This article should be cited as

Switzer, A.D., 2013. Measuring and analyzing particle size in a geomorphic context. In: Shroder, J. (Editor in Chief), Switzer, A.D., Kennedy, D.M. (Eds.), *Treatise on Geomorphology*. Academic Press, San Diego, CA, vol. 14, Methods in Geomorphology, pp. 224–242.

Measuring and Analyzing Particle Size in a Geomorphic Context

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Abstract

Measuring the particle-size distribution of sediments is a fundamental tool in geomorphology. Boulder- and cobble-size material is generally measured by direct measurement whereas a wide variety of techniques are available to determine grain-size distributions for sand- to clay-dominated sediments. Commonly, a combination of methods is needed and no particular technique can be considered 'more accurate' or 'more precise' than another. This chapter reviews the main techniques used to obtain the particle-size distribution of sediments samples and outlines some of the uses and limitations of each technique along with a commentary on popular methods to present grain-size data.

Keywords

Cobble-cam; Folk; Geomorphology; Grain size; Particle size; Sedimentation; Settling tube; Shepard; Sieving; Stokes law; Udden–Wentworth; Wolman pebble count

Glossary

ASTM - ASTM International, (formerly the American Society for Testing and Materials (ASTM)) is an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services.
ISO - The International Organization for Standardization (ISO), is an international standard-setting body composed of representatives from various national standards organizations.
LDA - Laser diffraction analysis (LDA) is a technique which utilizes properties of the diffraction patterns of a laser beam passed through a substance, to measure the size of particles. Laser diffraction analysis is based on the principle that the intensity of light scattered by a particle is directly proportional to the size of the particle. Commonly, the laser is passed through the substance being examined, and the diffracted light focused onto a detector which measures the angular distribution of the intensity of the scattered light.
PSA - In geomorphology, particle-size analysis (PSA) can be considered as any measurement of the size distribution of individual particles in a soil or sediment sample.
PSD - The particle-size distribution (PSD) (also known as grain-size distribution) of a granular material (e.g., sediment) is a list of values or a mathematical function that defines the relative amounts of particles present, sorted according to size.
SEM - Scanning electron microscopy.

Introduction

The grain or particle-size distribution (PSD) of sediments reflects relative energy and is one of the fundamental environmental factors that control the erosion on the surface, transport in the atmosphere, and water bodies and deposition of sediment particles, on the Earth and other planetary bodies. Particle size is also relevant to many aspects of engineering, petroleum, and agriculture industries (e.g., controls on aquifer porosity and permeability in petroleum and groundwater studies). In most landform systems, the PSD of constituent sediments reflects morphological characteristics associated with the physical processes of landform development (e.g., Klingeman and Emmett, 1982,McCave and Syvitski, 1991, Mason and Coates, 2001, Finkl, 2004, Buscombe and Masselink, 2006, Cheetham et al., 2008 and Warrick et al., 2009). At any site of sediment mobility the PSD varies considerably through space (e.g., bedforms and landforms) and time, thereby exerting control over physical transport and sedimentation processes (Warrick et al., 2009). The variety of grain sizes (Figure 1) encountered by geologists, geomorphologists, and archeologists means that no one technique can be applied to all environments and their associated landform components. It is generally desirable to have a convenient, repeatable, precise, accurate, and representative means by which to assess sediment grain sizes when reconstructing palaeoenvironments or investigating processes (see discussions of Syvitski et al., 1991a, Syvitski et al., 1991b, Cheetham et al., 2008 and Donato et al., 2009). Of course, the variety of landforms and sediments occurring in depositional systems means that this desire must be traded against logistics of collection/analysis, sample sizes, representativeness of samples collected versus results obtained, and in many cases the economics of analysis. A myriad of PSA techniques are available to the geomorphologist, particularly for those working with sand-sized material. A number of papers exist that compare different techniques, and in many cases, comment on the limitations or inaccuracies of one technique with respect to another (e.g., Agrawal et al., 1991; McCave and Syvitski, 1991, Syvitski et al., 1991b and Konert and Vandenberghe, 1997; McCave et al., 2006; Cheetham et al., 2008).

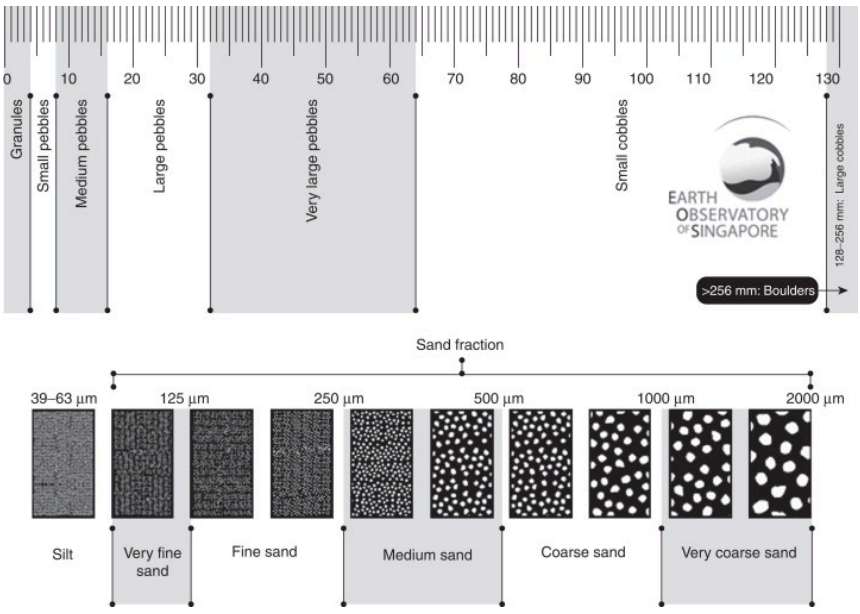


Figure 1. - A grain-size comparator chart (to scale). The chart shows the different size fractions from silt (63 µm) through to large cobbles (128–256 mm). Such charts are useful for field comparisons.

Measuring the Size of a Particle

Providing a definition for a 'particle' is not an easy task. According to the Dictionary of Geological Terms, second editon (1984: 370), a particle is "a general term, used without restriction as to shape, composition, or internal structure, for a separable or distinct unit of rock e.g. a fragment or grain." This differs slightly from 'clasts,' which are defined as "an individual constituent grain, or fragment of a detrital sediment or sedimentary rock, produced by the physical disintegration of a larger rock mass" by the same source (p. 90). In geomorphology, the particles measured are generally composed of inorganic mineral grains or rock fragments, although in some cases they may be organic. Some particles will exhibit relatively molecular homogeneity (e.g., quartz grains) whereas others such as rock fragments will be inhomogeneous in composition. Invariably, particles in most natural sediments or soils will also be of varied density and shape (*link to other chapter on shape*). This is problematic, particularly when analyzing platy sediments, carbonates, evaporates, and sediments of highly variable density. One example is the analysis of carbonate grains (see reviews in Folk and Robles, 1964; Kench and McLean, 1997; Kench, 1997) where the vastly different densities and shapes occurring in biogenic sediments mean that measurement devices and techniques will respond differently to the same particle. It is therefore very important that any researcher compares the results from two different types of sizing instruments. This chapter is not an attempt at an exhaustive review of the problems and issues of particle-size analysis (PSA). Throughout the chapter problems that arise with particular techniques or types of analysis will be considered. In such cases some topical references will be cited. In order to contain the word length of this paper this work will primarily deal with an assumption that the basic analysis needs of the reader pertain to near-spherical grains of homogenous composition, for example, quartz sands. Grain shape is also covered in detail elsewhere in this volume (*link to other chapter on shape*).

Particle Size, Grain Size, and Particle Sizing

A comprehensive text edited by Syvitski, 1991a and Syvitski, 1991b shows that although there are many methods for grain size, none have been adopted as a comprehensive standard in sedimentology and geomorphology. One could argue that the use of protocols of the International Standards Organization (ISO) or American Society for Testing and Materials (ASTM) are comprehensive standards (e.g., International Standard Organization, 2009 and International Standard Organization, 1999a; ISO 9276-6, 2008 and ISO 13320, International Standard Organization, 1999a and International Standard Organization, 1999b; ASTM, 2010) however, it is apparent that these standards are primarily the result of a desire for consistent and comparable reporting procedures within particular disciplines, rather than a result of applied research or a technical comparison of applicability to particular situations.

The Imperfect Sphere: A Universal Problem in Geomorphology

Applying a single method or technique to particle size that is overlapping and comparable is implausible as the universal technique would need to be equally applicable to regular and irregular shapes. The simplest particle shape with respect to three-dimensional geometry is a sphere, and visual inspection (microscopy or image analysis) is the most straightforward measurement technique. When examining a sphere, its perimeter, projected cross-sectional area, surface area, and volume can be described unambiguously by one linear dimension (the diameter of the projected cross section) provided you have a cross section through the mid-point of the sphere. Furthermore, a sphere is the only shape that is geometrically isotropic, i.e., the projected cross-sectional diameter remains constant regardless of the angle of view. The problem in the natural world is that almost all natural particles project a different cross section at all angles of view. As a result, for any nonspherical particle neither surface area nor volume can be inferred from the projected cross section.

Overcoming the Irregularity of Particle Shape

The fact that an irregular particle can present a different cross section depending on orientation is only one of the many measurement problems faced when determining particle size. A second problem is that the cross section of an irregularly shaped particle has different ‘diameters’ depending on where the chord is drawn (Webb, 2008). To overcome this limitation and to simplify statistics many techniques assume sphericity and as such produce an equivalent sphere value as all particle-sizing techniques aim to provide a single number that is indicative of particle size. Most sizing techniques therefore assume that the material being measured is spherical and report the particle size as the diameter of the ‘equivalent sphere.’ In most cases the equivalent sphere approximation for an irregularly shaped particle is dependent on the physical property measured by the chosen technique (Figure 2). For example, laser diffraction techniques provide a diameter of the sphere that yields an equivalent light scattering pattern to the particle being measured.

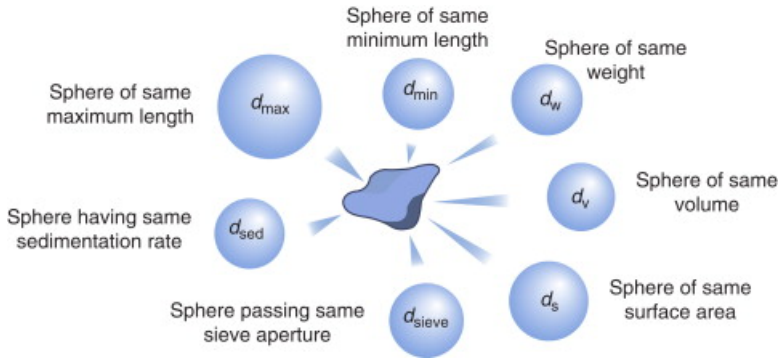


Figure 2. - The primary goal of particle-sizing techniques is to provide a number indicative of the particle size. However, particles are three-dimensional objects for which at least three parameters (length, breadth, and height) are required for a complete description. Most sizing technques therefore assume that the material being measured is spherical and report the particle size as the diameter of the ‘equivalent sphere’ which would give the same response as the particle being measured. Courtesy of Alan Rawle, Malvern Instruments Ltd.

Choosing the Right Particle-Sizing Technique or Instrument

The particle-sizing instrument and technique selected must be suitable for the material to be measured and must also provide data to meet the specific needs of the user. In some cases, this might mean fast, repeatable analyses, or it may mean high-resolution and very accurate or precise results. In geomorphology and sedimentology, the determination of the particle-size distribution alone is seldom the ultimate objective; determining how a particle was transported or investigating the process of deposition or landform development is generally the reason for the measurement. In this regard, the characteristic actually being measured and related to size is commonly more important than the actual particle size. However, particle size still remains one of the key components in landscape reconstructions and process studies (Cheetham et al., 2008). For example, sediment samples taken from river paleochannels are commonly analyzed for PSD. Here, the primary interest is to characterize the deposition mechanism and palaeoenvironments or to link process and landform together through physical properties. For example, Chen et al. (1996) used grain size as a proxy for sedimentation velocity to reconstruct the energy regime of paleochannels in northern China. All different particle-sizing techniques are likely to produce different size results for the same particle, and all of them are likely to be technically 'correct.' The best instrument for the application (the best size definition) may be the one that most closely relates the 'particle size' to the application of the user.

Sample Preparations: A General Note on Labeling and the Selection of Materials for Particle-Size Analysis

In most geomorphology, sedimentology, or soil laboratories, numerous samples enter the laboratory at any one time. A first step is to systematically check the material to ensure legible identification numbers and labels are in place by laying out cores, sample bags, bottles, or blocks of material sequentially. It is important to note external sample identification and numbering, unless engraved on indestructible material, may become unreadable (McManus, 1988). As a result relabeling with external or additional labels is almost always needed (this is particularly the case for sandy samples). During this checking process any gaps in a sampling sequence may also be identified and samples lacking clear labels can be returned to their correct sequential position. If misplaced samples cannot be identified with certainty, they have little value for subsequent analysis and should be discarded.

In terms of PSD determination, further sample preparation depends on the form of the size determination to be undertaken. For example, cobbles and pebbles may require cleaning before examination. In most cases, washing in water is sufficient to remove mud coatings (assuming data from the muds is unwanted). Conversely, sands derived from oceanic, hypersaline or brackish conditions may contain quantities of salt within their pore spaces that can become deposited during drying, cementing adjacent particles together, and thus producing misleading analyses (see Loring and Rantala, 1992).

Where fine (mud) material is present, some techniques (e.g., sieve/pipette) require a user to separate them by wet sieving so that the sands and mud fractions can be

examined separately using different techniques (see note in Box 1). In such cases it is important that fine separation be carried out before drying of the sediment because silts and clays can produce crusts or durable pellets on heating (McManus, 1988).

Although these crusts or pellets may break down to individual particles during analysis, there is no guarantee that individual flakes of clay would become separated by purely physical means. Combining these techniques may require dividing the sample into two fractions to permit later recombination of the different analytical results.

Box 1 - **A note of caution on salts and clays in saline environments**

Fine-grained (silt and clay) samples collected from saline environments (e.g., estuaries, hypersaline lakes) can be problematic as the behavior of the finest size fractions is partially determined by the relative concentration, and composition of salts in the interstitial waters. The hydrochemistry partially determines if clays remain as discrete particles or cluster together (forming flocs or aggregates) with diameters much larger than the individual component particles. In such cases, washing the sample changes the salt concentrations possibly inducing separation or aggregation of the particles (that in the natural system would have been transported in a floc or aggregate). Hence the size analysis may not be a true indicator of the relationship between the particles and their dynamics. Although this issue is widely recognized, most researchers remove salts before subjecting samples to water based treatments (e.g., pipette, hydrometer, or laser PSA). Removal of water salts from fine sediments is best achieved using dialysis, although, Buller and McManus (1979) suggested that washing sands three times with 1 L of deionizer or distilled water will clean a 200 g sediment sample of salts. The issue of removing salts is also discussed succinctly in the landmark paper on treating marine sediments by Loring and Rantala (1992). This issue can also be partially overcome by adding a dispersing agent to assist the separation of individual particles. However, a caveat exists as some particles are transported and deposited as flocs. For example, on the Cooper floodplain in Central Australia sediments in river channels and dunes are characterized by clay-rich mud aggregates (or pellets) that exist in the river channels (Nanson et al., 1986, Nanson et al., 1988 and Rust and Nanson, 1989) and in lunettes on the lee side of playa lakes (e.g., Butler, 1956; Bowler, 1973)). In such a case the treatment and process of disaggregating the sediments would not be reflective of the process of bedload and aeolian transport of the aggregates. Those using settling characteristics (e.g., settling tube) for clays also face an additional hurdle, as clay particles will commonly combine naturally to produce flocs or aggregates giving a misleading guide to the dynamics of the depositional environment as flocs settle at greater rates than their individual component particles. It is worthwhile to note that in almost all situations size analysis of fine particles comes with inherent assumptions that present problems, as the pre-analytical preparations can largely determine the results obtained.

Grain (Particle) Size Scales: The Udden–Wentworth Scale

The Udden–Wentworth scale (Table 1) has a relatively simple geometric progression of sizes that are based on a logarithmic scale (phi (ϕ) scale) developed by Krumbein (1934). The ϕ scale uses the (negative) logarithm to the base 2 of the grain diameter (D, in millimeters) instead of simply the diameter itself, expressed as

This means that each size grade limit is twice as large as the next smaller grade limit. For example, 32 mm is 25, 64 mm is 26, and so forth.

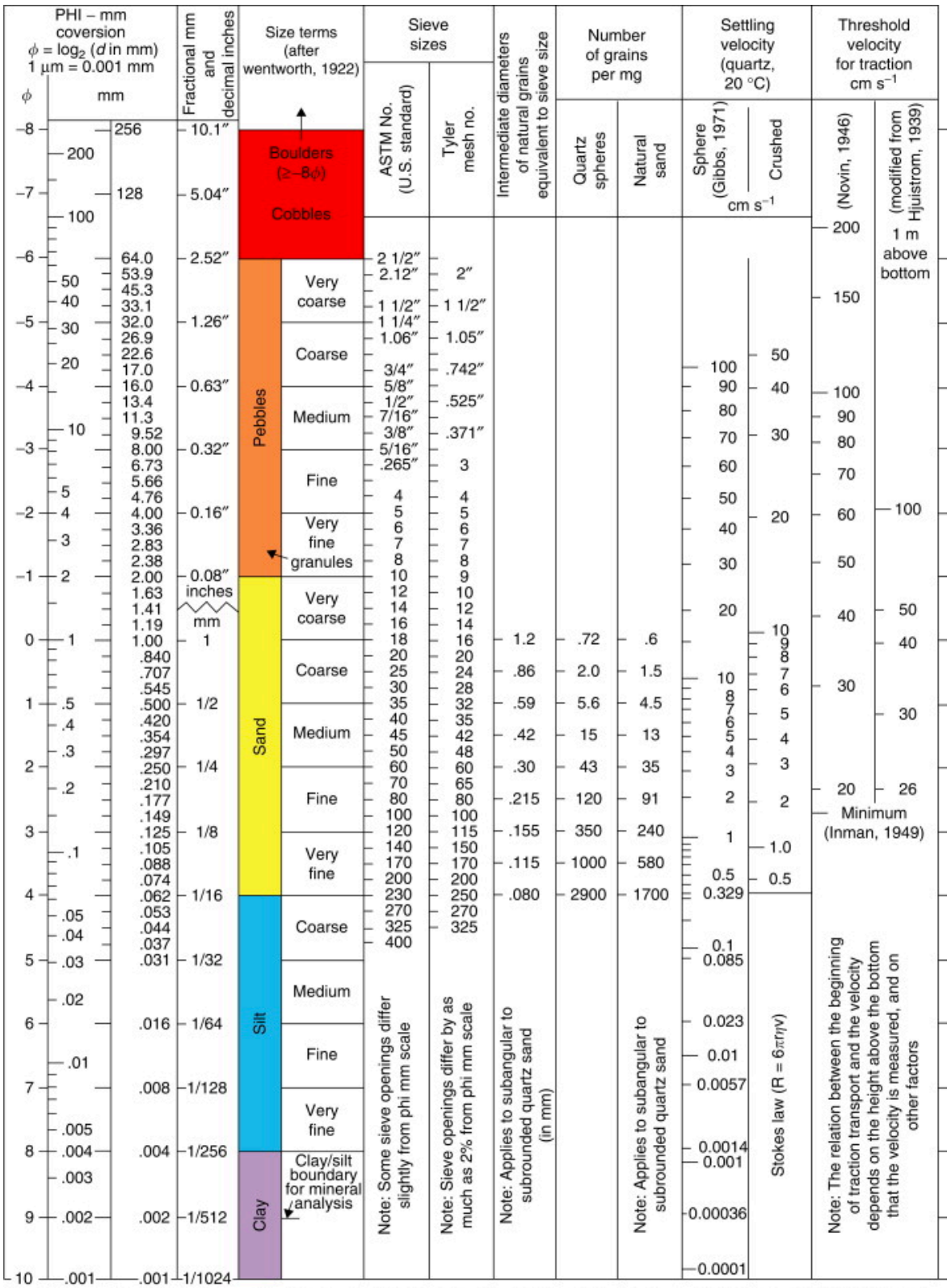
Using the phi scale also simplified the statistical computations popularized in the 1950s and 1960s (e.g., Folk, 1954, Folk, 1955 and Folk et al., 1970). Folk (1954) developed and later refined a sediment textural classification scheme to describe mixtures of mud, sand, and gravel that define the basic descriptive names for both unconsolidated and lithified sediments. A modification of the phi scale in the 1960s generally agreed that by adding a nominal value of Do=1 the phi system becomes dimensionless allowing it to be correctly used for statistical analysis to derive factors such as the inclusive standard deviation, skewness, and kurtosis of grain-size distributions (McManus, 1963 and Krumbein, 1964)

$$\phi = -\log_2(D), \quad (\text{mm})$$

where Do is the diameter of a 1 mm grain.

The Udden–Wentworth scale was further modified in the late 1990s by Blair and McPherson (1999) who upon recognizing that boulder sizes in natural environments can range well beyond the 4.1 m maximum of the Udden–Wentworth scale, proposed an expanded size scale to include mega-gravels up to an astonishing 1075 km in diameter (see Chapter 14.13). Although the original and modified forms of Udden–Wentworth scale remain the most popular scale in geomorphology, it is becoming apparent that the advent of laser-based technologies, primarily developed from the materials engineering and pharmaceutical industries, is reflected in a move to the practice of using microns (μm) (e.g., Pye and Blott, 2004 and Cheetham et al., 2008).

Table 1. Comprehensive correlation table showing the relationships between phi sizes, millimeter diameters, size classifications (Wentworth, 1922), and ASTM and Tyler sieve sizes. The table also shows the corresponding intermediate diameters, grains per milligram, settling velocities, and threshold velocities for traction



Source: Reproduced from Poppe, L.J., Eliason, A.H., Fredericks, J.J., Rendigs, R.R., Blackwood, D., Polloni, C.F., 2000. Grain-size analysis of marine sediments: methodology and data processing. In: Poppe, L.J., Polloni, C.F. (Eds.), USGS East-coast Sediment Analysis: Procedures, Database, and Georeferenced Displays. U.S. Geological Survey, Open-File Report 00-358, CD-ROM.

Despite the general consensus on the Udden–Wentworth scale, a considerable and long-running inconsistency remains. This relates to the finer fractions where despite agreement on the form of the scale and grade boundaries in the coarser ranges, different authors still place the silt-clay boundary variously at 2 μm (Briggs, 1977 and Friedman and Sanders, 1978), which is a size commonly used by soil scientists, or at 4 μm, as in the original Udden–Wentworth system (Tanner, 1969 and Pettijohn, 1975), or at 3.9 μm. The same can be said for silt/sand boundary as summarized by a thought provoking, although not terribly conclusive, discussion on this issue by Hesse (2003). The majority of geomorphologists place the silt/sand boundary at 63 μm or 4 Phi (see Table 1).

Analytical Techniques

The following section reviews a number of common techniques for the analysis of materials of different grain sizes. In some cases a step-by-step process is described, for others references are supplied to key studies where step-by-step explanations can be found.

Grain-Size Analysis of Gravel, Cobble, and Boulder Material

The task of obtaining accurate grain-size data from coarse sediments >64 mm can be time-consuming and challenging. For example, Kellerhals and Bray (1971) and Adams (1979) recommended that a sample mass for statistically acceptable sieve analysis of cobble size material would range from tens to hundreds of kilograms depending on grain size. Obviously, this is far more material than most researchers would like to extract from the landscape. This appears excessive although it makes sense as sampling for PSA in some environments (gravel-bed rivers, gravel beaches) is generally aiming to characterize an extremely large population of sedimentary particles for which a complete census is impractical. Sampling of coarse sediments must be random, comprise enough grains for an adequate sample size, and be drawn from a relatively homogenous environment that is representative of the landform in question. For environments dominated by sand-size sediments and finer, it is relatively easy to obtain a large enough sample that can be analyzed in the lab. In contrast, PSA analysis in environments dominated by gravel-, cobble-, and boulder-size material commonly needs requisite sample sizes that are too large or impractical to be transported off-site for measurement or logistically impractical to sieve in the field.

The analysis of particle sizes of coarse unconsolidated sediments may be achieved through direct measurement of individual pebbles, by pebble counts and more recently by camera-based analysis (Warrick et al., 2007 and Warrick et al., 2009). Traditionally the lengths of representative diameters or axes are determined with the aid of vernier calipers (e.g., Briggs, 1977) by placing the particle (e.g., pebble) on a flat surface and measuring the length of the intermediate axis, *I*. In this text we will use *L*, *I*, and *S* for large, intermediate, and short axes, respectively (many studies use A, B, and C (e.g.,Switzer and Burston, 2010)). The length of the largest axis, L, is always at right angles toI. A further rotation of the particle by 90° about that axis reveals the shortest axis, S. Three mutually perpendicular axes may be used to characterize the particle (Figure 3(a)). Averaging the

three lengths, I, L, and S, yields a mean diameter (DM) for the particle. Alternatively, a mean diameter can be derived by immersing the pebble in water to determine the volume of water displaced, from which the volumetric diameter is obtained (McManus, 1988).

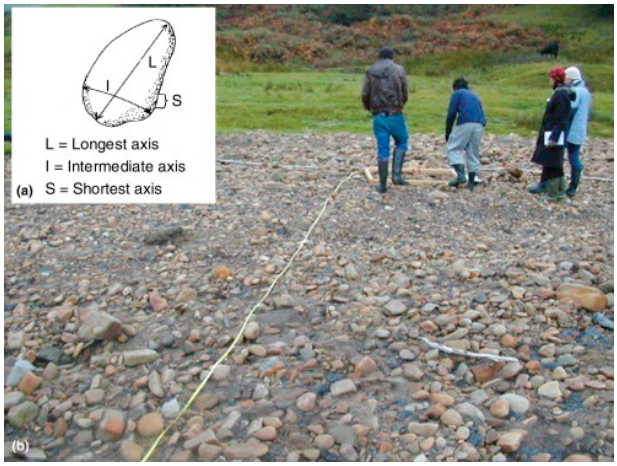


Figure 3. (a) The measuring approach to pebbles for a Wolman pebble count. (b) Students conduct Wolman pebble counts in the Ashop River, Derby County, England. Photograph courtesy of Farah Alamgir, Loughborough University.

Two techniques for gravel and cobble analysis

To negate the problem of transporting large amounts of gravel material to the laboratory, geomorphologists have developed various field-sampling techniques and protocols. The most enduring of such protocols is the Wolman Pebble Count (Figure 3(b)), primarily used in gravel-bed rivers (Wolman, 1954). This technique involves randomly collecting and measuring at least 100 particles from a homogeneous area of a streambed (similar analysis can be applied to mixed or gravel beaches (Jennings and Shulmeister, 2002;Miller et al., 2011)). Generally a grain-size distribution is developed as the cumulative frequency of numbers of clasts of different size classes. If the sampled clasts are of the same density, which will generally only be true if sampling clasts derived from one homogenous lithology, the results obtained will be comparable to a distribution by weight (Kondolf, 1997; Kondolf et al., 2003). If the target material (landform) is composed of particle sizes of heterogeneous-composition material, or recognizable facies, the analysis may be improved by collecting populations of particles from each facies before calculating a weighted average of grain-size distribution with estimated proportions of the sampled landform occupied by each facies. A detailed discussion of this issue is in Kondolf et al. (2003).

Cobble cam: An example of new gravel-size analysis technologies

Cobble cam is relatively a new autocorrelation technique developed by Rubin (2004) to measure grain-size of fluvial and coastal gravel bars using digital photographs (Warrick et al., 2009). This technique uses digital photos that are obtained from ~1 m above the ground surface of a landform containing granule- to cobble-sized sediment (e.g., a gravel bar). The cobble cam is calibrated with physical measurements of the intermediate and long dimensions of clasts in the field that are compared to the short and

long axes, respectively, measured from the digital photographic images. In most cases calibration curves for the autocorrelation technique are generated from a series of the 'best-sorted' (well-sorted) samples in the digital photographs (Warrick et al., 2007 and Warrick et al., 2009). Further analysis of gravel and boulder materials in a geomorphic context is provided in the paper of Felton (*link to chapter on gravel*).

Analytical Techniques for Materials Composed Primarily of Sand, Silt, and Clay

Geomorphological investigations of landforms composed primarily of sand, silt, and clay material, generally require the routine application of PSA (see reviews of Syvitski, 1991a and Syvitski, 1991b; Cheetham et al., 2008).

Several methods of obtaining particle-size distribution data are presently available for use in sandy/muddy sediments. These include sieve/hydrometer (combined), X-ray attenuation, scanning electron microscopy (SEM), sedimentation, and laser diffraction techniques. The particle-size distribution of sediments has many applications in geomorphology, for example, in fluvial geomorphology the PSA of a candidate deposit allows for the determination of the paleocurrent conditions required to quarry and transport sediment grains (Hjulstrom, 1939, Moss, 1962, Moss, 1963 and Miller et al., 1977). Clearly this is not the only consideration, as grain morphology (see Chapter 14.20) also affects a particles resistance to entrainment in a fluid and its time in suspension (Folk, 1980; McCave et al., 2006; Cheetham et al., 2008). In almost all aspects of geomorphology PSA along with determinants of grain morphology and the analysis of sedimentary structures, provide a primary diagnostic tools for the interpretation and reconstruction of palaeoenvironments (e.g., Leopold et al., 1964,Moss, 1972, Reineck and Singh, 1975 and Schumm, 1977; Folk, 1980; McCave and Syvitski, 1991, Lario et al., 2001, Miall, 2006 and Cheetham et al., 2008).

Sieving

Sieving is perhaps the oldest and most traditional of the analytical techniques for sand and gravel sized material (Krumbein and Pettijohn, 1961; Folk, 1980Buller and McManus, 1979). With an appropriate stack of sieves (Figure 4), particles between 0.002 and 250 mm in size may be separated into regular size class intervals. Although it is possible to sieve silt particles, sieving is primarily used for size determination of sand-sized material or greater (McManus, 1988). Sieve screens for dry sieving are commonly made of strong wire mesh of stainless steel or brass with finer wire meshes used for smaller particles. In contrast, wet sieving equipment is generally stainless steel or plastic with Nylon sieves.

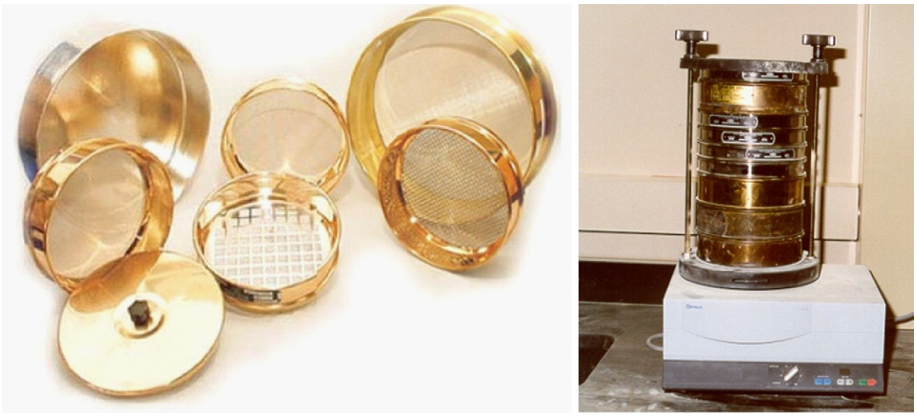


Figure 4. Brass sieves of different sizes and a Retch™ sieve shaker. Sieving has been a fundamental grain-size technique for the best part of a century.

Dry sieving

The coarsest sieve required is placed at the top of the stack in which the square screen openings become progressively smaller down the stack. Sieving generally gives the intermediate measure of a particle because of the way particles orient themselves to pass through the mesh. The particle sieve size can either be defined as the smallest sieve size through which a particle can pass (D_{pass}), or as the largest sieve size through which the particle did not pass, the retaining sieve size (D_{ret}). The number of sieves reflects the number of size fractions and hence the relative level of analytical detail. Once the sample is in place, the sieve stack is generally agitated by a mechanical shaker for a predetermined time interval, usually 15–20 min. The material retained in each sieve is commonly emptied onto a sheet of paper, by tapping gently in a direction diagonal to the mesh and sweeping with appropriate sieve brushes to release particles that are stuck in the mesh (McManus, 1988). Each fraction of sediment obtained is weighed (usually to □0.01 g). The sieve mesh sizes, raw weights, weight percentages, and cumulative percentages, finer or coarser than the specific sieve, can then be calculated.

Potential errors in dry sieving

Dry sieving is subject to potential errors from many sources such as; particle aggregation where aggregates form clusters considerably larger than the original single component grains (this can be checked by hand lens or binocular microscope); incomplete cleaning of the mesh (leftover particles can restrict the aperture spaces) and overloading of sieves that can restrict the opportunity for particles to progress down the nest to the appropriate mesh. McManus (1965) suggested that a sieve load should not exceed 4–6 grain diameters high. Overloading may also cause mesh distortion which also introduces error. For sand samples □100 g of material is generally adequate for sieving but larger weights are required for coarse gravelly deposits (McManus, 1988). Considerable disagreement also exists on the standardization of sieving time (Lewis and McConchie, 1994a and Loizeau and Stanley, 1994; McManus, 1988; Dalsgaard et al., 1991). For most purposes acceptable reproducibility of analyses is obtained after 20 min (Dalsgaard et al., 1991).

Wet sieving

Since many types of sediments contain mixtures of coarse and fine particles, the dry sieving technique may not be appropriate for examination of the finer parts of the sample. Traditionally, the finer particles require other methods of analysis (e.g., pipette analysis) for which the separation of coarse and fine fractions was customarily made at the silt/sand boundary. To wet sieve samples, some workers dry the whole sediment sample to a constant weight at ~110 °C before resaturating in water containing a dispersant such as sodium hexametaphosphate (Calgon). The sample is then periodically stirred in water for ~1 h before being washed through 2000 and 63 μm sieves until the water runs clear. The total content of different fractions can be determined as the difference between the initial and the retained material weights. Although this analysis comes with a cautionary note, some clay sized particles can become structurally altered at ~100 °C; so if any further study is to be undertaken on the clay fraction, this method may not be appropriate. If further analysis is to be undertaken one can use two identical subsamples (one dried and one not). This will allow the collection of an undisturbed mud fraction, whose proportional contribution to the whole sediment is now known from the other subsample.

Sedimentation methods for sand, silt, and clay

Before the advent of particle-size analysis by laser, the grain-size analysis of silts and clays was primarily based on indirect computations of diameters based on observation of the grains in fluids or the response of the fluids to grain-induced displacement. These methods are collectively known as sedimentation methods and are based on the speed with which particles settle through fluids. Such information yields settling velocities from which equivalent grain diameters are then computed.

Computation of the equivalent diameters from settling velocities of particles is based on Stokes' Law of settling which assumes that sediment particles are dominantly spheres of identical densities (almost certainly not true for most natural sediments). Stokes' law is based on the principle that when a particle is in static water it settles at a constant velocity during which the gravitational force exerted on the particle is balanced by fluid resistances represented by viscosity and the particle-drag coefficient. The balance is normally represented by the equation:

$$V_s = \frac{D^2(\rho_s - \rho)g}{18\mu}$$

where V_s is the settling velocity, D the particle diameter (mm), ρ_s and ρ the densities of the grain and water, respectively, g is the gravitational acceleration, and μ is the dynamic viscosity of the fluid. The size can then be determined by reorganizing to

$$D = \sqrt{\frac{18\mu V_s}{(\rho_s - \rho)g}}$$

The pipette method

One inexpensive sizing technique for the mud fraction is the pipette method that relies on the principle that particles in a dilute suspension settle through a column of water at velocities that are dependent on their size (see Krumbein and Pettijohn, 1961). If the sample behaves according to the Stokes Law then repeatedly sampling at a constant depth in the water column yields progressively finer and finer sediments. Investigating the temporal variations of particle concentrations at the set depth will indicate the relative abundance of particles whose diameters may then be calculated. Standard tables of timing are available (Table 2) although when applying Stokes' Law the dynamic viscosity of the water is important and it is therefore important to try to ensure thermal consistency as the analysis may take several days.

Table 2. Withdrawal times and depth tables for 20, 24, and 32 °C based on Krumbein and Pettijohn (1961) andMilner, 1962a and Milner, 1962b). Times are in hours (h) minutes (min) and seconds (s)

	Analysis at 20 °C		*Analysis at 24 °C*		*Analysis at 32 °C*	
Phi	*Depth (cm)*	*Time*	*Depth (cm)*	*Time*	*Depth (cm)*	*Time*
4	20	20 s	20	20 s	20	20 s
5	10	1 min 56 s	10	1 min 45 s	10	1 min 30 s
6	10	7 min 44 s	10	6 min 58 s	10	6 min
7	10	31 min	10	28 min	10	23 min
8	10	2 h 3 min	10	1 h 51 min	10	1 h 34 min
9	5	4 h 6 min	10	7 h 24 min	5	2 h 58 min
10	5	16 h 24 min	5	14 h 50 min	5	6 h 11 min
11	5	62 h 15 min	5	59 h 20 min	5	24 h 43 min
12			5	237 h 20 min		
13			5	949 h		

Generally a pipette is inserted slowly and gently into the fluid until the inlet is at a given distance below the surface. An initial volume is withdrawn (e.g., 20 ml) at the given time from the start of settling (based on Stokes law). The sediment-laden fluid is then released into a small labeled beaker with excess particles washed into the beaker using distilled water. Successive samples are extracted from the suggested depth in the column at time intervals which calculations reveal particles of known diameter (see Table 2 afterKrumbein and Pettijohn, 1961). The number of aliquots extracted relates to the completeness of the dataset. To determine silt and clay content at 20 °C one needs only withdraw samples at 20 s at 20 cm for silt (4 phi) and 2 h and 3 min at 10 cm for clay (8 phi). The beakers containing the sampled fluids are then dried to constant weight before weighing. A small correction may be needed for dispersant and this is achieved by comparing the weights of successive withdrawals as both contain the same amount of dispersant (□2% of the original amount of dispersant powder). Since each aliquot is □2% of the original sediment water mixture a simple calculation will give the full size distribution based on continued withdrawals to the finest required size. The total weight of sediment undergoing analysis should be 50 times the sediment extracted in the initial (58 s) sample. Commonly a stable temperature may be possible but not to the required 20 °C. Tables have been established for other temperatures (Table 2) where the different viscosities

require the reduction or extension of sampling times. The quantities of initial sample used vary, although generally 10 and 20 g l^{-1} give the most satisfactory reproducibility. Higher concentrations can be hindered by settling convection where upward motion of circulating waters impedes settling (Kuenan, 1968). The main advantage of this simple technique is that it requires little specialist equipment and is relatively easy to do.

The sedimentation tube

The second technique based on settling velocity is the sedimentation tube, which unlike the pipette technique that is confined to analysis of silts and clays, can be applied to sand samples as well. The roots of this popular technique can be traced back to the early twentieth century (e.g., Emery, 1938). The technique is based on the principle that particles released simultaneously at the top of a large, broad water-filled tube settle out into a smaller diameter tube at the base. Initially the heights of accumulation at known time intervals are measured by optical micrometer, pan collection, or cameras and the particle sizes calculated (Dyer et al., 1996). The introduction of pressure transducers and electrical recorders to determine the temporal variations of weight in the water column were also significant advances (e.g., Zeigler et al., 1960). The growing popularity of laser- and image-based grain-size analysis techniques has meant that this method is not as prominent as it used to be although several companies still make instruments of this type (e.g., the sedimentometer by Topas).

As in the pipette method, the particles are released from the water surface, generally by holding 2–5 g of wet sample on a plate and lowering into the water column. The sample is kept small to minimize hindered settling which can decrease settling velocities and give unrepresentative results (Richardson and Zaki, 1954). The tube diameter is also important, particularly for coarse sediments (Channon, 1971). Sedimentation tubes also need static water conditions and since most are at least 2 m in height they can develop internal convection currents unless maintained in thermally stable conditions (see discussion of Dyer et al., 1996).

The interpretation of data from sedimentation tubes is complex because although individual particles may permit confident calculation of particle diameters, the behavior of clusters of particles of a range of sizes is less easy to calculate (Dyer et al., 1996). Traditionally individual tubes are calibrated against well characterized particles, such as single spheres (e.g., Zeigler and Gill, 1959) or clusters of spheres of single sizes and combinations of sizes (e.g., Schlee, 1966). Recently international comparative calibration exercises have occurred (e.g., Dyer et al., 1996 and Agrawal and Pottsmith, 2000 for marine and estuarine sedimentation).

Generally the particle sizes in the sediment are calculated from the settled sample weight at specific time intervals. The measured settling velocities are converted into ‘equivalent sedimentation diameters,’ or the diameters of spheres settling at the same rate as the natural particles being tested (e.g., Gibbs et al., 1971). In a noted advance Baba and Komar (1981) set about investigating the settling of natural quartz sands in an attempt to derive intermediate diameters from settling tubes that could be compared and combined with sieve analysis. Their work resulted in a paper by Komar and Cui (1984), which

extended the work of Gibbs et al. (1971) and enabled the calculation of intermediate grain diameters (McManus, 1988). Although some early comparisons of sizes determined by sieving and settling techniques suggested that settling techniques overestimated the size of fines and under-estimated the size of sands (e.g., Sengupta and Veenstra, 1968 and Sanford and Swift, 1971) and the application of correction factors allowed the comparison of intermediate diameters from both sieving and settling techniques within appropriate error (Komar and Cui, 1984). These authors did note some deviations related to heavy minerals grains with densities considerably greater than quartz and to minerals whose shapes differ from the spherical (e.g., mica flakes) (Box 2).

Box 2 Problems with sedimentation techniques and fine-grained natural material

Unfortunately, as particles decrease in diameter, they become increasingly cohesive as surface ionic charges grow in relative significance. In rivers and estuaries, these materials commonly form flocs or aggregates with strong inter-particle cohesion. A solution lies in the use of the natural waters in which sediment and ionic concentrations may be high (Peirce and Williams, 1966; Dalsgaard et al., 1991). Other problems are encountered where organic particles interfere in sedimentation (Duck, 1983). This limitation can be partially overcome by using a dispersing agent during sample preparation. Sodium hexametaphosphate solution is perhaps the most popular dispersing agent, and it can be made up in the laboratory or one can use commercially available mixtures, like Calgon.

Laser diffraction analysis (LDA)

LDA has become increasingly popular over the past 15 years as a method for the analysis of particle-size distribution of sediments and soils. A variety of instruments have been developed by different manufacturers (e.g., Beckman-Coulter, Malvern, Retsch, Horiba), which vary in terms of the range of sizes that can be analyzed and the diversity of options for data processing. Standard operating procedures for laser diffraction analysis have also been published (e.g., International Standard Organization, 1999a,International Standard Organization, 1999b and ASTM, 2010), although they are fairly generalized and aimed mainly at industrial powders rather than natural soils and sediments. The LDA technique works on the principle that a laser directed through a cell will be diffracted by particles that pass through the beam. The instrument measures the particle-size characteristics of a sediment sample using the principles of laser diffraction and relies on the fact that the diffraction angle is directly proportional to the particle size. In all instruments the angle and intensity of laser light scattered by a suspended sediment sample are selectively measured and are generally converted to a volume distribution based primarily on the Mie optical theory (some machines e.g., Malvern Mastersizer 2000 can be set to use Fraunhofer) (de Boer et al., 1987). Previous work has shown that, if appropriate sample preparation and handling procedures are employed, laser diffraction provides a precise method for the analysis and comparison of sediments, soils and similar material (Blott and Pye, 2006; Pye and Blott, 2004 and Cheetham et al., 2008). However, less attention has been given to the question of ‘accuracy’, although it has long been

recognized that there will be significant differences between results obtained using laser diffraction compared with other methods (Agrawal et al., 1991 and Agrawal and Pottsmith, 2000). Many authors have also shown that laser diffraction underestimates the amount of clay compared with pipette and hydrometer analysis (e.g., McCave et al., 1986, Loizeau et al., 1994, Konert and Vandenberghe, 1997, Beuselinck et al., 1998, Beuselinck et al., 1999a and Beuselinck et al., 1999b), and significant differences have also been noted between laser diffraction and sieving results for some sands (e.g., Shillabeer et al., 1992, Konert and Vandenberghe, 1997 and Hayton et al., 2001). In contrast, recent work by Cheetham et al. (2008) showed that the use of LDA for fluvial sands produced precise and repeatable results when compared to other techniques.

General process for LDA analysis

Background measurements are generally taken on the suspension medium (characteristically water) based on recommendations from the manufacturer. To assess the comparability of samples prepared using different methods of dispersion, two sample sets can be analyzed. The first set is agitated under ultrasound for 1 min or until the sample is visibly disaggregated. The other group can be treated with 50 ml of 0.1% sodium hexametaphosphate and soaked overnight.

Commonly, the samples are added to the instrument using a large beaker or dispersion bath and agitated by ultrasound until the laser obscuration is in the optimum range for the instrument. Too high obscuration levels results in inter-particle interference whereas too low obscuration leads to poor signal-to-noise ratio. The data output can then be grouped according to standard outputs including, standard sieve-size fractions for correlation statistics (Folk, 1980; Tanner, 1991a and Tanner, 1991b; Christiansen and Hartmann, 1991), Percent volume data can also be used (see later Section).

Other PSA techniques

Other techniques used in geomorphology include electrical zone sensing (EZS), X-Ray sedimentation and scanning electron microscopy (SEM). The EZS approach is based on the Coulter principle (e.g., Coulter counter) where a sample is dispersed at low concentration in an electrolytic (i.e., conducting) solution, and is then drawn through a small aperture (sensing zone) that has electrodes on either side of it. As each particle enters the sensing zone it causes a temporary change in the measured electrical impedance across the opening. The amplitude of this impedance pulse is proportional to the particle's volume and hence, can be used to infer size. Potential errors come from the coincident passage of two or more particles through the sensing zone as this can cause the instrument to count the combined pulse height of multiple small particles as a single large particle, thereby skewing the size distribution. A second potential problem in EZS, which is also a concern in LDA, is particle asymmetry where flaky particles (e.g., clays) rotate as they pass through the aperture leading to potential oversizing (Milligan and Krank, 1991).

The X-ray sedimentation technique for determining the relative mass distribution of a sample by particle size is based on two physical principles: sedimentation theory and the absorption of X-radiation.

These two theories are embodied in an analytical instrument called the SediGraph. Any particle settling in a liquid will achieve a terminal velocity when the gravitational force balances the buoyancy and drag forces on the particle. This is dependent on the size and the density of the particle, and the density and viscosity of the liquid. A beam of photons (X-rays, in this case) passing through a medium is attenuated in proportion to the path length through the medium, its concentration, and the extinction coefficient of the medium (Coakley and Syvitski, 1991). Using Stokes and Beer-Lambert laws mean that interpretation of raw data is achieved to determine the relationship between the basic measurements and the reported size distribution (Loveland and Whalley, 2001).

SEM can be used to count the number of particles in different size fractions (Ly, 1978; Goldberg and Richardson, 1989). This type of analysis is a time-consuming technique, but it can be sped up by using a grid of set scale and choosing a field of view with a specific magnification then counting particles of a particular size fraction (Cheetham et al., 2008). Automated microscopy and image-analysis techniques can provide a means of repeatable and routine characterization of particle size and shape using automated microscopy and image-analysis techniques. Commonly, particle shape information is generated from the analysis of thousands of particles and displays of particle size and shape data are s upported by images of all the particles to provide further visual understanding of the measurement data (Goldberg and Richardson, 1989). A number of shape parameters can also be calculated for each particle in order to increase the sensitivity of the analysis to subtle variations in particle morphology (Cheetham et al., 2008).

Interpretation of Particle-Size Data

Although the analysis of particle size in sediments is commonly used in the identification of sedimentary environments, landforms, and facies in a variety of depositional settings (e.g., Folk and Ward, 1957, Huang and Goodell, 1967, De Falco et al., 2006, Nichol et al., 2007 and Donato et al., 2009) a considerable variability remains in presentation techniques. The pioneering work by Udden (1914), Wentworth (1922), Krumbein, 1934 and Krumbein, 1938, Inmam (1952), and Folk and Ward (1957) established descriptive statistics that are still used in geomorphology and sedimentology to characterize particle-size distributions (i.e., sorting, skewness, and kurtosis) (see Table 3 and glossary).

Table 3. Grain-size parameters and their common indicative meaning

Parameter	*Description*	*Main indicative meaning in PSA*
Mode	On a size frequency histogram the size class in which the greatest percentage is recorded provides the modal class. On the size frequency distribution plot the highest point on the curve provides the modal value	The modal size represents the commonest grain size in a distribution. Frequency curves with several peaks indicate polymodal distributions potentially indicating the presence of more than one population of grains
Median (Md)	Half of the grains are coarser and half finer than the median diameter. This is most readily determined from the 50% line of the cumulative distribution curve	Although useful for unimodal sediments, in polymodal distributions (most natural sediments are polymodal) the median may fall in the tails of two subpopulations of grains
Mean (M)	The measure of average grain size, the mean is computed from sizes of particles spread through a range of percentile values. In its simplest form the Graphic Mean, *M* can be calculated by averaging the 16th, 50th and 84th percentiles in a cumulative frequency curve. This assumes that three values alone are sufficient to give a useful mean. More percentage values may be averaged which approximates to the mean of moment statistics	The mean is the most commonly presented parameter of sediment size and is often presented with a measure of standard deviation to express the basic properties of a sediment (e.g., poorly sorted fine sand)
Sorting (s)	There are two common measures of sorting; the graphic standard deviation (s) (Inmam, 1952), which provides a measure of the spread of one standard deviation on either side of the mean and the inclusive graphic standard deviation (Folk and Ward, 1957) which defines a spread of 1.65 standard deviations either side of the mean	Sorting relates to the range of grain sizes. Well-sorted samples have a small range (aeolian sediments are commonly well sorted (i.e., grain sizes are very similar) hence it can be said that winds sort sediments well). Glacial sediments are commonly poorly sorted (meaning there is a large spread of grain sizes in glacial deposits)
Skewness *(a)*	In a normal distribution with a bell-shaped frequency curve the median and mean values coincide. Any tendency for a distribution to lean to one side, i.e., to deviate from normality, leads to differences between the median and mean values. These differences are used to characterize the asymmetry or skewness of the curve and are determined from the value of the mean less the median, all divided by the range used in defining the mean	Skewness has a positive or negative value when more fine or more coarse materials are present. Skewness is a positively or negatively signed dimensionless number; it has neither metric nor phi value and lies within the range -1 to $+1$
Kurtosis	A measure of the 'peakedness' of the distribution. Although frequently calculated kurtosis rarely receives much attention. The kurtosis is a measure of the dispersion and the normality of the distribution. Kurtosis is a ratio of the spreads of the tails and center of the distribution (and is therefore also dimensionless)	Generally kurtosis is a second indicator of sorting where very flat curves equate to poorly sorted sediments or those with bimodal frequency curves that are platykurtic, whereas strongly peaked curves are considered leptokurtic and exhibit very good sorting of the central part of the distribution

Use of Bivariate Plots (Scattergraphs)

Numerous approaches have been utilized to interpret particle-size data in geomorphology. Commonly, summary statistics (mean grain size, sorting, skewness, and kurtosis) of particle-size distributions (Folk, 1980 and Folk and Ward, 1957) have been plotted on bivariate scattergrams, from which researchers have identified graphic envelopes within which deposits of particular environments are plotted (Mason and Folk, 1958, Friedman, 1961 and Friedman, 1967, 1979; Moilola and Weiser, 1968, Buller and McManus, 1972, Tanner, 1991a, Tanner, 1991b, Duck, 1994 and Lario et al., 2002). Several other approaches are reviewed in detail by Syvitski, 1991a and Syvitski, 1991band Gale and Hoare (1991). Despite the extent and detail of PSA investigations over the last 100 years, most attempts to determine the environment of deposition from particle-size data are primarily site specific and are generally inadequate as an unequivocal means of palaeoenvironmental reconstruction. However, it is clear that particle-size data obtained by any means can be used in conjunction with other evidence to determine the environment of deposition of a sedimentary body or landform. For a discussion on bivariate plots the reader is referred to Tanner (1991a) who acknowledges the inherent problems faced when using such plots and examined methods that may assist in the resolution of the environment of deposition.

Scattergraphs and Ternary Diagrams

For many years sedimentologists and geomorphologists have attempted to use scattergraphs of grain-size data to distinguish between different depositional environments or landforms. No universal models exist to distinguish past depositional environments using these graphic presentation approaches (McManus, 1988 and Lario et al., 2002). Samples are generally plotted onto ternary plots (Figure 5) or scattergraphs (bivariate plots). Attempts to discriminate between different depositional settings, via bivariate plots, are based on the primary assumption that the statistical parameters reliably reflect differences in sediment transportation and deposition (Sutherland and Lee, 1994a and Sutherland and Lee, 1994b). Many studies have tried to make environmental sense from bivariate plots of parameters that describe the sample size spectrum (Stewart, 1958, Friedman, 1961, Friedman, 1967, Buller and McManus, 1972, Friedman and Sanders, 1978, Tanner, 1991a and Tanner, 1991b) and the success has been varied for several reasons, such as over-simplified discrimination, for example, beach versus river where dunes and other depositional settings are ignored (Socci and Tanner, 1980). For example, inclusive mean and inclusive mean standard deviation were plotted from samples taken from a Holocene paleoestuary that contained two overwash sandsheets (Switzer et al., 2005). The analysis clearly distinguished the overwash sandsheets from estuarine muds, hill-slope materials and floodtide deltaic sediments (Figure 6). This is not always the case and the comparison between mean grain size and sorting is generally over simplified and in most cases there is a clear covariance between mean grain size and sorting (Tucker, 1990). Griffiths (1967) explained that as both mean grain size and sorting are hydraulically controlled in most environments the best-sorted sediments in almost all environments will have mean grain size in the range of fine sand sizes.

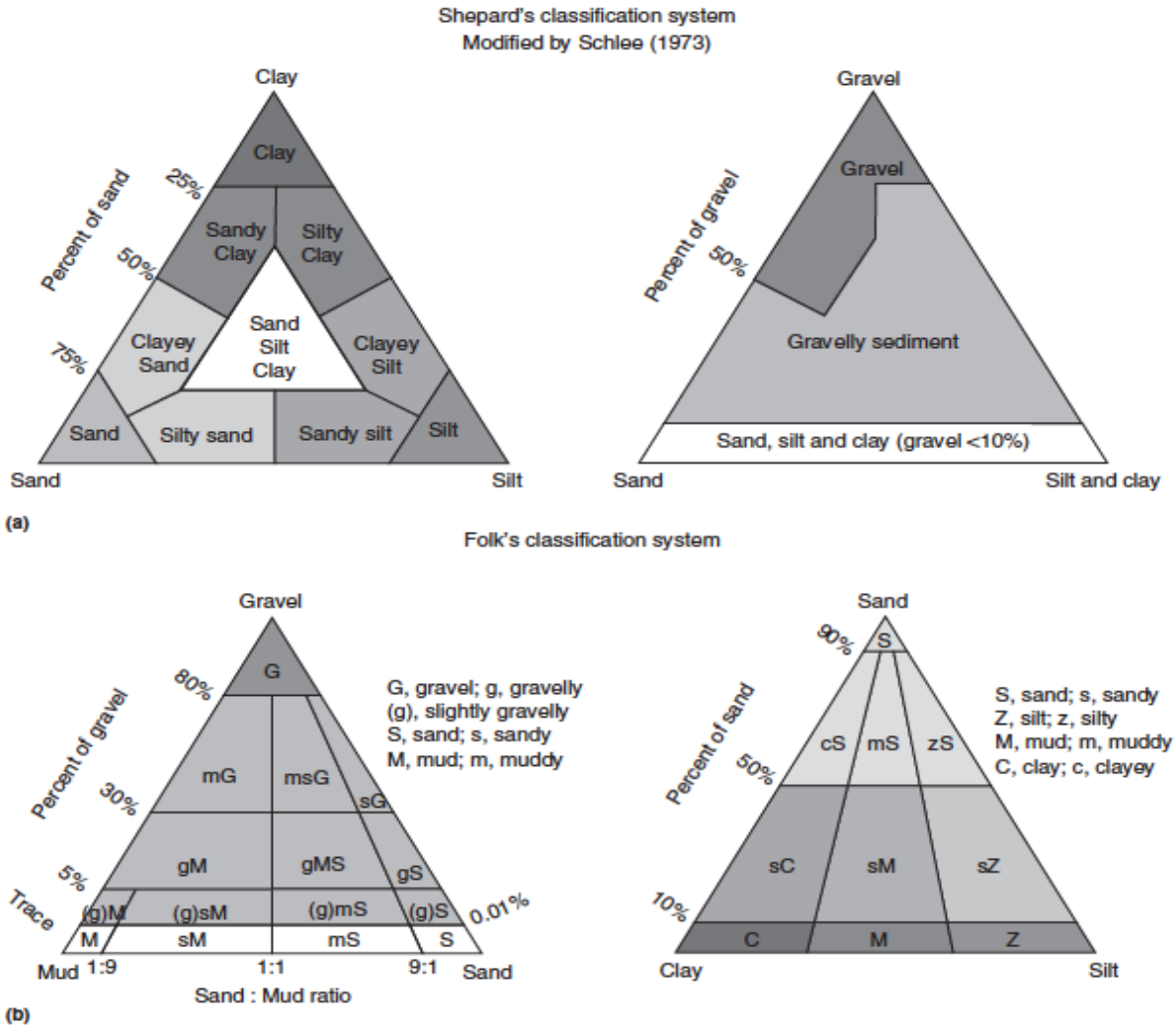


Figure 5. Tripartite sediment classification schemes for sediments. Most geomorphologists use one of the systems described either by Shepard (1954) or Folk, 1954 and Folk, 1980. The original scheme by Shepard (1954)does not allow for sediments with significant amounts of gravel and was subsequently modified by the addition of a second ternary diagram to account for the gravel fraction (Schlee, 1973). The system devised by Folk, 1954 and Folk, 1980 is also based on two triangular diagrams and has 21 categories. Folk's scheme stresses gravel focusing on high velocity flows whereas Shepard's classification scheme emphasizes the ratios of sand, silt, and clay because they reflect sorting and reworking (Poppe et al., 2000). Courtesy of USGS.

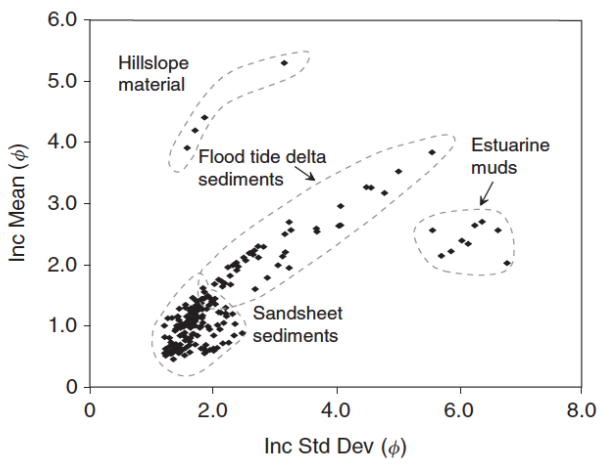


Figure 6. A scattergram of inclusive mean (Inc Mean ϕ) and inclusive mean standard deviation (Inc Std Dev ϕ) of samples taken from a Holocene estuary fill thatcontains two overwash sandsheets (Switzer et al., 2005). Grain populations indicative of overwash sandsheets, estuarine muds, hillslope materials, and floodtide deltaic sediments are identified.

Recent Advances in Data Presentation

Where PSA plays a major role in the analysis most researchers will find that conventional graphical summary statistics such as graphical mean, median, mode, standard deviation, skewness, and kurtosis are still the preferred method of displaying PSDs (e.g., Folk, 1966, 1980; Griffiths, 1967, Friedman and Sanders, 1978 and Wang and Ke, 1997; Al-Zamel et al., 2007 and Mwakumanya and Bdo, 2007). This is despite the noted limitations of such statistics to adequately characterize the grain-size distribution (Blott and Pye, 2001).

Recent work has seen some notable attempts at new analysis and display techniques (e.g., Donato et al., 2009). This is primarily a result of recent advances in instrumentation (e.g., LDA) that mean it is now possible to analyze many samples economically. Many researchers have noted that PSD from a considerable number of sedimentary environments are required before a statistically significant application of derived statistical parameters could be used to characterize environmental trends (e.g., Ward, 1980, McLaren, 1981, McLaren and Bowles, 1985, Donato et al., 2009 and Pilarczyk et al., 2011).

Those familiar with grain-size analysis statistics are fully aware that the use of these statistics was not developed for use in a particular facies or landform analysis framework but was primarily developed for the ease of calculation and characterization of the PSD from graphical cumulative frequency curves. As such, the derived statistics were simply a convenient way of working with the data (primarily from sieving and pipette at the time). In geomorphology, the statistical parameters used in the middle of the twentieth century have persisted. This is in spite of significant advances in technology (i.e., laser particle-size analysis) that have greatly enhanced the ability to characterize large quantities of PSD data. This can now be done with considerable statistical rigor using modern computing.

Using Modern PSD Datasets

Most modern instrumentation (e.g., LDA) can provide the complete PSD in a high resolution, precisely measured and easily comparable form that is then available for a variety of statistical analysis using multivariate techniques (e.g., cluster analysis) that make the identification of PSA determined facies and environments possible. Rapid analysis of PSDs can now also provide abundant data for high-resolution grain-size studies on cores and surface samples that with the benefit of multivariate statistics and 3D surface plots allows better characterization of sedimentary processes (e.g., Beierle et al., 2002, Van Hengstum et al., 2007 and Donato et al., 2009) Combining the PSD data with other relevant data (e.g., texture, carbonate content, faunal data) can adequately discriminate landforms and environments (e.g., Switzer et al., 2005 and Switzer and Jones, 2008; Pilarczyk et al., 2011; Van Hengstum et al., 2011).

In one recent example Donato et al. (2009) tested a new technique using PSD data and multivariate cluster analysis (Q-mode) to define modern environmentally defined facies distributions determined in Sur Lagoon, Oman. In this example they used blind clustering of PSD data and compared it to surface topography, remote sensing and visual field

surveys. This allowed a comparison of the PSD data to the mapped distribution of sedimentary facies to determine the effectiveness of PSD for determining lagoon sub-environments in the geological record (see previous work by Loizeau and Stanley, 1993,1994). Donato et al. (2009) found that surface plots of PSD data allowed a qualitative interpretation of the characteristics of the entire PSD that can provided key insights into depositional processes and the dynamics of modern environmental conditions. This method is especially useful for distinguishing multiple sedimentary processes, which can appear as additional modes within the PSD (see studies of Pilarczyk et al., 2011; Van Hengstum et al., 2011). Given the ease at which large amounts of particle size data can now be obtained, such techniques can now be applied to most depositional environments and landforms at high spatial or temporal resolution. Donato et al. (2009)noted that a combination of conventional summary statistics with PSD surface plots increases the utility of PSA as a paleoenvironmental proxy for identifying changes in clastic and organic depositional processes in lake sequences. Similar approaches have since been applied to other environments. One example of recent application is in the investigation of paleo-landforms in coastal karstic basins (Figure 7) by Van Hengstum et al. (2011). In this example, sediment particle size is plotted down core using size as the x axis, depth down core as the y axis and volume as the z axis. The different modes are visible in many cases and this technique shows particular promise for polymodal sediments.

The Same but Different: A Concluding Note on Comparing Different Techniques

In a recent commentary on the ‘correctness’ of the results obtained for particle-size measurements by two or more different analytical techniques, Webb (2008) stated that “Provided that the instruments used are capable of producing high-quality data, the pertinent questions, then, are, ‘was the sample properly prepar ed and properly presented to the instrument,’ and ‘were the analytical parameters applied correctly’” (Webb, 2008: 3). If the answer to both is ‘yes,’ then both analytical results probably are equally correct; they are just expressed in different terms. Recent reviews clearly show that some Earth scientists still express concern about comparisons of particle-sizing results by different techniques (see discussion of Cheetham et al., 2008). The techniques commonly compared are sieving, sedimentation, imaging (including microscopy and machine vision), EZS, and light scattering (laser diffraction). Invariably, the determination of any particle-size distribution on the same sediment sample by all of these techniques and others will, in all cases where the samples are not perfect spheres of homogenous weight and composition, yield different results for mean size, modal size, and quantity distribution by size. So which technique is ‘correct’ or provides the most ‘accurate’ representation of the sediment population? If the sample is prepared properly and the analytical parameters are correctly applied then all the answers are ‘correct,’ but they are just measuring different things and applicants of these techniques must be aware of the limitations of each technique. It is clear that geomorphologists must consider factors other than size or sample preparation that could affect the reported size value. Generally errors from these sources are associated with nonspherical particles, variation in particle density or even the

inappropriate application of the measuring instrument (e.g., Sieves for coralline sands (see discussion of Kench, 1997)).

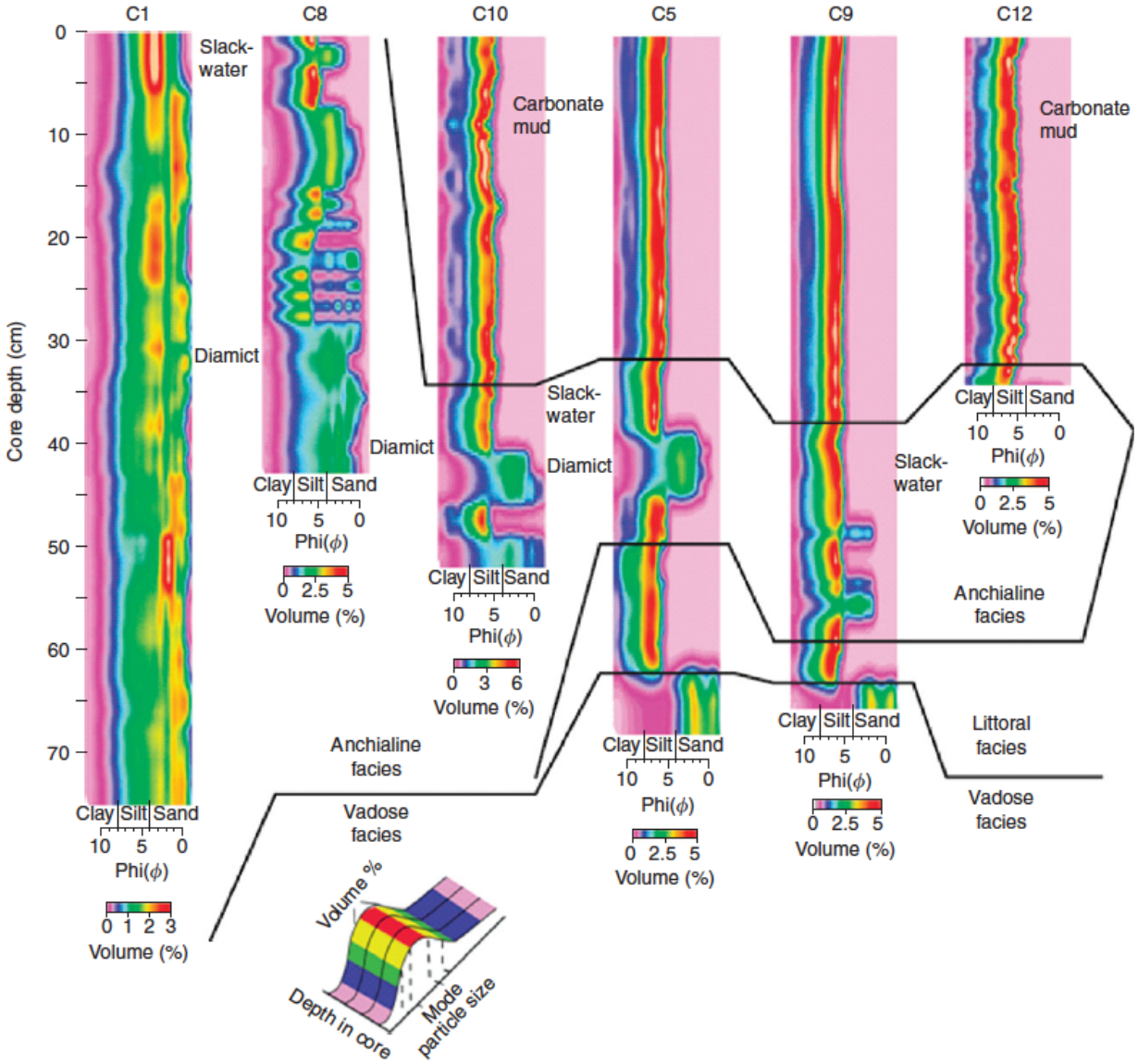


Figure 7. Sediment particle size data from a coastal karst basin in Bermuda from Van Hengstum et al. (2011). Sediment samples are plotted down core using size as the x axis, depth down core as the y axis and volume as the z axis. This technique is based on the work of Bierle (2001) and shows particular promise for presenting data where high resolution sampling has been conducted on polymodal sediments. Modified and reproduced from van Hengstum, P.J., Scott, D.B., Gröcke, D.R., Charette, M.A., 2011. Sea level controls sedimentation and environments in coastal caves and sinkholes. Marine Geology 286(1–4), 35–50.

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