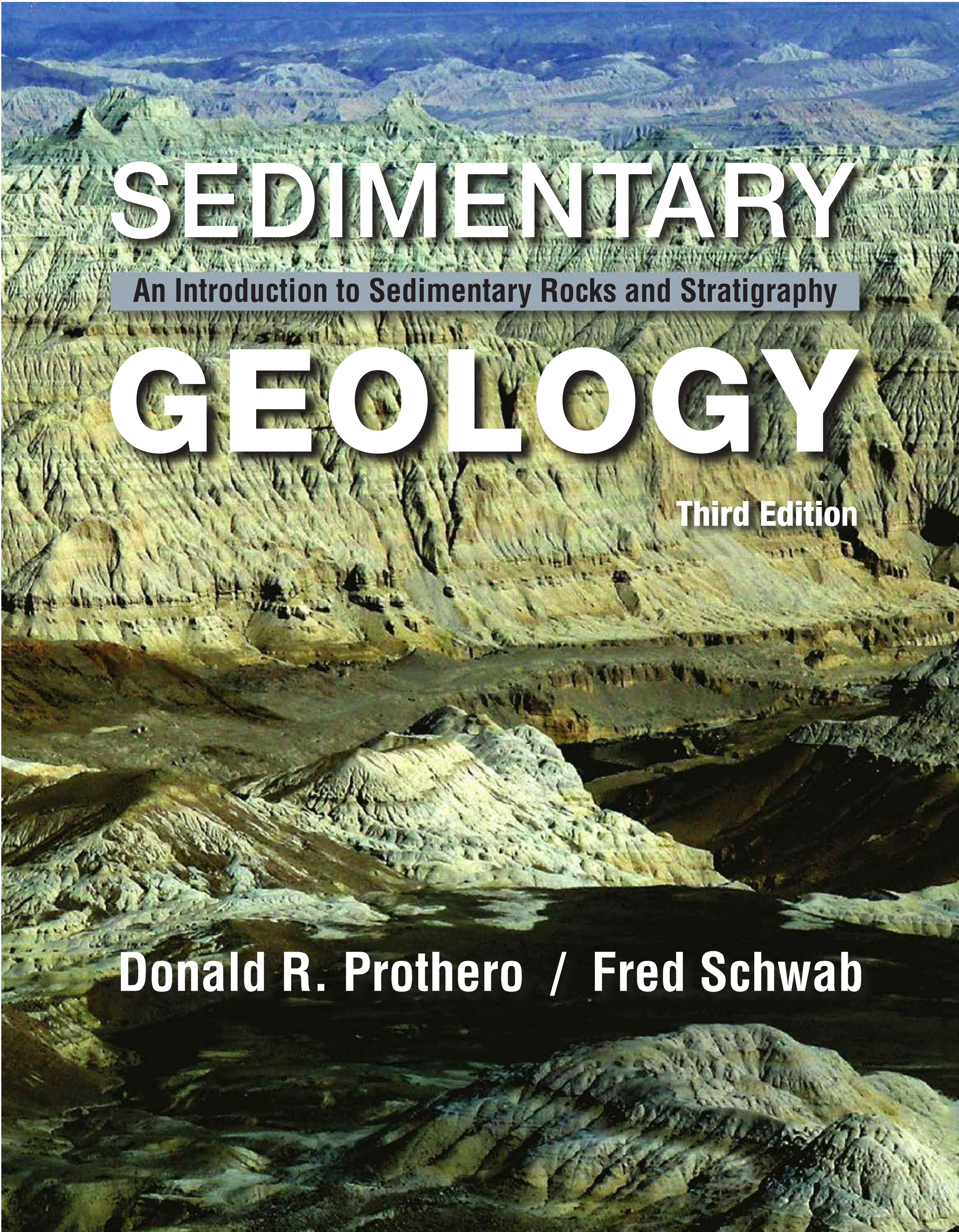
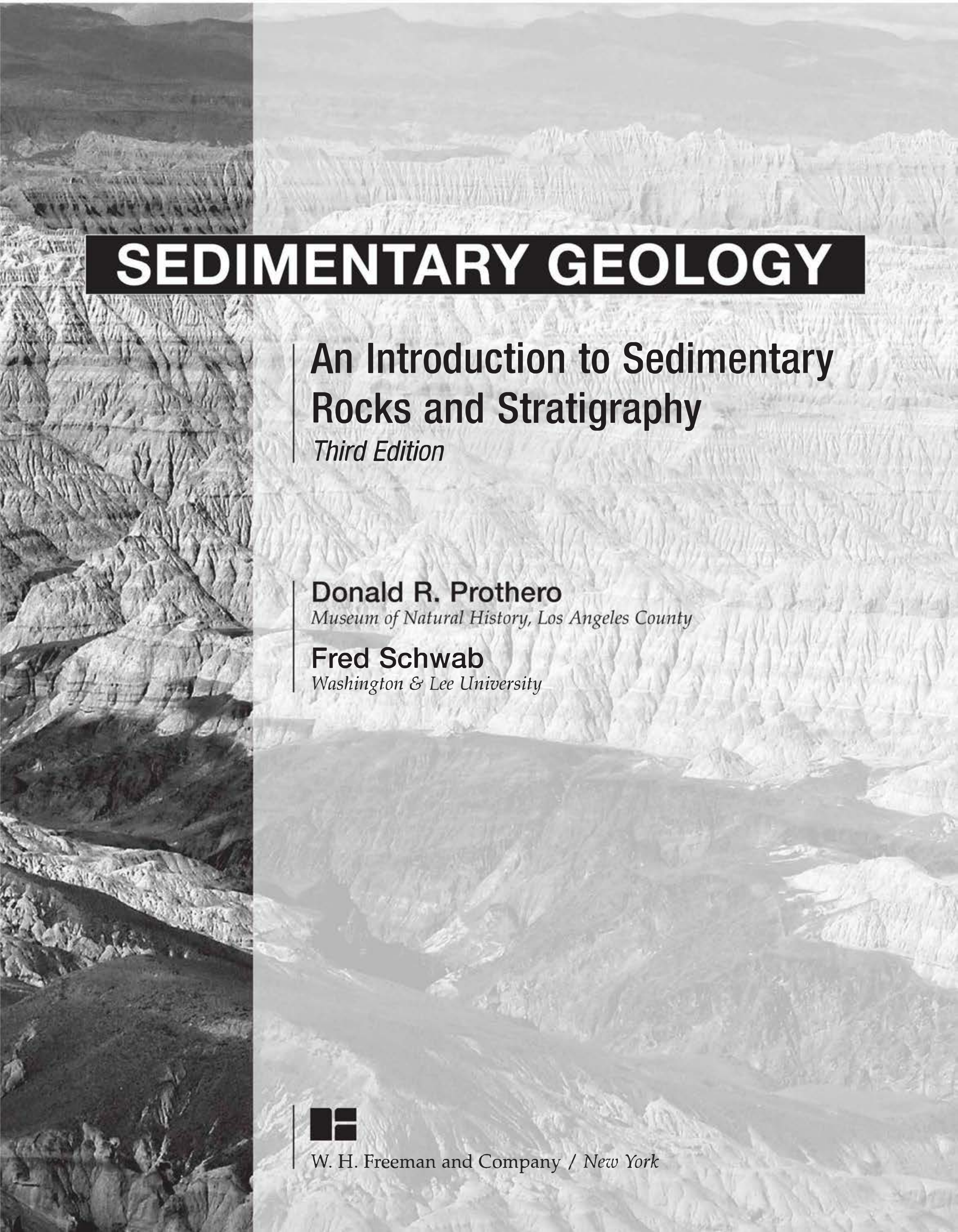


SEDIMENTARY GEOLOGY

An Introduction to Sedimentary Rocks and Stratigraphy

Third Edition

Donald R. Prothero / Fred Schwab



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An Introduction to Sedimentary Rocks and Stratigraphy

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Donald R. Prothero
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W. H. Freeman and Company / *New York*

To our wives, Teresa Levelle and Claudia Aarons Schwab, for their amazing patience and tolerance

Publisher: Jessica Fiorillo
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Illustrations: Norm Nason, Fine Line Illustrations, Pat Linse
Production Manager: Paul W. Rohloff
Composition: Progressive Information Technologies
Printing and Binding: RR Donnelley

Library of Congress Control Number: 2012951759

ISBN-13: 978-1-4292-3155-8
ISBN-10: 1-4292-3155-6

Printed in the United States of America

First printing 2013

W. H. Freeman and Company
41 Madison Avenue
New York, NY 10010
Houndmills, Basingstoke RG 21 6XS, England

www.whfreeman.com

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PREFACE

To the Instructor

OVER THE PAST THREE DECADES, WE have introduced many talented undergraduate students to sedimentary geology: in the classroom, in the laboratory, and in the field. The first and second editions of this book were a direct outgrowth of our earlier experiences, and this third edition builds on the strong success of those earlier editions. This text is written especially for undergraduates and is designed specifically for use in a first course in both sedimentary rocks and stratigraphy. We emphasize general principles that students need to master. We intentionally avoid overwhelming students with details, exceptions, or overly specialized examples. Coverage is deliberately weighted in favor of the varieties of sedimentary rocks such as conglomerate, sandstone, mudrock, limestone, and dolostone that make up 99% of the sedimentary rock column. There is a general summary of aqueous geochemistry because a clear understanding of weathering and chemical sedimentation requires it. Similarly, principles of fluid mechanics are covered so that sedimentary structures, sediment entrainment, and sediment deposition can be adequately understood. Not every detail and nuance of the stratigraphic code is discussed, but a reading of the text will provide students with a good grasp of the relative strengths and weaknesses of various methods of dating and correlation.

We believe that this new edition is a significant improvement over the first and second editions. Those editions enjoyed remarkable success, perhaps because they so fortunately and correctly targeted the market. Why is this edition better? First of all, a number of users kindly sent us various suggestions about what needed improvement, culling, or expansion. The occasional imprecision was eliminated. We expanded coverage in some areas, such as petroleum geology and chemostratigraphy. We tried to do a better job of understanding and interpreting the sedimentary rock record in the context of an Earth that has evolved through time.

Sedimentary Geology assumes only a single-course background in introductory geology. Additional exposure to historical geology, mineralogy, and petrology is helpful but not crucial. We review or introduce relevant concepts from these fields, as well as from physics, chemistry, and statistics. The level of detail reflects our experience with undergraduate readers and the preferences of instructors. For example, there is little detailed discussion of how rock and mineral components can be discriminated optically. This would require too much space and time, and is probably more adequately presented in published manuals selected by the individual instructor. We recognize that most faculty prefer to design their own laboratories and field trips in order to best capitalize on their own local geology and their personal passions and expertise. We also have not covered to any substantial degree topics like well-logging and subsurface analysis. Undergraduates can better acquire these specialized skills on the job, especially if their understanding of sedimentary geology rests on a strong solid base.

The nucleus for the book is Prothero's 1990 textbook *Interpreting the Stratigraphic Record*. Most of the chapters from that book were substantially modified, updated, and shortened. Schwab added new chapters that emphasized the sedimentary rock record expressly for a comprehensive volume that would cover both stratigraphy and sedimentary rocks. We have worked together harmoniously and diligently in order to blend our writing styles. Style, approach, and pedagogy are, we hope, cohesive and uniform. This third edition of *Sedimentary Geology* builds on the strengths of the first and second: it is intentionally balanced, yet current. Any success earned by this text deservedly belongs to the many bright, well-motivated students who over the years were never shy about letting us know what works and what doesn't. Finally, we hope this text conveys to the students who read, and we hope, enjoy, just how fascinating the world of sedimentary rocks can be.

To the Student

We revised this textbook to help you understand the Earth's sedimentary rock record. The book's tone is intentionally conversational and, we hope, reader-friendly. This new edition incorporates a number of suggestions that readers and users of the first and second editions sent our way. A number of relatively minor errors that appeared in the second edition have been eliminated. We've expanded coverage in a few areas in response to readers' demands.

For example, there is far better coverage of petroleum geology and chemostratigraphy, a bit more emphasis on timely topics such as glacial sedimentation, the role of meteorite impacts on sedimentation, and the long-term secular greenhouse and icehouse states of our evolving planet.

We've also put together a reasonably comprehensive glossary of key terms from the text. Nomenclature and jargon typically get out of hand in any scientific discipline, and a concise but comprehensive glossary seemed the best way to keep the complex terminology of our field in perspective.

In addition, we've put together a list of interesting web sites relevant to the study of sedimentary geology at the end of most chapters.

We would like to share with you the reasons we became "soft rock" geologists and that compelled us first to write, and then rewrite, this text.

1. *Sedimentary geology is probably the most practical and valuable course in the undergraduate geology curriculum.* We live on a planet whose surface is dominated by sediment and sedimentary rocks. Geologists, regardless of interest or objective, will invariably encounter the Earth's sedimentary shell. One of the ultimate goals of geology is to decipher the terrestrial rock record. While igneous rocks and metamorphic rocks are historical "snapshots," they record only brief, short-lived episodes in Earth's history. It is the sedimentary rock record that acts as an almost continuous movie film of that history. The stratified record provides a rational, almost complete documentary record of our planet's history.

2. *A background in sedimentary geology is essential for most jobs in geology.* Most jobs in geology require some familiarity with the Earth's sedimentary rock record. This was more obvious in the middle to later twentieth century, when the energy business traditionally employed two out of three geologists. That figure has now been reduced to only one out of three geologists, but it is as true as ever that coal, oil, natural gas, and nuclear fuels are housed in stratified rocks. The newer, rapidly exploding areas of employment in environmental geology are primarily "soft-rock" based. A good third of all geologists today are environmental geologists. They seek water in sedimentary rocks, they're preoccupied with cleaning up air and water pollution, they fight to remediate damaged sites. What areas of specialty knowledge are important to the environmental sciences? Certainly aqueous geochemistry, fluid flow, and a knowledge of the temporal and spatial distribution of stratified rocks, precisely the areas with which sedimentary geologists are most familiar.

3. *Sedimentation and stratigraphy: conciseness, flexibility, and adaptability.* This book comprehensively covers two principal fields of sedimentary geology: sedimentary petrology and stratigraphy. Sedimentary petrology deals primarily with properties of sedimentary rocks (composition, texture, sedimentary structures), their classification, and nomenclature. Stratigraphy defines and describes natural bodies of rock (mainly, but not exclusively sedimentary rocks). Sedimentary petrologists focus particularly on how a rock forms, what it is derived from, and how the material was transported from the source and deposited in a particular setting (such as a delta, alluvial fan, submarine fan). Stratigraphers are obsessed by questions of rock age, fossil content, position in a succession, and correlation in time and space. Curricular modifications of the past decade or so have necessarily trimmed the undergraduate calendar markedly. A full-term separate course in sedimentation, followed by a second full-term course in stratigraphy, are no longer viable options in many cases. While this book can easily serve as a text for such a two-term classical approach, it has been intentionally designed as a solid base for a single course, multi-objective format.

4. *Sedimentary rocks: fascinating, intriguing, and fun!* We authors are the truly lucky ones. We've found a subject area that is both challenging and fun, and this book gives us a marvelous opportunity to share our excitement with you, to tempt you to come along with us and further explore this fascinating area of geology. We are rewarded monetarily for doing something we well might do for free—if we could afford it—because it's so entertaining to us. Untrained observers looking at a ledge of sandstone see simply an ordinary rock. A trained sedimentary geologist, on the other hand, sees a fascinating glimpse of ancient history. A hungry, carnivorous dinosaur scrambling up the banks of a meandering river formed as periodic flash floods deposited and grains eroded from lofty, granitic mountain peaks 20 kilometers to the east. Likewise, a simple block of limestone in a slab of building stone comes to life in the mind of a carbonate sedimentary geologist, conjuring up the image of an ancient tropical lagoon filled with bizarre, extinct marine plants and animals. And from the bluffs bor-

dering the Grand Canyon, where the casual tourist sees a photogenic stack of colored rock bands, the skilled stratigrapher sees a record of the ancient Earth that presents an intriguing challenge to decipher.

Acknowledgments

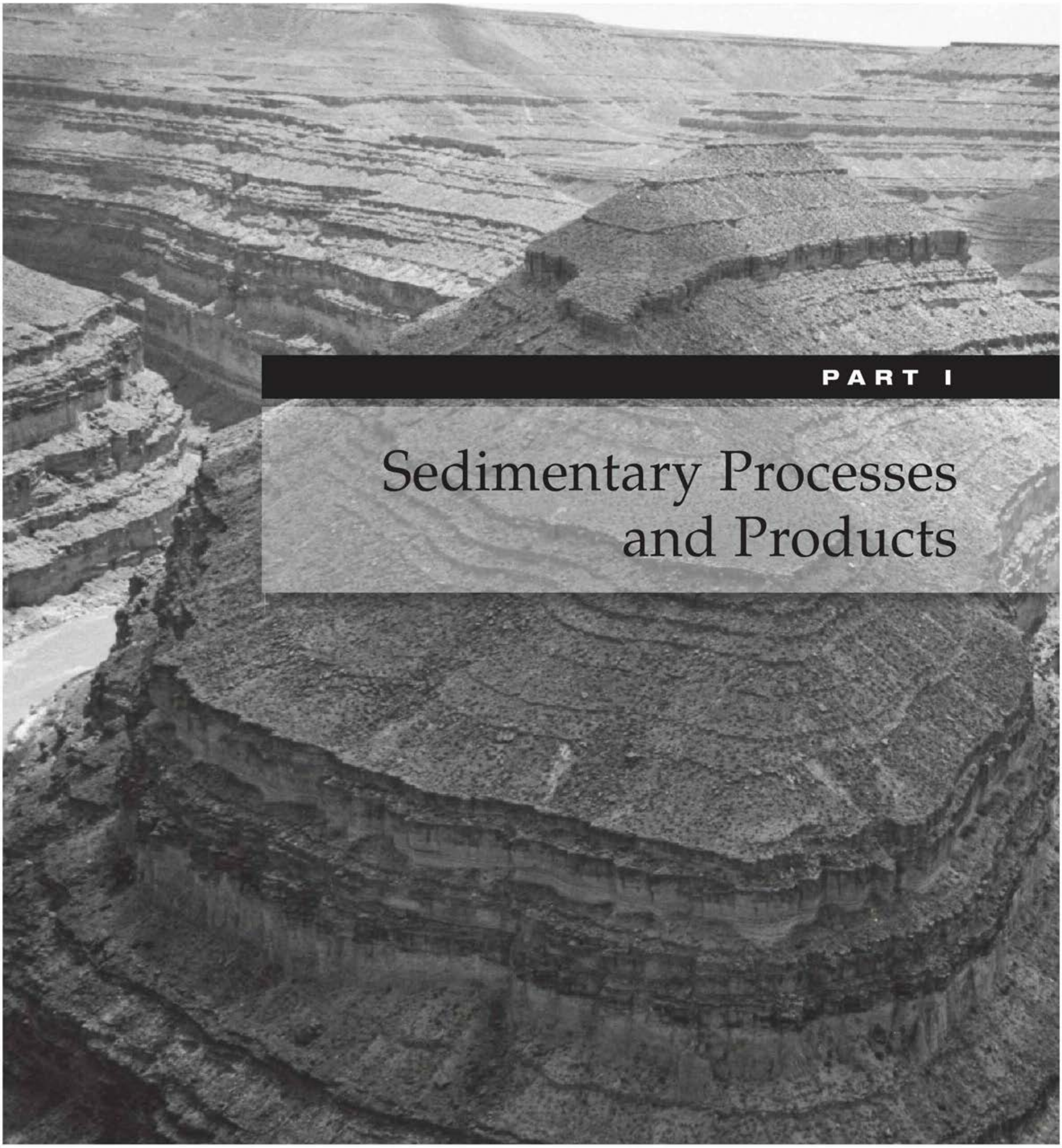
We thank Ray Ingersoll, Dewey Moore, Ray Siever, and Don Woodrow for reviewing substantial portions of the manuscript of the first edition. For reviewing the second and third editions, we thank Rónadh Cox, Williams College; K. Siân Davies-Vollum, University of Washington - Tacoma; Carol B. de Wet, Franklin & Marshall College; Zoran Kilibarda, Indiana University Northwest; David N. Lumsden, The University of Memphis; Fred Read, Virginia Polytechnic Institute and State University; Raymond Rogers, Macalester College; Bruce M. Simonson, Oberlin College; Mark A. Wilson, The College of Wooster. We thank all the reviewers acknowledged in *Interpreting the Stratigraphic Record;* much of what we learned from them influenced the new parts of this book as well as the old. We also thank the many colleagues who are acknowledged in the captions for the generous use of their photographs. Clifford Prothero also helped by printing many of the photographs used in this book.

Fred Schwab's work on this volume honors the three sedimentary geologists who most influenced him professionally. Bob Reynolds of Dartmouth College first introduced him to sedimentary rocks. Bob Dott of the University of Wisconsin showed him how much fun it can be to study them in the field and the classroom. Ray Siever of Harvard University, by example, steered him to a career largely devoted to understanding these fascinating deposits. Schwab also thanks John D. Wilson, President Emeritus of Washington & Lee University, and Ed Spencer, his department chairman for the past three decades, the two colleagues most responsible for nurturing an academic setting in which teaching, research, and writing mutually flourish. He also thanks his four favorite field assistants (and kids), Kimberly, Bryan, Jeffrey, and Jonathan, for continued support and encouragement during these efforts.

Our editors, Bill Minick and Heidi Bamatter, were a constant inspiration in bringing this project to completion. Many other people at W. H. Freeman and Company have contributed greatly to this book: Jennifer Bossert, project editor; Blake Logan, designer; Christine Buese, photo editor; Janice Donnola, illustration coordinator; and Paul Rohloff, production manager.

PART I

Sedimentary Processes and Products



Entrenched meanders cut through Permian sediments at Goosenecks of the San Juan River, Utah. Road in upper left corner shows scale. *(Courtesy of Dr. John Crossley.)*

CHAPTER

1

Sedimentary Rocks: An Introduction

WE SUBSTANTIALLY REVISED THE FIRST AND SECOND EDITIONS OF THIS BOOK while retaining our original objectives: to help you better understand (1) the processes that erode, transport, and deposit sediments (**sedimentology**); (2) the characteristics and origins of sedimentary rocks (**sedimentary petrology**); and (3) the complex distribution of the sedimentary rock record in space and time (**stratigraphy**). The first two areas are the subjects of Chapters 1 through 14. The field of stratigraphy is covered in Chapters 15 through 19.

Analysis of sedimentary rocks involves *description* and *interpretation*. Description is straightforward: "What can we see when we examine a sedimentary rock? What characteristics does it exhibit?" Interpretation is more subjective because it requires us to make inferences about the features described. The following case studies illustrate these contrasting approaches.

Sedimentary Rock Description: A Case Study

To describe any igneous, sedimentary, or metamorphic rock, it must be carefully examined in the field at outcrops, as a hand specimen, or by using thin sections and a petrographic microscope. Detailed description allows the distinguishing properties of any rock to be identified and characterized, and it is a necessary first step to understanding the rock's origin. Although the description of sedimentary rock properties is straightforward, it does require a sound understanding of the theoretical factors that control rock features.

Place a hand specimen of sedimentary rock in front of you and examine it as you read this chapter. What physical properties are visible and how can they be characterized?

Obviously, your response will depend on the sedimentary rock selected. Unfortunately, randomly choosing just any sedimentary rock specimen to illustrate the principles of sedimentary rock description might be a wasted exercise. For example, very fine grained, homogeneous rocks such as shale or rock salt reveal few distinguishing features. Describing them is a quick and easy task, but not a particularly enlightening one. The description of a coarser-grained sedimentary rock such as conglomerate (essentially lithified gravel) reveals much more about the rock's origin.

The mouth of the Russian River in northern California shows the process of sedimentation in a microcosm. Sediments are eroded from the weathered hills (at right) and are transported down the river into the sea (note the plume of muddy water at the mouth of the river). Once the sediments settle out of the water and are deposited, they can become sedimentary rock *(University of Washington Libraries, Special Collections, John Shelton Collection, Shelton 979.)*

In the following discussion, we describe a specific conglomerate (Fig. 1.1) that may differ from the sedimentary rock that you have before you. Our reference conglomerate is composed mainly of pebbles of pre-existing rocks and minerals. The technical term for chunks or broken fragments is **clasts** (from the Greek *klastos,* meaning "broken"). Although the term clast does not imply a specific size (grain diameter), a standardized clast size scale is used. For example, clasts with maximum diameters of 4 to 64 mm are pebbles. Our conglomerate also contains subordinate amounts of finer clasts with diameters from 2 to 1/16 (or 0.0625) mm; we call these *sand.* By convention, coarser pebbles are collectively lumped as **framework** and the finer sand as **matrix.** A third component, chemical **cement,** glues the sand and pebbles together to form a cohesive rock.

A short list of physical properties can be used to characterize a rock specimen: color, composition, texture, sedimentary structures, fossil content, and geometry or architecture. Table 1.1 summarizes these properties for our conglomerate specimen. Although this table is simplified, it also intentionally includes a few examples of the technical terminology (jargon) that can complicate straightforward scientific description.

FIGURE 1.1 Hand sample of a coarse, poorly sorted conglomerate with well-rounded cobble- and pebble-sized clasts. *(Photo by D. R. Prothero.)*

Color

Color is easy to describe and is one of the more striking properties of a sedimentary rock. Color usually reflects some aspect of the rock's composition. Bulk color can reflect the color of major mineralogical components. The net color of a conglomerate depends on the kinds of pebbles that compose it; for example, white quartz, pink feldspar, or speckled black and white volcanic rock fragments. The matrix might be a different color. Color can also be controlled by minor constituents such as the cement filling the spaces between pebbles and sand grains. Carbon-rich cements impart a black to dark gray color; iron-rich cements produce a reddish to orange color. Staining or weathering of a rock surface can also produce color changes. Despite these complications, color can be summarized straightforwardly. Color is not treated as an independent property, however, but as an aspect of sedimentary rock composition.

Composition

Although the composition of sedimentary rocks can be described in terms of chemistry or mineralogy, the more conventional method is mineralogical. Why?

First, determining the overall chemical composition of a sedimentary rock (routinely expressed in terms of major oxides) is a complex procedure requiring sophisticated technical equipment. Such procedures are impractical both in the field and for the rapid description of sedimentary rock samples in hand specimen.

More important, describing the composition of a sedimentary rock using bulk chemistry is misleading because it often obscures important genetic distinctions. For example, the chemical composition of a conglomerate composed of pebbles of quartz, a quartz-rich sandy matrix, and silica cement would closely resemble the chemical composition of a different type of sedimentary rock known as bedded chert. (Both would be approximately 99% SiO_2.) Bedded chert consists of interlocking crystals of chalcedony and microcystalline quartz. Many cherts form when fine-grained siliceous oozes made up of the shells of floating pelagic plankton recrystallize after being buried on the abyssal ocean floor. But quartz-rich gravel and intermixed sand may be deposited by surf and longshore currents along shorelines.

As another example, the chemical composition of a deposit of quartz pebbles cemented with precipitated calcium carbonate might mimic that of a limestone in which quartz sand grains are embedded.

TABLE 1.1 Physical Properties of Sedimentary Rocks (Specifics of a Representative Example; see Fig. 1.1)

Color	>2 mm (pebble framework): White to gray 2–$\frac{1}{16}$ mm (sand-sized matrix): White to brown to gray
Composition	>2 mm pebble- and cobblesize framework components: 95% quartz, 5% metaquartzite 2–$\frac{1}{16}$ mm sand-sized matrix: 90% or more monocrystalline quartz Cement (trace): Siliceous (chert and chalcedony)
Texture	Type: Clastic (as opposed to crystalline) Grain sizes (two distinct groupings): A coarser-grained pebble (4–64 mm) framework A finer, coarse sand (1–2 mm) matrix (Note: The presence of trace amounts of a presumably crystalline cement, not visible in Fig. 1.1, is implied by the cohesiveness of the conglomerate.) Variation in clast diameter: Moderately sorted Shape: Pebble and sand grains are subequant (an elongation to pebbles) Roundness: Pebbles: Very well rounded (ultrasmooth corners) Sand: Well rounded Grain surface textures: 90% of grains are frosted Fabric: Weak subparallel alignment of pebble long axes
Sedimentary structures	Thickly bedded; top of bedding surfaces marked by 1-cm-high symmetrical ripple marks; internally cross-bedded (troughs, 6 cm high) and laminated; abundant worm burrows
Fossil content	Scattered, poorly sorted, broken fragments of heavily ribbed, thick-shelled marine brachiopods (Devonian)
Sedimentary rock geometry	Blanket-shaped conglomerate bodies with constant thickness and length-to-width ratios of roughly 1:1 interbedded with laminated and cross-laminated well-sorted quartz arenite

Similar chemistries falsely imply identical rocks and similar modes of origin, when important differences exist. For practicality and accuracy, the composition of a sedimentary rock either at an outcrop or as a hand specimen is described in terms of mineralogy, not chemistry.

Characterizing the composition of a sedimentary rock in terms of the mineralogy (or petrology) of its components is quick and straightforward and provides a clearer insight into the rock's origin. Crude estimates of the relative abundance of major mineralogical components (for example, quartz, feldspar, micas, and rock fragments) can be made visually, especially if individual grains are large and distinct. Pebbles in coarse-grained rocks such as conglomerate can be counted and categorized. All the pebbles in a chalked-off area on the surface of an outcrop may be counted, or all the grains that make contact with a string placed across an exposure may be tabulated. Analyzing the mineralogical composition of finer-grained rocks such as sandstone and limestone requires point-counting of thin-sectioned samples with a petrographic microscope.

Texture

Texture refers to the size, shape, and arrangement of the grains that make up a sedimentary rock.

Texture Types There are two fundamentally different textural types: *clastic* and *crystalline.* Conglomerates exhibit mainly *clastic* texture. They contain individual fragments (clasts) of pre-existing rocks

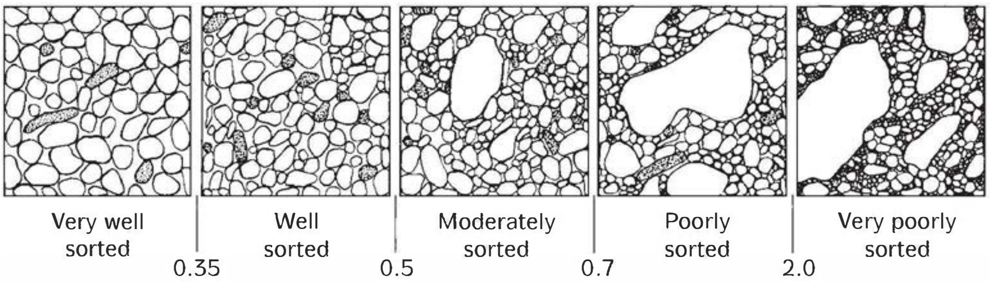


FIGURE 1.2 Standard images for visually estimating sorting. Numbers are sorting (standard deviation) values expressed in phi units that can be calculated using the standard formula shown in Table 5.3. *(After Compton, 1962: 214; by permission of John Wiley, New York.)*

and minerals that were transported and deposited as discrete particles. In clastic textures, grain boundaries touch one another tangentially. When grains are interlocked or intergrown, the texture is referred to as crystalline. Crystalline textures result from the in situ precipitation of solid mineral crystals. Most igneous rocks have crystalline textures that formed when magmas cooled and solidified. A single sedimentary rock can exhibit both clastic and crystalline texture. For example, although the coarser framework and finer matrix of conglomerate are clastic, the cement that provides the rock's cohesiveness is a low-temperature, crystalline-textured precipitate.

Grain Size Clasts or crystals are conventionally categorized by their maximum grain diameter. The diameter can be estimated visually, but accurate measurements require more sophisticated methods. It is often necessary to disaggregate (break apart) consolidated sedimentary rocks and separate grains on the basis of size by passing them through a nest of wire mesh sieves of different sizes. It is also practical to group grain diameters into categories called size classes; for example, boulders, pebbles, cobbles, sand, silt, or clay (see Table 5.1).

Variation in grain size in clastic sedimentary rocks is known as **sorting.** A well-sorted sedimentary rock shows little variation in grain diameter; a poorly sorted sedimentary rock exhibits large deviations from the mean grain size (Fig. 1.2).

Shape and roundness (angularity) are other aspects of texture that are particularly applied to clastic sedimentary rocks.

Shape Are the clasts equidimensional (*equant*)? Are they disklike sheets or flakes? Are they needlelike (prismatic) or elongate? Shape is often described in terms of **sphericity.** Equant grains (whether they be cubes or spheres) have high sphericity; those with one or more dimensions of unequal length have lower sphericity.

Roundness (Angularity) The roundness or angularity of grains refers to the sharpness or smoothness of their corners.

Clast shape and roundness can be categorized by using standardized grain silhouettes (Fig. 1.3). For conglomerates, this can be done visually in hand specimen, but the analysis of finer-grained clastic sedimentary rocks requires more complicated analytical methods. The shape and angularity of crystals in crystalline sedimentary rocks are not usually analyzed (with some important exceptions), because they provide little information about rock genesis.

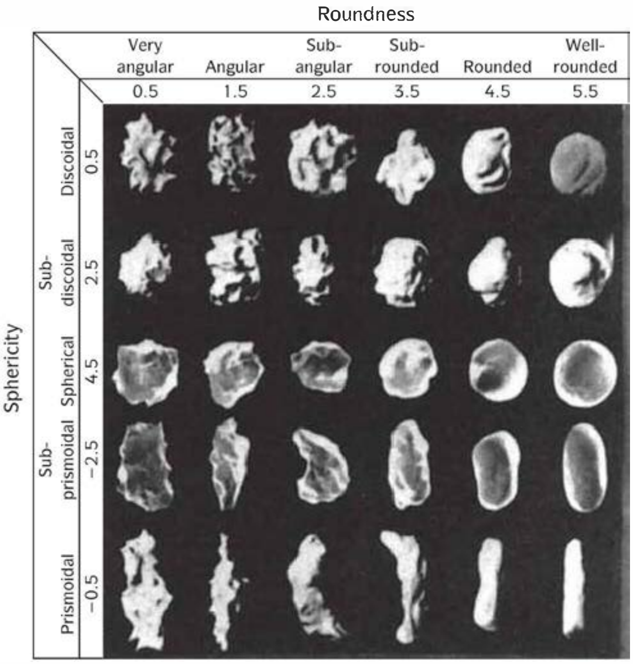


FIGURE 1.3 Standard images of roundness and sphericity for quantitative estimates of grain shape. *(Powers, 1953 by permission of American Geological Institute.)*

Even though shape and roundness are related (that is, an increase in roundness is usually accompanied by increased sphericity), they can be quite independent properties. An equant grain freshly broken out of a rock can be very angular (see Fig. 1.3), and many natural clasts that are disk-shaped or elongate can be very well rounded.

Other clastic textural features are discussed in more detail in later chapters. These features include (1) sand and coarser clast **grain surface features** such as crescent-shaped pits or a surface gloss or frosting; and (2) **textural fabrics,** specifically the common orientation of such alignable components as the long axes of pebbles or the short axes of flaky mineral fragments.

Fossil Content

Examination of a sedimentary rock often reveals organic remains, either hard parts (fossil shells and bones or their replacements) or such traces of organisms as tracks, trails, and burrows (**ichnofossils**). Fossil content can be characterized not only by the specific type of organic remains found but also by the characteristics of such remains (for example, whole or broken).

Sedimentary Structures

Some features of sedimentary rocks are best studied in outcrop; for example, sedimentary structures. These are large-scale, three-dimensional features of sedimentary rocks (discussed in detail in Chapter 4). The most common sedimentary structure is **stratification,** the bedding or layering exhibited by all sedimentary rocks. Primary stratification is a consequence of deposition of the clasts grain by grain over time and is originally horizontal. A single **sedimentation unit** (a band or layer of sediment of similar composition and texture deposited under consistent, almost identical conditions) can vary in thickness laterally and vertically.

Most other sedimentary structures can be classified in relation to stratification. Ripple marks, raindrop imprints, and mudcracks develop on the top of bedding planes; sole marks include a variety of structures developed on the base of stratification surfaces; cross-bedding and graded bedding occur within individual strata.

Sedimentary Rock Geometry

The geometry of a sedimentary unit is a large-scale feature of sedimentary rocks that may not be obvious in a single field exposure. The geometries or three-dimensional shapes of sedimentary rock bodies range from sheetlike blankets to elongate ribbons or shoestrings. Accurate description of sedimentary rock architecture requires excellent three-dimensional exposure to permit measurement of lateral variations in internal organization, thickness, and extent.

Summary

These properties, though not comprehensive, do include the essential descriptive aspects of sedimentary rocks. The properties are straightforward and can be recognized and described by a geologist with a trained eye using relatively unsophisticated analytical tools. With practice, the descriptive process becomes routine. No matter how unexciting, rock description is the essential first step in the analysis and interpretation of a sedimentary rock. Even by itself, description is useful because it sets out the criteria by which one sedimentary rock can be distinguished from another, a prerequisite for accurate classification, interpretation, and mapping.

Finally, the challenging task of description is simply the means to a more ambitious end: using these descriptive characteristics to *understand* and *interpret* the origin and evolution of sedimentary rocks.

Sedimentary Rock Interpretation: A Case Study

What do we really want to know about any sedimentary rock? What information can be inferred from each of the physical characteristics just discussed? We seek the answers to rather simple questions.

1. When was the sedimentary rock unit deposited and over how broad a region?
2. With what other rock units is the sedimentary rock contemporaneous?
3. From what kinds of source rocks were the sediments derived?
4. Where was that source located? Was it near or far from the depositional site, and in what direction?
5. Was the source a mountainous highland or an area of low relief?
6. How was the material transported to the depositional site from the area where it was weathered and eroded? Was it blown by the wind, bounced along the channel of a flowing river, moved by the surf and longshore currents, or carried by a sheet of slow-moving glacial ice?

7. In what kind of physical setting did the sedimentary rock form? Was it deposited by an ancient river delta system? Is it a lithified desert dune complex?

8. How have the color, composition, texture, and other physical properties of the sedimentary rock been modified in the time since deposition?

Answering these questions helps us understand the genesis of a sedimentary rock. Answers to such questions are formally embodied as *stratigraphy, provenance, dispersal, transporting agent, depositional setting, paleogeography, sedimentary tectonics,* and *diagenesis.* Figure 1.4 summarizes these interpretive aspects for a typical sedimentary rock.

Stratigraphy

Stratigraphy studies the distribution of stratified rocks through time and space. If an ultimate goal of sedimentary geology is to reconstruct the history of the Earth at various stages of its development, it is imperative to determine how widely scattered sections of the sedimentary rock record are temporally related (*correlation*). Very precise reconstructions of sediment source and depositional setting are of questionable value if they cannot be correlated correctly and tied to the standard geologic time scale. A precise description of the stratigraphy of a sedimentary unit includes its stratigraphic age (for example, Early Cambrian), and a detailed knowledge of the units with which it is correlated.

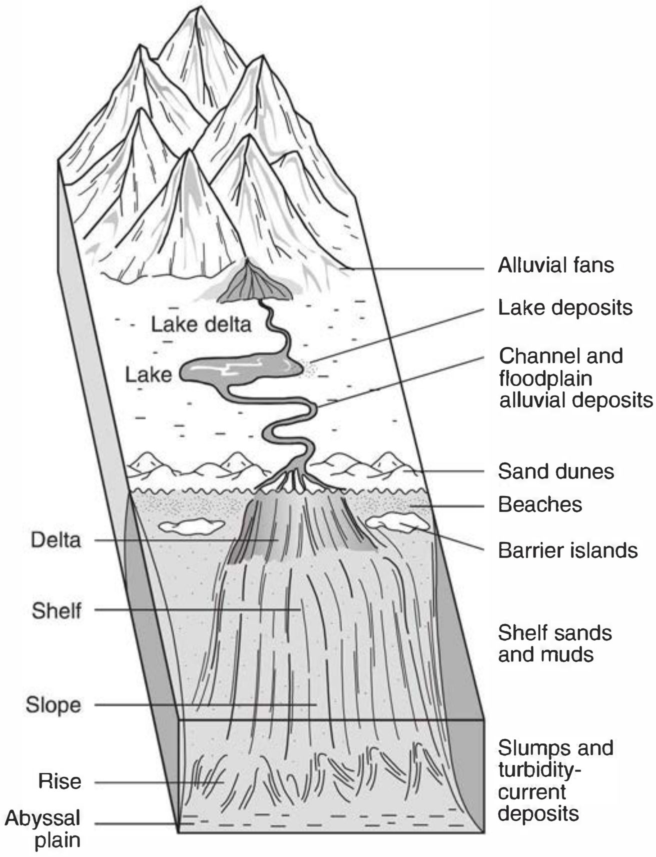


FIGURE 1.4 The downhill path of sediment transport and deposition. From weathered particles freshly eroded from the mountains to the depths of the ocean, various sedimentary environments are encountered. *(After Press and Siever, 1986: 301; by permission of W. H. Freeman and Company, New York.)*

Provenance

The term **provenance** is derived from the French verb *provenir,* "to come forth," and it refers to all aspects of the sources from which a particular sedimentary rock is derived. Of particular concern are the source area's composition, location, and topographic relief. What kinds of rocks made up the source area? Were they igneous, metamorphic, or sedimentary rocks—or perhaps a mixture of all three? Can the source areas be identified more specifically as granite or basalt, schist or marble, limestone or dolomite? Location includes both the distance to the source and the direction of the source. Source relief refers to whether the source was high (mountainous) or low. A precise description of provenance is the following statement: "This sedimentary rock was derived from a mountainous andesitic volcanic island arc located 100 km east of the depositional area."

Dispersal

Dispersal describes the pattern by which material is eroded from the source, transported away, and deposited elsewhere. The pattern of sediment transport and redistribution must be described precisely in terms of time, space, and mechanism. Such description requires a thorough understanding of both the transporting agent and the depositional setting. A paleocurrent dispersal system might be described as follows: "This sedimentary unit was transported from west to east down a series of subparallel submarine canyons etched into a broad, north-south trending continental shelf 200 km wide."

Transporting Agent and Depositional Setting

These two aspects of a sedimentary rock are interrelated. The **transporting agent** is the mechanism responsible for moving a sedimentary component from where it was produced by weathering to where it was finally deposited. Common transporting agents are river (fluvial) systems, submarine turbidity flows, slow-moving continental glacial ice sheets, and episodic windstorms. **Depositional setting** or environment can be described piecemeal in terms of such factors as salinity, water depth, water temperature, and current flow velocity. It is better summarized in terms of a geomorphic unit (that is, a three-dimensional landform) such as a delta, a tidal flat, or a terminal glacial moraine. This description provides us with a mental picture that conveys what that portion of the Earth looked like at the time and place pinpointed by the particular sedimentary rock in question.

Paleogeography and Sedimentary Tectonics

It is possible to reconstruct the **paleogeography** of a region—the areal distribution through time of the physical geography—by integrating inferences about provenance, dispersal, transporting agent, and depositional setting. Paleogeographic maps can be broadly based global or regional reconstructions showing the gross distribution of continental blocks, ocean basins, mountain belts, and continental lowlands. With finer focus, paleogeographic maps show mountain fronts, alluvial fan complexes, glaciated mountain valleys, and so on. The historical evolution of a region, regardless of scale, can be summarized as a series of sequential paleogeographic maps. It is crucial to understand **sedimentary tectonics**—the dynamic context in which a sedimentary rock is deposited (for example, the area along a continental margin bordering an active convergent plate margin). Sedimentary rocks are arguably the most useful tools for reconstructing ancient plates and plate margins.

Diagenesis

Diagenesis is a comprehensive term for all changes (short of metamorphism) in texture, composition, and other physical properties that occur in a sedimentary rock after it is deposited as a sediment up until the time it is examined. Diagenetic processes of compaction, recrystallization, and cementation play a crucial role in converting sediment to sedimentary rock. They can also alter or obscure the original sedimentary rock texture, composition, color, and sedimentary structures, thus making it impossible to know what such properties were like originally. For example, a sandstone originally composed of roughly equivalent proportions of limestone and volcanic rock clasts might be altered long after deposition by acid groundwater percolating through the rock. Selective dissolution of all limestone clasts could produce a diagenetically altered end product containing no trace of a carbonate source rock.

Sedimentary Geology: Goals

Sedimentary geologists interpret provenance, dispersal, transporting agent, depositional setting, paleogeography, sedimentary tectonics, and diagenetic history. These interpretations are based on such properties as mineralogy and texture, which can be linked to these factors. It is crucial to understand which inferences can be based on texture, which on sedimentary structures, and so on. For example, fossil content helps fix the age of a sedimentary rock but implies nothing about source relief. Cross-bedding and ripple marks provide information about dispersal, depositional setting, and paleogeography, but they yield no information about rock age. Table 1.2 summarizes these various interpretive aspects of sedimentary rocks, linking each with the descriptive properties from which they are typically inferred. The discussions of major rock categories (Chapters 5, 6, 11, 13, and 14) include the physical characteristics of each and detail the linkage between their descriptive properties and their genesis.

Sediments and Sedimentary Rocks: Major Categories

Many sedimentary rocks are produced by a cycle of weathering, transport, deposition, and diagenesis of sediment (Fig. 1.5), each stage of which puts its own imprint on the sediment. (Particles of sediment can also originate from explosive volcanism or by organic precipitation.) Weathering is the destructive breakdown of pre-existing igneous, metamorphic, and sedimentary rocks by physical disintegration and chemical decomposition. It occurs at or near the Earth's surface, where pre-existing rocks at relatively low temperatures and pressures come into contact with water (the hydrosphere), living organisms (the biosphere), and the atmosphere. Weathering generates a variety of products: soil, disaggregated rock debris, and constituents dissolved in groundwater and runoff. The removal of weathering products from the weathering site constitutes **erosion. Transportation** is the movement of weathering products (either as discrete fragments of pre-existing material or as components dissolved in water) from the sites where they are produced to the sites where they accumulate.

TABLE 1.2 Sedimentary Rock Genesis: The Relevant Database

Interpretive Property	Best Indicators
Stratigraphy: Unit age, distribution, and correlative rock units	Fossil content
Provenance:	
Source area composition	Sedimentary rock composition
Source area location	Primary directional structures Regional variations in texture and thickness
Source area relief	Sedimentary rock composition Texture Geometry
Dispersal	Primary directional structures Texture Geometry
Transporting agent and depositional setting	Texture Sedimentary structures Geometry Fossil content
Paleogeography and sedimentary tectonics	Stratigraphy Provenance Dispersal Transporting agent Depositional setting
Diagenesis	Composition Texture Sedimentary structures

When transportation ends, **deposition** of sediment begins. Sedimentary rocks are produced by burial, compaction, recrystallization, and cementation (collectively, **lithification,** the making of sedimentary rocks from sediment).

Because weathering products are transported, deposited, and ultimately transformed into sediment and sedimentary rocks in distinctive ways, three broad categories of sedimentary rock are recognized: detrital, biogenic, and chemical (Table 1.3). A fourth category, "other sedimentary rocks," accommodates sedimentary rock types generated by processes other than weathering.

Nature is seldom as neat and tidy as the classification schemes scientists devise to organize natural phenomena. Many sedimentary rock types straddle these boundaries and do not fall into a single pigeonhole. The biochemical category, for example, includes two varieties of rock called sedimentary ironstone and iron formation. Neither is exclusively produced by organisms; some varieties are produced by inorganic chemical processes. Bearing in mind that classification is artificial, what are the salient characteristics of each major grouping?

Detrital sedimentary rocks consist mainly of clasts of pre-existing rocks and minerals that have been physically transported and deposited as discrete fragments. Because they represent material eroded from the Earth, they are also termed **terrigenous.** They are produced when transporting agents such as running water or the blowing wind pick up (entrain) soil and loose rock debris and transport the clasts away from the weathering site, eventually depositing them as layers of gravel, sand, or mud. Terrigenous material can also be subdivided into (1) **extrabasinal** grains weathered and eroded from sources outside the depositional basin into which they were later deposited; and (2) **intrabasinal** grains eroded and reworked from

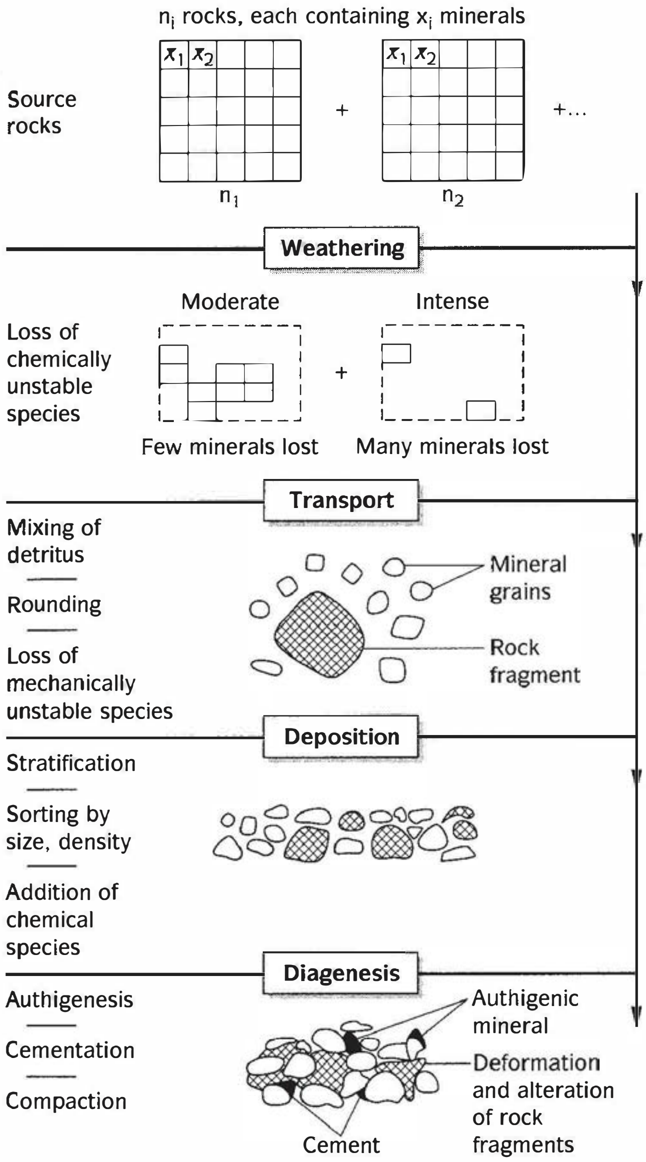


FIGURE 1.5 The sedimentary cycle of sandstone. Through the processes of weathering, transport, deposition, and diagenesis, the weathered fragments of pre-existing rocks are turned into sedimentary rock. *(After Pettijohn, Potter, and Siever, 1987: 26; by permission of Springer-Verlag.)*

essentially contemporaneous materials deposited within the same basin. Terrigenous material consisting mainly of bits and pieces of quartz and other silica-rich minerals is called **siliciclastic.** Consolidation (lithification) of detrital sediment (most of which is terrigenous siliciclastic material) by compaction and cementation transforms it into sedimentary rock. Individual subcategories are distinguished based on predominant clast size (particle diameter). In conglomerates, a large proportion of fragment diameters exceed 2 mm. In sandstone, most clasts range from 2 to 1/16 (or 0.0625) mm. Mudrock consists of clasts with diameters of less than 1/16 mm.

Biogenic, biochemical, or **organic sedimentary rocks,** as the names imply, are formed by organic activity. Although organisms play the predominant role in creating these rocks, they do so in a variety of ways. In some cases, organic metabolism simply modifies the chemical environment and sediment is precipitated directly from saturated fresh or ocean water. Alternatively, organisms precipitate carbonate, phosphate, and silicate minerals to manufacture their shelly and bony components. Plants concentrate carbonaceous material directly by photosynthesis as they manufacture plant tissue, which becomes the raw material of coal. Other types of carbonaceous sedimentary deposits such as oil shale (kerogen) and petroleum (mainly methane and paraffins) are generated by bacterial activity.

Complicating the premise that this category is completely distinct from clastic sedimentary rocks is the fact that after biochemically and organically precipitated minerals are formed, they typically experience a brief period as physically transported intrabasinal grains (allochems and intraclasts) before becoming consolidated sedimentary rocks.

Subdivisions of this category are distinguished on the basis of overall sedimentary rock chemistry. The three main varieties are (1) carbonate rocks (limestone and dolomite), (2) silicate rocks (chert), and (3) phosphate rocks.

Chemical sedimentary rocks result from the nonorganic, physicochemical precipitation of solid crystalline minerals as the dissolved constituents reach saturation. The best examples of chemical sedimentary rocks are layered evaporite sequences composed of anhydrite, gypsum, and halite (rock salt) that grow from brines that develop as seawater evaporates. Precambrian iron formations and Phanerozoic ironstones also fall within this category, although such deposits may also be produced by organisms.

Other sedimentary rock types consist of various sedimentary rocks whose origin is unrelated to weathering. Nevertheless, most share the clastic (fragmental) textures and variations in clast size that characterize sediments generated by weathering. **Pyroclastic** sedimentary rocks, like volcaniclastic terrigenous sedimentary rocks weathered from volcanic source rocks, contain abundant volcanic glass shards and rock fragments but are produced by explosive volcanism rather than weathering. **Meteoritic** clastics are created when extraterrrestrial bodies impact the crust at high velocity. **Cataclastic** sedimentary rocks are coarse-grained, angular sedimentary deposits of restricted extent. Some are produced by gravity-driven movements such as

TABLE 1.3 PRINCIPAL SEDIMENTARY ROCK CATEGORIES

1. **Siliciclastic (epiclastic, detrital, or terrigenous) sedimentary rocks**

Genesis: The physical disintegration and chemical decomposition of pre-existing rocks generates fragments of rocks and minerals (termed clasts, regardless of size). Clasts are picked up and transported as discrete particles by moving bodies of water, wind, and ice as well as by various kinds of gravity-induced movements. Deposition occurs on a particle-by-particle basis as transporting agents slow, stop, or melt.

Siliciclastic sedimentary rocks are further subdivided on the basis of principal clast size into conglomerate and breccia, sandstone, and various types of mudrock (claystone, siltstone, mudstone, and shale).

2. **Biogenic, biochemical, or organic sedimentary rocks**

Genesis: Physical disintegration and chemical decomposition of pre-existing rocks and minerals generate chemical components dissolved in runoff and groundwater. This dissolved material is transported into standing bodies of water (playas, lakes, the ocean), where it is extracted directly or indirectly by organisms and precipitated as solid, crystalline minerals.

Biogenic, biochemical, or organic sedimentary rocks are further subdivided on the basis of their principal chemical component. Major categories are carbonate rock (limestone and dolostone), chert (silicate rock), and phosphate rock.

3. **Chemical sedimentary rocks**

Genesis: Physical disintegration and chemical decomposition of pre-existing rocks generate chemical components dissolved in runoff and groundwater. This dissolved material is transported into standing bodies of water (playas, lakes, the ocean), where it is precipitated largely by purely chemical, inorganic processes.

The principal purely chemical sedimentary rock type is evaporite. Precambrian banded iron formations and Phanerozoic ironstones can be tentatively placed here, although they can probably just as easily be categorized as biogenic, biochemical, or organic sedimentary rocks.

4. **Other sedimentary rocks**

Genesis: This category includes all clastic sedimentary rocks that are produced by processes other than the physical and chemical weathering of pre-existing rocks.

The major varieties of this group of sedimentary rocks are subdivided on the basis of the mechanism by which the clasts are produced. Principal types include pyroclastics (generated by explosive igneous activity), meteoritics (produced by the impact of extraterrestrial bodies), and cataclastics (related to collapse or tectonism).

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landslides. Others form when the roofs of caverns (produced by groundwater solution) collapse, creating collapse (solution) breccias. Still others are generated along fault and fracture zones and where sedimentary rocks crumple and fragment as they are folded.

The Earth's Sedimentary Shell

Thickness, Volume, and Distribution

Most of the solid Earth consists of igneous and metamorphic rocks (typically 90% to 95% of the upper 16 km or 10 miles of the crust). Table 1.4 and Fig. 1.6 summarize the extent of exposure, the volume, and the mass of Earth's sediment and sedimentary rock shell.

Most of the surface of the solid Earth is either sediment or sedimentary rock! Ignoring surface soil cover (the raw material of sediment), almost the entire surface of the Earth (approximately 90%) is covered with sediments or sedimentary rocks. Roughly three-fourths of Earth's *land area* (30% of the surface area) is mantled with a relatively thin (thicker in mountain systems) veneer of sediments, sedimentary rocks, and metasedimentary rocks. Across the three-fourths of Earth's surface that is under water, sediments are almost everywhere. Most of the continental shelf, slope, rise, and deeper ocean basins are mantled with sediment. Igneous rocks are restricted to the crest of the mid-ocean ridge-rise system and marginal volca-

TABLE 1.4 Various Estimates of the Relative Distribution of Sedimentary Rocks

Relative abundance of sedimentary rocks (Pettijohn, 1975)
Based on surface area exposure
Areas above sea level 75%
Areas below sea level 25%
Based on volume (as a percentage of upper 16 km of the solid Earth)
Sedimentary rocks 5%
Igneous and metamorphic rocks 95%

Sediment–sedimentary rock shell compared to the overall crust and mantle (Ronov and Yaroshevsky, 1969)

	Volume (millions of km^3)	Mean Global Thickness (m)
Sedimentary rock shell, direct measurement	400–1,000	800–1,000
Sedimentary rock shell, chemical methods	1,000–2,000	1,000–2,000
Continental crust	62,100	40,000–70,000
Oceanic crust	26,600	6,000
Total crust	89,700	6,000–70,000
Total mantle	898,000	2,900,000

Thickness and volume of the sedimentary rock shell in various tectonic provinces

	Volume (millions of km^3)	Mean Thickness (m)
Poldervaart (1955)		
Deep oceanic regions (trenches and abyssal plain)	80.4	300
Cratonic platforms	52.5	500
Young (post-Precambrian) fold belts	126.0	5,000
Suboceanic regions (continental shelves)	372.0	4,000
Total volume	630.9	
Ronov and Yaroshevsky (1969)		
Oceanic regions	120	400
Subcontinental crust (shelf and rise areas)	190	2,900
Cratonic platforms	110	1,800
Phanerozoic fold belts	390	1,800
Total volume	940[a]	10,000

[a] Includes 10% volcanics.

nic arcs. Any extraterrestrial field geologist landing on Earth for an initial survey would need this textbook, rather than texts dealing with igneous or metamorphic rocks.

This extensive surface exposure stands in sharp contrast to the small *volume* of sediments and sedimentary rocks compared with the volume of igneous and high-grade metamorphic rocks. Adjusting for topographic differences within the crust, only about 5% to 10% of the volume of the outermost, 16-km-thick, solid terrestrial shell is sediment, sedimentary rock, and metasedimentary rock. Although this value can be estimated in several ways, all suggest that if Earth's sediment and sedimentary rock shell were

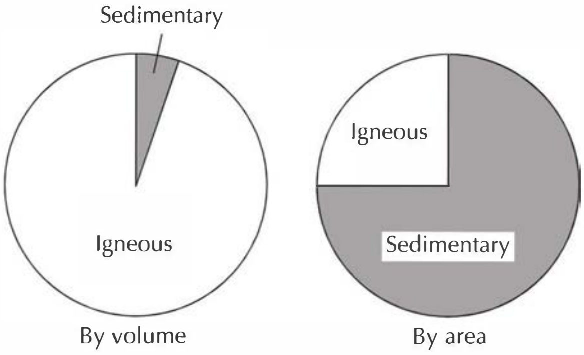

FIGURE 1.6 Relative abundance of igneous and sedimentary rocks in the crust of the Earth. *(Data from Clarke, 1924: 34.)*

spread around the globe as a uniformly thick carpet, its thickness would total only 800 to 2000 m.

The overwhelming areal exposure of sedimentary rocks in contrast with their limited volume underscores the position of Earth's sediment and sedimentary rock shell as an outer envelope of solid material concentrated at or near the interface of the hydrosphere, biosphere, atmosphere, and lithosphere. This is the logical consequence of the rock cycle (or system), the process by which the different rock types are transformed into one another. Weathering—the combination of physical and chemical processes that produces the raw material of sediment—and erosion—the process that leads to sediment transportation and deposition—can occur only near Earth's surface. And any sediments or sedimentary rocks carried below the shallow, near-surface zone of weathering and erosion will become metamorphosed or melted by the increased temperature and pressure at depth, which effectively removes them from the sedimentary rock inventory.

How are these data on sedimentary shell area, thickness, and volume determined?

Direct Measurement Areal exposures of sediments and of igneous, metamorphic, and sedimentary rocks are directly measured from maps showing bedrock geology and surficial geology of the continental blocks and ocean basins. Subsurface maps compile thickness data derived directly from drill holes or indirectly from reflection and refraction seismology. Table 1.4 compares variations in overall thickness of the sediment–sedimentary rock package in different regions; for example, continental cratons versus continental shelves. The total sedimentary rock volume, determined by combining estimates of surface area with the thickness of the sediment–sedimentary rock column, yields a globe-girdling sedimentary rock shell between 800 and 1000 m thick!

Geochemical Measurement The total volume of the sedimentary rock package can also be determined by comparing the chemistry of seawater, sedimentary rocks, and Earth's crust (Clarke, 1924). The procedure is crudely analogous to determining how much of a solid powdered dye must be dissolved in a beaker of originally clear water of known volume to bring it to a measurable tint.

Estimates based on chemistry require two pieces of data: (1) the overall abundance of a specific component (typically sodium, potassium, or calcium) dissolved in seawater (stated as a percentage); and (2) the percentage abundance of that constituent in the source rocks from which it is ultimately derived (via chemical weathering).

For example, if the present volume of seawater were spread about the Earth, it would generate a global sea roughly 1 km deep. Seawater contains 1.14% sodium. The average granite contains 2.83% sodium. If one assumes a hypothetical granitic continent 16 km (10 miles) thick as the source of sodium dissolved in seawater, the resulting ratio ($1 \text{ km} \times 1.14\%/2.83\% \times 16 \text{ km} = 1.14/45.28$) suggests that the total sodium contained in seawater requires the dissolution of only about 1/35 (45.28/1.14) of the 16-km-thick granitic continent, or 450 to 500 m—by inference equal in thickness to the total terrestrial sedimentary shell. This figure must be increased by a factor of one-third (to roughly 750 or 800 m), because sedimentary rocks typically contain 0.9% sodium (in other words, only two out of every three sodium ions remain in seawater).

Various independent studies, using a wide variety of dissolved components and different kinds of potential source rocks, yield other results. The thickness of a globe-girdling sedimentary shell, however, straddles a narrow range from 800 to 2000 m.

The fact that these contrasting methods yield totals that differ only by as much as a factor of roughly two suggests that the figure is accurate. The higher total from the chemical approach reflects the recent conclusion by some geologists that considerably more weathered sodium (or potassium, or calcium) exists and either is incorporated into undiscovered (or destroyed) evaporite deposits or is locked up in conventional sandstone and mudrock.

The Role of Weathering, Sedimentation, and Recycling in Continental Crustal Evolution

Weathering, erosion, and sedimentation may have played significant roles in the conversion of primitive Archean basic or ultrabasic volcanic arcs and protocontinents into the granitic continents that exist today. For example, Taylor and McClennan (1985) argue that weathering and sedimentation promote chemical differentiation in a variety of ways. Sedimentary rock sequences rich in continental crustal components—such as silica (SiO_2) in quartz-rich sandstone and potassium (K_2O) in feldspar-rich alluvial fans filling continental rift valleys—are seldom returned to Earth's interior via subduction, because they rarely accumulate in trenches and on the abyssal seafloor. Instead, they tend to be permanently incorporated into continental blocks, enriching the crust in SiO_2 and K_2O.

How can chemical differentiation via weathering and selective fractionation of components during transport and deposition be effective in light of the almost trivial volume of the sedimentary rock shell compared to that of the overall crust and mantle? As Table 1.4 shows, a global sedimentary rock shell 1000 to 2000 m thick (a volume of 500 to 1000 million km^3) (Pettijohn, 1975) is only about 1/90 of the total crustal volume (90,000 km^3) and as little as 1/1000 of the volume of the mantle!

Surprisingly, the total volume (or mass) of sediment generated over time might greatly exceed the volume or mass of Earth's existing sedimentary rock shell! If, as many geologists contend, much of Earth's sedimentary rock shell has been recycled—that is, repeatedly weathered, eroded, retransported, and redeposited—the total volume of sediment might greatly exceed the present sedimentary rock volume. For example, 100 km^3 of sediment eroded from a block of granitic crust—deformed, uplifted, weathered, eroded, and redeposited as a second, entirely recycled 100 km^3 of sediment—represents a total volume of sedimentation of 200 km^3, double the actual volume of sediment or sedimentary rock that survives.

Considerable data exist to support this idea that the Earth's sedimentary shell is continually recycled.

1. Dissolved sodium presently enters the sea at a rate that is 40 to 50 times that necessary to account for all sodium now dissolved in seawater. This implies much faster rates of weathering and sedimentation than most geochemists concede (Gregor, 1968).

2. Detailed studies of the provenance of modern sediments in the coterminous United States show that most (79%) are weathered and eroded from sedimentary rocks rather than from igneous or metamorphic rocks (Gilluly, Reed, and Cady, 1970).

3. Detailed analysis of basement rocks in the coterminous United States reveals that large volumes of Phanerozoic crystalline rocks, perhaps as much as 60 million km^3, are recrystallized from sedimentary rock sequences (Gilully, Reed, and Cady, 1970). If the Phanerozoic crystalline continental crust of the United States (1/20 of the global continental surface; the Phanerozoic is about 1/6 of geologic time) is typical, the total volume of global sedimentation must greatly exceed 1000 to 2000 million km^3.

4. The uneven volume of preserved sedimentary rock sequences as a function of age further supports massive recycling. If Earth's sedimentary shell results from the progressive accumulation of sediment over time, the volume of sedimentary rocks should vary systematically by age. For example, the volume of rocks of Precambrian age—from 4000 Ma (Megennia, or million years before present) to roughly 543 Ma—should greatly exceed that of rocks of Phanerozoic age (543 Ma to the present). Precisely the opposite is true (Garrels and Mackenzie, 1971). Even taking into account the probability that older sequences are less well exposed because they are covered or masked by younger sequences, only a fraction of very old sedimentary rocks remains (Fig. 1.7). Estimates show that the volume of Mesozoic and Cenozoic sequences (a 250-million-year time interval) roughly matches the volume of Paleozoic sequences (a 250- to 300-million-year time interval). The entire volume of sedimentary rocks of Precambrian age (representing a time interval roughly 10 times that of the Paleozoic) approaches the volume of all Phanerozoic (Paleozoic, Mesozoic, and Cenozoic) sequences.

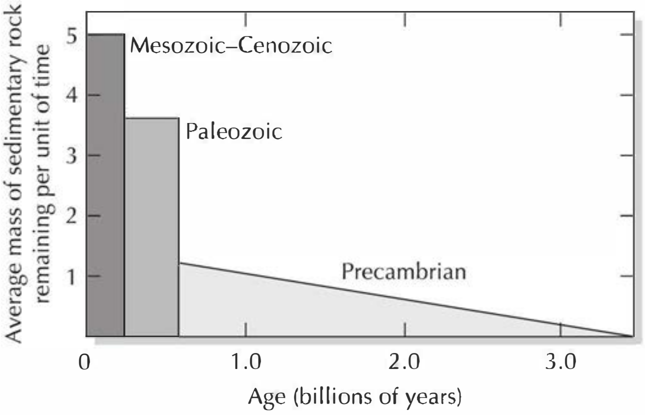

FIGURE 1.7 Relative existing volume of sedimentary rocks of differing ages plotted as blocks whose areas are proportional to rock volume. The comparatively small volume of Precambrian rocks (one-third of the total volume; 85% of geological time) supports the conclusion that the sedimentary rock column is repeatedly recycled. *(After Garrels and Mackenzie, 1971: 258.)*

Based on all these factors, many geologists argue that the volume of sedimentary rocks produced over geologic time exceeds the volume of Earth's sedimentary rock shell by a factor ranging from at least 5 or 6 to as much as 40 or 50 (Gilully, Reed, and Cady, 1970; Garrels and Mackenzie, 1971). At the very least, we must accept sediment recycling as an important phenomenon and concede the possibly significant roles of weathering and sedimentation as mechanisms for chemical differentiation of the crust from the mantle.

What Rock Types are Most Abundant?

Now that we have an idea of the total volume of the Earth's sedimentary shell, it would be interesting to know what proportion of that shell is siliciclastic sedimentary rocks, what proportion is biogenic, what proportion is chemical, and so on. There are several ways to arrive at an answer.

A count of the sedimentary rock specimens found in the reference sample collection of a typical sedimentary petrology laboratory would reveal that a large number of sedimentary rock types exist. A cursory examination of sedimentary rock exposures closest to that laboratory, however, would demonstrate that only a few sedimentary rock types are common. In fact, careful surveys show that the three most abundant sedimentary rock types, collectively totaling 90% to 95% of Earth's sedimentary shell, are carbonate (limestone and dolostone), sandstone, and mudrock (Table 1.5). Where do these estimates come from? What is their significance?

Estimating the relative abundance of major sedimentary rock types is done in two ways: (1) by direct observation and measurement of rock types visible in exposed sections; and (2) by numerically juggling geochemical data comparing the composition of major sedimentary rock types with the composition of their likely ultimate source rocks.

Stratigraphers studying sedimentary rock sequences on a centimeter-by-centimeter basis traditionally assign exposed rocks to a single rock type. Local exceptions aside, such rock types as banded iron formations and bedded evaporites are uncommon. Conversely, limestone and the various kinds of mudrock (shale, claystone, mudstone, and siltstone) are found almost everywhere. Table 1.5 lists the overall relative abundance of the three major rock types based on field description. The figures shown are an average of four compilations listed by Pettijohn (1975).

Table 1.5 also shows the mean percentage of major sedimentary rock types based on geochemical calculations (again, an average of four calculations that appear in Pettijohn, 1975). With this procedure, the average chemical compositions of mudrock, sandstone, and carbonate are numerically weighted so that their proportions generate a chemical composition identical either to granite or to some other igneous rock thought to be a reasonable ultimate source of sedimentary rocks.

The results from these two methods are intriguing. Both pinpoint the same three rock types and rank them in the same order. Which procedure is closer to the truth, and how can significant differences in detail between the two be explained? The values obtained using weighting of chemical compositions are probably more accurate. Rock types differ drastically in terms of their potential for preservation in the stratigraphic record. Most stratigraphers measure stratigraphic sections within continental platform areas or in the less deformed, less metamorphosed portions of mobile belts, which biases these estimates in favor of shallow-water sedimentary sequences such as quartz-rich sandstone, limestone, and dolostone. Finer-grained detrital mud is typically winnowed from these areas and transported

TABLE 1.5 Relative Abundance of the Major Sedimentary Rock Types

	Percentage		
	Carbonate	Sandstone	Mudrock
Direct measurement methods[a]	22	31	47
Geochemical methods[b]	8	13	79
Average of both methods	15	22	63

[a] Pettijohn, 1975: 20.
[b] Pettijohn, 1975: 21.

to deeper-water continental rise areas or onto the abyssal floor of the ocean basins. These areas are intensely deformed and metamorphosed and are consequently ignored by most stratigraphers. Traditionally, stratigraphers also ignore the significant amounts of mud in limestone, dolostone, and sandstone.

In any case, even though the final figures are not absolutely accurate, they serve a useful purpose. The amount of coverage by individual rock type in this book bears little relationship to the overall abundance of the rocks. For example, even though almost two-thirds of the sedimentary rock shell is mudrock, mudrocks are discussed in only one chapter. On the other hand, such rock types as evaporites and banded iron formations, which do not even appear in the inventory, together warrant a separate and distinct chapter. Why such discrepancies?

First, the coverage in this book is based not on relative abundance but on how successfully analyses of various rock types answer the questions posed earlier in this chapter. For example, questions about sedimentary provenance, dispersal, paleogeography, and tectonics can be answered with reasonable precision using sandstone data. Mudrocks provide little information about these characteristics. Second, certain types of sedimentary rock—for example, such organic deposits as coal and petroleum—are important economic resources. It is crucial to understand the origin and evolution of such deposits to improve our ability to find and exploit them. Finally, the formation of such rock types as bedded evaporites and banded iron formations requires unusual conditions that have existed rarely in geologic history. This fact explains the relative scarcity of these deposits compared to rocks such as mudstone, sandstone, and limestone, and it underscores the relevance of such lithologies as keys to our understanding of the Earth.

CONCLUSIONS

Despite its minor volume (as little as 1/20 of the upper-most 16 km of the solid Earth), we can learn much from the present sedimentary rock shell. It is important that we understand it for several reasons.

1. Sedimentary rocks are economically important. They contain the world's entire store of petroleum, natural gas, coal, and fertilizer. Sediments and sedimentary rocks constitute a principal reservoir for groundwater.

2. Sedimentary rocks are the primary repositories of the fossil record, on which rests our understanding of the evolution of life.

3. Because changes in the sedimentary rock record over time both reflect and control the character of the atmosphere, hydrosphere, and biosphere, understanding sedimentary rocks is crucial to deciphering the origin and evolution of these spheres.

4. The sedimentary rock record offers the clearest insights into the history and evolution of our planet. When properly understood and interpreted, sedimentary rocks allow us to reconstruct paleogeography beginning at the local scale. (Where were the mountains? Which way did river systems flow? In which direction did the shoreline run?) On a global scale, accurate interpretations of paleogeography, paleoclimatology, and depositional settings based on sedimentary rocks allow us to draw conclusions about the distribution of continental blocks and ocean basins as well as the origin and evolution of mountain systems.

5. Earth's history is a continuum of events whose character changes through time and space. Folds and faults—the structural features produced by orogenic episodes—and igneous and metamorphic rock complexes provide but fleeting glimpses of Earth's history. They are snapshots of what the Earth was like in past moments, whereas sedimentary rocks are analogous to motion picture film. This book aims to show how that film can best be developed, analyzed, and understood.

FOR FURTHER READING

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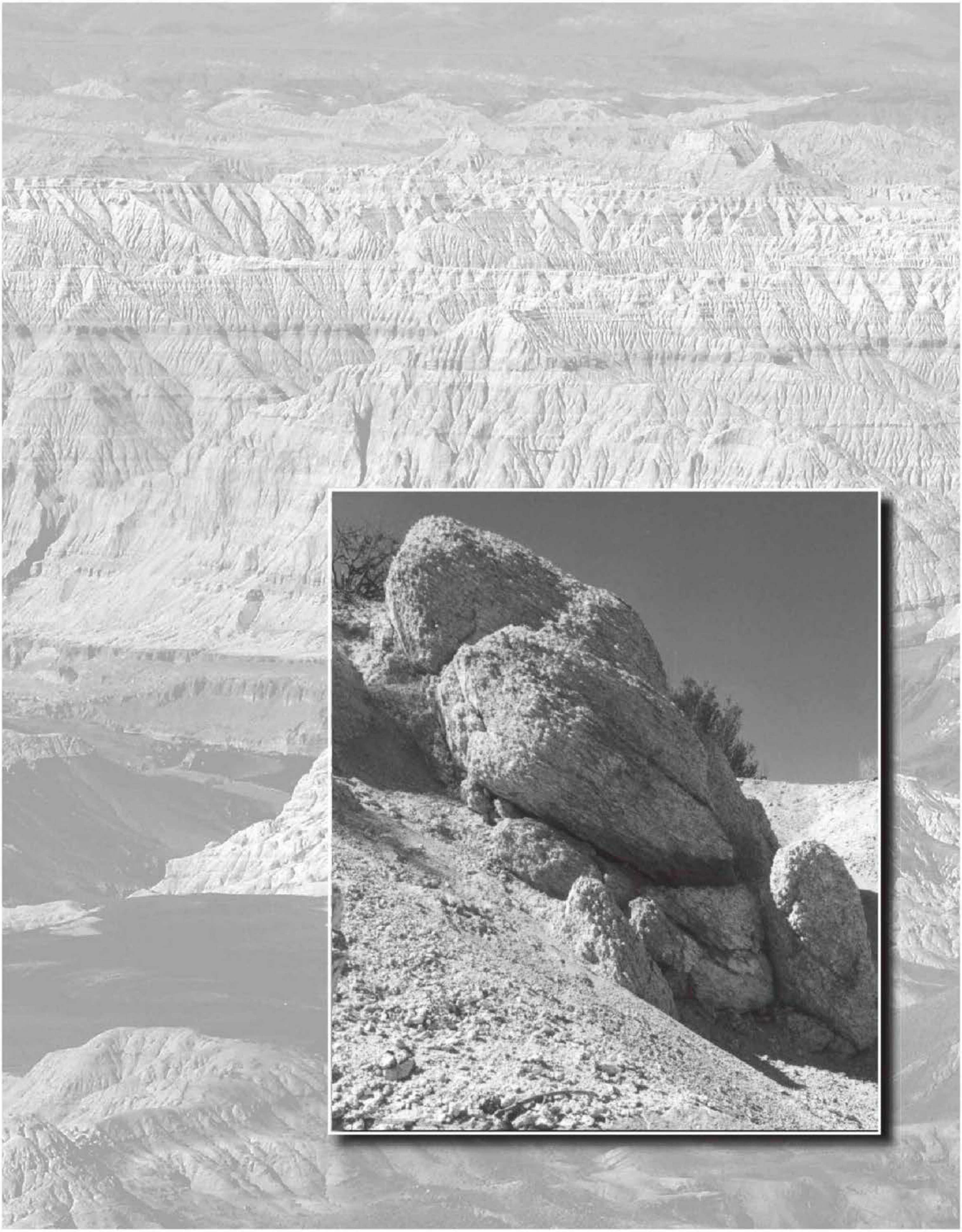

CHAPTER 2

Weathering and Soils

IF YOU STROLL AMONG THE OUTCROPS ON A TYPICAL GRANITIC BATHOLITH, such as the San Gabriel Mountains, you will notice that most of the rocks are granodiorites and quartz monzonites. In any given sample, the dominant minerals are feldspars, with plagioclases constituting 30% to 50% of the rock and K-feldspars typically ranging from 5% to 35%. In almost any igneous rock, quartz is typically only 5% to 10%, with a maximum of about 25% to 30% in a quartz-rich granite and none whatsoever in diorites or gabbros (or their volcanic equivalents, andesite and basalt).

But if you scramble down into the washes and ravines that drain the granitic mountains and examine the sand washing off those same rocks, you will see that quartz is already a much higher percentage of the sand and that feldspars are much less common. If you follow a mountain stream down to the ocean and look at the sand on the beach, you will find that nearly all the sand is quartz and that feldspars are relatively rare. In most beach sands, quartz may be 80% to 95% of the sand-sized fraction. Clearly, some process is at work to decrease feldspar abundance, because feldspars go from being the most abundant mineral in Earth's upper crust to being one of the scarcest in the detritus that was disintegrated and decomposed from that crust.

Where did all those feldspars (and the enormous quantities of aluminum, calcium, and sodium that make them up) go? Where did all that extra quartz come from? Because quartz is pure silica, we can deduce that some aluminum, calcium and magnesium must have been lost from the initial proportions found in igneous rocks. Since they can't leave the planet, these chemicals must go somewhere. Most of them end up as components of clay minerals.

The same conclusion could be drawn by examining ancient sandstones. Although the minerals in these rocks were derived largely from igneous and metamorphic parents, much as they are in modern sediments, many ancient sandstones have few feldspars. The average sandstone is 50% to 70% quartz, and many sandstones are 99% pure quartz. Just as happens today, some process in the geologic past must have altered the proportion of minerals from a parent rock to a final sedimentary end product. That process is **weathering.** Sediments and sedimentary rocks would not exist without weathering, the combination of processes by which preexisting rocks physically disintegrate and chemically decompose into soil, loose clasts, and dissolved components. Weathering products constitute the raw materials from which sedimentary rocks are made.

Deeply weathered granitic rocks from the San Gabriel Mountains break down into coarse sedimentary particles, which accumulate below them. *(Courtesy of D. Prothero.)*

Weathering is the simple consequence of exposing pre-existing rocks to the conditions at Earth's surface: low temperature and pressure, organic activity, and chemically active substances such as water and atmospheric gases. Physical and chemical weathering are the means by which pre-existing rocks and minerals change and come into equilibrium with this surface environment.

Soil consists of untransported products of physical weathering, typically loose, unconsolidated, mainly resistant, compositionally altered mineral residue (for example, grains of quartz, feldspar, mica, and rock fragments). Soil becomes sedimentary rock if it is eroded, transported (generally, by any of four agents: wind, ice, running water, and gravity), and deposited as **sediment.** Compaction and cementation convert sediment to sedimentary rock. Chapter 3 discusses how weathered clastic residues are actually entrained, carried away, and eventually deposited.

Chemical weathering generates various types of material. Some products are ions in solution (for example, potassium, sodium, and silica). These are transported as dissolved constituents in groundwater and surface runoff and are eventually precipitated as sediment. Other chemically weathered material is modified solid mineral residue (for example, clay minerals). Clay minerals are eroded and transported much as are coarser-grained clasts.

This chapter outlines the processes of physical and chemical weathering and summarizes how rocks disintegrate and decompose as a function of climate and topography.

Physical Weathering: Disintegrating Rock into Clasts

There are four major mechanisms of physical (mechanical) weathering: freeze-thaw, insolation, stress release (unloading), and organic activity. Each is a slow, unspectacular process that leads to the same result. Solid, unyielding, erosion-resistant rock is converted into smaller, movable, unconsolidated rock and mineral debris.

Freeze-Thaw

In *freeze-thaw,* the active agent is water; the active catalyst is hourly, daily, weekly, or longer term temperature changes. At temperatures hovering near 0°C, water freezes into ice and melts into water repeatedly. When water freezes, a 9% to 10% volume expansion occurs. Water freezing along cracks and fissures developed in solid masses of rock must expand. Forces as great as several kilograms per square centimeter gradually split the rock apart. The term *ice-wedging* is used interchangeably with freeze-thaw. It was coined to describe situations in which ponded films of water in fractures expand into solid masses of ice that wedge apart masses of rock.

Several factors promote freeze-thaw. The process works best where fractures are abundant. Fractures might be columnar joints produced when lava cools, joints formed during extension or bending of bedrock, or joints formed along bedding planes. A moist climate in which the daily temperature range roughly straddles the 0°C mark further increases the likelihood of freeze-thaw. A similar, less common process occurs when salts such as halite and gypsum crystallize in cracks and crevices. Evaporation of trapped brines can lead to the growth of more voluminous crystals that force apart the solid rock mass.

Insolation

Insolation refers to stresses generated when minerals are exposed to changing temperatures and undergo differential thermal expansion and contraction. When the latticework of adjacent minerals enlarges and collapses as bedrock surface temperatures rise and fall, expansion and contraction cracks develop and cause the solid rock to disintegrate. This process is common in arid climates such as the Sahara and Mojave deserts, where daily temperature fluctuations of 20° to 30°C are common. In wetter climates, moisture facilitates insolation. Minerals such as clays hydrate and swell, then contract and desiccate, generating additional stress and strain. Insolation creates mechanical weathering products that are indistinguishable from those produced by freeze-thaw.

Stress Release

Stress release occurs when rocks buried beneath overlying material experience high confining pressures. As surface weathering and erosion proceed, overburden is removed, confining pressures drop, and the deeper-seated rock mass expands. A series of expansion cracks or joints develops roughly parallel to the ground surface; these joints evolve into a series of onionlike sheets or slabs of rock separated by crudely curved, subparallel cracks. Because these cracks are likely passageways for water, they become sites of freeze-thaw. Exfoliation—the spalling of curved slabs of rock from bedrock surfaces—and spheroidal weathering (Fig. 2.1)—a process in which solid rock