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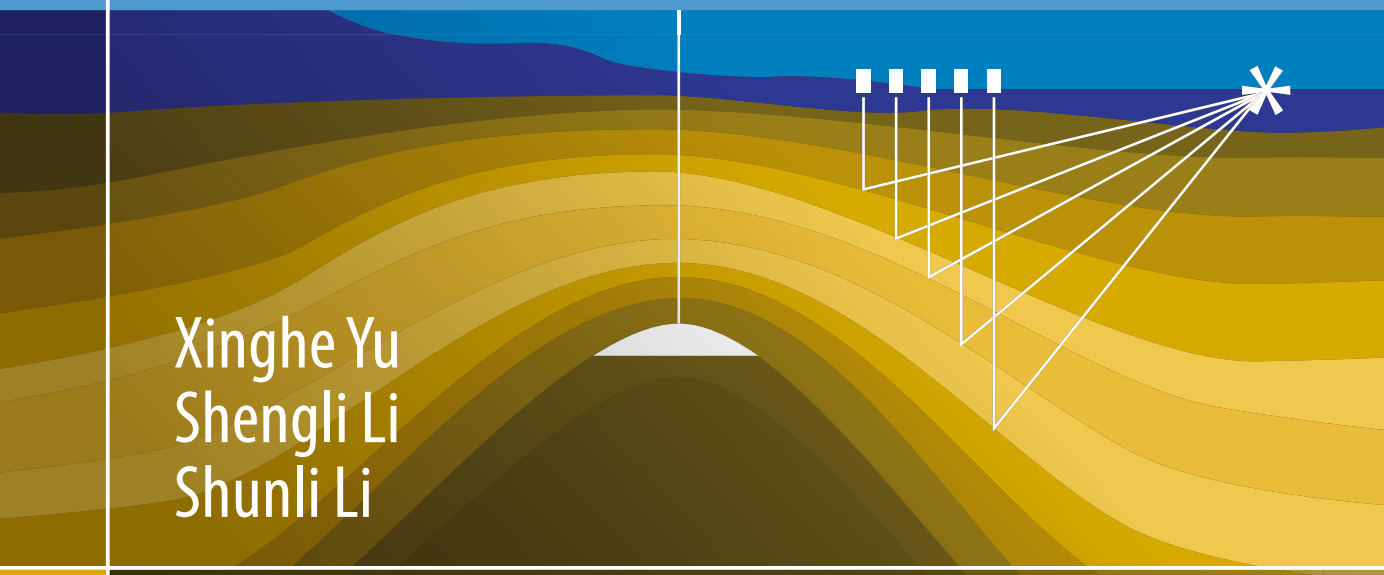

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Shengli Li
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Clastic Hydrocarbon Reservoir Sedimentology

Springer

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Preface

It has been over five years since the first publication of *Clastic Petroleum Reservoir Sedimentology* in September 2002, and since this time, it has been used as a textbook for graduates majoring in geology in universities and colleges where recognition and good reputation have been attributed to teachers and students, particularly at the China University of Geosciences (CUG) (Beijing). The book has also been used as a text in over 20 domestic professional training courses related to petroleum reservoir and sedimentology, particularly at three giant petroleum companies (PetroChina, Sinopec, and CNOOC), which reflects the considerable attention accorded to it by professionals in industrial and academic circles. With the development of hydrocarbon exploration, a larger number of petroleum geological scientists consider that this book not only carries the function of theoretical direction for scientific research, but also has significant practical value in the practice of hydrocarbon exploration. Hence, there is a great expectation for the second edition.

For the first edition, some readers pointed out the shortcomings therein and proposed certain amendments, which were valued by me. Owing to new academic accumulation in reservoir sedimentology and the advancement of scientific research in recent years, my intention was to make systematical modification and supplementation to the book, and thus had the idea of publishing the second edition. For the above-mentioned reasons, I completed the second edition in 200 days by further systematizing the original manuscript, referring to lecture notes, scientific achievements, published articles, and new academic points of view over recent years, and by making word-by-word modifications of the first edition and adding new chapters. This second edition is now about to be published, and I would thus like to cite the same famous Chinese proverb, as in the foreword to the first edition, "Human life is limited, but knowledge is limitless." Since I am restricted in view and shallow in understanding, this book will thus be used in the way of throwing out a minnow to catch a whale.

There are thirteen chapters in this book, covering many aspects of clastic petroleum reservoir sedimentology. This book, in addition to the latest trends in domestic and overseas reservoir studies, and along with basic knowledge, such as essential reservoir characteristics, diagenesis, and reservoir heterogeneity, also covers depositional features and reservoir characteristics of all types of depositional systems (alluvial fans, rivers, lakes, delta, shorelands,

and deepwater) for clastic rock. Furthermore, this book presents detailed discussions on the classification of each system, geologic features, sedimentary sequences, identification marks, facies models, and corresponding reservoir characteristics. Moreover, in consideration of the fast development of sequence stratigraphy in China, Chapter 4, "Theory and Methods for Studying Clastic Sequence Stratigraphy," has been added.

In the process of re-publication, I would like to thank the people who participated in the compilation and modification, as follows: Assoc. Prof. Li Shengli (Chaps. 4 and 11), Dr. Zheng Xiujuan (Chap. 1), Master Bai Zhenhua (Chaps. 4 and 5), and Master Fu Ju (Chap. 6); in addition, people who participated in error checks, supplementation, and data compilation include Zou Dejiang, Yang Fan, Ren Xiaojun, Chang Shuyun, Zhan Lufeng, Zhang Shuping, Li Mei, Sun Xiangcan, Yuan Kun, and Gao Dongchen; in addition, Dr. Zheng Xiujuan, who fully proofread the text from the first edition. I would like to express my gratitude to Profs. Qiu Yi'nan, Wang Defa, Zheng Junmao, Tian Shicheng, and other experts and scholars who proposed excellent suggestions for amendment. It should be noted that the second edition of this book is generously subsidized by the Graduate School of CUG (Beijing) and the Specialized Research Fund for the Doctoral Program of Higher Education of China (20050491001). I would also like to mention my wife Miss Hu Yihong and family members who have been involved in the compilation of this book. Many thanks for their great patience, passion, and complete support during the long period of compilation and modification.

Beijing, China
December 2016

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Contents

Introduction 1

With continuing global hydrocarbon exploration and development, improved descriptions of hydrocarbon reservoirs, and associated studies, the appearance (spatial distribution) and internal properties (physical property) of petroleum reservoirs have become the focus of hydrocarbon exploration and developmental research. However, the external shape (configuration) and distribution law of the internal properties within petroleum reservoirs under different geological conditions are related to their formation environment and associated conditions, and sedimentary petroleum reservoirs that are formed by particular depositional systems have differing distribution laws and heterogeneity characteristics. It is thus necessary to analyze the geological processes and sedimentary environment of the various types of reservoirs. Diagenesis also imposes a remarkable influence on the internal properties of reservoirs. Therefore, the overall characteristics of a petroleum reservoir depend on three factors affecting heterogeneity, the "stage of tectonic evolution, diversity of the sedimentary environment, and the complexity of diagenesis," and gaining a basic knowledge of these areas and associated theory gives a solid foundation in reservoir sedimentology.

As a key branch of sedimentology, reservoir sedimentology is categorized as applied sedimentology. It is therefore necessary to conduct an overall review of the formation and development of sedimentology, as doing so provides a basis for the analysis of historical studies and associated developmental trends of reservoir sedimentology. Sedimentary environment and sedimentary facies are key components of sedimentology, and are the basis for lithofacies restoration and palaeogeography, research on the distribution of depositional systems, explanations of seismic facies, the building of isochronous sequence stratigraphic frameworks, basin analysis, and prediction of the distribution of favorable reservoirs. Therefore, to enable study in these areas, it is firstly necessary to define the concept and connotations of a sedimentary environment and facies, and to gain an understanding of the role of the facies model, as well as similarities and differences between reservoir models.

1.1 Formation and Development of Modern Sedimentology

The definition of sedimentology was first put forward by H. A. Wadell in 1932 as, "A science for sediments research." In 1978, Friedman and Sanders then gave a complete definition of the sedimentology research field in the *Principles of Sedimentology* as, "A science for research on sediments, sedimentation process, and sedimentary rock and sedimentary environment." Furthermore, in 1980 the *Glossary of Geology* defined sedimentology as, "A science of research on sediment resources, description and classification of sedimentary rocks and research on the formation process of sediments."

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From the initial proposal of its concept to the present day, sedimentology has been constantly developed, enriched, and improved through the tireless efforts of global sedimentologists. In the beginning, actualism (i.e., uniformitarianism) contributed to the development of the subject, when, the formally published *Principles of Geology* (1837), Lyell proposed that, "Ongoing geologic processes in modern times once occurred with the essentially same intensities or ways during the whole geological period, and ancient geological events may be explained by phenomena and roles observed today." This definition was then encapsulated by A. Geikie in 1905, with the phrase, "The Present is the Key to the Past." Since then, the intersection and infiltration of different subjects, such as interinfiltrations between sedimentology and oceanography, physics, chemistry, aerology, hydrology, plate tectonics, petroleum geology, paleontology, geophysical logging, and seismic stratigraphy have played a considerable role in its development. Lately, the introduction of new technologies, such as the invention, use, and popularization of the polarizing microscope, X diffractometer, scanning electron microscope, energy disperse spectroscope (EDS), mass spectrometer, computed tomography (CT), nanometer (NM), and computers, have accelerated the development of sedimentology.

It can be said that sedimentology has mainly transitioned through two historical development periods, early modern times and modern times, and its development in early modern times can be further divided into three phases, as follows.

1.1.1 Emerging Phase (1830–1894)

Most of the research conducted during this phase focused on paleobiological strata, coal, and bioherms. In 1837, Lyell published an epoch-making monograph, the *Principles of Geology*, in which he put forward the principle and method of actualism, and stated that, "The Present is the Key to the Past." This book offered guidelines for later geological scientific research. Then, in 1857, Sorby first used the polarizing microscope in rock research, and determined that, "Using all polarization means is an absolute necessity," which lifted the veil for the microscopic study of rocks. In 1884, Murray and Renard collaborated to write *Deep-sea Deposits*, which could be used in the classification and description of deep-sea sediments. Furthermore, in 1894, Walther wrote the *Introduction to Geology as a Historical Science*, and put forward the concept of a "facies sequence," namely, Walther's law (law of correlation of facies), which determined, "The principle that facies that occur in conformable vertical successions of strata also occur in laterally adjacent environments. [Only laterally adjacent and dependent facies can be vertically superimposed in the absence of a hiatus]." A limited number of monographs emerged during this period, and their enormous influence and considered academic viewpoint on sedimentology cannot be ignored, even today (Table 1.1).

1.1.2 Initial Formation Phase (1894–1931)

Due to the high demand for minerals, geological exploration evolved in line with social development. Sedimentary studies (sedimentary rocks) were historically encouraged, data accumulated, and a collection of monographs and articles (Table 1.1) were published. As early as 1881, sedimentologists began studying heavy minerals using a microscope, and thus analyze the source direction and properties of sediments. In 1913, F. H. Hatch and R. H. Rastall co-authored the book, *Petrology of the Sedimentary Rocks*, and in 1914, G. K. Gilbert conducted the first flume experiments with sand of different grain sizes and different flow intensities to solve problems in the use of hydraulic power to mine gold, which was an important step in hydrodynamic experiments. Following this, H. B. Milner published *Sedimentary Petrography* in 1922, and W. H. Twenhorel edited *Treatise on Sedimentation* in 1926. Also in 1922, Wentworth first determined the power of 2 as a grain size boundary for dividing clastic sediment particles, and 2 mm as the upper limit grain size of sand, thereby leading the

Table 1.1 Representative works in the development of sedimentology before 1950 and associated contribution

Phase	Year	Author	Book or Article Title	Main Viewpoint or Functions, and Significance
Emergence	1837	C. Lyell	*Principles of Geology*	Proposing the principle of actualism, that "The Present is the Key to the Past"
	1884	J. Murray et al.	*Deep-sea Deposits*	Beginning of classification and description of deep-sea sediments
	1894	J. Walther	*Introduction to Geology as a Historical Science* (in three volumes)	Proposing Walther's law, and first use of the phrase, "comparative petrology"
Initial formation	1905	van't Hoff	*Evaporite*	Proposing the viewpoint of chemical precipitation
	1913	F. H. Hatch et al.	*Petrology of the Sedimentary Rocks*	Sedimentary petrology starts to serve as an independent branch of geoscience separated from stratigraphy. Later, research begins to be conducted on flume experiments; the division of grain size tends to become scientifically quantitative, and more attention is paid to research on sedimentation
	1922	H. B. Milner	*Sedimentary Petrography*	
	1922	C. K. Wentworth	*A Scale of Grade and Class Terms for Clastic Sediments*	
	1925	Twenhorel	*Sedimentation*	
	1926	W. H. Twenhorel	*Treatise on Sedimentation*	
	1929	Lucien Cayeux	*Sedimentary Rocks of France*	
	1931	Society for Sedimentary Geology (SEPM) in United States	First publication of *Journal of Sedimentary Petrology*	Marking the emergence of sedimentology as an independent discipline
Professional studies	1932	Nalivkin (Д. В. Наивки)	*Study of Facies*	Sedimentary petrology trends veer from qualitative research to become semi-quantitative, and greater importance is attached to research on sedimentation and sediment formation mechanisms
	1932	M. C. Svecovs. (M. C. Швецов)	*Petrology of the Sedimentary Rocks*	
	1939	P. D. Trask	*Recent Marine Sediments*	
	1939	Twenhorel	*Principles of Sedimentation*	
	1940	M- C- Pustovalov. (M- C- вечов)	*Petrology of the Sedimentary Rocks*	
	1949	F. J. Pettijohn	*Sedimentary Rocks* (3rd edition, revised and published in 1975)	A significant milestone in the maturity of sedimentary petrology
	1950	P. D. Trask	*Applied Sedimentation*	Proposing the concept and quantification method of sorting coefficients

classification of sandstones and conglomerates to the field of science quantization. Subsequently, in 1929, Lucien Cayeux from France published the first volume of *Sedimentary Rocks of France*, focusing on siliceous rocks. Thereafter in 1931, SEPM began publication of the *Journal of Sedimentary Petrology*. The abovementioned works show the development of sedimentary petrology

into an independent discipline that is separate from stratigraphy.

1.1.3 Professional Study Phase (1932–1950)

With the application of new technologies in the field of sedimentology, including differential thermal analysis and X-ray diffraction, research on sedimentary rocks tended to become semi-quantitative. A series of monographs and articles (Table 1.1) on sedimentary petrology were successively published and released during this period. In 1932, Nalivkin (Д. В. Наивкин) published the *Study of Facies*; and in 1932 and 1940, M. C. Svecovs. (М.С. Швецов) and M- C-Pustovalov (М- С- вечов) respectively published the *Petrology of the Sedimentary Rocks*. P. In 1934, Krumbein conducted quantitative research on a sedimentary environment, applied the roundness and shapes of clasts, and determined three main factors–boundary conditions, grains, and energy within a depositional system–and took the lead in applying statistics to sedimentology. D. Trask published *Recent Marine Sediments* in 1939 and *Applied Sedimentation* in 1950. In 1940, M. T. Halbouty researched the provenance, marine transgression and regression, change of an ancient shoreline, and the stratigraphic pinch out and petroleum prospect of the Gulf of Mexico. Furthermore, in 1949, Pettijohn wrote *Sedimentary Rocks*, which marked the mature growth stage of sedimentary petrology. Consequently, the development of early modern sedimentology focused mainly on the discussion of the formation mechanism of various conventional sedimentary rocks from the angle of a single sedimentary petrology discipline.

1.2 Development and Features of Modern Sedimentology

Since the end of World War II and the subsequent start of a global cold war, all countries have attached great importance to, and increased investment in, the development of science and technology. Due to the above stimulation and the influence of new demands on the scientific community, accelerated development has occurred within all disciplines. The division of labor of science itself tends to be elaborate, without exception of sedimentology development. It is precisely because of the rapid development of modern science that leaps have been made in the progress of sedimentology every 10 years, and as a subject it experienced four obvious development stages between the mid-20th century to the early 21st century. These are presented as follows:

1.2.1 Basic Maturity Phase (1950s–1960s)

After World War II, countries globally accelerated construction of their economies (particularly European countries and the USA), and the global industrial revolution entered a new period. Owing to demands for mineral resources in accordance with industrial development, sedimentology gradually transformed from a basic pure scientific theory into an applied science, and became increasingly connected with production practice, particularly in oil and gas exploration. After 1950, there was significant development in terms of research scale and direction with respect to modern sediments, and a number of monographs and literature (Table 1.2) were published and released. Representative works include *From Sedimentary Petrology to Sedimentology*, published by D. J. Doeglas in 1951; *Petrology of Sedimentary Rocks,* released by A. Vatan in 1954; *Primary Structures in Some Recent Sediments*, released by E. D. Mckee in 1957; *Paleocurrents and Basin Analysis*, co-authored by F. J. Pettijohn and P. E. Potter in 1963, *Atlas and Glossary of Primary Sedimentary Structures*, published in 1964; and Use of Vertical Profile in Environmental Reconstruction, proposed by Visher in 1965. During the same period, H. N. Fisk investigated the modern Mississippi Delta in detail, and the study of a Bahamas beach by L. V. Illing represented the first detailed research on modern carbonate deposition, which

Table 1.2 Representative works during the basic maturity phase and associated contribution (1951–1969)

Year	Author	Book or Article Title	Main Viewpoints or Functions, and Significance
1950	P. H. Kuenen et al.	*Turbidity Currents as a Cause of Graded Bedding*	A new chapter of research on turbidity current was opened
1951	D. J. Doeglas	*From Sedimentary Petrology to Sedimentology*	Sedimentology was at a new stage during the development of sedimentary petrology and a new field of geoscience was developed
1955	Ye Lianjun	*Sedimentary Conditions of Manganese Deposit in China*	A huge impact was made in relation to research on sedimentary deposits in China
1955	Liu Hongyun	*Paleogeographic Map of China*	Compilation of the first complete palaeogeographic atlas in China
1957	E. D. Mckee	*Primary Structures in Some Recent Sediments*	Emphasis on primary structure features formed under different sedimentary environments
1957	F. J. Pettijohn	*Sedimentary Rocks*	A significant mark in the maturation of sedimentary petrology, and an historical summary of sedimentary petrology over the last half century
1959	R. L. Folk	*Practical Petrographic Classification of Limestones*	Marking a new stage in research of carbonate rock
1961	A. Fi. Bouma et al.	*Turbidite*	Proposition of the famous Bouma Sequence
1961	Chiefly edited by Zeng Yunfu and Liu Baojun	*Sedimentary Facies and Paleogeography*	Ending the primary use of work of international scholars in domestic teaching colleges in China, and an attempt to use textbooks in sedimentary petrology written by domestic scholars
1962	Dai Donglin	*Petrology of the Sedimentary Rocks*	
1962	Chiefly edited by Liu Baojun	*Research Method of Sedimentary Rocks*	
1962	Chiefly edited by Wu Chongjun	*Petrology of the Sedimentary Rocks*	
1963	P. E. Potter et al.	*Paleocurrents and Basin Analysis*	A new lead is taken in conducting research on sedimentology by considering the basin as a whole
1964	Ye Zhizheng, Meng Xianghua and He Qixiang	*Texture-generic Classification of Carbonate Rock*	Marking the beginning of the modern concept of carbonate rock research in China
1967	W. L. Fisher et al.	*Depositional systems in Wilcox Group (Eocene) of Texas and Their Relationship to Occurrence of Oil and Gas on Gulf Shores*	Proposition of the concept and connotations of a depositional system

thereby played a significant role in guiding scientists to recognize carbonate rock from a new perspective. The progress made during this phase covers modeling applications, and genetic interpretation and graphic methods, particularly in relation to the subjects listed below; thus the development of sedimentology was of epoch-making significance.

1.2.1.1 Knowledge of Turbidity Current and Tractional Currents

It was initially believed that tractional currents were the main hydrodynamic process involved in the formation mechanism of clastic rocks. However, a new chapter of research on turbidity currents developed following the publication of *Turbidity Currents as a Cause of Graded Bedding* by Kuenen and Migiorini in 1950. After this publication, research on the formation and distribution of turbidity currents earned widespread attention in the field of geoscience, which resulted in a revolution in the field of sedimentology. Thereafter, under the guidance of Kuenen, A. H. Bouma conducted research on turbidity currents and flysch formation, proposed features of turbidity sediments, and built the famous "Bouma Sequence" in 1961. He then edited *Turbidite* together with A. Bronwer, forming two characteristic theories between the 1950s and 1960s: The Biochemical Origin of Carbonate Rock and The "Bouma Sequence" of a Turbidity Current.

1.2.1.2 Role of Flume Experiments in Sedimentary Structure Interpretation

In the early 1960s, American geologists applied the concept of hydraulics in a flume experiment, and from their experimental results determined the hydraulic conditions for the formation of bedding and ripples (Simons and Richardson 1962). Their experiments determined that the bedform changing sequence of a nonviscous bed when flow velocity is increased and depth reduced is that of no movement → lower flat bed → sand ripples → sand waves → dune → transition area → upper flat bed → antidunes → scour pit and chute. The change in sandy bedform was well explained for various sedimentary structures, where the mechanism and hydrodynamic conditions were formed by tabular, trough cross bedding, and parallel bedding.

1.2.1.3 Grain Size Analysis for the Interpretation of Hydrodynamic Conditions

R. Passega and G. S. Visher put forward a C-M diagram and cumulative probability graph explained by a tractional current in 1964 and 1969, respectively, which analyze and explain a sedimentary environment based on hydrodynamic conditions by virtue of grain size quantification; thus, genetic analysis became more scientific and feasible.

1.2.1.4 New Phase for Research on Carbonate Rocks

In 1959, R. L. Folk introduced a genetic point of view for clastic rocks in relation to the classification of carbonate rocks. He also classified and explained clastic rocks, and revealed the identity of carbonate rocks and terrigenous clastic rocks in terms of their formation processes and mechanisms. This marked a new phase in research methods and associated knowledge of carbonate rocks.

1.2.1.5 Construction of Vertical Sedimentary Sequence or Facies Model

In 1965, Visher constructed 13 facies models from the perspective of vertical sedimentary sequences. These included four river models, four regression models, two transgression models, one delta model, one deep-sea model, and one lake facies model. The construction of a vertical model formed the foundation for the recognition of sedimentary facies, especially for the specific operation of analyzing sedimentary facies from field and downhole data.

1.2.2 Summary and Improvement Phase (1970s)

In the early 1970s, A. V. Carozzi translated the book *Carbonate Rocks* (written in French by Caye) into English for wider circulation, and in 1971, R. G. C. Bathurst published *Carbonate Sedimentary and their Diagenesis*. These achievements represented the mature phase in the study of carbonate rocks. During this period, a large number of summary monographs on sedimentology emerged (Table 1.3), for example Morgan edited *Deltaic sedimentation: Modern and Ancient* in 1970, R. C. Selley completed *Ancient Sedimentary Environments*, J. R. Allen wrote *Physical Process of Sedimentation*, and R. M. Garrels and F. T. Mackenzie coauthored *Evolution of Sedimentary Rocks.* In 1972, Blatt and Middleton co-authored *Origin of Sedimentary Rocks*, which summarized various mechanisms for the formation of sedimentary rocks, and quoted research achievements from hydromechanics. In the same year, *Sand and Sandstone,* coauthored by F. J. Pettijohn, P. E. Potter, and R. Siever, was formally published; this book summarizes important achievements made during research on clastic rocks previously determined at a seminar in Canada in 1964, and holds that sandstone can play an important role in tracing stratum history. In 1973, Reineck from Germany and Singh from Indian co-authored and published *Depositional Sedimentary Environments with Reference to Terrigenous Clastics* from the perspective of sedimentary structure research. In 1976, R. G. Walker from Canada compiled *Facies Models*, and R. C. Selley rewrote *An Introduction to Sedimentology* (2nd Edition) (Selley 1976). In the late 1970s, the most noteworthy achievement is that of *Sedimentary Environments and Facies*, which was chiefly edited by H. G. Reading in 1978, and *Principles of Sedimentology* published by G. M. Friedman and J. L. Sanders, which systematically summarizes geologic features and the formation mechanisms of various sedimentary environments, thereby reflecting the highest level of sedimentology research at that time.

The above works comprehensively upgraded and summarized the theory of sedimentology to an authoritative stage, particularly in relation to clastic rocks, thereby laying a firm foundation for further developments in sedimentology. At this point in time, Chinese scholars mainly learned and applied new theories and technologies obtained from overseas, and universities began writing trial textbooks on the *Petrology of Sedimentary Rocks* and *Sedimentary Environments and Facies*, thus guiding college students in China within a discipline originally consisting of scattered knowledge towards one with systematic study. The author began to learn the science of sedimentology under the guidance of these works. It is worth mentioning that some universities in China (for example, Beijing Graduate School of Wuhan Geological College, and Chengdu College of Geology), together with production departments, conducted research on the sedimentary environment of sedimentary minerals and petroleum resources, as well as the genesis of minerals, and published a number of papers and monographs on continental deposition in our country, thereby opening a new page in the development of sedimentology in China.

To conclude, the general features during this period are as follows: ① extensive research on identifying marks of sedimentary facies was conducted, and facies models were constructed for various sedimentary environments to enhance the operability of sedimentology research; ② research on sedimentary facies had an obvious evolutionary viewpoint; namely, analyzing the changes in depositional facies from the perspective of evolution; ③ facies analysis within global sedimentary basins was initiated; ④ knowledge of gravity flow was incorporated in the interpretation and classification of a particle supported mechanism; and ⑤ the theory of sedimentology was applied in hydrocarbon exploration and development.

In the 1960s–1970s, when the petroleum industry faced a large transition, reservoir sedimentology as a new science emerged at the right moment to better explain the formation and evolution of petroleum reservoirs. It used the

Table 1.3 Representative works during the summary and improvement phases associated contribution (1970–1980)

Year	Author	Book or Article title	Main viewpoints or functions, and significance	Remarks
1970	S. J. Pieson	*Geologic Well Log Analysis*	Applied well-logging to research on oildom sedimentology for the first time	
1970	R. C. Selley	*Ancient Sedimentary Environments*	Defined the relationship between environment and facies, and systematically introduced the geologic features of various sedimentary environments	2nd edition in 1976; 3rd edition in 1985
1970	J. R. Allen	*Physical Process of Sedimentation*	Put forward the control of sedimentary processes and sediment distribution, and a mutual relation between "deposition rate" and "settlement rate"	
1971	R. G. C. Bathurst	*Carbonate Sediments and Their Diagenesis*	Incorporated diagenesis as the main research content in relation to carbonate rock, thereby bringing associated research to maturity	
1972	H. Blatt et al.	*Origin of Sedimentary Rocks*	Summarized various formation mechanisms of sedimentary rocks, and quoted achievements in hydromechanics	2nd edition in 1980
1972	F. J. Pettijohn et al.	*Sand and Sandstone*	Proposed the viewpoint that "sandstone is able to play an important role in retrospecting stratum history"	2nd edition in 1987
1973	H. E. Reineck et al.	*Depositional Sedimentary Environments with Reference to Terrigenous Clastics*	Elucidated the geologic features of various terrigenous clastic sedimentary environments based on sedimentary structure, in order to lay a theoretical foundation for recognition of sedimentary facies	2nd edition in 1980
1974	K. J. Hsu et al.	*Pelagic Sediments: On Land and Under the Sea*	Provided a new understanding of deep-sea sediments	
1976	R. G. Walker	*Facies Models*	Expounded facies models formed by various sedimentary environments to give research on sedimentology had an analogous example	2nd edition in 1986; 3rd edition in 1992
1977	P. R. Vail	*Seismic Stratigraphy*	First to combine seismic data and sedimentary facies analysis	
1976	R. C. Selley	*An Introduction to Sedimentology*	Systematically expounded hydrodynamic conditions and methods of sediment transport and sedimentation mechanisms under different environments	2nd edition in 1982
1978	H. G. Reading	*Sedimentary Environments and Facies*	These two monumental works gave an overall summary of the theory of sedimentology, and reflected the highest, most current, level of research on sedimentology. They are thus classic works on sedimentology	2nd edition in 1986; 3rd edition in 1996
1978	G. M. Friedman et al.	*Principles of Sedimentology*		
1973	Sun Shu	*Studies on The Phosphate Rocks in Western Szechuan*	First to apply the theory of sedimentology in analysis of the distribution of sedimentary minerals. Published reports and monographs satisfied sedimentary features of continental facies in China, which opened a new page for the development of sedimentology in China	
1978	Li Jiliang et al.	*On the Features of Turbidite Sequences in Some Regions of China*		
1978	He Qixiang	*Sedimentary Rocks and Depositional Ore Deposits*		
1980	Liu Baoli	*Petrology of the Sedimentary Rocks*		

basic theory and method of sedimentology, and involved the prediction of macroscopic and microscopic characteristics of reservoirs in the search for hydrocarbon reservoirs.

1.2.3 Theory Sublimation Phase (1980s)

This was a comprehensive, fast, and vigorous development period for global sedimentology, and also a rapid developmental stage for sedimentology in China (Table 1.4). During this period, many new viewpoints and theories were expounded, and knowledge was gained particularly in relation to the genesis of special sediments, mainly in the following areas.

1.2.3.1 Storm Deposition

In 1975, J. C. Harms discovered hummocky cross bedding, which is iconic bedding from a storm event. Although hummocky cross bedding is found extensively at a continental shelf near the shore (Duke 1985), it was also discovered in estuaries, tidal flats, and delta-marginal environments (J. Bourgeois 1980), and even as deep-water turbidite. It was therefore evident that hummocky cross bedding and other various representative signs of storm events needed to be comprehensively distinguished. Also during the 1980s, R. H. Dott (1988) put forward the concept of episodic sedimentation, and pointed out that there may be an average status or balanced state in some environments, and also a deviation from the average status. Using the deposition of a

Table 1.4 Main Representative works during theory sublimation phase and associated contribution (1981–1990)

Year	Author	Book or Article title	Main viewpoints or functions, and significance
1983	W. E. Galloway	*Terrigenous Clastic Depositional Systems*	Gradually led theory and methods used in depositional system analysis to a systematic stage, and to practical applications
1983	R. A. Davis	*Depositional Systems*	
1984	A. D. Miall	*Principles of Sedimentary Basin Analysis*	Presented basin analysis as an integration of a number of studies such as stratigraphy, structural geology, and sedimentology
1985	A. D. Miail	*Architectural-Elements Analysis: A new Method of Facies Analysis Applied to Fluvial Deposits*	Proposed new concepts for architectural element and bounding surface hierarchy, divided rivers into 12 categories, and conducted quantitative research on the heterogeneity of fluvial reservoirs at different levels, with the aim of making research on sedimentology more operable
1988	A. D. Miall	*Reservoir Heterogeneities in Fluvial Sandstones*	
1988	W. Nemec et al.	*Fan Deltas*	Put forward a genetic classification method for a delta structure
1988	P. R. Vail	*Handbook of Sequence Stratigraphy*	Marks the birth of sequence stratigraphy, highlights an isochronal stratigraphic framework, and determines four effects that affect the sequence (i.e., tectonic movement, sea level eustacy, sediment supply, and climate change)
1988	J. B. Sagree	*Basics of Sequence Stratigraphy*	
1988	J. C. Wagoner	*SEPM Special Publication in Sequence Stratigraphy*	

(continued)

Table 1.4 (continued)

Year	Author	Book or Article title	Main viewpoints or functions, and significance
1981	Institute of Geology and Geophysics (CAS)	*Petrology of the Sedimentary Rocks*	Based on high start, sedimentology in China applied advanced overseas theories to systematically summarize and upgrade domestic geologic features, thereby forming a theory of sedimentology using Chinese characteristics
1981	Lithofacies Palaeogeography Committee of China	Initial issue of *Lithofacies Palaeogeography*	
1981–1982	Sun Shu et al.	*Evolution of Henan-Shaanxi Sedimentary Basin of the Middle And Late Proterozoic Age*	
1982	Wang Yinghua et al.	*Early Paleozoic Carbonate Petrology in Northern China Platform*	
1983	Sedimentology Society of China	*Initial issue of Acta Sedimentologica Sinica*	
1983	Ye Lianjun	*Sedimentary Associations of the Northern China Platform*	
1985	Wang Hongzhen	*Paleogeographic Atlas of China*	
1986	Wu Chongjun	*Sedimentation Types of Lake Sand Body*	
1986	Zeng Yunfu, Xia Wenjie	*Petrology of the Sedimentary Rocks*	
1986	Sun Yongchuan, Li Huisheng	*Clastic Sedimentary Facies and Sedimentary Environment*	
1986	He Qixiang et al.	*Reef facies Deposition in Xisha Islands*	
1987	Sun Shu et al.	*Sedimentation of Extensional Basins in Platform Regions of China*	
1987	He Jingyu, Meng Xianghua	*Sedimentary Rock, Sedimentary Facies Model and Construction*	
1987	Yu Suyu, He Jingyu	*Petrology of the Sedimentary Rocks*	
1987	Ye Lianjun	*Current Status and Development Trends of Sedimentology*	
1988	Ye Lianjun, Sun Shu et al.	*Advances and Prospects of Sedimentology in China*	
1989	Sha Qing'an	*Deposition of Holocene Beach in Dafu Bay, Pingtan Island, Fujian and Diagenesis Thereof*	
1989	Zhu Xia	*Sedimentary Basins in China*	The first volume of *World Sedimentary Basins*
1989	Zheng Junmao, Pang Ming	*Research on Diagenesis of Clastic Reservoirs*	Systematically introduced methods for studying diagenesis of clastic reservoirs

nearshore wind-wave zone as an example, positive deviation may cause storm deposition, while negative deviation may cause non-deposition or a hard bottom.

1.2.3.2 Flysch Formation

As early as 1978, Friedman and Sanders in *Principles of Sedimentology* defined flysch as a product specific to marine strata. Prior to this, it had been considered that flysch was only produced in deep-sea troughs, and that steep slopes and turbidity currents were thought to be necessary and sufficient conditions for its formation. In the 1980s, it became acknowledged that flysch may be produced in other environments (such as in basins on continental slopes or continental margins).

1.2.3.3 Basin Analysis and Research on Sedimentary System

In accordance with a geotectonic environment, Sun Shu, a Chinese scholar, conducted systematic research on the clastic sedimentary environment and lithofacies paleogeography of sedimentary basins in Henan and Shaanxi in 1981, and summarized their formation and evolutionary history to discuss the zonation of sedimentary iron deposits.

In 1984, A. D. Midi determined basin analysis to be an integration of stratigraphy, structural geology, and sedimentology. He also answered paleogeographic evolutionary problems relating to basins, and published the *Principles of Sedimentary Basin Analysis*. Furthermore, Galloway and Hobday published *Terrigenous Clastic Depositional Systems* in 1983, and R. A. Davis published *Depositional Systems* in the same year (Davis 1983). In 1982, the editor-in-chief, Scholle and Spearing, compiled the publication, *Sandstone Depositional Environments*, which contained a large number of colorful pictures. In addition, the theory of plate tectonics became one of the theoretical foundations of sedimentation.

Studying the sedimentation and evolutionary laws of different types of basins is a major topic in the understanding of relations between tectonics and sedimentation. Construction of a depositional basin model involves analysis of the depositional system of different types of basins, and integrated research into the sedimentary filling pattern and basin evolutionary process. At present, theory and methods for the analysis of depositional systems have moved into a systematic stage.

1.2.3.4 Impact of Diagenesis on Porosity

Following further progress and developments made in hydrocarbon exploration, and the constant introduction of new technologies and new methods, there was a breakthrough in research into the diagenesis of clastic rocks in the late 1970s. Among such breakthroughs, was the discovery that a large amount of secondary porosity is formed by diagenesis in sandstone. Representative articles include, *Diagenesis in Sandstones* by Blatt (1979), *Diagenesis and Pore Evolution of Sandstones (Sand Layers)* by Zhu Guohua (1982), *The Chemistry of Secondary Porosity* by Surdam et al. (1984), *Application of Organic/Inorganic Diagenesis to Porosity Prediction* by L. J. Crossey (1986), and *Diagenesis of Clastic Reservoirs* by Zheng Junmao (1989). All these mark the mature stage of diagenesis research and theory.

1.2.3.5 Hierarchical Analysis and Formation of Configuration Concept

At the Second International Symposium on Rivers in 1985, Miall put forward the concept of "Configuration or Architecture Elements," and "Bounding Surface Hierarchy" for the hierarchical classification of rivers, and divided river sediments into 8 basic architectural elements. He also proposed 12 river depositional models, which guided research on the depositional system into a new historical period. Three features or ideas in this respect were as follows: highlighting the hierarchical concept; embodying the three-dimensional (3D) structure of sediments and internal lithofacies; and obtaining research on rivers using a simple morphological classification stage. These are of historical significance in the formation and development of reservoir sedimentology, and on improvements in

sedimentology, and have been of evident guidance and reference to date. In particular, these concepts have been extensively applied in high water-cut oilfields when conducting research on intercalation during efficient development.

1.2.3.6 Further Developments in Geotectonic Sedimentology

Along with the systematization of classifying sedimentary basins according to plate tectonics (Dickinson 1979; Ye Lianjun 1983; Xu Jinghua 1985; Klein 1987; Zhu Xia 1989), scholars around the world have conducted systematic research on the sedimentation of different sedimentary basins, and discussed the formation, development, and evolution of sedimentary basins in various geotectonic backgrounds based on the fundamental theories of continental dynamics, plate tectonics, and sedimentology. Furthermore, from the perspective of construction and evolution, scholars have focused on discussing the distribution law of the sedimentary system within the basin, on the basis of sedimentary control, in order to predict the distribution of sedimentary minerals.

1.2.3.7 Delta Structure—Genetic Classification

In the publication, *Fan Deltas*, which was chiefly edited by Nemec and Steel in 1988, Orton and Mcpherson (1988) further divided a megaclast delta into a fan delta and a braided river delta, and applied a structure in the form of a genetic classification method to enable the scientific partition of a delta depositional system. In this respect, great leaps were made in delta research.

1.2.3.8 Rise of Sequence Stratigraphy

Vail et al. published an essay on seismic stratigraphy with the American Association of Petroleum Geologists (AAPG) in 1977. The essay proposed two major viewpoints, the first of which was that a sequence consists of mutually integrated and genesis-related strata, of which the top and bottom margins are the plane of unconformity and corresponding conformity surface. The second viewpoint was that the genesis of a sequence is basically or completely controlled by changes in global sea level. Following this, in 1988, as editor-in-chief, C. K. Wilgas compiled a special issue called *Integrated Research Method for Sea-level Changes–Sequence Stratigraphy*. In addition, P. R. Vail and J. B. Sagree chiefly edited the *Handbook of Sequence Stratigraphy* and *Basics of Sequence Stratigraphy*, where it was determined that *a* stratigraphic sequence is produced by the interaction of geological factors such as tectonic movement, global sea level eustasy, sedimentation, and climate change. A new science, known as sequence stratigraphy, was born with the advent of these works.

In relation to the knowledge contained in the above texts, a large number of famous international scholars revised their monographs and textbooks, and published second or third editions (Table 1.3), such as *Sedimentary Environments and Facies* (2nd edition in 1986) chiefly edited by Reading, *Facies Models* (2nd edition in 1986) edited by R. G. Walker, *Depositional Sedimentary Environments with Reference to Terrigenous Clastics* (2nd edition in 1980) edited by H. E. Reineck, *An Introduction to Sedimentology* (2nd edition in 1982), and *Ancient Sedimentary Environments* (2nd edition in 1978, and 3rd edition in 1985) edited by Selley, *Sandstone Depositional Model* (2nd edition in 1978 and 3rd edition in 1985) edited by Klein, *Sand and Sandstone* (2nd edition in 1987) edited by Pettijohn, and *Origin of Sedimentary Rocks* (2nd edition in 1980) edited by H. Blatt. The extra sections in these re-publications mostly include basin analysis, the principle of sequence stratigraphy, and research on depositional systems, which makes these works more systematic and theoretical.

Geoscientific research in China at the time was mainly "Following Thought, Imitable Research," and was focused on studying related knowledge from developed countries within Europe and the USA. Therefore, scientists were able to single out principal contradictions, and as a result a number of texts were compiled by systematically summarizing and upgrading geologic features by applying advanced theories from overseas. For example, Chongjun (1986)

conducted systematic research on a Mesozoic-Cenozoic lake basin sand body in China, and determined that the distribution and characteristics of the lake basin's sand body were controlled by tectonic activity, terrain, provenance, and climatic condition. In addition, he supported a link between the determination of sand body types and the zonal division of depositional facies within a lake basin, and advocated that a sandy lake basin could be divided into five categories: a turbidity sand body, delta sand body, fan delta sand body, submarine alluvial fan sand body, and a beach bar sand body; the distribution, formation and characteristics of which were then systematically summarized. During this period, a large number of representative monographs and textbooks (Table 1.4) were published: *Petrology of the Sedimentary Rocks* (1980), chiefly edited by Baoban; *Paleogeographic Atlas of China* (1985), chiefly edited by Wang Hongzhen; *Lithofacies Paleogeography Basis and Working Method* (1986), chiefly edited by Liu Baoban and Zeng Yunfu; *Petrology of the Sedimentary Rocks*, chiefly edited by Zeng Yunfu and Xia Wenjie; *Clastic Sedimentary Facies and Sedimentary Environment* (1985), chiefly edited by Yongchuan, Huisheng; and *Petrology of Sedimentary Rocks*, chiefly (1987) edited by Yu Suyu and He Jingyu.

1.2.4 Discipline Permeation Phase (1990s)

Both the depth and width of research on sedimentology expanded in line with the introduction of new technologies and approaches. Rapid developments in seismic technology and integrated electric well-logging interpretation technology opened a new and wider approach towards research into sedimentology. Previous studies had mostly focused on the analysis of one-dimensional or two-dimensional sections, and it was therefore necessary to introduce a new concept of 3D space to apply the new approaches. Between the late 1980s and early 1990s, research on depositional systems entered a true 3D space era through the use of 3D seismic data, and promoted the rapid development of the graphic workstation.

New technologies and approaches were also reflected in the development of new instruments, equipment, and tools, such as the isotope assay, cathode luminescence, X-ray diffraction, scanning electron microscope (SEM), electronic probe, paleomagnetism, paramagnetic resonance, automated imager, and remote sensing technology, all of which have played an important role in research to the present day.

China began conducting research on continental reservoir sedimentology in the early 1970s. By the late 1980s, reservoir sedimentology had entered a new stage by virtue of implementation of "China Petroleum Reservoir Research" by the former CNPC, which was headed by Qiu Yinan, and a series of research reports and monographs were published in relation to this project. With almost 30 years of practice, the future of reservoir sedimentology based on Chinese characteristics and research methods was summarized by Qiu Yinan (1992) as, "The main task of reservoir sedimentology is to acquire abundant quantitative geological knowledge to set up a continental reservoir geologic model using an outcrop survey." In the 1990s, reservoir sedimentology had already become a key subdiscipline of sedimentology.

The science of sedimentology had penetrated a number of other disciplines and embarked on a journey at a higher level. To be specific, a large number of classic monographs, and those concerning sequence stratigraphy, were revised and re-published (Table 1.5). The most representative works include *Sea-level Changes: An Integrated Approach*, edited by C. K. Wilgas from the USA in 1991; *Facies Models: Response to Sea Level Change*, re-published by Roger G. Walker and Noel P. James from Canada in 1992; and *Depositional System* (2nd edition), republished by R. A. Davis from the USA in 1992. In addition, Einsele from Germany edited and published *Sedimentary Basins: Evolution, Facies and Sediments Budget*, and later revised it as a