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Editorial

An introduction to petroleum and natural gas exploration and production research in China

1. History

China is a huge country in eastern Asia. It is the world's most populous country with a population of 1.3 billion. Most of the Chinese people live in densely populated areas in the eastern third of the country where most of China's major cities and nearly all the farming land are located. About 36% of the people live in regional cities and towns and the rest live in rural areas. Mainland China has 10 cities with a population of more than 3 million each in the urban area. They are Shanghai, Beijing (capital of the nation), Chongqing, Tianjin, Wuhan, Harbin, Shenyang, Guangzhou, Chengdu and Nanjing (Fig. 1). As one of the world's oldest civilization, China has a written history of nearly 4000 years. The Chinese people take great pride in their nation's long history.

A fossil anthropoid unearthed in the town of Yuanmou in Yunnan Province, southwest China is referred as "Yuanmou Man", who lived about 1.7 million years ago and is China's earliest primitive man known so far. "Peking Man", who lived in the Zhoukoudian area near Beijing 600,000 years ago, was able to walk upright and could make and use simple tools. The Neolithic age started in China approximately 10,000 years ago. Relics from this period have been found all over China.

The Xia *Dynasty* (family of rulers) was found in 2070 B.C. Its activities were centered along the Yellow River in the central China. The Xia Dynasty is the earliest known Chinese dynasty and was succeeded by the Shang Dynasty (1600–1046 B.C.) and the Western Zhou Dynasty (1046–771 B.C.). The following Spring and Autumn (770–476 B.C.) and Warring States (475–221 B.C.) saw the decline in power of the ruling house and struggles for power among the regional powers.

In 221 B.C., Ying Zheng (259–210 B.C.), ruler of the State of Qin and a man of great talent and bold vision, established a centralized, unified, multi-ethnic state in the Chinese history for the first time—the Qin Dynasty (221–207 B.C.). He called himself Qin Shi Huang meaning "First Emperor of Qin". He standardized the written scripts, weights and measures, and currencies. More importantly, he set up a centralized government system and gave his country a lasting ideal-national unity. The strong central government structure was kept in some form by the following dynasties for the next 2000-odd years. He mobilized over 300,000 people over a period of a dozen years to build the Great Wall of China, which stretches for 5000 km in northern China.

The Qin Dynasty was succeeded by the Han Dynasty (206 B.C.–A.D. 220), Three Kingdom Period (220–265), Jin Dynasty (265–420), the Southern and Northern Dynasties (420–589) and Sui Dynasty (581–618). In 618, Tang Dynasty was established by Li Yuan. Li Shimin, son of Li Yuan, adopted a series of liberal policies, pushing China's feudal society to its peak. Many historians consider the Tang period (618–907) the golden age of Chinese civilization. By 660s, China's influence had extended to many city-states in Central Asia. During this period, extensive economic and cultural relations were established with a number of countries including Japan, Korea, India, Persia and Arabia.

The Tang Dynasty was followed by the period of the Five Dynasties and Ten States when almost continual warfare was prevalent. In 960, the Song Dynasty was established and lasted until 1279. In the

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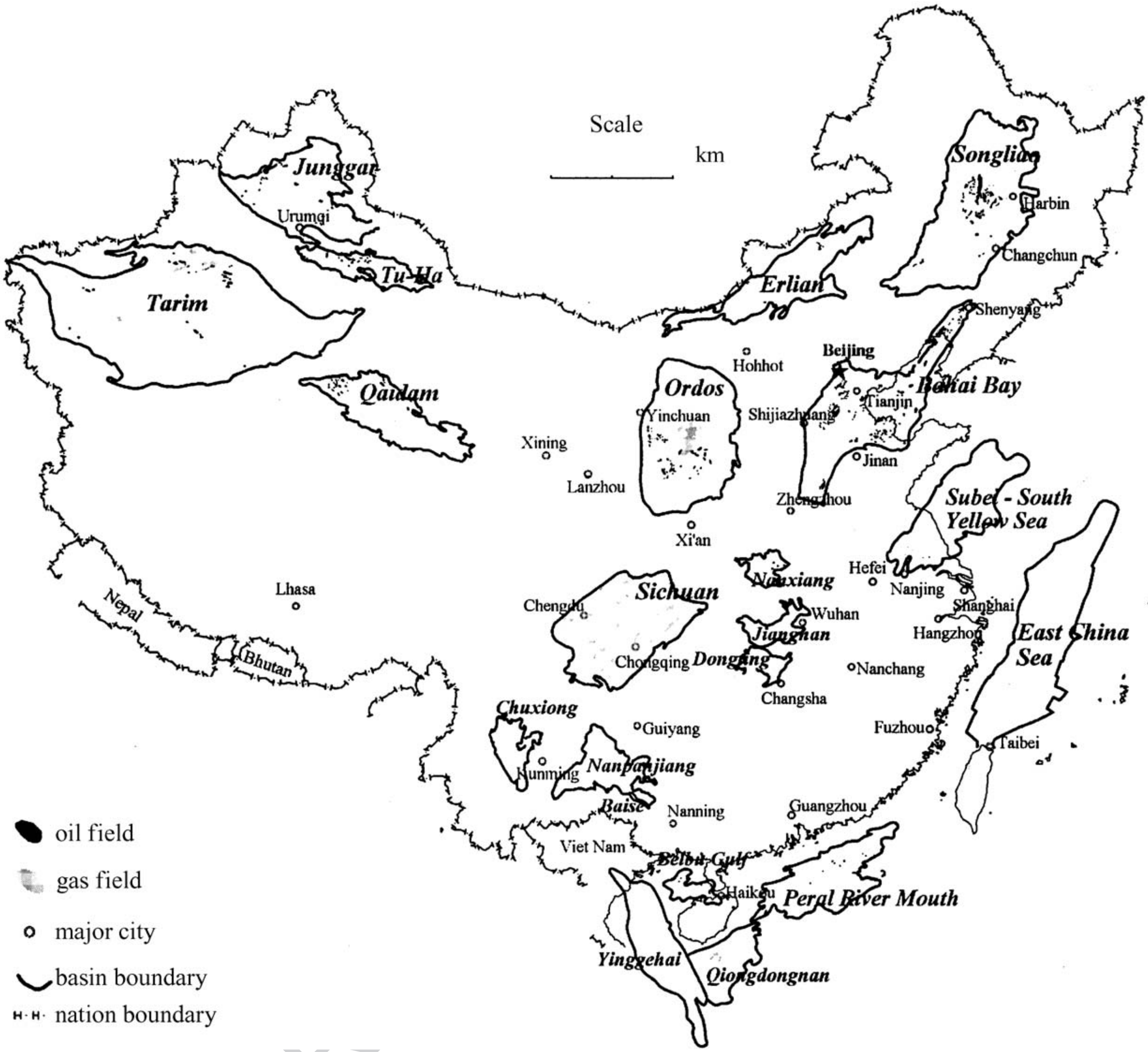

Fig. 1. Locations of China's major basins and oil/gas fields.

Song Dynasty, China was in the front rank of the world in astronomy, science and technology. In 1271, Kublai, a grandson of Genghis Khan, conquered the Central Plain, founded the Yuan Dynasty (1271–1368), and make Dadu (today's Beijing) the capital. During the Song-Yuan periods, the "four great inventions" in science and technology by Chinese people in ancient times—papermaking, printing, compass and gunpowder—were further refined and introduced to other countries, making great contributions to world civilization.

The succeeding Ming Dynasty ruled China from 1368 to 1644. It was established in Nanjing by Zhu Yuanzhang. When his son Zhu Di took the throne in 1402, he built the palaces, temples, city walls and moat in Beijing and officially moved the capital to Beijing in 1421. The imperial palaces in Beijing's Forbidden City reached its current splendor largely through the efforts of Ming architects.

The Manchus of northeast China established the Qing Dynasty (1644–1911) in 1644. Kangxi (reigned from 1661–1722) was the most famous emperor of the period. He brought Taiwan under Qing rule. He reinforced the administration of Tibet and effectively administrated over 11 million km^2 of Chinese Territory.

During the 19th century, the Qing Dynasty declined rapidly and ended in 1911 when the revolution led by Dr. Sun Yat-sen overthrew the Qing Dynasty and established the Republic of China. Following several wars from 1924–1949, the Peoples Republic of China was founded in 1949.

2. Background

2.1. Geography

Located in the east of the Asian continent, on the western shore of the Pacific Ocean, China has a land area of about 9.6 million km^2, trailing only Russia and Canada. The territory of China spans over 49 latitudes from north to south and over 60 latitudes from east to west. China extends over 5000 km both from north to south and from east to west.

China's topography was completely formed around the emergence of the Qinghai–Tibet Plateau, which was uplifted over the past several million years due to the collision of the Indian and Eurasian plates. Taking a bird's eye view of China, the terrain gradually descends from west to east like a four step "staircase". The young Qinghai–Tibet plateau has an average elevation of over 4000 m above sea level and constitutes the top of the staircase. The second step has an average elevation of 1000–2000 m and it includes the gently dipping Inner Mongolia Plateau, the Loess Plateau, the Yunnan–Guizhou Plateau, the Tarim Basin, the Junggar Basin, and the Sichuan Basin (Fig. 1). The third step, dropping to an elevation of less than 1000 m, comprises the Northeast Plain, the North China Plain and the Middle–Lower Yangtze Plain from north to south. The continental shelf of eastern China forms the fourth step of the "staircase". Plains account for 35% of the total land area of China.

China abounds in rivers. The rivers draining 1000 km^2 or larger areas are numbered more than 1500. The Yangtze and Yellow Rivers are the two largest rivers in China. The Yangtze is 6300 km long, the third longest river in the world, trailing only the Nile in Africa and the Amazon in South America. It is a transportation artery linking the west with the east. The Yellow River has a total length of 5464 km. Its valley is one of the birthplaces of ancient Chinese Civilization.

2.2. Oil and natural gas exploration and production

China is one of the first countries who discovered and used oil and natural gas. Historically, China led the world in technology on natural gas and salt exploration. The first oil well drilled by a rig was recorded in Miaoli, Taiwan in 1878. On mainland China, the first oil well-Yan-1 was drilled in Yanchang County, Shaanxi Province in the Ordos Basin) in 1907 and it discovered the first commercial oil field-Yanchang Field in China. From 1907 to early 1950s, few discoveries were made. In 1949 when the People's Republic of China was founded, the national oil output was only 120,000 tons (or 2400 bbl/day). Over the past 50 years, China's petroleum industry has made great progress and its domestic oil production has been around 3.3 million bbl/day since 1996 but its annual natural gas production has just passed through 1 trillion cubic feet (Tcf) because of its insufficient pipeline infrastructure.

From 1949 to the present day, four significant breakthroughs have been made in China's oil and gas exploration and production. The first breakthrough was achieved in late 1950s when the exploration focus was shifted from the west to the east. It was marked by the discovery of the Daqing Oil field, the largest field in China, in the Songliao Basin in 1959. This discovery indicates that nonmarine sediments were not only capable of generating oil but could generate enough oil to form giant fields. The second breakthrough was made in the Bohai Bay Basin in 1960s and early 1970s when a number of major oil fields were discovered. By 1978, China's oil output passed though the milestone of 100 million tons per year (or 2 million bbl/day). The third breakthrough was made in late 1970s when the eastern offshore basins were opened for cooperative exploration and production with foreign companies. Offshore oil and gas production has increased from 1800 barrels oil equivalent per day (boe/day) in 1982 to 467,000 boe/day in 2001. The fourth breakthrough was achieved in late 1980s when the policy of "Stabilizing the East and Developing the West" was launched. Since then, numerous significant discoveries have been made in the major basins in western China including Tarim, Ordos, Junggar, Sichuan, Tu-Ha and Qaidam (Fig. 1). The current oil production in these basins is over 450,000 bbl/day.

The current oil and natural gas exploration and production in China are under auspices of PetroChina, which is the largest listed subsidiary of China National Petroleum (CNPC), Sinopec (China Petroleum and Chemical) and the China National Offshore Oil (CNOOC). PetroChina and Sinopec are responsible for the onshore exploration and production whereas CNOOC handles offshore exploration and production. By the end of 1999, 460 oil fields and 162 gas fields had been found in China (Fig. 1). At the end of 2001, China has a remaining proven oil reserve of about 24 billion bbls. PetroChina, Sinopec and CNOOC account for 64%, 21% and 15% of the China's total crude oil production of around 3.3 million bbl/day, respectively. The oil reserves and production are largely confined to four major basins: Songliao, Bohai Bay, Ordos, and Junggar Basins (Fig. 1). Oil production in the Songliao and Bohai Bay Basins makes up over 60% of the total domestic oil output. Recent onshore major oil discoveries have been made in the Bohai Bay, Ordos and Junggar Basins. Recent offshore oil exploration interest has centered on the Bohai Sea area of the Bohai Bay Basin and the Pearl River Mouth Basin. The giant Penglai 19-3 Oil Field discovered by Phillips Petroleum in the Bohai Sea in 1999 was one of the largest oil discoveries in 1990s in China.

China's domestic remaining proven reserves of natural gas is about 48.5 Tcf. The country's largest reserves of natural gas are located in the Ordos, Tarim, Sichuan and Qaidam Basins in central and northwest China (Fig. 1). Construction of PetroChina's ''West-to-East Pipeline,'' which will transport gas in the Tarim Basin to Shanghai and pick up additional gas in the Ordos Basin along the way, began in late 2002 and will be completed by end of 2004. The pipeline consists of nearly 3800 km, 1016-mm mainline and 294 km of 813, 508 and 406 mm lateral lines. It eventually could serve as a trunkline which could be extended to receive gas from Central Asia. Over the past 10 years, China have discovered five major gas fields: Sulige, Qingbian, Yulin, Wushenqi and Mizhi in the northern part of the Ordos Basin (Fig. 1). These fields are estimated to hold proven in place gas reserves of over 35 Tcf. Some natural gas from the Ordos Basin will be put into the West-to-East Pipeline, which passes through the area and help make it economically viable. A pipeline was completed in 1997 between the Ordos Basin and Beijing, and a second pipeline is planned in the near future, as demand for natural gas in Beijing, Tianjin, and nearby Hebei province already is outstripping the capacity of the original pipeline. Another proposed pipeline project would link the Russian natural gas grid in Siberia to China and possibly South Korea via a pipeline from the Kovykta gas fields near Irkutsk, which hold reserves of more than 50 Tcf. The pipeline would have a planned capacity of 2.9 billion cubic feet per day (Bcf/d). Aside from these huge projects, other pipelines are being developed to link smaller natural gas deposits to other consumers. A pipeline was completed in early 2002 linking the Sebei natural gas field in the Qaidam Basin with consumers in the city of Lanzhou. Another planned project would link gas deposits in Sichuan province in the southwest to consumers in Hubei and Hunan provinces in central China at an estimate cost of $600 million.

Offshore gas projects also are becoming a significant part of China's gas supply. The Yacheng 13-1 field, discovered in the Qiongdongnan Basin of the South China Sea in 1983, has been producing gas for Hong Kong and Hainan Island since 1996. It has a proven in place gas reserves of 3 Tcf. The Chunxiao and three other gas fields in the Xihu Trough in the East China Sea are planed to be put into production in 2004. The gas will be supplied to Shanghai through a subsea gas pineline of about 450 km.

3. This special issue

Research activities on petroleum and natural gas exploration and production are undertaken by both academia (universities and research institutions) and oil companies. The three national oil companies: CNPC, Sinopec and CNOOC all have their central research institutes which undertake scientific research related to their upstream activities. Universities and research institutions attached to the Chinese Academy of Sciences conduct both fundament research funded by Chinese Ministry of Science and Technology and

National Natural Science Foundation of China and collaborative research with the three national oil companies and their subsidiaries.

The presentations in this special issue represent the wide range of current petroleum and natural gas exploration and production research activities in China, with papers in the areas of exploration, reservoir characterization, geofluids, petroleum migration and accumulation, structural geology and production operations. The first contribution after this introductory remark is authored by Guo et al. It is the biography of late Professor Tian-min Guo, an international renowned expert in petroleum science and chemical engineering. It summarizes his great achievements in his over 50 years teaching and scientific research. This special issue is to commend his contributions to the petroleum science and engineering. The paper entitled ‘‘A review on the gas hydrate research in China’’ is authored by late Professor Tian-min Guo et al. It gives an overview on the gas hydrate related research in China over the past decade in the areas of basic research, status of the exploration of natural gas hydrate resources in South China Sea and development of hydrate-based new technologies. The authors conclude more and more Chinese institutions will be involved in this type of research and abundant gas hydrate resources will be likely to be found with the improvement of research capacity in the next decade. The paper by Song et al. documents the types of the geochemical characteristics of four types of natural gas (coal-formed cracking gas, coal-formed thermal gas, oil-type thermal gas and mixed gas) and features of gas reservoirs in the China’s foreland basins. It further discusses the source rock intervals for each of the four types of gas in different foreland basins. One of their main findings is that abnormally high pressures are widely developed in these foreland basins and natural gas accumulations are characterized by multiple source rock-reservoir-seal combinations. The next paper by Wang also deals with natural gas in China. It illustrates how to classify Chinese gas fields into four types in terms of timing and gas charging and entrapment. Accumulation model and characteristics of each of the four types are clearly documented with field examples in different basins in China. His studies indicate that almost 50% of Chinese gas fields are characterized by gas chagrining and entrapment in Cenozoic times. Gas exploration should be carried out with different approaches by taking timing of gas charging, reservoir, trap and preservation conditions into consideration.

In the paper entitled ‘‘A preliminary study of mantle derived fluids and their effects on oil/gas generation’’, Jin et al. present the features of mantle derived fluids and their effects on oil/gas generation in the Dongying Depression of the Bohai Bay Basin. Based on investigations of isotopic geochemistry, organic geochemistry and thermodynamics, they demonstrate that hydrogenation by H-rich fluids derived from the mantle likely occurred in the Dongying Depression. The authors conclude that mantle-derived fluids have important effects on hydrocarbon generation as they provide both reaction energy and materials, which has implications for the worldwide oil and gas exploration.

The Dongying Depression is one of the most petroliferous depressions in China. In this nearly 6000 km^2 depression, 34 oil/gas fields have been found with proven in place oil reserves of 15 billion bbl. The oil/gas habitat of the depression is presented in ‘‘Oil/gas distribution patterns in Dongying Depression, Bohai Bay Basin’’ authored by Li. A complex structural framework resulted in the formation of complex reservoirs and different trap types, which in turn led to different oil/gas distributions in different structural trends in the depression. More importantly, the paper concludes that great exploration potential still exists in this depression in spite of its 40 years exploration history. The following paper by Zhang illustrates how to apply an integrated approach to explore lacustrine turbidites in Jiyang Sub-basin of the Bohai Bay Basin. The techniques involve an integration of multi-disciplinary approaches of sequence stratigraphy, seismic velocity data analyses and an optimization process. The application of these techniques in the lacustrine basin setting has been proved to be quite successful as approximately 438 million bbls of proved in place oil reserves were discovered from 1996 to 2001 in turbidite reservoirs in the Jiyang Sub-basin. These techniques can be probably used in other lacustrine basins in the world.

The paper by Pang et al. documents the oil and gas migration and accumulation models in the Qaidam Basin. Continuous permeable sandstones, faults and fractures constitute the main migration pathways. In different parts of the basin, the main migration pathways are different. Along the basin margins hydrocarbons accumulate in sandstone reservoirs whereas not only sandstones but also fractured mudstones comprise reservoirs in the basin interior. The paper concludes that each of the four models proposed can be used to target different prospects in the basin.

The next three papers are all on the Tarim Basin. Tang et al. illustrate how salt structures were evolved and how they controlled oil/gas accumulation in the Kuqa foreland belt. The Lower Tertiary salt sequence divides the Moso-Cenozoic strata into three tectonosequences. They conclude that the subsalt sequence are the favorable places for hydrocarbons to accumulate as source rocks are largely confined to the subsalt sequence and salt beds can act as excellent cap rocks. The paper by Lu et al. deals with oil and gas accumulations in the Ordovician carbonates in the Tazhong Uplift, which, together with the Tabei Uplift, hosts most of the discovered oil and gas fields in the Tarim Basin. In the Tazhong Uplift, oil and gas were locally sourced. Oil and gas migration is characterized by a short lateral migration through sand bodies and unconformity surfaces and a vertical migration by faults. The paper concludes that the northern slope and the northwestern pitchout end of the uplift are the favorable exploration fairways. The paper by Wang et al. demonstrate the oil migration in the Lunnan region of the Tabei Uplift. Their pyrrolic nitrogen compound distribution based technique, which has been successfully used in other basins of the world, clearly illustrates the migration patterns for different reservoir intervals in the Lunnan region. They conclude that the oils reservoired in the Ordovician and Carboniferous migrated laterally from west to east. In contrast, the oils reservoired in the Triassic and Jurassic first migrated vertically via fault conduits from the Ordovician source kitchen and then migrated laterally from north to south.

The paper by Liu and Lee is on geochemistry of source rocks in the Baise Basin, south China. They present abundant new geochemical and organic petrological data for this relatively unknown small basin. The quality of source rocks is assessed by investigations of kerogen types and maturity of organic matter. Their research results will no doubt provide useful guidance for the future exploration in the basin.

Mu and Cao illustrate how to detect sandstone reservoirs with absorption coefficients of seismic reflections. This new technique is developed by combining experimental results of seismic physical modeling in the laboratory with the Biot theory. Sandstone reservoirs can be directly detected with the reflection amplitude attenuation characteristics. They conclude that this technique has been successful in finding oil and gas reservoirs in the central western China. It may be applied to other basins of the world.

The paper entitled ‘‘Measurement and corresponding states modeling of asphaltene precipitation in Jilin reservoir oils’’ is co-authored by researchers from three institutions involving University of Petroleum, CNPC’s Research Institute and University of Illinois at Chicago. In the paper, Zhao et al. present their experimental results for the asphaltene precipitation for two oil samples under pressure and with/without CO_2-injections. Based on the results, they propose a generalized corresponding states principle (CSP) to predict asphaltene precipitation. The proposed CSP theory is a comprehensive model which embodies previous specialized modelings in this field of research. They conclude that the theory is capable of extending to correlate/predict the asphaltene precipitation in the high-pressure CO_2-injected reservoir oil system.

The paper by Gao and Gao illustrate how to calculate tubing behavior in high pressure and high temperature wells (HPHT) based on plastic incremental theory in plastic mechanics. Both laboratory experiments and the field’s testing data have proved that the method is feasible. They conclude that its successful applications in three HPHT wells in China have verified its practicality.

In their paper, Zhang et al. demonstrate the effects of different acidic fractions in crude oil on dynamic interfacial tensions in surfactant/alkali/model oil systems. They measured dynamic interfacial tensions of different acidic fractions against alkaline and/or surfactant solutions in the laboratory. They have established the relationships between the molecule structure and interfacial tensions.

The paper by Cheng et al. is a simulation study of steam-foam-drive in the super-viscous oil reservoir. Using their numerical simulator for the Gaosheng Oil Field in the Bohai Bay Basin, they studied the steam-foam-drive under different operating conditions and proposed optimal operational practice. The research results may have some guidance for the production of super-viscous oil from thick pay zones in other basins in the world.

In the paper entitled "A study on the size and conformation of linked polymer coils", Li et al. investigate a linked polymer solution (LPS) with dynamic light scattering (DLS) and scanning electron microscope (SEM). They present some important findings regarding the size and the conformation of linked polymer coils (LPC) in LPS. Furthermore, they propose a new method to investigate the plug property of LPC by filtrating diluted LPS pass through a micro porous filter membrane under low pressure.

In their paper, Chen and Zhang demonstrate the impacts of fracture width and confining pressure on the fracture toughness. They found that the influence of fracture width on the toughness is very clear and that of the confining pressure is significant and linear. These findings provide theoretical basis as well as reliable experimental procedures for correctly determining the fracture toughness, which is required for maximizing the effectiveness of the stimulation of low permeability reservoirs.

The last paper in this special issue is authored by Zhao et al. It is on processing of heavy crude oils. It demonstrates that supercritical fluid extraction and fractionation (SFEF) is an important tool to prepare narrow-cuts from a variety of petroleum vacuum residua. It also develops a generalized feedstock characteristic index, K_H. The authors conclude that the narrow-cut data can be used to develop critical properties of residue fractions and K_H to assess the feedstock reactivity and processability. Their findings have important applications in the processing of heavy crude oils.

The wide spectrum of the topics dealt with in this special issue reflect the wide spectrum of research activities in China. Production of this special issue took over one year to complete. In response to a call for contributions 22 manuscripts were submitted and nineteen were chosen for publication in this special issue after a lengthy review process. The editors of this special issue would like to thank the Elsevier Earth Sciences Editorial Office in the Netherlands and specially Ms. Tirza van Daalen, for their cooperation and encouragement in publishing this special issue.

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