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SOIL PARTICLE SIZE ANALYSIS - AN INTERPRETATIVE GUIDE FOR EXCAVATORS.

Matthew Canti

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Summary

The methods and interpretations of particle size analysis are discussed at a level intended for the non-specialist. Emphasis is placed on the understanding of cumulative distribution curves - the data format most commonly used in archaeological reports. Further details of the problems inherent in the methodology are introduced in a series of text-related appendices.

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SOIL PARTICLE SIZE ANALYSIS
AN INTERPRETATIVE GUIDE FOR EXCAVATORS

1. Introduction

The aim of this report is to provide a non - specialist with the means to interpret soil and sediment particle size analysis. This requires no more than basic scientific knowledge from the reader, but the layout offers additional material in the Appendices for those inclined to further study.

2. What is particle size analysis?

The mineral fraction of a soil (as distinct from the organic fraction) is made up of particles ranging in size from centimetres (rocks and boulders) down to micron (0.001mm) and sub-micron level (clays). Particle size analysis aims to measure what percentage of the soil weight is made up of the different size grades.

(The "size" of particles - Appendix 1.)

3. Methods

IN THE FIELD - finger texturing provides a rough guide to the percentages of particles and is usually presented as a verbal class grouping such as Sandy Loam. These groupings are based on the textural triangle (See next page) and therefore represent estimates of a 3-class analysis, the classes being Sand (2mm-60um), Silt (60-2um), and Clay (< 2um). This method is too subjective for detailed interpretations to be made, but can, with care, provide much of the fundamental information required in the field.

(Finger texturing - Appendix 2.)

IN THE LAB - dried soil is disaggregated in water and the suspension poured through a nest of sieves from a chosen upper limit down to 63um, the residue being collected. The sieves are then dried and their contents weighed.

The wet residue is subjected to a sedimentation test. This relies on known laws governing the rate at which particles of a given size settle in water. A suspension is left to settle out and its density is tested by hydrometer at various intervals; the density at any interval can be ascribed to the presence of particles of a certain size range (e.g. after 15 minutes, particles at 10cm depth will all be 11um or finer). After sedimentation is complete, a full calculation can be made of the percentages present. Sedimentation tests can also be carried out by pipette removal of a known quantity of suspension, followed by drying and weighing;

(Sedimentation Problems - Appendix 3.)

Once the sieve and sedimentation values are available, the two sets of data have to be married at the 63um point to produce a single set of figures for the whole soil. There are inherent errors at this stage, since the two methods measure slightly different properties.

(Curve joining Problems - Appendix 4.)

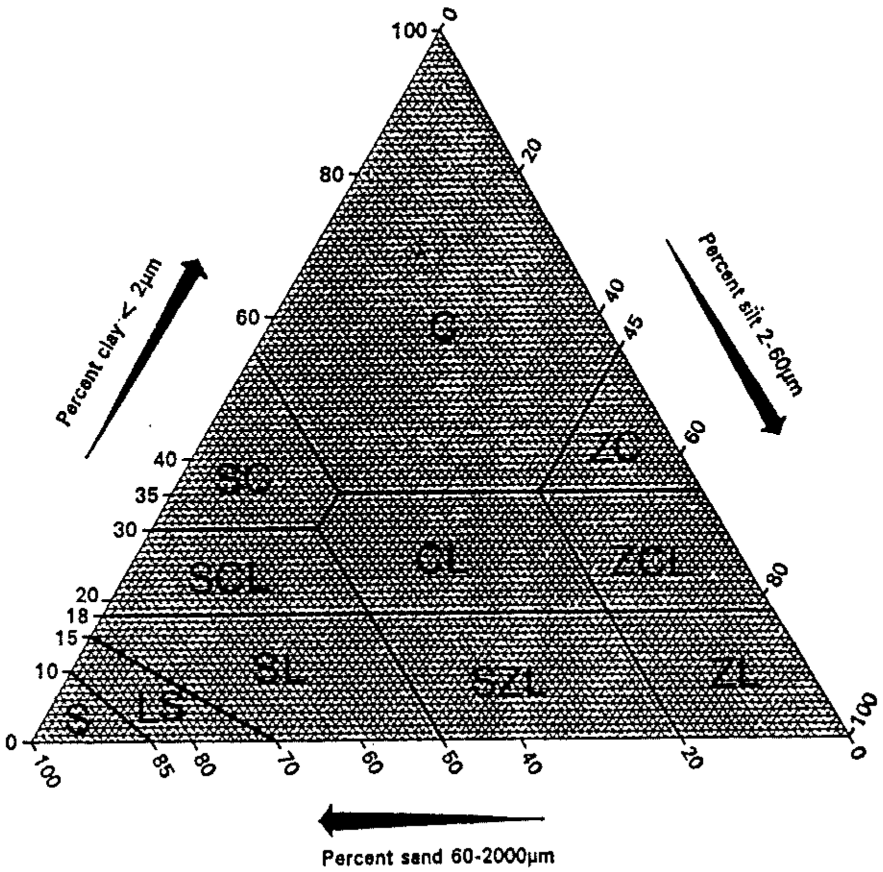
4. Presentation of results

The standard particle size grades in use by most workers are as follows:-

SAND (S) 2mm-60um		SILT (Z) 60um-2um		CLAY (C) <2um
Coarse (CS)	2mm-600um	Coarse (CZ)	60um-20um	
Medium (MS)	600um-200um	Medium (MZ)	20um-6um	
Fine (FS)	200um-60um	Fine (FZ)	6um-2um	

Results are frequently presented as simple numerical percentages either for Sand, Silt and Clay or including the subgradings Coarse, Medium and Fine. To arrive at a textural name, the 3 grades are read off into the diagram below:-

Figure 1. The textural triangle
(C=Clay, L=Loam, S=Sand, Z=Silt)



This presentation offers a laboratory analogue for the field results produced by finger texturing (See 3.Methods). It deals only with the "fine earth fraction", i.e. the fraction smaller than 2mm. To achieve a more interpretatively useful result, it is desirable for the percentages to be drawn up into some form of graph. This allows visual comparisons and therefore stimulates additional hypotheses for explaining the results.

HISTOGRAMS - are sometimes produced and are the clearest way of visualising the distribution. Their chief drawback is that the choice of class groupings affects the position of the peaks and troughs. Furthermore, it is almost impossible to display a group of soils on the same diagram in such a way as avoids confusion.

CUMULATIVE DISTRIBUTION CURVES - are more commonly used. Although they are less immediately accessible, they have the advantage of being unique (i.e, unlike histograms, there can be only one curve for a given sample). They are also readily distinguished from each other when presented on the same diagram.

A logarithmic scale is preferred for the particle size divisions. This convention arose historically in sedimentology for mathematical reasons, but is mainly useful because it allows the full distribution to be shown on one diagram, whilst retaining the fine detail in the important 100um - 2um section of the curve. Taking Figure 2 as an example, it would require approximately 5 metres of graph paper to show the whole curve at the scale to be found around the 20um mark.

(The use of a logarithmic scale - Appendix 5.)

Ancient Monuments Laboratory results are often presented as cumulative curves on a logarithmic scale, so the next section is devoted to understanding this particular type of diagram.

5.Reading Cumulative Curves

Figure 2 shows the particle size distribution of a soil on solifuction material at Buxton, Derbyshire. The distribution is shown as a cumulative curve and as a histogram, with different vertical scales to allow both curves onto the same paper. Lines of construction have been drawn to show the relationship with the three main class groups in Figure 1. From these constructions, it is apparent that the slope of the cumulative curve is the all-important feature. Since this sediment is deposited chaotically, there is no special tendency for one size of particle to predominate; this leads to no special peaks in the histogram and therefore no dramatic slopes in the cumulative curve. On the other hand, Figure 3 shows a well sorted river sand from Churchstanton in Devon. Here, water sorting has produced a strong peak in the histogram around 90 - 300um and the correspondence with slope on the cumulative curve can be clearly seen. It should be noted here that the histograms on Figures 2 and 3 are deliberately truncated at the 1.4um mark. It is typical of the problems presented by histograms that there is no consistent way of displaying the unknown ultrafine (<1.4um) part of the data, whereas the cumulative curve can stop at any point without introducing visual distortion or apparent over-representation.

Additional notes on Figures 2 and 3

- The top horizontal scale "Phi" is used by some workers, but can be ignored for the purposes of this report.

- The lefthand vertical scale applies to the cumulative curve (e.g., on Fig 2, 68% of the particles are finer than 100um)
  The righthand vertical scale applies to the histogram (e.g, on Fig 2, 3.6% of the particles fall within the size range 353 to 500 um). All scales are based on weight.

(The phi scale -See Appendix 5.)

Three more examples are provided in this section (Figures 4,5 and 6) to assist the reader in understanding the relationship between cumulative curves and histograms. Only the shape of the histograms are displayed and their scales are arbitrary.

Figure 4 is a wind-sorted dune sand from Porthcothan, Cornwall. Wind is capable of sorting particles more precisely than water, so the tendency toward a steep central section in the cumulative curve is more marked than in the river deposit on Figure 3.

Figure 5 is a marsh deposit from Alcester, Warwickshire. In this example the water was flowing extremely slowly; most of the sand and a large proportion of the silt were already deposited somewhere upstream, leaving mainly clay which was settling out in the sluggish channels.

Figure 6 shows a soil whose particle size distribution is bimodal. This could be, for example, a clifftop soil inheriting silt from its parent material and blown sand from the shoreline below. The initial difficulty that many observers find with interpreting cumulative curves is best illustrated around the 80um mark on this example, where the material present is less than 6% even though the curve touches 68% on the "percent finer than" scale.

PARTICLE SIZE ANALYSIS

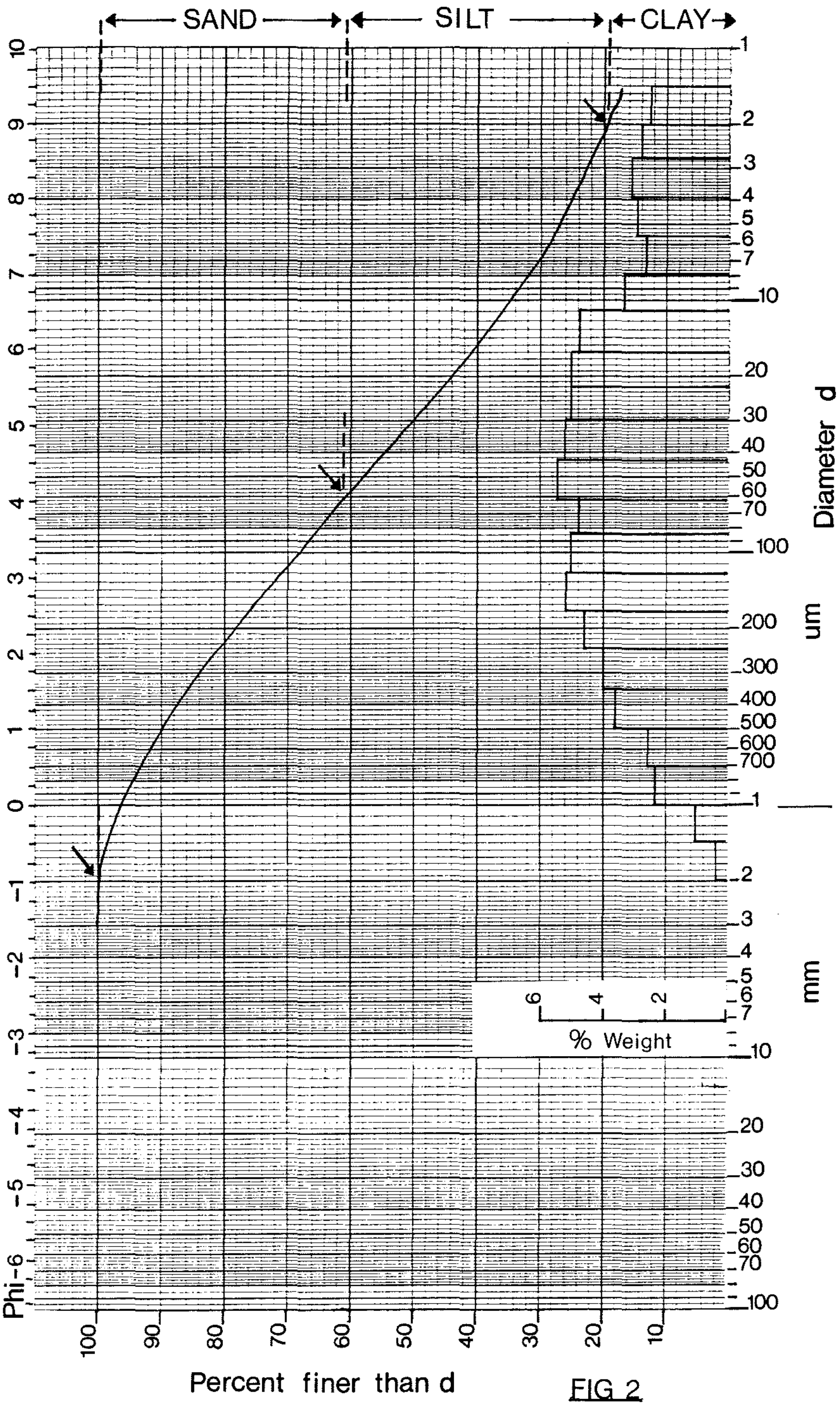


FIG 2

PARTICLE SIZE ANALYSIS

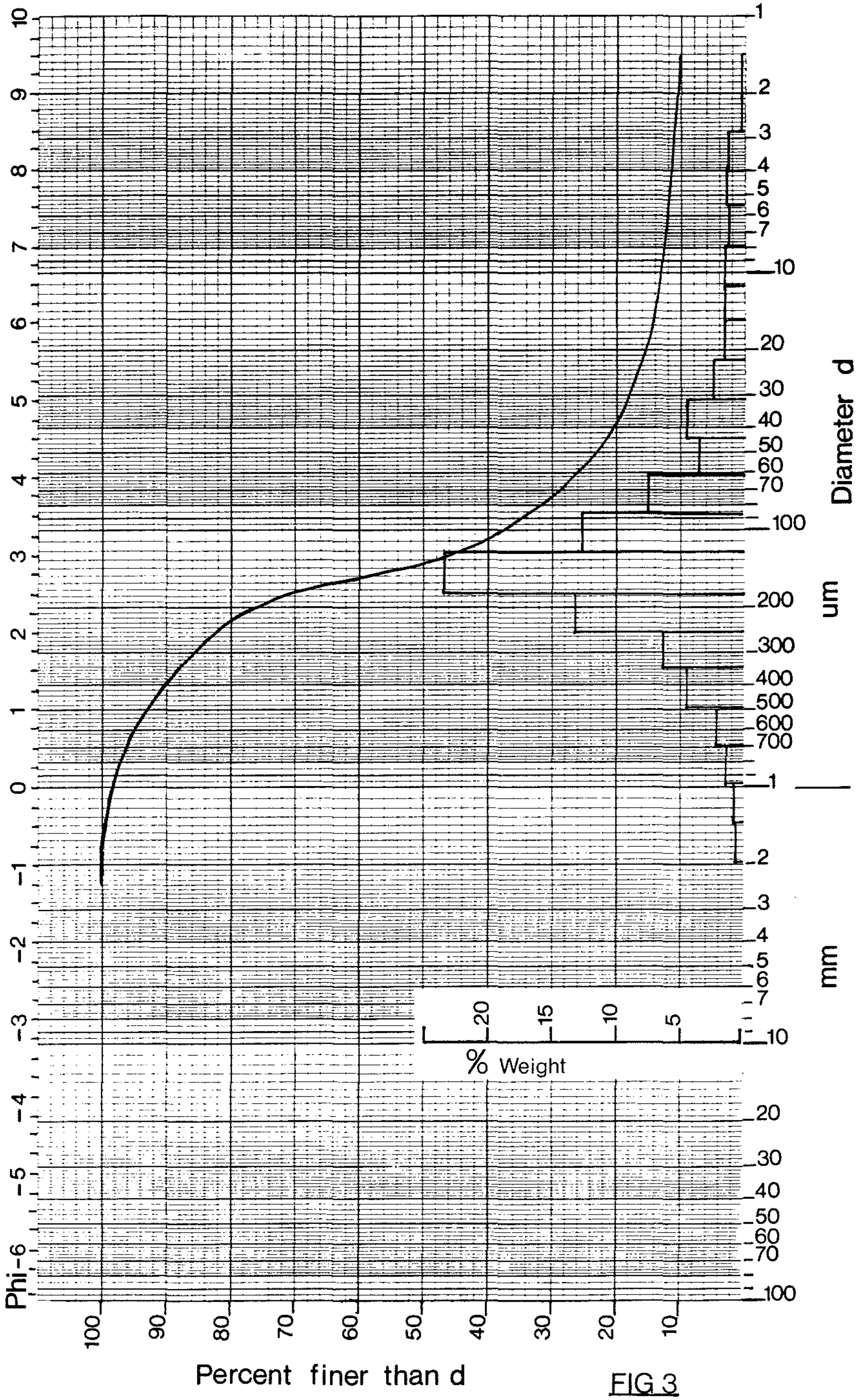


FIG 3

PARTICLE SIZE ANALYSIS

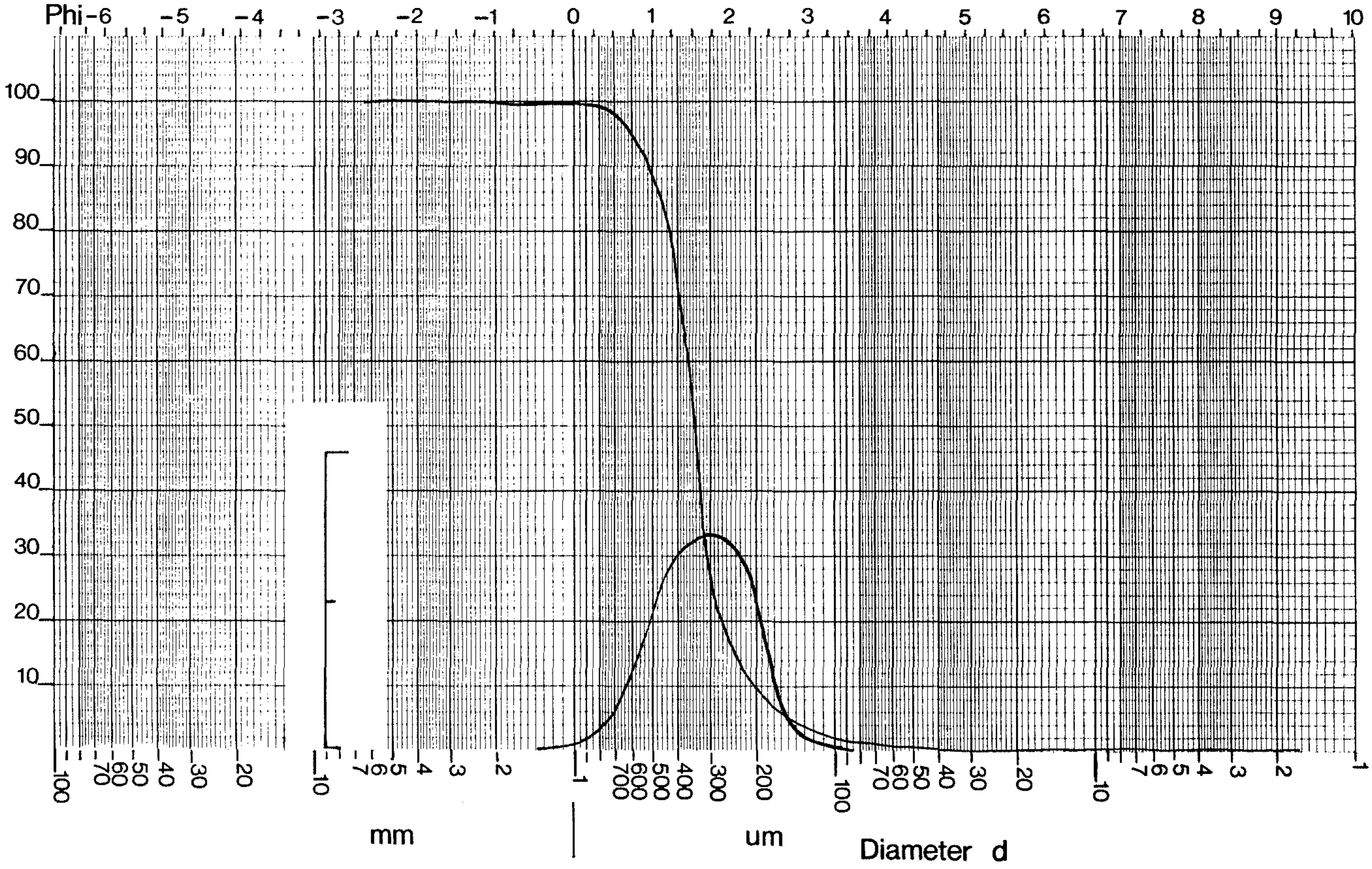


FIG 4

PARTICLE SIZE ANALYSIS

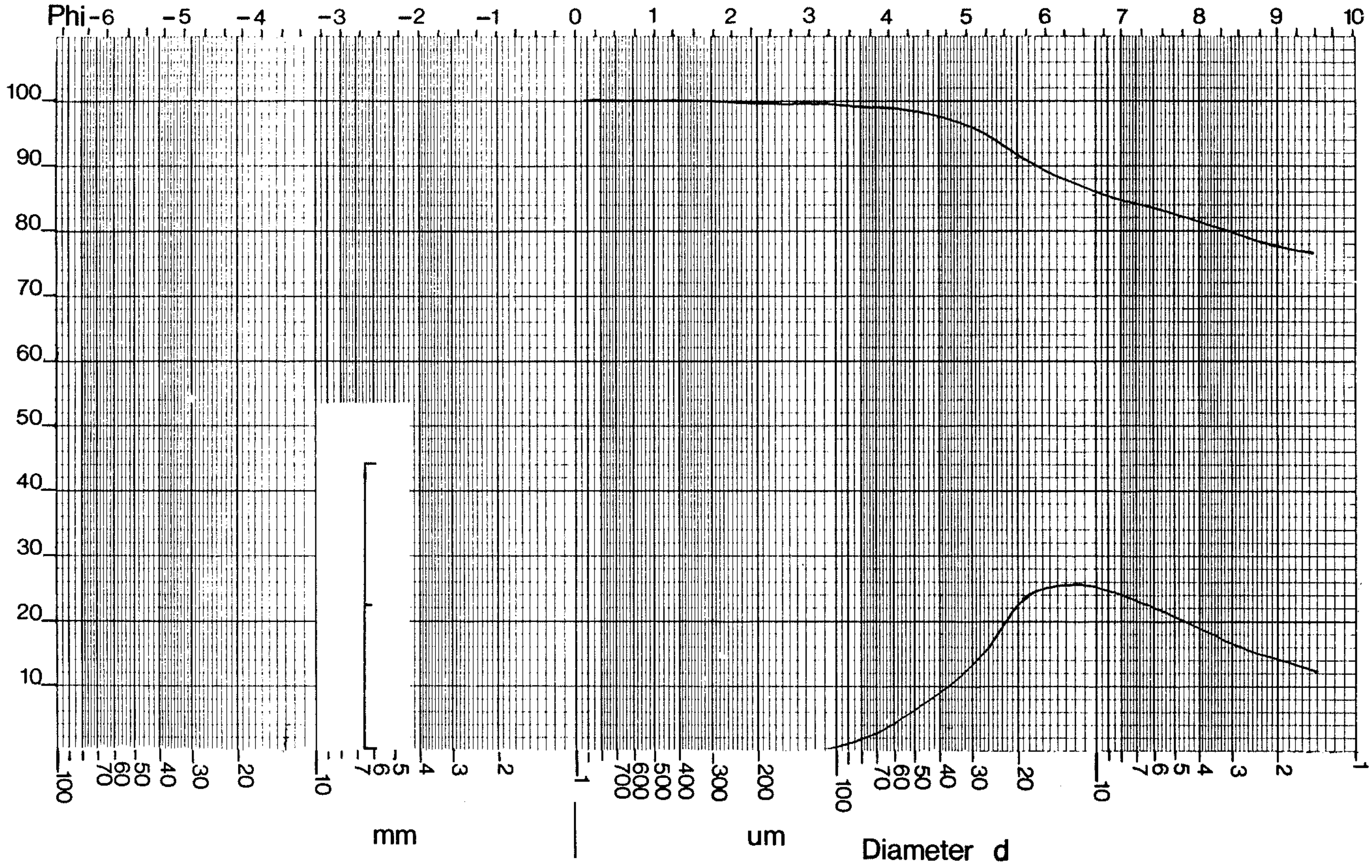


FIG 5

PARTICLE SIZE ANALYSIS

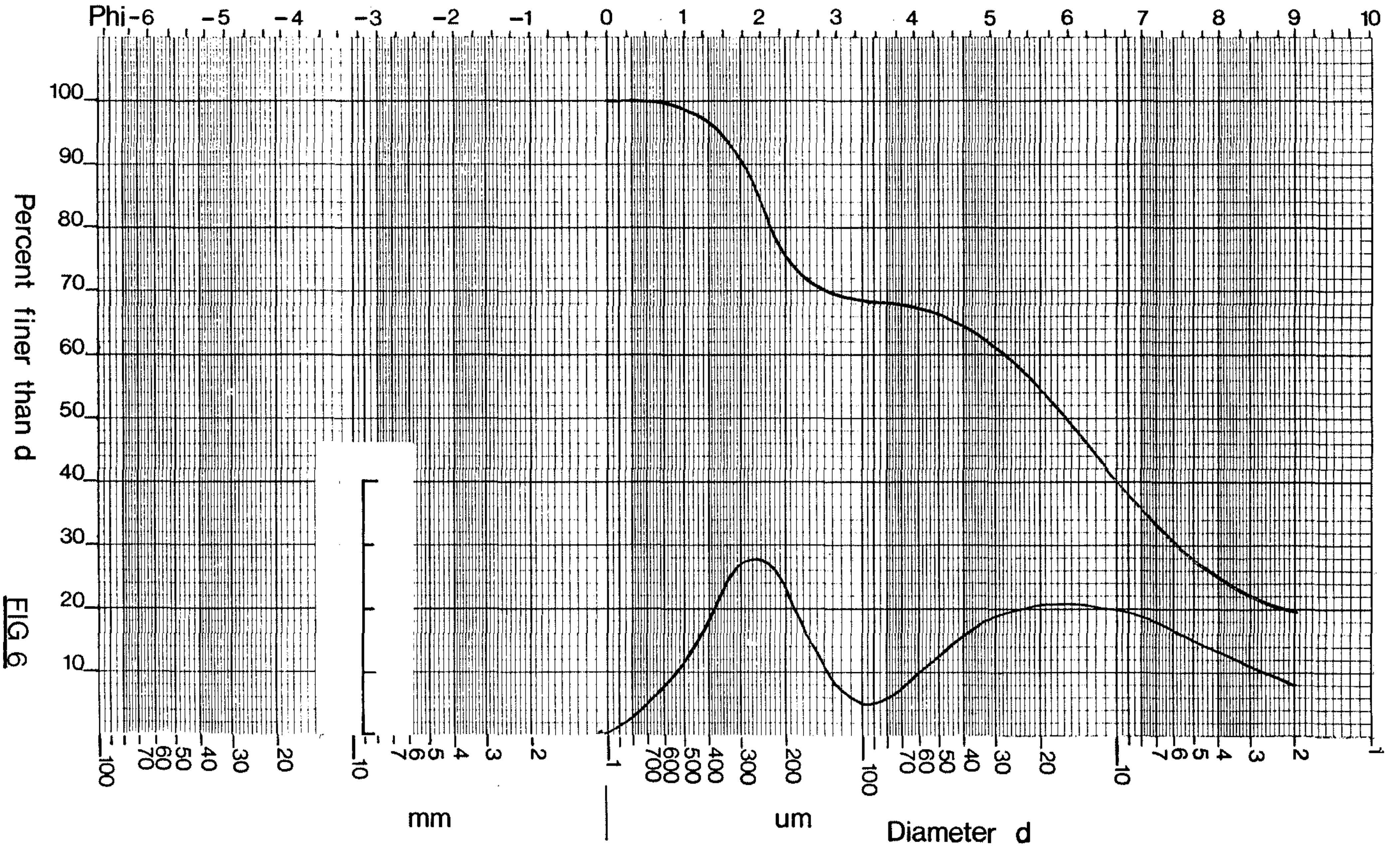


FIG 6

6. Accuracy

Before going on to interpretation (in the next section) it is neccessary to clarify the issue of the accuracy inherent in curves. Essentially, the question here is "How different do two curves have to be if they are not to be considered identical?". It is only likely to arise where two related soils are being analysed and where the likelihood of in-sample variation has been assessed. This discussion will, therefore, deal only with :-

a) Comparing like with like.

b) Samples assumed to have no in-sample variation.

The curves currently produced by the Ancient Monuments Lab. are composed of 24 sieve readings (128mm to 45um) and 5 sedimentary readings (20um to 1.4um). Repeat testing shows the accuracy of the individual readings to be around +/- 1%.

However, these readings are subsequently joined by a curve drawing equation which effectively interpolates the values between the actual readings. As long as the curve does not slope markedly, there is little danger of inaccuracy creeping in; but if the curve becomes steep, then large errors become possible at a given point on the steep part of the curve. To illustrate this issue, the steep curve on Figure 4 should be visualised as having been drawn 2mm to the right of its present position. This tiny change would alter the 400um reading from 72% to ca.80% - an error of 8%.

(Interpolating a smooth curve - Appendix 6.)

This, and other forms of error (See Appendices 2.1, 3.2 and 3.3) combine to mean that exact error bars cannot be ascribed to the curve. The practical solution to this problem is to apply the following rules of thumb :

1) Assume a general "error cloud" along the curve of +/- 2%.

2) Allow for potential errors of +/- 2% to +/- 8% on steep parts of the curve.

3) Allow for +/- 5% in the area of the curve below 5um if dark (organic) soil has been tested <u>whether</u> or not the organic matter was peroxide treated. (Appendix 3.)

7. Interpretation

The examples of curves in Figures 2 to 6 have been largely concerned with pure sediments whose make-up is attributable to the agent of deposition. When examining the curves of soils, there are additional factors to be considered.

The particle size distribution of a soil is the result of :-

1) The distribution in the rock or sediment(s) from which it has developed.

2) Soil processes affecting the size of particles e.g. weathering, dissolution, cementation.

3) Soil processes affecting the distribution of particles e.g. clay translocation, cryoturbation.

4) Biogenic effects on the distribution of particles e.g. burrows and earthworm casts.

5) Erosional effects occurring after redistribution e.g a topsoil developed in an old subsoil after the original topsoil has been removed.

6) Man's effects e.g dumping of extraneous material.

Most of these factors interrelate in some way to affect each other. However, they vary greatly in significance and, initially at least, it is the parent material that plays the major role.

Parent Material Effects

The majority of grains in the sand and silt fraction of soils are formed of silica whose dissolution rate is negligible over the archaeological timescale. When dealing with parent materials with a weatherable component, such as chalk, the transient nature of the grains must be considered as well as the composition of the insoluble residue which is usually present. Both chalk and hard limestone, for example, usually contain an extremely silty quartz residue, albeit in very small amounts.

Further complexity is added when more than one parent material is involved. The example shown in Figure 6 has two "shoulders" indicating a clear likelihood of two grain sources, but such clearcut examples are rare. Many parts of Southern Britain have topsoils with higher silt content than their subsoils. This difference is increasingly ascribed to wind-blown silt (loess) from periglacial times, even though there are few preserved deposits of pure loess in Britain. Thus, it seems that these soils were thoroughly mixed after deposition, but appear in section to have derived only from the underlying geology.

Soil Process Effects

Weathering of minerals can increase the fine (silt and clay) fraction of a soil and the rate can vary within a profile leading to different textures at different depths. Cementation, mainly by Iron and Aluminium can generate "pseudo - particles" that are coherent enough to escape normal dispersion procedures. These would normally, however, be spotted and allowed for during the sieving phase.

Clay translocation, if well developed, has a significant effect on the fine end of curves for both the receiving and the depleted horizons. Figure 7 shows a set of curves for different depths of a soil affected by clay translocation. The clay has been washed successively downprofile to build up at the base, while the topsoil becomes increasingly depleted. In the field, the impression was given of the subsoil and topsoil being unrelated; but on seeing the similarity in the coarse end of the curves, it becomes far more likely that both are the end result of a process. Of course, particle size analysis cannot furnish a proof in this example; an acceptable alternative hypothesis would be wind-blown silt partially mixed into the topsoil and grading down to natural parent material below. Further lines of evidence, such as micromorphology, must be overlapped to provide the final interpretation.

Biogenic Effects

Burrowing animals will usually disrupt pedological and depositional reorganisations such as have been described above. The same can be said for tree-throw, which tends to bring subsoil materials to the surface and cause pockets of varying textures in the profile. The action of earthworms, however, can have a marked sorting effect in soils with a coarse component. Those species that produce casts are capable of building anything up to 1cm per annum on the surface of suitable soils. The casts rarely contain particles larger than 1mm, so a well worked profile will show a depletion of coarse sand in the topsoil and a converse enrichment in the horizon immediately below. In soils with a stone, boulder or artifact content, a clear line of this reject material will sometimes be found at the base of the upcast horizon.

Figure 8 shows the idealised effect of worm action on a stone rich river deposit. This has been produced mathematically by assuming simply that worms ignore all particles larger than 1mm and ingest all the rest. Note that the sharp downturn of the "upcast" curve results from the simplicity of the model; in reality, the corner would be cut by a smoother curve due to a more variable preference model and the contaminating effect of other processes.

Erosional Effects

Soil movement is continuous in all slope soils, and must therefore be considered as part of the dynamics of particle size analysis wherever conditions are suitable. If erosion occurs after processes have produced significant variations ,then apparently anomalous distributions, vis-a-vis the parent materials, can occur. On archaeological sites, erosion is frequently a major factor of soil history, owing to its acceleration by clearance and agriculture.

Man's Effects

Man's direct effects on the grain size curve are mainly in the area of disturbance and dumping. These often produce materials with little relationship to underlying sediments, in which case particle size analysis can be useful in determining source areas.

Indirectly, agricultural practices have a significant effect on the other factors discussed above, particularly erosion. Soil improvement, such as liming, drainage and ploughing alters the balance of processes beyond all recognition. In the case of earthworm activity for example, a sudden increase in numbers will lead to greater soil mixing and the possibility of a worm worked topsoil developing; at the same time, the effect of centuries of clay translocation may well be wiped out.

PARTICLE SIZE ANALYSIS

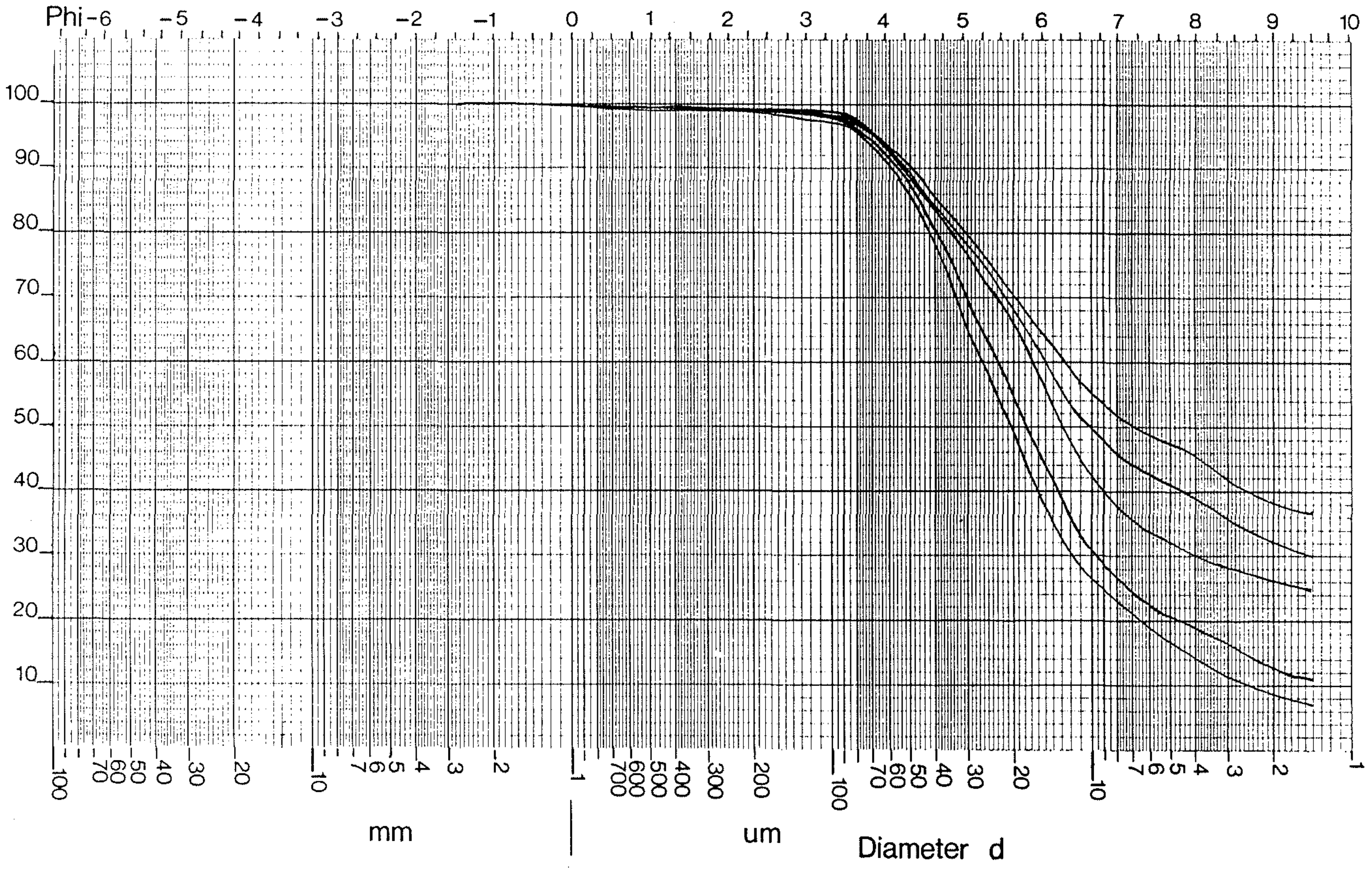


FIG 7

PARTICLE SIZE ANALYSIS

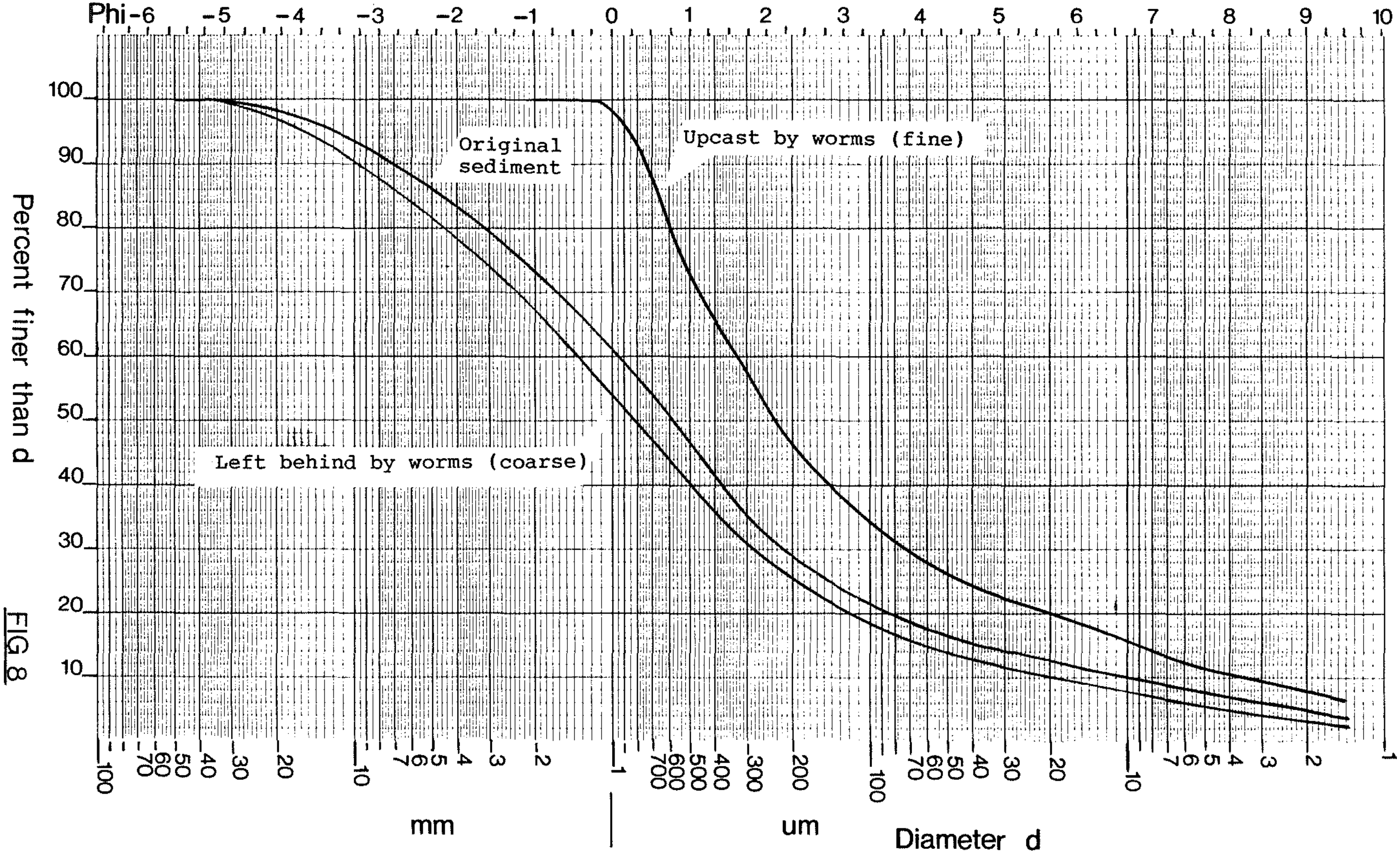


FIG 8

7. Conclusion

The discussion of interpretation is not intended to be a complete guide, any more than the earlier treatment of methods could be said to provide a recipe. Ultimately, it is the specialist's job to weigh up the complex interrelationships between processes and to assess the relative importance of the technical niceties touched on in this report. It is hoped that a framework for understanding this type of analysis has been developed, as well as a lead-in for further study in the Appendices that follow.

APPENDIX 1. - THE SIZE OF PARTICLES

Soil particles come in a range of shapes varying from spherical through ellipsoids to rod-shaped, platy or irregular. This means that, at a detailed level, there is no final way of defining their size. The problem is best illustrated by imagining a plate and a ball made from exactly the same volume of material:-

On sieving, their size will be registered as that of their smallest cross-section, producing very different results. In practice, the size differences are not as large a problem as they are in theory. This is because:-

1) Most sand and silt fractions are largely composed of quartz, which tends towards spherical, cubic and ellipsoid shapes.

2) Sieving rarely offers the opportunity for all particles to slip through in their smallest orientation, so an equalising factor is operative.

3) Particle size analysis will frequently be comparing soils of like parentage. Thus, even if the parent rock is (for example) rich in micas (very platy), the sizing errors will tend to be systematic to the whole suite of samples, and therefore not affect between-sample interpretation.

A more serious result shows up in the subsequent sedimentation test, which is badly affected by the varying flow resistance presented by different particle shapes.(see Appendix 4.)

Shackley (1975) outlines some of the approaches to the size problem which have been discussed in the past, but these apply mainly to optical particle size analysis. If mechanical means are to be used, (which normally means sieve and sedimentation), then the variations must simply be allowed for in a general appreciation of the accuracy of the method. There can be no mathematical adjustment to cover all eventualities, so the particle shapes would have to be pre-assessed if correction factors were to be applied. Since no convention exists to define the size of the two shapes above, such a procedure would have no validity.

APPENDIX 3. - FINGER TEXTURING

Finger texturing, with practice, can confidently assign a soil or sediment to one of the classes of the textural triangle (Fig 1). Ultimately, it is neccessary to practice on soils of known particle size distribution, but verbal guidelines can be helpful:-

Sand (2mm-60um) - feels gritty and can generally be heard if rubbed moist close to the ear.

Silt (60um-2um) - feels soapy/greasy. A moist ball of pure fine silt has a spongy, almost elastic quality when repeatedly pressed. Finely decomposed humus feels very similar, so when black or dark brown soils are being assessed, allowance must be made.

Clay (<2um) - feels sticky and appreciable amounts stick to the fingers when a moist ball is compressed.

The following table can be used to distinguish approximate class groupings (from Limbrey 1975)

	Clay	Sandy clay	Sandy clay loam	Sandy loam	Loamy sand	Sand	Sandy silt loam	Clay loam	Silty clay	Silty clay loam	Silt loam
Sand grains can be detected by hand and eye											
Leaves colour on fingers											
Surface can be made to shine											
Can be made to cohere into pellets when worked moist											
Pellets break up if distorted and fall apart when dry											
Pellets dry out hard											
Can be moulded into shapes											
Silty feel apparent											
Silty feel dominant											
When dry, rubs off on fingers as loose fine powder											
When dry, blows away in slightest draught											

APPENDIX 4 - SEDIMENTATION PROBLEMS

According to Stokes Law of settling, a particle of diameter D will settle a distance H in a time T thus:-

$$D = \sqrt{\frac{18N}{(P_1 - P_2)G}} \times \sqrt{\frac{H}{T}}$$

Where N = Viscosity of the liquid
P_1 = Density of the particle
P_2 = Density of the liquid
G = Acceleration due to gravity

Galehouse (1971) lists 9 major limitations on this basic theory including that particles must be smaller than 50um, larger than 0.5um, perfectly smooth, spherical and rigid. Of these conditions, it is probably sphericity that causes the most obvious error, particularly at the clay end of the scale. Clay particles are usually laminar in shape and therefore settle in a zigzag fashion, similar to a dropped sheet of paper.

Wadell (1934) attempted to improve on Stokes Law by recalculating the formula for application to flattened spheres, which resemble more closely the average particle shape. This type of approach probably gives a better approximation, but has not been widely used.

Owing to the wide variety of such problems, it has become the norm to accept a simple Stokes Law calculation on material finer than 63um. Although clay is continuously over-estimated, there is at least a general agreement on method. Thus, as with the size problems in Appendix 1, the error involved is partly systematic from lab to lab. Difficulties only arise when comparisons are attempted with some of the new non-sedimentary techniques, such as laser diffraction, but the cost of the neccessary equipment precludes their current acceptance as a standard.

The error allowance at the fine end of the scale must be significantly increased for dark (organic) topsoils. Although it is standard to remove the humus with Hydrogen peroxide, there is frequently a residual effect, probably owing to the intimate nature of clay/humus interactions and the likely electrochemical changes on clay surfaces.

APPENDIX 4.- CURVE JOINING PROBLEMS

From a reading of Appendices 1 and 3, it should now be apparent that sieve and sedimentation techniques measure two different properties, both of which bear some close relation to particle size. In the case of sieves, it is the smallest square through which the particle will fall; and in the case of sedimentation, it is the speed at which the particle settles in water.

Sieves are only practical down to around 45um, and sedimentation becomes increasingly unworkable with particles larger than about 70um. Consequently, a sieve curve is normally produced for the >63um fraction, and a sedimentation curve for the fraction <63um. It is quite common for the slopes of the two curves to match poorly at the 63um mark, so that if they are drawn purely as measured, a small kink will result. When normal hand drawing of the curves is employed, this kink can be removed by eye. However, if any form of automated drawing or later analysis is needed, then a mathematical correction must be applied. Most workers agree that sieve data should be sacrosanct, and any losses or gains should be carried out in the upper (least accurate) part of the sedimentation curve. The British Standard 1377 recommends interpolation between the last sieve (63um) reading, and the 40um result from sedimentation. This proceedure will usually be satisfacory to the eye, but computer-read data can still produce a small peak. Ancient Monuments Laboratory data is currently interpolated by a smoothing function between 63um and 20um to avoid spurious peaks developing. To control this unusually large leap, a 45um sieve reading is also taken and is used to check the machine interpolations.

APPENDIX 5. - USE OF A LOGARITHMIC SCALE

Most well-sorted sediments have a grain size distribution that approaches log-normality. This means that, if plotted as a histogram on log paper, they will tend to fit a bell-shaped normal distribution. Originally, sedimentologists plotted cumulative curves on log/probability ordinate paper which brought the S-shaped curve out as a straight line, enabling superior interpolation of points for use in statistical tests.

Apart from the convenience of a log-paper plot (see section 4) there is an inherent sense in viewing the curve with increasing fineward detail. A 10um size difference is of no interpretative significance between stones of say 1cm width, but is highly significant in both soil and sedimentary studies when found among material at the fine end of the graph (10 - 2um).

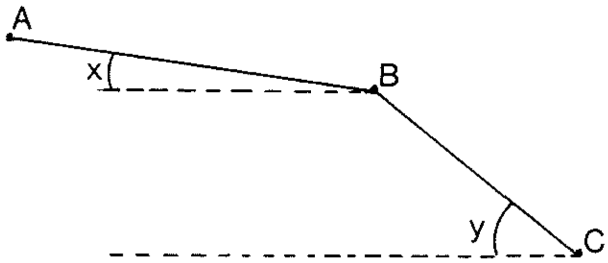
The Phi scale was introduced by Krumbein (1934) to give an arithmetical transformation from logarithmic values. Thus, on any graph in this report, it can be seen to be of regular spacing where the diameters are logarithmic. The Phi scale is still widely used, but is not quoted in archaeological reports to avoid the implicit additional complexity.

A full discussion of logarithmic distributions, the phi scale and their associated literature can be found in Folk (1966).

APPENDIX 6. - INTERPOLATING A SMOOTH CURVE

The sieve and sedimentation method of particle size analysis produces a number of points on the graph but does not provide information on the values between those points. At the crudest level, the points could simply be joined by straight lines to give an interpolation, or a smooth curve could be drawn through them by eye. Reproducibility can only be achieved by a mathematical method, although even this is subject to erroneous initial assumptions.

The interpolation function used on Ancient Monuments Laboratory data was written in-house by P.Linford. It is broadly comparable with other accepted methods (see for instance Press et.al (1986) Chap.3) and works as follows:-



The three points A,B,C are joined and the the angles X and Y are calculated. The gradient at B is given as Tan $\left(\frac{X+Y}{2}\right)$

This proceedure is carried out at all points on the curve, using the points either side of it to specify the gradient. Once the gradients are known, a cubic equation (of the form y=ax +bx +cx=d) is solved to find a curve that satisfies the gradient conditions between each pair of points.

Essentially, this formula proposes that at each measured point, the curve is exactly halfway through its current change of direction. While this proposition is obviously going to be untrue some of the time, it is on average more likely to be true than any other such proposition.

REFERENCES

British Standard 1377 "Methods for testing soils for civil engineering purposes." British Standards Institution, London.

Folk R.L. (1966) "A review of grain size parameters" Sedimentology, 6, 73-79.

Galehouse J.S.(1971) "Sedimentation analysis." In Carver R.E. (1971) "Proceedures in Sedimentary Petrology." John Wiley and Sons, New York.

Krumbein W.C.(1934) "Size frequency distribution of sediments." Journal of Sedimentary Petrology, 4, 65-77

Limbrey S. (1975) "Soil Science and Archaeology" Academic Press, London.

Press W.,Flannery B., Teukolsky S.,Vetterling W.T. (1986) "Numerical Recipes. The art of scientific computing." Chap 3. Cambridge University Press.

Shackley M. (1975) "Archaeological Sediments. A survey of analytical methods". John Wiley and Sons (Halstead Press) New York.

Wadell H. (1934) "Some new sedimentation formulas" Physics 5, 281-291.