Grain Size Analysis

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GRAIN SIZE ANALYSIS

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Synonyms

Granulometry; Particle size analysis

Definition

Grain size analysis is an analytical technique typically conducted within the earth sciences and implemented as a routine laboratory study. Other disciplines, such as archaeology and geoarchaeology, also use it regularly. It is a sedimentological analysis carried out in order to determine the size of the different particles that constitute a particular unconsolidated sedimentary deposit, sedimentary rock, archaeological locus, or soil unit. The main goal of this procedure is to determine the type of environment and energy associated with the transport mechanism at the time of deposition; this is done by inference from the sizes of the sediment particles analyzed and their distributions.

Introduction

Granulometry is a basic analytical technique that has wide applications within the earth and archaeological sciences. Particle or grain size is a fundamental attribute or physical property of particulate samples or sediments and sedimentary rocks (Folk, 1980; Friedman and Sanders, 1978). Much can be said from analyzing not only the size of clastic or detrital (inorganic), bioclastic (organic), or chemical particles but also from the overall size distribution, size fraction percentages, textural maturity of the sediment or sorting, surface texture attributes of a particle, and sphericity/angularity and shape of a particle (Krumbein and Sloss, 1963; Syvitsky, 2007). Several sediment, soil, or material properties are directly influenced by the size of its particles, as well as their shape (form, roundness and surface texture or the grains) and fabric (grain-to-grain interrelation and grain orientation), such as texture and appearance, density, porosity, and permeability.

The size of particles is directly dependent on the type of environmental setting, transporting agent, length and time during transport, and depositional conditions, and hence it possesses significant utility as an environmental proxy (McManus, 1988; Stanley-Wood and Lines, 1992). Grain size is related to a multitude of external factors acting on a local or regional scale. For example, in the coastal and marine setting, grain size is related to the bathymetry and geometry of the basin, nutrient regime, biogeochemical oceanography, coastal processes, net sedimentary inputs from land sources, and outputs. The study of

these particles can elucidate their provenance (source materials), the various processes they may have endured during their transport (by air, land, or water), their final depositional environment, and final burial setting (how much energy was present at that time; e.g., from waves or currents), and other physical and chemical factors.

Traditionally, sediments were divided into three principal categories: gravel, sand, and mud. The latter is further divided into silt and clay, mostly based on mineralogical distinction rather than (hydro-)dynamic properties. Since the early 1900s, standardization of such size ranges has been defined (Figure 1) based upon different grade scales constrained by particle size limits or range boundaries. The size of the particles is based on their nominal diameter, traditionally reported in millimeters (mm), micrometers (μm) or phi (Ø) units. The Wentworth or Udden-Wentworth scale (Udden, 1914; Wentworth, 1922) divides the size ranges into textural classes with specific terminology, from boulders (> 200 mm) to clay (< 0.004 mm). It is a geometric scale in which each size limit is 1/2 or twice the millimetre value of the next (Figure 1). The Krumbein Ø scale (Krumbein and Sloss, 1963) is a logarithmic scale modified from the Udden-Wentworth one and based on conveniently calculated round values, to avoid dealing with mm fractions (Figure 1). Classification of detrital sediments is based upon the quantification of, or relationship between, the proportions/percentages/ratios of different particle size fractions or textural classes within a mixed sediment (Shepard, 1954; Folk, 1980), as seen in Figure 2.

Grain size analysis is often part of the basic, initial set of analytical laboratory procedures scientists conduct upon sediment/soil samples and/or sediment cores are recently collected in the field. The purpose of such analysis is to (1) obtain a deeper understanding of paleo-environmental features or modern environmental impacts, (2) reconstruct past sedimentary transport histories, depositional conditions, or sediment provenance, or (3) analyze in detail a catastrophic event, such as a tsunami or hurricane deposit, for example.

Depending on the thickness and regional extent of the sedimentary layer, unit, deposit, or archaeological locus, scientists collect one or multiple samples within that unit in order to obtain representative material and, with sufficient sampling, a more accurate statistical result. The resulting grain size analyses of samples collected from a single unit are averaged in order to obtain the overall particle size distribution.

Several analytical methodologies can be applied in the study of granulometry and the distribution of particle sizes within a sample or specific material (Table 1). These vary in terms of applicability, technique, apparatus, and cost (Table 2). Nonetheless, the method selected would depend on the range of particle size, the degree of consolidation of the material and the purpose of the analysis. Traditional analyses include counting (individual clasts, manually), sieving, and settling, for gravelly, sandy and muddy materials respectively. Modern analyses (Table 1) have used the same analytical principles (count, sieve and settle), however, the methodologies are much improved today due to better instrumentation and automatization (Table 2), including laser diffraction and imaging techniques (e.g., spectrometry), without discarding traditional sieving and settling (hydrometer and pipette analysis) methodologies (Syvitski, 2007).

Contextual granulometry

Granulometry in geoarchaeology

Granulometry can be considered a perfect example of geoarchaeological research in which the application of an earth sciences technique is used to understand aspects of the archaeological record. For example, in order to obtain a better understanding of the composition of a locus or stratigraphic unit, grain size analyses would be a basic parameter to estimate in order to differentiate the matrix from the clasts/aggregates (*geological terms*) or inclusions (*archaeological term*), within the same locus/unit,

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and/or across loci/units. This information enables a more precise understanding of particles that might be related to natural deposition versus those deriving from an anthropogenic origin – as some anthropogenic deposits have granulometric characteristics that cannot be compared to any natural pattern since they derive exclusively from artificial behaviors. An example is the differentiation between naturally-derived and anthropogenically-produced submerged sedimentary units found within the same archaeologically-rich coastal region of Caesarea Maritima, Israel (Reinhardt *et al.*, 2006). The detailed analysis of *Glycymeris* spp. (saltwater clam) bio-clast distributions found at different stratigraphic intervals indicated two distinct naturally marine-derived tsunami phases; these were compared to an anthropogenically induced and/or mixed ballast and pottery layer amid naturally occurring medium sand-sized siliciclastic sedimentation related to normal marine and winter storm conditions. However, subsequent reinterpretations by some of the authors, based primarily on particle size distributions (diameters < 2 mm) and several sedimentary textural and structural features, now suggest a tsunami origin for the previously identified anthropogenic layer (Morhange *et al*., 2014). This is an example of the complexity in weighting one analytical proxy more others, or the difficulty of identifying and characterizing natural from anthropogenic units in complex environmental and reworked archaeological settings.

Paleoenvironmental reconstruction

One of the goals of geoarchaeological research is to understand previous natural and anthropogenic events that took place within an archaeological context, either happening in sequence or ongoing intermittently. Based on such information, the environmental history of a site can be reconstructed from its beginnings. As a primary analytical technique, particle size analysis should always be accompanied by other basic analyses that have the potential to enhance comprehension of a targeted locus or sedimentary unit within the archaeological context. Examples of such other proxies are micropaleontology, and isotope and chemical analyses. The combined use of several analytical laboratory procedures increases the likelihood of obtaining data useful in elucidating the depositional context as a whole, and with decreasing margin of error. Underwater archaeological sites, and especially those situated along coastal areas, are among the more complex settings within which to reconstruct the stratigraphic succession of ancient environments. This is due not only to the submerged conditions, but also to the highly dynamic processes occurring therein, including sea-level changes, severe storms, extreme events such as tsunamis, littoral currents, and sediment movement, etc. In conjunction with these, prolonged and heavy human occupation of the (ancient) coastline adds to the complexity of the setting. Nonetheless, well-documented reconstructions of the lateral and/or vertical progression of environments due to continuous environmental evolution, abrupt natural changes, and man-made constructions can be seen throughout ancient coastlines. Examples from the Mediterranean include the reconstruction of the now submerged ancient city and port of Alexandria on the Nile Delta, Egypt (Mostafa *et al*., 2000), the reconstruction of the harbor complex of Caesarea Maritima, Israel – the largest constructed artificial harbor in the Mediterranean (Reinhardt *et al*., 2006), and the understanding of the destruction of ancient Palaikastro in Crete following the great eruption of Santorini in the Late Bronze Age (Bruins *et al*., 2008).

Analytical procedures and particle sizing techniques

One of the particularities of grain size analysis is the importance of estimating correctly the different size fractions that constitute the ensemble of the material being analyzed. In theory, each particle constituting the sample is to be analyzed individually, and the final result is the combination of all the individual measurements. Particles are complex three-dimensional objects with specific lengths, widths, and thicknesses, however (Folk, 1980; Stanley-Wood and Lines, 1992). Only perfect spheres can be completely described by a single number, i.e., their radius or diameter. So, in order to simplify the measurement process, particles are most commonly conceptualized as one-dimensional spheres rather than three-dimensional objects with irregular shapes. A cylinder with X length and Y diameter can be equivalent to a sphere of Z diameter that has the same volume as the cylinder. This is called the Concept of Equivalent Spheres (Jennings and Parslow, 1988). This concept can be applied to a number of different

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measuring properties of a particle, such as maximum and minimum diameter, surface area, volume, or weight. Based on this concept of equivalent spheres, sedimentation rates can be calculated, and simple things such as sieve aperture sizes can be specified (Folk, 1980; McManus, 1988).

If a sample is measured using different technical means, the results of each technique may not be equivalent because different apparatuses measure different parameters of the equivalent spheres. Therefore, consistency and comparability must be maintained. Grain size analyses can be performed by various means, in both dry and wet settings, depending on the type of material and its major constituent fraction. The coarse fraction of the sediment (> 0.063 mm) is commonly separated through dry sieving, whereas the finer sediment can be isolated by settling or sedimentation (using a hydrometer), or using laser diffraction (see Tables 1 and 2). Preparation of the sample is also a crucial point in the determination of a credible and accurate grain size measurement, and hence the importance of the objective of the study. If the target material is clastic, removal of other allochthonous materials is compulsory (e.g. organics, carbonates, oxides, salts, etc.) to avoid erroneous measurements and vice versa (Figure 3).

Sieving analysis

Sieving is the most basic of the particle sizing techniques. It consists of having the sediment pass through (by agitation) a series of stacked sieve meshes with defined opening sizes. Each sieve catches the size fraction that is larger than its mesh size, so that the successive sieves break up the sample into decreasing size fractions. The sediment fraction retained in each sieve is weighed in order to obtain its percentage relative to the whole sample. This technique can be used under dry or wet conditions.

The advantages of sieving are that it is cheap and user friendly, useful when dealing with very coarse samples and the physical separation of the sample is the end result. Its limitations are its low resolution and precision, that dry particles smaller than 50 μm or cohesive materials are very difficult to separate using this technique, and that results are influenced by the operator and the duration of agitation/shaking used, i.e., the technique itself (Folk, 1980; Krumbein and Sloss, 1963).

Sedimentation or settling

Sedimentation is the oldest of the techniques used in particle size analysis. It measures the rate of sedimentation of particles suspended in a liquid. Its advantages include its relatively low cost, and its ease of applicability to soils or very fine sediments (for which it is the traditional method). Its limitations are that it is useful only for a limited range of particle sizes, that it is not useful for sediment < 5 μm, and that it is extremely sensitive to particle shape (geometry) (Jennings and Parslow, 1988; Stanley-Wood and Lines, 1992).

Laser diffraction

Laser diffraction measures the angular dependence of laser light scattered by an ensemble of particles. Its advantages are that it can handle a very wide range of particle sizes (from < 100 nm to ~ 2–3 mm), that measurements can be made rapidly and thus large numbers of samples can be processed, and that results are accurate and repeatable (Syvitski, 2007).

Laser diffraction measurements provide particle size distributions with great detail. This enhancement in technical size measurement has greatly improved the ability to differentiate and compare different environments, and sometimes even better understand their dynamics.

When using a laser diffraction particle size analyzer, sediment can be run dry or wet. If wet, however, it is advised to pour out as much water as possible from the container to minimize errors. In either case, homogenizing and dispersing the sample prior to insertion into the machine is always a must, in order to analyze a truly representative portion of the sample.

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The limitations of laser diffraction include that it is not suitable for very coarse or nano-materials. It is a medium resolution technique and is applied to the whole (ensemble) sample.

Dynamic light scattering

Dynamic light scattering measures scattered light intensity variations due to Brownian motion of particles in suspension within a liquid. Its advantages are that its dynamic range is well suited to nano-materials (< 1 nm to 1 μm), its measurement speed is rapid so that it can handle larger numbers of samples, and its results are accurate and repeatable. Its limitations include the inability to analyze dense materials, and its medium resolution (Syvitski, 2007).

Particle size distributions

In nature, sediments do not consist of only one kind of particle, but rather an amalgamation of various particle sizes, hence it is logical to consider grain size as a continuous variable. Only perfectly mono-dispersed samples possess particles of exactly the same size, for example, highly sorted sand winnowed through hydrodynamic processes. Most natural samples contain a range, or distribution, of different particle sizes and shapes.

As a result of manual or instrumental measurement of grain size, a size frequency spectrum is obtained. Such spectrum is determined by the count of grains, weight or volume percent of a particular particle fraction within a specific size interval. The resulting spectrum can be deployed as a distribution of grain sizes based on the relative frequency of their number per size fraction (Figure 4). The most common graphic depiction used to represent the different grain sizes within a sample consists of a statistical distribution encompassing all resulting fractions based on their relative frequency (quantity or volume).Two common representations are used routinely: relative frequency and cumulative distribution curves (e.g., Figure 4). The different shapes of the relative frequency distribution curve can be interpreted as how well sorted the sample is: a narrow size range or narrow Gaussian shaped curve implies a well-sorted sample, whereas a larger size range or ample Gaussian shaped curve implies a poorly sorted sample (i.e., a wide range of particle sizes). Moreover, the more asymmetric the curve is within a single distribution, or if the latter presents several frequency peaks (as seen in Figure 4), the greater modality of the sample: poly-modality is shown by the greater frequency of distinct and different grain size range peaks. These different frequency groups are called populations and imply an ample modality of grain size fractions within the same sample, and vice versa.

Particle size distributions are based upon statistics, and description of the statistical parameters will usually depend on how the data are to be used. These calculated statistical parameters may give insight into various aspects of the environmental, depositional and transport conditions the sediment grains endured, linking them to particular sedimentary systems. Three common parameters are the mean, the median, and the mode (Figure 4). The mean is the average size of the entire sample, as seen in Figure 4. The median is the diameter where 50% of the particles are below or above that threshold. It is by far the easiest measure to determine but the least useful as it does not reflect the extremes of the curve (Folk, 1980). The mode is the particle size with the highest frequency, as seen in Figure 4, but it is not a good proxy of the overall sediment mixture (Folk, 1980). The only instance where all of these three parameters coincide is when the frequency distribution curve is a perfectly symmetrical Gaussian curve.

Other important statistical parameters obtained from the analysis of the distribution of particles – which can help elucidate how uniform, symmetric or well sorted the sediment sample is – are the standard deviation, skewness and kurtosis (Folk, 1980). The standard deviation is a precise measure of the scatter of grain size values from the mean, corresponding then to a measure of spread or sorting of the sample. In combination with the mean, the standard deviation is the most useful and widely applied value in granulometric statistics. Three limits are useful when computing standard deviations within a single sample: 1 standard deviation (±σ) from the mean implies that 68% of the grain size values fall within this

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limit; 2 standard deviations (±2σ) corresponds to 95% of the particles; and 3 standard deviations (±3σ) to 99% (Folk, 1980).

The skewness is used to establish the normality or symmetry of the distribution, hence to quantify the degree of dispersion within a sample, rather than only visualizing it on a frequency histogram. The closer the skewness value is to zero, the more symmetrical (i.e., normal or uni-modal) the distribution is. Asymmetrical and multi-modal sediment mixtures exhibit high values of skewness, to maximums of +1.00 and -1.00. The positive and negative sign of the skewness value indicates whether the asymmetrical tail extends to the left or right of the curve as follows (Folk, 1980). Distribution curves highly skewed to low grain size values show a negative value and are diagnostic of environments with higher concentrations of silts and clays. The opposite are environments with higher concentrations of coarser materials which show curves skewed to higher grain sizes, hence positive values. Extremely turbid systems such as grain or turbidity flows are diagnostic of negatively skewed distributions. Tsunami, colluvial, debris flows and torrential river deposits are diagnostic of positively skewed and multi-modal distributions.

The kurtosis is also a quantitative measure to describe the degree of Gaussian normality of the grain size distribution, but in terms of how acute or flat the curve is. This is a sorting relation between the end members of the curve and its center (Folk, 1980). If the central portion of the curve is peaked, hence better sorted than its tails, the distribution curve is said to be leptokurtic with values > 1.00. The opposite, a flat-peaked curve with a large spread of grain size in the centre, is called platikurtic, with values < 1.00. Normal probability curves have a kurtosis of 1.0 (Folk, 1980). Both kurtosis and skewness values are ratios of dispersion; thus, they are dimensionless and do not have units.

Summary

Grain size analysis is a fundamental tool for classifying unconsolidated materials and sediments, sedimentary rocks, and sedimentary environments. Quantitative analysis of the percentages of different particulate sizes yields one of the most fundamental physical properties of clastic sediments and sedimentary rocks. Grade scales, such as the geometric Udden-Wentworth or the logarithmic Krumbein Ø scales, which correspond to grain size intervals with a regular relationship to one another, were created to maintain a standardized statistical estimate of the measurement of the size of a particle, because grain size is considered a continuous variable. The almost exclusive purpose behind sizing grains is to obtain a frequency distribution of particle sizes.

A variety of principles and specific methodologies can be applied to differentiate and characterize the particle sizes of unconsolidated materials and sediments or sedimentary rocks. The traditional analytical principles behind granulometry (counting, sieving, and settling) are still frequently used today, and in some instances, they cannot be superseded by modern techniques because certain particle ranges lie beyond the measureable limits of sensitive minuscule sensors. For this reason, when dealing with particle size analyses, it is also important to consider the particle size range of the material to be analyzed, how narrow or wide this might be, in order to select the most appropriate measurement method(s). Gravels and boulders are mostly counted manually. Pebble sizes can be determined by sieving. Sands, silts, and clays can be measured either by sieving (wet and dry conditions) or settling (hydrometer, pipette). However, automated modern techniques such as laser diffraction or dynamic light scattering can make the measurement process much faster and accurate than traditional techniques, and a greater number of samples can be analyzed at a time.

Selection of the particle size technique to use is dependent not only on the precision and accuracy required for each sample measurement, but also the skills of the operator and the time that can be spent per measurement. Another important factor to consider is the cost of the equipment and any consumables

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associated with that particular technique. The choice of method is basically dictated by the objective of the study and the degree of consolidation of the material. This is the reason why it is imperative to have an understanding of the complexity of the environmental system and/or archaeological site targeted for study, as well as the natural processes that may have affected the locale, both in past and present times, in order to have a better analytical appraisal of the environmental conditions and contributions of events to the resulting stratigraphical signatures.

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Cross-references

Aeolian Settings: Loess
Aeolian Settings: Sand
Alluvial Settings
Archaeological Stratigraphy
Coastal Settings
Colluvial Settings
Lacustrine Settings
Mass Movement
Paleoenvironmental Reconstruction

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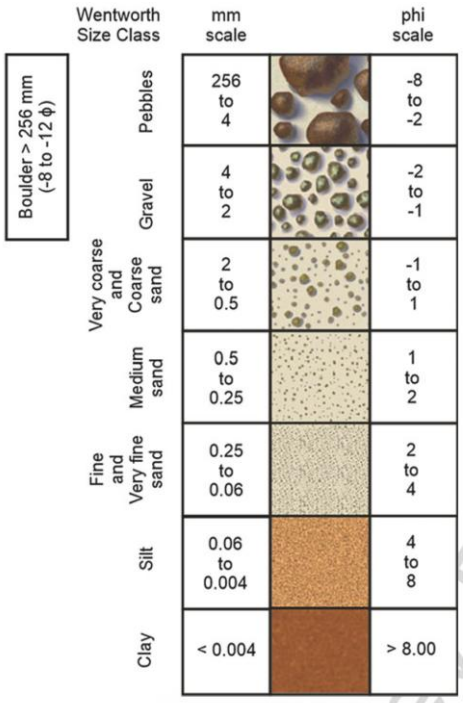
Tables & Figures

Grain size analysis, Table 1 Commonly used grain size characterization techniques and the particle size ranges (from nanometers, nm, to millimeters, mm) with which they function optimally. The upper and lower range limits are only a guide, as these limits may vary from one application or instrument to another

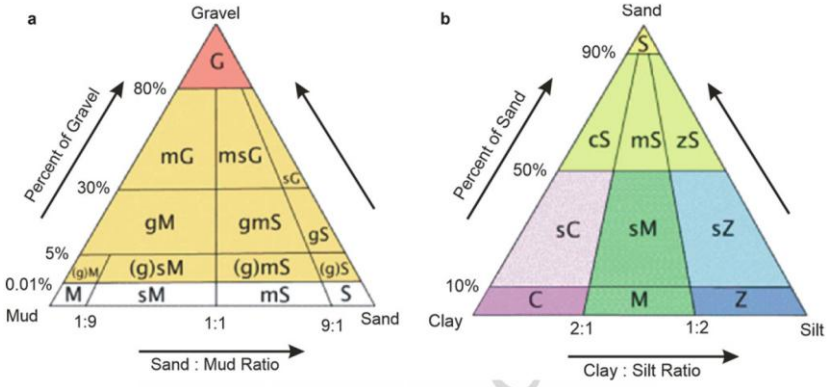
Particle Size Range	0.1 nm	1 nm	10 nm	100 nm	1 µm	10 µm	100 µm	1 mm	10 mm
Applicable Analytical Technique									
Sieving									
Laser Diffraction									
Settling									
Dynamic Light Scattering									

Grain size analysis, Table 2 Suitability of commonly used grain size characterization techniques: an increasing number of stars indicates a higher degree of appropriateness for each indicator

Analytical technique	Rapid	Resolution	Dynamic range	Sampling	Wet	Dry
Sieving	*	*	*	*	*	*
Laser diffraction	***	**	****	***	*	*
Settling	*	**	**	**	*	
Dynamic light scattering	***	**	***	**	*	



Grain size analysis, Figure 1 Diagram showing the different ranges of particle size, based on the Udden-Wentworth and Ø grain size scales for siliciclastic sediments (Wentworth, 1922; Krumbein and Sloss, 1963).



Grain size analysis, Figure 2 Ternary diagrams (**a** and **b**) showing Folk's classification system of sediments: textural terminology conceived as a graphical representation of the relative proportions of different grain size typologies, resulting in 21 major categories (Folk, 1980). The abbreviations are: *G* gravel, *g* gravelly, *(g)* slightly gravelly, *S* sand, *s* sandy, *M* mud, *m* muddy, *Z* silt, *z* silty, *C* clay, *c* clayey.

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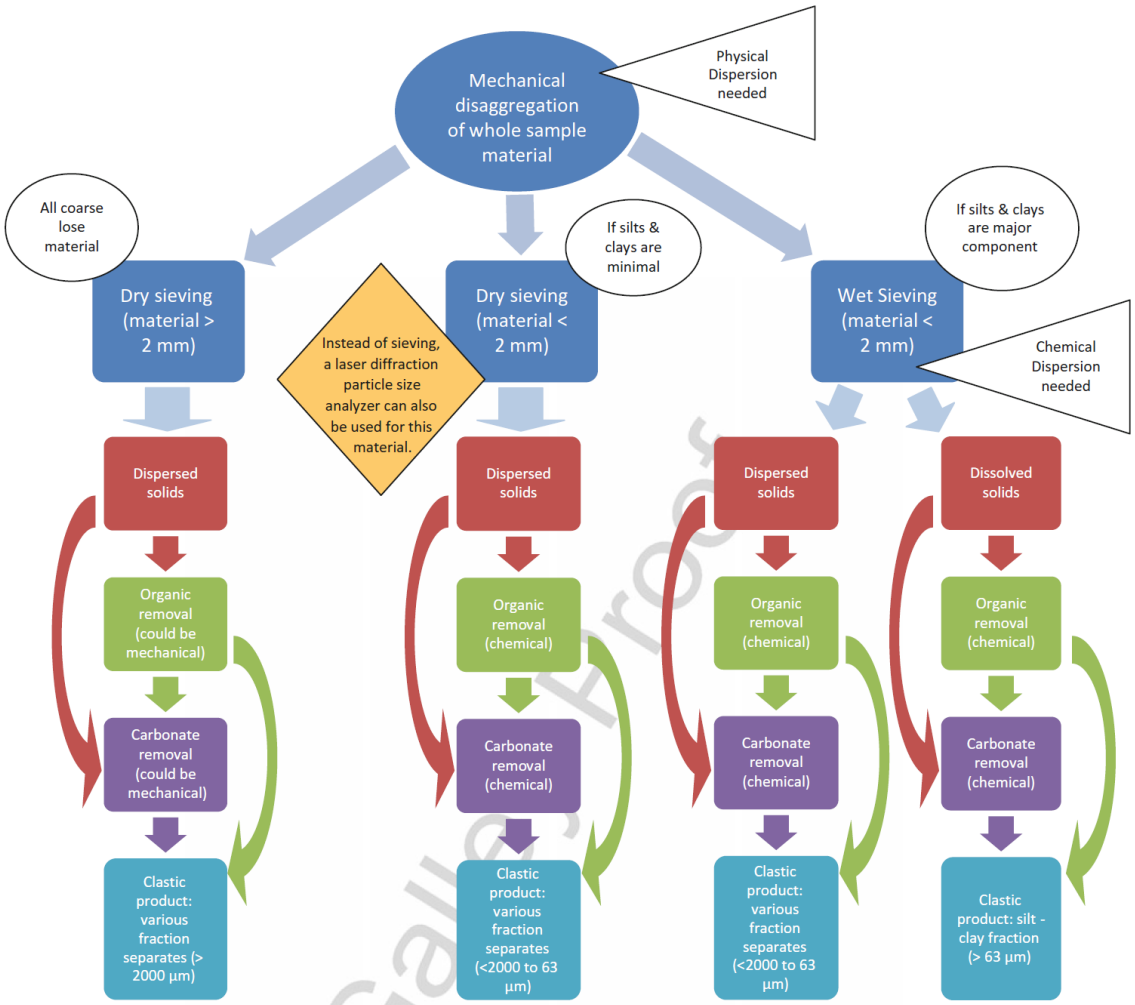
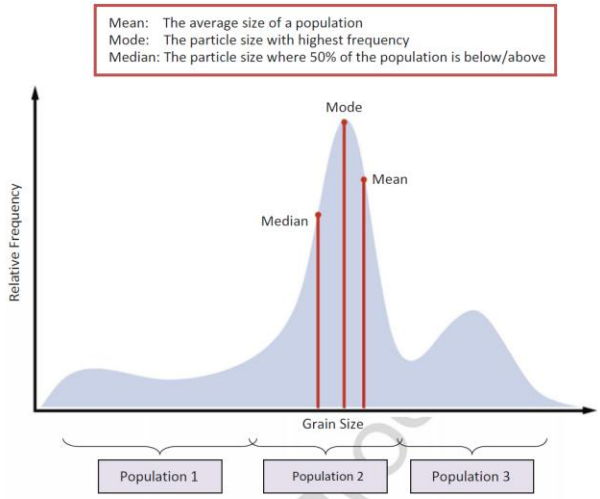


Grain size analysis, Figure 3 Flow diagram generalizing the steps taken when dealing with particle size analyses. Steps may be bypassed or more procedures may be added depending on the amount, type, condition, and size distribution (gradation) of each sample. For example, iron oxide removal with chemical agents may be needed in some samples in lieu of organic matter or carbonate removal. The same is true for the removal of any soluble salts. Chemical dispersion with appropriate dispersing chemicals such as Na-hexametaphosphate, Na_2PO_7, or NaOH (among others) is needed after removal of cementing and flocculating agents, mostly when dealing with silt and clay materials. The number of fractions of clastic "end product" would depend on the number of sieves used during the sieving process. Most laser diffraction particle size analyzers are specialized in a particular range of size fractions in order to avoid obstruction and/or laser errors, e.g., sand fraction (maximum particle size of 2,000 µm), or fine fraction (maximum particle size of 200 µm).



Grain size analysis, Figure 4 Graphical representations of a grain size distribution: relative frequency distribution curve of a sediment sample, illustrating the statistical concepts of Median, Mode and Mean. Three different grain size "populations" can be depicted for this particular multimodal sample.

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