J Forensic Sci, Jul. 1975, Vol. 20, No. 3

Francis Fitzpatrick,[1] *B.S. and J. I. Thornton,*[1] *D.Crim.*

Forensic Science Characterization of Sand

The occurrence of sand as a separate soil component is common in many desert and beach communities and in streambeds. When it occurs as physical evidence in a crime scene, it therefore becomes important to attempt to characterize sand from the environment from which it has originated.

Sand is defined as any rock particle between 0.05 and 2.0 millimetres in diameter, but usually is composed of calcium carbonate (limestone), aluminum silicate (feldspar), or silicon dioxide (quartz). The occurrence of quartz is so universal that the term "sand" is usually applied to quartz sand grains [*1*]. To understand the nature of these grains, it is necessary to consider the factors present at the formation and subsequent transportation of this sand and the influence these factors will have on forensic evaluations.

The origins of sand may be traced to the early history of the earth when molten materials were gradually solidified into rocks as the earth began to cool. As the earth developed an atmosphere and weather patterns, the action of the running water caused these granitic rocks, largely composed of oxygen, aluminum, and silicon, to break down or weather [*2*]. When this granitic rock was formed from the cooling magma, high quartz (characterized by a bond angle of 180 deg between the silicon-oxygen atoms in the crystal) was transformed into low quartz as the ambient temperature fell below 573°C. Since this low quartz is characterized by a bond angle of 105 deg, this transformation required a decrease in material volume, or alternately an increase in density; thus, molecular stresses began. These stresses speed the weathering process of a quartz particle, which eventually emerges as a sand grain. These changes occur at the c/a axes of crystal symmetry (Fig. 1), which measure the shape of the unit cell [*3*]. The change in volume attendant with the transition from high to low quartz places stresses parallel to the c-axis, thus affecting the initial shape of the grain. The sizes and shapes of sand grains, therefore, are influenced by the sizes and shapes of quartz crystals in the granitic rock.

The two major agencies affecting sand grains after their formation are wind and water [*4*]. The transportation of sand by wind occurs primarily where the vegetative cover is sparse or absent, allowing the wind to shift the grains, setting them in motion. The size of sand grains is much larger than clay or silt, and unlike clay or silt, sand grains cannot be suspended in the air. Sand grains move in jumps, reaching a height of half a foot. Even strong winds seldom raise grains higher than a foot, although individual grains will be occasionally jolted up far enough to lodge in your

---

Contribution from the Criminalistics-Forensic Science Program, University of California, Berkeley, Calif. Received for publication 10 Sept. 1974; accepted for publication 5 Nov. 1974.

[1] Research Assistant and Assistant Professor, respectively, School of Criminology, University of California, Berkeley, Calif. Mr. Fitzpatrick is now associated with the Orange County Sheriff Coroner Department, Santa Ana, Calif.

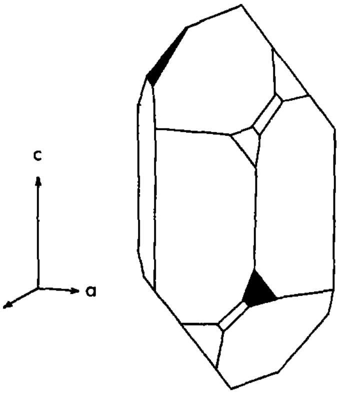

FIG. 1—*Axes of quartz symmetry c/a.*

eyes [*5*]. Surface grains will be jolted by the landing sand grains; some will rise up a slight distance to be carried away in turn and others will slowly creep along the surface. This interaction, promulgated by the wind, will affect the ultimate roundness of the grains. Abrasion by the wind will only take place with particles larger than 0.05 mm. However, since this is the defined lower limit of sand grain diameters, it can be expected that all grains will be abraded, to varying degrees, by wind action. As will be discussed later, desert and dune environments usually show rounder grains.

The action of water upon a sand grain is important, but not as significant as the action of wind. The action of water typified by mountain streams is to roll and bounce the grain along the stream bottom [*1*]. This bouncing will contribute to the rounding of the sand grain but 10 to 100 times less than the extent of the action of wind. Wave action on a grain of sand will contribute to the rounding of that grain, but as the action of the wave transports the grain away from shore, ocean currents cease to affect the grain movement as it falls to a depth greater than 50 ft.

Chemical action has little influence on the rounding of sand grains, although it does have an important influence on surface appearances. The repeated action of desert dew (as dissolved CO_2) on the grain surface tends to impart a dull, opaque color on the surface of the grain, and is precipitated in irregular layers over the surface of the grain as silicic acid [*6*]. Conversely, the action of water in river and beach environments can defrost and polish the grain if the water contains silicon dioxide.

Little frosting is found on grains larger than 1.5 mm, but since deserts show a wide distribution of grain sizes, most grains will be frosted in a true desert environment. As one travels from the sea to the desert, a frosting gradient is observed. Dunes near the beaches will show little frosting and deserts will show almost total frosting.

Under stereomicroscopic magnification, frosting will be readily observed. This differentiation is an important factor in initial grain sample separations.

The most reliable differentiation of sand grains is related to the *shape*, rather than the *size* of individual grains. Since grain shape is a function of the actions of wind and water, a comparison of the roundness of grains will yield significant information about their environment. As far back as 1914 [*7*] the significance of grain shape became apparent and quantitative methods of analysis were explored. Between 1932 and 1935 Wadell [*8*] succeeded in defining two grain shape parameters: roundness, or the lack of sharpness of corners, and sphericity, the resemblance of a sand grain to a sphere. Sphericity was defined mathematically by a comparison of grain surface area, that is,

$$\psi = \frac{s}{S} \tag{1}$$

where

ψ = true sphericity,
s = surface area of an imaginary sphere of a volume equal to that of the particle, and
S = the actual surface area of the particle.

This equation was later modified to a less tedious form,

$$\phi = \frac{dc}{Dc} \tag{2}$$

where

ϕ = shape value,
dc = diameter of a circle equal in area to the area obtained by planimetry, and
Dc = diameter of the smallest circle circumscribing the projection.

Wadell's method [8] of measuring roundness involved the projection of the grain to a magnified size, the inscribing of circles of a known radius around each rounded edge, and the inscribing of the largest circle possible within the grain (Fig. 2). By summing the smaller inscribed radii, dividing by the radius of the largest inscribed circle, and again by dividing by the number of radii measured, a value of roundness is obtained. A value of 1 corresponds to a sphere.

This method gives excellent results in describing a grain by two parameters—roundness and sphericity. As can readily be appreciated, this method is tedious and thus unsuited

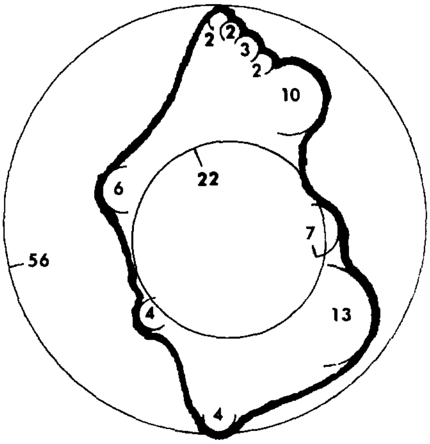

FIG. 2—*Wadell* [8] *sand grain roundness determination. The roundness value is given by* $[\Sigma (r/n)]/R$ *where* r *is the radius of a corner,* n *is the number of corners, and* R *is the radius of the maximum inscribed circle. The solution for this example gives* $(53/10)22 = 0.24$ *roundness value.*

for rapid examination of even small numbers of grains. However, because the basis of this method is sound and yields definitive results, scientifically ordained shortcuts founded on the Wadell principles have proven useful. In 1953 Powers's scale [*9*] was developed as a speedy, accurate method for approximating the roundness of a grain based on Wadell's method. Powers's work involved the sculpturing of a series of models of sand grains, imparting to each grain model a different degree of sphericity and roundness. The Wadell values for these models were calculated and the models were photographed. By comparing the magnified images to the Powers's photographs, a suitable category can be chosen for the particle under consideration.

The Powers method represents a balance between expediency and the accuracy of the Wadell method. However the accuracy obtainable by this method, especially for the experienced operator, far surpasses other methods of roundness analysis.

The Powers roundness models make use of six grade terms with a range of roundness values with which each is associated. These range from 1.0 (well-rounded) to 0.12 (very angular) (see Table 1). To determine the roundness of a grain, each particle is assigned to one of the classes, depending upon the photograph to which the grain most nearly compares (Fig. 3). An average roundness value of a group of particles is determined by multiplying the number of particles in each class by the geometric mean associated with that class. The sum of these products is divided by the total number of grains counted [*9*].

TABLE 1—*Powers roundness grades.*

	Wadell Values	
Grade Terms	Class Intervals	Geometric Mean
Very angular	0.12–0.17	0.14
Angular	0.17–0.25	0.21
Subangular	0.25–0.35	0.30
Subrounded	0.35–0.49	0.41
Rounded	0.49–0.70	0.59
Well-rounded	0.70–1.00	0.84

Studies using the Powers scale [*10,11*] have reconfirmed the earlier conclusions of McCarthy [*12*] in his comparison of sand roundness; that is, generally desert sands are more rounded, dunes less rounded, and beach sand angular. Thus, as one moves from the coast to the deserts, the grains become progressively better rounded. These observations are consistent with the theories of wind action on sand surfaces. As the clastic fragments are transported inland, the wind affects the angularity of the grains [*4*] by abrading the edges. Also, it has been found that the better rounded particles are selectively transported by the wind, since the round particles are more conducive to elastic collisions, which result in the grain being rebounded back into the influence of the wind's transportative action. The roundness value of the desert sand will often be much greater than the value of beach sand [*11*].

There exists a correlation between sand size and roundness values. Krumbein

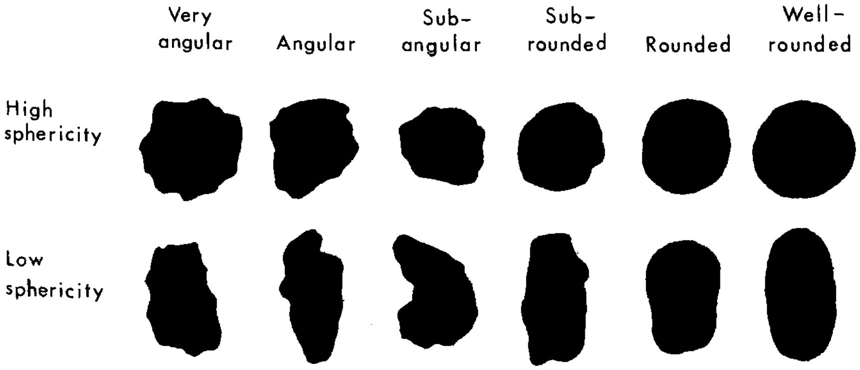

FIG. 3—*Powers scale* [9] *for visual estimation of roundness.*

and Pettijohn [*13*] and McCarthy [*12*] conclude that roundness increases with grain size. This phenomenon is expected since the larger particles have larger areas for contact with other grains. It can also be expected that more collisions of greater momentum will take place between these larger grains and it is these repeated collisions which ultimately affect the roundness of the grains. Krumbein and Sloss [*14*], however, use a more expanded scale than that of Powers, as depicted in Fig. 4.

Since the correlation between size and roundness is so high [*12*], it is essential to break the sample down into uniform size batches. With an exemplar sample, sieves can be used to effect this size differentiation; with evidence samples other methods must be used if the sample is small (for example, less than 100 particles). These methods will be considered later. By arranging the grains into convenient batches (for example, 10% of the total sample for 10 batches of differing size intervals), the roundness values from the

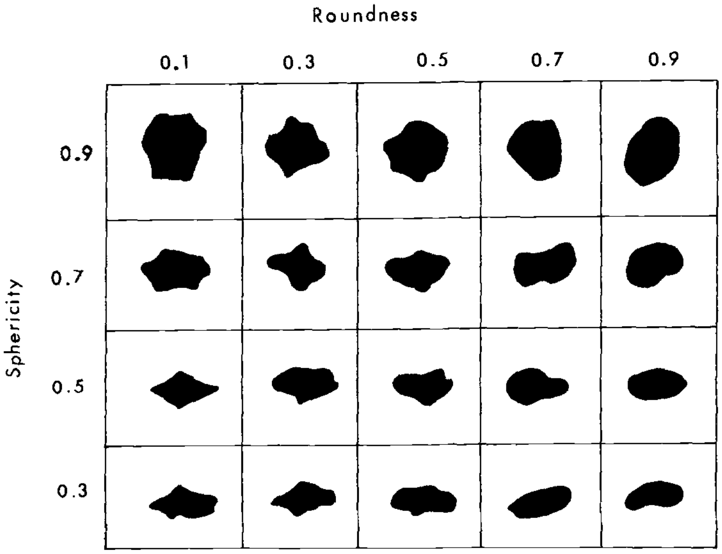

FIG. 4—*Krumbein's scale* [13] *for visual estimation of sphericity and roundness.*

Powers scale can be plotted as the abscissa and the size interval as the ordinate (Fig. 5). The results of the evidence and exemplar evaluations may be plotted concomitantly and the results will be apparent. Small roundness differences do not allow conclusions of themselves, but larger differences will allow for judicious interpretations.

FIG. 5—*Graphical representation of Powers roundness values versus size of sand grains.*

Of lesser importance than roundness in determining environmental histories is the similarities of the shape of a grain given by the three axes: length l, width w, and height h. The first two measurements can be made with a calibrated ocular micrometer, or the grains may be projected and measured directly from the projection. The height measurement may be effected with the fine adjustment drum on the microscope or with an objective micrometer.

The Hagerman method (Fig. 6) cited in Krumbein and Pettijohn [*13*] uses a ratio of width to length plotted against length to give profile shape. Zingg [*15*] uses a width-to-length ratio plotted against thickness-to-width ratio (Fig. 7). Some authors [*16*] have used variations of these length and width measurements and variations of their

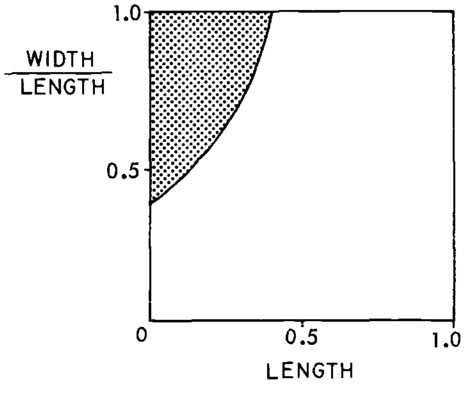

FIG. 6—*Hagerman's plot* (*cited in Ref* 13) *of ratio of width to length versus length. The boundary grain is shown by the line.*

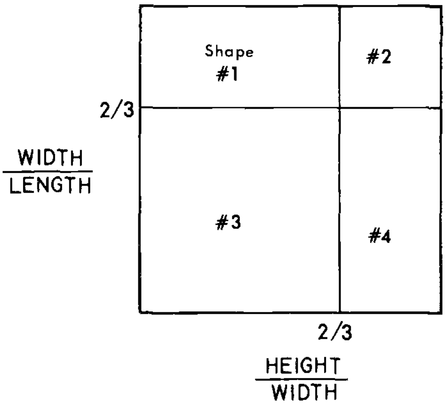

FIG. 7—*Zingg* [15] *plot for three dimensions. Shape 1 represents a disk (oblate spheroid), Shape 2 is spherical, Shape 3 is bladed (triaxial), and Shape 4 is rodlike (prolate spheroid).*

graphic presentations, for example, the "elongation function," the ratio of length to width plotted against the percentage of grains in the sample of that elongation function.

It is the belief of the writers that the quickest, most reliable method of characterizing shapes of a small number of sand particles is the Hagerman plot. It can be accomplished accurately with an ocular micrometer or microprojector and does not embrace the inaccuracies attendant with microscopic height measurements. The expected results with this method (as well as any other size analyses) will not offer conclusive findings in some cases; rather, trends will become evident. If a sample has a spheroid trend and a comparison sample has a rod-shaped trend, conclusions can be confidently drawn; with large areas of overlap, conclusions are more tenuous because the shape of the distribution is related to sedimentation conditions at the time of deposit (for example, turbulence and current velocity) [*16*]. Since depositional conditions can vary widely over a small area, disagreement of boundaries is not always indicative of different environments. Similarly, agreement of boundaries is not of itself indicative of common origin; when this agreement is combined with the results of roundness evaluations, however, it can add force to the conclusions drawn.

Davis and Dexter [*17*] have recently reported the elucidation of two highly accurate methods of shape analysis. The first method compares particle arc lengths with the distance of an arbitrary length about the outline of the particle (Fig. 8). The value of *S-D*, where *S* is the arc length and *D* is the chord, will yield a measure of the sinuosity of the outline between A and B. When the ratio of the arc length *S* to perimeter *P* is small,

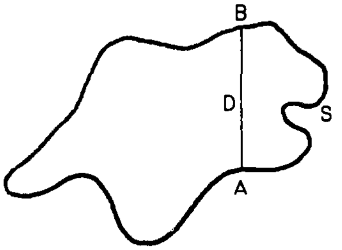

FIG. 8—*Davis-Dexter* [17] *method of particle shape determination.* D *is the chord,* S *is the arc length, and* A *and* B *are points on the particle outline.*

the *S-D* value will be representative of small corrugations in the particle. At a large *S/P* ratio, *S-D* will be sensitive to large corrugations only. If a large number of measurements is taken, with A and B being moved about the outline, the average of *S-D* should describe the shape of the particle very well. The shape function for a particle can be described as:

$$F(S/P) - 15/16(P/S) \times \text{average of } [1 - (D/S)^2]^2 \qquad (1)$$

where $[1 - (D/S)^2]^2$ describes the *S-D* value mathematically to eliminate dimensions and allow variation in particle size. $15/16(P/S)$ is included in order that the function not tend to zero as S/P tends to zero. Equation 1 may be reworked to yield:

$$F(S/P) = 15/16S \int_0^P [1 - (D/S)^2]^2 \, dP \qquad (2)$$

By subtracting the shape function $F(S/P)$ of a circle from the shape function of the particle, the measure of sphericity $G(S/P)$, is obtained:

$$G(S/P) = F(S/P)_{\text{particle}} - F(S/P)_{\text{circle}} \qquad (3)$$

The results are graphed as $G(S/P)$ versus S/P values (Fig. 9). For all shapes, $G(S/P)$ is a continuous function of S/P.

The second shape measure reported by Davis and Dexter [*17*] is obtained by taking the discrete Fourier transform of normalized curvatures about the outline and producing spectra with them. The outline is reproduced (or spotted with the Quantimet® computer, Metal Research Ltd.) and a number of points are generated about the outline so that the points are equally spaced. Using complex notations we may define a point z_n by rectilinear coordinates where $z_n = x_n + iy_n$, and u_n is the difference between two

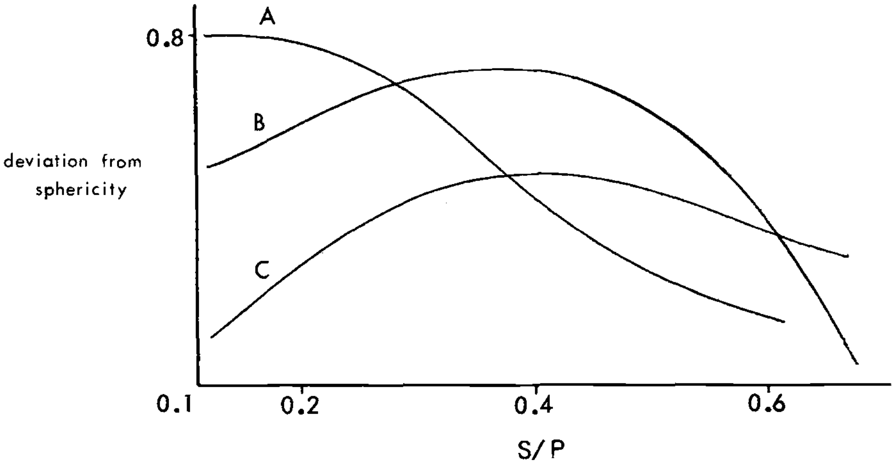

FIG. 9—*Davis-Dexter* [17] *measurement of grain asphericity of three fractions of a sandy soil, as produced from the function* G(S/P) *of Eq 3.*

consecutive points such that $u_n = z_{n+1} - z_n = r_n \exp(i\phi_n)$. The magnitude of the line is defined as r_n (Fig. 10) and the direction as $\Delta x/\Delta y$. Furthermore, the measure of curvature of a particular segment is given by

$$f_n = \exp[i(\phi_{n+1} - \phi_n)] - 1 \tag{4}$$

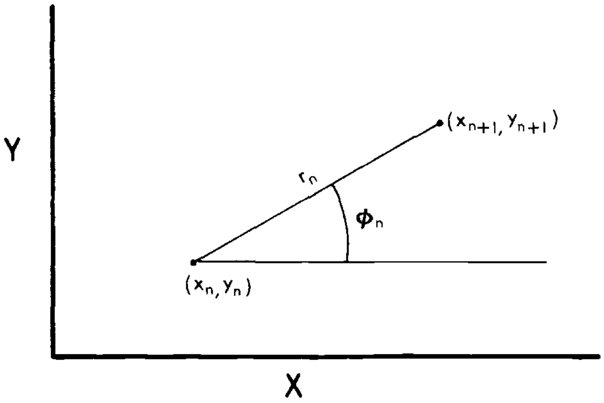

FIG. 10—*Term definition for Davis-Dexter* [17] *spectrum analysis of particles.*

By calculating the ratios of consecutive u_n values, values of f_n are obtained. By determining $F(k)$, where

$$F(k) = \sum f_n \exp(-2\pi ikn/N) \tag{5}$$

(the discrete Fourier transform of f_n), the curvature can be described in terms of discrete line spectra when we multiply $F(k)$ by its complex conjugate to eliminate complex notation so that

$$S(k) = F(k) \times \bar{F}(k) \tag{6}$$

where $S(k)$ is the discrete spectrum (Fig. 11). The N in Eq 5 is the total number of points generated by interpolation from the original data such that they are equally spaced around the outline.

Although these methods afford accurate evaluations of shape analysis, the data require computer manipulation and are also tedious for sand application. Moreover, the time and care required for these methods of shape analysis are not warranted by the information obtainable from them; rather, careful roundness measurements and Hagerman plots will provide superior information relating sand grains to their environment.

Size measurements are the final morphological characteristic to be considered in this evaluation of granulometric measurements. Size of sand grains and their distribution is a poor method of characterizing grain environments for forensic purposes. The usual amount of sand necessary for a complete statistical treatment of size distributions is greater than 30 to 50 grams, an amount often out of the realm of evidence samples.

Although size distribution analyses may be of relatively little value, the writers

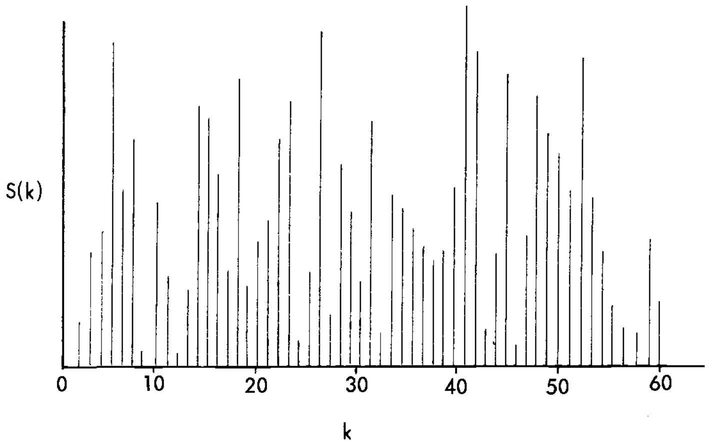

FIG. 11—*Discrete spectrum of a normalized curvature of one fraction of a sandy soil.*

recommend that they be carried out when an adequate sample is available. Since initial size measurements must be made prior to roundness determinations, the additional work of a weight percentage analysis is minimal and may provide some meaningful information, particularly for the distribution of beach sands. A procedure to follow is to sieve the sample through sieves from Mesh 5 (corresponding to 2.54 mm) to Mesh 200 (corresponding to 0.063 mm). The weight of the grains retained by each sieve is calculated as the percentage of the total sample weight. With a sample of less than 100 particles, however, this sieving method should not be attempted, since the inherent error in sieving and weighing procedures precludes accurate results. With less than 100 particles only microscopic measurements should be made.

It should be noted that grade scales, scales of sizes used to conveniently present data, exist for the analysis of sand. These geometric scales enable the examiner to decrease the range of grade classes without sacrificing minor differences in that class. Of most widespread use is the logarithmic phi scale [*13*] defined as

$$\phi = -\log_2 d$$

where d is the diameter of particle in millimetres.

Although graphic representation of results can be presented in many ways, histograms and cumulative curves will often represent results more sensitively if they are combined with the use of a geometric grade scale such as the phi scale. Sieves, for example, represent a use of geometrical relationships between sieve number and sieve hole diameter to reflect this sensitivity.

To evaluate the results of weight percentages, the weight percent retained in a sieve is plotted against the sieve size; comparisons with other grain samples become easier with the use of this plot (Fig. 12). Only major peak differences are indicative of differing sources; minor variations are to be expected.

Recent developments in computer science have made grain measurements speedy and highly accurate. The Quantimet® (QM) by Metal Research Ltd. and the Leitz Intergramat® are two such instruments. These instruments are able to evaluate differences in voltage in a selected field corresponding to the field of view on the microscope.

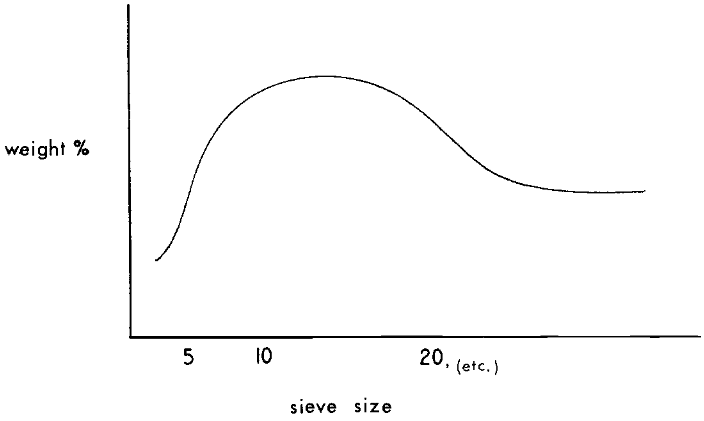

FIG. 12—*Graphical representation of weight % per size of grains retained by various sieves.*

Such features as grain boundaries, inclusions, and pores respond to areas darker or lighter than a selected threshold level. Voltage changes are indicated by meter fluctuations and analyzed by a dedicated computer; the parameters of a particle are given as the output. More recent developments feature a "light pen" which can be used in conjunction with the monitor to select individual particles for analyses.

The applications of these instruments are important in all phases of particle analysis, including size determinations, diameter measurements, orientations of a particle, dislocations, etc. The use of these instruments should prove valuable in sand analysis.

In any consideration of microscopic measurements it is necessary to offer a consistent procedure to follow to insure that these measurements will be independent of orientation and examiner's prejudice. The computer methods, as well as many nonautomated particle measurement systems, make use of the Martin's and Feret's statistical diameters [*18-20*]. Martin's statistical diameter [*19*] is defined as the statistical intercept diameter which intersects the approximate bisect of a particle. Feret's diameter [*20*] is defined as the distance between two tangents on the opposite side of an outline of a particle, parallel to an arbitrary fixed axis (Fig. 13). As is apparent, orientation is an important factor in making these measurements. For consistent results, the length axis is best measured when Feret's diameter approximately equals Martin's diameter. For the measurement of the width axis, however, Feret's diameter does not necessarily equal Martin's diameter. Thus, the smallest diameter value of Martin's intercept should be taken as the width measurement. This will yield the most consistent results. Additionally, it has been shown [*21*] that Feret's diameter introduces large errors for the measure-

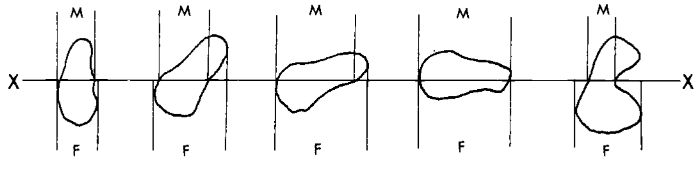

FIG. 13—*Measurements of the Feret* (20) *and Martin et al* [19] *diameters.* M *denotes Martin's diameter,* F *is Feret's diameter, and* X *is an arbitrary axis of bisection.*

ment of elongated particles of irregular shape, since the tangential points on these shapes are difficult to determine.

The choice of a measurement system for sand grains is partly a matter of convenience. Martin's statistical diameter is more suitable for grains projected on a screen. Comparison reticules may be better for visual work, but increase the time necessary for measurements. By combining the use of Martin's diameter with microscopic measurements, it is possible to evaluate sand grains speedily and accurately.

The morphological comparison of sand samples, roundness, shape, and size distribution can become tedious operations. However, these operations, in combination, generally provide a definitive method for determining the environment (beach, dune, or desert) of a sand grain sample. Conclusions are more valid if the examiner attempts to understand the principles of sedimentation in relation to sand deposits. Cognizant of the inherent pitfalls of sand comparison (for example, incorrect sampling technique or examiner bias), the examiner should endeavor to perform all the tests proposed in granulometric determinations and inspect the results for similarities and dissimilarities before drawing a conclusion.

While granulometric determinations of environment have proved to be valuable tools to sedimentary petrologists and paleogeologists, the inherent errors introduced in any measurement procedure prove to be a limiting factor. For this reason, other methods have been sought.

Recent developments in electron microscopy and its applications have made this instrument a valuable tool to all of the natural and life sciences. By 1962 the transmission electron microscope (TEM) had been used extensively to identify environments by examining grain textures [*21*], and by 1968 Krinsley and Donahue [*22*], after examining over 4000 grains with the TEM, published a glossary of terms and photomicrographs of environmental features of sand grains. The conclusions of this study provided only tentative results for certain environments, however [*23*]. The advent of the scanning electron microscope (SEM) has made it possible to revise earlier TEM studies, however, and provide more conclusive information to relate surface texture to environmental history.

The SEM has proved to be a superior instrument for the evaluation of sand grain textures because, unlike the TEM, the SEM does not require a tedious and time-consuming casting procedure of the sand particle. These casting procedures often introduce artifacts into the final image which are unrelated to the texture of the grain. The image of the cast obtained by TEM requires experience in interpretation and evaluation, and as such is not particularly suited for court presentation in forensic situations. The SEM, however, yields an easily interpretable photograph of incredible depth of field, a simulated phenomenon of three dimensions, and requires comparatively little skill in operation.

The most complete work on SEM grain texture-environment interpretations has been conducted by Krinsley and Margolis [*23*]. As is reported, the advantage of the SEM is that only two hours are needed to examine in detail 25 to 50 grains, a time factor ten times faster than a comparable TEM treatment. Additionally, the detail is more easily interpreted.

The procedure followed in preparing grains for SEM treatment is to coat the grains with gold in a vacuum evaporator (the gold coating increases surface conduction for the electron beam). As many as 100 grains can be cemented (with Duco cement) on a single SEM plug. With the SEM a number of grains can be examined at one time before a selected grain is magnified (Fig. 14).

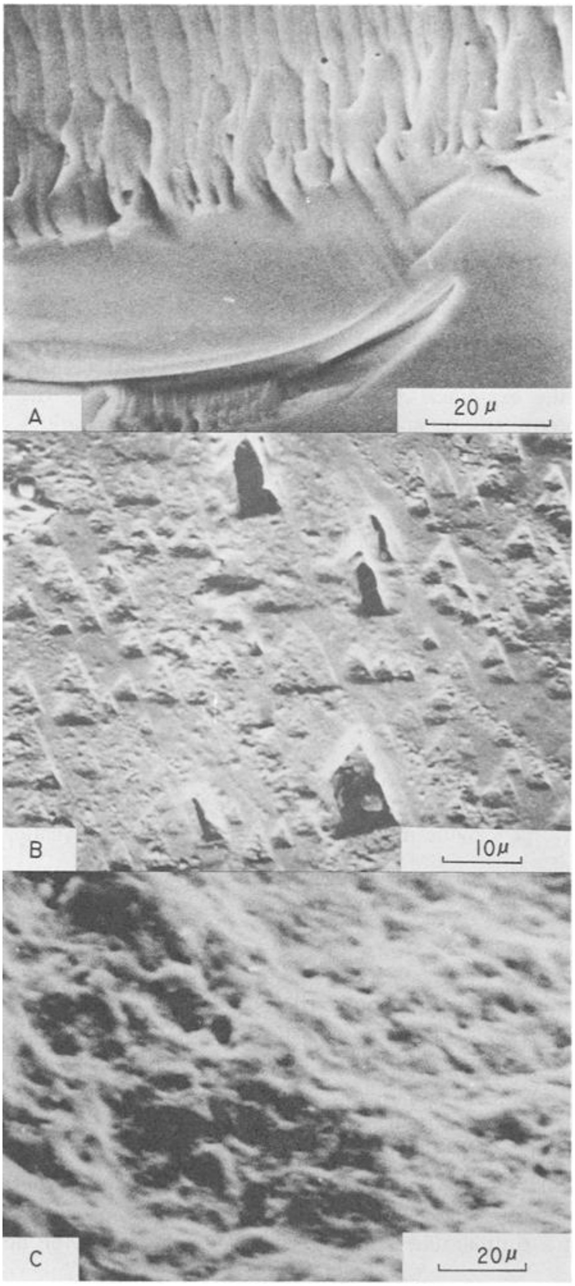

FIG. 14—*Scanning electron micrographs of sand grains illustrating features indicating processes involved in the formation of the grain.* (a) *Glacial—the grain exhibits steplike fractures, curved conchoidal fractures with arc-shaped steps, and subsidiary steplike fractures on otherwise smooth surfaces.* (b) *Littoral—the grain shows triangular, crystallographically oriented etch pits characteristic of abrasion in an aqueous environment.* (c) *Desert—typical eolian sand grain showing plates smoothed and subdued by etching and deposition of silica. Note the low relief in comparison to littoral and glacial sands.* (Micrographs supplied through the courtesy of Dr. Stanley Margolis.)

Since large variability can be found on individual grains, a statistically valid procedure to follow is to examine 50 to 100 grains from a sample and record the occurrence of each feature. The criteria [*23*] for identifying various environments from sand surface textures are as follows.

Littoral (Beaches)

Littoral (beach) environments are characterized by:

1. Blocky-conchoidal breakage patterns, probably produced by the grinding of pebbles and sand in a high energy medium. They possess a great surface-to-depth ratio and tend to increase in number in high energy (100-cm annual breaker height) beaches.
2. Small V-shaped indentations, probably caused by grain-to-grain collisions in an aqueous medium.
3. Straight or slightly curved grooves or scratches measuring 1 to 15 μm in length, probably caused by one grain dragging across another grain.
4. Chatter marks (rare) and subparallel indentations averaging 0.5 μm in length and probably produced by one grain skipping across another.
5. Orientated V-shaped patterns resulting from chemical etching in seawater.

It may be possible with a large sample size to relate size, distribution, and indentation depth to the energy conditions on a specific beach environment.

Eolian (Deserts, Dunes)

Characteristics of eolian (desert or dune) environments are:

1. Meandering ridges, probably produced by the wearing away of breakage blocks during transport by the impactation of one grain over another. These areas are more rounded than blocky-conchoidal patterns found on beach sand.
2. Graded arcs, less common than ridges and probably representing percussion fractures. The arcs are in concentric series, graduating in size to form a fan shape.

Desert samples can also be distinguished by flat pitted surfaces replacing the blocky patterns. This pitting may be chemical etching from "desert dew" or from abrasive action; also, orientated fracture patterns have been observed on desert sands.

Glacial (Mountains)

Glacial (mountain) environments are distinguished by:

1. Various sizes of conchoidal breakage patterns, probably related to glacial sediment size.
2. High relief (as compared with littoral or eolian relief); this is probably a function of the energy of the glacier available for grinding.
3. Semiparallel steps, which may be caused by sheer stresses.
4. Arc-shaped steps, probably caused by percussion and similar to eolian graded arcs.
5. Parallel striations (of variable lengths), probably caused by the movement of sharp edges against the grain or by cleavage.
6. Imbricated breakage blocks.
7. Irregular small-scale indentations, often associated with conchoidal breakage patterns.

It has been postulated by Krinsley and Margolis [*23*] that Characteristics 3, 4, 6 grade into each other. It has also been tenuously reported that a worn glacial surface without chemical or mechanical action being evident may be diagnostic of a glacio-fluvial (river) environment.

Conclusion

As is evident, environmental determinations of sand grains can be accomplished only with a careful application of the Krinsley-Margolis criteria. The examiner is urged to consult their study before attempting a SEM examination of sand surface textures.

The forensic implication of granulometric and scanning electron microscopic sand analysis is such that when used adjunctively, the examiner may be able to make valid judgments concerning the environment from whence a grain of sand has come.

These methods become important since it is crucial to note that sand cannot be treated as a soil sample in forensic evaluations; such techniques as density gradients, for example, may be inappropriate. Density gradients will fail to yield significant results because quartz sand grains show a uniform density of 2.65 g/cm^3. Although dissimilar results are indicative of dissimilar localities, similar density gradient results are only indicative of similar densities of minerals and not similar localities. Density variance from 2.65 g/cm^3 is a function of the detrital minerals (rutile, zircon, etc.) which may be clinging to, or mixing with, the grains. However, these minerals are often indicative of several different depositional sites. Thus, their presence or absence is not limited to a particular locale or beach environment and the resulting layering of these particles in a density gradient is not unique to a particular locale but only to meteorological factors at time of deposition. Sand must therefore be treated separately from soil samples until extensive research involving density distributions of sand is completed.

One apparent source of difficulty in determining the environment from which a sand sample has come is the possibly conflicting results of the presence of industrial sand. This sand is brought to a site from distant localities for construction or other industrial purposes. It should not prove difficult to distinguish these sands from "surface" sands (usually encountered in forensic situations), since these surface sands will be lighter in color than the dull orange-yellow color which usually characterizes underground sands [*24*]. The yellow-orange color is the result of yellow pellicles of hematite (Fe_2O_3) or limonite ($2Fe_2O_3 \cdot 3H_2O$) deposited on the grain at such depths that weathering factors cannot polish and clean the surface of the sand grain. These iron oxides can be chemically analyzed [*25*].

With the use of the SEM, construction and industrial sands may be easily differentiated from surface sands, since the industrial sands may show a diagenetic surface pattern (that is, two different environmental surface patterns). These "foreign" sands can also be treated as any usual sand sample with granulometric determinations.

No matter whether granulometric methods or electron microscopy methods are used for sand identification, the examiner must consider all areas of agreement and disagreement in the results, and conclusions are possible only after a careful evaluation of all phases of the examination. The methods discussed should form the skeleton of a comprehensive system of uniform sand evaluation with the results of each method available in an effectively interpretable and presentable form.

References

[*1*] Kunen, Ph. H., "Sand," *Scientific American,* Vol. 202, No. 4, April 1960, pp. 94-110.

[*2*] Krinsley, D. and Smalley, I., "Sand," *American Scientist,* Vol. 60, No. 3, May-June 1972, pp. 286-291.

[*3*] Smalley, I., "Formation of Quartz Sand," *Nature,* Vol. 211, No. 5048, 30 July 1966, pp. 476-477.

[*4*] Kunen, Ph. H., "Sand—Its Origin, Transportation, Abrasion and Accumulation," Alex du Toit Memorial Lecture No. 6, *Transactions of the Geological Society of South Africa,* Annexure to Vol. 62, 1959, 33 pp.

[*5*] Bagnold, R., *The Physics of Blown Sand and Desert Dunes,* Methuen, London, 1941.

[*6*] Kunen, Ph. H. and Perdok, W., "Frosting and Defrosting of Quartz Grains," *Journal of Geology,* Vol. 70, No. 6, Nov. 1962, pp. 648-658.

[*7*] Udden, J., "Mechanical Composition of Clastic Sediments," *Geological Society of America, Bulletin,* Vol. 25, No. 4, 1914, pp. 655-744.

[*8*] Wadell, H., "Volume, Shape and Roundness of Rock Particles," *Journal of Geology,* Vol. 40, No. 5, 1932, pp. 443-451; "Sphericity and Roundness of Rock Particles," *Journal of Geology,* Vol. 41, No. 3, 1933, pp. 310-331; and "Volume, Shape and Roundness of Rock Particles," *Journal of Geology,* Vol 43, 1933, pp. 250-280.

[*9*] Powers, M., "A New Roundness Scale for Sedimentary Particles," *Journal of Sedimentary Petrology,* Vol. 3, No. 2, June 1953, pp. 49-60.

[*10*] Beal, M., and Shepard, F., "Determining Environment by Roundness," *Journal of Sedimentary Petrology,* Vol. 26, No. 1, 1956, pp. 49-60.

[*11*] Mason, C. and Folk, R., "Determination of Beach, Dune and Aeolian Flat Environment by Size Analysis, Mustang Island, Texas," *Journal of Sedimentary Petrology,* Vol. 28, No. 2, 1958, pp. 211-226.

[*12*] McCarthy, G., "Eolian Sands: A Comparison," *American Journal of Science,* Vol. 30, No. 176, 1935, pp. 81-95.

[*13*] Krumbein, W. and Pettijohn, F., *Manual of Sedimentary Petrography,* Appleton, New York, 1938.

[*14*] Krumbein, W. and Sloss, L. L., *Stratigraphy and Sedimentation,* Freeman, San Francisco, 1955.

[*15*] Zingg, T., "Bittag zur Schotteranalyse," *Schweizerische Mineralogische und Petrographische Mitteilungen,* Vol. 15, No. 1, 1935, pp. 39-140.

[*16*] Moss, A., "The Physical Nature of Common Sandy and Pebbly Deposits," Part 1, *American Journal of Science,* Vol. 260, No. 5, 1962, pp. 337-373; Part 2, *American Journal of Science,* Vol. 261, No. 4, 1963, pp. 297-343.

[*17*] Davis, P. F. and Dexter, A. R., "Methods for Quantitative Description of Soil Particle Shape," *Journal of Soil Science,* Vol. 23, No. 4, 1972, pp. 448-455.

[*18*] Heywood, H., "A Comparison of Measuring Microscopical Particles," *Transactions of the Institution of Mining and Metallurgy,* Vol. 55, 1946, pp. 391-404.

[*19*] Martin, G., Blyth, C. E., and Tongue, H., "Researches in the Theory of Fine Grinding," *Transactions of the British Ceramic Society,* Vol. 23, No. 2, 1923-1924, pp. 61-78.

[*20*] Feret, L., "Le Grosseur des Grains des Matières Pulverulentes," *Association Internationale pour l'Essai des Materiaux,* Vol. 2, Group D, Zurich, 1931, cited in Ref *18*.

[*21*] Krinsley, D. and Takahashi, T., "The Surface Textures of Sand Grains, An Application of Electron Microscopy," *Science,* Vol. 138, No. 3507, 16 March 1962, pp. 923-925.

[*22*] Krinsley, D. and Donahue, J., "Environmental Interpretation of Sand Grain Surface Textures by Electron Microscopy," *Geological Society of America, Bulletin,* Vol. 79, No. 6, 1968, pp. 743-748.

[*23*] Krinsley, D. and Margolis, S., "A Study of Sand Grain Textures with the Scanning Electron Microscope," *Transactions of the New York Academy of Sciences, Series II,* Vol. 31, No. 5, May 1969, pp. 457-477.

[*24*] Brown, J., "Depositional Histories of Sand Grains from Surface Textures," *Nature,* Vol. 242, No. 5397, 6 April 1973, pp. 396-398.

[*25*] Jones, J., "The Identification of Sand," *Police Journal,* Vol. 14, No. 2, April-June 1941, pp. 209-215.

School of Criminology
University of California
Berkeley, Calif. 94720