PETROLIFEROUS SEDIMENTARY BASINS IN CHINA AND BASIN ANALYSIS

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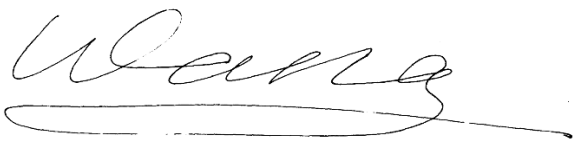
Petroleum Industry Press

PREFACE

Since the founding of the People's Republic of China, glorious achievements in petroleum industry of China have been accomplished. The annual production of crude oil has increased from 120,000 t in 1949 to 146,000,000 t in 1995, and that of natural gas has reached 17,000,000,000 m^3. Meanwhile, Chinese petroleum scientists and engineers are open minded, bold in making innovations, and make painstaking efforts to achieve great successes in creating the theory of petroleum geology with Chinese characteristics.

Petroleum exploration is the basis of development of petroleum industry. It is of great importance for developing the petroleum industry and upgrading the science and technology in China by means of continuously enriching and developing the theory and techniques of petroleum exploration. Prof. Tian Zaiyi, a petroleum geologist with extensive working experience and profound academic attainments, fully analyzed the petroleum exploration practice in China and incorporated the latest development in the theory and methods of basin analysis at home and abroad, published the book "*Petroliferous Sedimentary Basins in China and Basin Analysis*" co-authored with his colleague. This monograph thoroughly summarizes the theory and techniques of petroliferous sedimentary basins, reflects the development of modern petroleum geology, and attains a great theoretical level and academic value. The ten items for the analysis of hydrocarbon-bearing sedimentary basins as well as the basic conditions and general standards for performing basin analysis proposed in the book will play an important role in guiding petroleum exploration practice at present and years ahead.

China is rich in petroleum resources, and the potential of petroleum exploration is great. Nevertheless, the shortage of backup reserves is still an important factor restricting the development of petroleum industry. Therefore, to further intensify the studies of petroliferous sedimentary basins and provide new frontiers and favorable fields for petroleum exploration is still a tough assignment for geologists. I am convinced that the publication of the book could promote the progress in the research of petroleum geology in China, and meanwhile sincerely hope that the book could be gradually perfected with repeated practice in petroleum exploration and the development of modern science and technology.



Wang Tao
August 1996 , Beijing

PREFACE

The present book "*Petroliferous Sedimentary Basins in China and Basin Analysis*" by Professor Tian Zaiyi and his research group, published by the Petroleum Industry Press, is a monograph combining practical experiences and theoretical research of the authors over long years and summarizing the recent progress in petroliferous sedimentary basin analysis at home and abroad. As far as I know, this is the first book in China to discuss systematically the petroliferous sedimentary basins using the principles and methods of basin analysis. The publication of this book will certainly promote studies in petroleum exploration and in petroleum geology. May I herewith extend my sincere congratulations to the authors.

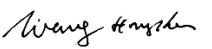
Oil and gas are preserved in sedimentary basins. The geological foundation of petroleum exploration is the analysis of hydrocarbon-bearing sedimentary basins. Petroleum geologists in China have long recognized the importance of study on the sedimentary basin as a whole and emphasized the comprehensive research of petroleum geology. As an overall study of the controlling factors on the regularities of hydrocarbon occurrence in sedimentary basins, the object and content of this book have gone beyond the classical field of petroleum geology which is confined to the studies of formation mechanisms of oil and gas pools. It serves as the guiding thought of petroliferous sedimentary basin analysis, and has gradually improved and perfected itself through the development of modern science and technology in petroleum exploration. The theory and practice of petroleum exploration in nonmarine basins of China are the main characteristics of this research, and are an important contribution of Chinese petroleum geologists to petroleum geology as a scientific discipline.

The geological study on basins has been a popular subject amongst the frontier fields of Earth sciences in the world during the last two decades, and the petroliferous sedimentary basin analysis has become one of the active frontier subjects in recent years. This subject is concerned with multidisciplinary theoretical and technical study, and the major theme is to study the sedimentary basin as a basic geotectonic unit for hydrocarbon generation and storage, quantitatively and dynamically modeling subsidence and burial history, tectonic development history, sedimentation and thermal evolution history, as well as hydrocarbon generation, migration and accumulation history of basins based on mathematical models. The modern analysis of petroliferous sedimentary basins should be a comprehensive analysis of geological studies closely related to dynamic numerical modeling because of the multidisciplinary and complicated nature of the studies on petroleum geology.

The importance of oil and gas in the national economy and national defense is known to everybody. Within over 40 years since the founding of the People's Republic of China, great success in petroleum industry has been achieved, and China has become one of the major oil producers in the world. The scientific and technological level of petroleum exploration has also been tremendously enhanced. However, the situation is rather serious if viewed from the angle of the "Ninth Five Year Plan" and from the demands of economic growth upon energy resources. In order to realize the strategic policy of "Stabilizing in the East, and Developing in the West", petroleum geologists are facing an urgent and glorious task to increase quickly the backup reserves. Therefore, introducing of new theories and new techniques, strengthening and deepening of the research on petroliferous basins are a task which brooks no delay.

Professor Tian has long been engaged in the studies of petroleum geology, and has acquired rich practical experiences as well as profound theoretical attainments. In this book, he and his colleagues have incorporated the latest development in theory and method of basin analysis at home and abroad, which are applied in his overall and systematic treatise of the petroliferous sedimentary

basins in China on the basis of his own theoretical studies and practical experiences of petroleum exploration and development. After reading the book, I am first of all impressed by its adoption of the view of tectonic mobilism and of historical tectonics in the study of the relationship between basins and orogenic belts. Secondly, the basin analysis is performed on the basis of basin dynamics and of dynamic processes, and the contradictory relationship between field and laboratory, entirety and part, basement and cover, formation and deformation, as well as horizontal and vertical movements, have all been well treated. Thirdly, the international modern concepts and methods of basin analysis in the 1980's have been absorbed and applied, so as to establish an overall view on basin analysis and to formulate systematic views and methods which enclose the controlling factors over oil and gas and the main content of basin analysis. Finally, the principle of combining theory with practice is implemented in the book, containing both principles and methods with concrete and detailed example analysis. I am sure this book will prove to be of a high practical value and capable of providing an important guide for practice.



Wang Hongzhen
August 1996, Beijing

FOREWORD

World-wide practice in petroleum exploration for a century indicates that sedimentary basins are the basic geological unit for hydrocarbon generation and occurrence. As pointed out by Perrodon A. (1980), a French petroleum geologist, "there is no petroleum if there is no basin", which profoundly clarifies the relationship between sedimentary basins and hydrocarbon occurrence. Whether a sedimentary basin can become a petroliferous basin, however, is controlled by a series of factors. Fully analyzing these factors becomes an important subject for petroleum explorationists.

Traditional petroleum geology is centered on generation mechanism of hydrocarbon accumulations, emphasizing the key elements such as generation, reservoir, seal, migration, trapping, preserving of hydrocarbon occurrences and pool-forming regularities. In fact, such key elements for hydrocarbon generation are controlled by the type of sedimentary basins and evolution features. The latter is a key factor determining hydrocarbon generation and distribution. Therefore, to effectively explore for hydrocarbon and evaluate hydrocarbon prospects, advanced geological theory and exploration techniques must be employed to analyze the petroliferous basin as a unit. This is just the core content of the book.

Hydrocarbon prospecting and exploration is an applied science requiring endless practice and study. The processes of petroleum exploration are repetitions of practice-cognition-re-practice-ré-cognition on subsurface petroliferous geological bodies. Correct theories play an important role in successful practice. A breakthrough in cognition is the prerequisite for exploration breakthrough. As Pratt W. E. (1952) pointed out, "in the final analysis, the place where petroleum is firstly found is in people's mind". How to apply the knowledge acquired in practice and to predict hydrocarbon accumulation zones through dialectical thinking would be a serious test.

China is the earliest country in the world that have found and developed hydrocarbon resources. Sedimentary basins of about 6,700,000 km^2 on land and offshore continental shelf in China are the broad area for petroleum exploration. Since the founding of the People's Republic of China, the petroleum industry in China has been tremendously grown from 120,000 t in 1949 to over 100 million t in 1978, and 146 million t in 1995 in annual output , becoming one of the five largest oil producers. However, the level of petroleum exploration is not balanced, and is still not high as a whole. According to recent resource evaluation results, within the known petroliferous basins in China, the proved hydrocarbons in the eastern part account for 35% of the resources estimate, and 14.65% in the western part, and proved gas only 4% in the central part. Therefore, the potential in petroleum exploration is tremendous. Right now, urgent and higher demand for energy has been created by the fast growth of national economy. As a major energy resource, petroleum should make its due contribution for the high speed development of national economy. As a geologist engaged in petroleum prospecting and exploration for half a century, the senior author feels a heavy responsibility. Since the 1950s, technology and theory support and promote each other in petroleum exploration and have been greatly developed and advanced. Active academic exchanges with scientists from home and abroad and technology import have made many fields in the studies of petroleum geology basically reach international level. Great progress in quantification and modeling of studies on petroleum geology has been achieved due to development in petroleum exploration, geological laboratory techniques as well as computer techniques. These have provided a favorable condition for the analysis of petroliferous sedimentary basins.

Potter P. E. and Pettijohn F. J. (1977) are the earlier researchers abroad in sedimentary basin analysis. In their book "*Paleocurrent and Basin Analysis*", a basic idea of

"study the basin as an entirety" was proposed for the first time. The main content of the book is to fully analyze lithofacies, paleocurrent, sediment type and tectonic background of basins, finally restore and reconstruct paleo-geographic environments of basins, and establish sedimentary models of basins. The book emphasizes the importance of paleocurrent measurement and systems in basin analysis. In 1984, Maill A. D. published the book "Principles of Sedimentary Basin Analysis", providing a process for analyzing fill-up and evolution history of sedimentary basins, and discussing the relationships between global tectonics and sedimentation. In the area of quantitative analysis of basins, Allen P. A. and Allen J. R. (1990) introduced in their book "*Basin Analysis: Principle and Application*" a method for basin tectonics, sedimentation and fill-up evolution analysis in terms of basin dynamics, discussing the application of basin analysis principle in evaluation of oil plays. In the same year, Lerche I.(1990) published a book entitled "*Basin Analysis: Quantitative Methods*", describing a method for mathematical modeling of petroliferous basins, emphasizing the method and application of thermal history modeling.

Chinese scientists in as early as the 50's and 60's recognized the importance of studies of basins as an entirety (Tian Zaiyi, 1960; Zhu Xia, 1965), and summarized the general rule of oil control of the basin in the exploration practice in Songliao and other basins, proposed a concept of hydrocarbon generation system. However, because of the limitation of scientific development level at that time, it was only in the mid 80's, that entirety analysis of basins began to be widely carried out, and quantitative analysis modeling of basins was performed (Li Taiming, 1989; Shi Guangren, 1989; Pang Xiongqi *et al.*, 1993; Xin Quanlin *et al.*, 1993). Practice has shown that basin analysis is the important condition for successful petroleum exploration. Basin analysis modeling has become an important part of petroleum exploration, and has shown a good prospect. To summarize timely the experience and progress in petroleum exploration and basin analysis studies, to establish basin analysis theory and methodology systems with Chinese characteristics, are surely of theoretical and practical significance. This is the basic starting point of the authors to write the book.

The book, co-authored by Prof. Tian Zaiyi and Zhang Qingchun, is based on the theoretical studies and practical experience in petroleum exploration and development of the first author for 50 years, and incorporates the new development in basin analysis theories and methods from home and abroad. There are four chapters in the book. The first chapter is an introduction to petroliferous basins. Starting from the basin features in combination with theory and practice in petroleum exploration at home and abroad, 9 major factors controlling hydrocarbon occurrence of basins are summarized. These factors are the conditions for the formation of petroliferous basins. The authors suggest that every link in the generation of hydrocarbon and the formation of hydrocarbon pools is realized in the evolution process of sedimentary basins. Therefore, sedimentary basins are the basic geological units for hydrocarbon generation and preservation, which forms the principle for the analysis of petroliferous sedimentary basins in theory and practice. As a negative structure of the crust, basins, like orogenic belts, are important components of the crust, and their evolution and distribution are controlled by the crustal evolution and regional tectonics. Therefore, we must investigate regional tectonics and evolution rules first, and then study the relationships between basins and orogenic belts. The second chapter discusses spatial distribution and development feature of regional tectonic units in China on the basis of historical tectonics. The controls of multistage, multi-cycle crustal tectonic evolution on sedimentary basins are analyzed. Formation and reformation features of sedimentary basins in geological history have been discussed on a macroscopic scale, clarifying the areas for finding oil. Since the basins at different tectonic locations in different tectonic regime show different in petroliferous abundance, and therefore it is of important theoretical significance to deeply understand basins and guide petroleum exploration through the ways of subdividing sedimentary basins and investigating their similarities and differences. In the third chapter, 16 prototype of basins from 4 categories of petroliferous sedimentary basins in China formed in rifted environment, convergent environment, strike-slip tectonic environment and cra-

tonic tectonic environment in geological history are subdivided based on the tectonic location of sedimentary basins, crustal types and evolution, geodynamic features as well as tectonic regime related to plate activities according plate tectonic theory. Examples are analyzed in the chapter. Formation and evolution of the Meso-Cenozoic overlapping basins in China are also finally discussed. Chapter 4 deals with , in a larger space, 10 contents of petroliferous basin analysis, basic conditions and general standards for performing basin analysis. Systematic and detailed analysis of the 10 items of petroliferous basin analysis is performed by using geodynamics, structural geology, sedimentology, petroleum geology, geochemistry. fluid dynamics and mathematical geology. A concept of synthetic analysis and modeling of petroliferous basins is proposed by using routine geological analysis in combination with mathematical modeling. A method of basin analysis modeling system and its application in the Damintun sag is introduced. The whole book is characterized by the following peculiarities:

- The analysis of petroliferous basins is guided by activity, historical tectonics and dialectical materialism;
- Entirety and systematization of basin analysis are emphasized;
- Multi-factor synthetic analysis method is used on the basis of single factor analysis;
- Qualitative description is combined with quantitative dynamic analysis modeling;
- New theory and techniques are fully used, emphasizing interdisciplinary cooperation, making use of the advantage of multiple disciplines;
- Theory is closely related to practice.

Publication of the book is encouraged and supported by Dr. Wang Tao, President of the China National Petroleum Corporation (CNPC) and Academician Wang Hongzhen, Professor of China University of Geoscience. Strong supports also come from the Research Institute of Petroleum Exploration and Development, and Exploration Bureau of CNPC, Daqing Oil Field, Liaohe Oil Field, Dagang Oil Field, Tarim Petroleum Exploration and Development Headquarters and Petroleum Industry Press. The figures are drawn by Mr. Liang Daxin, a senior engineer. The authors sincerely thank all the colleagues who support the publication of the book.

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March 3, 1996, Beijing

CONTENTS

CHAPTER 1 INTRODUCTION TO PETROLIFEROUS SEDIMENTARY BASIN

1.1 Sedimentary Basin as the Basic Geological Unit for Oil/gas Generation and Occurrence

Oil/gas generation and accumulation that took place during the evolution of Earth's crust has its own regularities and uniqueness. The process of the generation, evolution, migration and accumulation of hydrocarbons is closely related to the sedimentary basin as the structural element and is strictly governed by the tectonic evolution of the basin. Sedimentary basin is a rifted or depressed area filled with water and formed in a certain period of geological history. It was dominated by negative movement and received the fill-up of sediments of enough thickness to form a sedimentary body, thick in the center and thinning toward the boundary. This structural feature of the sedimentary basin constitutes the basic condition for oil/gas generation and accumulation. In the long geological history, at the same time with continued subsidence and deposition, the sedimentary basin also takes in terrestrial organisms from rivers and the organic remains from seas and lakes. Enrichment of such organic matter is the basis for oil/gas generation. With the filling up of sediments and increased burial, a higher geotemperature favored maturation of organic matter, in which a series of biochemical and chemical reaction occurred to generate oil and gas. Oil and gas in the source rock migrated in the direction of lower potential energy under the action of geopressure and crustal stress. Primary and secondary migration ended up at a place with favorable trapping conditions and oil and gas were accumulated in the reservoir bed. So sedimentary basin is the basic geological unit for oil and gas generation. The generation of oil and gas and the formation of oil/gas pools are inseparable from the process of the evolution of sedimentary basin, and such a relationship is the basic connotation of the petroliferous sedimentary basin.

The close relationship between oil/gas and sedimentary basin has been gradually recognized and strengthened in the long period of human practice. The experience in oil/gas exploration and development over two hundred years has told us that the discovered oil/gas fields are all distributed in the sedimentary rocks in different types of basins. Oil/gas fields are found in both marine and continental deposits (Fig.1-1). They are distributed in the sedimentary rocks of shallow sea, deltaic and deep lake facies. In terms of geological age, oil and gas are found in sedimentary rocks of all ages from the pre-Cambrian to the Pleistocene of the Quaternary. For example, one oil field and oil/gas seepages are found in China in the dolomite of middle/upper Proterozoic Wumishan Formation. The Quiriquire field in Venezuela and the Summer-land field in California have commercial reservoirs from Pliocene and Pleistocene formations. Oil/gas fields are also found in Pleistocene formations in Baku and Turkmenistan (Zhang Wanxuan and Zhang Houfu, 1981). Such occurrences of oil and gas are closely related to the enrichment of organic matter in sedimentary rocks, and are also related to some extent to the occurrences of such combustible mineral deposits as coal and oil shale.

In studying the generation of hydrocarbons in ancient rocks, petroleum geologists also study the organic matter in modern marine and lacustrine sediments to recognize the on-going process of the conversion of organic matter into oil and gas. A study on the modern sediments in the Qinghai Lake demonstrates that with increasing depth and finer grain size organic carbon content and redox potential increase in a regular pattern (Fig.1-2), with organic carbon as high as 3%. The asphalt content in the sediments is 0.063-0.204%, averaging 0.117% with a distribution pattern similar with organic carbon (Lanzhou Institute of Geology of Chinese Academy of Sciences, 1979). Abundant organic matter is found in the continental shelf of the Gulf of Mexico and California, Caspian Sea and Black Sea of the former Soviet Union, where petroleum has been generated.

Conversion of organic matter into oil and gas, which itself is mobile and will not stay where it was deposited as solid mineral deposits, has led to the concept of migration and accumulation and eventual preservation of oil and gas in some traps. Oil and gas were trapped and preserved in the reservoir rock with favorable porosity and permeability and covered by tight rocks of a certain thickness. Favorable trapping and sealing of the reservoir rock caused by crustal stress has resulted in accumulation of oil and gas and eventually a pool of a certain size.

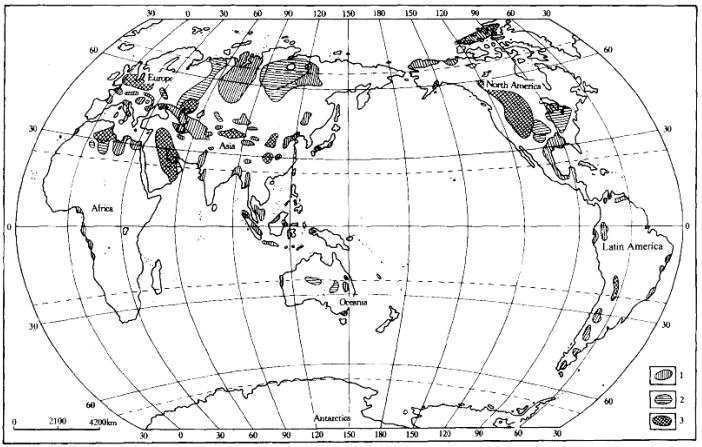

Fig. 1-1 Map showing distribution of major petroliferous sedimentary basins of the world. (after Gan Kewen *et al.*, 1982, simplified and modified). 1—Meso-Cenozoic petroleum-producing basin; 2—Paleozoic (or middle to late Proterozoic) petroleum-producing basin; 3—Paleozoic (or middle to late Proterozoic)-Meso-Cenozoic petroleum-producing basin.

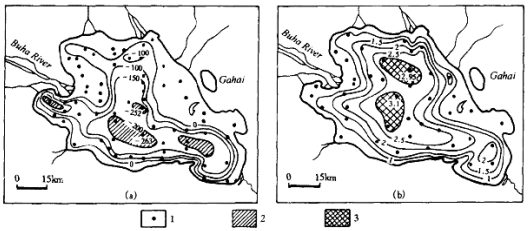

Fig. 1-2 Maps showing distribution of Eh value and organic carbon content of the bottom sediments in the Qinghai Lake. (after Lanzhou Institute of Geology of Chinese Academy of Sciences, 1979). (a) Eh isogram (mV in unit); (b) Isogram of organic carbon content (%). 1—Observed point; 2—Eh value smaller than -200mV; 3—Organic carbon greater than 2.8%.

With the progress of oil and gas exploration, especially onshore exploration, it is gradually recognized that oil/gas generation and accumulation are related to the sedimentary basin in a certain stage of geological history and to the superposed basins in the inversion of crustal movement.

Since the 50's, Chinese and foreign geologists have analyzed and studied the regularities of oil/gas generation and enrichment as viewed from oil/gas bearing sedimentary basins, and provided guidance for exploration practice with such regularities (Brod I. O. and Yeremenko N. A., 1953; Weeks L. G. , 1952; Tian Zaiyi, 1960; Zhu Xia, 1965; Chapman R. E., 1973; Petroleum Geology Group, Department of Geology, Northwest University, China, 1979; Perrodon, A., 1980; Zhao Zhongyuan, 1988, 1990; Zhao Xikui, 1991). Perrodon A., a French geologist, made a brilliant exposition in his "*Petroleum Geodynamics*", in which he stated in the first chapter that there is no oil without basin. Now such a statement has become common sense for geologists. However, it is also well accepted that a basin may not necessarily have oil. Oil/gas bearing basin is a sedimentary basin in which oil/gas field(s) or reservoir(s) have been found or a sedimentary basin with oil/gas show or predicted prospect. Evidently, oil/gas bearing basins are only part of the sedimentary basins. Not all oil/gas bearing basins have large size fields, nor is any place in the basin oil-rich. The statistical data (Halbouty M. T., 1976) indicated that in the 600 major sedimentary basins, large size oil/gas fields have been found in 75 basins, accounting for 13%, small and medium size oil/gas fields in 215 basins, accounting for 37% and the remaining 50% are less prospective or require further exploration work. Gan Kewen's data in 1992 of 517 sedimentary basins indicated that large size oil/gas fields have been found in 73 basins and small and medium size oil/gas fields in 138 basins. Oil/gas flow only are found in 47 basins and significant discovery has not been found yet in 259 basins (about 50%). These figures tell us that the formation of oil/gas bearing basins depends on various geological factors of the basin and a series of factors control or influence oil/gas generation and enrichment. The type, structure and evolution of an oil/gas bearing basin control the temporal and spatial distribution of oil and gas. Therefore, in order to evaluate and predict prospect and find oil/gas resources, we must begin with the study of basins and establish a firm concept of the whole basin. The first author of this book pointed out as early as in the early sixties that we must find the oil-containing structure in the whole basin under the sedimentary environment of the source rocks (Tian Zaiyi, 1960). In summarizing oil/gas exploration in China in the fifties, Professor Zhu Xia clearly stated that in finding oil and gas we must look from the angle of the whole basin to investigate the whole picture, and then to select the favorable areas based on sedimentary structure and so on. He further indicated that the basic unit of an oil province should be the oil/gas bearing basin and the correct knowledge of these basins is of great significance in both theory and practice (Zhu Xia, 1965).

1.2 Controlling Factors of Sedimentary Basins on Oil/gas Generation and Occurrence

Petroleum geology is a branch of applied geology that focuses on the formation and prediction of oil/gas pools. Before the discussion of the controlling factors of sedimentary basins on oil/gas occurrence, we need to understand the mechanism of oil/gas pool formation. The formation of an oil/gas pool occurred during the geological event of formation of mineral deposits in the process of sedimentary basin evolution. This process is the combination of chemical kinetics (oil/gas generation) controlled by temperature, pressure and effective heating period and a hydrodynamic process (oil/gas migration) controlled by pressure, buoyancy and fluid potential. Such a combined process is governed by basin evolution in deep burial, kinetic background and the specific stage of evolution. Therefore, in order to make sure whether there existed the conditions for oil/gas generation and occurrence, we need first to study the regional structural features, paleo-geographical setting and earth dynamics of the formation and evolution of a sedimentary basin, to study the subsidence history of the basin, fill-up sequence and other geological thermodynamic processes, to study time-space matching of source, reservoir, seal that arise from the above conditions and the conditions for migration, accumulation and preservation. Evidently, it is a highly integrated systems project. We must firmly establish the concept of the whole basin, follow the theory of activity, take the sedimentary basin as the basic geological structural unit for oil/gas generation and occurrence, adopt new, upgraded theory and techniques to carry out basin analysis focused on the formation of oil/gas pools. The concept of the whole basin has a dual implication. First, the whole first phase basin, the prototype basin. The basin what we observe now is often not the original one, but the result of tectonism, erosion, etc. Therefore we need to restore the features of the prototype basin as a whole according to the principles of tectonism and deposition. Second, the whole combination basin resulting from superposition of multiple prototype basins in the dynamic transformation of Earth's crust. Our exploration objective often exists in such combination basins. The combination of multiple basins should

be analyzed as a whole, which contributes to a more effective exploration program.

Apparently, in order to comprehensively master the basin concept, we must first restore the history of basin evolution. Restoration of the growth and evolution of a basin is no longer difficult, given the advance of computer technology and quantitative geology. Numerical simulation/modeling of an oil/gas bearing basin (Shi Guangren *et al.*, 1989, 1994; Pang Xiongqi *et al.*, 1993) has played a significant role in practice and has demonstrated great vitality to become a routine means for basin analysis and research on petroleum geology. Herein a general description of the controlling factors of sedimentary basins on the generation and occurrence of oil and gas is given, starting from the exploration practice in the oil/gas bearing basins in China to expound that the sedimentary basin is the basic geological unit for oil/gas generation and occurrence.

1.2.1 A sedimentary basin formed under a certain tectonic environment is favorable to oil/gas generation and evolution, if under long-term continued subsidence

The distribution of sedimentary basins in Earth's crust is controlled by tectonics and crustal movement. The heterogeneity of Earth's crust or lithosphere constituents, structural anisotropy and fault blocked and layered continental crust have caused considerable variation between different tectonic environments. During the process of crustal movement, the vertical or horizontal movements of geological bodies, large or small, cause differential adjustment of the mantle materials; at the same time, thermal decay in deep burial also resulted in strong activities of Earth's crust to form uplift or depression, folding or faulting in the upper zones of Earth's crust, and even volcanic activities. It is in such a variation of Earth's crust that a sedimentary basin is formed. From the point of view of plate tectonics, sedimentary basins can be classified into rift basins formed by extension of lithosphere, compressional depression basins formed by plate subduction or collision compression or flexure of lithosphere and strike-slip basins formed by lateral movement of lithosphere or crustal blocks. The configuration, size, initiation and growth of a basin is closely related to the evolutionary sequence of plate movement. Generally rocks are not likely to break under compressional stress but are easily rifted under tensile stress. Therefore, lithosphere is easily extended and becomes thinner under a tensile condition to form a rift basin. Girdler R. W. *et al.* (1970) studied the east African rift system and came to the model of rift growth and volcanic activities that result from mantle upswelling, thinning of Earth's crust and horizontal extension (Fig. 1-3, a). Wilson J. T. *et al.* (1975) claimed that the different types of continental margin is the product of plate movement at different stages, i.e. from east African rift to Red Sea inter-continental rift (Fig. 1-3, b), then to Atlantic Ocean type passive continental margin basin (Fig. 1-3, c) and to various types of sedimentary basin developed in the Pacific rim active continental margin arc-trench system formed by oceanic crust subduction (Fig. 1-3, d), and finally Himalayan type collision joint zone (Fig. 1-3, e), accompanying the disappearance of oceanic crust and ocean contraction (for exempla, the Mediterranean Sea) that leads to the growth of all kinds of foreland basins and intermontane basins. At the same time, due to earth dynamics and strong out-of-balance of plate margins strike slip faulting occurred at any stage of plate movements to form tenso-shear or compresso-shear basins on its sides (Fig. 1-3, f).

Irrespective of its size, for a basin formed under various tectonic environments the unity of opposites between subsidence and deposition holds for the entire process of basin growth. These two usually do not match each other. For an oil/gas bearing basin, continued subsidence is the necessary condition for the generation of oil and gas. Short term fluctuation is not excluded in the so-called continued subsidence. So long as continued subsidence is in force for the whole basin, it is favorable to the basin becoming oil/gas bearing. A relatively stable depositional environment can be kept only under continued subsidence of the basin to form massive sediments. This is the geological basis for oil/gas generation. Meanwhile, rate of subsidence versus rate of deposition also has a great influence on depositional cycle and combination of source, reservoir and seal of the basin. This is the reason to analyze the subsidence history and fill-up history of the basin.

1.2.2 Multi-cyclicity of crustal movement leads to multi-cyclicity of structural evolution and deformation of the basin and the formation of source-reservoir-seal combinations at different stages and various types of oil/gas pools

The history of crustal structural evolution demonstrates the multi-cyclicity of crustal movements, i.e. stronger crustal movements at a certain period and relatively stable at another period in a rise-and-fall pattern of growth. This can be attributed to the multi-cyclic activities of plate movements. At each stage corresponding

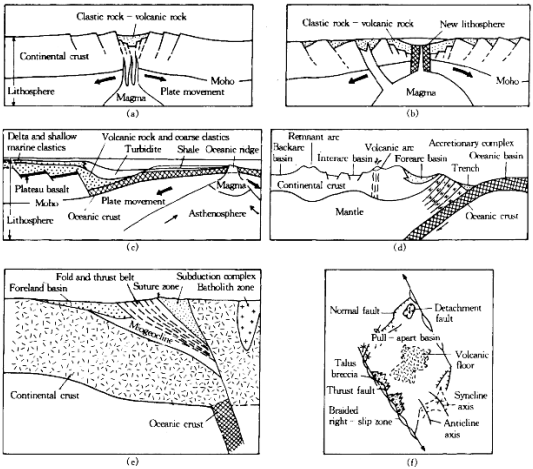

Fig. 1-3 Sketch diagrams showing extension-compression-strike slip activities of plates and development of sedimentary basins. (after Dewey J. F. and Bird J. M., 1970; Crowell J. C., 1974; Dickinson W. R., 1976 modified). (a)Intracontinental rift; (b)Intercontinental rift; (c)Passive continental margin; (d)B-type subduction; (e)A-type subduction; (f)Pull-apart basin.

sedimentary basins were formed under a unified dynamic mechanism. During subsequent growth and evolution, the basins formed at different stages inherited from the older or superposed with each other to various degrees to form multi-cyclic sedimentary basins. Vertically multi-layered structures exist and are generally separated by angular unconformities. Stratigraphic sequence, type of structural variation and depositional system differ in different structural layers., signifying the difference in the formation mechanism of basins at different stages. Each structural layer is the remains of the prototype basin at the corresponding stage. Put together, they formed the combination basin we observe today.

The evolution of a multi-cyclic basin often resulted in multi-stage oil/gas generating formations and multi-stage combinations of source-reservoir-seal. Early stage under-compensation, middle-stage stable subsidence and late-stage over-compensation all took place in each cycle of basin evolution or each stage of prototype basin growth. In the stage of stable subsidence deep water reducing environment existed to receive fine-grained muddy clastics or carbonates, as the most favorable period of source rocks growth. The early and late stages of basin growth are characterized by coarser grain size mostly of sandstones, as the stage of growth of good reservoir rocks. This feature gives rise to a complete depositional cycle of coarse-fine-coarse in a section of basin. Certainly, because of complexity in crustal movements an incomplete half-cycle was formed sometimes. Superposed basin of multi-cyclic growth inevitably resulted in multi-stage oil/gas formations and multi-stage combined cycle of source-reservoir-seal in a section. Large sedimentary basins in China are featured by multi-cyclic growth, that gave rise to multiple cycles of basin formation and multiple cycles of fluctuations in the growth of each prototype basin, and consequently, multiple source rocks and multiple cycles of source, reservoir and seal combination. For example, in the Meso-Cenozoic depression cycle of the Junggar basin there are five lower order sedimentary cycles (Fig. 1-4).

In summary, the combination basin of multiple cycle growth is very important in terms of petroleum geology.

The growth of the later superimposed basin resulted in deeper burial of the early prototype basin and facilitated maturation of early source rocks. At the same time, multiple superposed movements and faulting and unconformities in the basin caused inter-connection between structural layers and multiple migration and accumulation to form various types of primary and secondary pools.

1.2.3 Control of palaeoclimate on oil/gas-bearing basins

Palaeoclimate of the sedimentary basin is one of the important conditions for enrichment and preservation of organic matter. Research on continental oil/gas bearing basins tells us that the amount of organic matter in the sedimentary basin depends on the palaeoclimate and palaeo-aqueous medium when deposits were laid down. Generally under a humid to semi-humid, warm climate, a certain water depth in the lake basin, flourishing of organisms and a certain salinity are the necessary conditions for accumulation and preservation of organic matter. It is in such a way that favorable conditions for oil/gas generation could come into force. On the contrary, under arid to semi-arid climate water body contracted with larger salinity and organic content decreased significantly, that adversely affected the formation of source rocks. Variation in palaeoclimate seriously affected the potential of oil/gas generation. Therefore, palaeoclimate has a great influence on the formation of oil/gas bearing basins.

Variation of climatic zones on the earth is a complicated subject of natural science. It is mainly governed by latitude, atmospheric circulation, distribution of sea and land, landform, etc. Latitude and atmospheric circulation are the main factors that decide the distribution of climatic zones (Fig. 1-5), while waters and landform are responsible for local climatic zones. Therefore, the climate on earth surface is characterized by both horizontal and vertical zonation.

The basic data for analyzing palaeoclimate are the remains and phenomena preserved in sedimentary rock formations that reflect palaeoclimate. Lithological features, fossils, palaeo-ecology, stable isotopes as well as loess and lake deposits are used to study and restore palaeoclimate.

Oil/gas exploration practice in China tells us that the humid to semi-humid paleoclimatic cycles in the late Permian, late Triassic, early-middle Jurassic, early Cretaceous, early Tertiary governed the cyclic change in organic matter. Fig. 1-6 is a palaeoclimate evolution map restored from lithological indicators in northwest China since the late Carboniferous. It can be seen that oil shale formation generally took place under humid to semi-humid climates. In the early-middle Jurassic, temperate zone humid zone prevailed in northern China and Cycadophyta and Filices flourished. Important coal formations were formed in the middle-lower Jurassic, which are favorable formations for finding coal-derived oil and gas.

Besides, in the same period of basin formation, cyclic change in palaeoclimate is also observed. For example, in the rift basin in east China, closeness to the Pacific Ocean and influence by transgression and magmatic activities contributed to cyclic change in palaeoclimate. Taking the Palaeogene rift basin in the Jiyang depression as an example, the humidity coefficient of spore pollen in the middle and lower intervals of the fourth member of the Shahejie Formation is only 40, signifying a dry and hot climate with the formation of evaporite. It is 242 in the middle interval of the third member of the Shahejie Formation, signifying a humid and warm climate. It is 80 in the upper interval of the second member of the Shahejie Formation, signifying a fairly arid climate. It rose to 138 again in the first member of the Shahejie Formation, signifying a fairly humid climate. The middle and upper intervals of the fourth member of the Shahejie Formation and the upper interval of the second member of the Shahejie Formation are two comparatively arid periods; the climate changed from arid to humid and warm in the upper interval of the fourth member of the Shahejie Formation and the middle and lower intervals of the first member of the Shahejie Formation, where carbonate rocks were developed (Du Yunhua, 1990). Multicyclic change in climate has led to interlayered deposition of evaporites and organic shales that are favorable to the generation and preservation of oil and gas.

1.2.4 Sedimentary system, facies and diagenetics control the richness of oil/gas pools

Exploration practice worldwide in oil/gas bearing basins has demonstrated that the formation and distribution of reservoir rocks and source rocks in any period in the basin are controlled by the paleostructural environment and palaeodepositional conditions in basin evolution. Source rocks are mostly distributed in shallow-intermediate seas and deep-shallow lakes deposits. Reservoir rocks are mostly of deltaic, littoral, shallow sea, shallow lake, deep-shallow sea (lake), turbidite and carbonate rock platform facies. Sedimentary basins of various types have separately a relatively stable sedimentary facies and system. For each sedimentary system the conditions for accumulation and preservation of oil and gas vary due to the difference in sedimentary environment, kerogen and its evolution. The study on sedimentary

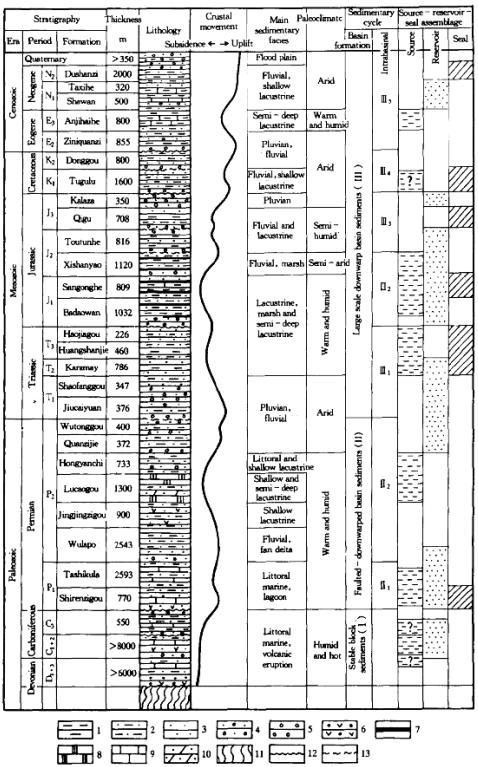

Fig. 1-4 Tectono-sedimentary cycles of the Junggar basin. 1—Mudstone; 2—Sandy mudstone; 3—Sandstone; 4—Sandy conglomerate; 5—Conglomerate; 6—Pyroclastic rocks and tuff; 7—Coal bed; 8—Oil shale; 9—Limestone; 10—Sandy dolomite; 11—Metamorphic rocks; 12—Unconformity; 13—Disconformity