolation method according to the extent of available detailed data (Sheng Xiujie, 2015; Liu Zuodong et al., 2017). Potential areas for exploration were selected according to a comprehensive system of scoring parameters, which provided a firm basis for target selection (Lerchel, 2004; Liu Chenglin, 2012). This parameter system considered three components: the

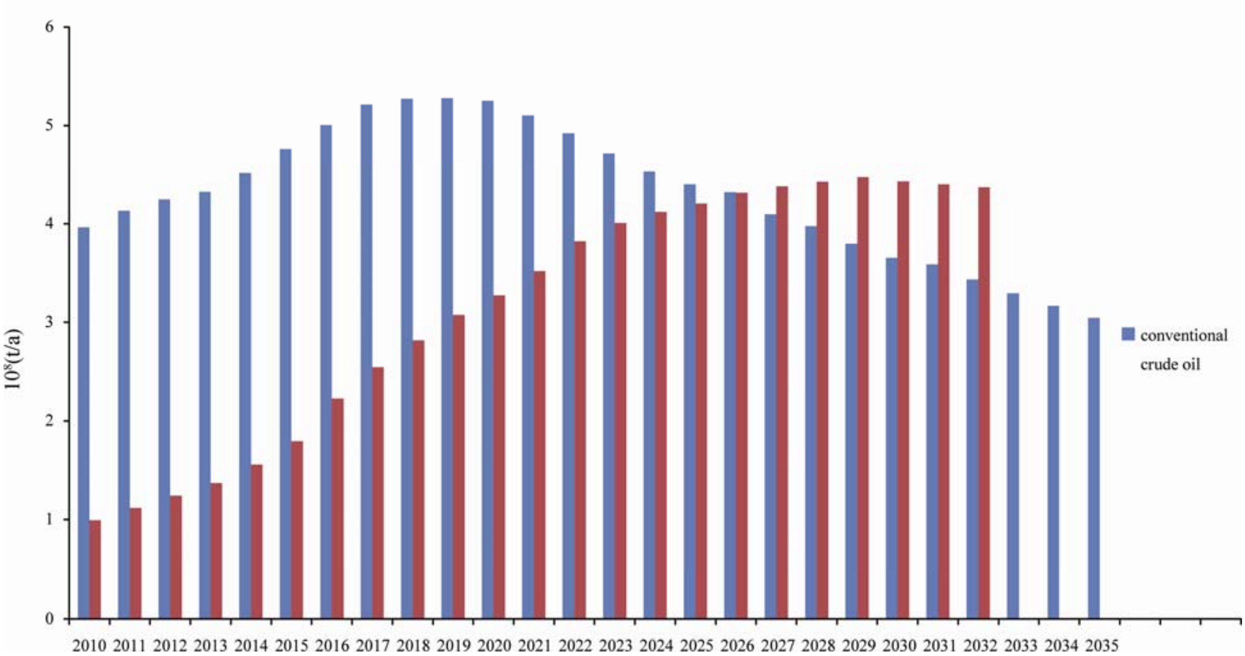

Fig. 2. Global heavy oil and oil sands production from 2000 to 2016 and forecast production from (Unit:10^8 t/year).

condition of the reservoir, the magnitude of resources and the development environment. Resource magnitude was given a relatively large weighting owing to the many geological factors considered in the calculation of resources. The reservoir condition is closely connected with the development method, so factors influencing the selection of development method, including burial depth, thickness, effective porosity, oil saturation etc., were considered. In addition, the political situation, economic standing and international status were key factors in assessing the development environment (Zou Caineng et al., 2013). Countries which have had a good relationship with China were given a higher score with regard to potential future cooperation.

The present study is more comprehensive than previous evaluations of global oil-and-gas resources (Rogner, 1997; James et al., 2004; Meyer et al., 2007; Hinkle and Batzle, 2006; Suter, 2007; Ronald and Troy, 2010), with updated data and the use of different evaluation methods depending on the level of detail of data available from the various regions considered. It not only illustrates the geological distribution of heavy oil and oil sands by basin type, reservoir age, and the relationship between the geological setting and the occurrence of heavy oil and oil sands, but the updated results also combine technological, political and economic factors, indicating beneficial areas for future cooperation.

4 Results

4.1 Distribution of global heavy oil and oil-sand resources by region

The majority of the heavy oil evaluated in this study occurs in the Americas. This region has 72.69 billion tonnes of total recoverable resources of heavy oil, of which South America and North America are responsible for 32% and 25% respectively. The Middle East has 17.67 billion tonnes of total recoverable resources of heavy oil, accounting for 14% of the total. These are followed in descending order by Asia, Russia, Europe and Africa (Fig. 3a).

Oil-sand resources are mainly found in North America, where the total recoverable resources of oil sands are 39.47 billion tonnes, accounting for 61.54% of the total oil -sand resources in the world. Russia also has abundant oil-sand resources, with 15.63 billion tonnes of recoverable resources, accounting for 19% of the global total. Oil-sand resources in Asia, Europe and Africa are smaller (Fig. 3b). The East Venezuela Basin and Maracaibo Basin in South America also have rich oil sands, although both oil sands and extra-heavy oil occur in these basins and are difficult to distinguish, so both are treated in this study as heavy oil resources.

4.2 Distribution of recoverable resources andgeological resources of heavy oil and oilsands by country

heavy oil are widespread globally. Venezuela, USA, Saudi Arabia and Mexico are the top four countries, with a combined total of 81.72 billion tonnes of recoverable resources of heavy oil, accounting for 64.4% of total recoverable resources of heavy oil in the world. Amongst these countries, Venezuela produces mainly extra-heavy oil, while the other countries produce mainly heavy oil (Fig. 4a).

Oil-sand resources are most abundant in Canada, followed by Russia. Technically recoverable resources of oil sands in Canada alone comprise 30% of the global total. Although Russia has no commercially produced oil sands, its oil-sand resources are relatively large: about 24.37% of the total global oil-sand resources by a conservative estimate (Fig. 4b).

4.3 Distribution of recoverable resources of heavy oil and oil sands by basin

Heavy oil resources distributed over 69 basins are evaluated in this study, 63 of which occur outside China.

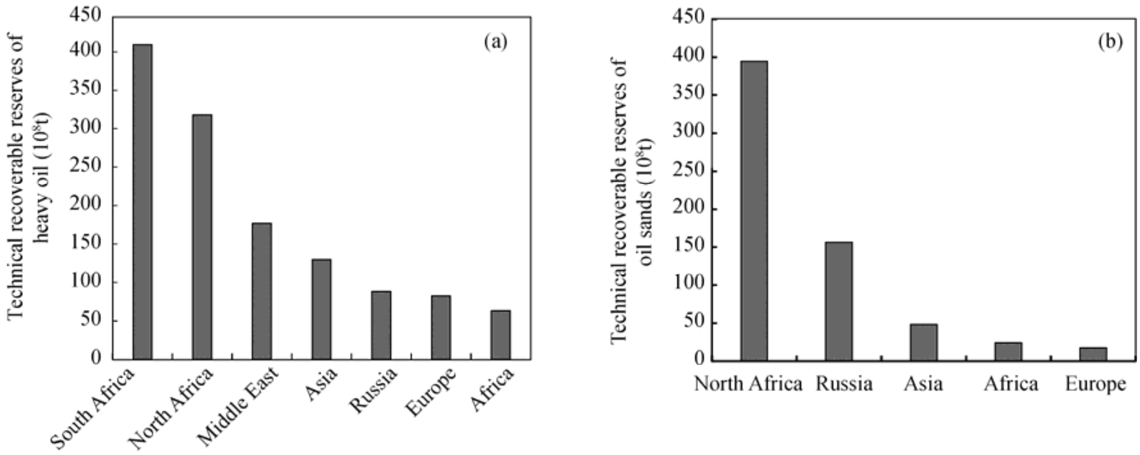

Fig. 3. Distribution of recoverable resources of heavy oil and oil sands in various regions.

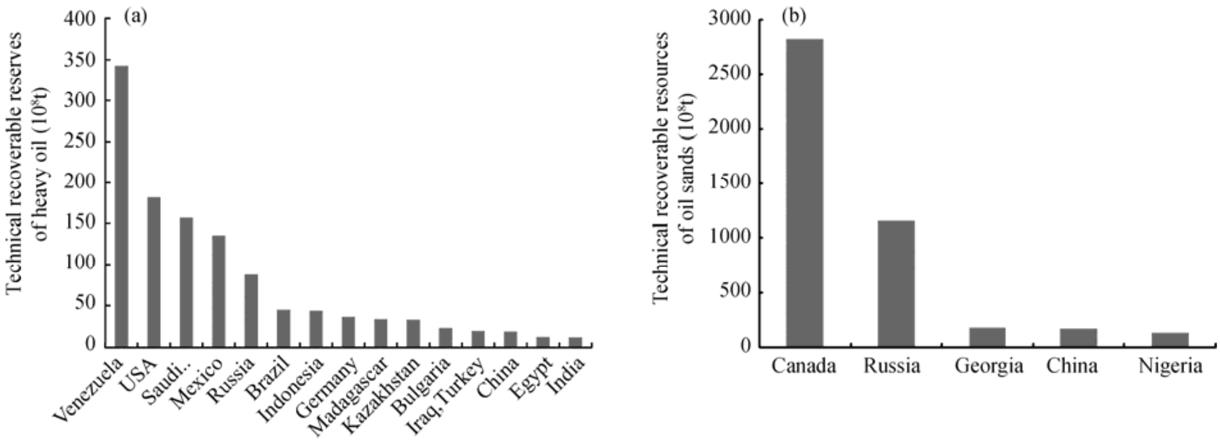

Fig. 4. Histograms of top 15 heavy oil-rich countries and top 5 oil-sand-rich countries.

The Venezuela Basin is the most prolific (chiefly extra-heavy oil), followed by the Arabian province Basin. The Tampico Basin in Mexico and the San Juan Basin in USA contain mainly heavy crude oil (Fig. 5a).

Oil-sand resources have been evaluated across 32 basins globally, 29 of which are outside China. Oil-sand resources are most abundant in the Alberta Basin, the East Siberia Basin and the Volga-Ural Basin (Fig. 5b).

4.4 Distribution of recoverable resources of heavy oil and oil sands by basin type

Basins rich in heavy oil are mainly of passive continental-margin type (Fig. 6a). In terms of basin classification, the Central Arabian Basin is a passive continental margin basin. The heavy oil in the Gulf of Mexico and Brazil are also produced from passive continental-margin basins. The major oil-sand resources are in foreland basins. (Fig. 6b).

4.5 Distribution of recoverable resources of global heavy oil and oil sands by formation type

Both heavy oil and oil sands are concentrated in shallow formations. Some oil sands occur within Cambrian-Vendian systems, chiefly in the East Siberian Basin, but owing to their low oil content (wt%) these oil sands are much poorer in quality than those in the Canadian basins (Fig. 7).

5 Controls on the Distribution of heavy oil and Oil Sands

We have found that heavy oil (heavy crude oil and extra -heavy oil) and oil sands occur mainly in North America, South America and the Middle East Region (Brew,1999; Lui et al.,2012; Tong Xiaoguang, 2014, Sadouni, 2018). Although the Middle East and Russia have abundant heavy oil, unconventional resources have not yet been explored or are undeveloped owing to the large quantity of conventional oil present. North America and South America have a long history of development and the highest level of technology, which is one reason why these two regions have the largest technically recoverable resources. Besides technology, the geological background has a large influence on the distribution of resources. The formation of heavy oil and oil sands is mainly controlled by the tectonic setting, basin type, source rock and reservoir scale, and the subsequent processes of oil degradation (Zhang Guangya et al., 2012). The known major resources of heavy oil and oil sands, which comprise residual hydrocarbons remaining after the formation and destruction of large-scale conventional oil accumulations, are stratabound and mainly occur in Mesozoic-Cenozoic basins. In general, most large sedimentary basins containing heavy oil and oil sands display a gentle structure, with source and reservoir rocks

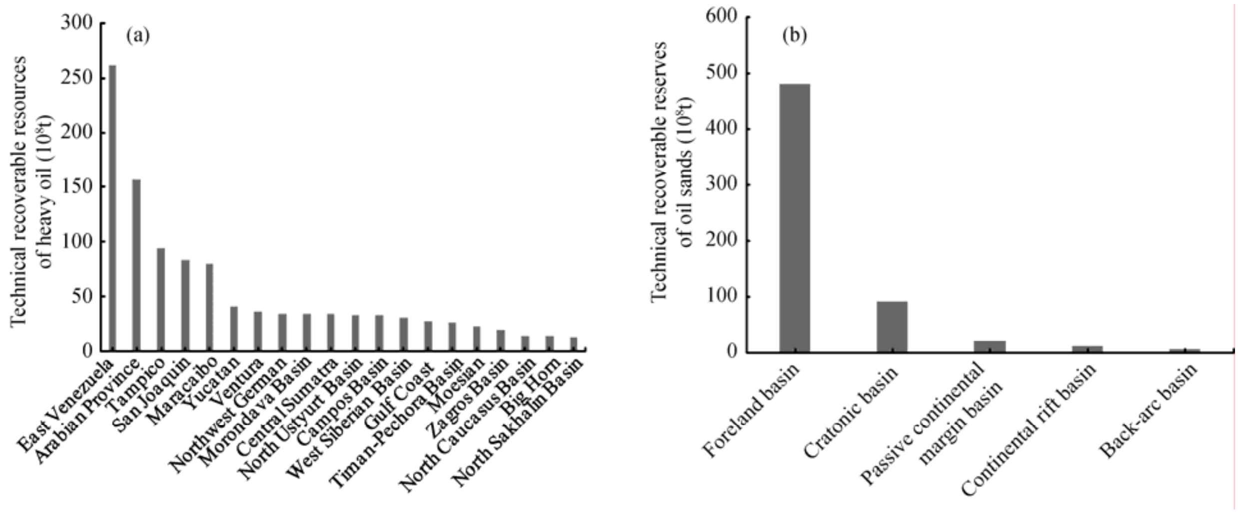

Fig. 5. Histograms of top 20 heavy oil-rich basins and top 10 oil-sand-rich basins.

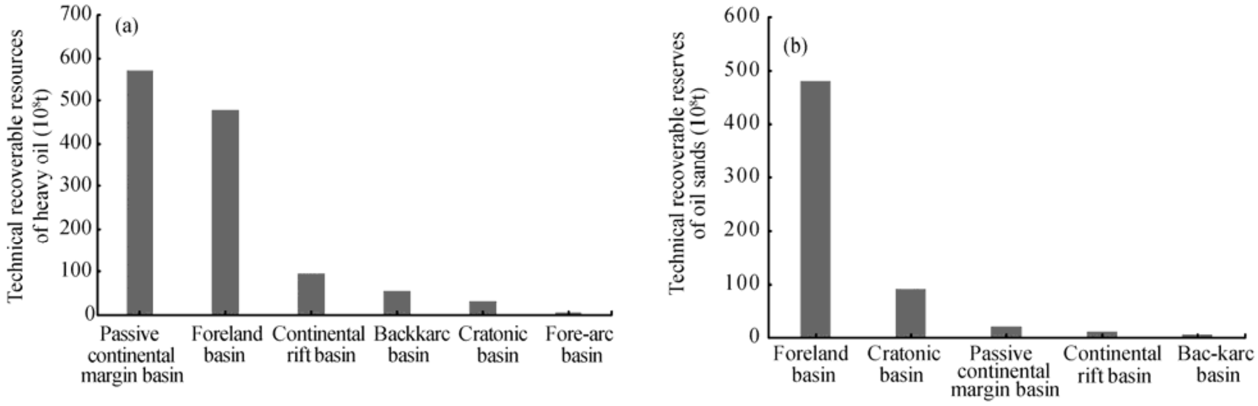

Fig. 6. Histogram of heavy-oil and oil sands resources in various types of basins.

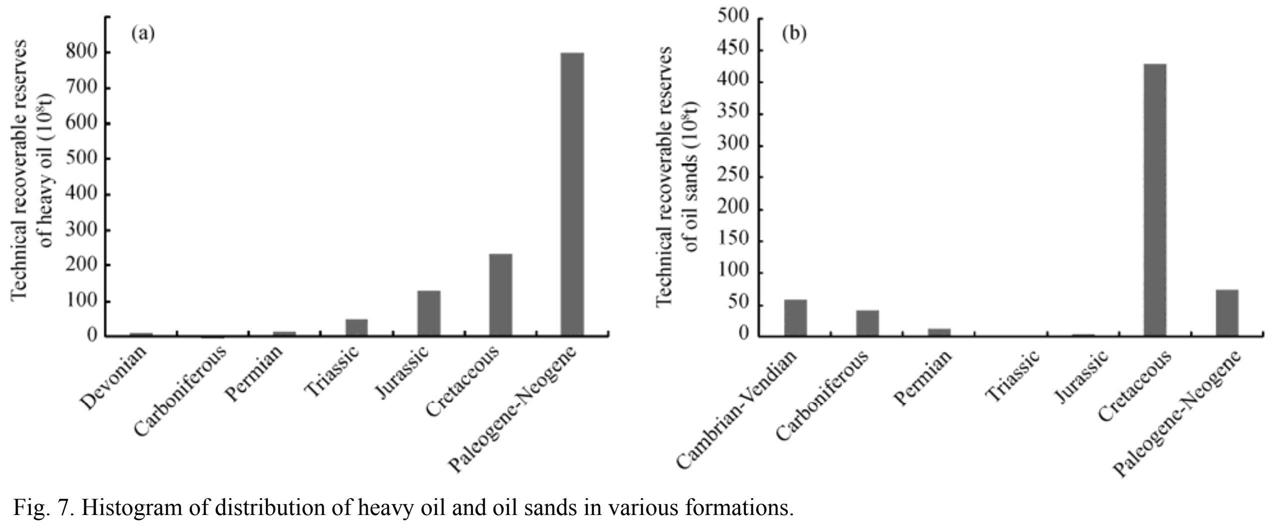

Fig. 7. Histogram of distribution of heavy oil and oil sands in various formations.

in planar contact, and where shallow-buried heavy oil has experienced long-distance migration, strong degradation, and the reservoir is non-structural and formed during the Cretaceous period.

5.1 Late reservoir formation favours accumulation of heavy oil and oil sands

The time of formation is the most important factor for accumulations of heavy oil and oil sands. Masters (1987) have suggested that perhaps 5% of the oil is immature, i.e. of low-density, while the remaining 95% has undergone transformation from conventional to heavy oil influenced by post-accumulation process including biodegradation, water-washing and (possibly) evaporation. As a form of "residual" resource, the later the alteration, the more the heavy oil and oil sands will have been preserved. More than 95% of global oil-sand resources occur in Cretaceous and later strata. The only oil sands with significant commercial value occurring within Palaeozoic (and older) reservoirs are found within the East Siberian Basin (Можегова, 2011; Du Jinghu et al., 2013; Ma Feng et al., 2015). Although huge in quantity, the oil sands in the East Siberian Basin has relative low oil-content (Karnyushina et al., 2013). For instance, the low-grade oil sands in Canada have an average oil content of 6.8 wt%, while those in the East Siberian Basin average only 2 wt%. The larger scale of hydrocarbon migration since the Cretaceous period is related to the age-distribution of major source rocks. Continuous generation and charging of oil and gas during the Cenozoic era is necessary for improving the mobility of oil within oil sands. Hence, the quality of heavy oil and oil sands is significantly enhanced by their later formation.

5.2 Source rock and reservoir parameters favourablefor the accumulation of heavy oils and oil sands are thesame as those for conventional oil and gasaccumulations

As with conventional hydrocarbons, heavy oil and oil-sand resources need an extensive high-quality source rock to provide a high oil- and gas-generating capacity. The source rocks of large-scale heavy oil and oil sands are characterized by TOCs above 3% (up to 24.3%) (Table 1), with organic matter of moderate maturity. In the northern part of South America, a large marine ingression during the Late Cretaceous gave rise to the most important source rock in this region–the world-class late Cretaceous shallow marine source rock (Liu Yaming et al., 2014). Oil and gas are generated within basinal depressions to the west or north where the source rocks, mostly mudstones of neritic facies, are thick (generally >100 m), contain abundant organic matter (TOC 0.25–16%), and are of moderate maturity (Ro >0.5).

Heavy oil and oil sands occur here mostly in Cretaceous, Tertiary and Jurassic reservoirs. The reservoirs are generally shallow, poorly cemented, and with high porosity and permeability (Table 1). Within basins rich in heavy oil and oil sands, the resources are generally concentrated in a series of major reservoirs. For instance, heavy oil mainly exist in the Cretaceous Oficina Formation in the East Venezuela Basin, which is composed of sandstones of fluvial and deltaic facies, and some sandstones of neritic facies. The sands have an extensive sheet-like morphology, gradually thinning from the western fore-deep belt to the eastern slope belt, and finally pinching out across the Guyana shield. Heavy oil in the Alberta Basin is concentrated in the Cretaceous McMurray Formation, which is composed of medium-grained quartz sandstone and fine-grained sandstone.

5.3 Shallow burial depth and typically strata-bound occurrence

Both heavy oil and oil sands in South America and oil sands in North America are found in shallow formations. The heavy oil in the East Venezuela Basin lies at depths between 100–2000 m. The oil sands in the Alberta Basin are at an even shallower depth (generally <200 m, and mostly exposed at the surface). The main cap rocks are Late Cretaceous and Tertiary mudstones of neritic facies; interlayered mudstones and asphaltic seals also control accumulations locally. Since the reservoir lies at a shallow depth where the sealing capacity is poor, oxic surface waters are likely to penetrate the reservoir, increasing the density of the oil. The formation of heavy oil and oil sands involves various physical and chemical processes operating between their generation and accumulation, which increase both the oil density and viscosity. Such processes include biological degradation, water washing, oxidization, evaporation and distillation. The accumulation and dissipation of oil is a dynamically balanced process. During long-distance migration the lighter components of the oil continuously escape, which coupled with biological degradation of the crude oil gradually increases its density and viscosity. The conditions required for an effective seal are therefore gradually reduced, so that the a balance arises between the accumulation and leakage of oil, and the whole hydrocarbon-accumulation process becomes stable, forming heavy oil and oil sands within dipping formations. Hence, shallow burial depth is a favourable, though not a necessary, condition for forming oil sands.

The temperature of oil degradation must lie within the temperature range of microbial activity (<80°C) (Anjos, 2008): too high a temperature may lead to the death of

Table 1 Statistics on parameters of major source rocks and reservoirs in main heavy crude oil and oil sand basins around the world

Parameters	Alberta	Volga–Ural	East Siberia	Utah	East Venezuela	Maracaibo	Arabia Province	Pre–Caspian	Campos
Major source rock age	C, D	C, D	Riphean	Eocene	K	K	K/T	C–P	K
Effective source rock area (km^2)	132798	357000	347000	18067	162060	23000	49000	36250	40000
Source rock thickness	25–135	60–160	80–300	24 –90	35–130	150–610	Up to 120/200	400	100–300
TOC (%)	2–24.3	12.4	3–15	Mean 6%, Up to 20%	2–6	5.6–16	Up to 14.3%	4.4	4
R_O	>0.5	0.6–1.2	0.5–0.9	0.7–1.3	>0.5	0.8–1.2	1.0	0.65–1.6	0.6–1.5
Reservoir age	K	C	V	E_1–E_2	R	R	K	K	K_1–E_1
Net reservoir thickness	55	8.08	15	80	15–240	80	11	1–48, mean 5.27	61
Effective porosity	30	28.5%	20.4	20	28–35	25	14.67	28.5%	26
Oil saturation	72	70	60	75	85–95	75–85	81	70	80
Reservoir depth	750	1284			150–1900		1400–2400	500	
API	9	≤10	≤ 10	≤10	7–20	15	20	23	19

Data from Adams et al., 2006; Anjos et al., 2008; Можегова., 2011; Zhang Guangya, 2012; Li Bing, 2012; Liu Yaming et al., 2013; Fan Yuhai, 2017; Chang Cheng, 2017.

microbes, resulting in the failure of biological degradation and therefore of heavy oil generation. This explains the scarcity of heavy oil and oil sands buried deeper than 3000 m, even in deep-water basins. For example, nearly half of oil production in Brazil is heavy oil from the Campos Basin and the Santos Basin, 95% of which occurs at depths less than 2500 m (Fig. 8). According to statistical results, 95% of heavy oil occurs at depths of less than 3000 m, and the shallower the burial depth, the lower the API of the oil. Additionally, on analysing oil densities within the Cretaceous system in various basins, densities are found to be controlled by hydrodynamic pressure in addition to reservoir temperature. For example, the results of a study of basins in Canada, Nigeria, Argentina and elsewhere indicate that the highest densities occur at the oil-water contact.

As mentioned above, the increase in oil density is most commonly associated with longer-distance migration. Taking the East Venezuela Basin and the Alberta Basin as examples, the oil accumulated in the slope-belt following long-distance migration of hundreds of kilometres from the hydrocarbon-generating depressions within the fore-deep belt (Adams et al., 2010; Christopher, 1984). The major migration pathways are along bedded sand bodies connected by faults and unconformity planes. The main migration pathways from hydrocarbon-generating depressions to slope-belts are faults and unconformity planes; those from slope-belts to zones of heavy oil and oil -sand accumulation are mainly unconformity planes and intrastratal sandstones. Faults connect reservoirs during the oil-accumulation process. High-porosity and high-permeability sandstones in the Upper Cretaceous and Paleogene are the predominant lateral-migration pathways (McCrimmon, 2002). Oil migration follows a step-up between the deep interval and the intermediate interval, and another to the shallower interval. With the increase of migration distance, oil properties change. Along the migration pathway between the more deeply buried region and the heavy-oil and oil-sand belt, natural gas, conventional oil, heavy oil and oil sands appear in turn (Fig. 9). Hence, oil sands are typically stratabound.

5.4 Three hydrocarbon accumulation models depending on basin types

5.4.2 "Degradation along slope" model

This model occurs mostly along large-scale slope-belts and the shallower portions of frontal uplift-belts. Substantial volumes of oil and gas generated from a deep mature source rock in the fore-deep region of a basin migrate to the sand bodies on the slope-belt and the frontal uplift-belt. Most of the sand bodies connected with the atmosphere represent oxidizing environments, with reservoir temperatures suitable for microbial activity, so that the oil and gas are susceptible to water washing, oxidization and biodegradation, leading to the formation of heavy oil and oil-sand resources. The "degradation along slope" model has the longest migration distance of the three models (up to 150 km–200 km). For example, the Alberta Basin, the Orinoco heavy oil belt in the East Venezuela Basin（Liu Yaming et al., 2013）and the Volga-Ural Basin (Fa Guifang et al., 2012; Li Bin et al., 2012; Xu Jianhua, 2016). This model is most frequently associated with foreland basins (Fig. 10), and less commonly with passive continental-margin basins such as the Central Arabian Basin.

5.4.2 "Destruction by uplift" model

This model involves existing oil accumulations in shallow formations within folded thrust belts, or those involved in large-scale uplift of ancient cratonic regions, which were subsequently uplifted to the surface and converted to oil sands owing to oxidation and biodegradation. This model chiefly occurs in two types of basin: (1) foreland basins, for example by local uplift of

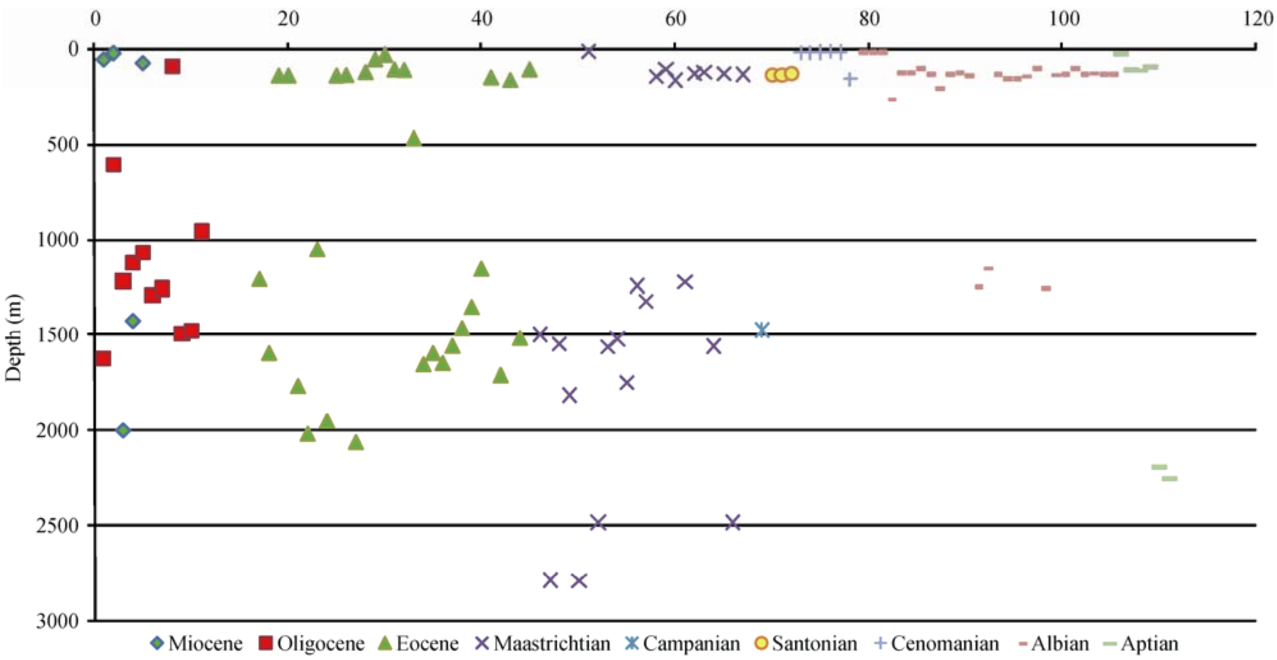

Fig. 8. Burial depth and occurring formations of heavy oil resources in Brazil (data source: IHS Energy).

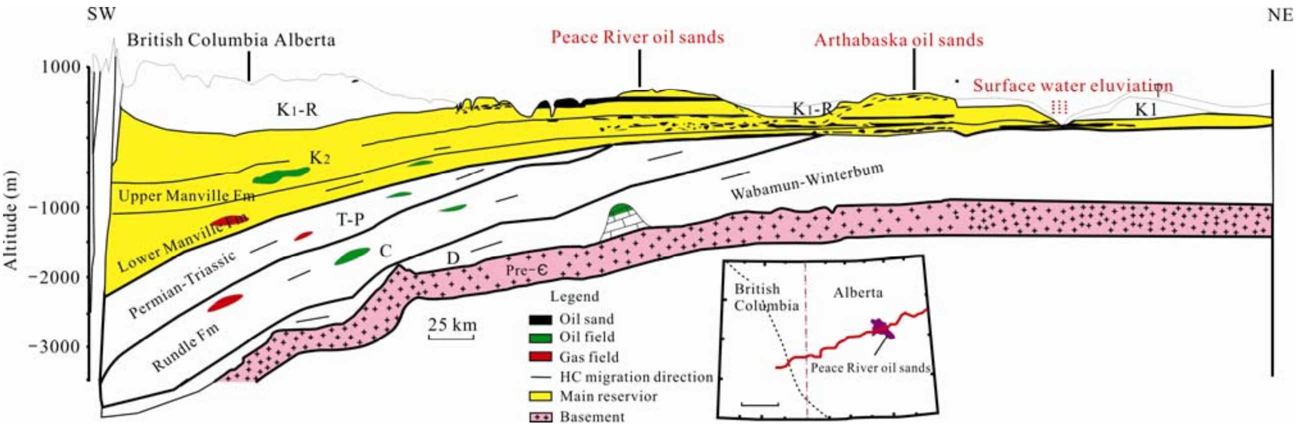

Fig. 9. Model of oil-sand accumulation in Alberta Basin (modified from Zou Caineng, 2015).

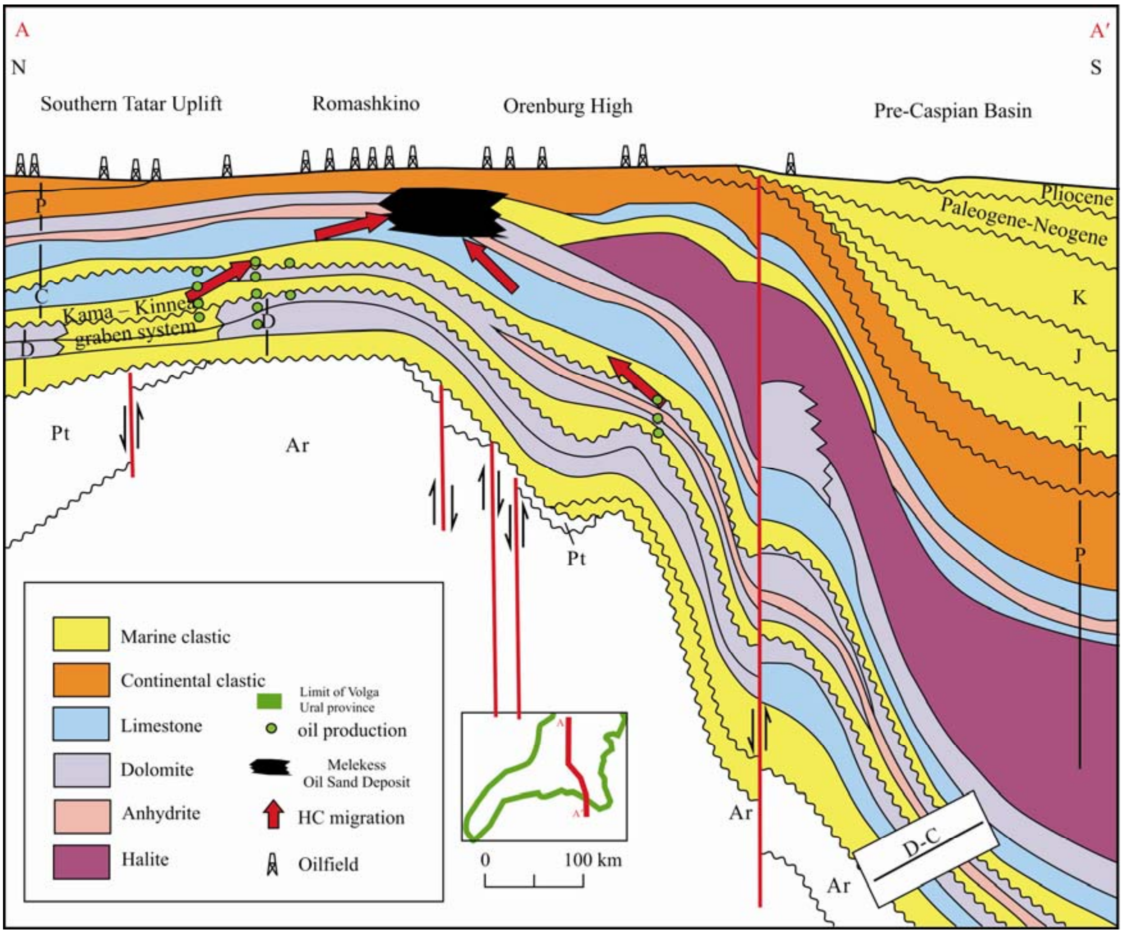

Fig. 10. Accumulation model of oil sands in Volga-Ural Basin (modified from Peterson and Clarke, 1983).

the foreland folded belt, although this type of reservoir is usually small in scale; the Uinta Basin belongs to this type; (2) ancient cratons: the uplift of a large-scale craton can form major oil reserves, the East Siberia Basin (Fig. 11) being a typical example. After the Cambrian, the East Siberian Platform was uplifted steadily and suffered erosion, leading to destruction of conventional oil and gas reservoirs during the Vendian, and the formation of massive oil-sand deposits at the surface or in shallow formations (Du Jinhu et al., 2013; Liang Yingbo and Zhao Zhe, 2014; В.Б А.,2008).

5.4.3 "Transportation along faults" model

Two forms of this model occur. first, faults conduct surface waters into the subsurface, where they come into contact with crude oil which undergoes oxidation and water washing; second, light components leak through faults, a great deal of asphaltene remains and is then sealed by the cap rock, forming a heavy oil reservoir. This model mostly occurs in rift-basin and passive continental-margin basin settings, such as the Arabian Basin and the West Siberia Basin (Lovelock, 1984). Taking the Singar graben in the Arabian Basin as an example (Gao Ningning

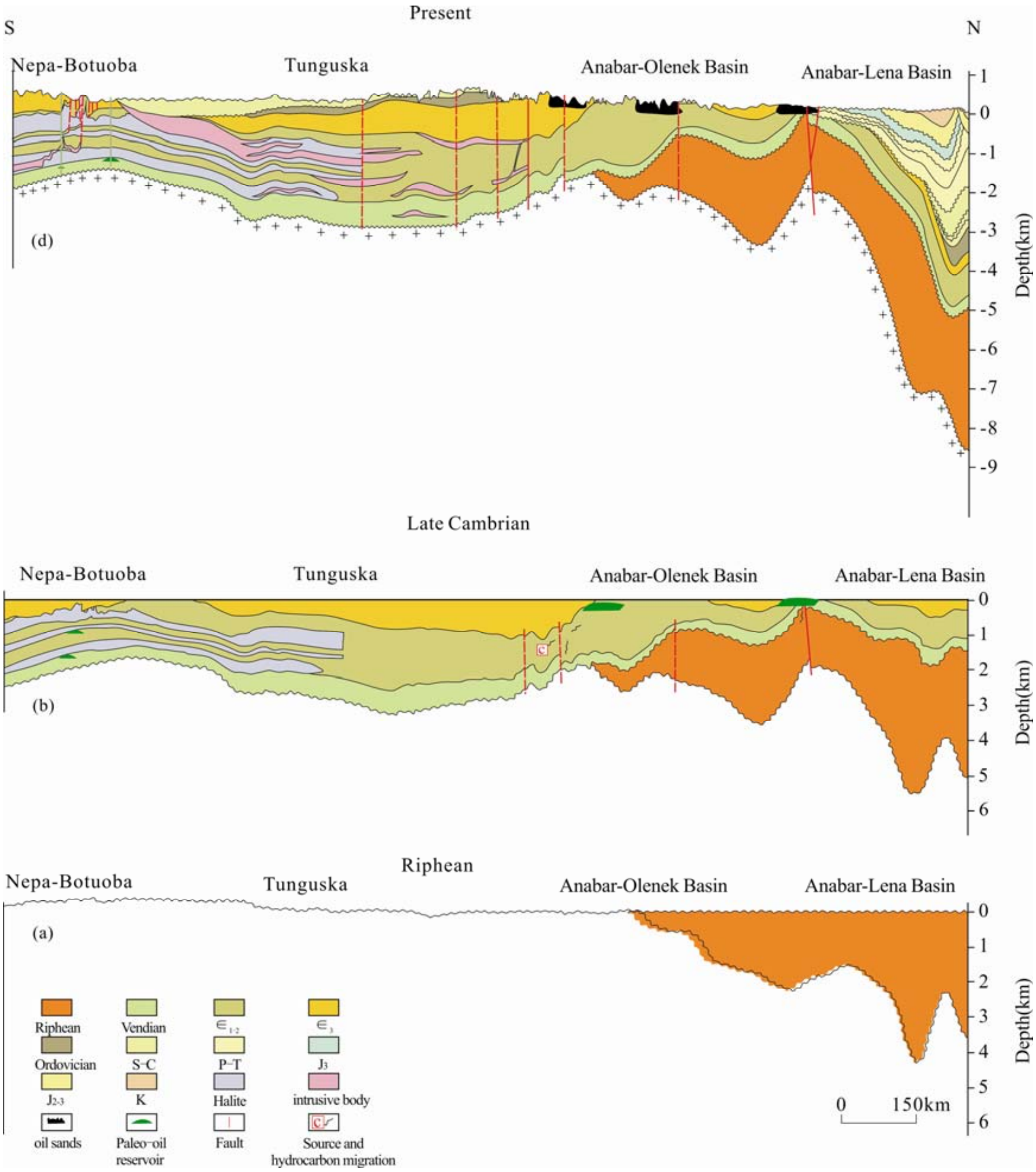

Fig. 11. “Destruction by uplift” model in East Siberia Basin.

et al., 2015), the oil and gas mostly migrated vertically for up to 1000 m, but less than 20 km laterally. The migration and thickening of heavy oil in the West Siberia Basin occurred during a period of active Turonian-Pleistocene tectonism. The Lower Cretaceous heavy oil reservoir was at a shallower depth than now (Kontorovich, 1997). Moreover, faults in the sedimentary cover played an important role in hydrocarbon migration, degradation and accumulation. The faults cutting through the early Cretaceous cap rock, clastic reservoir beds in the Neocomian and Aptian–Cenomanian successions, and source rocks in Late Jurassic Bazhenov Formation formed a well-connected system. Owing to biodegradation, water washing and oxidation etc. the crude oil in the reservoir became more viscous and higher-density. After formation of the heavy oil reservoirs, the Late Cretaceous-Paleogene and Neogene-Quaternary successions were deposited above the Cretaceous (Fig. 12)

6 Target Screening

6.1 Ranking basis

heavy oil and oil sands will be important oil resources in the future, so their future development strategy needs to be considered. We have ranked favourable regions in the basins assessed, taking into account not only the magnitude of their resources, but also their present importance, future potential and ease of development. The method adopted has been to score and rank all the favourable regions in the assessed heavy oil and oil-sand basins, and to use their composite scores as a basis for selection. In this scoring we have mainly considered three

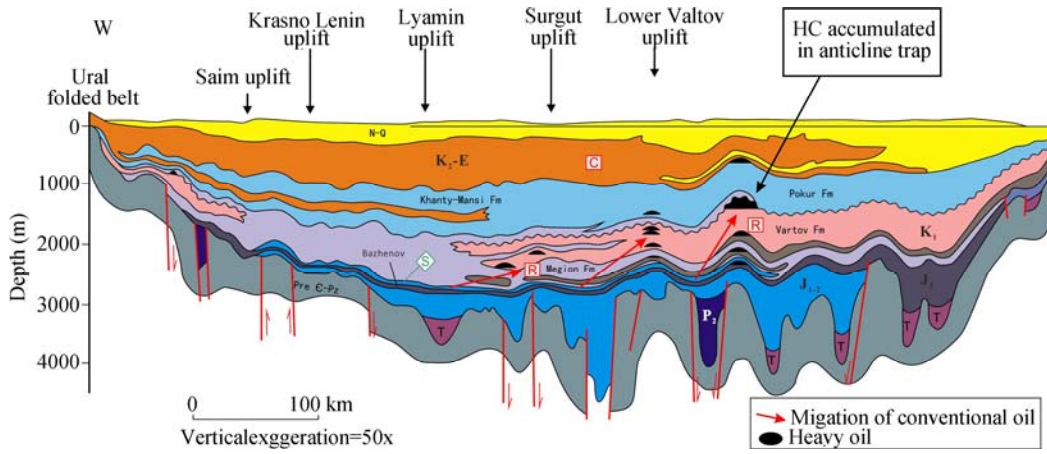

Fig. 12. Accumulation model of heavy oil in Western Siberian Basin (modified from EIA, 1997).

aspects of heavy oil and oil sands: resources, production status of resources, and production environment. The major parameter used for assessing resources was the geological (in-place) resources. For the production status we considered the major parameters determining the mode of production, such as burial depth, reservoir thickness, porosity, and oil saturation. These are also essential parameters in resource assessment and reservoir assessment. The production environment dominantly involved the regional situation, economic situation, and international environment of the target basins (Zhang Guangya et al., 2012; Qiuzhen et al., 2013), which were divided simply into three categories. The specific classification and corresponding scores are listed in Tables 2 and 3.

Table 2 Scoring rules for selection of regions favourable for heavy oil production

Factors scored	Grading		
Buried depth (m)	<1000	1000–2000	>2000
Score	3	2	1
Thickness (m)	<4	4–8	>8
Score	1	2	3
Effective porosity (%)	<18	18–25	>25
Score	1	2	3
Oil saturation (%)	<60	60–70	>70
Score	1	2	3
Geologic resources (108 t)	<10	10–75	>75
Score	2	4	6
Development environment	Worse	Moderate	Better
Score	1	2	3

Table 3 Scoring rules for selection of regions favourable for oil sand production

Factors scored	Grading		
Buried depth (m)	<900	900–1600	>1600
Score	3	2	1
Thickness (m)	<4	4–8	>8
Score	1	2	3
Effective porosity (%)	<18	18–25	>25
Score	1	2	3
Oil saturation (%)	<60	60–70	>70
Score	1	2	3
Geologic resources (108 t)	<10	10–75	>75
Score	2	4	6
Development environment	Worse	Moderate	Better
Score	1	2	3

6.2 Region selection

Regions considered to hold potential for developing heavy oil and oil-sand resources were divided into three types: (1) regions with substantial known resources and a mature level of development; (2) regions with limited development that can be brought into production at the appropriate time; and (3) regions with large potential resources suitable for development in the medium- to long -term. These are considered in turn below.

6.2.1 Regions with substantial known resources and a mature level of development

The Americas are in the lead in terms of reserves and development of heavy oil and oil sands. They have a low investment risk, and thus emerge as of highest priority.

(1) Oil sands in Canada: Canada has abundant resources and a highly developed oil-sand industry. Moreover, Canada possesses a stable political environment, well-developed industrial infrastructure, a robust financial system and a mature regulatory system. We therefore consider it as first choice for oil-sand investment. Despite the fall and continuing low oil price since 2014, oil-sand production in Canada has remained stable. This is because, unlike with other crude-oil developments, the cost of abandoning oil-sand projects is high, so production from oil sands continues during periods of low oil price. Nonetheless, any increased oil-sand production during this period can come only from existing projects, not new projects. Although operating costs are high, oil-sand projects have the advantages of a higher recovery factor and a longer life-cycle. Oil-sand production will remain stable for an extended period, so that new investments in oil sands will have a significant impact on oil-sand production. Moreover, in the event that a large number of development projects are postponed, technical services become under-utilized so that the cost drops, which is beneficial for the return ratio on investment into new regions.

According to our assessment, the recoverable oil-sand resources of Canada are 38.447 billion tonnes. The oil-sand resources in Canadian Alberta are chiefly in the Cretaceous McMurray Formation. The primary exploration target is the foreland slope, and the secondary target is the folded thrust belt, at depths between 0–400 m.

(2) Extra-heavy oil in the East Venezuela Basin: Venezuela has witnessed economic recession and a deteriorating political environment since 2014, but the probability of a civil war in Venezuela is regarded as low. Thus the Orinoco heavy oil belt in Venezuela is also one of the selected strategic regions for PetroChina. The major productive formations of the East Venezuela Basin are the Miocene Oficina Formation and the Oligocene Merecure Formation (Villarroel, 2008). In this region, stratigraphic and composite traps are the major targets for heavy oil exploration, also including structural traps. Among these, composite structural-stratigraphic traps are the most important, and various hydrodynamic traps and lithological traps are secondary targets, with the depths of prospective horizons between 61–1860 m. According to our assessment results, the recoverable extra-heavy oil resources of the East Venezuela Basin are 26.075 billion tonnes.

6.2.2 Regions with limited development that can be brought into production at the appropriate time

(1) Oil sands in the Volga-Ural Basin: There are few foreign companies exploring for oil and gas in Russia, and most of them explore in co-operation with Russian state oil companies. However, Russia welcomes foreign companies (especially those with advanced technologies) to participate in oil and gas exploration in deep-water and unconventional oil and gas. But Russia has very severe fiscal and taxation policies. Improved co-operation with Russia requires that its oil and gas external cooperation strategy is fully understood.

Oil sands in the Volga-Ural Basin are mostly concentrated in the South Tatar Uplift, some surrounding uplifts and the margins of depressed areas. Reservoirs have an average depth of 1284 m, a limited thickness (up to only about 3.5 m), porosity of 20.8%, very high oil saturation (84%), and the highest geological resources (314.6×10^8 t) among all the assessed basins. But the technology adopted to date has been cold production with a lower recovery ratio, so that technically recoverable resources are only 41.33×10^8 t.

(2) Oil sands in the Pre-Caspian Basin: The Pre-Caspian Basin straddles two countries, Russia and Kazakhstan. Of these, Kazakhstan is situated within the Silk Road economic belt, and is an important hub between areas of oil supply and market demand. In the past few years, Kazakhstan has issued a series of privileged policies on economic development, and protection of investors' rights and interests. Hence, heavy oil-projects in the Pre-Caspian Basin should in our opinion be prioritised. The favourable Cretaceous oil-sand assessment units of the Pre-Caspian Basin are situated in the Pre-Caspian Sub-basin, where the reservoir has a shallow burial depth (on average 500 m), thickness of 5.27 m, effective porosity up to 28.5%, and lower oil saturation (70%). The best-fit production method is steam-drive, and technically recoverable resources are up to 32.71×10^8 t.

6.2.3 Regions with large potential resources suitable for development in the medium- to long-term

Saudi Arabia, with a good investment environment and stable economic growth, is considered to be one of the best Arabian countries for investment in the Middle East and North Africa. It has huge investment potential and plentiful geological oil reserves. However, Saudi Arabia is reluctant to allow foreign companies to participate in its oil exploration and production, and only investment in natural gas is permitted at present. Saudi Arabia can thus only be a target for medium- to long-term consideration.

The Middle East has huge heavy oil resources. According to the results of this assessment, the Middle East has more than 121.3 billion tonnes of geological heavy oil resources. In 2015, the daily heavy oil production in the entire Middle East was about 1.639 MMbbl/day; the major heavy oil plays are in shallow formations (generally <2000 m). The region has extensive carbonate reservoirs (Cretaceous-Miocene).

West Arabian Basin (sub-basin of Arabian province): 31 heavy oil fields have been discovered here, and the heavy oil in all these fields is in formations less than 2800 m deep. Of these, oil reserves within Cretaceous and Paleogene reservoirs comprise about 87% of the total reserves. Most heavy oil reserves are in limestone reservoirs (accounting for 86% of the total resources), some are in dolomite reservoirs, and a small proportion of the resources are in sandstone reservoirs. The assessment unit considered to have the highest potential is the Cretaceous. The most favourable area in this assessment unit is in the Singar graben and part of the Euphrates graben, where the reservoir has a burial depth of about 1500 m, significant reservoir thickness (11 m), quite low porosity (15%), high oil saturation (81%), and geological resources of 204×10^8 t. The current production technology is steam huff-and-puff, with technically recoverable resources of 29.2×10^8 t. With a good development environment, we consider that this area should be kept under review, and that it will be suitable for investment at some future date.

The Jurassic assessment unit in the Central Arabian Basin (a sub-basin of the Arabian province) is located in the Salman uplift in the western part of the Basin where the reservoir, although at a depth up to 2400 m, has the largest thickness of all the assessment units, at 41.8 m, quite a high porosity of 22.5%, and an oil saturation of 81%, so that its geological resources (560.3×10^8 t) are the highest amongst the basins assessed. However, the most suitable production technology in this unit is steam huff-and-puff, with technically recoverable resources of only 83.5×10^8 t. Despite this, it is still regarded as one of the best potential regions for future development.

7 Conclusions

Heavy oil and oil-sand resources are abundant throughout the world: global geological resources of heavy oil and oil sands are 126.74 billion tonnes and 64.13 billion tonnes, mainly concentrated in 69 heavy oil basins and 32 oil-sand basins. Over the next 20 years, global heavy oil and oil-sand production will continuously increase. The global distribution of large-scale hydrocarbon-rich basins containing such resources is very uneven, they occur mainly in America, Russia and the

Middle East. The heavy oil and oil sands occur mainly in shallow formations, generally of Cretaceous age and younger, in foreland basins and passive continental-margin basins.

heavy oils and oil sands are residual oil resources, and their accumulation is favoured by late-stage development. The formation of large-scale heavy oil and oil-sand resources requires a high-quality source rock and reservoir. The oil generated migrates long distances along faults, unconformity planes and interconnected sandstones to the basin slope, where it accumulates in areas which have undergone long-term uplift. Late-stage reconstruction leads to multiple mechanisms for the oil to increase in density. The hydrocarbon-accumulation process can be divided into three types: degradation along slope, destruction by uplift, and transportation along faults. Among these, the degradation-along-slope type mostly occurs in foreland basins; destruction-by-uplift occurs mostly in shallow formations within the folded thrust-belts of basins or large-scale uplifts in ancient cratons; and transportation-along-faults chiefly occurs in rift basins and passive continental-margin basins.

We conclude that future consideration should be given to three types of region: (1) mature regions such as the oil sands in Canada and extra-heavy oil in Venezuela; (2) regions with a low level of exploration but huge hydrocarbon potential and accessibility to foreign investment, such as the Russian Volga-Ural Basin and the Pre-Caspian Basin; and (3) regions with huge hydrocarbon potential but which are currently inaccessible for independent foreign investment, such as the Arabian Basin in the Middle East.

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