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TECHNICAL COMMUNICATION

GRADISTAT: A GRAIN SIZE DISTRIBUTION AND STATISTICS PACKAGE FOR THE ANALYSIS OF UNCONSOLIDATED SEDIMENTS

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ABSTRACT

Grain size analysis is an essential tool for classifying sedimentary environments. The calculation of statistics for many samples can, however, be a laborious process. A computer program called GRADISTAT has been written for the rapid analysis of grain size statistics from any of the standard measuring techniques, such as sieving and laser granulometry. Mean, mode, sorting, skewness and other statistics are calculated arithmetically and geometrically (in metric units) and logarithmically (in phi units) using moment and Folk and Ward graphical methods. Method comparison has allowed Folk and Ward descriptive terms to be assigned to moments statistics. Results indicate that Folk and Ward measures, expressed in metric units, appear to provide the most robust basis for routine comparisons of compositionally variable sediments. The program runs within the Microsoft Excel spreadsheet package and is extremely versatile, accepting standard and non-standard size data, and producing a range of graphical outputs including frequency and ternary plots. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: grain size statistics; moments method; sediments

INTRODUCTION

Grain size is the most fundamental property of sediment particles, affecting their entrainment, transport and deposition. Grain size analysis therefore provides important clues to the sediment provenance, transport history and depositional conditions (e.g. Folk and Ward, 1957; Friedman, 1979; Bui *et al*., 1990). The various techniques employed in grain size determination include direct measurement, dry and wet sieving, sedimentation, and measurement by laser granulometer, X-ray sedigraph and Coulter counter. These methods describe widely different aspects of 'size', including *maximum calliper diameter, sieve diameter* and *equivalent spherical diameter*, and are to a greater or lesser extent influenced by variations in grain shape, density and optical properties. For this reason, the results obtained using different methods may not be directly comparable, and it can be difficult to assimilate size data obtained using more than one method (Pye, 1994). All techniques involve the division of the sediment sample into a number of size fractions, enabling a grain size distribution to be constructed from the weight or volume percentage of sediment in each size fraction.

FUNDAMENTALS OF GRAIN SIZE ANALYSIS

In order to compare different sediments, grain size distributions have most frequently been described by their deviation from a prescribed ideal distribution. Computations performed assuming a normal, or Gaussian,

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distribution, with an arithmetic grain size scale, are seldom used in sedimentology, since too much emphasis is placed on coarse sediment and too little on fine particles (McManus, 1988). Consequently, geometric scaling is usually employed to place equal emphasis on small differences in fine particles and larger differences in coarse particles (Figure 1). Most sedimentologists have adopted the logarithmic Udden–Wentworth grade scale (Udden, 1914; Wentworth, 1922), where the boundaries between successive size classes differ by a factor of two. In order to facilitate graphical presentation and statistical manipulation of grain size frequency data, Krumbein (1934) further proposed that grade scale boundaries should be logarithmically transformed into phi (ϕ) values, using the expression $\phi = -\log_2 d$, where d is the grain diameter in millimetres (Table I). Distributions using these scales are termed 'log-normal', and are conventionally used by sedimentologists (e.g. Visher, 1969; Middleton, 1976).

Some workers have advocated comparisons with alternative distributions. For example, it has been claimed that additional information can be gained if both the grain size and frequency scales are logarithmically transformed (e.g. Bagnold and Barndorff-Nielsen, 1980; Hartmann and Christiansen, 1992). However, the majority of sedimentologists have yet to be convinced that such 'log-hyperbolic' distributions provide any significantly greater insight into the processes involved (e.g. Wyrwoll and Smith, 1985, 1988), and most still use the log-normal distribution.

The parameters used to describe a grain size distribution fall into four principal groups: those measuring (a) the average size, (b) the spread (sorting) of the sizes around the average, (c) the symmetry or preferential

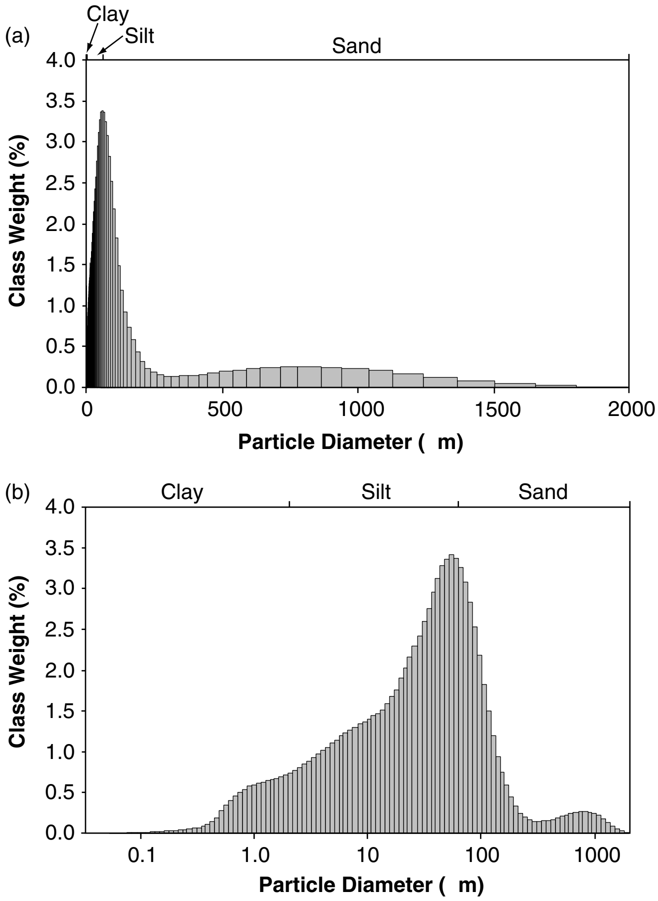

Figure 1. Grain size frequency histograms for a poorly sorted glacial till (Lowestoft, UK), analysed by laser granulometer and plotted with (a) arithmetic size scale and (b) geometric size scale

Table I. Size scale adopted in the GRADISTAT program, compared with those previously used by Udden (1914), Wentworth (1922) and Friedman and Sanders (1978)

Grain size		Descriptive terminology			
phi	mm/ m	Udden (1914) and Wentworth (1922)	Friedman and Sanders (1978)	GRADISTAT program	
			Very large boulders		
−11	2048 mm				
			Large boulders	Very large	Boulders
−10	1024				
			Medium boulders	Large	
−9	512	Cobbles			
			Small boulders	Medium	
−8	256				
			Large cobbles	Small	
−7	128				
			Small cobbles	Very small	
−6	64				
			Very coarse pebbles	Very coarse	Gravel
−5	32				
			Coarse pebbles	Coarse	
−4	16	Pebbles			
			Medium pebbles	Medium	
−3	8				
			Fine pebbles	Fine	
−2	4				
		Granules	Very fine pebbles	Very fine	
−1	2				
		Very coarse sand	Very coarse sand	Very coarse	Sand
0	1				
		Coarse sand	Coarse sand	Coarse	
1	500 m				
		Medium sand	Medium sand	Medium	
2	250				
		Fine sand	Fine sand	Fine	
3	125				
		Very fine sand	Very fine sand	Very fine	
4	63				
			Very coarse silt	Very coarse	Silt
5	31				
			Coarse silt	Coarse	
6	16	Silt			
			Medium silt	Medium	
7	8				
			Fine silt	Fine	
8	4				
			Very fine silt	Very fine	
9	2	Clay			
			Clay	Clay	

spread (skewness) to one side of the average, and (d) the degree of concentration of the grains relative to the average (kurtosis). These parameters can be easily obtained by mathematical or graphical methods. The mathematical 'method of moments' (Krumbein and Pettijohn, 1938; Friedman and Johnson, 1982) is the most accurate since it employs the entire sample population. However, as a consequence, the statistics are greatly affected by outliers in the tails of the distribution, and this form of analysis should not be used unless the size distribution is fully known (McManus, 1988).

Prior to the availability of modern computers, the calculation of grain size parameters by the method of moments was a laborious process. Approximations of the parameters can, however, be obtained by plotting frequency data as a cumulative frequency curve, extracting prescribed values from the curve and entering these into established formulae. Many formulae have been proposed (e.g. Trask, 1932; Krumbein, 1938; Otto, 1939; Inman, 1952; McCammon, 1962) although the most widely used are those proposed by Folk and Ward (1957). Such techniques are most appropriate for the analysis of open-ended distributions, since the tails of the distribution, which may include extreme outliers, are ignored. With the development of computerized data analysis, however, calculation of both method of moments and graphical parameters can be automated, and some of the original advantages of graphical techniques no longer apply.

THE GRADISTAT PROGRAM

It is with the wide-ranging needs of researchers in geomorphology and sedimentology in mind that the GRADISTAT program has been written. It provides rapid (approximately 50 samples per hour) calculation of grain size statistics by both Folk and Ward (1957) and moments methods. While programs capable of analysing grain size data have been published in the past (e.g. Isphording, 1970; Slatt and Press, 1976; McLane, cited in Pye, 1989; Utke, 1997), these are often cumbersome to use or allow little modification for individual requirements.

The program, written in Microsoft Visual Basic, is integrated into a Microsoft Excel spreadsheet, allowing both tabular and graphical output. The user is required to input the percentage of sediment present in a number of size fractions. This can be the weight retained on a series of sieves, or the percentage of sediment detected in size classes derived from a laser granulometer, X-ray sedigraph or Coulter counter. The following sample statistics are then calculated: mean, mode(s), sorting (standard deviation), skewness, kurtosis, and a range of

Table II. Statistical formulae used in the calculation of grain size parameters and suggested descriptive terminology, modified from Krumbein and Pettijohn (1938) and Folk and Ward (1957) (f is the frequency in per cent; m is the mid-point of each class interval in metric (m_m) or phi (m_ϕ) units; P_x and ϕ_x are grain diameters, in metric or phi units respectively, at the cumulative percentile value of x)

(a) Arithmetic method of moments

Mean	Standard deviation	Skewness	Kurtosis
$\bar{x}_a = \dfrac{\Sigma f m_m}{100}$	$\sigma_a = \sqrt{\dfrac{\Sigma f (m_m - \bar{x}_a)^2}{100}}$	$Sk_a = \dfrac{\Sigma f (m_m - \bar{x}_a)^3}{100\sigma_a{}^3}$	$K_a = \dfrac{\Sigma f (m_m - \bar{x}_a)^4}{100\sigma_a{}^4}$

(b) Geometric method of moments

Mean	Standard deviation	Skewness	Kurtosis
$\bar{x}_g = \exp \dfrac{\Sigma f \ln m_m}{100}$	$\sigma_g = \exp \sqrt{\dfrac{\Sigma f (\ln m_m - \ln \bar{x}_g)^2}{100}}$	$Sk_g = \dfrac{\Sigma f (\ln m_m - \ln \bar{x}_g)^3}{100 \ln \sigma_g{}^3}$	$K_g = \dfrac{\Sigma f (\ln m_m - \ln \bar{x}_g)^4}{100 \ln \sigma_g{}^4}$

Sorting (σ_g)		Skewness (Sk_g)		Kurtosis (K_g)	
Very well sorted	<1·27	Very fine skewed	$<^{-}1{\cdot}30$	Very platykurtic	<1·70
Well sorted	1·27–1·41	Fine skewed	$^{-}1{\cdot}30$ to $^{-}0{\cdot}43$	Platykurtic	1·70–2·55
Moderately well sorted	1·41–1·62	Symmetrical	$^{-}0{\cdot}43$ to $^{+}0{\cdot}43$	Mesokurtic	2·55–3·70
Moderately sorted	1·62–2·00	Coarse skewed	$^{+}0{\cdot}43$ to $^{+}1{\cdot}30$	Leptokurtic	3·70–7·40
Poorly sorted	2·00–4·00	Very coarse skewed	$>^{+}1{\cdot}30$	Very leptokurtic	>7·40
Very poorly sorted	4·00–16·00				
Extremely poorly sorted	>16·00				

(c) Logarithmic method of moments

Mean	Standard deviation	Skewness	Kurtosis
$\bar{x}_\phi = \dfrac{\Sigma f m_\phi}{100}$	$\sigma_\phi = \sqrt{\dfrac{\Sigma f (m_\phi - \bar{x}_\phi)^2}{100}}$	$Sk_\phi = \dfrac{\Sigma f (m_\phi - \bar{x}_\phi)^3}{100\sigma_\phi{}^3}$	$K_\phi = \dfrac{\Sigma f (m_\phi - \bar{x}_\phi)^4}{100\sigma_\phi^4}$

Sorting (σ_ϕ)		Skewness (Sk_ϕ)		Kurtosis (K_ϕ)	
Very well sorted	<0·35	Very fine skewed	>$^+$1·30	Very platykurtic	<1·70
Well sorted	0·35–0·50	Fine skewed	$^+$0·43 to $^+$1·30	Platykurtic	1·70–2·55
Moderately well sorted	0·50–0·70	Symmetrical	$^-$0·43 to $^+$0·43	Mesokurtic	2·55–3·70
Moderately sorted	0·70–1·00	Coarse skewed	$^-$0·43 to $^-$1·30	Leptokurtic	3·70–7·40
Poorly sorted	1·00–2·00	Very coarse skewed	<$^-$1·30	Very leptokurtic	>7·40
Very poorly sorted	2·00–4·00				
Extremely poorly sorted	>4·00				

(d) Logarithmic (original) Folk and Ward (1957) graphical measures

Mean	Standard deviation	Skewness	Kurtosis
$M_Z = \dfrac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$	$\sigma_I = \dfrac{\phi_{84} - \phi_{16}}{4} + \dfrac{\phi_{95} - \phi_5}{6{\cdot}6}$	$Sk_I = \dfrac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \dfrac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)}$	$K_G = \dfrac{\phi_{95} - \phi_5}{2{\cdot}44(\phi_{75} - \phi_{25})}$

Sorting (σ_1)		Skewness (Sk_1)		Kurtosis (K_G)	
Very well sorted	<0·35	Very fine skewed	$^+$0·3 to $^+$1·0	Very platykurtic	<0·67
Well sorted	0·35–0·50	Fine skewed	$^+$0·1 to $^+$0·3	Platykurtic	0·67–0·90
Moderately well sorted	0·50–0·70	Symmetrical	$^+$0·1 to $^-$0·1	Mesokurtic	0·90–1·11
Moderately sorted	0·70–1·00	Coarse skewed	$^-$0·1 to $^-$0·3	Leptokurtic	1·11–1·50
Poorly sorted	1·00–2·00	Very coarse skewed	$^-$0·3 to $^-$1·0	Very leptokurtic	1·50–3·00
Very poorly sorted	2·00–4·00			Extremely leptokurtic	>3·00
Extremely poorly sorted	>4·00				

(e) Geometric (modified) Folk and Ward (1957) graphical measures

Mean	Standard deviation
$M_G = \exp \dfrac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$	$\sigma_G = \exp\left(\dfrac{\ln P_{16} - \ln P_{84}}{4} + \dfrac{\ln P_5 - \ln P_{95}}{6{\cdot}6}\right)$
Skewness	**Kurtosis**
$Sk_G = \dfrac{\ln P_{16} + \ln P_{84} - 2(\ln P_{50})}{2(\ln P_{84} - \ln P_{16})} + \dfrac{\ln P_5 + \ln P_{95} - 2(\ln P_{50})}{2(\ln P_{25} - \ln P_5)}$	$K_G = \dfrac{\ln P_5 - \ln P_{95}}{2{\cdot}44(\ln P_{25} - \ln P_{75})}$

Sorting (σ_G)		Skewness (Sk_G)		Kurtosis (K_G)	
Very well sorted	<1·27	Very fine skewed	$^-$0·3 to $^-$1·0	Very platykurtic	<0·67
Well sorted	1·27–1·41	Fine skewed	$^-$0·1 to $^-$0·3	Platykurtic	0·67–0·90
Moderately well sorted	1·41–1·62	Symmetrical	$^-$0·1 to $^+$0·1	Mesokurtic	0·90–1·11
Moderately sorted	1·62–2·00	Coarse skewed	$^+$0·1 to $^+$0·3	Leptokurtic	1·11–1·50
Poorly sorted	2·00–4·00	Very coarse skewed	$^+$0·3 to $^+$1·0	Very leptokurtic	1·50–3·00
Very poorly sorted	4·00–16·00			Extremely leptokurtic	>3·00
Extremely poorly sorted	>16·00				

cumulative percentile values (the grain size at which a specified percentage of the grains are coarser), namely D_{10}, D_{50}, D_{90}, D_{90}/D_{10}, $D_{90}-D_{10}$, D_{75}/D_{25} and $D_{75}-D_{25}$.

In the program, the method of moments is used to calculate statistics *arithmetically* (based on a normal distribution with metric size values, seldom used in sedimentology but available with some Coulter sizing instruments), *geometrically* (based on a log-normal distribution with metric size values) and *logarithmically* (based on a log-normal distribution with phi size values), following the terminology and formulae suggested by Krumbein and Pettijohn (1938). Specified values are then extracted from the cumulative percentage curve using a linear interpolation between adjacent known points on the curve. These are used to calculate Folk and Ward parameters *logarithmically* (as originally suggested in Folk and Ward (1957), based on a log-normal distribution with phi size values) and *geometrically* (based on a log-normal distribution with metric size values). Formulae used in these calculations are presented in Table II.

The statistical parameters are also related to descriptive terms. The mean grain size is described using a modified Udden–Wentworth grade scale (Table I). For terminology to be consistent with the silt and sand fractions, gravel is redefined here as a fraction containing five subclasses ranging from very fine (2 mm) to very coarse (64 mm). Clasts larger than 64 mm are described as boulders. The terms granule, pebble and cobble have been removed, and it is recommended that their use be reserved for the description of rounded or subrounded clasts. 'Shingle' may also be defined simply as rounded gravel. Sorting, skewness and kurtosis are described here using the scheme proposed by Folk and Ward (1957). However, to avoid confusion as to whether skewness terms relate to metric or phi scales, positive skewness is renamed 'fine skewed' (indicating an excess of fines), and negative skewness is renamed 'coarse skewed' (indicating a tail of coarser particles).

The program provides a physical description of the textural class (such as 'muddy sandy gravel') after Folk (1954). Also included is a table giving the percentage of grains falling into each size fraction. For sieving results, the program warns the user if a significant amount (>2 per cent) of sediment has been lost during analysis. In terms of graphical output, the program provides graphs of the grain size distribution and cumulative distribution of the data in both micrometre and phi units, and displays the sample grain size on gravel–sand–mud and sand–silt–clay triangular diagrams. Samples can be analysed individually, or up to 250 samples may be analysed together with all statistics being tabulated. An example printout from the program is shown in Figure 2.

TECHNICAL POINTS

To calculate reliably the grain size statistics of a sample, the entire size distribution must be defined. At the coarse end, there is a requirement to enter at least one size class larger than the largest particles in the sample. At the fine end there is a complication with sediment remaining in the pan after sieving analysis. The larger the quantity of sediment remaining in the pan, the less accurate the calculation of grain size statistics, with statistics calculated by the method of moments being most susceptible. Errors in Folk and Ward parameters become significant only when the size distribution of more than 5 per cent of the sample is undetermined. If a sample contains up to 1 per cent of sediment in the pan the user can either calculate the statistics ignoring the pan fraction, or specify a size which is considered to be representative of the finest particles in the pan, such as 1 m (10 ϕ). For samples containing between 1 and 5 per cent of sediment in the pan, it is recommended that the pan fraction be ignored and size statistics reported for the sand and gravel fractions only. Samples containing more than 5 per cent of sediment in the pan should ideally be further analysed using a different technique, such as sedimentation or laser granulometry, although as noted previously, there are difficulties in merging data obtained by different methods.

METHOD COMPARISON

Previous studies have compared the statistics derived by moments and graphical methods (e.g. Folk, 1966; Koldijk, 1968; Davis and Ehrlich, 1970; Jaquet and Vernet, 1976; Swan *et al.*, 1978). The ability of GRADISTAT to analyse rapidly large numbers of samples has allowed the direct comparison of grain size statistics for over 800 samples, comprising marine gravels, sands and muds, desert and coastal dune sands, soils and

SAMPLE STATISTICS

SAMPLE IDENTITY: **Mablethorpe L2D1** ANALYST & DATE: S. Blott, 19/10/2000

SAMPLE TYPE: Unimodal, Well Sorted TEXTURAL GROUP: Sand

SEDIMENT NAME: Well Sorted Fine Sand

	m	ϕ
MODE 1:	185.5	2.432
MODE 2:		
MODE 3:		
D_{10}:	126.8	1.984
MEDIAN or D_{50}:	184.1	2.441
D_{90}:	252.9	2.979
(D_{90} / D_{10}):	1.994	1.502
$(D_{90} - D_{10})$:	126.1	0.996
(D_{75} / D_{25}):	1.437	1.239
$(D_{75} - D_{25})$:	66.79	0.523

GRAIN SIZE DISTRIBUTION			
GRAVEL:	0.0%	COARSE SAND:	0.0%
SAND:	98.4%	MEDIUM SAND:	11.0%
MUD:	1.6%	FINE SAND:	79.7%
		V FINE SAND:	7.7%
V COARSE GRAVEL:	0.0%	V COARSE SILT:	0.5%
COARSE GRAVEL:	0.0%	COARSE SILT:	0.2%
MEDIUM GRAVEL:	0.0%	MEDIUM SILT:	0.1%
FINE GRAVEL:	0.0%	FINE SILT:	0.2%
V FINE GRAVEL:	0.0%	V FINE SILT:	0.3%
V COARSE SAND:	0.0%	CLAY:	0.2%

	METHOD OF MOMENTS			FOLK & WARD METHOD		
	Arithmetic m	Geometric m	Logarithmic ϕ	Geometric m	Logarithmic ϕ	Description
MEAN ($\bar{x}$):	186.2	174.8	2.518	182.5	2.455	Fine Sand
SORTING (σ):	51.64	1.591	0.670	1.311	0.390	Well Sorted
SKEWNESS (Sk):	−0.179	−5.522	5.522	−0.091	0.090	Symmetrical
KURTOSIS (K):	3.852	48.69	48.69	1.025	1.024	Mesokurtic

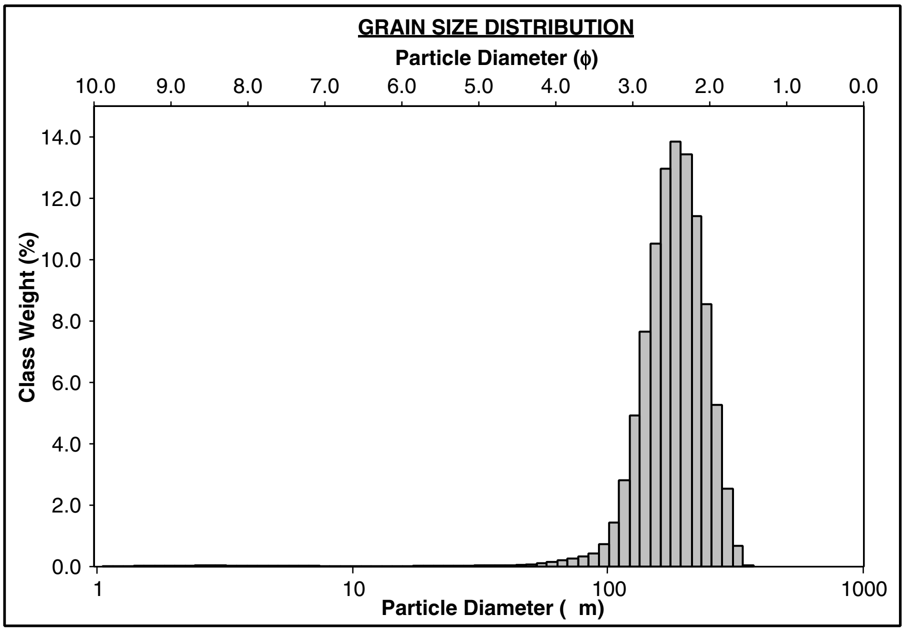

Figure 2. Example GRADISTAT printout, with logarithmic frequency plot, for a coastal dune sand (Lincolnshire, UK)

glacial tills. The relationships between graphical and moment parameters are illustrated in Figures 3 and 4 for geometric and logarithmic statistics. While arithmetic statistics have been included in the GRADISTAT program for reasons of completeness, it is recommended that the more representative geometric or logarithmic statistics be used to characterize sediments as general practice.

It is clear that relationships between the methods are similar for geometric and logarithmic statistics. Geometric mean and sorting values for either method are related to their logarithmic counterparts by simple logarithmic relationships. Geometric and logarithmic skewness parameters are inversely related since metric and phi scales operate in opposite directions, while geometric and logarithmic kurtosis values are identical.

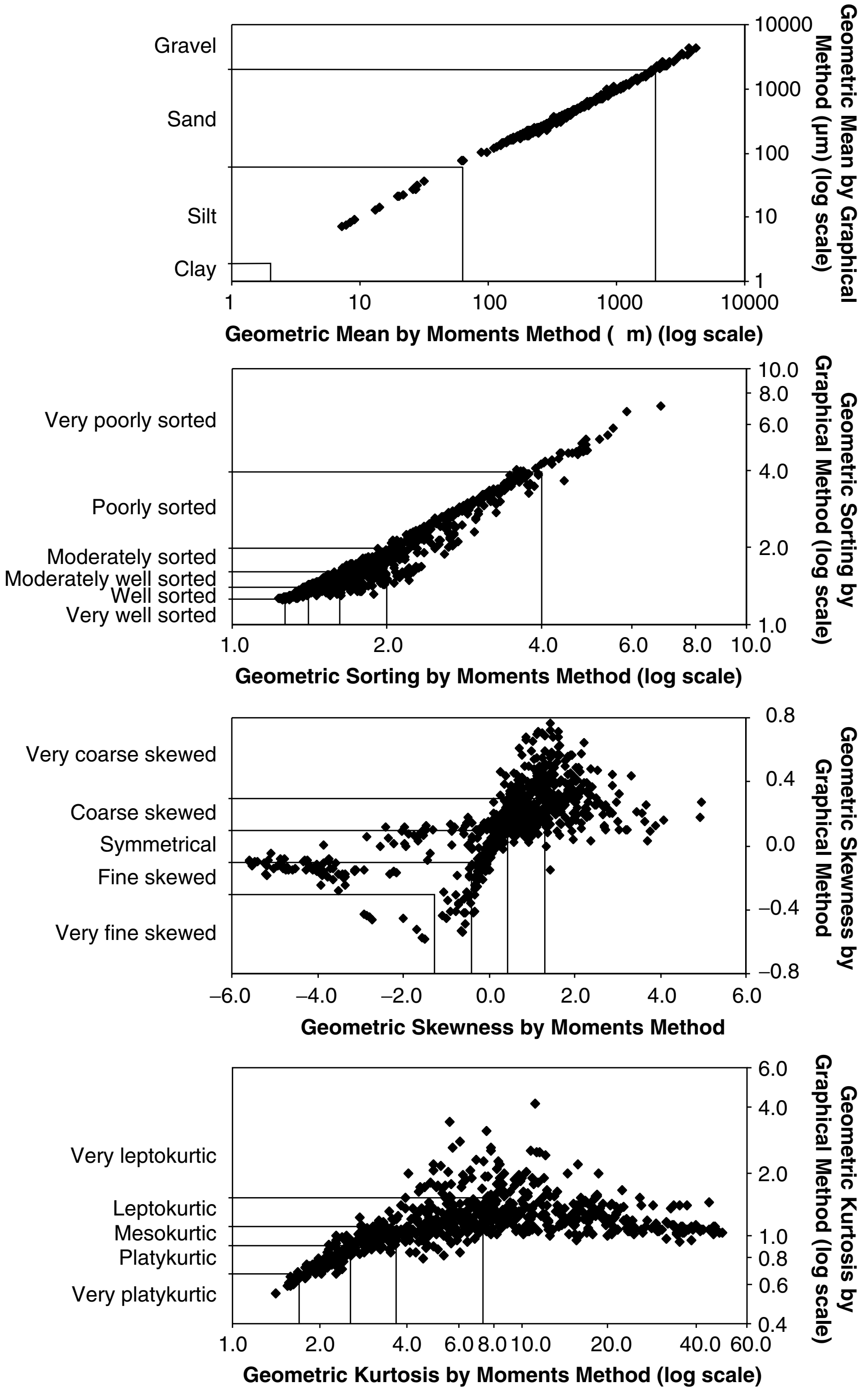

Figure 3. Comparison of statistical parameters calculated using the geometric method of moments and Folk and Ward (1957) graphical method. Analysed samples are marine gravels, sands and muds, desert and coastal dune sands, soils and glacial tills

The relationships between graphical and moment parameters can be explained by differences in the emphasis each method places on different parts of the grain size distribution. The graphical method places more weight on the central portion of the grain size curve and less on the tails. The upper and lower limits of calculations

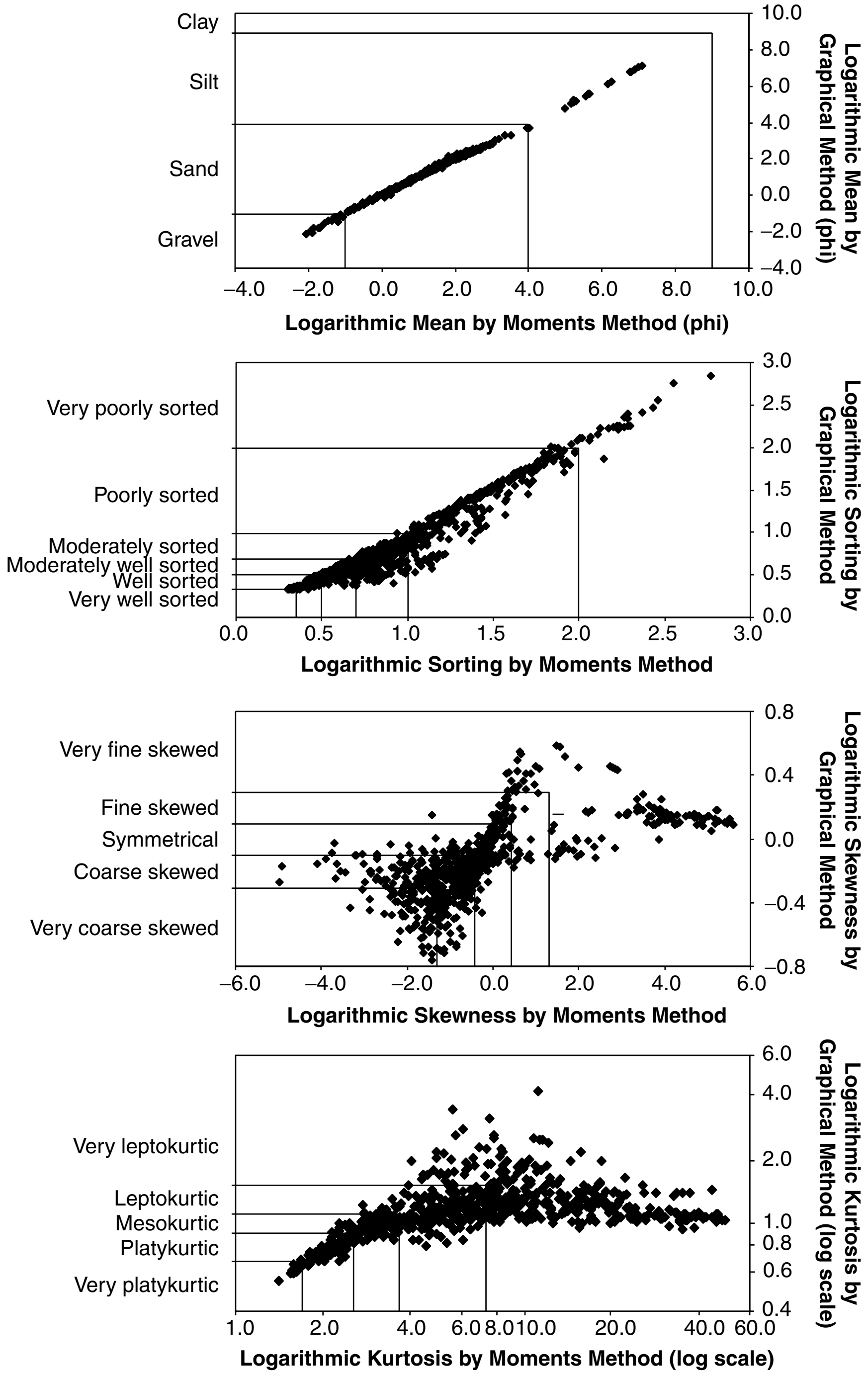

Figure 4. Comparison of statistical parameters calculated using the logarithmic method of moments and Folk and Ward (1957) graphical method. Analysed samples are marine gravels, sands and muds, desert and coastal dune sands, soils and glacial tills

are at 95 and 5 per cent of the distribution respectively, and sediment outside these limits is ignored. The first order moment measure (mean) also places more emphasis on the central portion of the curve, and consequently the graphical mean closely approximates the moment mean (Figures 3 and 4).

With higher order moments, however, parameters become more sensitive to the tails of the distribution. While there is clearly a linear relationship between graphical and moment sorting, there is better agreement for well sorted sediments (low sorting values), since grains are concentrated in the central portion of the grain size distribution. For less well sorted sediments, the graphical method generally produces better sorting values since sediment in the tails of the distribution is ignored. The difference is greatest for samples that are well sorted except for a fine or coarse tail representing less than 5 per cent of the sample weight (such as the dune sand shown in Figure 2). Alternatively, graphical sorting can exceed moment sorting if the central portion of the distribution is the least sorted, such as for multimodal sediments (Swan *et al.*, 1978).

With the highest order moments of skewness and kurtosis, the differences between the methods become much greater. While skewness values are comparable for log-normally distributed sediments (skewness value of zero), kurtosis parameters are inherently different, since a log-normal distribution takes a value of 1·0 for the graphical method and 3·0 for the method of moments. The convention used by some authors (e.g. Krumbein and Pettijohn, 1938) to subtract 3·0 from the moments value to standardize the measure around zero is not followed here. Values higher than 1·0 (or 3·0) indicate a leptokurtic (strongly peaked) distribution, smaller values a platykurtic (relatively flat) distribution. For sediments that are far from log-normal, the higher order moments of sorting, skewness and kurtosis interact in complicated ways (Swan *et al.*, 1978). The result is that as skewness and kurtosis increase, the percentage of sediment in the tails of the distribution increases, and the relationships between the graphical and moment parameters break down.

One of the advantages of the Folk and Ward method is the opportunity to convert parameter values to descriptive terms for the sediment. The relationships illustrated in Figures 3 and 4, although unclear in some instances, have been used to assign corresponding descriptive terms to geometric and logarithmic moment values, presented in Table II. These terms are intended as a guide only, since it is clear from the previous discussion that higher order parameters can be difficult to interpret. Sorting in particular is known to be a sinusoidal function of mean grain size, with medium and fine sands generally exhibiting better sorting than clays, silts and gravels (Inman, 1949; Folk and Ward, 1957).

OTHER DESCRIPTORS

A variety of alternative parameters can be used to differentiate between different sediments. Engineers commonly quote the median, or D_{50} size value, together with a measure of dispersion, such as D_{90}/D_{10}, $D_{90}-D_{10}$ or $D_{75}-D_{25}$ (the interquartile range). For soils work, where the materials in question are commonly multimodal, it may be most appropriate simply to cite the values for the primary, secondary and tertiary modes, the median, and a measure of distribution spread, such as $D_{90}-D_{10}$. These descriptors are provided by the GRADISTAT software and frequently prove to be more reliable than the standard size statistics, especially when sediments are clearly multimodal.

DISCUSSION AND CONCLUSIONS

Although the GRADISTAT program is extremely flexible in terms of input and output, it remains the responsibility of the user to interpret the results in a manner appropriate to the questions being addressed. Care should be taken when interpreting open-ended distributions, or where the sediment is not unimodal. It should also be noted that all methods of particle size analysis are influenced by factors such as grain shape, density, and sometimes optical properties. While some methods specify grain size frequency per unit weight, others specify grain size per unit volume. It is therefore not appropriate to compare directly results obtained using different methods. In some instances, however, it may be possible to apply calibration factors.

Comparison of the Folk and Ward graphical method and the method of moments has indicated that both methods have drawbacks. The graphical method is relatively insensitive to sediments containing a large particle size range in the tails of the distribution. This can be either an advantage or a disadvantage depending on the particular problem under study. The moment method can equally overemphasize the importance of long tails with low frequencies, and in these circumstances the Folk and Ward method is likely to describe more accurately the general characteristics of the bulk of the sample. Previous workers have been divided about the relative merits of graphical and moment statistics. If only the mean grain size and sorting values are required, the graphical and moments methods produce similar results. If, however, the skewness or kurtosis are to be determined, in our experience the Folk and Ward measures provide the most robust basis for routine comparisons of compositionally variable sediments. Although most sedimentologists have traditionally worked with phi units, in our opinion statistics expressed geometrically (in metric units) are to be preferred to logarithmic statistics (in phi units), since the phi scale is seldom used amongst biologists, archaeologists, soil scientists or engineers, and results are easier to visualize. Any study incorporating grain size analysis must include a clear statement of the measurement technique and the method used in the calculation of any statistics. In many circumstances it will be appropriate to employ more than one method, since comparison of results obtained in different ways may provide additional insight into the processes involved.

ACCESSING THE SOFTWARE

The universal availability of Microsoft Excel should enable use of the GRADISTAT program by many workers, and allow efficient transfer of data and statistics between other applications. The file GRADISTAT.xls is compatible with Microsoft Excel 97 or 2000 (versions 8.0 and 9.0), and can be downloaded from the *Earth Surface Processes and Landforms* software web site (URL: http://www.interscience.wiley.com/jpages/0197–9337/sites.html).

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REFERENCES

Bagnold RA, Barndorff-Nielsen OE. 1980. The pattern of natural grain size distributions. *Sedimentology* **27**: 199–207.
Bui EN, Mazullo J, Wilding LP. 1990. Using quartz grain size and shape analysis to distinguish between aeolian and fluvial deposits in the Dallol Bosso of Niger (West Africa). *Earth Surface Processes and Landforms* **14**: 157–166.
Davis MW, Ehrlich R. 1970. Relationships between measures of sediment-size-frequency distributions and the nature of sediments. *Geological Society of America Bulletin* **81**: 3537–3548.
Folk RL. 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. *Journal of Geology* **62**: 344–359.
Folk RL. 1966. A review of grain-size parameters. *Sedimentology* **6**: 73–93.
Folk RL, Ward WC. 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology* **27**: 3–26.
Friedman GM. 1979. Differences in size distributions of populations of particles among sands of various origins. *Sedimentology* **26**: 3–32.
Friedman GM, Johnson KG. 1982. *Exercises in Sedimentology*. Wiley: New York.
Friedman GM, Sanders JE. 1978. *Principles of Sedimentology*. Wiley: New York.
Hartmann D, Christiansen C. 1992. The hyperbolic shape triangle as a tool for discriminating populations of sediment samples of closely connected origin. *Sedimentology* **39**: 697–708.
Inman DL. 1949. Sorting of sediments in the light of fluid mechanics. *Journal of Sedimentary Petrology* **19**: 51–70.
Inman DL. 1952. Measures for describing the size distribution of sediments. *Journal of Sedimentary Petrology* **22**: 125–145.
Isphording WC. 1970. FORTRAN IV program for calculation of measures of central tendency and dispersion on IBM 360 computer. *Journal of Geology* **78**: 626–628.
Jaquet JM, Vernet JP. 1976. Moment and graphic size parameters in sediments of Lake Geneva (Switzerland). *Journal of Sedimentary Petrology* **46**: 305–312.
Koldijk WS. 1968. On environment-sensitive grain-size parameters. *Sedimentology* **10**: 57–69.
Krumbein WC. 1934. Size frequency distributions of sediments. *Journal of Sedimentary Petrology* **4**: 65–77.
Krumbein WC. 1938. Size frequency distribution of sediments and the normal phi curve. *Journal of Sedimentary Petrology* **8**: 84–90.
Krumbein WC, Pettijohn FJ. 1938. *Manual of Sedimentary Petrography*. Appleton-Century-Crofts: New York.
McCammon RB. 1962. Efficiencies of percentile measures for describing the mean size and sorting of sedimentary particles. *Journal of Geology* **70**: 453–465.
McManus J. 1988. Grain size determination and interpretation. In *Techniques in Sedimentology*, Tucker M (ed.). Blackwell: Oxford; 63–85.

Middleton GV. 1976. Hydraulic interpretation of sand size distributions. *Journal of Geology* **84**: 405–426.
Otto GH. 1939. A modified logarithmic probability graph for the interpretation of mechanical analyses of sediments. *Journal of Sedimentary Petrology* **9**: 62–75.
Pye K. 1989. GRANNY: a package for processing grain size and shape data. *Terra Nova* **1**: 588–590.
Pye K. 1994. Properties of sediment particles. In *Sediment Transport and Depositional Processes*, Pye K (ed.). Blackwell: Oxford; 1–24.
Slatt RM, Press DE. 1976. Computer program for presentation of grain-size data by the graphic method. *Sedimentology* **23**: 121–131.
Swan D, Clague JJ, Luternauer JL. 1978. Grain size statistics I: evaluation of the Folk and Ward graphic measures. *Journal of Sedimentary Petrology* **48**: 863–878.
Trask PD. 1932. *Origin and Environment of Source Sediments of Petroleum*. Gulf Publishing Company: Houston.
Udden JA. 1914. Mechanical composition of clastic sediments. *Bulletin of the Geological Society of America* **25**: 655–744.
Utke A. 1997. *SediVision 2.0*. Springer-Verlag: Heidelberg.
Visher GS. 1969. Grain size distributions and depositional processes. *Journal of Sedimentary Petrology* **39**: 1074–1106.
Wentworth CK. 1922. A scale of grade and class terms for clastic sediments. *Journal of Geology* **30**: 377–392.
Wyrwoll KH, Smith GK. 1985. On using the log-hyperbolic distribution to describe the textural characteristics of eolian sediments. *Journal of Sedimentary Petrology* **55**: 471–478.
Wyrwoll KH, Smith GK. 1988. On using the log-hyperbolic distribution to describe the textural characteristics of eolian sediments: reply. *Journal of Sedimentary Petrology* **58**: 161–162.

