Sand and Sandstone

F.J. Pettijohn P.E. Potter R. Siever

Sand and Sandstone

Second Edition

With 355 Figures

Springer Science+Business Media, LLC

F.J. PETTIJOHN
Professor Emeritus of Geology, The Johns Hopkins University,
Baltimore, MD 21218/USA

PAUL EDWIN POTTER
Professor of Geology, University of Cincinnati,
Cincinnati, OH 45221/USA

RAYMOND SIEVER
Professor of Geology, Harvard University,
Cambridge, MA 02138/USA

Library of Congress Cataloging in Publication Data
Pettijohn, F.J. (Francis John), 1904–
Sand and sandstone.
Includes bibliographical references and index.
1. Sand. 2. Sandstone. I. Potter, Paul Edwin.
II. Siever, Raymond. III. Title.
QE471.2.P47 1987 552'.5 86-17925

Originally published by Springer-Verlag Berlin Heidelberg New York in 1987

Typeset by Bi-Comp, Inc., York, Pennsylvania.

9 8 7 6 5 4 3 2 1

ISBN 978-0-387-96350-1 ISBN 978-1-4612-1066-5 (eBook)
DOI 10.1007/978-1-4612-1066-5

Sand and Sandstone—Illustrious Forefathers

Henry C. Sorby, 1826–1908

The first to study rocks in thin section and a pioneer in the study of sand: sedimentary structures, paleocurrents, provenance, and diagenesis. He also founded carbonate petrology and metallography. Truly an outstanding innovator and observer and the ultimate model of what a creative individual working alone can accomplish.

Johan A. Udden, 1859–1932

Pioneer Swedish–American frontier scientist at Augustana College in the American Midwest. Systematically studied the size distribution of sand and was one of the first to relate it to process and environment in *The Mechanical Composition of Wind Deposits,* published in 1898. A devoted teacher and a great contributor to a broad vista of sedimentology.

Lucien Cayeux, 1864–1944

Emphasized the "natural history" of a sediment from its earliest deposition to its most recent diagenetic event, placing great reliance on thin section petrography. A prolific publisher with a long career as a teacher. His monographs, such as *Les Roches Sedimentaires de France, Roches Siliceuses,* set a high standard.

Marcus Goldman, 1881–1965

An American who studied with Thoulet at Nancy, Cayeux at Paris, and Walther at Halle, he was the pioneer sedimentary petrologist in America. His Ph.D. thesis on the Cretaceous of Maryland and his study of the Catahoula (Tertiary) sandstone of Texas were milestone papers.

Paul D. Krynine, 1901–1964

An imaginative thinker, he emphasized careful thin section petrology and deductive thinking. A leader in linking tectonics and sandstone compositions. Because he was never afraid to speculate, many of today's controversies about sandstones would have been instantly familiar to Krynine.

Philip H. Kuenen, 1902–1976

The origin and properties of sand and the origin and characteristics of turbidity currents in both the modern and ancient environment were only a few of his favorite topics. Both were studied in the field, on the oceans, and experimentally in the laboratory. He had imagination, ingenuity in experimentation, and a farsightedness in sedimentary dynamics possessed by few.

William C. Krumbein, 1902–1979

The size distribution of sand, shape, roundness, porosity, and permeability, sand mineralogy, the petrographic classification of sandstones, diagenesis via Eh and pH, beach processes, facies maps and their interpretation, statistical and computer analysis all show his sustained innovation and application of quantitative methods and statistical approaches.

Edwin D. McKee, 1906–1984

Studies of modern and ancient sandstones on five continents plus field and experimental investigations of stratification, trace fossils, and ancient paleo-environments were the contributions of this long-term member of the U.S. Geological Survey. An authority on the classical sections of the Grand Canyon region, he applied his special knowledge of that area to many general problems of sandstones, especially to eolian sedimentation.

Preface to the Second Edition

The first edition appeared fourteen years ago. Since then there have been significant advances in our science that warrant an updating and revision of *Sand and Sandstone*.

The main framework of the first edition has been retained so that the reader can begin with the mineralogy and textural properties of sands and sandstones, progress through their organization and classification and their study as a body of rock, to consideration of their origin—provenance, transportation, deposition, and lithification—and finally to their place in the stratigraphic column and the basin.

The last decade has seen the rise of facies analysis based on a closer look at the stratigraphic record and the recognition of characteristic bedding sequences that are the signatures of some geologic process—such as a prograding shallow-water delta or the migration of a point bar on an alluvial floodplain. The environment of sand deposition is more closely determined by its place in such depositional systems than by criteria based on textural characteristics—the "fingerprint" approach. Our revision reflects this change in thinking.

As in the geological sciences as a whole, the concept of plate tectonics has required a rethinking of our older ideas about the origin and accumulation of sediments—especially the nature of the sedimentary basins. These had been categorized as geosynclines of one kind or another. We now have to redefine these in terms of plate tectonics. Plate motions generate depositional basins. How do we classify these and recognize them in the ancient record? What does the study of sandstones contribute to this problem? We are still feeling our way and the criteria for recognition of the several types of basins and the characteristics of their fill are only partially understood. A number of papers have appeared that focus on the sands in particular.

We now know a good deal more about the relations between bedforms and the internal current structures of sandstone and modern and ancient flow regimes; hence we have incorporated this new knowledge in the second edition. We have also added a chapter on paleocurrents. It is not enough to study the process of sand transport and the bedforms but we need also to reconstruct the transport pattern to better understand the paleogeography at the time of deposition. Sandstones are the prime record of these paleocurrents.

Also a great deal of progress has been made in sedimentary geochemistry, especially of diagenesis. These advances have led to extended revision of the subject as it relates to sandstones. We are now learning to use new tools for investigating sandstone composition—the scanning electron microscope, the electron microprobe, and others. These tools provide data we did not have and the means to refine our interpretations. We take cognizance of these new data in our treatment of provenance and diagenesis.

We note also that just as thin-section studies of ancient sandstones are routine, so also this technique is now being applied to the study of modern sands. Such sections provide a much better means for identification of rock and mineral grains and for point-counting. They have greatly enhanced our ability to compare ancient and modern sands.

We also became aware that sedimentology has become truly cosmopolitan. Whereas formerly most of the relevant literature came from the English-speaking world, especially the United States, Canada, and Great Britain and from western Europe, it is now truly international. We have taken account of this expanded literature in our revision.

During this revision we were made acutely aware of the great quantity of excellent work on sand and sandstone that is represented by the flood of literature on the subject that has appeared since the first edition. It became obvious that we could neither completely survey all the world's work nor even refer to all of the new developments in the geology of sands, the application of other disciplines to sand study or the application of sand studies to practical matters such as the search for oil or mineral deposits. What we hope is that we have covered most of the major advances that have become part of the body of knowledge we call the geology of sand and sandstone.

Acknowledgments

We thank all those who helped with the second edition of *Sand and Sandstone*.

Those who read text include: H.E. Clifton, U.S. Geological Survey, Menlo Park, California; Jorge della Farvara, PETROBRAS, Rio de Janeiro, Brazil; J.A. Gilreath, Schlumberger Offshore Services, New Orleans, Louisiana; R.V. Ingersoll, University of California at Los Angeles, California; J. Barry Maynard, University of Cincinnati, Cincinnati, Ohio; J.H. McGowen, ARCO Research, Plano, Texas; Rafael Unrug, Wright State University, Dayton, Ohio; and W. Zimmerle, Deutsche Texaco, Celle, West Germany. Richard Spohn, Geology Librarian of the University of Cincinnati, was most helpful.

We also thank our typists for their care and patience: Wanda Osborne and Joan Harman of Cincinnati, Christine Levitt of Harvard, and Kate Francis of Johns Hopkins.

November 1, 1986

F.J. Pettijohn
P.E. Potter
R. Siever

Preface to the First Edition

This book is the outgrowth of a week-long conference on sandstone organized by the authors, first held at Banff, Alberta, in 1964 under the auspices of the Alberta Association of Petroleum Geologists and the University of Alberta, and again, in 1965, at Bloomington, Indiana, under the sponsorship of the Indiana Geological Survey and the Department of Geology, Indiana University. A 200-page syllabus was prepared for the second conference and published by the Indiana Geological Survey. Continuing interest in and demand for the syllabus prompted us to update and expand its contents. The result is this book.

We hope this work will be useful as a text or supplementary text for advanced undergraduate and graduate courses in sedimentation, sedimentary petrology, or general petrology and perhaps will be helpful to the teachers of such courses. Though we have focussed on sandstones we have necessarily included much of interest to students of all sediments. We hope also that it will be a useful reference work for the professional geologist, especially those concerned with petroleum, ground-water, and economic geology either in industry or government. Because the subject is so closely tied to surface processes it may also be of interest to geomorphologists and engineers who deal with beaches and rivers where sand is in transit.

This work presupposes a general knowledge of the elements of mineralogy, chemistry and statistics on the part of the reader. As no investigation of sediments—especially sandstones—can be considered adequate or complete without careful microscopical analysis, we also presume, therefore, that the user of this book has the knowledge and skills needed to study sands and sandstones under the microscope.

On the other hand, some cognate fields of knowledge are less familiar to geologists and while we did not include a section on statistics or thermodynamics, we did include a section on the principles underlying fluid flow and the propulsion of granular materials. We feel that some knowledge of this subject will become increasingly important in understanding physical sedimentation and the resulting textures and structures of sands.

The book is organized in such a manner as to lead the reader from consideration of the component grains in a sandstone to the analysis of sandstones in the sedimentary basin as a whole. The first half is largely descriptive, a summary of what is known about sandstones beginning with the components, their composition (Chapter 2) and geometrical properties (Chapter 3), progressing to the larger organization and structure (Chapter 4) to the whole rock itself (Chapters 5, 6 and 7). The second half of the book is more largely interpretative and process-oriented. It includes the processes of sand formation (Chapter 8), transportation and deposition (Chapter 9), and post-depositional alteration (Chapter 10). The book concludes with a résumé of the relation of sands to their environment of deposition and to other sediments (Chapter 11) and a summary of their distribution in space and time (Chapter 12). We have included a synoptic review of several better-known sedimentary basins in which an integrated approach—involving stratigraphy, sedimentary petrology, and paleocurrents—was used to unravel geologic history.

For the most part, analytical techniques are omitted. They are adequately covered in several modern texts and manuals (see references, p. 19). Exceptionally, however, we have included a short appendix on the art of petrographical description and analysis which, like field work, is best learned perhaps from experience under the guidance of a skilled master of the subject. We felt it worthwhile, however, to set down some guiding principles as these are seldom made explicit in most published works.

We did not include many "case histories" because, unlike in law or psychiatry, we feel that the student can turn to no better source of instruction than the rocks themselves. No course on this subject can be considered adequate or complete without a well-integrated program of field and laboratory studies. The student, under the supervision of his teacher, should work out his own problems. The clinic is a better guide to practice than the case book.

References to the literature are of two kinds—actual citations in the text to specific papers and a collection of annotated references. The latter for the most part supplement rather than repeat the text citations. Both are placed at the end of the appropriate chapters. In general, our references are selective, that is, although they include some older classic papers, emphasis is on the more recent ones. In many cases, such as the chapter on sedimentary structures, we did not feel the need of an in-depth review of the literature inasmuch as several specialized modern works which contain an extensive bibliography are readily available.

As is inevitable in a work of this kind, much of what is contained therein is a compilation from many sources which transcend and go beyond the immediate and direct experience of the authors. We have tried to acknowledge our debt to these sources at the appropriate places. We also wish to acknowledge the helpful criticism of those who read sections of this work when it was in manuscript form. In particular, we are indebted to Earle McBride, University of Texas, for checking our glossary of rock names applied to sandstones, to Robert L. Smith, U.S. Geological Survey, William F. Jenks, University of Cincinnati, and Richard V. Fisher, University of California at Santa Barbara, for reading the chapter on volcaniclastic sands, to Lee Suttner for criticism of Chapters 4 and 6, to Gerald V. Middleton of McMaster University, Yaron M. Sternberg of the University of Maryland and John B. Southard of the Massachusetts Institute of Technology for their help with the chapter on transport and deposition, to S.V. Hrabar of the Humble Oil Company for reading all of Chapter 11 and Donald A. Holm of Williams, Arizona, and Richard Mast of the Illinois Geological Survey for reading parts of it, to D.A. Pretorius of the University of Witwatersrand and R.W. Ojakangas of the University of Minnesota at Duluth for their comments on portions of Chapter 12, and to Miriam Kastner for help in the X-ray and electron probe analysis of the Trivoli Sandstone. Alan S. Horowitz of Indiana University read and helpfully edited many of the chapters. We wish to thank Mrs. Susan Berson, Miss Kathleen Feinour, Miss Jean Dell'Uomo, Mrs. Debby Powell, and Miss Cynthia Worswick for the final typing of the manuscript and our

publishers for their help in the preparation of the illustrations and seeing the work through the press.

To emphasize our spirit of teamwork we have listed our names in alphabetical order.

January 1, 1972

F. J. PETTIJOHN
P. E. POTTER
R. SIEVER

Contents

Part III. Processes that Form Sand and Sandstone

Sand and Sandstone