Properties of sediment particles

Part II

Particle size distribution, sediment fabric and packing

Grain size

- Grain size is a fundamental property of sediments
- The sizes of particles in a deposit is linked to
  - Weathering,
  - Erosion
  - Transport processes
  - Depositional environment
- It is thus an important parameter which is used in combination with other data to interpret the origin of any particular sedimentary deposit

Other applications...

- Ecologists use grain size data when studying ecosystems
- Engineers use grain size data to estimate permeability and stability of sediments under load
- Hydrogeologists use grain size data to empirically estimate hydraulic conductivity of aquitards/aquifers
- Geochemists use grain size data to study kinetic reactions and the affinities of fine-grained particles and contaminants
- The goal is to accurately measure individual particle sizes to determine their **frequency distribution**, and to calculate a **statistical description** that adequately characterizes the sample
- The techniques and equipment used for particle-size analysis must be **fast**, **accurate**, and yield highly **reproducible** results

Grain-size scales

- Sediment “particles” range in size from a few microns to a few meters (wide range!)
  - Logarithmic or geometric scales are more useful
- Udden-Wentworth scale
  - Geometric scale (fixed ratio)

Udden-Wentworth scale

U. S. Standard Sieve Mesh #		Millimeters (1 Kilometer)	Microns	Phi (ϕ)	Wentworth Size Class	
				-20		
		4096		-12		
		1024		-10	Boulder (-8 to -12ϕ)	
Use		256		-8		
wire		64		-6	Cobble (-6 to -8ϕ)	
squares		16		-4	Pebble (-2 to -6ϕ)	GRAVEL
5		4		-2		
6		3.36		-1.75		
7		2.83		-1.5	Granule	
8		2.38		-1.25		
10		2.00		-1.0		
12		1.68		-0.75		
14		1.41		-0.5	Very coarse sand	
16		1.19		-0.25		
18		1.00		0.0		
20		0.84		0.25		
25		0.71		0.5	Coarse sand	
30		0.59		0.75		
35	1/2	0.50	500	1.0		
40		0.42	420	1.25		
45		0.35	350	1.5	Medium sand	SAND
50		0.30	300	1.75		
60	1/4	0.25	250	2.0		
70		0.210	210	2.25		
80		0.177	177	2.5	Fine sand	
100		0.149	149	2.75		
120	1/8	0.125	125	3.0		
140		0.105	105	3.25		
170		0.088	88	3.5	Very fine sand	
200		0.074	74	3.75		
230	1/16	0.0625	62.5	4.0		
270		0.053	53	4.25		
325		0.044	44	4.5	Coarse silt	
		0.037	37	4.75		
	1/32	0.031	31	5.0		
Analyzed	1/64	0.0156	15.6	6.0	Medium silt	
	1/128	0.0078	7.8	7.0	Fine silt	MUD
by	1/256	0.0039	3.9	8.0	Very fine silt	
		0.0020	2.0	9.0		
Pipette		0.00098	0.98	10.0	Clay	
		0.00049	0.49	11.0		
or		0.00024	0.24	12.0		
		0.00012	0.12	13.0		
Hydrometer		0.00006	0.06	14.0		

Logarithmic phi scale

- Allows grain-size data to be expressed in units of equal value

$$\phi = -\log_2 d$$

Or...

$$\phi = -\log_{10} d / \log_{10} 2$$

- Sand-sized particles have positive phi values (practical)

Measuring grain size

- Large particles
  - Caliper or tape
- Granule- to silt-size particles
  - Sieving techniques
- Clay-size particles
  - Pipette analysis (laborious process)
  - Automatic-recording settling tubes
  - Photohydrometer
  - Sedigraph
  - Laser-diffraction size analyser
  - Electro-resistance size analyzers
  - Image analysis

Sieves

Settling velocity of particles

- Settling velocity
  - Fluid viscosity
  - Size, shape, and density of the particles
- Interaction of viscous resistance (drag) and gravity

Stoke's Law

$$V = \frac{1}{18} \frac{(\rho_s - \rho_f) g D^2}{\mu} \qquad (1)$$

ρ_s = particle density (quartz = 2.65g/cm^3)

ρ_f = fluid density (water = 1g/cm^3)

g = gravitational force; 980.7 cm/s^2

D = diameter of the grain

μ = molecular dynamic viscosity

(the viscosity of water at 20°C is 1 centipoise (cP) or 0.01g · cm^{-1}·s^{-1})

Accurate estimates for particles < 0.1 – 0.2 mm

$V \propto d^2$ but $\propto 1/\mu$

In practice...

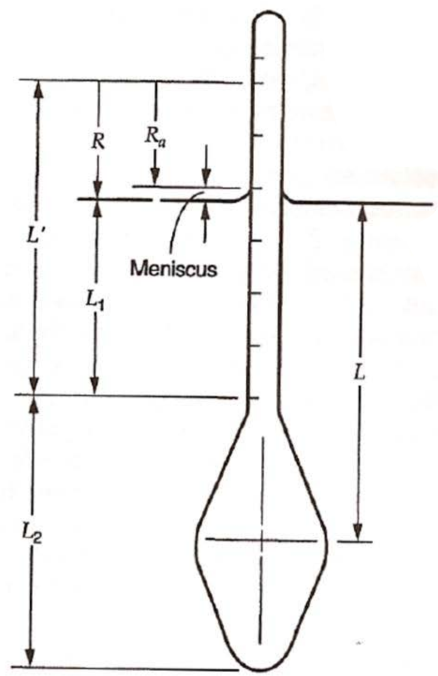
Re-arranging Eq. (1) to calculate the diameter D

$$V = \frac{1}{18}\frac{(\rho_s - \rho_f)gD^2}{\mu} \rightarrow D = \sqrt{\frac{18\mu v}{g(\rho_s - \rho_f)}} \rightarrow D = \sqrt{\frac{18\mu}{g(\rho_s - \rho_f)}}\sqrt{\frac{L}{t}}$$

$$C = \sqrt{\frac{18\mu}{\gamma}} \quad \rightarrow \quad \boldsymbol{D} = \boldsymbol{C}\sqrt{\frac{\boldsymbol{L}}{\boldsymbol{t}}}$$

$$where\ \gamma = g\rho = specific\ weight\ (g \cdot cm^{-2} \cdot s^{-2})$$

Hydrometer



$v = L/t$ cm/s
$L = L_1 + 1/2(L_2 - V_b/A_{grad})$
$L_1 \cong 10.5$ cm for $R = 0$
$L_1 \cong 2.30$ cm for $R = 50$
$L_2 \cong 14$ cm (ASTM)
$V_b \cong 67.0$ cm^3
$A_{grad} \cong 27.8$ cm^2 for 1000 mL graduated cylinder (not a hydrometer jar)
R_a = actual reading
$R = R_a$ corrected for meniscus

L is effective depth and t is readings time (e.g. 1min, 2min, 4, 8, 15, 30min, 1hr, 2, 4, 8, and 24hrs

Figure 1: Hydrometer dimensions and terms

Percentage of fine particles

$$P_f = a\frac{R_c}{M_s} \times 100\%$$

- P_f is % of particles in suspension, R_c = corrected hydrometer reading, *a* is a correction factor (usually 1 if assuming *Specific Gravity* = 2.65), and M_s is the mass of the dry sample <0.063 mm that was poured in the cylinder (usually 50g)
- To plot the percentage on a composite curve that includes particles >0.063mm, the % has to be adjusted to take into account the % passing (<0.063mm) relative to the total sample.

$$P = \frac{P_f \times \%\, passing}{100}$$

Example of results

Time (min)	Rc	Pf (%)	% corr.*	L (cm)	L/t	C	D (mm)
1	45.00	89.0	30.4	8.8	8.88	0.0124	0.0368
2	40.00	79.2	27.0	9.6	4.8	0.0124	0.0272
4	35.00	69.3	23.6	10.4	2.6	0.0124	0.0200
8	30.00	59.4	20.2	11.2	1.4	0.0124	0.0147
16	27.00	53.4	18.2	11.7	0.731	0.0124	0.0106
30	24.00	47.5	16.2	12.2	0.407	0.0124	0.0079
60	21.65	42.8	14.6	12.5	0.208	0.0125	0.0057
150	18.65	36.9	12.6	13.0	0.087	0.0125	0.0037
1440 (24hrs)	16.70	33.0	11.3	13.2	0.009	0.0130	0.0012

*This is the value that is used to build a composite grain size curve that takes into account all size fractions in the sample

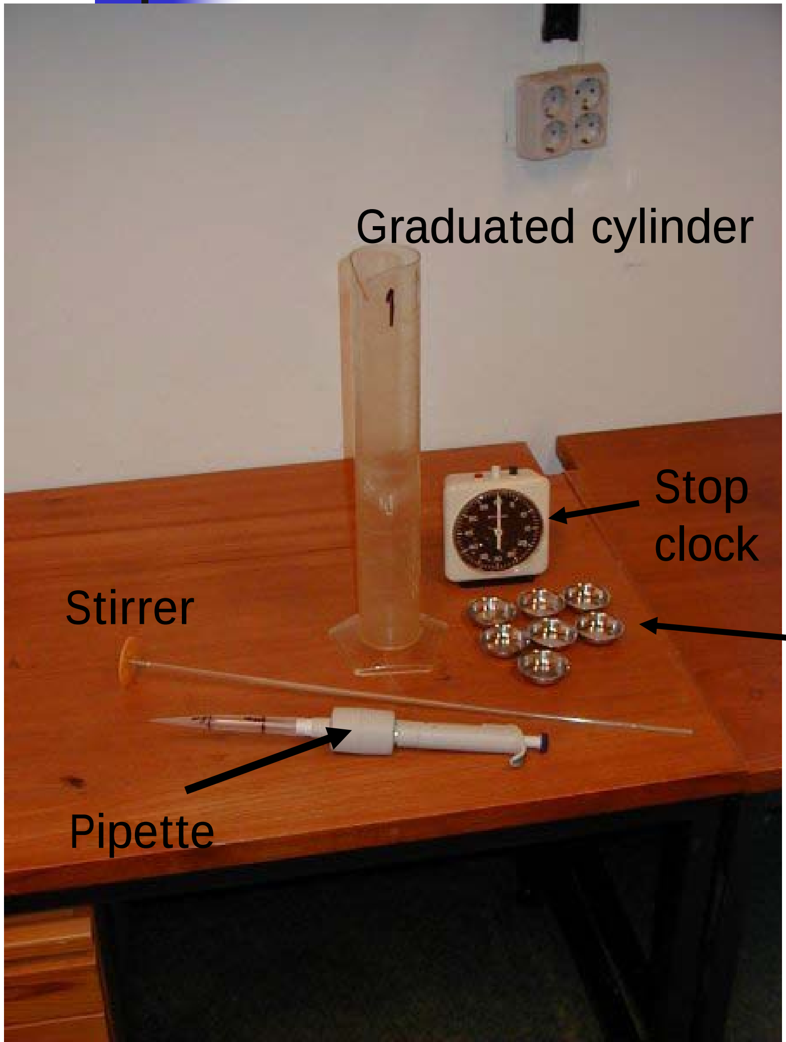
In this example, the fraction used in the hydrometer test represents 34.1% of the total sample

Exercise: Build a cumulative curve of the hydrometer results.

Main assumptions

- Laminar flow
- Spherical particles
- Uniform composition (density)
- Smooth surface
- Particles do not interfere w each other

Pipette analysis



Many sedimentation laboratories have discontinued or limited the use of pipette and hydrometer techniques because of inherent problems with settling

-Brownian motion;
-Thermal convection;
-Irregular particle shape;
-Manipulation error
-The time

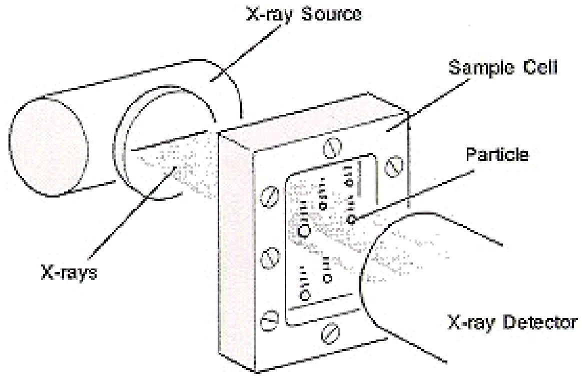
For example, over 24 hours are required to extend down to 11 phi at room temperature

Photohydrometer

- Settling tube
  - Empirically relates changes in intensity of a beam of light passed through a column of suspended sediment to particle settling velocities (thus to particle size)

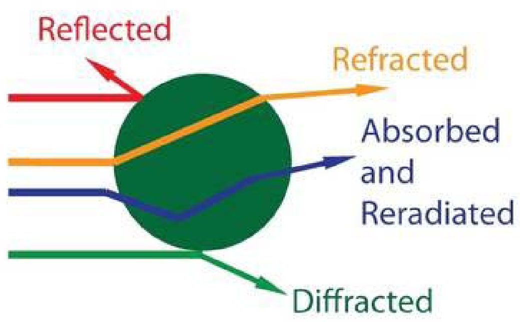
Sedigraph

- Particle size is determine by measuring the attenuation of a finely collimated X-ray beam as a function of time and height in a settling suspension
- The X-ray beam does not disturb the suspension
- X-ray absorption is used to determine the % of total particle mass at different points in the cell.



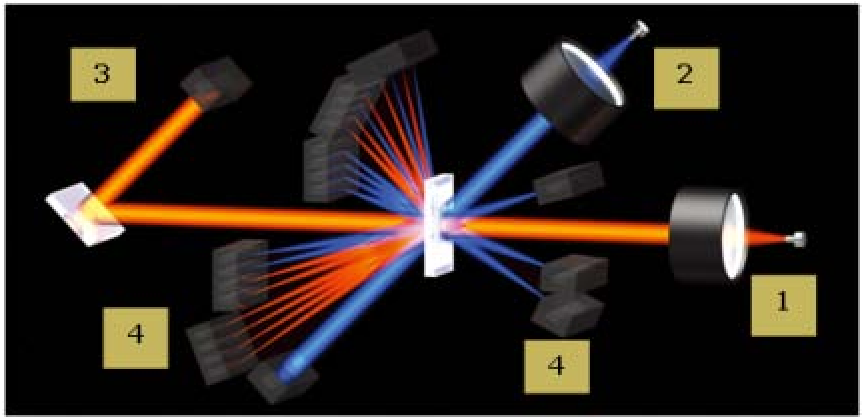
Laser diffraction

- For particles larger than about 20 microns the vast majority of light is scattered by diffraction. The scattered light is at relatively high intensity and low angle.
- For particles smaller than 20 microns refracted light becomes increasingly important to calculate an accurate particle size. The scattered light is at relatively low intensity and wide angle for these smaller particles. The use of a refractive index and the Mie scattering theory is necessary to produce accurate results in this size range



The basic workflow of a laser diffraction particle size analysis breaks down into two parts:

1- Measure scattered light angle and intensity
2- Transform that scattering data into a particle size distribution

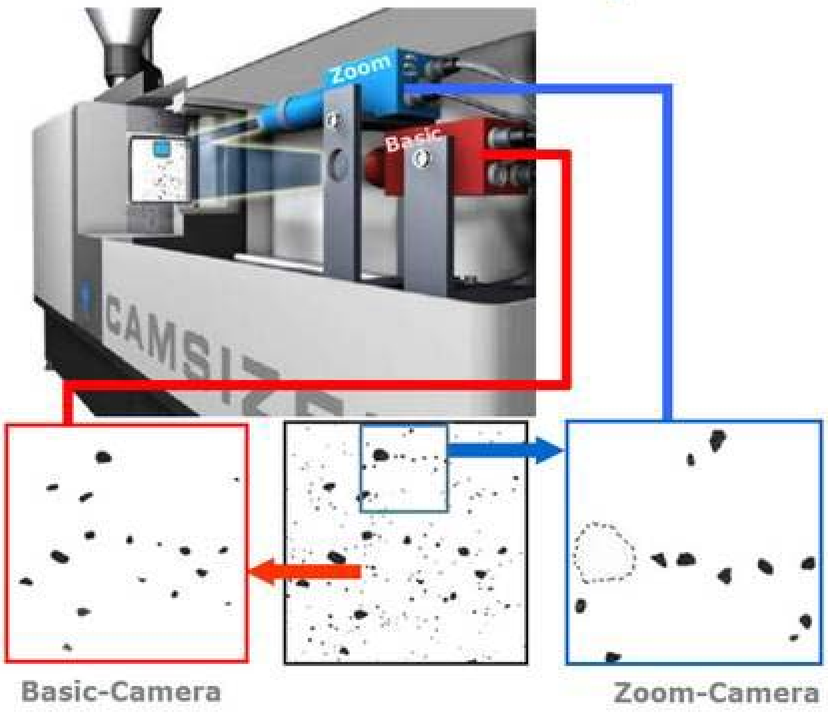


A simplified layout for an optical bench. 1: Red wavelength laser diode for larger particles, 2: Blue LED for smaller particles, 3: Low angle detectors for larger particles, 4: Side and back angle detector arrays and smaller particles.

http://www.horiba.com/scientific/products/particle-characterization/technology/laser-diffraction/fundamentals-of-diffraction/

Digital image analysis

- Measuring range depends on the system:
  - from 1 µm to 8 mm
  - from 20 microns to 30 millimeters
- Analyze particle size and shape



http://www.horiba.com/scientific/products/particle-characterization/particle-size-analysis/details/camsizer-602/

Grain size data

- Typical grain size data table

A

ϕ Size	Raw weight (gm)	Individual weight percent	Cumulative weight percent
−1.0	0.43	0.5	0.5
−0.5	2.13	2.5	3.0
0.0	4.25	5.0	8.0
0.5	6.80	8.0	16.0
1.0	9.35	11.0	27.0
1.5	12.75	15.0	42.0
2.0	13.58	16.0	58.0
2.5	12.75	15.0	73.0
3.0	9.35	11.0	84.0
3.5	6.80	8.0	92.0
4.0	4.25	5.0	97.0
4.5	2.13	2.5	99.5
5.0	0.43	0.5	100.0
	85.00		

Method of moments

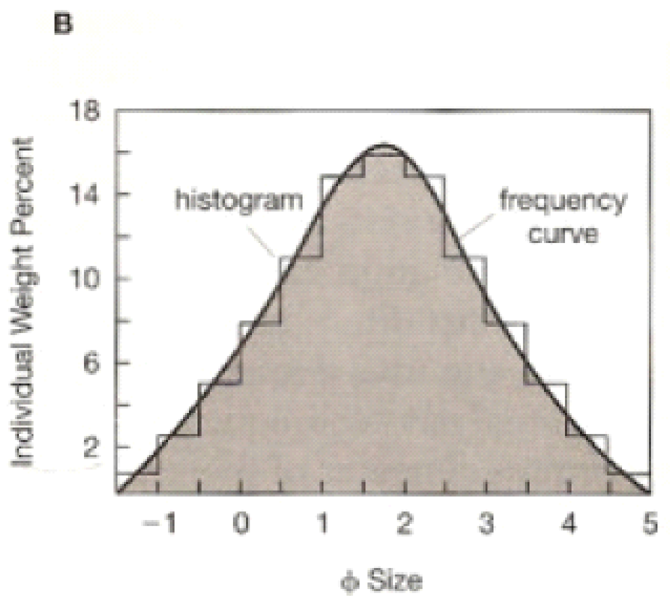
- Grain-size parameters are calculated from values of
  - f: weight freq. (%) in each class interval
  - $m\phi$: the midpoint value of each class interval in phi units (or mm)
  - The 1st moment gives the mean ($\bar{x}$)
  - The 2nd moment gives the sorting (σ)
  - The 3rd moment gives skewness (α_3)
  - The mean-cubed deviation is also frequently used

Advantages

- Statistical parameters are calculated directly from the sieve data
- Millimeter values can be used
- The formulas can easily be programmed into a computer

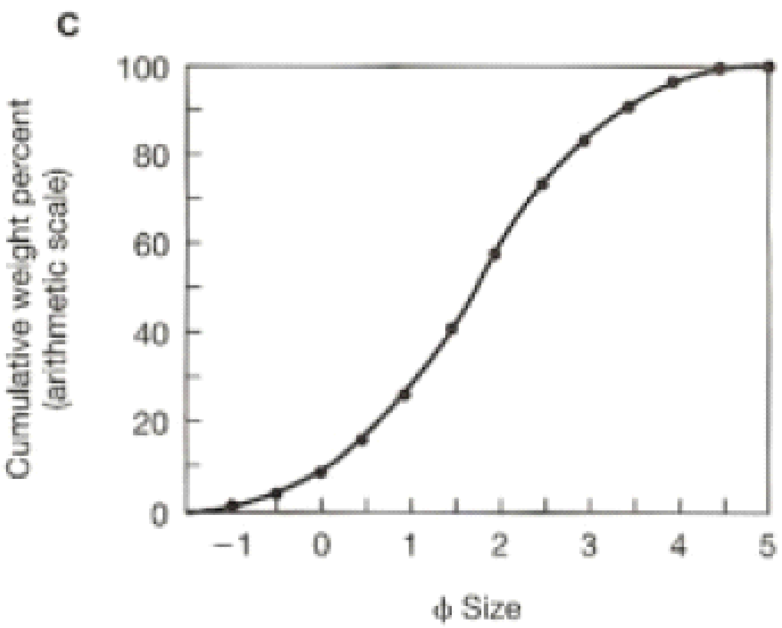
Graphical plots

- Histograms and freq. curves
  - Quick and easy to visualize approx. average grain size and the sorting
  - The shape is affected by the sieve interval used
  - Not very useful for statistical analysis



Graphical plots

- Cumulative curves
  - Its shape is much less dependent of the sieve interval used
  - Allow many calculations
  - Arithmetic or log probability scales



Graphical-statistical methods

- Statistical parameters
  - Average grain size
    - Mode
      - Most frequently occurring particle size (midpoint of class interval)
      - Steepest pt. on a cum. curve
      - Highest pt. on a freq. curve or tallest bar on histogram
      - Most terrigenous sediments are either unimodal or bimodal; but some are even polymodal
    - Median size (midpoint)
      - 50^{th} percentile on the cum. curve
    - Graphic mean
      - Approx. of the arithmetic mean using selected percentile values

$$Mz = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$$

Graphical-statistical methods

- Phi standard deviation
  - Mathematical expression of sorting
    - Range of grain sizes and the spread around the mean

$$\sigma_i = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$$

    - Indication of the effectiveness of the depositional environment in separating (sorting) grains of different sizes

Sorting

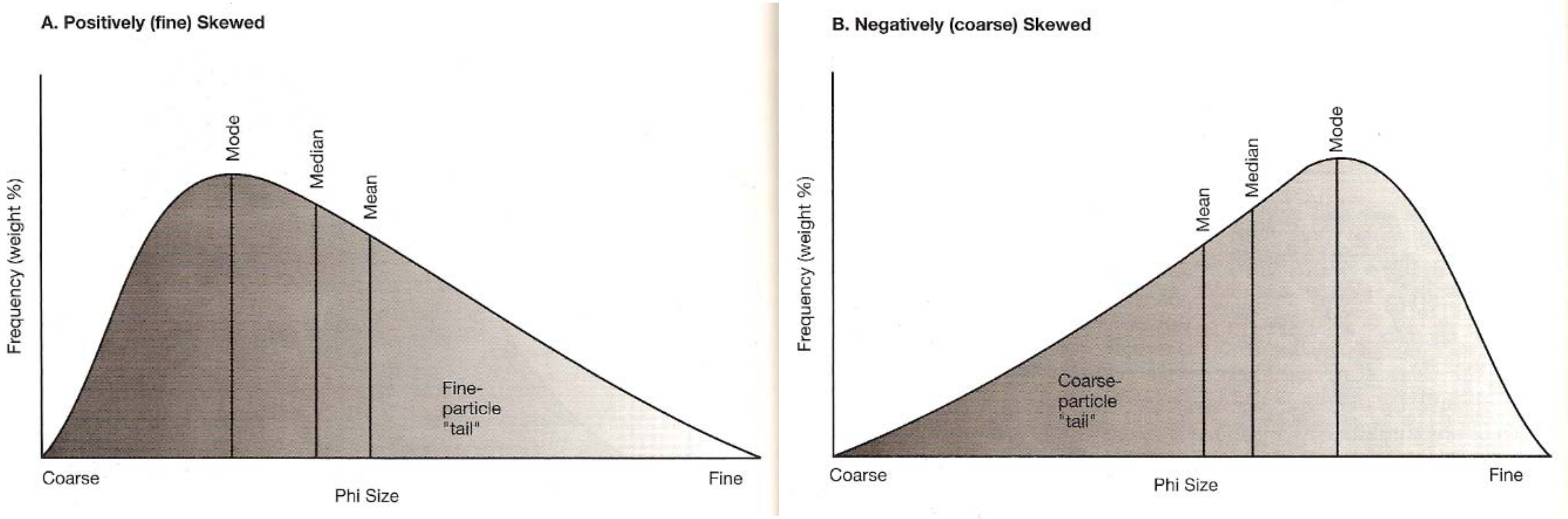
- Sorting depends on
  - The geology of the source area
  - Distance to source
  - Grain-size itself
    - Sandy sediments are the most well sorted
  - Depositional mechanisms
    - Normal vs catastrophic
    - Sandy deposits of deserts, beaches and shallow shelf seas are better sorted

Standard Deviation	
$<0.35\phi$	very well sorted
$0.35–0.50\phi$	well sorted
$0.50–0.71\phi$	moderately well sorted
$0.71–1.00\phi$	moderately sorted
$1.00–2.00\phi$	poorly sorted
$2.00–4.00\phi$	very poorly sorted
$>4.00\phi$	extremely poorly sorted

Graphical-statistical methods

- Skewness
  - The frequency curves of most natural samples generally show some degree of asymmetry, or **skewness**
  - Reflects sorting in the ‘tails’ of a grain-size population

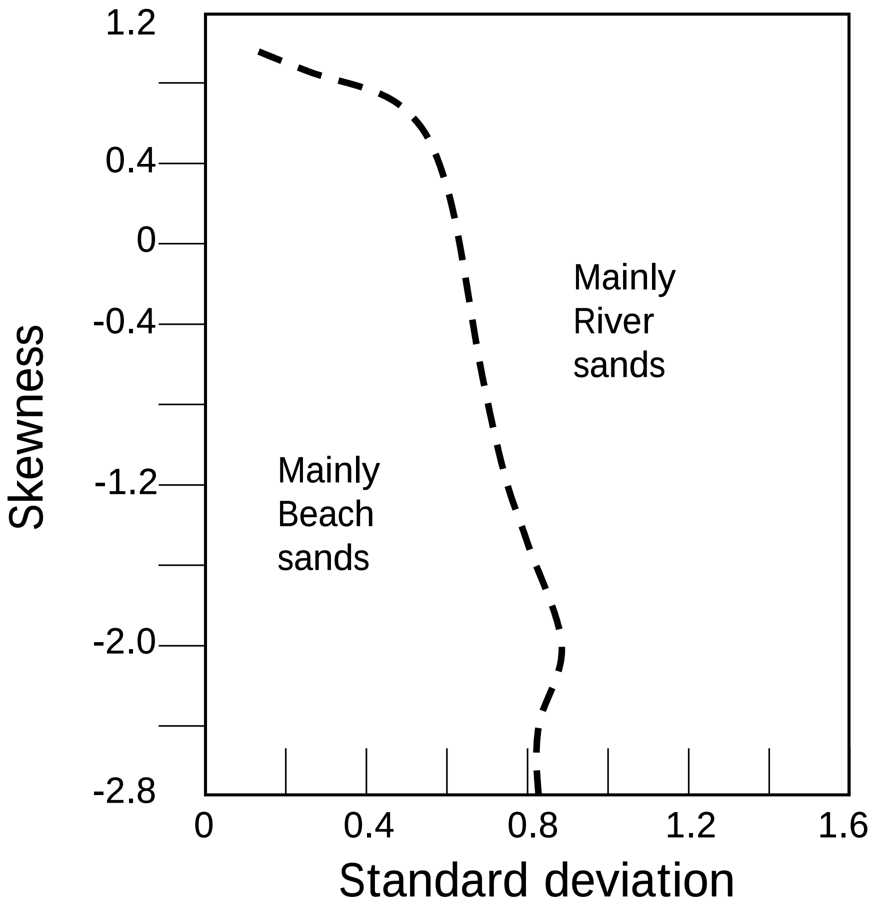
Skewed grain-size populations



Skewness and depositional process

- Beach sands tend to have a negative skew
  - Fine components have been carried away by the persistent wave action
- River sands are usually +ly skewed
  - Much silt and clay is trapped between larger grains
- Some desert dune sands have a neg. skewed
  - Much of the silt is blown out of the system (dust plumes)

Friedman graphs



Limitations

- Grain-size distributions reflect **processes**, not environments
  - Several different processes may well have operated in one environment
  - Similar processes do take place in different environments
- Sediments can have recorded a complex history
  - e.g. Multiple reworking
- Can have multiple inherited characteristics

Recommendations

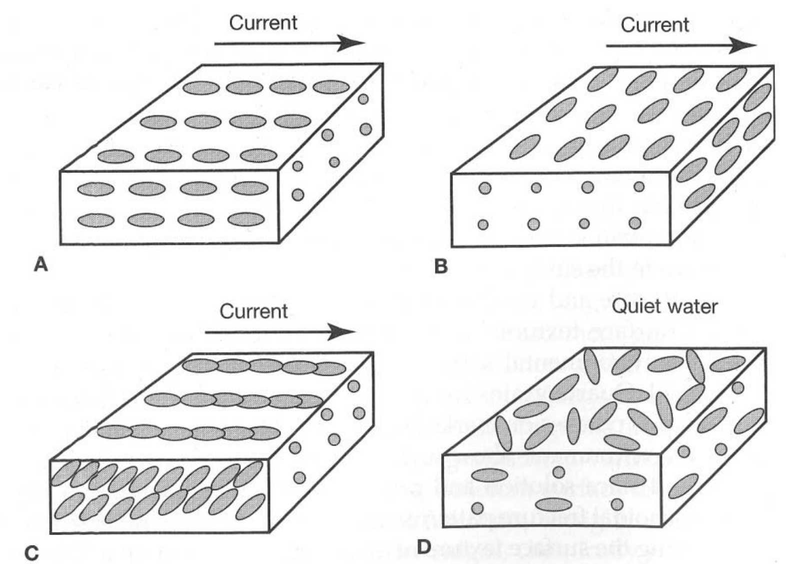
- Grain-size data should be considered as only one of the available tools
  - Sedimentary structures
  - Sediment composition
  - Sediment-landform associations
  - General geologic/stratigraphic context
  - Etc.

Sediment fabric

- The fabric of sediments
  - The 3D orientation (or lack of it) in space and the packing of the elements (e.g. discrete particles) of which a sediment (or rock) is composed
    - Control physical properties
      - Bulk density
      - Porosity
      - Permeability
    - Usually stronger with platy/elongated particles
- Caused by transport and depositional processes
  - Water or ice flow velocities

Types of fabric

- Align parallel to the current direction (A)
- Grains oriented normal to current flow (B)
- Imbrication (C)
- Lack of preferred orientation/imbrication (D)
  - Isotropic
  - Anisotropic



- Primary, autokinetic
-Secondary, allokinetic

Preferred orientation

Lack of preferred orientation?

Caution: the orientation of a section is not always ideal...

Fabric shape

- 3D fabrics: a-b plane, a-axis orientation
- Stereographic and equal area projections
- Statistical analysis of axial data
  - e.g. Eigenvalue method

Principal component analysis

- Sedimentologists have been interested in eigenvalues because they are related to fabric shape
- Fabric shape is largely determined by the mode of sediment transport/deposition
  - Eigenvalues may tell us something about how a sediment was deposited

Eigenvalue method

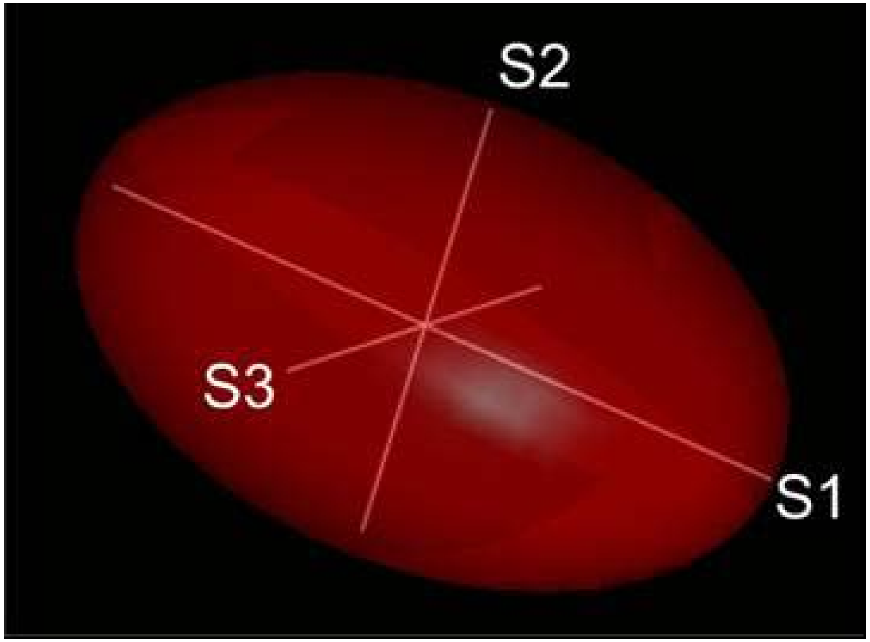
- Observations are resolved into three orthogonal vectors (V_1, V_2, V_3); V_1 = max. clustering, V_3 = min. clust. (i.e. is normal to the preferred plane of the fabric)
- The degree of clustering is given by:
  - Normalized vector magnitudes (eigenvalues) (S_1, S_2, S_3)
    - Degree of clustering data about the respective vectors

$$S_1 > S_2 > S_3$$

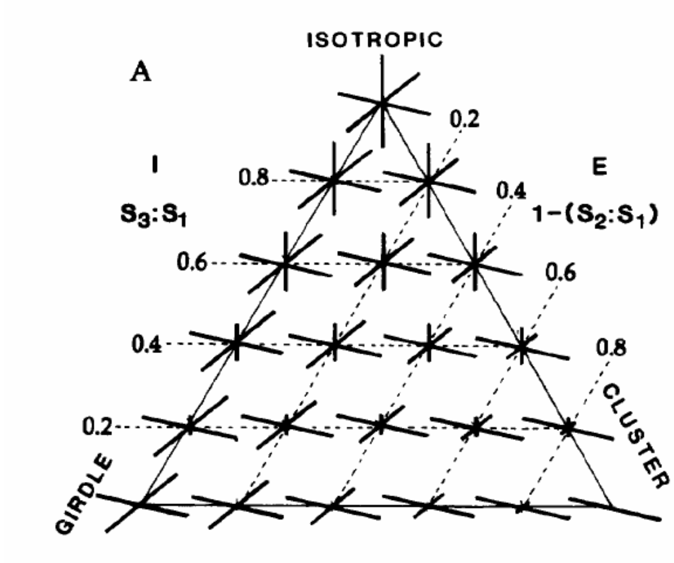
$$S_1 + S_2 + S_3 = 1$$

3D shape of data distribution

- The three normalized eigenvalues (S1, S2, S3) are the principal components of an ellipsoid approximating the shape of data distribution in three dimensions



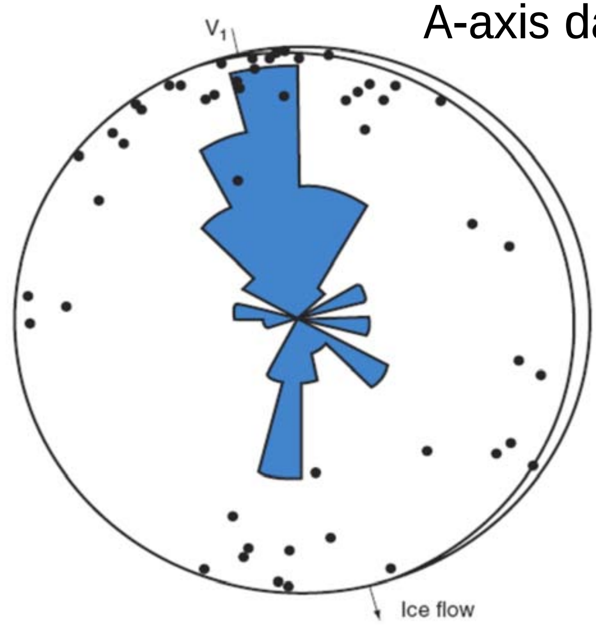
Fabric shape



$S_1 \approx S_2 > S_3$

$S_1 > S_2 \approx S_3$

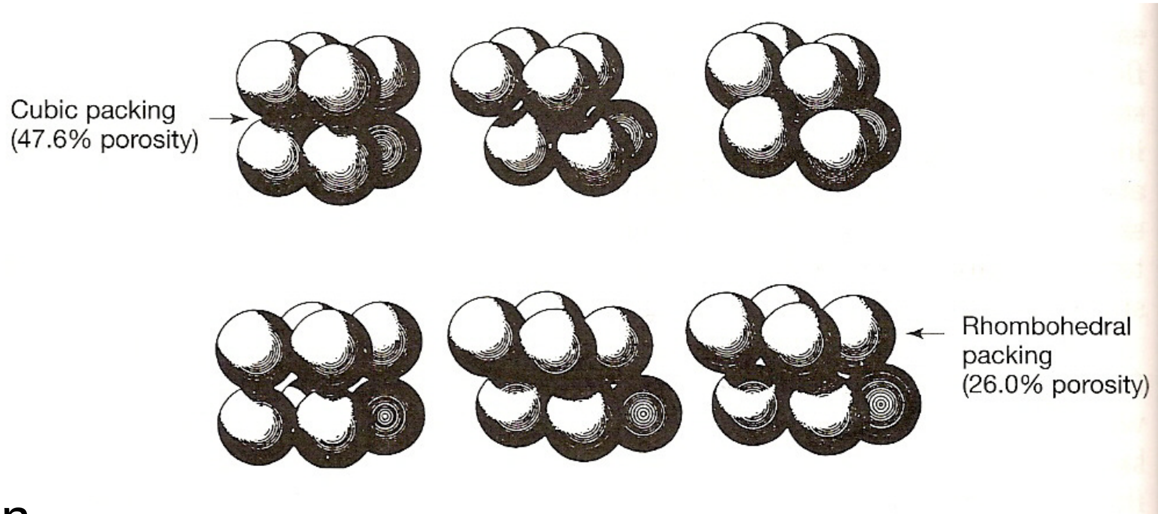
A-axis data



Lambert equal-area (Schmidt) plot

Grain packing

- Spacing or density patterns of grains
  - Grain size
  - Shape
  - Fabric
  - Degree of compaction
- Packing strongly affects
  - Bulk density
  - Porosity
  - Permeability



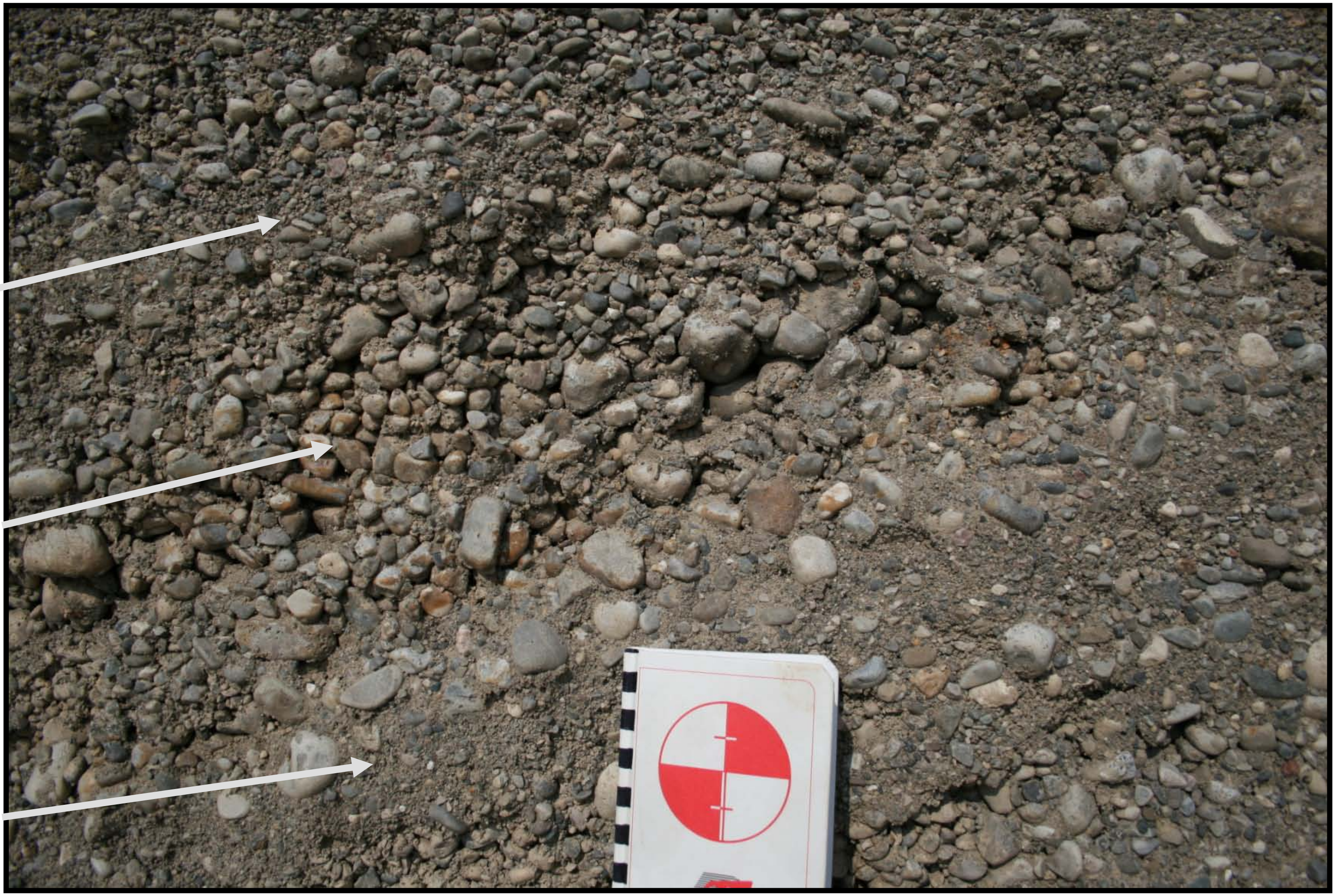
Clastic sediment facies

Clastic sediment facies

Framework bimodal gravel

Openwork gravel

Polymodal gravel



Openwork gravel: gravel packed loosely with unfilled voids