PRINCIPLES OF SEDIMENTOLOGY AND STRATIGRAPHY

FOURTH EDITION

SAM BOGGS, JR.

Principles of Sedimentology and Stratigraphy

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Preface

The roots of sedimentology and stratigraphy extend back to the 16th century; however, these disciplines are still growing and changing. Geologists continue to "fine tune" sedimentologic and stratigraphic concepts through a variety of research avenues and by using an array of increasingly sophisticated research tools. The result is a continuous outpouring of fresh data and new ideas. In fact, it is becoming increasingly difficult to keep abreast of the flood of new information appearing in the geological literature. A glance through recent issues of a well-known sedimentology journal reveals important new papers on sedimentation and tectonics, depositional systems, carbonates, biosedimentology, diageneis, provenance, geochemistry, sediment transport and sedimentary structures, stratigraphic architecture, chronostratigraphy, numerical modeling, paleoclimatology, sequence stratigraphy, and basin analysis—to name but a few research areas.

I make no claim that I have, in this fourth edition of *Principles of Sedimentology and Stratigraphy*, fully evaluated all of these new data or captured all of the new ideas and concepts that may have been put forward since publication of the third edition. I have, however, tried to weave important new information into the basic structure of previous editions and revise concepts that may have become outdated. In addition, I have reorganized some of the chapters, added numerous references to pertinent new research articles and books, and added a significant number of new photographs, line drawings, and tables. I hope that these changes increase both the readability of the book for students and also keep them abreast of recent developments in the fields of sedimentology and stratigraphy.

As mentioned in the preface to the third edition, career opportunities for geology students are shifting away from the more traditional avenues of petroleum and mining geology toward environmental geology and other disciplinary areas that deal with problems of society. To be prepared for these careers, students need to gain a solid foundation in the basic principles of sedimentology, stratigraphy, and related sciences, as well as to develop insight into innovative applications of these principles to areas of study such as environmental analysis, paleoclimate evaluation, groundwater resources, and marine pollution. I hope that this book provides a useful part of the basic background that students need to advance into these exciting career fields.

I want to thank the following people for reviewing the Third Edition. I used their reviews to guide me in the preparation of the Fourth Edition:

Edwin J. Anderson, Temple University; Janok P. Bhattacharya, University of Texas – Dallas; Charles W. Byers, University of Wisconsin; Beth Christensen, Georgia State University; Joachim Dorsch, Saint Lewis University; James E. Evans, Bowling Green State University; Larry T. Middleton, Northern Arizona University; Michael R. Owen, Saint Lawrence University; Bruce Selleck, Colgate University; and Mark A. Wilson, College of Wooster.

SAM BOGGS, JR.

Introduction

Kinds of Sedimentary Rocks

This book describes and discusses the physical, chemical, and biological characteristics of sedimentary rocks and the interpretations that we draw from these characteristics about the origin of sedimentary rocks. Geologists disagree somewhat about how the various kinds of sedimentary rocks should be classified; however, such rocks can conveniently be placed into three fundamental groups on the basis of composition and origin: siliciclastic, chemical/biochemical, and carbonaceous.

Siliciclastic sedimentary rocks are composed dominantly of silicate minerals, such as quartz and feldspar, and rock fragments (clasts). These materials originate mainly by the chemical and physical breakdown (weathering) of igneous, metamorphic, or (older) sedimentary rock. Conglomerates, sandstones, and shales belong to this group. Silicate detritus, including silicate minerals, rock fragments, and glass shards, can also be generated by explosive volcanism. Siliciclastic sedimentary rocks that formed mainly from the products of explosive volcanism are called **volcaniclastic** rocks. **Chemical/biochemical** sedimentary rocks are composed of minerals precipitated mainly from ocean or lake water by inorganic (chemical) and/or organic (biogenic) processes. They include limestone, chert, evaporites such as gypsum, phosphorites, and iron-rich sedimentary rocks. Evaporites are probably precipitated entirely by inorganic processes resulting from evaporation of lake or seawater. Biogenic processes, as well as inorganic processes, play an important role in the formation of many limestones and likely play some role in the origin of chert, phosphorites, and iron-rich sedimentary rocks. **Carbonaceous** sedimentary rocks contain a substantial amount (>~15 %) of highly altered remains of the soft tissue of plants and animals, referred to as organic matter. The principal carbonaceous rocks are coal and oil shale. Carbonaceous sedimentary rocks make up only a small fraction of the total sedimentary record; however, these rocks (especially coals) have great economic importance as fossil fuels.

Distribution of Sedimentary Rocks in Time and Space

Sedimentary rocks are confined to Earth's outer crust, where they make up only 5–10 percent of the outer 10 miles (16 km) or so of the crust. On the other hand, they are the most common rocks at Earth's surface. Sedimentary rocks and sediments cover nearly three-fourths of Earth's land surface and most of the ocean floor. They range in age from Precambrian to modern. The first sedimentary rocks were deposited nearly four billion years ago, at which time most of Earth's surface was covered with volcanic rocks. The relative proportion of sedimentary rocks at Earth's surface has increased progressively with time, as weathering processes brought about decomposition of other kinds of rock and deposition of the decomposition products to form sedimentary rocks.

Sedimentology Versus Stratigraphy

The record of Earth history locked up in sedimentary rocks dates back almost four billion years. It is the study of this reservoir of Earth history that constitutes the sciences of sedimentology and stratigraphy. **Sedimentology** is the scientific study of the classification, origin, and interpretation of sediments and sedimentary rocks. It is often difficult to draw a sharp distinction between sedimentology and **stratigraphy**, which is defined simply and broadly as the science of rock strata. In general, however, sedimentology is concerned with the physical (textures, structures, mineralogy), chemical, and biologic (fossils) properties of sedimentary rocks and the processes by which these properties are generated. It is these properties that provide much of the basis for interpreting the physical features, climate, and environmental conditions of Earth in the geologic past. Stratigraphy, on the other hand, is concerned more with age relationships of strata, successions of beds, local and worldwide correlation of strata, and stratigraphic order and chronological arrangement of beds in the geologic column. Stratigraphy finds special applications in the study of plate reconstructions (plate tectonics) and in the unraveling of the intricate history of landward and seaward movements of ocean shorelines (transgressions and regressions) and rise and fall of sea level through time. Particularly exciting developments in stratigraphy have come about recently by applying the principles of seismology and paleomagnetism to stratigraphic problems.

Brief History of Sedimentology and Stratigraphy

Sedimentologic and stratigraphic study date back to about A.D. 1500 with the observations of Leonardo da Vinci on fossils in sedimentary rocks of the Italian Apennines. Since that time, a steady drumbeat of progress in understanding sedimentary rocks has taken place, punctuated at intervals by significant new developments in tools and techniques for studying sedimentary rocks and emergence of new concepts and ideas about their origin. Especially noteworthy among these seminal events were (1) initiation of the use of the microscope to study fossils by Robert Hooke in the latter part of the 17^{th} century, (2) elucidation of the concept of uniformitarianism (loosely, the present is the key to the past) by James Hutton in the late 18^{th} century, (3) the birth of biostratigraphy (study and interpretation of sedimentary rocks on the basis of the fossils they contain) by William Smith in the early 19^{th} century, (4) application of the petrographic microscope to study of sedimentary rocks by Henry Clifton Sorby around 1850, (5) development of one of the most far-reaching concepts in geologic philosophy—seafloor spreading and global plate tectonics—in the early 1960s, and (6) emergence of the concepts of seismic stratigraphy (study of seismic data for the purpose of extracting stratigraphic information), sequence stratigraphy (application of the concept of depositional sequences to stratigraphic interpretation), and magnetostratigraphy (study of rock magnetism as a stratigraphic tool) in the 1960s and 1970s. The pace of new developments in sedimentology and stratigraphy continues to the present time, spurred by the availability of technologically advanced laboratory tools such as the scanning electron microscope and mass spectrometer and development of advanced field procedures such as the ability to drill deep holes in the ocean floor and recover sediment cores in water several thousand meters deep.

Why Study Sedimentary Rocks?

The sheer abundance of sedimentary rocks at Earth's surface provides a partial answer to a question frequently asked by students, "Why should we study sedimentary rocks; why bother?" In addition to their abundance, however, they are also important because of information they yield about Earth's history and because of the economic products they contain. All geologic study is aimed in one way or another at developing a better understanding of Earth's history. All rocks, whether sedimentary, igneous, or metamorphic, contain clues to some aspect of this history, but sedimentary rocks are unique with regard to the information they provide. From the composition, textures, structures, and fossils in sedimentary rocks, experienced geologists can decipher clues that provide insight into past climates, oceanic environments and ecosystems, the configurations of ancient land systems, and the locations and compositions of ancient mountain systems long since vanished. Thus, study of sedimentary rocks forms the primary basis for the sciences of paleoclimatology (study of climates throughout geologic time), paleogeography (study and description of the physical geography of Earth's past), paleoecology (study of the relationship between ancient organisms and their environment), and paleooceanography (study of the characteristics of ancient oceans). In addition, many sedimentary rocks have economic significance. Most of the world's oil and gas and all of its coal are contained in sedimentary rock successions. Iron-bearing minerals, uranium minerals, evaporite minerals, phosphate minerals, and many other economically valuable minerals also occur in these rocks.

Thus, the disciplines of sedimentology and stratigraphy, while having their roots in studies dating back to the early 16th century, are still vibrant, exciting, growing disciplines. I hope that this book will help students capture some of this sense of excitement: It provides an integrated view of sedimentology and stratigraphy. The first few chapters are devoted to description and discussion of the processes that form sedimentary rocks, the physical, chemical, and biological properties of rocks that result from these processes, and the principal kinds of sedimentary rocks. Succeeding chapters deal with sedimentary environment and their interpretation from the rock record; stratigraphic relationships revealed through study of lithology, seismic reflection characteristics, remanent magnetism, fossils, and radiometric ages; and basin analysis, which is the integrated sedimentological and stratigraphic study of sedimentary rocks.

Additional Sources of Information

Numerous references are made throughout this book to research papers that provide detailed information about particular topics. In addition, a list of pertinent monographs is provided at the end of each chapter. Readers should find these research papers and books a useful starting point for additional literature research. Finally, Appendix E furnishes an extended list of Web sites where online information about sedimentology and stratigraphy is available.

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PART I

Origin and Transport of Sedimentary Materials

Sediment transport in the braided Kongakut River, Arctic National Wildlife Refuge, Alaska

Sedimentary rocks form through a complex set of processes that begins with **weathering**, the physical disintegration and chemical decomposition of older rock to produce solid particulate residues (resistant minerals and rock fragments) and dissolved chemical substances. Some solid products of weathering may accumulate *in situ* to form soils that can be preserved in the geologic record (paleosols). Ultimately, most weathering residues are removed from weathering sites by erosion and subsequently transported, possibly along with fragmental products of explosive volcanism, to more distant depositional sites.

Transport of siliciclastic detritus to depositional basins can involve a variety of processes. Mass-transport processes such as slumps, debris flows, and mud flows are important agents in the initial stages of sediment transport from weathering sites to valley floors. Fluid-flow processes, which include moving water, glacial ice, and wind, move sediment from valley floors to depositional basins at lower elevations. When transport processes are no longer capable of moving sediment, **deposition** of sand, gravel, and mud takes place, either subaerially (e.g., in desert dune fields) or subaqueously in river systems, lakes, or the marginal ocean. Sediment deposited at the ocean margin may be reentrained and retransported tens to hundreds of kilometers into deeper water by turbidity currents or other transport processes. Sediments deposited in basins are eventually buried and undergo physical and chemical changes (**diagenesis**) resulting from increased temperature, pressure, and the presence of chemically active fluids. Burial diagenetic processes convert siliciclastic sediments to lithified sedimentary rock: conglomerate, sandstone, shale.

Weathering processes also release from source rocks soluble constituents such as calcium, magnesium, and silica that make their way in surface water and groundwater to lakes or the ocean. When concentrations of these chemical elements become sufficiently high, they are removed from water by chemical and biochemical processes to form "chemical" sediments. Subsequent burial and diagenetic alteration of these sediments generates lithified sedimentary rock: limestone, chert, evaporites, and other chemical/biochemical sedimentary rocks.

In summary, the origin of sedimentary rocks involves weathering of older rock to generate the materials that make up sedimentary rock, erosion and transport of weathered debris and soluble constituents to depositional basins, deposition of this material in continental (terrigenous) or marine environments, and diagenetic alteration during burial to ultimately produce lithified sedimentary rock. Because weathering plays such a critical role in generating the solid particles and chemical constituents that make up sedimentary rocks, Chapter 1 focuses on the physical and chemical processes of weathering, the nature of the resulting weathering products, and a brief discussion of soils. Chapter 2 continues with a detailed discussion of the various processes by which sediment grains are transported from weathering sites to depositional basins. Other aspects of the origin of sedimentary rocks are introduced and discussed in succeeding chapters, as appropriate.

1

Weathering and Soils

1.1 INTRODUCTION

Weathering involves chemical, physical, and biological processes, although chemical processes are by far the most important. A brief summary of weathering processes is presented here to illustrate how weathering acts to decompose and disintegrate exposed rocks, producing particulate residues and dissolved constituents. These weathering products are the source materials of soils and sedimentary rocks; thus, weathering constitutes the first step in the chain of processes that produce sedimentary rocks.

It is important to understand how weathering attacks exposed source rocks and what remains after weathering to form soils and be transported as sediment and dissolved constituents to depositional basins. The ultimate composition of soil and terrigenous sedimentary rock bears a relationship to the composition of their source rock; however, study of residual soil profiles shows that both the mineral composition and the bulk chemical composition of soils may differ greatly from those of the bedrock on which they form. Some minerals in the source rock are destroyed completely during weathering, whereas more chemically resistant or stable minerals are loosened from the fabric of the decomposing and disintegrating rock and accumulate as residues. During this process, new minerals such as iron oxides and clay minerals may form *in situ* in the soils from chemical elements released during breakdown of the source rocks. Thus, soils are composed of survival assemblages of minerals and rock fragments derived from the parent rocks plus any new minerals formed at the weathering site. Soil composition is governed not only by the parent-rock composition but also by the nature, intensity, and duration of weathering and soil-forming processes. It follows from this premise that the composition of terrigenous sedimentary rocks such as sandstones, which are derived from soils and other weathered materials, is also controlled by parent-rock composition and weathering processes.

Most ancient soils were probably eroded and their constituents transported to furnish the materials of sedimentary rocks; however, some survived to become part of the geologic record. We call these ancient soils **paleosols**. Weathering and soil-forming processes are significantly influenced by climatic conditions. Geologists are greatly interested in the study of past climates, called paleoclimatology, because of this relationship and because paleoclimates also influenced past sea levels and sedimentation processes as well as the life forms on Earth at various times.