Krumbein & Sloss

Stratigraphy and Sedimentation

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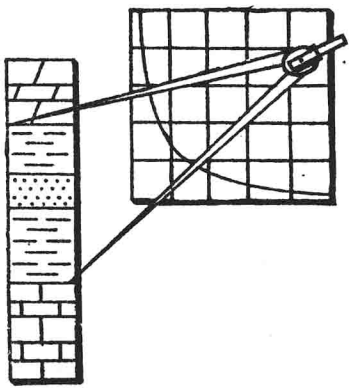

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Preface

It is a remarkable circumstance that one of the most rapidly expanding fields of integrated geology, that of stratigraphy and sedimentation, has received no comprehensive textbook treatment since publication in 1913 of Grabau's *Principles of Stratigraphy,* with subsequent minor revisions. In the intervening decades, great volumes of data have been added to the record and important strides have been taken toward the establishment of new principles and interpretations.

Excellent texts and reference works on many aspects of sedimentation have appeared, and descriptive stratigraphy has achieved abundant recognition as an applied and academic science. Beyond the level of elementary historical geology, attempts at integration of the diverse components of stratigraphy and sedimentation are so widely scattered through the geologic literature that they are beyond the reach of undergraduate and beginning graduate students.

It is the purpose of this book to assemble and integrate the facts, principles, and hypotheses bearing upon stratigraphy and sedimentation in a form that may be studied and assimilated in an efficient manner. The book is the outgrowth of a combined course presented by the authors at Northwestern University. The course was designed to meet the needs of senior students in geology and to serve as an introduction in advanced stratigraphy for beginning graduate students. Prerequisites include the normal sequence of undergraduate courses in geology and related sciences. Some field experience with sedimentary rocks is assumed, preferably a formal field-mapping course.

The authors hope that the book will at least partially fulfill the need for a text in courses of this type. It is also hoped that it will be of use to the many practicing stratigraphers for whom the pressure of work prevents thorough reading of a voluminous and scattered scientific literature.

It is noteworthy that in Grabau's time there was no separation, real or implied, between stratigraphy and sedimentation. In fact, sedimentation as an independent science had not yet been born. The 1920's and 1930's witnessed the rise of sedimentation as an important field of

investigation, with an accompanying trend toward separation in practice and concept between stratigraphy and its robust offshoot. More recently, the trend has been toward reintegration, and it is the intent of the authors to accelerate this trend by showing the close relation between the two domains.

The subject matters of stratigraphy and sedimentation are interwoven in the text as firmly as logical treatment will permit. The earliest chapters introduce the reader to certain basic concepts. These serve to show that his further progress in stratigraphic thinking cannot be realized without consideration of sedimentary rocks, their properties and classification, and the processes and environments which they represent. These topics, plus an exposition of the role of paleontology in stratigraphy, conclude the descriptive part of the book.

In the last six chapters, the fundamental facts and principles developed earlier are applied to the interpretation of stratigraphic data. These latter chapters explore concepts and fields which remain in an active state of flux as this is written. Therefore, the material must be viewed as a summation of one stage in an evolutionary progression which is far from complete. In this regard, the authors will consider their efforts rewarded if some of the principles expounded herein stimulate the growth of new concepts to replace them.

The present volume represents the combined efforts of the two authors. Their differences in training and experience led naturally to an apportionment of topics to one or the other. In all instances, however, individual chapters were prepared with a view toward continuity.

The level of discussion and the detail of treatment vary from chapter to chapter. Certain topics are treated in a purely descriptive manner, whereas others are given a more detailed analytic discussion. The descriptive approach is used for topics which are adequately discussed in standard textbooks and may be considered part of the common body of geologic knowledge. Here are included descriptions of sedimentary properties and of selected sedimentary rocks. Limitations of space dictate a treatment which is brief yet adequate to serve the book's purpose. Supplementary readings in standard sources are given for further detail.

Topics treated in a more expanded and analytic manner include those which are not adequately discussed in standard reference books, or which are on the forefront of current thought and require more detailed consideration. In this treatment, an effort is made to present

the various sides of controversial positions wherever encountered. In as many cases as possible, however, an opinion is expressed, favoring one view or another in order to leave the reader with a clearly defined case. The critical reader, because of wider knowledge or superior interpretation, will find himself in disagreement with some of the opinions expressed. For this, the authors offer no apology, but hope that their treatment is sufficiently objective to leave room for individual interpretation.

An important pedagogical purpose of this book is to acquaint the student with the standard literature of stratigraphy and sedimentation. This purpose is accomplished by selected readings from a number of textbooks and periodicals. Two objectives have been kept in mind. One is to direct the student's attention to other sources for further information on topics necessarily treated briefly; the other is to make available to the student other points of view than those discussed in this volume. It is the authors' hope that this approach will prepare the student more effectively to develop his own judgment in controversial subjects.

Almost all reference material is cited from American publications, although an attempt is made to show the influence of European thinking on the development of principles and concepts. For the most part, the references emphasize publications of the last twenty-five years, inasmuch as this literature is integrated, by way of bibliographies, with accounts of earlier developments for the more advanced reader.

Very little space is devoted to purely descriptive stratigraphy, except to illustrate specific topics. It is felt that the application of principles can be made more effective if reference is made by the individual reader or class to stratigraphic sections and conditions in the area of direct local interest. The burden of supplying the necessary collateral material accordingly lies with the instructor or experienced reader.

The authors are indebted to many individuals who have aided in the framing of concepts, the organization of the text, and the gathering of specific examples for illustration. Particularly are they indebted to E. C. Dapples and other colleagues in the Department of Geology at Northwestern University, and to F. J. Pettijohn of the University of Chicago. The authors have benefited immeasurably from informal discussions with many petroleum geologists. It is not possible to render individual credit to these numerous individuals, but it is hoped that they will not be disappointed by the form in which their contributions have been integrated and expressed. The authors are also indebted

to Mrs. C. L. Neigh for her excellent drafting of many illustrations in this book.

An expression of gratitude is due Northwestern University, the Gulf Oil Corporation, and the Phillips Petroleum Company for relief from obligations to permit completion of this manuscript. The final form of the volume is due in no little measure to the efforts of W. H. Freeman and Company who have given the authors every cooperation and have been responsible for the arduous tasks of editing and book manufacture.

W. C. Krumbein
L. L. Sloss

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CHAPTER 1

Introduction

SCOPE OF STRATIGRAPHY AND SEDIMENTATION

Stratigraphy

STRATIGRAPHY is defined in the opening paragraph of Grabau's (1913) monumental *Principles of Stratigraphy* as "The inorganic side of historical geology, or the development through the successive geologic ages of the earth's rocky framework or *lithosphere.*" The definition reflects the original concept of stratigraphy as the branch of geologic science concerned with the description, organization, and classification of stratified rocks.

The emphasis which Grabau placed on organic processes and organic factors in his book widened his definition and indicates that the scope of the science had already broadened to include most of paleontology beyond systematics and descriptive morphology. In the succeeding decades, the science has continued to enlarge in scope. It may now be considered as the integrating science which combines data from almost all other branches of earth science in a form from which historical geology emerges as a natural product.

Stratigraphy, like many other geologic fields, has remained in a largely descriptive stage of development during much of the past century and a half. During this time, the greater part of stratigraphic effort has, of necessity, been directed toward describing and compiling data on the vast volume of sedimentary rocks of the earth's crust.

Prior to World War I, stratigraphers were principally engaged in the descriptive stratigraphy of rocks in outcrop. This phase continues today and is still far from completion. In the past three decades, and with gathering momentum up to the present, the body of descriptive stratigraphy has been further swollen by the addition of enormous volumes of data pertaining to subsurface strata, largely as a result of oil exploration and exploitation.

Past generations of stratigraphers, although primarily engrossed in the task of description, developed a number of significant principles applicable to the interpretation and analysis of sedimentary data. Many of these principles remain useful today; others, which were valid working hypotheses at one stage of stratigraphic knowledge, have failed the test of time as new data came forth to challenge them. The influx of subsurface information, plus new techniques and tools for the treatment of sedimentary materials, has required the critical re-examination of time-honored concepts. In recent years, stratigraphers have been forced to modify or discard a number of earlier guiding principles, sometimes at a rate faster than they could be replaced by more acceptable ideas. More recently, however, the development of new concepts and the re-evaluation of old principles have permitted stratigraphers to keep pace with the demands made by an expanding knowledge.

This book is primarily concerned with the exposition and application of stratigraphic principles which appear sound in the light of these newer observational data. It should be clear to the reader, however, that, in a swiftly moving science, the accepted principles of today may become the historical references of tomorrow.

Sedimentation

Sedimentation, in a strict sense, refers to the processes responsible for the formation of sedimentary rocks, including the origin, transportation, and deposition of rock-forming materials, their diagenesis and lithification. In the broader sense commonly implied, sedimentation expands to encompass sedimentary petrology and sedimentary petrography, which combine to cover the study, description, classification, and interpretation of sedimentary rocks.

Inasmuch as sedimentary rocks are the fundamental materials of stratigraphy, the stratigrapher is more dependent on sedimentation than on other contributing fields, with paleontology ranking as a close second. The prominent place accorded sedimentation and lesser coverage of paleontology in this primarily stratigraphic text reflects the fact that the undergraduate training of most geologists is lacking in basic sedimentation, while paleontology usually receives adequate attention. With this in mind, emphasis is placed on those aspects of sedimentation having a direct application to stratigraphy and stratigraphic concepts.

The close relationship between sedimentation and stratigraphy is

clarified by the comparison with the relationship between biology and paleontology. Biology is primarily concerned with organic processes and organic patterns operating at the present moment. Organic processes and patterns operating through geologic time have produced a paleontologic record which must be interpreted by application of principles derived from biology. Similarly, the study of recent sediments, their processes of formation and distribution, establishes the guiding principles for interpretation of ancient sedimentary rocks. The stratigraphic record is largely the result of the continuity of sedimentary processes through the dimension of geologic time.

The study of sediments and sedimentary processes has made great strides in recent years. New techniques have been developed for analysis of the dynamic, physicochemical, and biochemical behavior of sedimentary materials in transport and after deposition. These advances have been paralleled by refined methods for measuring and quantifying a wide variety of physical and chemical attributes of sediments. In addition, the growing field of oceanographic research has provided an abundance of data to aid in the explanation of complex sedimentary patterns. It is the task of the stratigrapher to apply these newer approaches to an integrated interpretation of ancient sedimentary rocks.

Academic versus Applied Stratigraphy

There has been a tendency toward a well-defined cleavage between "academic" stratigraphy and "practical" or "applied" stratigraphy. Academically the science was directed toward analysis of the sedimentary record in terms of the reconstruction of geologic history and the description and nomenclature of various stratigraphic units. Applied stratigraphy was thought to be confined to the recognition and location in favorable positions of rock units associated with mineral products.

Today, the barrier between these two apparently disparate fields of endeavor has all but disappeared. Many of the principles and concepts considered to be of purely academic interest are found to be directly applicable to the solution of practical problems. With the recognition of intensive stratigraphic research as a valid approach to oil finding, the practicing stratigraphers have become among the most active in the development of advanced stratigraphic concepts and principles.

ARRANGEMENT OF SUBJECT MATTER

Physical Stratigraphy and Biostratigraphy

The subject matter of the science of stratigraphy is conveniently, if somewhat artificially, divisible into two major parts, as shown by Table 1-1. **Physical stratigraphy** includes all the components of sedimentation plus the physical aspects of analytical and interpretative

Table 1-1 COMPONENTS OF STRATIGRAPHY

PHYSICAL STRATIGRAPHY	BIOSTRATIGRAPHY
Observation and organization	
Stratigraphic column	Biostratigraphic column
Sedimentary petrology	Paleontology
Properties of sedimentary particles	Morphology
Properties of sedimentary aggregates	Properties of fossil assemblages
Classification of sediments	Classification of organisms
Sedimentary processes	Biologic processes
Analysis	
Lithologic correlation	Biostratigraphic correlation
Time-rock correlation	
Sedimentary tectonics	Organic evolution
Interpretation and synthesis	
Paleogeography	

stratigraphy. Under the heading of **biostratigraphy** are placed the numerous phases of biology and paleontology applicable to stratigraphic studies.

As the chart indicates, practically all the components of physical stratigraphy are paralleled by analogous components in biostratigraphy. An important distinction must be drawn, however. Under the principle of uniformitarianism, it may be assumed that the materials of physical stratigraphy have remained relatively constant throughout geologic time and have displayed uniform responses to the operating physical and chemical laws. The organic materials of biostratigraphy, on the other hand, have changed progressively in form and character with advancing geologic time, under the influence of organic evolution.

Organization of Stratigraphic Data

The first step toward treatment of a stratigraphic problem lies in the observation and organization of the basic materials, as shown in

Table 1-1. These are the successions of sedimentary rock observable in outcrop or made available by well drilling. The history and current practice followed in organization and classification of the stratigraphic column are covered in Chapter 2.

For the reader who lacks experience and training in the various techniques used in gathering stratigraphic information, these are outlined in Chapter 3.

In Chapters 4 and 5, the properties, composition, and classification of sediments and sedimentary rocks are discussed. It is assumed that the reader has a working knowledge of elementary paleontology, so that the equivalent discussion of the biostratigraphic parallels to these sedimentary subjects in Table 1-1 is omitted.

The fundamental background requisite to the organization of sedimentary materials must include knowledge of the processes of sedimentation, certain biologic factors important to stratigraphy, and a survey of the physical and biological attributes of sedimentary environments. These topics are the subject matter of Chapters 6, 7, and 8.

Analytical Stratigraphy

Stratigraphic analysis involves the integration of stratigraphic data derived from description and organization. Such integration makes use of fundamental principles in the conversion of raw data to a form susceptible to interpretation. The more analytical aspects of stratigraphic investigation are introduced in Chapter 9 by consideration of lateral variation in character of sediments. Understanding of lateral variation, or facies change, in a body of sediment calls for integration of much of the subject matter in the preceding chapters and is a basic prerequisite to comprehension of the complex problems of stratigraphic correlation. Correlation, or demonstration of equivalency of stratigraphic units, is discussed in Chapter 10.

The tectonic behavior of the earth's crust is recognized as an important factor influencing the thickness and character of accumulating sediments. The nature of the tectonic framework of sedimentation and the description and terminology of the various tectonic elements are given in Chapter 11. Chapter 12 relates the principles of tectonic geology to theoretical and applied approaches to sedimentary tectonics.

As the culminating stage in analysis and presentation of stratigraphic data, Chapter 13 is devoted to the consideration of numerous types of stratigraphic maps and techniques of three-dimensional stratigraphic mapping.

Interpretative Stratigraphy

Most stratigraphic studies are undertaken with a view toward the solution of some problem or combination of problems in paleogeography, historical geology, or economic geology. Interpretative stratigraphy is the final phase of study in which the data previously gathered, organized, and analyzed are caused, by interpretation and synthesis, to yield the required information.

There are many approaches to interpretative stratigraphy, depending on the purpose for which the end product is designed. In Chapter 14, broad-scale paleogeography is discussed as an important aspect of stratigraphic interpretation.

Bibliographic References

Much of the subject matter of this book is scattered through an extensive and growing scientific literature. References to important papers are given throughout the text and these references are arranged in a comprehensive bibliography at the end of the book. In addition, each chapter has a short bibliography of supplementary reading appended.

Standard textbooks are used for the supplementary reading; in many instances, to expand topics treated briefly because of space limitations or because of indirect applicability to stratigraphy. The more complete bibliography at the end of the book provides a working set of references for more advanced work.

The standard references, which are used throughout the book for supplementary reading, include works which should be available to students during the reading of the text. The following list comprises the most frequently used sources:

1. Grabau, A. W. (1913) *Principles of stratigraphy,* A. G. Seiler & Co., New York. The classic English-language text and reference on the entire field of stratigraphy and sedimentation.

2. Krumbein, W. C., and Pettijohn, F. J. (1938) *Manual of sedimentary petrography,* D. Appleton-Century Co., New York. An advanced text and reference on methods of sedimentary analysis.

3. LeRoy, L. W. (1950) *Subsurface geologic methods,* Colo. School of Mines, Golden, Colorado. A reference symposium on subsurface methods by a number of authorities.

4. Pettijohn, F. J. (1949) *Sedimentary rocks,* Harper & Brothers,

New York. An intermediate-level text and reference on description and interpretation of sedimentary rocks.

5. Shrock, R. R. (1948) *Sequence in layered rocks,* McGraw-Hill Book Co., Inc., New York. An intermediate-level reference on the primary structures of rocks, with emphasis on field interpretation.

6. Sverdrup, H. U., Johnson, M. W., Fleming, R. H. (1946) *The oceans,* Prentice-Hall, Inc., New York. The classic reference on the physics, chemistry, and biology of the oceans.

7. Trask, P. D. (1939) *Recent marine sediments,* Am. Assoc. Petrol. Geol., Tulsa, Oklahoma, p. 428-453. An advanced reference symposium on properties and occurrence of recent sediments, with consideration of methods of sedimentary analysis.

8. Twenhofel, W. H. (1950) *Principles of sedimentation,* McGraw-Hill Book Co., Inc., New York. An intermediate-level textbook on sedimentary rocks and sedimentary processes.

A new book, published while this volume was in proof, should be included in this list of important supplementary readings:

Kuenen, P. H. (1950) *Marine geology,* John Wiley & Sons, Inc., New York. This book summarizes the status of knowledge in a field closely related to the study of sediments.

CHAPTER 2

The Stratigraphic Column

INTRODUCTION

SEDIMENTARY rocks are the basic materials of the science of stratigraphy. Natural outcrops, excavations, quarries, mines, and well-bores serve to make these materials abundantly available for study. There are over 40 million square miles of surface exposure of sedimentary rocks, and an enormous mass of stratigraphic data has accumulated, although but a small percentage of this area is known in geologic detail. This mass constantly grows as more areas are explored stratigraphically and as new data from the continental shelves and marine basins are added to the record.

Exploration for mineral resources, and their exploitation, brings to light vast quantities of stratigraphic information. Oil-well drilling accounts for over 30,000 wells penetrating more than 25,000 miles of sediments each year in the United States alone.

It is the task of the stratigrapher to assemble and integrate this mountain of information so that it can make a useful contribution to earth science. Such assembly and integration require three logical steps. First, the succession of sedimentary rocks which forms the **stratigraphic column** of each area must be established. Second, the stratigraphic column must be subdivided and differentiated into significant and useful units. Third, these units and the physical and biologic events they represent must be related to their proper positions in terms of geologic history.

The first step, compilation of the stratigraphic column, is a familiar operation to all geologists and needs no direct discussion at this point. Certain aspects are more appropriately covered in the following chapter and in Chapter 10. This present chapter is primarily concerned with the more controversial subjects of subdivision of the

stratigraphic column and the relationship of the subdivisions to the geologic-time scale.

EVOLUTION OF STRATIGRAPHIC CLASSIFICATION

The terminology and many of the concepts employed today in subdivision of the stratigraphic column are legacies from a time when detailed geologic information was very scanty. It is necessary to review the historical evolution of nomenclature and theory in order to evaluate properly their significance today and the modifications required in the light of expanded knowledge.

Early Concepts

So far as the advancement of stratigraphic geology is concerned, the Dark Ages persisted well into the middle of the 18th Century. Perhaps this retarded renaissance of scientific interest may be explained by the dominating influence on prevailing thought patterns of a strict interpretation of the *Book of Genesis*. Under this influence, all of geologic time was considered to amount to but a few thousands of years; sediments were ascribed to the action of the Biblical Flood; and fossils were variously interpreted as evidence of creatures engulfed by the Flood, inventions of the Devil, or "figured stones."

This philosophical environment did not foster a wide interest in the materials of the lithosphere, except in the search for useful minerals. Few questions were raised as to the organization of earth materials, and, although successions of strata were self-evident in many areas, radical speculation on their origin and significance was not encouraged. Therefore, stratigraphy as a science made slight progress over its status as of 2,000 years earlier.

First Attempts at Organization

In the latter half of the 18th Century, a new age of enlightenment dawned, and, with it, a developing interest in man's physical surroundings, including stratified rocks. It is natural that men responsible for quarrying, coal and metal mining, and the exploitation of other mineral resources should be the first to recognize a need for working hypotheses to guide their exploration and production efforts. The writings of the time record several attempts to coordinate the data on sedimentary rocks made available by mining and quarrying operations and to express these data in logical terms.

Lehman. Among the more significant of these attempts is recorded in the work of Lehman, a German mining engineer. In 1755, he published a classification of the rocks of the earth's crust, dividing them into three categories:

1. Crystalline rocks devoid of fossils and believed to be of chemical origin prior to the advent of life. These were designated by a term which may be translated as *primitive.*
2. *Secondary* rocks, fossiliferous and stratified, and containing particles eroded from older rocks.
3. Loosely consolidated surficial sands and gravels, termed *alluvial.*

It is now obvious that the connotations of relative age according to lithology implicit in Lehman's classification are not necessarily valid. That is, types included in his primitive and secondary categories are known from all positions in the stratigraphic column. Nevertheless, the classification provided a generalized framework for the orderly study and treatment of rocks and was, therefore, a significant advance in constructive thinking.

Werner and Neptunism. The generalizations developed by Lehman as to the relative age of the various rock types of the earth's crust were seized upon by Werner, the highly influential professor at the Freiberg Mining Academy. Werner was the first great organizer of geologic materials and is responsible for bringing at least a semblance of order out of the chaotic hodgepodge of mineralogic, petrologic, and stratigraphic data available to his generation. Although he published very little, his brilliant lectures dominated geologic thought during the last quarter of the 18th and early decades of the 19th Centuries.

The basic concept of Werner's geologic philosophy was belief in an all-encompassing ocean which gradually receded to its present proportions while precipitating and forming all of the materials visible in the earth's crust. Because of the emphasis on an oceanic derivation for all rocks and minerals, Werner and his followers were known as the "Neptunists."

By the late 1790's, Werner had modified Lehman's classification as follows:

1. *Primitive (Urgebirge) series.* Including what are now recognized as intrusive igneous rocks and high-rank metasediments. These were considered the first chemical precipitates derived from the ocean before emergence of land areas.