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The geology and hydrocarbon potential of petroliferous basins in China

Of the 9.6 million km² of land area and 3 million km² of sea area in China, an area of 5.5 million km² is covered by explorable sedimentary basins. The in-situ potential resources are estimated at 78 billion tonnes of oil and 33 trillion m³ of natural gas. There have been significant exploration successes in oil and gas exploration in several different types of basin in formations of wide ranging ages. The prospects for further success are very favourable.

Introduction

In China, a total area of 4.2 million km² is covered by unmetamorphosed sedimentary strata; another 1.3 million km² of the continental shelf includes basins covered with less than 200 m of sea water, giving a total of 5.5 million km² of exploitable sedimentary basins.

By 1950, only three oilfields; Yumen, Yanchang and Dushanzi in north-west China were producing, with a total annual crude output of 0.2 million tonnes (4000 b/d) only two gasfields, Shiyougou and Shengdengshan in the Sichuan Basin, were producing and the annual natural gas output totaled 10 million m³ (1 million ft³/d). In the past four decades, China's oil and gas industry has constantly grown. In the 1950s, the Yumen oilfield was developed and gas production of the Sichuan Basin increased. Subsequent discoveries include the Karamay giant oilfield and Lenghu oilfields in north-west China. In the 1960s, the Lower Cretaceous, super-giant Daqing Oilfield in the Songliao Basin was discovered and developed. (the Daqing Oilfield has yielded 55 million tonnes of oil per year, or 1.1 million b/d). In the 1970s, the Bohai Gulf Basin was discovered by the Shengli, Liaohe, Dagang, Huabei and Zhongyuan Petroleum Administrations. This is a Tertiary rift-depression basin with various types of fault-block oil and gas traps and buried-hill traps. (A total of 153 oilfields have yielded 60 million tonnes of oil per year, or 1.2 million b/d). In the 1980s, China cooperated with major foreign oil companies on geophysical exploration and drilling for petroleum in the broad continental shelf of China. In the Bohai Gulf, Beibu Gulf and the Pearl River Mouth Basin, 20 oil and gas fields have been discovered. Ten production oilfields and one gasfield have already been established with an annual production of 6.4 million tonnes of crude oil and 300 million m³ natural gas. More recently, petroleum exploration has been rejuvenated in Western China's five petroliferous basins (the Tarim, Junggar, Turpan, Qaidam and Ordos basins). In the Tarim Basin, the newly discovered oil traps are in Ordovician, Carboniferous, Triassic, Jurassic, Cretaceous and Tertiary strata. The coal-genetic oil traps of the Turpan-Hami Basin are in Jurassic rocks, while in the Central Ordos Basin, large proven gas traps are in Ordovician strata. Meanwhile, the new discoveries in the Erlian Basin, the Kailu Basin and the Bose Basin are significant exploration successes in Inner Mongolia Mesozoic rift basins, south China Tertiary remnant basins and several other basins with small traps and high oil flows.

By 1993, China's crude oil production was 144 million tonnes per year (or 2.8 million b/d). Natural gas production was 15.8 billion

m³ per year (or 1.5 billion ft³/d). More than 300 oilfields and 100 gas fields have been developed. Cumulative production of oil was 2.5 billion tonnes and cumulative production of natural gas was 200 billion m³.

The potential resources of oil and gas have been estimated using the methods of basin modelling, pay evaluation and trap evaluation by the Research Institute of Petroleum Exploration and Development with the Petroleum Administration in 1986. The in-situ resources were placed at 78 billion tonnes of oil and 33 trillion m³ of natural gas, which is really a large figure. With proven reserves and the present cumulative production of oil and gas, China has undoubtedly a large oil and gas potential.

Geological evolution

The Chinese craton is composed of the Sino-Korean, Yangtze and Tarim massifs and numerous smaller continental fragments fringed by orogenic belts of different ages. The continent and the continental shelf of China have experienced a complex geological history of plate convergence and divergence from the Proterozoic to the Mesozoic (Huang Jiqing et al., 1981; Li Chunyu et al., 1984 and Wang Hongzhen et al., 1985). Tectonic movements (subduction and collision) between the Siberian and Chinese Plates during the Proterozoic and Palaeozoic caused the closure of the Palaeo-sea and accretion of the Chinese craton, forming the E-W collision belts and depressions. Very thick Palaeozoic marine deposits were laid down in intracratonic basins.

Mesozoic and Cenozoic tectonism mainly caused by the retreat of Tethys and collision between India and Eurasia exerted strong compression on western China. The E-W-trending mountain chains appeared as a major geologic feature, persisting to the present day. Pacific subduction became even more intense after the Yanshanian Orogeny and the whole of east and central China was affected by Pacific tectonism. New NNE-trending mountain chains inherited the previously existing E-W geological characteristics, forming a series of intraplate rift-depression basins in the eastern part of China (Zhu Xia, 1979; Li Desheng, 1980; Tong Chongguang, 1980; Hu Jianyi et al., 1982). The Chinese craton was pulled apart, and there was a rise of the upper mantle. Eastern China was entirely dominated by rifting tectonism (Walcott, 1970; Ziegler, 1975; Murrell, 1976; Li Desheng, 1980, 1982; Ma Xingyuan, 1986). The Chinese craton and the sedimentary basins lying on it in which thick lacustrine sediments are deposited owe much of their evolution and present day configuration to this tectonic history.

Geological characteristics of oil and gas basins in China

Non-marine facies oil generation

As early as the 1940s, the Chinese geologists Pan (1941) and Sun (1943) put forward the theory that petroleum could be generated in non-marine sediments. For example, the source rocks of Yanchang oilfield of Ordos Basin and Yumen oilfield of Jiuquan Basin are non-

Figure 1 Tectonic types of oil and gas basin in East Asia (after Li, 1985). 1 Western large-scale composite basin;

2 Western mountain front and intermontane basin; 3 Central intraplate subsidence basin;

4 Eastern intraplate rift-subsidence basin; 5 Eastern epicontinental rift-subsidence basin;

6 major fault zones; 7 West Pacific subduction zone; 8 Yarlung Zangbo river collision belt.

marine. In the 1950s, oil fields were discovered successively in the Junggar Basin, the Qaidam Basin and the Central Sichuan Basin in non-marine source rocks of Mesozoic and Cenozoic age. Many Chinese petroleum geologists and geochemists have described oil generation in rocks of non-marine facies, and have discussed the source materials, environment and conversion conditions. In the 1960s, the discovery and development of the super-giant Daqing Oilfield in the Songliao Basin has proved that petroleum can accumulate in continental facies rocks, and that oilfields in non-marine sediments may be very prolific and reach super-giant size. The Daqing Oilfield has yielded a peak production of 50 million tonnes of oil per year (1 million b/d) for 19 years. By 1994, the cumulative oil productions of Daqing was 1.3 billion tonnes (or 91 billion barrels).

Following the large-scale regression, which occurred in the Late Permian (north China) or Middle Triassic (south China), lacustrine deposits of Mesozoic and Cenozoic age were extensively laid down. The continental rock series were developed in various basin centres during periods of rifting and depression. The source rocks are of different ages and are widespread in Late Permian, Late Triassic, Early-Middle Jurassic, Early Cretaceous, Palaeogene and Neogene sediments. Those of Early Cretaceous and Palaeogene age are the most important.

Continental oil is generated in lacustrine deposits rich in terrigenous organic matter. In particular high carbon-number mole-

cules originating from wood-wax (phyto-wax) constitute the basis for continental crude oil with high wax and low sulphur contents.

Tectonic classification of oil and gas basins in China

Many classifications have been proposed for Chinese oil and gas basins, such as Huang Jiqing, 1957; Chen Guoda, 1965; Zhu Xia, 1980; Guan Shicong et al., 1981; Li Desheng, 1982; Guo Lingzhi et al., 1983 and Bally, 1986. A new classification is based on plate tectonics theory, especially since the Meso-Cenozoic, combined with data from geophysical surveys and drilling. Three basic types of oil and gas basins in China are proposed (Figure 1):

- The basins in eastern China can be classified as tension types (some of them are of the tensile shearing type). Bouguer gravity anomalies in the east range from 0 to -50 mGal, the crustal thickness is 25-35 km, and the geothermal gradient is 3.5-4.5°C/100 m. Examples include the Songliao Basin, the Bohai Gulf Basin, the Subei-South Yellow Sea Basin, the Nanyang-Biyang Basins, the Jiangnan Basin, the Beibu Gulf Basin, the Yinggenhai Basin and Zhujiang River Mouth Basin.
- The basins in central China can be classified as transitional types. These basins have been affected by both the Trans-Eurasian Tethys tectonism and the circum-Pacific tectonism, with dual extensional and compressional-shearing mecha-

nisms. Basins in this category include the Ordos Basin, the Sichuan Basin and the Chuxiong Basin. Bouguer gravity anomalies in the central part of China range from -100 to -250 mGal, the crustal thickness is 35–45 km, and the geothermal gradient 2.5–3.0°C/100 m.

- Basins in western China are compressional types (some of them of compressional-shearing type). These basins have been formed by the northward-impacting Indian Plate. Examples include the large-scale composite basins, such as the Junggar and Tarim basins; piedmont basins such as the Osu Basin, Kuqa Basin, Yecheng Basin, Jiuquan Basin and Minle Basin; and intermontane basins like the Turpan Basin. Bouguer gravity anomalies in the west part of China range from -100 to -575 mGal, crustal thickness is 45–70 km, and the geothermal gradient is 2.0–2.50°C/100 m.

During the palaeo-plate tectonic stages, there were widespread marine transgressions on to the China Craton. Thick carbonate sediments and marine origin source rocks are distributed in some Palaeozoic petroliferous basins in the platform regions.

Mesozoic and Cenozoic lacustrine facies models

More than 90% of China's crude oil is produced from Meso-Cenozoic terrestrial reservoir formations and petrophysical properties are important in the evaluation oil and gas pools within them. Ye Lianjun, Sun Shu, Wu Chongyun (1986) and Qiu Yinan et al., (1980) have established two models (depression and rift) for Meso-Cenozoic lacustrine facies using drilling records, well logging data and 3-D seismic data.

Composite megastructural oil and gas belts

The Bohai Gulf Basin was subjected to strongly differential block-faulting in the Tertiary. A series of normal faults developed and abundant oil and gas reserves have been trapped in complex geological structures. Chinese petroleum geologists and geophysicists have proposed, after long study, that different pay-horizons and different trap-types may evolve in similar ways and interact with each other, in megastructural oil and gas belts. This theory has led to a better understanding of oil and gas generation, and of the 'rules' of hydrocarbon distribution and abundance in the Bohai Gulf Basin. There are six conceptual models for megastructural oil and gas belts, distributed around the source area centres:

- the central anticline composite megastructural belt;
- the low buried-hill composite megastructural belt;
- the highly uplifted composite megastructural belt;
- the syndimentary fault and roll-over anticline megastructural belt;
- the structural slope composite megastructural belt, and
- the basin trough lithological megastructural belt.

Applying this theory, in the Bohai Gulf Basin, the Shengli, Liaohe, Dagang, Zhongyuan, Huabei Petroleum Administrations and the Bohai Oil Corporation improved development technology, and 153 oil and gas fields (including 12 giant oilfields) have been exploited. Since 1986, crude oil production in the Bohai Basin has reached 60 million tonnes per year. By the end of 1994, cumulative oil production was 1.05 billion tonnes (or 7.35 billion barrels). The Bohai Gulf Basin has become another important oil and gas province of China.

Buried-hill oil and gas traps

The continent and the continental shelf of China have had a complex geological history during which uplifted parts of the basement have undergone weathering and karstification over long geological periods. Oil and gas from later overlying formations, have migrated into the basement rocks and held in what have been termed buried-hill traps (Yan Dunshi, Wang Shangwen, Tang Zhi, 1980).

The Yaerxia oilfield, discovered in 1959 in the Jiuquan Basin, NW China, was the first recognised buried-hill oil trap. The Lower

Cretaceous greyish black shales are considered to be the source bed here, and the Silurian metamorphic series below a Cretaceous unconformity forms the buried-hill trap. Its cumulative oil production was 600 000 tonnes.

In July 1975, the Renqiu oilfield in Hebei Province was discovered. This oilfield lies in the Jizhong depression of the Bohai Gulf Basin. The discovery well penetrated a Proterozoic Wumishan dolomite reservoir formation and the tested flow rate of oil was 1000–3000 tonnes/d. During 1977–1981, the annual oil production was maintained at more than 10 million tonnes. Cumulative oil production up to 1994, was 120 million tonnes (or 840 million barrels). Chinese geologists have proposed that the oil comes from the Oligocene Shahejie formation in the Yaoyang sag. Since the discovery of the Renqiu Oilfield, exploration has been undertaken in similar basins, such as the Jizhong, Jiyang, Liaohe, Huanghua and Bozhong depressions. To date, more than 40 tilted fault block-buried hill oil traps have been discovered. Among them, the Dongshenpo–Jingganpo buried-hill trap is another giant. The reservoir rocks are Archaen gneiss plus Middle and Late Proterozoic carbonates.

Coal-genetic hydrocarbons

Coal measure strata are widespread in China, and include Early Carboniferous, Permo-Carboniferous, Late Permian, Early Triassic, Late Triassic, Early–Middle Jurassic, Late Jurassic and Tertiary series, distributed in different giant sedimentary basins. The high humic organic matter (type III) in these occurrences has been divided by Chinese natural gas geologists and geochemists into two subtypes. Type III₁ (containing sapropel) is a kerogen with liquid hydrocarbon-generating potential, while type III₂ kerogen is a typical gas-generating source material (Bao Ci et al., 1988; Huang Difan et al., 1991; Dai Jinxing et al., 1992). It is interesting to note that the coal-genetic hydrocarbons either accumulated in the coal series themselves, or migrated into reservoir formations above or below.

By the use of multidisciplinary techniques including gas geochemistry, many coal-genetic gasfields have been proved in recent years, such as the Triassic Xiujiahe Formation Zhongba Gasfield; the Triassic Xiangxi Formation Suinan Gasfield in Sichuan Province; the Palaeogene Sha-4 member Wenliu Gasfield in Henan Province; the Permo-Carboniferous Suqiao Gasfield in Hebei Province; the Oligocene Y13-1 Gasfield in offshore Yinggehai Basin and the offshore Miocene and Oligocene Pinghu Gasfield in the East China Sea Basin. Recently, the Jingbian–Hengshan Gasfield in the central part of the Ordos Basin was discovered. Its reservoir rocks are Lower Ordovician Majiakou karstic dolomites which underlie, with unconformity, source rocks in the Middle Carboniferous coal series. The structure of the gasfield is a gentle west-dipping monocline. Eastwards, the Majiakou dolomites display an up-dip facies change to salt and gypsum which constitute the cap rocks.

Coal-genetic oilfields have been discovered in Middle and Lower Jurassic strata—in the Qiketai Formation, Sanjianfang Formation, Xishanyao Formation (J₂) and Badawan Formation (J₁) in the Turpan and Junggar basins, north-west China. The Shanshan Oilfield was discovered in 1989 and the Qiuling Oilfield in 1990 in a U-shaped anticlinal belt of the Turpan Basin. In the eastern Junggar Basin desert area, the new Cainan Oilfield was discovered in 1991. In 1993, the annual production of these three oilfields was 2.6 million tonnes (52 000 b/d). The oils are typical non-marine coal-derived light oils with low specific gravity (0.79–0.82), low viscosity, low sulphur, medium wax content and rich in wet gas.

Exploration of Palaeozoic marine sediments

The Sichuan Basin, covering an area of 230 000 km², lies in the central part of the Yangtze Craton. The gas pay horizons including Sinian, Carboniferous, Permian and Triassic carbonates are of marine facies. The Sichuan Basin is China's most important gas producer, delivering 44% of the annual natural gas production. The cumulative production is 140 billion m³.

The Tarim Basin is one of the largest and least explored inland basins in China, with an area of 560 000 km². Multiple source rocks for hydrocarbon generation occur in thick Palaeozoic marine platform deposits and in Meso-Cenozoic terrestrial deposits. The Tarim basin has been an object of special attention by seismic exploration and deep drilling since 1983-1984, leading to the discoveries of eight oil and gas fields and 23 structures with oil or gas shows in Tabei, Lunnan, Tazhong and South-west Slope. The reservoir formations are Ordovician platform dolomites; Carboniferous transitional facies carbonates and clastics; and Triassic, Jurassic, Cretaceous and Tertiary terrestrial clastics. Four oilfields, Lunnan, Sang-tamu, Jiefangjudong and Donghetang, have been developed. In 1994, the annual crude oil production was 2 million tonnes which may increase to 5 million tonnes in 1996, when the Tazhong number four Oilfield which lies in the central part of Taklimakan Desert comes on-stream. In 1993, the south-east part of the Tarim Basin, with an area of 73 000 km² (divided into five blocks) was open to foreign oil companies bidding for exploration contracts. The total oil and gas potential resources in the Tarim Basin have been estimated at 19.1 billion tonnes, made up of 10.7 billion tonnes of oil and 8.4 trillion m³ of natural gas. The potential, in-situ oil and gas resources of marine Palaeozoic strata have been estimated to be 14 billion tons, about 73% of the total resources. The non-marine Meso-Cenozoic strata has been estimated to hold in situ, 5.1 billion tons, about 27% of the total resources. Thus, the Tarim basin is a very important frontier area for petroleum exploration in Palaeozoic marine sedimentary rocks of China.

The Ordos (Shanxi-Gansu-Ningxia) Basin, 320 000 km² in area is located on the west part of Sino-Korean massif. The Yanchang Oilfield was discovered as early as 1907. Reservoir rocks at Yanchang and in the Changqing oilfield are terrestrial facies Upper

Triassic Yanchang sandstones and Lower Jurassic Yanan sandstones. Annual production of the Yanchang and Changqing oilfields was 6 million tonnes in 1994 and cumulative oil production was 30 million tonnes. In 1986, the discovery of the Tianchi gas structure in the western part of the basin and, in 1989, of the Jingbian gasfield in the central part of basin were breakthroughs in deep gas exploration. The gas reservoir rocks are Lower Ordovician Majiakou dolomites. This discovery has established the presence of new frontier areas for exploration in Palaeozoic marine facies in the Ordos Basin. Now, a 2000 km² area of gas has been established, with proven reserves of 200 billion m³. The Ordos Basin will become the next important gas province in central China.

The successes in the Sichuan, Ordos and Tarim basins give hope of discoveries being made elsewhere. For example, thick Palaeozoic marine sediments are widespread in southern China, but little work has been done on exploring them.

Conclusion

Practical and theoretical research work has demonstrated that over China's vast onshore and offshore areas, geological conditions are favourable for the generation and accumulation of oil and gas and there are many new frontier areas for exploration. In the future, through the in-depth study of petroleum geology, and using new techniques and methods in exploration and exploitation, more oil and gas reserves will be found and developed both on- and offshore, including new giant oil and gas fields. Chinese geoscientists will do their best to further develop the petroleum industry and the science of petroleum geology in China.

Figure 2 Polycyclic oil and gas basins in China

1 metamorphic basement; 2 trough; 3 platform; 4 uplift; 5 composite basin; 6 rift-subsidence basin; 7 intermontane basin; 8 mountain front basin; 9 continental crust margin basin; 10 & 11 oil and gas horizons.

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