Discrimination of depositional environments using sedimentary characteristics in the Mega Kalahari, central southern Africa

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SUMMARY: Unconsolidated Kalahari sand covers 2.5 million km^2 of central southern Africa, the 'Mega Kalahari', extending far beyond the Kalahari Desert of today. Relic aeolian, lacustrine and fluvial landforms indicate that in the Quaternary the Kalahari sand has been deposited and reworked by a variety of processes. Large areas of the sand have no identifiable landform associations, and because of this, sedimentological studies are necessary for a better interpretation of the palaeoenvironmental history of the Mega Kalahari. To this end, almost 200 Kalahari sand samples, in and not in identifiable landform associations, were collected and analysed in order to: investigate sedimentological characteristics; determine whether different processes have imparted distinct sedimentological characteristics to the sand; and thereby attempt to determine the depositional environments of samples without prior knowledge of the landform associations. Three methods have been used: (1) standard sedimentological techniques of grain size and shape determination; (2) multivariate discriminant analyses, to determine whether depositional environments could be better distinguished by considering grain size and shape parameters in combination; and (3) scanning electron microscope analyses of samples which lie centrally in any group identified by statistical analyses. Results indicate that aeolian processes have dominated the environmental history of the Kalahari sand, with only limited modification by subsequent processes. Multivariate discriminant analysis achieved only limited success in differentiating process environments. SEM investigations best identified the subtle modification of sand characteristics by non-aeolian processes, because individual grain textures are more readily adjusted than overall sample fabrics, and may therefore be the best technique for elucidating palaeoenvironments from sediment characteristics.

Unconsolidated Kalahari sand covers an area of 2.5 million km^2 in central southern Africa (Cooke 1964), extending from humid tropical Zaire to semi-arid Botswana (Fig. 1). This area has been termed the 'Mega Kalahari' (*eg* Thomas 1986*a* and *b*) in order to distinguish it from the smaller area known today as the Kalahari Desert (*eg* Cooke 1985; Jones 1982). Uncertainty surrounds the age and origin of the Kalahari sand. Maufe (1930), for example, considered it to be of Tertiary age, whilst Bond (1948) preferred the Pleistocene as the time of original deposition. Poldervaart (1957) and Bond (1948), utilized heavy mineral studies to infer the source areas and direction of transport of the surface sands of southeastern Botswana and Zimbabwe, respectively. However, in a systematic study in Botswana, Baillieul (1975) suggested that *in situ* subsurface bedrock weathering and bioturbation had made significant contributions to the sand. Boocock & Van Stratten (1962) also noted that even the youngest Kalahari sand may have been derived from underlying bedrock.

Despite these doubts about the provenance of the Kalahari sand, it is clear that it has been reworked on a number of occasions in the Quaternary period. The evidence for this was first recognized by Grove (1969) in the presence of a range of landforms produced under various palaeoenvironmental conditions. The most extensive are systems of fossilized sand dunes (*eg* Lancaster 1981; Thomas 1984), the northernmost of which is now covered by tropical rain forest in Zaire and Angola (Goudie 1983). Palaeolake beds and strandlines (*eg* Grey & Cooke 1977; Shaw 1985) and fossil drainage lines (Boocock & Van Stratten 1962) indicate more humid Quaternary conditions while pans, sometimes associated with lunette dunes (*eg* Lancaster 1978) testify to fluctuating hydrological conditions.

Palaeoenvironmental research in the Mega Kalahari has largely been concerned with evidence derived from landforms, although some investigations do include sediment descriptions (*eg* Lancaster 1978; Cooke 1980). Pettijohn *et al.* (1972) noted from the literature that over 80% of all sedimentological studies had been conducted to determine environments of deposition, however there has been limited application of grain size and shape studies to the sediments of the Mega Kalahari. The purpose of this paper is thus threefold: (1) to report the sedimentological characteristics of the Kalahari sand where found in known landform associations; (2) to see whether such sand has distinct characteristics imparted by the processes responsible for the

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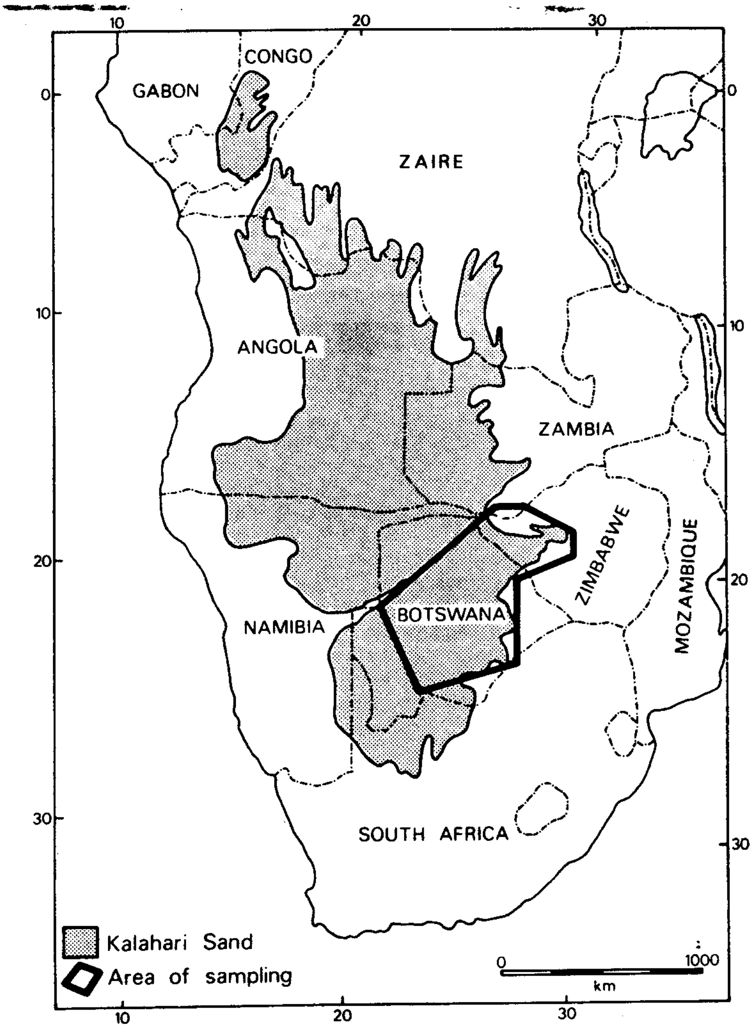


FIG. 1. Distribution of Kalahari sand in central southern Africa (after Cooke 1964). The area within which sampling was undertaken for this study is also shown.

formation of the relevant landforms; and (3) to examine whether palaeoenvironmental information may be gained from the sedimentological characteristics of the sand alone.

Sampling framework

The term 'Kalahari sand' is not well defined in the literature. It is used in a broad sense in this paper to include sediments which form the unconsolidated surface deposits in the Mega Kalahari, regardless of association with specific landforms. Various constraints limited sampling to only part of the Mega Kalahari (Fig. 1); nevertheless, some 250 000 km^2 were included in the study area. The full sediment sampling programme involved the collection of 254 samples each weighing approximately 300 g and taken using a 12 cm diameter auger from a depth of 30 cm to ensure consistency of sampling and to avoid the potentially disturbed surface layer. From the total sample collection, 198 were utilized in this study. Each was classified as coming from one of seven landform categories: relict linear dune ridge crest ($n = 46$); interdune ridge trough ($n = 25$); pan floor ($n = 21$); pan surround ($n = 12$); palaeolake floor ($n = 18$); palaeodrainage floor ($n = 21$) and no landform association ($n = 55$). The first six represent the range of environments in which the Kalahari sand was deposited in the Quaternary period (*eg* Jones 1982; Thomas 1987).

The pans included in the study were all located in western Zimbabwe and northeastern Botswana. Unlike those in the southwestern Mega Kalahari, they lacked evidence, especially fringing lunette dunes, which would confirm their deflational origin (Goudie & Thomas 1985), and probably result from the interaction of both wind and zoological activity (Flint & Bond 1968). They are nevertheless a very important landscape component in the western Mega Kalahari, especially within the depressions between relict dune ridges. A pan surround, as the name implies, is an area separated from a pan floor and the surrounding environment by distinct breaks of slope and, unlike the pan floor, is not normally inundated seasonally with standing water.

The final category of sample classification was used for samples from areas which were devoid of recognizable landforms. These came from the Livingstone area of Zambia, and from E of the Gwayi river in Zimbabwe, but also from other locations throughout the study area.

Sediment analyses

Standard laboratory techniques were used to determine particle size and shape characteristics and the heavy mineral content of the samples. Following treatment to remove any organic material and to disaggregate the sediment, particle sizes in the sand fraction were determined by sieving at 0.25 phi intervals. The grain size distribution of the silt and clay fractions were investigated using a CILAS 715 laser granulometer (Cornillault 1972), which combines rapid determination with accuracy during repeated measurements. Descriptive sample statistics, or textural parameters, were then calculated from the grain size data.

Following separation of the quartz and heavy mineral components of the sand-size fractions of samples by the gravity method (Carver 1971), particle shape characteristics were determined for the quartz fractions. Shape and heavy mineral analyses only involved 48 samples because of the time-consuming nature of the methods. These samples were selected to retain the balance of both the spatial and landform characteristics in the overall sample framework.

Results

Textural parameters

Textural parameters are sample statistics used to describe particle size distributions within sediments, and those calculated according to the equations of Folk & Ward (1957) have been widely employed. Although their underlying assumption of a log-normal grain size distribution in sediments has been questioned recently (Barndorff-Nielsen *et al.* 1982; Christiansen *et al.* 1984) and the log-hyperbolic function favoured (Flenley *et al.* this vol.), the Folk & Ward (1957) parameters of mean grain size, sorting (standard deviation), skewness and kurtosis have been employed in this study. This may be justified by their common usage (*eg* Folk 1966; Besler 1983), and by the fact that Wyrwoll & Smyth (1985) found no apparent advantage in using the parameters of the log-hyperbolic as opposed to log-normal distributions in their study of dune sands.

Some studies utilizing Folk & Ward parameters have only investigated the grain size distribution of the sand fraction of a sample in detail. Friedman (1967), for example, treated the combined silt and clay fraction as one size class, characterizing it as either 4.25 or 6.00 phi, largely because of the added difficulties of measuring fine particles in the tail of the distribution. Yet Friedman (1967, 1979) has also noted that it is largely additions and subtractions to the fines which impart environmental significance to grain size distributions. The use of the laser granulometer allowed the particle size distribution in the fine fractions of samples in this study to be fully investigated and incorporated in the calculation of the textural parameters.

Table 1 shows the average values of grain size characteristics for samples grouped according to landform classification. General characteristics of the Kalahari sand emerge, such as the fact that the mean falls in the fine sand fraction, and that there is positive skewness and bimodality. These have been identified before and have been attributed to aeolian activity (Baillieul 1975; Cooke 1980; Thomas 1985). But such generalizations mask considerable variation between individual samples, and are of little value in attempting to determine depositional environments on sedimentological grounds. Alternatively, bivariate plots of different combinations of grain size parameters have been advocated by a number of authors as a method suitable to distinguish between modern sediments deposited by different processes. This method is based on the assumption that different processes of transportation result in variations in grain size distribution. These are reflected in the statistical parameters which, when plotted as scattergrams, produce bivariate clusters of samples affected by the same process, and separation of those samples

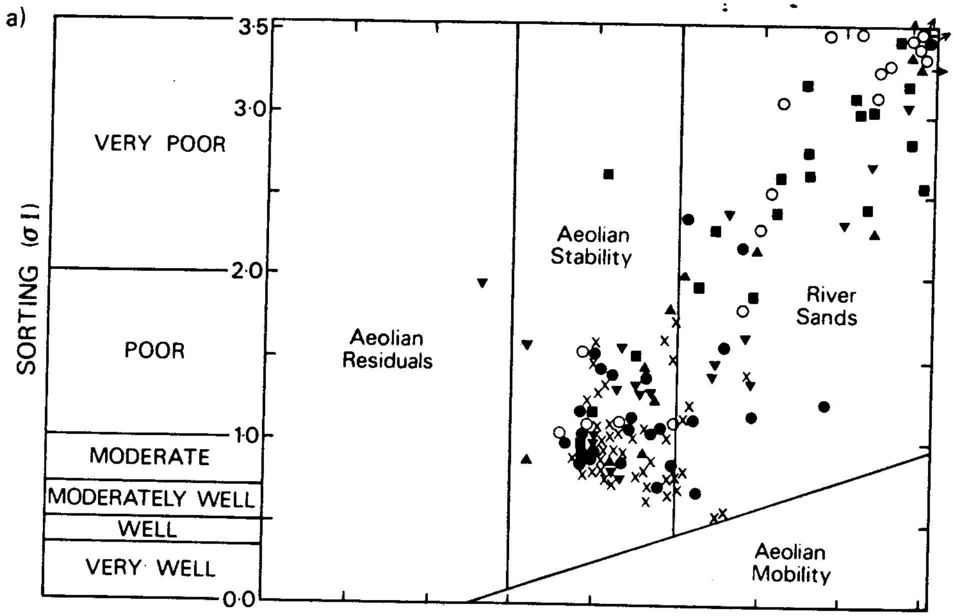
TABLE 1. *Graphical size distribution moments and percentage sand, silt and clay for Mega Kalahari sand samples from landform elements*

Landform element	*n*	sand particle grade %					graphical moment			
		coarse	med	fine	silt	clay	mean φ	sort. φ	skew.	kurt.
ridge crest	46	7.87	35.78	50.78	4.59	1.04	2.13	1.01	0.16	1.18
trough	25	9.81	30.64	45.08	11.42	3.52	2.43	1.31	0.15	1.53
pan	21	10.79	27.07	33.94	22.36	6.42	3.09	2.49	0.51	1.12
pan surround	12	10.61	26.31	43.60	10.32	5.59	2.88	2.07	0.41	1.76
palaeolake	18	13.19	25.45	32.59	19.60	10.40	3.32	2.46	0.48	1.16
fossil channel	21	7.60	30.90	43.63	14.71	2.24	2.58	1.72	0.44	1.40
unclassified	55	11.16	34.17	44.53	7.14	1.96	2.20	1.32	0.27	1.38

influenced by different processes. Figures 2 and 3 show plots of some combinations of parameters which have been attributed an ability to distinguish sands from different process environments. It is clear that the Kalahari sand displays considerable variation in the range of values of each parameter, and that such variation occurs both within and between landform categories.

Besler (1983) termed the plot of mean grain size versus sorting the 'response diagram' and felt sufficiently confident about its powers of discrimination to draw clear boundaries between plot clusters representing different desert process environments. Figure 2*a* shows that whilst there is some separation between samples from wind- and water-worked environments in the Mega Kalahari, considerable overlap also occurs. Other bivariate plots of Folk & Ward type parameters have been used successfully in the literature (*eg* Friedman 1961; Martins 1965; Moiola & Weiser 1968; Hails & Hoyt 1969). The percentage of silt and clay (<62 μm) was also successfully incorporated in bivariate plots by Friedman (1979), especially where skewness was involved.

In general, bivariate plots achieve some discrimination use in this investigation (Figs 2 and 3) but do not achieve a good and clear distinction of different environments, as has also been found by Schlee *et al.* (1964), Ahlbrandt (1979) and Vincent (1985) in other studies. This is because of the wide range of parameter values within each landform class. Ahlbrandt (1979) suggested that in the case of aeolian sands, ineffectiveness occurred because of variations in the grain size characteristics of the original sand sources. It is therefore not surprising that such variability in



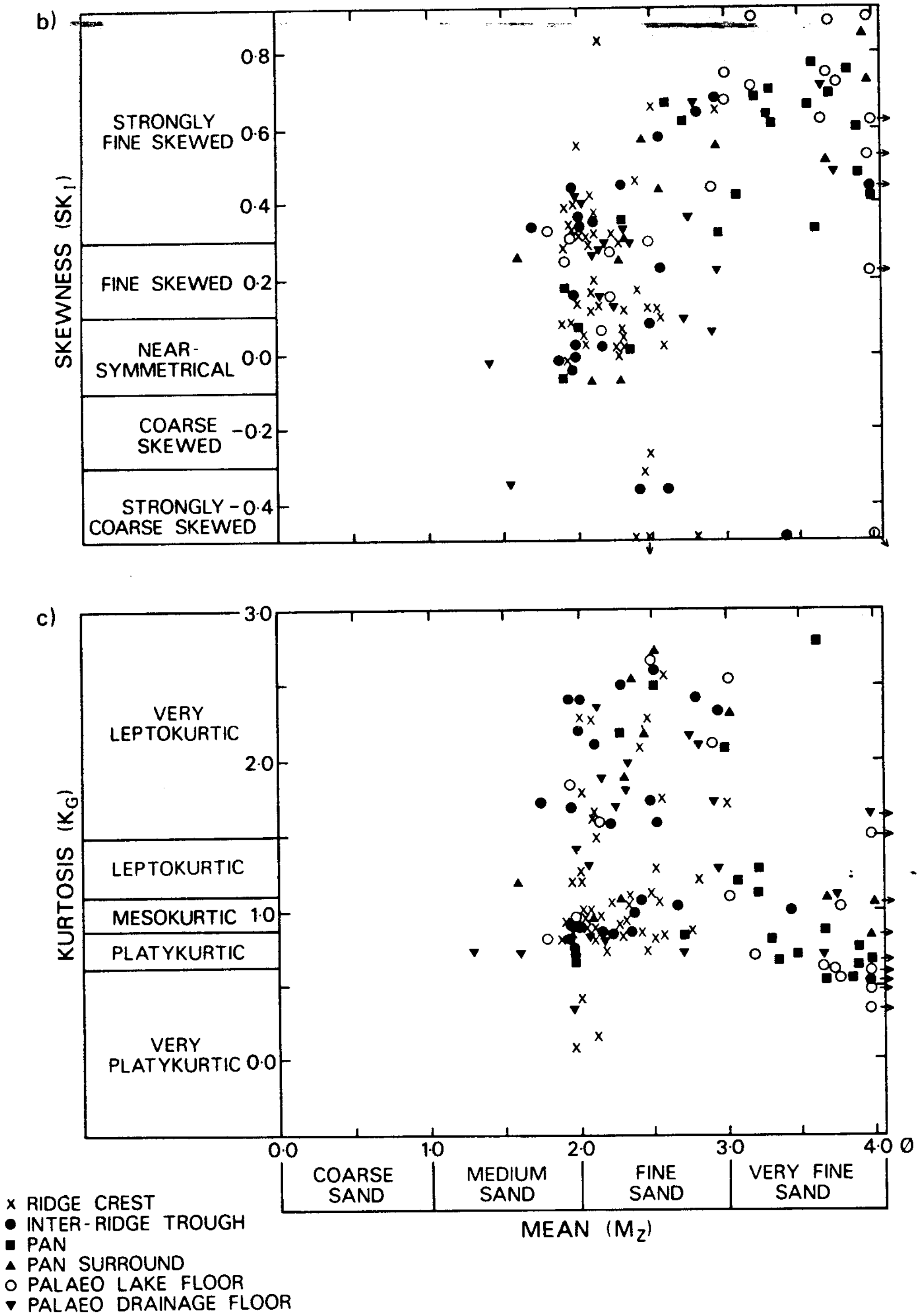


FIG. 2. Bivariate plots of (*a*) sorting, (*b*) skewness and (*c*) kurtosis against mean grain size, for samples classified according to their landform associations.

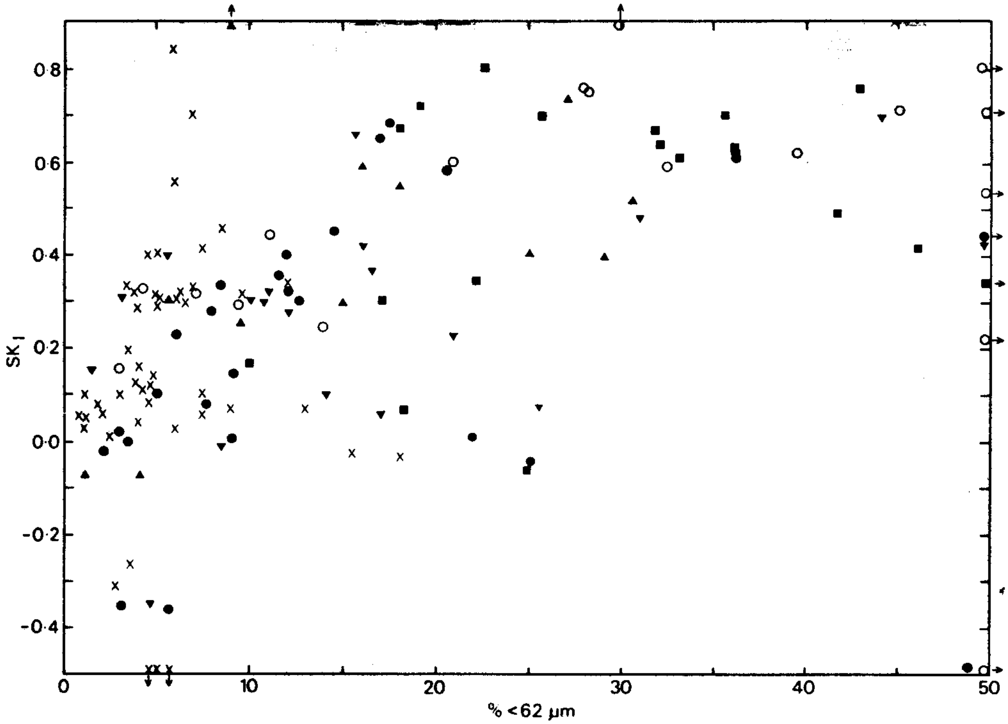


FIG. 3. Plot of skewness versus percentage finer than 62 μm (the silt and clay fraction). Symbols as in Fig. 2.

textural parameters occurs even within the sand from the relict dune forms of the Mega Kalahari, which are spatially extensive (Thomas 1984) and incorporate sand derived from distant provenances (Bond 1948; Poldervaart 1957) as well as from local sources (Baillieul 1975).

Shape

As Pettijohn *et al.* (1972) note, particle shape is very significant when investigating transport processes; but despite this, there have been relatively few studies which consider grain roundness and sphericity. Quartz grains in aeolian sands have often been attributed a high degree of roundness (Savory 1965; Ahlbrandt 1979). Goudie & Watson (1981) summarized the causes of the apparent roundness of desert sand grains as the superior abrasional potential of wind, aeolian shape sorting, chemical solution, and the roundness inherited from parent sediments. Variations in grain roundness characteristics between samples may therefore yield information imparted by different depositional processes in the Mega Kalahari.

Forty-eight samples were analysed, with quartz grains examined at 0.5 phi intervals in the sand fraction. One hundred grains were randomly chosen from each interval and, using a binocular microscope, were allocated to the appropriate roundness grade of Powers (1953). After examination, mean rho values (Folk 1966) were calculated for each size fraction and for each sample as a whole. Sphericity was similarly investigated used Rittenhouse's (1943) visual comparison chart and Waddell's (1933) numerical values.

Regardless of landform association, roundness increases with increasing grain size (Fig. 4*a*) but the degree of rounding is less than implied elsewhere in the literature (*eg* Savory 1965; Lockett 1979). Goudie & Watson (1981) and Folk (1978) noted similar trends in sands from other deserts, but it is also the case in the samples under consideration here that there is a reduction in roundness in the two coarsest size grades. Using the Wilcoxon matched-pairs signed ranks test, the data were analysed to test whether statistically significant differences in roundness existed between the samples from the different landform associations, but none emerged. Goudie & Watson (1981) found that within the Namib Desert, roundness did not vary across linear dune profiles. Thus from the current study and those conducted previously, grain roundness does not appear to be affected by sorting processes during aeolian transportation, or by other processes during reworking of the sand in the Mega Kalahari.

Figure 4*b* shows that, as with roundness, sphericity increases with grain size, but again no statistically significant distinction between sands from different landform associations exists. With reference to the particle form diagram of Dobkins & Folk (1970), it is probably most appropriate to describe sphericity values in terms of particle compactness and bladedness. None of the Kalahari sand samples, whatever the grain size, may be described as highly compact, but most mean sample values are compact (Fig. 4*b*).

Mean sample sphericity values occupy a narrow range of values. The degree of particle sphericity is important in the selective transportation of particles (Krumbein 1941; Mattox 1955; Morris 1957; Willetts *et al.* 1982). It may be especially important in the case of the larger grains mobilized by the wind as the creep load, since more compact grains are most likely to be mobilized. It may tentatively be suggested, therefore, that the degree of compactness of the Kalahari sand grains is an indication of the historical significance of sorting by wind transport. This is independent of the degree of rounding of the grains, which is a facet of edge abrasion (Barrett 1980) and is therefore an indication only of grain modification *during* transportation. The mutual independance of particle roundness and sphericity is attested to by the lack of a statistically significant correlation between the two shape parameters.

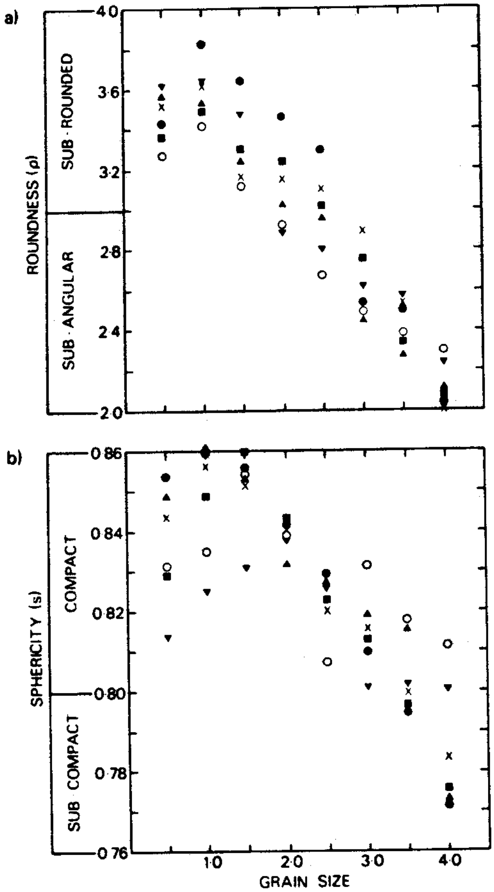


FIG. 4. Variations in (*a*) mean particle roundness and (*b*) mean particle sphericity with grain size, according to landform classification. Symbols as in Fig. 2.

Heavy minerals

Heavy mineral analyses of the samples were undertaken following standard procedures. The heavy mineral assemblages in sands can provide useful information about the character of the source rocks (Rubey 1933), and have also been used to differentiate sands deposited in different environments (*eg* Hand 1967). The main purpose of the heavy mineral studies of the Kalahari sand samples was to attempt to determine sub-regional variations in provenance following Bond (1948), Poldervaart (1957) and Baillieul (1975), and is therefore beyond the scope of this paper. Nevertheless, following the discriminatory powers which Hand (1967) and others found heavy minerals in sand to have, the percentages of zircon and staurolite (significant heavy minerals in the Kalahari sand) and total percentage of heavy minerals in each sample were included in the multivariate discriminant analyses.

Discriminant analysis

Discriminant analysis has been successfully used to differentiate modern sand bodies (Moiola *et al.* 1973, 1974; Moiola & Spencer 1979; Patro & Sahu 1977). It may therefore be an appropriate method of differentiating sands deposited in varied palaeoenvironments on the basis of their textural and shape characteristics (Pettijohn *et al.* 1972).

Multiple discriminant analysis is a statistical technique used to distinguish between more than two populations; the number of discriminating functions which may be produced is $g-1$, where g is the number of groups under consideration, or v, equal to the number of variables. The first function which is derived is the one which describes the maximum variance between groups and the minimum variance within groups. Accounts of the mathematical working of the technique are available in Klecka (1975). Various methods are available for the assessment of the individual contribution of each variable to the discriminating functions. Rao's method was the one which was selected for use in the analyses which follow. This method produces the greatest possible separation between groups of variables by choosing only the variables which contribute the largest increase in Rao's parameter, which is simply a measure of distance. Variables are therefore selected for inclusion in the discriminatory functions in decreasing order of importance. By so doing, it is then possible to distinguish variables which are important in group differentiation.

An attraction of this technique for the present research problem is that it is possible to classify cases of unknown origin within an already established framework. This is achieved by producing a classification function for each group, and then assigning individual cases to the groups on the basis of comparison of the group's classification functions and the individual case's discriminant functions. This can be used not only with cases whose group memberships are unknown, but also with cases where group affinity is known. By doing the latter, an assessment of the effectiveness of the discrimination is achieved and, in turn, it is possible to evaluate the ability of the variables to effect discrimination.

There are three ways in which the significance of the discriminant functions may be tested statistically. During the production of discriminant functions, eigenvalues are computed. These measure the relative importance of the function, when one function's eigenvalue is expressed as a percentage of the total eigenvalues of all functions. Wilks' lambda tests the significance of the discriminating information which is not accounted for in a function and all preceding functions. The larger lambda is, the less is the discriminating information remaining. Because it is possible to convert lambda into a chi-squared test, the statistical significance of functions can be determined. Finally, canonical correlations test the derived functions against predicted group memberships. The canonical correlation squared is the proportion of the variance in the discriminant function explained by the groups. Clearly, when the functions and groups have a high degree of correlation, the explanation provided by the functions is valid.

Multiple discriminant analysis (Nie *et al.* 1975) was used in this study to attempt to distinguish between the sediments sampled from different landform associations by considering variables in unison; it was also used to classify samples according to landform associations.

Data sets

Two data sets were used. Data set 1 consisted of all the samples in the study grouped according to landform associations and those without such associations. The six variables used to provide the discriminatory information were the four moments of the grain size distribution (mean, sorting, skewness and kurtosis), plus percentage silt and clay.

Data set 2 contained only the 48 samples which had been subject to shape and heavy mineral investigations. Therefore in addition to the six variables used with data set 1, five others were available for inclusion: mean roundness (rho), mean sphericity, heavy mineral percentage, percentage zircon and percentage staurolite.

Results

Using data set 1, five discriminating functions were produced, accounting for all the variance in

TABLE 2. *Measures for determining (a) the significance of and (b) contribution of variables to discriminant functions, data set 1*

	Function 1	Function 2	Function 3	Function 4	Function 5
(a) *Significance*					
Eigenvalue	1.910	0.171	0.117	0.018	0.003
% variance	86.07	7.71	5.27	0.83	0.12
Canonical correlation	0.810	0.382	0.324	0.135	0.053
Wilks' lambda	0.749	0.877	0.979	0.997	—
Chi squared	0.023	0.153	0.715	0.593	—
(b) *Variable*					
Mean	−0.113	−0.577	0.917	1.068	−1.005
Sorting	0.792	0.068	0.193	−1.184	0.541
Kurtosis	−0.194	0.869	0.355	0.521	−0.407
% Silt & clay	0.544	0.570	−1.049	0.351	0.427

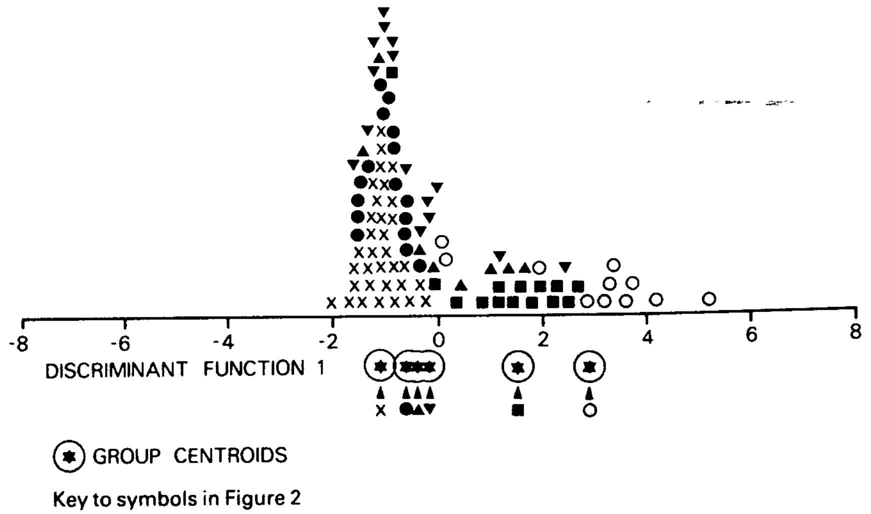


FIG. 5. Discriminant frequency plot of samples according to landform association for function 1, on the arbitrary scale −8 to +8.

the data set. Table 2a shows that most of the variance is accounted for by the first function (86.07%). Indeed, canonical correlation indicates that in this analysis only the first function is well correlated with the groups, and the chi-squared tests show that this function is the only one which is statistically significant. The variables of sorting, and silt and clay percentages contribute most to its discriminatory power (Table 2*b*).

Figure 5 demonstrates that even in the case of function 1, there is a considerable degree of group overlap and that group centroids are not well separated. The results of the classification stage of the analysis verify this, with only 49% of all samples being correctly classified into their appropriate landform association group. The greatest success rates are with the samples from dune ridges and not surprisingly, mudflats (77.1% and 72.7% correctly classified), which come, respectively, from the environments with the lowest and highest silt and clay contents. As under half of all samples were correctly classified, the variables included in data set 1 do not provide a reliable basis for attempting to establish the processes responsible for the deposition of Kalahari sand of unknown landform association except perhaps if classification was simplified and discrimination only on the basis of whether wind or water deposited.

When data set 2 was analysed using the technique, five discriminant functions were again produced, and again only function 1 was statistically significant, accounting for 84.79% of the variance between groups. The additional variables included did not enhance the discrimination between groups or contribute significantly to function 1.

Discussion

The lack of success in distinguishing depositional environments in the Mega Kalahari using bivariate plots of grain size distribution moments is unsurprising in view of the variable effectiveness of the method in separating modern sands. Discriminant analysis has, however, proved to be very effective (Moiola & Spencer 1979). Because of this it is necessary to explore the possible reasons for its relative ineffectiveness in *this* study. There are two major areas which need consideration: the nature of the variables used; and the depositional history of the Kalahari sand.

In studies of modern sands, the independent variables which formed the basis of the calculation of discriminant functions have been weight fractions in grain size classes or textural parameters (Moiola & Spencer 1979). The variables used in the present study correspond with those used previously. There is, therefore, no reason to suspect an incapacity of the technique to discriminate appropriately, though the validity of grain size parameters based on the assumption of a normal grain size distribution as used here has recently been subject to scrutiny.

Before the technique could be employed to classify samples of unknown origin into different groups, discriminant functions were established for samples from known landform elements. This assumes that samples taken from different landforms in the Mega Kalahari represent a sedimentary response to variable processes. The results of the discriminant analysis suggest that this assumption was incorrect insofar as the processes responsible for the different landforms either did not impart distinctive attributes on the Kalahari sand, or that any significant distinctions which did exist have been removed or blurred with the passage of time.

The extensive linear and other dunes testify to periods when aeolian processes have been effective in the Mega Kalahari during the Quaternary (Thomas 1984, 1986*a*). Provenance studies have also indicated the importance of aeolian processes (Baillieul 1975; Savory 1965; Binda & Hindred 1973). However, the origin of the sand is unclear: both Baillieul (1975) and Savory (1965) have suggested that in some areas rivers played an important role, whilst weathering of local sandstones has also made its contribution (Baillieul 1975). Despite this, Bond & Fernandes (1974), Binda & Hindred (1973) and Thomas (1985) have shown that the Kalahari sand displays sedimentological characteristics akin to those of modern wind-blown sands. It may therefore be argued that, regardless of the processes responsible for initial deposition, aeolian processes have played a significant role in the development of grain texture and shape, and that processes responsible for non-aeolian landforms have not caused significant modifications. Non-aeolian processes have merely re-worked the already wind-sorted sand. The action of water has made no mark that can be detected by discriminant analysis using coarse parameters such as mean grain size, percentage clay, *etc*.

SEM investigations

The discussion so far has suggested that the poor separation of samples from different landform associations in the Mega Kalahari is due to the overriding influence of aeolian processes. This has been checked by using another line of evidence. One sample from each of the landform elements that formed the basis of the sampling programme was inspected using a scanning electron microscope. The samples chosen fell closest to the centroids of groups identified by discriminate analysis function 1.

SEM investigations of sand-grain surface texture are now widely used to reconstruct the transportation history of sediments (Bull 1981). They are based upon the assumption that different combinations of grain-surface features are diagnostic of different processes (Krinsley & Doornkamp 1973).

~~Following~~ usual practice, only quartz grains were investigated. The samples were pre-treated following standard procedures (Krinsley & Doornkamp 1973) and 20 or so grains of each selected from the 2.0–3.0 phi grain size range. The source of the samples was not identified during analysis in order to remove bias during observation.

Results

The characteristic grain-surface textures following aeolian transport are 'rolling topography', 'upturned plates' and 'dish-shaped concavities' (Krinsley & Doornkamp 1973), 'conchoidal fractures', 'star-cracks' and 'hertzian fractures' (Bull pers. comm.). These features were identified to varying degrees on grains in all six samples thus verifying the influence of aeolian processes regardless of present landform. Other textures were found to be superimposed upon this aeolian signature, a pattern also found on larger (0.0 phi) Kalahari sand grains by Bond & Fernandes (1974).

The textures identified on each sample are summarized below and in the micrographs of Fig. 6.

Dune ridge

This sample had a mixture of sub-rounded and sub-angular grains displaying surface textures produced by grain-upon-grain impacts. Small-scale mechanical impact pits were identified which coalesced to produce the upturned plates of Margolis & Krinsley (1971) and rolling topography (Krinsley & Doornkamp 1973).

Interdune trough

In terms of grain sphericity, grains of this sample were more compact than those from the ridge sample, and are perhaps good examples of 'millet seed' grains. The surface textures of grains in this sample were, in many respects, similar to the ridge sample, with a predominance of mechanical impact features including upturned plates.

Pan

As well as grains with concoidal fractures, dish-shaped concavities, smooth surfaces, and hertzian cracks—all indicative of aeolian transportation—there is also evidence of post-aeolian textural modification. This is in the form of a chemical surface modification to many grains

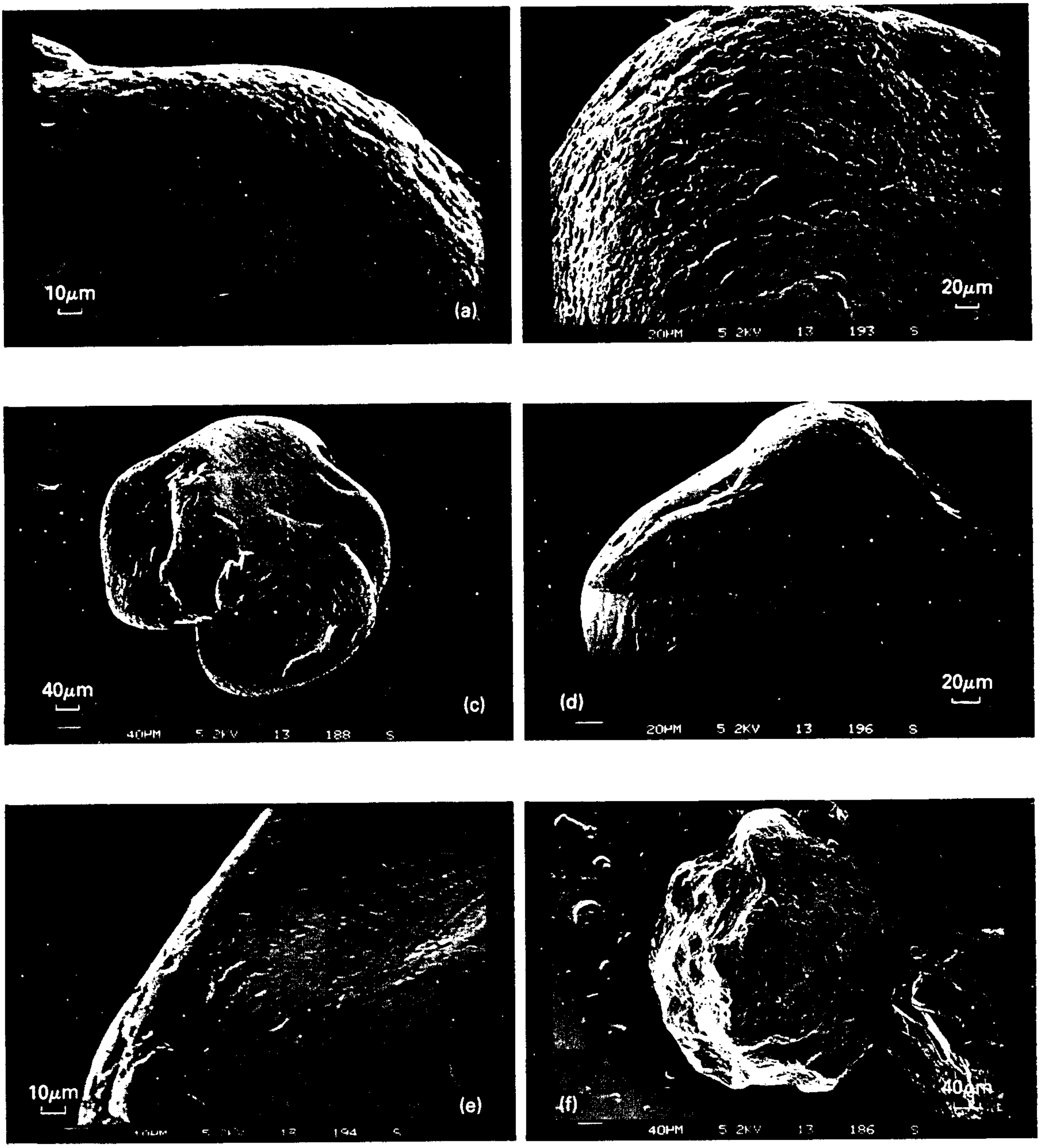


FIG. 6. (*a*)Detail of an aeolian quartz grain from the dune ridge crest sample, showing upturned plates. Scale bar 10 µm. (*b*) Grain from the inter-ridge trough sample. The whole grain surface is covered with upturned plates, resulting from the merging of small impact pits, each 20–40 µm long. The larger depression on the right is a dish-shaped concavity. Scale bar 20 µm. (*c*) Although from a pan, this grain displays typical aeolian textures, with rounded edges. dish-shaped concavities, impact pits (centre right) and hertzian fractures (centre). Scale bar 40 µm. (*d*) Detail of a grain from a pan surround: the hertzian fractures and edge rounding are due to aeolian action. The 'V' pits may be due to modification by chemical processes. Scale bar 20 µm. (*e*) Palaeolake sample, grain detail. The dish-shaped concavity has undergone sub-aqueous edge abrasion, giving rise to small, irregular impact pits. (*f*) Angular to sub-angular palaeochannel sand grains. Although upturned plates are identifiable on the central grain. the irregular surface is largely due to chemical weathering and to the precipitation of a varnish.

and is indicated by the presence of solutional 'V' pits, which Bull (1978) considered to be of sub-aqueous origin. The occurrence of many smoothed-grain surfaces, with a crypto-crystalline cover induced by solutional activity, could reflect changing grain-surface moisture experienced under fluctuating pan water-table levels.

Pan surround

This sample contained a mixture of sub-rounded and sub-angular grains whilst individual grains had much surface detail, dominated by hertzian fractures. Although these were undoubtedly produced by high-velocity aeolian impacts (Bull pers. comm.), the rounding of impact pit edges has resulted from subsequent chemical processes.

Palaeolake

The surface texture of some grains indicated aeolian activity. Others, though, showed modification by other processes, particularly chemical etching, and sub-aqueous edge abrasion. For example, Fig. 6*e* shows a grain where a dish-shaped concavity has been modified by edge abrasion as a result of water transport (*eg* see Goudie & Bull 1984), clearly showing that fluvial transport and lacustrine conditions have left their mark upon the aeolian sand grains.

Palaeochannel

The grains of this sample also showed textures resulting from a mixture of processes. Although aeolian textures were identified, there was a notable absence of high-energy impact features such as conchoidal fractures and star-cracks (Fig. 6*f*). Chemically weathered 'V'-shaped pits of sub-aqueous origin were also found, which bear witness to a fluvial environment.

In summary, the surface textures on individual grains from all of the landform elements indicate aeolian transport. However, these have been partially overprinted by non-aeolian processes in the pan, palaeolake and palaeochannel environments.

Conclusions

Not withstanding the doubts about Folk & Ward grain size distribution parameters, the homogeneous nature of Kalahari sand that is suggested by bivariate plots of these parameters is confirmed by discriminant analysis in which grain size, shape and mineralogical data are incorporated. Although this is a statistically complex technique, and despite the number of variables included in the analysis, only grain size parameters emerged as significant. The small separation of classified (*ie* discriminated) group centroids, and the large number of misclassifications of individual cases whose landform origin is known support the suggestion of homogeneity in the Kalahari sand. This homogeneity probably results from the overriding importance of aeolian activity in the environmental history of the Mega Kalahari.

The importance of aeolian processes in determining the sedimentological characteristics of the Kalahari sand is further demonstrated by SEM grain surface texture analysis. It has been possible, though, to distinguish secondary, non-aeolian textures on quartz grains from some present depositional environments. SEM analysis may, therefore, offer the best approach to palaeoenvironmental discrimination of the Kalahari sand, since individual grain surfaces appear to be more readily modified during reworking than is the overall grain size distribution or particle shape.

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References

AHLBRANDT, T. S. 1979. Textural parameters of aeolian deposits. *In*: MCKEE, E. D. (ed.) *A Study of Global Sand Seas*. US Geological Survey Professional Paper **1052**, 21–53.

BAILLIEUL, T. A. 1975. A reconnaissance survey of the cover sands in the Republic of Botswana. *Journal of sedimentary Petrology* **45**(2), 494–503.

BARNDORFF-NIELSON, O., DALSGAARD, K., HALGREEN, C., KUHLMAN, H., MØLLER, J. T. & SCHON, G. 1982. Variations in particle size over a small dune. *Sedimentology* **29**, 53–65.

BARRETT, P. J. 1980. The shape of rock particles, a critical review. *Sedimentology* **27**, 291–303.

BESLER, H. 1983. The response diagram: distinction between aeolian mobility and stability of sands and aeolian residuals by grain size parameters. *Zeitschrift für geomorphologie Supplementbund* **45**, 287–302.

BINDA, P. L. & HINDRED, P. R. 1973. Bimodal grainsize distributions of some Kalahari type sand from Zambia. *Sedimentary Geology* **10**, 233–237.

BOND, G. 1948. The direction of origin of the Kalahari sand of southern Rhodesia. *Geological Magazine* **85**, 305–313.

—— & Fernandes, T. R. C. 1974. Scanning electron microscopy applied to quartz grains from Kalahari type sand. *Transactions of the Geological Society of South Africa* **77**, 191–199.

Boocock, C & Van Staten, O. J. 1962. Notes on the geology and hydrogeology of the central Kalahari region, Bechuanaland Protectorate. *Transactions of the Geological Society of South Africa* **65**, 125–171.

Bull, P. A. 1978. A statistical approach to scanning electron microscope analysis of core sediments. *In*: Whalley, W. B. (ed.) *Scanning Electron Microscopy in the Study of Sediments*. Geo Abstracts, Norwich, 212–226.

—— 1981. Environmental reconstruction by electron microscopy. *Progress in Physical Geography* **5**, 368–397.

Carver, R. E. (ed.) 1971. *Procedures in sedimentary petrology*. Wiley Interscience, New York, 653 pp.

Christiansen, C., Blaesild, P. & Dalsgaard, K. 1984. Reinterpreting 'segmented' grainsize curves. *Geological Magazine* **121**, 47–51.

Cooke, H. B. S. 1964. The Pleistocene environment in southern Africa. *In*: Davis, D. H. S. (ed.) *Ecological Studies in Southern Africa*. Junk, The Hague, 1–23.

Cooke, H. J. 1980. Landform evolution in the context of climatic change and neo-tectonism in the middle Kalahari of north central Botswana. *Institute of British Geographers, Transactions* **5**, 80–99.

—— 1985. The Kalahari today: a case of conflict over resource use. *Geographical Journal* **151**, 75–85.

Cornillault, J. 1972. Particle size analyser. *Applied Optics* **11**, 265–268.

Dobkins, J. E., Jr & Folk, R. L. 1970. Shape development on Tahiti-Nui. *Journal of sedimentary Petrology* **40**, 1167–1203.

Flint, R. F. & Bond, G. 1968. Pleistocene sand ridges and pans in western Rhodesia. *Bulletin of the Geological Society of America* **79**, 299–314.

Folk, R. L. 1966. A review of grain-size parameters. *Sedimentology* **6**, 73–93.

—— 1978. Angularity and silica coatings of Simpson Desert sand grains, Northern Territory, Australia. *Journal of sedimentary Petrology* **52**, 93–101.

—— & Ward, W. C. 1957. Brazos River bar—a study in the significance of grain size parameters. *Journal of sedimentary Petrology* **27**, 3–27.

Freidman, G. M. 1961. Distinction between dune, beach and river sands from their textural characteristics. *Journal of sedimentary Petrology* **31**, 514–529.

—— 1967. Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sand. *Journal of sedimentary Petrology* **37**, 327–354.

—— 1979. Differences in size distributions of populations of particles among sands at various origins. *Sedimentology* **26**, 3–32.

Goudie, A. S. 1983. The arid earth. *In*: Gardner, R. A. M. & Scoging, H. (eds) *Mega Geomorphology*. Oxford University Press, 152–171.

—— & Bull, P. A. 1984. Slope process change and colluvium depositions in Swaziland: an SEM analysis. *Earth Surface Processes and Landforms* **9**, 289–299.

—— & Thomas, D. S. G. 1985. Pans in southern Africa with particular reference to South Africa and Zimbabwe. *Zeitschrift für Geomorphologie* **NF29**, 1–19.

—— & Watson, A. 1981. The shape of desert sand grains. *Journal of Arid Environments* **4**, 185–190.

Grey, D. R. C. & Cooke, H. J. 1977. Some problems in the Quaternary evolution of the landforms of northern Botswana. *Catena* **4**, 123–133.

Grove, A. T. 1969. Landforms and climatic change in the Kalahari and Ngamiland. *Geographical Journal* **135**, 191–212.

Hails, J. R. & Hoyt, J. H. 1969. The significance and limitations of statistical parameters for distinguishing ancient and modern sedimentary environments of the lower Georgia coastal plain. *Journal of sedimentary Petrology* **39**, 559–580.

Hand, B. H. 1967. Differentiation of beach and dune sand, using settling velocities of light and heavy minerals. *Journal of sedimentary Petrology* **37**, 514–520.

Jones, C. R. 1982. The Kalahari of Southern Africa. *Straiae* **17**, 20–34.

Klecka, W. R. 1975. Discriminant analysis. *In:* Nie, N. H., Hull, C. H., Jenkins, J. G., Steinbrenner, K. & Brent, D. H. (eds) *Statistical Package for the Social Sciences*. Second edn. McGraw Hill, New York, 434–467.

Krinsley, D. H. & Doornkamp, J. C. 1973. *Atlas of Quartz sand surface textures*. Cambridge University Press, 91 pp.

Krumbein, W. C. 1941. Measurement and geological significance of shape and roundness on sedimentary particles. *Journal of sedimentary Petrology* **11**, 64–72.

Lancaster, I. N. 1978. Composition and formation of southern Kalahari pan margin dunes. *Zeitschrift für Geomorphologie NF 22*, 148–169.

—— 1981. Palaeoenvironmental implications of fixed dune systems in southern Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **33**, 327–346.

Lockett, N. H. 1979. The geology of the country around Dett. *Rhodesia Geological Survey Bulletin* **85**, 198 pp.

Margolis, S. V. & Krinsley, D. H. 1971. Submicroscopic frosting on aeolian and subaqueous quartz grains. *Geological Society of America Bulletin* **82**, 3395–3406.

Martins, L. R. 1965. Significance of skewness and kurtosis in environmental interpretation. *Journal of sedimentary Petrology* **35**, 768–340.

Mattox, R. B. 1955. Eolian shape sorting. *Journal of sedimentary Petrology* **25**, 111–114.

Maufe, H. B. 1930. Changes of climate in Southern Rhodesia during late geological times. *South Africa Geographical Journal* **13**, 12–16.

Moiola, R. J. & Spencer, A. B. 1979. Differentiation of eolian deposits by discriminant analysis. *In:* McKee, E. D. (ed.) *A Study of Global Sand Seas*. US Geological Survey Professional Paper **1052**, 53–61.

—— & WEISER, D. 1968. Textural parameters: an evaluation. *Journal of sedimentary Petrology* **38**, 45–53.

——, SPENCER, A. B. & MCKEE, E. D. 1973. Linear discriminant analysis—a technique for analyzing sand bodies. *Geological Society of America Abstracts with Programs 1973 Annual Meeting* **5**, 741–742.

——, —— & WEISER, D. 1974. Differentiation of modern sand bodies by linear discriminant analysis. *Gulf Coast Association of Geological Societies Transactions* **24**, 321–326.

MORRIS, W. J. 1957. Effects of sphericity, roundness and velocity on traction transportation of sand grains. *Journal of sedimentary Petrology* **27**, 27–31.

NIE, N. H., HULL, C. H., JENKINS, J. G., STEINBRENNER, K. & BRENT, D. H. 1975. *Statistical Package for the Social Sciences*. Second edn. McGraw-Hill, New York, 674 pp.

PATRO, B. C. & SAHU, B. K. 1977. Discriminant analysis of sphericity and roundness data of clastic quartz grains in rivers, beaches and dunes. *Sedimentary Geology* **19**, 301–311.

PETTIJOHN, F. J., POTTER, P. E. & SIEVER, R. 1972. *Sand and Sandstone*. Springer-Verlag, New York, 618 pp.

POLDERVAART, A. 1957. Kalahari sands. *In:* CLARK, J. D. (ed.) *Proceedings of the 3rd Pan African Congress on Prehistory. Livingstone, 1955*, 106–114.

POWERS, M. C. 1953. A new roundness scale for sedimentary particles. *Journal of sedimentary Petrology* **23**, 117–119.

RITTENHOUSE, G. 1943. A visual method of estimating two-dimensional sphericity. *Journal of sedimentary Petrology* **13**, 79–81.

RUBEY, W. W. 1933. The size distribution of heavy minerals within a water-laid sediment. *Journal of sedimentary Petrology* **3**, 3–11.

SAVORY, B. M. 1965. Sand of Kalahari type in Sesheke District, northern Rhodesia. *In:* SNOWBALL, G. J. (ed.) *Science and medicine in Central Africa*. Perg mon Press, Oxford, 189–200.

SCHLEE, J., UCHUPI, E. & TRUMBILL, J. V. A. 196 Statistical parameters of Cape Cod beach an eolian sands. US Geological Survey Profession Paper **501-D**, D118–D122.

SHAW, P. 1985. Late Quaternary landforms an environmental change in northeastern Botswan the evidence of Lake Ngami and the Maba Depression. *Institute of British Geographers Tran actions* **10**, 333–346.

THOMAS, D. S. G. 1982. Evidence of Quaternar palaeoclimates in western Zimbabwe. Chapter *In:* WILLIAMS, G. J. & WOOD, A. (eds) *Geographic Perspectives on Development in Southern Afric* Univ. of N. Queensland Press (in press).

—— 1984. Ancient ergs of the former arid zones Zimbabwe, Zambia and Angola. *Institute of Britis Geographers, Transactions* **9**, 75–88.

—— 1985. Evidence of aeolian processes in Zimbabwean landscape. *Transactions Zimbab Scientific Association* **62**, 45–55.

—— 1986*a*. Ancient deserts revealed. *Geographi Magazine*, 11–15.

—— 1986*b*. Dune pattern statistics applied to Kalahari Dune Desert, southern Africa. *Zeitsch für Geomorphologie* **30**, 231–242.

VINCENT, P. J. 1985. Some Saudi Arabian dune san a note on the use of the response diagra *Zeitschrift für Geomorphologie* **29**, 117–122.

WADDELL, H. 1933. Sphericity and roundness of ro particles. *Journal of Geology* **40**, 443–451.

WILLETTS, B. B., RICE, M. A. & SWAINE, S. E. 19 Shape effects in aeolian grain transport. *Sedim tology* **29**, 409–417.

WYRWOLL, K.-H. & SMYTH, G. K. 1985. On using log hyperbolic distribution to describe the textu characteristics of eolian sediments. *Journal sedimentary Petrology* **55**, 471–478.

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Dumb-bells: a plotting convention for "mixed" grain size populations

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ABSTRACT

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The nature of "mixed" grain size populations modelled by log skew Laplace (and other) mixture distributions may be displayed and analysed by using the simple convention of plotting the parameter scores of the component populations as "dumb-bells" on three-dimensional and two-dimensional displays. An example is given using particle size data from dune ridge crest and pan sands from the Kalahari desert of central southern Africa.

Introduction

This paper describes a simple graphical plotting convention for investigating the results of the statistical modelling of mixed particle size distributions using log skew Laplace distributions which were introduced by Olbricht (1982) and Fieller et al., (1984, 1987, 1988, 1990a, b) as a "robust" statistical method for the modelling of grain size data. This particular set of statistical distributions incorporates the mathematical and sedimentological advantages of log hyperbolic models for grain size data as demonstrated by Bagnold and Barndorff-Nielsen (1980) and Barndorff-Nielsen et al. (1980), but calculation of estimates is notably easier, especially for less "pure" mass-size data sets. A general discussion of the relative advantages of the log skew Laplace, log hyperbolic and log normal distributions for particle size studies is given in Flenley (1988) and Fieller et al., (1990a, b). The plotting method can also be used to display other statistics calculated for mixture distributions.

Mixture distributions

Flenley (1985, 1988) and Flenley et al., (1987) evaluated and criticised existing procedures for identifying and analysing mixture distributions. These were based largely upon examination of log probability plots of the grain size distribution, following suggestions of Visher (1969). A particular criticism is that distinct straight line segments in a probability plot cannot be taken as evidence of mixture distributions; instead frequency diagrams or histograms of the actual grain size distribution should be examined, perhaps using log–log scales. Mixture distributions might then be evidenced by clear bimodality or, as in some of the examples discussed by Flenley et al. (1987), by a "shoulder" on a unimodal distribution. These authors demonstrated how log skew Laplace mix-

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ture models could be employed for the identification and mathematical modelling of the constituents of "mixed" grain size populations, even if the distribution is not bimodal.

A typical example of such an analysis applied to Kalahari dune ridge crest sample 108/1, together with the parameters which define the fitted log skew Laplace distributions, is shown in Fig. 1. This shows the log relative proportions in each $1/4\phi$ sieve plotted against log size, together with the fitted log skew Laplace mixture distribution. As each fitted log skew Laplace distribution is specified by three parameters (α, the fine grade coefficient; β, the coarse grade coefficient; μ, the modal log size), a mixture of two such log skew Laplaces, used to model "mixed" distributions, requires six parameters to specify the two constituent fitted distributions (i.e. α_1, β_1, μ_1, α_2, β_2, and μ_2) and a seventh, π, to specify their relative contributions—the "mixture coefficient" (for the sample 108/1 displayed in Fig. 1, the estimates of these seven parameters are, respectively, 0.24, 0.15, −2.06, 0.53, 0.20, −1.13 and 0.19). These seven parameters characterize the bimodal sample in a way similar to that in which the commonly used summary statistics (mean, sorting, skewness and kurtosis) are used to characterize simple sand samples, or the separate components of a clearly bimodal sample. Splitting bimodal samples into two for separate calculation of summary statistics is, however, not to be recommended since it ignores overlap of the two constituents, so biasing the statistics.

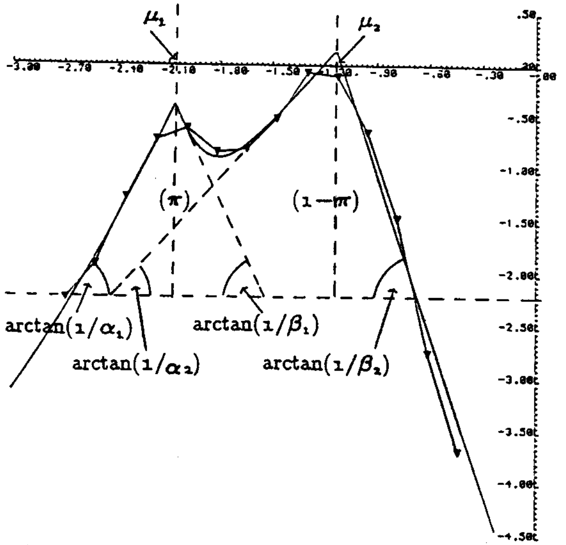

Fig. 1. Kalahari sample 108/1 and fitted log skew Laplace mixture.

Graphical plotting convention

The routine geological analysis of such data demands the presentation of the results in a simple, readily understood form. On occasion, it may be adequate to display plots of the actual data, showing how the "peaks" alter in relative location and intensity with passage across or through a deposit (e.g. Flenley et al., 1987). However, most sedimentological data require a more concise procedure capable of summarising information on parameter measures from notably larger numbers of samples.

Fig. 2 displays a simple, graphical device that achieves these objectives and that is immediately interpretable in process- or facies-related terms. The diagram illustrates the parameter estimates of 11 dune ridge crest samples (cubes) and 4 pan samples (dodecahedra), selected for illustrative purposes from a more extensive study of depositional environments in the Mega Kalahari (Thomas, 1987). Parameter estimates of all samples from this study are given in Forcheh (1988).

Fig. 2 is constructed as follows: the parameter estimates of each of the two log skew Laplace distributions comprising the mixed grain size population are plotted in three-dimensional space (i.e. α_1 vs. β_1 vs. μ_1 and α_2 vs. β_2 vs. μ_2) and the two points are then joined—each sample therefore forming a "dumb-bell". Thus, the complex distribution in Fig. 1 appears in this diagram as a single dumb-bell with (0.24, 0.15, −2.06) and (0.53, 0.20, −1.13) as the three-dimensional coordinates of the ends. The distance between the two ends is a composite measure of the differences in fine and coarse grade coefficients of the two constituents as well as the difference in their two modal log sizes. The display thus shows simultaneously the six parameters of primary geological interest. The seventh parameter (π, the mixing coefficient) may, in some studies (e.g. Flenley et al., 1987), also contain relevant information and this could be

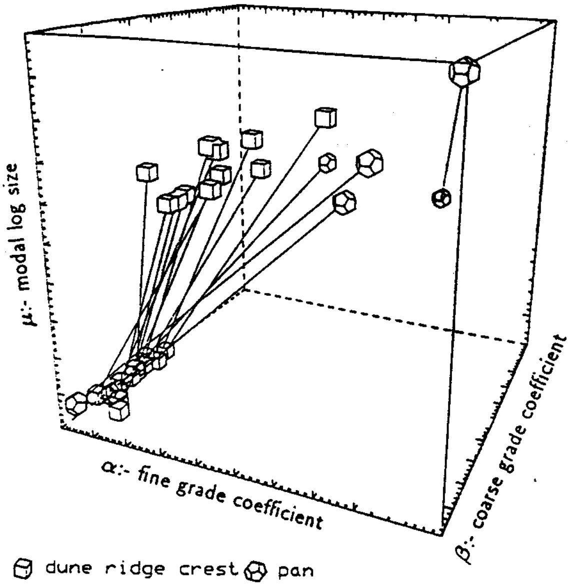

Fig. 2. Dumb-bell plot of dune ridge crest and pan samples: 1st view.

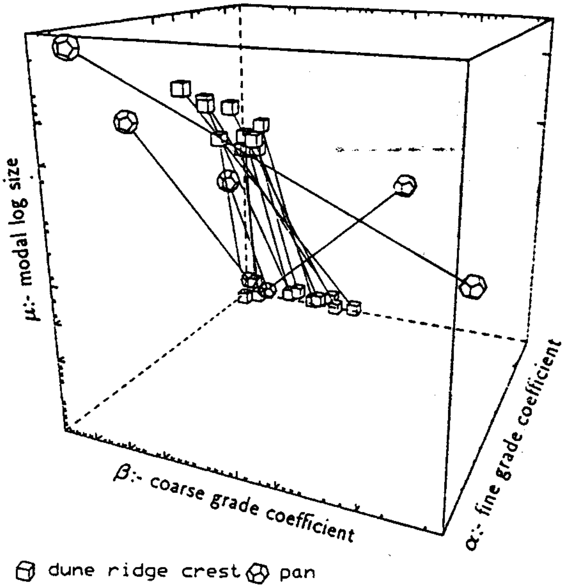

Fig. 3. Dumb-bell plot of dune ridge crest and pan samples: 2nd view.

analysed separately. Fig. 3 gives a second view of the same plot.

This method of display is similar to the "linked views" described by Tukey and Tukey (1981) and "*M* and *N*" plots of Diaconis and Friedman (1980). Their technique for displaying data on only four variables is to place two standard scatterplots of each of two variables side by side and link corresponding points between the two diagrams. The distinction of dumb-bell plots is that a single scatterplot can contain both sets of points, since the scales for $(\alpha_1, \beta_1, \mu_1)$ are the same as for $(\alpha_2, \beta_2, \mu_2)$, so the links between points are internal to the diagram. It is thus practicable to extend the idea to a three-dimensional plot displaying all six parameters. The same technique can be used to display parameter estimates of mixtures of any other three parameter distribution, any three out of four or more parameters of more complex mixture models, or any three conventional summary statistics calculated separately for each component.

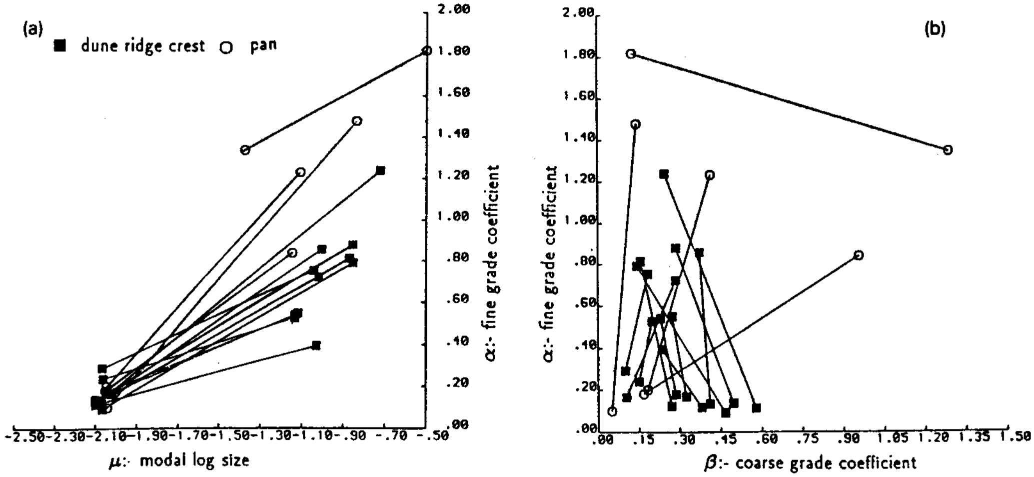

Fig. 4. Two-dimensional dumb-bell plots of (a) α vs. μ, and (b) α vs. β.

Of course, the parameters could be displayed two (or rather four) at a time in two-dimensional scatterplots as "flat dumb-bells" as shown in Fig. 4, which shows (a) α_1 vs. μ_1 and α_2 vs. μ_2 and (b) α_1 vs. β_1 and α_2 vs. β_2. A slight disadvantage of these two-dimensional plots is illustrated in Fig. 4b where it is not clear which end of each dumb-bell pertains to which mode of the mixture; with three-dimensional dumb-bells, the lower end must necessarily correspond to the leftmost peak (since $\mu_1 < \mu_2$).

Kalahari dune ridge and pan sediments

The Kalahari Desert, centred upon Botswana, and its former extensions under more arid climates during the Quaternary period, contain numerous, predominantly depositional, landforms and sedimentary features which are widely thought to be of palaeoenvironmental significance (Grove, 1969; Shaw and Cooke, 1986; Thomas, 1987; Shaw et al., 1988; Thomas and Shaw 1990a). These are developed in the surface units of the spatially extensive Jurassic to recent Kalahari Group sediments which extend over 2.5×10^6 km^2 of southern Africa (Thomas and Shaw, 1990b).

The most common surface unit of the Kalahari Group is the Kalahari Sand, which is widely regarded to be of aeolian origin or at least to have undergone major periods of aeolian reworking during the Quaternary. This is evidenced by the presence of extensive fields of sand dunes (Lancaster, 1981; Thomas, 1984) that are at least partially vegetated and in some cases are undoubtedly relict forms (Thomas, 1987). Lake basins, pan depressions and topographical hollows of various origins (Thomas and Shaw, 1990a) are also numerous and important features. These are developed within the Kalahari surface and have acted as local sedimentary sinks and therefore contain sediments which are a mixture of Kalahari Sand and finer, water transported material.

Many Kalahari sediment samples are bimodal in grain size distribution with modal peaks in the fine (particle diameter 0.0625–0.25 mm) and medium (0.25–0.5 mm) sand categories (Thomas, 1984, 1985 and Fig. 1). These characteristics are fairly common in aeolian sands (Cooke and Warren, 1972; Warren, 1972; Taira and Scholle, 1979) and are due to sorting processes operating during wind transport. Where Kalahari sediments have been further reworked or have been subjected to the addition of a finer water transported component, as in the case of pan samples, one of the modal peaks may become finer, possibly falling in the silt category, or the sample may be multimodal.

Figs. 2–4 show examples of parameters of fitted log skew Laplace mixture distributions plotted using the "dumb-bell" convention. This plotting method allows both relationships and differences between samples to be clearly recognised, which are in agreement with existing environmental interpretations of the sedimentological processes that have influenced deposits in this area during the Quaternary. All, except one, of the pan and ridge samples have one end of the dumb-bell that plots in the same region of the graph, a consequence of the major contribution which (aeolian) Kalahari Sand makes to the sediments of depositional features in the area. The divergence evident at the other ends of the dumb-bells results from the shifts in the grains size populations of the second modes of the ridge samples (relatively closely grouped) and the pan samples (divergent). One pan sample, consisting predominantly of silts and clays, displays no relationships to the other samples, having no common sand component, and its parameter estimates represented by the separated dumb-bell merely reflect two minor peaks in the much coarser range. These features would not be readily apparent from pairwise scatterplots of the six parameters—a total of fifteen possible combinations.

Discussion and conclusion

A previous study (Thomas, 1987) applied the technique of discriminant analysis to a range of sedimentary data in an attempt to differentiate sediment samples from a range of Kalahari depositional environments, including dune ridge crests and pan depressions. The degree of discrimination achieved was limited. This was largely ascribed to the environmental history of the Kalahari resulting in aeolian processes playing a significant rôle in the development of sedimentary characteristics, even when sediments have been finally deposited in a waterlain environment. This view was supported by SEM investigations of the samples (Thomas, 1987).

Some of the sedimentary data used in that study were the conventional summary statistics (mean, sorting, skewness and kurtosis) calculated using the commonly employed "Folk and Ward" procedure (Folk and Ward, 1957; Folk, 1966). Obviously, the identification and analysis of individual component grain size populations within a sample is not possible with this conventional style of analysis applied to the entire grain size data set from a sample. In particular, application of this method to bimodal samples (such as those involved in this study) disguises and ignores the existence, importance, nature and shape of the two modal peaks as well as the extent of their separation. This can waste potentially effective discriminating information.

Calculation of the standard summary statistics from a multimodal sample averages out the contributions from all the modes present. However, such grain size concepts as "typical size" and "sorting" are readily derived from the fitting of either simple or mixed log skew Laplace distributions. For example, the modal grain size(s) typify the one or several peaks. The values of α and β imply the degree of sorting in the "fine" and "coarse" grade components leading to each modal peak, and if desired these may be combined to produce a formal measure of sorting ($\alpha^2 + \beta^2$; Olbricht, 1982) which corresponds, for each component population, to the intention of the measure for "sorting" employed in the familiar Folk and Ward analysis.

The analyses presented here have been carried out using specially written mainframe computer Fortran and Pascal programmes, with a full perspective and hidden line removal three-dimensional display option, though the techniques are not restricted to such facilities. Implementations on microcomputers are under development by the authors. Reference to suitable methodology can be found in a number of sources. Estimates of the Laplace mixtures can be obtained by maximum likelihood using the EM-algorithm, following Jones and McLachlan (1989). It would also be possible to adapt the graphical approximations of Fieller et al. (1985), for a single Laplace model, along the lines of Bagnold (1941, pp. 119–124). This would give quick estimates "by hand" which could be plotted or used as initial values for computer-based techniques. Many standard PC packages are available for producing two-dimensional scatterplots; some will also present pseudo-three-dimensional plots. The links between the ends of the dumb-bells may have to be inserted by hand, but this is not a major drawback, particularly for two-dimensional scatterplots and with labelling of points.

The mass-size data investigated here were obtained by sieving using a mechanical shaker with sieves at $1/4\phi$ intervals (Thomas, 1984, 1987). Obviously, the more frequent and precise the mass-size measurement, the better the capacity of these procedures to identify and analyse multimodal grain size distributions. It is primarily this factor which determines the extent to which tri- and other multi-modal populations may be investigated. In these cases, samples would be represented by "articulated dumb-bells" in displays with the axes shown in Figs. 2–4.

Other investigations by the authors indicate that relatively simple bimodal distributions, which can be usefully investigated using this simple approach, are not uncommon. They occur, for example, in the cave sediments and surface tills at the Creswell Crags near Sheffield (Jenkinson and Gilbertson, 1984; Fieller et al., 1988, 1990a); in Libyan sand dunes (Flenley et al., 1987); and within archaeological midden sites in the machair sands of the Outer Hebrides. However, in other examples we have studied, plots of the mass-size data and the calculated mathematical models, have demonstrated that these data sets are not all satisfactorily modelled by single or "mixed" log skew Laplace distributions; in some cases, mixtures of (4 parameter) log hyperbolic or (2 parameter) log normal distributions are more appropriate. Two-dimensional dumb-bell plots are sufficient for the latter, but the former require display of a selection of 2 or 3 parameters at a time.

References

Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Methuen, London, 265 pp.

Bagnold, R.A. and Barndorff-Nielsen, O., 1980. The pattern of natural size distributions. Sedimentology, 27: 199–207.

Barndorff-Nielsen, O., Dalsgaard, K., Halgreen, C., Kulhman, H., Møller, J.T. and Schou, G., 1980. Variation in particle size over a small dune. Sedimentology, 29: 53–65.

Cooke, R.U. and Warren, A., 1972. Geomorphology in Deserts. Batsford, London, 394 pp.

Diaconis, P. and Friedman, J.H., 1980. M and N plots. Stanford Linear Accelerator Centre, Rep. PUB-2495.

Fieller, N.R.J., Gilbertson, D.D. and Olbricht, W., 1984. A new method for environmental analysis of particle size distribution data from shoreline sediments. Nature, 311: 648–651.

Fieller, N.R.J., Gilbertson, D.D. and Timmins, D.A.Y. 1985. Handfitting skew log Laplace distributions as an aid to the interpretation of particle size distributions. In: N.R.J. Fieller, D.D. Gilbertson and N.G.A. Ralph (Editors), Palaeoenvironmental Investigations: Research Design, Methods and Data analysis. Oxford, British Archæological Reports S258, pp. 127–136.

Fieller, N.R.J., Gilbertson, D.D. and Timmins, D.A.Y., 1987. Sedimentological studies of the shell midden sites. In: P.A. Mellars (Editor), Excavations on Oronsay: Prehistoric Human Ecology on a Small Island. Edinburgh University Press, Edinburgh, pp. 78–90.

Fieller, N.R.J., Gilbertson, D.D., Griffin, C.M., Briggs, D.J. and Jenkinson, R.D.S., 1988. The statistical modelling of the textural properties of cave sediments using log skew Laplace distributions. Ann. Soc. Géol. Belg., 111: 107–111.

Fieller, N.R.J., Flenley, E.C. and Olbricht, O., 1990a. The statistics of particle size data. Dep. Probab. Stat., Univ. Sheffield, Res. Rep. No. 358/90.

Fieller, N.R.J., Gilbertson, D.D., Griffin, C.M., Briggs, D.J. and Jenkinson, R.D.S., 1990b. Modelling the grain size properties of cave sediments using log skew Laplace distributions: Creswell Crags, near Sheffield, UK. Dep. Probab. Stat., Univ. Sheffield, Res. Rep. No. 359/90.

Flenley, E.C., 1985. Use of mixture distributions in the modelling of sand particle sizes. In: O.E. Barndorff-Nielsen, J.T. Møller, K. Rømer Rasmussen and B.B. Willetts (Editors), Proceedings of International Workshop on the Physics of Blown Sand. Dep. Univ. Aarhus, Theoret. Stat., Mem., 8, 3: 633–648.

Flenley, E.C., 1988. Statistical analysis of particle size data. Ph.D. Thesis, University of Sheffield, Sheffield, 272 pp.

Flenley, E.C., Fieller, N.R.J. and Gilbertson, D.D., 1987. The statistical analysis of "mixed" grain size distributions from aeolian sands in the Libyan pre-desert using log skew Laplace models. In: L. Frostick and I. Reid (Editors), Desert Sediments: Ancient and Modern. Geol. Soc. London, Spec. Publ., 35: 271–280.

Folk, R.L., 1966. A review of grain size parameters. Sedimentology, 6: 73–93.

Folk, R.L. and Ward, W.C., 1957. Brazos river bar: a study in the significance of grain size parameters. J. Sediment. Petrol., 27: 3–26.

Forcheh, N., 1988. The use of mixture distributions to model particle size data from the Mega Kalahari. Dep. Probab. Stat., Univ. Sheffield, Res. Rep. No. 313/88, 116 pp.

Grove, A.T., 1969. Landforms and climatic change in the Kalahari and Ngamiland. Geogr. J., 135: 191–212.

Jenkinson, R.D.S. and Gilbertson, D.D., 1984. In the Shadow of Extinction: A Quaternary Archaeology and Palaeoecology of the Lake, Fissures and Smaller Caves at Creswell Crags SSSI. University of Sheffield Monographs in Prehistory and Archaeology, Sheffield, 129 pp.

Jones, P.N. and McLachlan, G.J., 1989. Modelling mass-size particle data by finite mixtures. Commun. Stat.-Theor. Methods, 18: 2629–2646.

Lancaster, I.N., 1981. Palaeoenvironmental implications of fixed dune systems in southern Africa. Palaeogeogr., Palaeoclimatol., Palaeoecol., 33: 327–346.

Olbricht, W., 1982. Modern statistical analysis of ancient sand. M.Sc. Thesis, University of Sheffield, Sheffield, 86 pp.

Shaw, P.A. and Cooke, H.J., 1986. Geomorphic evidence for the late Quaternary palae oclimates of the middle Kalahari of northern Botswana. Catena, 13: 349–359.

Shaw, P.A., Cooke, H.J. and Thomas, D.S.G., 1988. Recent advances in the study of Quaternary landforms in Botswana. Palaeoecol. Afr., 19: 15–26.

Taira, A. and Scholle, P.A., 1979. Origin of bimodal sands in some modern environments. J. Sediment. Petrol., 49: 777–786.

Thomas, D.S.G., 1984. Ancient ergs of the former arid zones of Zimbabwe, Zambia and Angola. Trans., Inst. Br. Geogr., N.S., 9: 75–88.

Thomas, D.S.G., 1985. Evidence of aeolian processes in the Zimbabwean landscape. Trans. Zimbabwe Sci. Assoc., 62: 45–55.

Thomas, D.S.G., 1987. Discrimination of depositional environments using sedimentary characteristics in the Mega Kalahari, central southern Africa. In: L. Frostick and I. Reid (Editors), Desert Sediments: Ancient and Modern. Geol. Soc. London, Spec. Publ., 35: 293–306.

Thomas, D.S.G. and Shaw, P.A., 1990a. The Kalahari Environment. Cambridge University Press, Cambridge, 284 pp.

Thomas, D.S.G. and Shaw, P.A., 1990b. The deposition and development of the Kalahari Group sediments, central southern Africa. J. Afr. Earth Sci., 10: 187–197.

Tukey, P.A. and Tukey, J.W., 1981. Graphical display of data sets in 3 or more dimensions. In: V.D. Barnett (Editor), Interpreting Multivariate Data. Wiley, Chichester, pp. 189–279.

Visher, G.S., 1969. Grain size distributions and depositional processes. J. Sediment. Petrol., 39: 1074–1106.

Warren, A., 1972. Observations on dunes and bimodal sands in the Ténéré Desert. Sedimentology, 19: 37–44.

Discrimination of depositional environments using sedimentary characteristics in the Mega Kalahari, central southern Africa

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SUMMARY: Unconsolidated Kalahari sand covers 2.5 million km^2 of central southern Africa, the 'Mega Kalahari', extending far beyond the Kalahari Desert of today. Relic aeolian, lacustrine and fluvial landforms indicate that in the Quaternary the Kalahari sand has been deposited and reworked by a variety of processes. Large areas of the sand have no identifiable landform associations, and because of this, sedimentological studies are necessary for a better interpretation of the palaeoenvironmental history of the Mega Kalahari. To this end, almost 200 Kalahari sand samples, in and not in identifiable landform associations, were collected and analysed in order to: investigate sedimentological characteristics; determine whether different processes have imparted distinct sedimentological characteristics to the sand; and thereby attempt to determine the depositional environments of samples without prior knowledge of the landform associations. Three methods have been used: (1) standard sedimentological techniques of grain size and shape determination; (2) multivariate discriminant analyses, to determine whether depositional environments could be better distinguished by considering grain size and shape parameters in combination; and (3) scanning electron microscope analyses of samples which lie centrally in any group identified by statistical analyses. Results indicate that aeolian processes have dominated the environmental history of the Kalahari sand, with only limited modification by subsequent processes. Multivariate discriminant analysis achieved only limited success in differentiating process environments. SEM investigations best identified the subtle modification of sand characteristics by non-aeolian processes, because individual grain textures are more readily adjusted than overall sample fabrics, and may therefore be the best technique for elucidating palaeoenvironments from sediment characteristics.

Unconsolidated Kalahari sand covers an area of 2.5 million km^2 in central southern Africa (Cooke 1964), extending from humid tropical Zaire to semi-arid Botswana (Fig. 1). This area has been termed the 'Mega Kalahari' (*eg* Thomas 1986*a* and *b*) in order to distinguish it from the smaller area known today as the Kalahari Desert (*eg* Cooke 1985; Jones 1982). Uncertainty surrounds the age and origin of the Kalahari sand. Maufe (1930), for example, considered it to be of Tertiary age, whilst Bond (1948) preferred the Pleistocene as the time of original deposition. Poldervaart (1957) and Bond (1948), utilized heavy mineral studies to infer the source areas and direction of transport of the surface sands of southeastern Botswana and Zimbabwe, respectively. However, in a systematic study in Botswana, Baillieul (1975) suggested that *in situ* subsurface bedrock weathering and bioturbation had made significant contributions to the sand. Boocock & Van Stratten (1962) also noted that even the youngest Kalahari sand may have been derived from underlying bedrock.

Despite these doubts about the provenance of the Kalahari sand, it is clear that it has been reworked on a number of occasions in the Quaternary period. The evidence for this was first recognized by Grove (1969) in the presence of a range of landforms produced under various palaeoenvironmental conditions. The most extensive are systems of fossilized sand dunes (*eg* Lancaster 1981; Thomas 1984), the northernmost of which is now covered by tropical rain forest in Zaire and Angola (Goudie 1983). Palaeolake beds and strandlines (*eg* Grey & Cooke 1977; Shaw 1985) and fossil drainage lines (Boocock & Van Stratten 1962) indicate more humid Quaternary conditions while pans, sometimes associated with lunette dunes (*eg* Lancaster 1978) testify to fluctuating hydrological conditions.

Palaeoenvironmental research in the Mega Kalahari has largely been concerned with evidence derived from landforms, although some investigations do include sediment descriptions (*eg* Lancaster 1978; Cooke 1980). Pettijohn *et al.* (1972) noted from the literature that over 80% of all sedimentological studies had been conducted to determine environments of deposition, however there has been limited application of grain size and shape studies to the sediments of the Mega Kalahari. The purpose of this paper is thus threefold: (1) to report the sedimentological characteristics of the Kalahari sand where found in known landform associations; (2) to see whether such sand has distinct characteristics imparted by the processes responsible for the

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