PRINCIPLES, METHODS, AND APPLICATION OF PARTICLE SIZE ANALYSIS

EDITED BY

JAMES P. M. SYVITSKI

Principles, methods, and application of particle size analysis

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Much of the world's surface, even under the oceans, is covered in thick deposits of sedimentary particles – gravel, sand, silt, and clay. The nature of the deposits and their formation is very much dependent on the distribution of particles of different sizes. However, different instruments measure different attributes of a particle's size, based on how fast a particle settles in water, or the surface area of a particle, or its length. This book provides information on the how and why of particle size analysis in terms of understanding these sediment deposits.

Sponsored and encouraged by the International Union of Geological Sciences, this book presents a synthesis of the state of the art in particle size characterization. Thirty-three authors have combined their expertise to provide information on the latest theoretical principles, laboratory and field techniques of particle size analysis, and the manipulation and application of particle size data. The theory, procedure, calibration, and accuracy of various techniques are discussed, including settling tubes, sieves, image analysis, light scattering analysis, and thin-section analysis of rocks. Results of a world calibration (interinstrument and interlaboratory) experiment of particle size analyzers are highlighted, with recommendations for reporting size information in the scientific literature.

The needs both of research professionals and of students in earth, planetary, marine, and environmental sciences are addressed in this comprehensive and balanced work. Geographers, geologists, geophysicists, sedimentologists, stratigraphers, geotechnical engineers, geochemists, hydrologists, and oceanographers will all find this an important and useful resource.

Principles, methods, and application of particle size analysis

Thanks to my new and wonderful family:

Dianne L. Syvitski and
Eric W. H. Hutton

“The voyage of discovery lies not in seeking new horizons, but in seeing with new eyes.”

– Marcel Proust

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Preface

In 1983, members of the International Union of Geological Sciences – Committee on Sedimentology (IUGS–COS) expressed concerns on the state of automated particle size instruments used in the earth sciences and their apparent lack of calibration. The concerns of Professor E. Seibold (past president, IUGS) centered on the proliferation of user-built instruments (such as settling towers), that were essentially one of a kind and uncalibrated in the traditional analytical sense. Particle size information was typically reported in the international literature without concern for the analytical errors associated with such results. Were some of the presented data overinterpreted, considering the sampling, subsampling, and analytical techniques employed?

The IUGS–COS struck a working group on "modern methods of grain size analysis" in 1984, and I was asked by Dr. K. A. W. Crook (AUN, chairman IUGS–COS) to be its convener. Our objective was to determine the precision and accuracy of modern automated methods of particle size analysis and the role of these methods in investigation of earth processes and properties. Two meetings were convened (Dartmouth, Canada, in 1985, and Heidelberg, Germany, in 1987) with participants representing twenty countries. The working group agreed to initiate and participate in a world calibration experiment for particle size analyzers (see Chapter 13), and to publish these results together with overviews on automated instruments and the theory of particle size characterization.

Our result is this textbook formulated to address the needs of both students and research professionals in the earth science and oceanographic community. This community comprises:

1. sedimentologists and physical geographers, who use particle size data to understand the erosion, transport, and deposition of sediment;
2. geologists, who examine trends and patterns in the solid earth in response to surface processes of the past (stratigraphy, mapping, mineral deposits);
3. geotechnical and geological engineers, who determine the stability of sedimentary deposits under load;
4. geochemists and environmental scientists, who ascertain the kinetic reactions that occur between liquids and particles, either while particles are in motion or part of the solid earth; and
5. hydrogeologists, who study the flow of fluids through the solid earth, particularly sedimentary deposits that host the world's reserves of hydrocarbon deposits.

The twenty-four chapters that comprise this text are loosely organized into five parts. The first three introductory chapters (Part I) discuss the basic principles behind particle size analysis, including discussion on the nature of geological samples, the effect of grain shape and density on size measurement, the effect of pretreatment on geological samples, and the theory used in particle size analysis.

The ten chapters of Part II present the theory, methods, and calibration of the principal methods employed in particle size analyzers. These include settling tubes (Chapter 4), sieves (Chapter 5), image analysis (Chapter 6, size; Chapter 7, shape), electroresistance particle size analysis (Chapter 8), laser diffraction size analysis (Chapter 9), x-ray size analysis (Chapter 10), light scattering analysis (Chapter 11), and thin-section analysis of sedimentary rocks (Chapter 12). Chapter 13 presents the results of the IUGS–COS-sponsored interinstrument and interlaboratory experiment, where the precision and accuracy of these methods is ascertained using a variety of known standards.

Part III takes us out of the laboratory and into the geological environment, where particle size and concentration are being determined with minimal interference while the particles remain in motion. The science of in situ techniques remains immature, and we highlight just two techniques: laser diffraction (Chapter 14) and stereo photography (Chapter 15).

How particle size data are interpreted and manipulated, the subject of Part IV of the book, is a most controversial subject in the earth science community. Hundreds of scientists have tried to discern patterns in particle size information so as to understand the modern geological environments and provide a means to reconstruct the environmental conditions of previous geological periods. Some of these attempts have been successful, but most are based on regional trends that could not be considered universal. The chapters presented in Part IV provide examples of advances in this long history of sedimentological research. Chapter 16 introduces the concept of suite statistics, wherein statistical parameters of a group of samples (rather than a single sample) are investigated. Chapter 17 describes size frequency distributions of sediment samples in terms of the hyperbolic distribution, a distribution type that includes both the exponential and Gaussian distributions as end members. Chapter 18 provides a theoretical and numerical examination of multivariate analysis of large grain size data sets using Q-mode factor analysis. Chapter 19 uses the theory of fluid dynamics, supported by laboratory experiments, to understand the nature of size frequency distributions.

Finally, Part V provides examples of how grain size data can be applied in the earth sciences. They include applications to stratigraphy (Chapter 20), glacial geology (Chapter 21), marine geochemistry (Chapter 22), oceanography (Chapter 23), and marine geotechniques (Chapter 24). Together these chapters provide overviews or case histories that demonstrate the need for precise and accurate grain size data from sedimentary samples.

A reader, upon an initial glance at the table of contents, may wonder why the classical techniques of pipette and hydrometer, among other techniques developed over the past hundred years, were not included in a text on particle size analysis. These techniques are discussed throughout the book: In Chapter 1 they are described in terms of theory, and in many chapters they are considered in terms of interinstrument calibration. However, as clearly documented in Chapter 13 on instrument calibration, these manual techniques have had their day. They are imprecise and time consuming, and we encourage laboratories to consider their demise during new equipment acquisitions. They have been well described in at least a dozen sedimentological textbooks, most still available from earth science publishers.

Finally, I must add a disclaimer common to textbooks that describe commercial instruments and their performance. I, as a representative of the IUGS, in no way endorse or discredit any of the commercial instruments mentioned. Our contributors have presented facts that stand on their own merit. Readers should reach their own conclusions as to the appropriateness of a particular instrument or technique. Commercial instruments constantly change, mostly through improvements based on comments from scientists and design engineers.

James P. M. Syvitski
February 1991

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First I thank Dr. Jiri Brezina (Granulometry, Germany) for cochairing the two IUGS–COS sponsored meetings dealing with automated size analyzers and their calibration. This text is a direct outgrowth of and response to those meetings. Dr. Keith Crook (ANU) is acknowledged for his leadership at the helm of the IUGS–COS and for recognizing the need for illumination in the field of geological (as opposed to engineering) particle size characterization.

My role as editor was helped considerably by experienced colleagues at the Geological Survey of Canada, Bedford Institute of Oceanography, whom I deeply thank. On behalf of all the contributors, I applaud K. W. G. LeBlanc, who cheerfully dealt with fifteen word processing languages, permission-to-publish communication, and technical aspects of the book format. Thank you, Bill.

W. Gregory (DEMR, Communications Branch) reviewed many of the manuscripts for style. K. W. Asprey and his technical team in the AGC Soft Sediment Laboratory provided the IUGS calibration standards and their distribution to participants. A. Cosgrove and his graphics team provided drafting assistance on a number of chapters. I thank my management within the Geological Survey of Canada for their support of my seemingly never-ending work on this book. This volume comprises GSC Contribution No. 26590.

Each chapter has been subjected to the normal review process pertaining to international scientific journals. Submissions from countries where English is not the dominant language received initial editing before external review. Manuscripts were each reviewed by two or three experts in the field. I have been fortunate to have the following distinguished list of reviewers offer their time and expertise:

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Contents

I *Introduction*

There are two scientific disciplines that work with powders and their particle characterization. One is earth science, involving the study of natural deposits of gravels, sands, silts, and clays. The interest is not just in describing these varied deposits of sediment, but on ascertaining the origin of such deposit. Textbooks on lab methods have included Krumbein and Pettijohn (1938), Griffiths (1967), Carver (1971), and Folk (1974). The field is closely linked to the petroleum industry, mining industry, agriculture, forestry, fishing industry, and space programs.

The second discipline is that of powder technology, principally involving the chemical industry, where the properties of manmade powders and their quality control is of prime importance. Biomedical and military research, the paint industry, ceramic industry, and industrial incineration are but a few of the many sides to this research. Textbooks within this field include Allen (1981), Kaye (1981), and Barth (1984). Although a much younger science compared to geology, the field of powder technology has led the way in recent years, developing automated methods of particle size analysis. With close links to industry, automation means increased speed of analysis and precision of results, and thus increased profits.

Earth scientists have borrowed heavily from the powder technology industry, adapting many of the automated methods for use in their laboratories. In the earth sciences, the number of analyses required every year grows. Grossly approximated, the number of sediment samples analyzed worldwide is 800,000 per annum. At least 70% of these analyses involve automated size analyzers. Thus the field of powder technology has a significant impact on earth scientists, helping them cope with this ever-increasing deluge of samples to be analyzed.

In Part I, three authors, representing the triad of research (university, government, and industry), have provided their ideas on the nature of geological samples and the principles of size analysis. Although the theory of size-analytical methods based on a particle's settling rate should be familiar to many earth scientists, other fields of particle size theory, outlined in Chapter 1, may not be. They include optical attenuation and Mie theory, resistance pulse counting, laser diffraction spectroscopy, and photon correlation spectroscopy. Although this text does not address acoustic techniques for the determination of particle size, this field has become more of a science and less of an art with the passing of each year.

Chapter 2 reminds us that particle size may inherently be the most important fundamental property of a sediment sample. Secondary properties of a sediment, porosity and permeability, are very dependent on particle size. However, particle size is itself dependent on the user's definition and thus on two other fundamental properties of a sediment sample – grain density and grain shape.

Chapter 3 provides readers with a review on the nature of sediment samples and the effect of sample preparation (pretreatment). Are we interested in the size of natural particles, including pellets, aggregates, floccules, and agglomerates? Or are we interested in the nature of the size of individual grains that comprise these natural bundles of grains?

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1 Principles and methods of geological particle size analysis*

I. N. MCCAVE AND J. P. M. SYVITSKI

Introduction

Particle size is a fundamental property of sedimentary materials that may tell us much about their origins and history. In particular the dynamical conditions of transport and deposition of the constituent particles of rocks is usually inferred from their size. The size distribution is also an essential property for assessing the likely behaviour of granular material under applied fluid or gravitational forces, and gauging the economic utility of bulk materials ranging from foundry sands to china clay.

Among solid bodies only a sphere has a single characteristic linear dimension. Irregular sedimentary particles possess many properties from which several characteristic linear dimensions may be obtained. These include a particle's projected area, settling velocity, volume, lengths, and the size of a hole through which it will pass. These dimensions are, of course, not equivalent, save in special circumstances (e.g., for a sphere), a fact which is generally appreciated but usually overlooked. Krumbein & Pettijohn (1938) give a detailed analysis of the properties used as measures of particle size. Their book is *the* reference for all that we shall refer to as "classical" in this chapter. There is a huge variety of commercially available instruments, but we have not attempted to list them all (but see the appendix for names and addresses). A concise survey of the state of the market in 1987 was provided by Stanley-Wood (1987a) and a little earlier by Bunville (1984).

The nature of geological sediment samples

At the outset one must remember that we do deal with samples and determine sample, not population, properties. The strictures bearing on the statistical inferences that may be drawn from samples are lucidly set out by Griffiths (1967) and will not be rehearsed here.

Geological materials commonly contain a wide range of particle sizes from tens of millimetres down to clay of colloidal (<1 μm) size. Both the wide range and the fact that there is no lower size cutoff present analytical problems. The chemical industry also requires size analysis of powders and other materials (Barth, 1984). These are usually intended to contain a well characterized, usually narrow size (and shape) range with little material in the colloidal range, not wide spectrum size distributions. Many of the modern instruments currently being adapted for geological use were designed with these narrow-spectrum analytical requirements in mind (e.g., the Coulter Counter for blood cells, the laser particle sizer for fuel spray droplet size). Geologists should note that these instruments do not sense the whole clay range. It is as though they give a detailed description of the size of tails without saying whether they are attached to elephants or fish!

Under special circumstances we encounter materials that are well sorted (i.e., their grain size distributions have low standard deviations) and unimodal – for example, dune sands, gravels in some fluvial bars, and loess. However, many samples, even when moderately well sorted, are polymodal, and methods of analysis need to be able to resolve modal structure.

The degree of lithification of geological materials is very variable, but much apparently indurated material can be disaggregated by prolonged agitation together with some ultrasonic treatment. Rock that cannot be disaggregated can be analyzed only by measurement and counting in thin section for sand and silt, or equivalent outcrop methods for conglomerates. Only with complex back-calculations involving particle size, shape, and density values, can thin-section data be used for an understanding of the hydraulic properties of geological samples. Because of the small area of thin sections, the small sample volume of poorly sorted samples means that the coarser end of the size spectrum is underrepresented. Even if a sample may be disaggregated, this does not guarantee unaltered

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