Chapter 12

SAND SHEET AND LAG DEPOSITS IN THE SOUTHWESTERN DESERT

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ABSTRACT

Based on size analyses of sand sheet and lag deposits in the southwestern desert of Egypt, it is possible to distinguish these sediments from the more commonly studied eolian dune deposits. Sand sheets consist of a bimodal mixture of sand-size grains and coarser lag fragments which vary from -1.0 to -2.5 ϕ (2.0 to 5.7 mm) in modal grain size, and are well sorted. In contrast, the sand-size fraction of these deposits is much more poorly sorted, and exhibits wider variations in both sorting and skewness than does dune sand. Except on a local scale, there is no evidence for selective removal of a saltation fraction in sand sheets. Instead, the wide range of grain sizes and poor sorting of the sand-size fraction support formation of sand sheets by relatively infrequent high winds that are capable of disturbing the protective lag surface.

INTRODUCTION

Since Bagnold's (1941) classic study on the physics of windblown sand, most studies of desert sediments have concentrated on the erosion and deposition of sand-size material in an eolian environment. These studies have dealt primarily with dune morphology and stratification (McKee and Tibbitts, 1964; McKee, 1966; Sharp, 1966; McKee and Moiola, 1975; Ahlbrandt, 1979; Moiola and Spencer, 1979) and the textural characteristics of eolian dune sand as compared to those of other environments (Amstutz and Chico, 1958; Friedman, 1961; 1967; 1973; Martins, 1965; Moiola and Weiser, 1968; Shepard and Young, 1961). However, studies of the size characteristics of desert lag surfaces typical of extensive sand sheets are less numerous in the geologic literature. McKee (1966) and McKee and Moiola (1975) have analyzed the interdune regions of the White Sands dune field in New Mexico, which essentially consist of deposits from former dunes. Folk (1968), in an extensive review of desert floor sediments, found that "reg" was universally bimodal, consisting of a mixture of several populations of sand. Ahlbrandt (1979) and Moiola and Spencer (1979) combined 40 interdune and serir samples from a variety of deserts, and presented additional evidence for bimodality and textural differences between interdune and dune sand. Studies of coastal dunes have concentrated primarily on the dune sand textures (Mason and Folk, 1958; Inman and others, 1966) rather than interdune sediments, because of periodic reworking of the interdune sediments by water. Although these studies have provided much information on the nature of dune sands, these relatively small, interdune regions are not directly comparable to the vast expanses of sand sheet deposits in southwestern Egypt.

A wide variety of terms have been used to describe the sedimentary deposits in the open desert, including "desert pavement, hammada, lag gravel, interdune, reg, sand sheet and serir." In order to be consistent with Bagnold's (1933) naming of the Great Selima Sand Sheet the term "sand sheet" will be used in this paper to describe "A thin accumulation of coarse sand and fine gravel formed of grains too large to be transported by saltation, characterized by an extremely flat or plain-like surface broken only by small sand ripples" (AGI, 1974). Consequently, the term "sand sheet" is analogous to the "reg" samples described by Folk (1968), and some (but not all) of the "interdune" sediments of Ahlbrandt (1979). In this paper, the term "desert pavement" will be used to describe a surface of large, angular fragments (generally larger than a few centimeters) that may veneer a bare rock surface, or a layer of sand.

As described by Bagnold (1933), the Great Selima Sand Sheet occupies an area of about 52,000 km^2 stretching from Bir Tarfawi in the north to latitude 21° in the south. It is bounded on the west by the rocky terrain of the Gilf Kebir - Uweinat region, and on the east by Selima Oasis. In addition, numerous smaller sand sheet surfaces cover much of the Western Desert, where less than one fourth of the surface is covered by actively moving sand deposits and dunes (Gifford and others, 1979).

The study of sand sheet and associated deposits is important for several reasons: 1) These sediments provide a widespread, ubiquitous surface type in desert regions which can be correlated with tonal variations, visible on orbital images. 2) Larger size lag fragments protect the active moving sand, thus the size distribution of this material is important to studies of potential sand movement and desertification. 3) Surface materials with these size characteristics may be representative of windblown sediments on the surface of Mars (Maxwell and El-Baz, 1980).

Because of the dominant eolian environment on Mars, and the variations in sediment size seen at the Viking lander sites (Patterson and others, 1977; Zimmer and others, 1977), it is possible that large areas of Mars are made up of surface materials analogous to terrestrial desert pavements. 4) As suggested by Folk (1968), it is also possible that the desert floor environment may be present in ancient sandstones. Thus, investigation of the textural properties of the widespread sand sheets in the Western Desert will aid in the characterization of this environment.

The intent of this paper is first, to present the results of grain size analyses for sand sheet and dune samples, and second, to compare these two distinct desert environments on the basis of textural characteristics in the sand-size fraction alone (see below).

These results will then be compared to those reported from other major inland dune regions in order to typify the size characteristics of sand sheet deposits. Finally, some speculations on the nature of eolian sedimentary deposits on the martian surface will be made, based on data from the Western Desert.

METHODS

For the purposes of this study, the coarse and fine fractions of the bimodal sand sheet deposits are treated as two separate samples. While in the field, it became apparent that the method of sampling sand sheet deposits would greatly influence any later study of their textural characteristics. Sampling emphasis on the thin, surficial lag deposits would result in a greater weight percent of coarse material in the total sample (hence negative skewness), whereas emphasis on the underlying sand would fail to provide a representative sample of the coarse lag. Consequently, in order to provide data representative of both sediment modes and of the present-day eolian regime, only the top surface of the sand sheets was sampled.

All samples were obtained by scraping the top 2-3 cm of an area about 0.5 m^2 (about 600 gm). In some instances, where lag spacing was greater, wider areas of the sand sheets had to be scraped in order to provide a representative sample of the lag deposits. Samples were split and about 100 gm of each sample was sieved for 15 minutes at 1/4 ϕ intervals using a Rotap. Both frequency and cumulative frequency curves were plotted for each sample, and graphic textural parameters (Folk, 1974, p. 46-49) were calculated for the sand-size fraction. Because the width of the sampling field for the lag deposits is variable, it would not be valid to include the total samples of the lag and sand fractions in the calculation of graphic parameters. In any individual case, if the sample area were larger, the coarse fraction of the total sample would have been proportionally greater. Consequently, the lag and sand fractions are treated separately. For this study, the average size of lag was determined by visual estimate of the sieved separates which were compared with the bulk samples and photographs of the sampling sites.

DUNE SAND

Barchans

Samples of barchan dunes are from three localities: the dunes on the Kharga-Dakhla road within the Kharga depression, the Abu Hussein dune field west of Bir Sahara, and an individual low barchan south of Beacon Hill (Fig. 12.1). The individual barchans of the Kharga region are extensions of the longitudinal dunes north of the scarp bounding the depression, and range from 25 to 540 m wide (Embabi, 1967). Those of the Abu Hussein dune field are generally 300-500 m wide, and are not aligned in a north-south direction as are the barchans of the Kharga depression. Instead, the Abu Hussein barchans consist of laterally coalescing and individual dunes with a wide (almost 1 km) north-south interdune spacing. South of Beacon Hill, 2 samples were taken from a low barchan (approximately 2 m high).

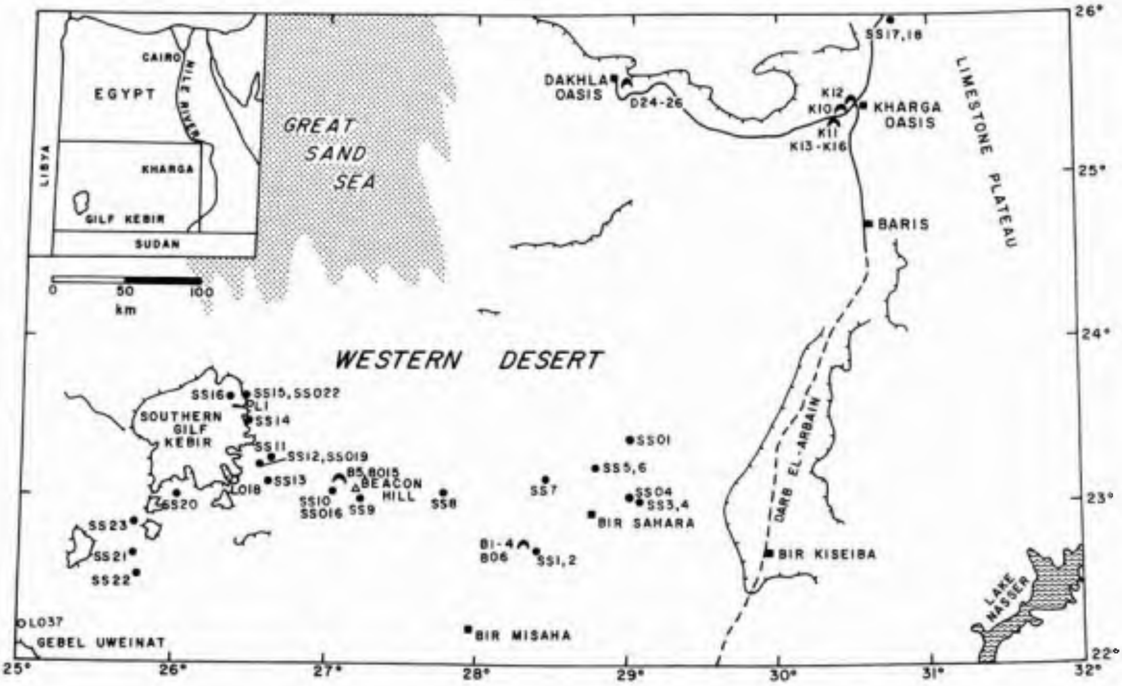

Figure 12.1 Location map of samples from sand sheets (solid circles), longitudinal dunes (open circles) and barchans (barchan-shaped outline) in the southern part of the Western Desert of Egypt.

The mean grain size of the barchans is 1.97 ϕ (0.27 mm) (Table 12.1). Dune sand of the Kharga-Dakhla region is slightly finer-grained than that of the Abu Hussein dune field, although there is no statistically significant difference between any of the localities. All barchan samples are well- to moderately-well sorted (average σ_I = 0.61 ϕ), and 12 out of the 17 samples are slightly fine-skewed. Despite the fact that these samples are from a different dune type and a different continent, sorting and skewness are virtually identical to those of longitudinal dunes in the Simpson Desert, Australia (Folk, 1971), and to inland dunes of North America and North Africa (Moiola and Weiser, 1968). Mean grain size of these dunes is slightly larger than that reported for Simpson Desert dunes (2.7 ϕ, 0.15 mm; Folk, 1971).

Longitudinal Dunes

The 19 samples of longitudinal dunes were taken from 3 dunes on the eastern side of the Gilf Kebir (Fig. 12.1), and 2 dunes in the Bahariya Oasis region north of Kharga. One dune in Bahariya was extensively sampled along the crest (10 samples), and was trenched in order to determine the internal structure. Samples from the Gilf Kebir include the longitudinal dune at the entrance to Wadi Mashi, the

Table 12.1 Summary of grain size statistics.

Environment	Mz(ϕ)	σ_I (ϕ)	SK_I	K_G*
Barchans n=17**	1.97±.52	0.61±.28	+0.026±.16	0.487±.041
Longitudinal Dunes n=19	1.80±.32	0.54±.19	+0.146±.15	0.521±.043
Coastal Dunes n=3	2.12±.25	0.56±.13	+0.155±.04	0.533±.039
Sand Sheets n=28	1.42±.76	1.13±.34	-0.015±.39	0.510±.106

*Transformed Kurtosis ($K_G/(1 + K_G)$).

**Includes 11 samples from Kharga-Dakhla region.

dunes east of Bagnold's 1938 camp (see El-Baz and others, 1980) and a low (whaleback?) dune northwest of Uweinat.

As might be expected, grain size parameters of these dunes are similar to those of the barchans. Longitudinal dunes are composed of medium sand (average Mz = 1.80 ϕ; 0.29 mm), are moderately well-sorted (σ_I = 0.54 ϕ), and are slightly fine-skewed (SK_I = +0.15). As is the case with barchans, sorting and skewness are similar to those reported for other inland dunes (Folk, 1971; Moiola and Weiser, 1968), whereas mean grain size is larger than Simpson Desert or "inland dune" sands, but is comparable to the medium-sand size reported for a seif dune in Libya (McKee and Tibbitts, 1964).

Coastal Dunes

For comparison with inland dunes of the Western Desert, 3 samples from the northern coast of Egypt are included in this analysis. All are from the crests of beach dunes in the Mersa Matruh region west of Alexandria, and are composed of calcareous sand rather than the quartz grains of the inland dunes. Unlike the north-south orientation of the inland dunes, the coastal dunes are oriented east-west, and have a seif-like appearance.

These calcareous sands have a smaller mean grain size (2.12 ϕ; .23 mm) than the average mean for inland dunes (Table 12.1), although several inland dunes have mean grain sizes that are less than these coastal dunes. Sorting (σ_I = 0.56 ϕ) and skewness (SK_I = +0.15) are also similar to values of both barchans and longitudinal dunes.

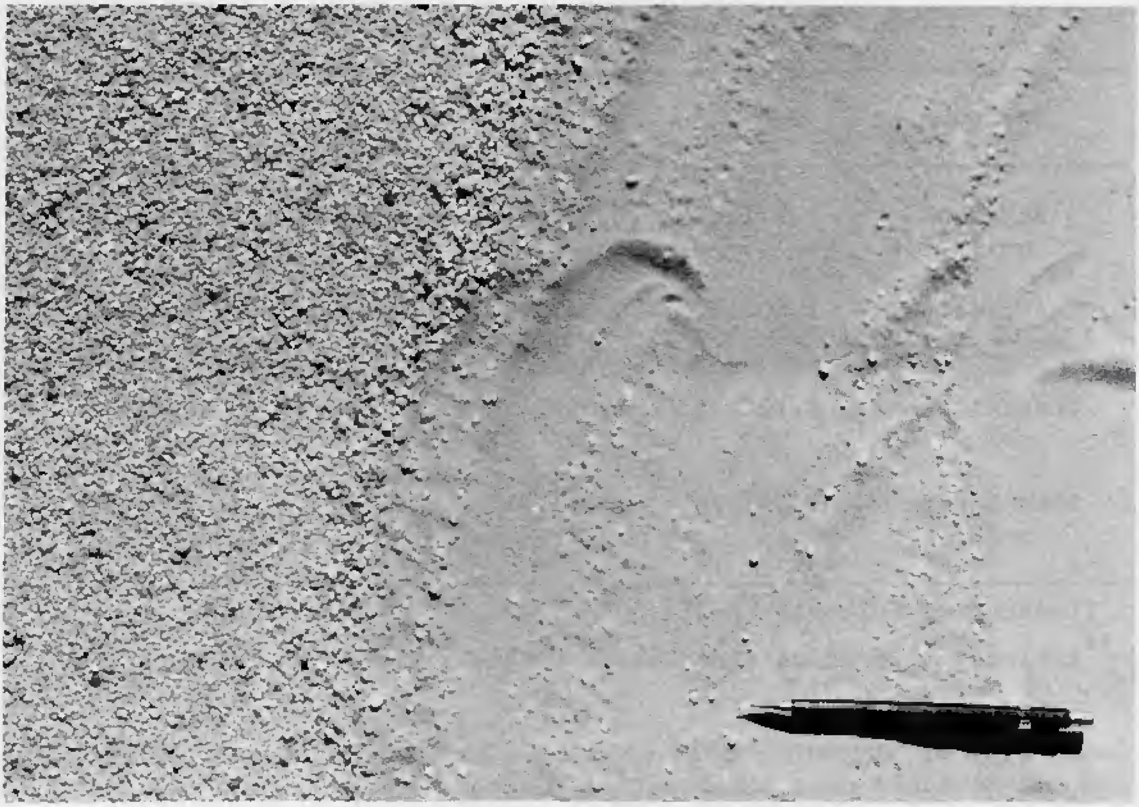

Figure 12.2 Typical lag-covered surface and underlying sand east of the Gilf Kebir plateau. Note the close spacing of the 1-grain thick lag surface; mean grain size of the coarse fraction is $-1.25\ \phi$ (2.4 mm). Pencil is 14.5 cm long.

SAND SHEETS

The 27 samples of sand sheets were taken from various locations ranging from the top of the plateau north of Kharga, to the southern end of the Gilf Kebir (Fig. 12.1). Although implied by the name given by Bagnold (1933), the Great Selima Sand Sheet is surfaced not by sand-size particles, but by coarser granule- to pebble-size lag that overlies and protects the sand. In a strict sense, only those samples between Bir Sahara and Beacon Hill, and the 5 samples southwest of the Gilf Kebir might be considered as belonging to a true sand sheet. On this extensive, featureless sand sheet, the spacing of coarse material is variable (Fig. 12.2). Granule-size grains may exhibit such close packing that they obscure the underlying sand. Such spacing was noted in both planar-bedded, featureless sand sheets, and in a field of flat-topped (truncated?) ripples east of the Gilf Kebir (Fig. 12.3).

Besides the rounded desert lag deposits that form the surface of the sand sheets, closely-spaced deposits of dark, locally-derived desert pavement occur near outcrops and in the lee of hills. These angular fragments range up to several cm's in diameter, and create dark streaks on the desert surface that emanate downwind from the topographic obstacle. In some cases, these dark streaks are large

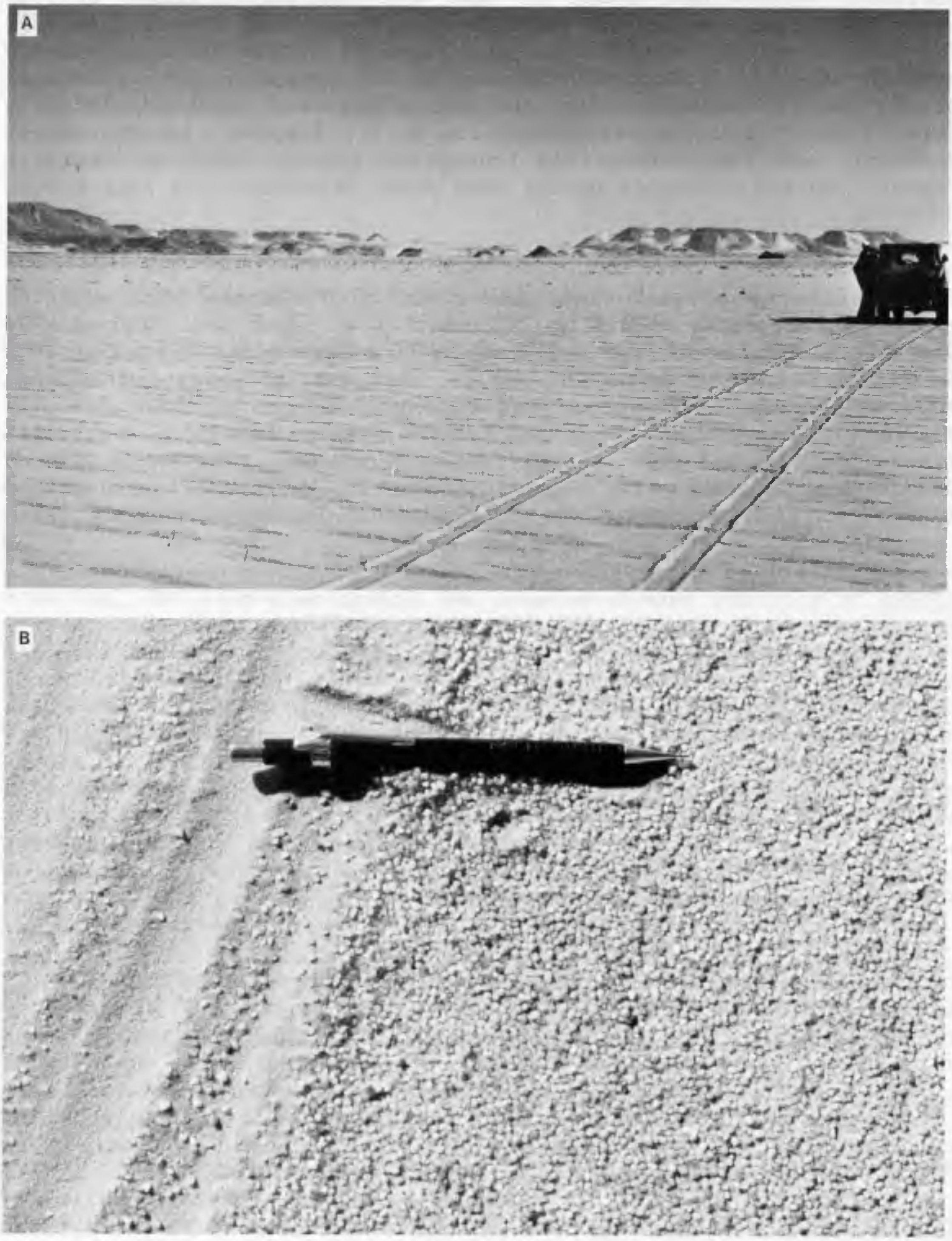

Figure 12.3 (A) Flat surfaced (truncated?) ripples of coarse lag deposits east of the Gilf Kebir. Planar surface may result from high speed winds needed for redistribution of lag. (B) Closely-spaced lag and underlying sand deposits of flat-topped ripples. Mean grain size of lag fraction is $-0.75\ \phi$ (1.7 mm). Pencil is 14.5 cm long.

enough to be visible on orbital images, and attribute their characteristic streamlined shape to the pattern of movement of the surrounding lighter-colored sand sheets (El-Baz and Maxwell, 1979a). The size range of individual coarse fragments within these streaks is strongly dependent on the distance from the source outcrop. Because of the local size variations, the desert pavement is not included in this study. It is doubtful that the larger fragments of the desert pavement have been extensively transported by the wind, as have the coarse, rounded fragments of the sand sheet deposits.

Coarse Fraction

The average size of the coarse fraction of the sand sheet samples ranges from about -1.0 ϕ to -2.5 ϕ (2.0 to 5.7 mm; Fig. 12.4). However, one-third of the samples have a coarse mode at -1.25 ϕ (1.0 to 1.2 mm). In an extensive review of the literature, Folk (1968) reported that the average size for desert lag varied from 1.4 ϕ to -1.0 ϕ (0.38 to 2.0 mm), and that for the Simpson Desert of Australia, the coarse mode was predominantly 0.25 ϕ (0.84 mm). The large size of the granule to pebble-size lag fraction in the Western Desert deposits is most likely the result of the widespread Nubian sandstone, which

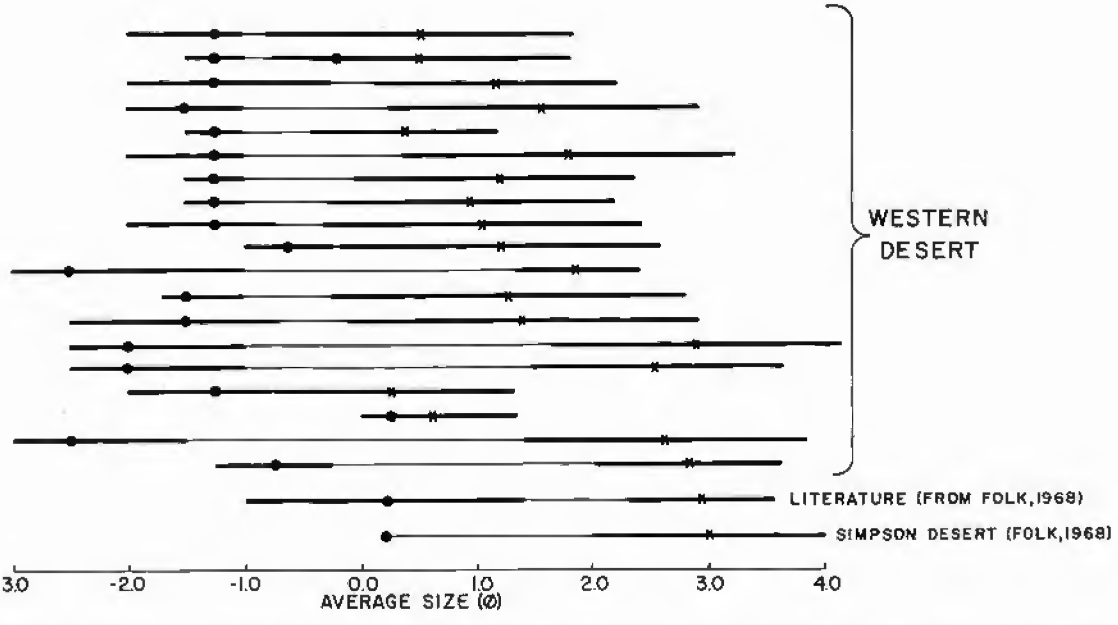

Figure 12.4 Average sizes for sand sheet deposits of Western Desert samples compared with those of previous studies. Average size for coarse fraction is visually estimated from field observations and sieved separates; average sand size is graphic mean. Sand sheet deposits are poorly sorted in the sand size fraction as indicated by heavy lines.

provides a source for the eolian sediments. However, the influence of locally derived material can only be documented where there are outcrops of rock other than sandstone (El-Baz and others, 1979b). The Eocene limestone north of Kharga provides one such example. Here, the lag fraction is composed almost entirely of limestone fragments that stand out against the background of reddish sand-size grains. South of the Kharga depression, however, quartz grains of the Nubian sandstone provide an immediate source for both lag and sand fractions of the sand sheets.

Fine Fraction

The fine fraction of the sand sheets (here used to denote the sand and smaller size fractions) exists both underlying and interspersed between lag pebbles and granules. Horizontally-bedded layers of sand separated by lag deposits were observed in several areas of the Great Selima Sand Sheet, although the total thickness of these deposits seldom exceeded a few 10's of centimeters (see Haynes, Chapter 9). Consequently, repeated episodes of deposition and winnowing have caused the build-up of the sand sheet surface, and have no doubt acted to smooth any pre-existing topographic relief.

As opposed to the lithologic variations noted within the coarse fraction, the sand-size grains are composed almost entirely of quartz (El-Baz and others, 1979b). Even north of Kharga, where the lag is composed entirely of limestone fragments, quartz grains predominate at sizes of 0.0 ϕ (1.0 mm) and smaller. The influence of the Nubian sandstone source rock, together with compositional segregation during weathering and transport are both responsible for these monomineralic sands. In a similar manner, the variations in color of the sand fraction may also be inherited from original hematite coatings of grains in the Nubian sandstone. However, in situ modification of these coatings (precipitation of additional hematite or abrasion or the coating due to transport) nonetheless remains a possibility. On these samples, there are no specks of carbonaceous material such as those found on reg grains from the Australian Simpson Desert (Folk, 1976).

Within the sand-size fraction, the sand sheet samples are almost nonmodal in their size distribution. Mean grain size for all the samples averages 1.41 ϕ (0.38 mm), larger than the average size for any of the dune environments, and the mean value for sorting is 1.13 ϕ . As is true for the coarse fraction, these sands have a larger mean grain size than the sand fraction of most desert lag deposits from the Simpson Desert, or those reported in the literature (Folk, 1968). Both skewness (SK_I = -0.015) and kurtosis (K_G = 1.14) lie within the range of dune sands.

COMPARISON OF TEXTURAL PARAMETERS

Although textural parameters have been used extensively for discrimination among river, beach, beach dune and inland dune sands (Mason and Folk, 1958; Friedman, 1961; 1967: Moiola and Weiser, 1968), few studies have presented detailed size analysis data for the extensive sand sheet environment. In a study of seif and interdune areas in northern Libya, McKee and Tibbitts (1964) presented histograms of the grain size distributions, noting that serir deposits were dominantly bimodal. Sharp (1966) discussed the dominantly unimodal sand of the Kelso dunes in southern California, but there are no extensive interdune tracts similar to sand sheets in this region. The first comprehensive analyses of grain size parameters for featureless desert plains are those of Folk on the Simpson Desert in Australia (Folk, 1968; 1971; 1976). Using graphic grain size parameters, Folk (1971) found systematic changes in the size distribution of sand from longitudinal dunes and the reg. According to his diagrams of the higher moments, there is considerable overlap in the fields of dune crests, windward flanks and leeward flanks. Warren (1972) presented cumulative curves for the size distribution of sands from seif, interdune flat and zibar (very gently undulating sand ridges) environments in the Tenere Desert of Niger. Both interdune flat and zibar sediments were found to have poorer sorting than dune sands.

In a study of the White Sands National Monument in New Mexico, McKee and Moiola (1975) found that the relatively small interdune areas are characterized by a high percentage of silt and clay, deposited from suspension and trapped by vegetation. Based on 40 interdune and serir samples, Ahlbrandt (1979) noted that the most significant textural differences within the eolian environment were between dune sands and those of the interdune and serir deposits. This distinction was further supported by the work of Moiola and Spencer (1979), who found that discriminant analysis of the quarter-phi weight fractions would separate inland dunes from interdune deposits. However, none of the above studies specifically treated a sand sheet type of environment, such as that which covers vast expanses of the southwestern Egyptian desert.

Sorting Versus Mean Grain Size

The poor sorting and wide variation of median grain size are responsible for the range of values for sand sheet sands compared to values from the dune environments (Fig. 12.5). Within the field of dune samples, there is no systematic relationship between size and sorting for the different dune types, nor any consistent variation with location on the dune. However, only three of the sand sheet examples fall in the field outlined by dune samples.

These results are consistent with those of Ahlbrandt (1979), in which interdune and serir samples were determined to be more poorly sorted than dune deposits (see Figs. 20 and 21 in Ahlbrandt, 1979). However, the major different between previous studies and the analyses presented here is in the treatment of the sand-size fraction as a discrete sample.

As shown in Figure 12.5, the sand sheets are characterized by moderate to poor sorting even within the sand fraction alone (excluding the coarse lag, which would create an additional tendency for poor sorting).

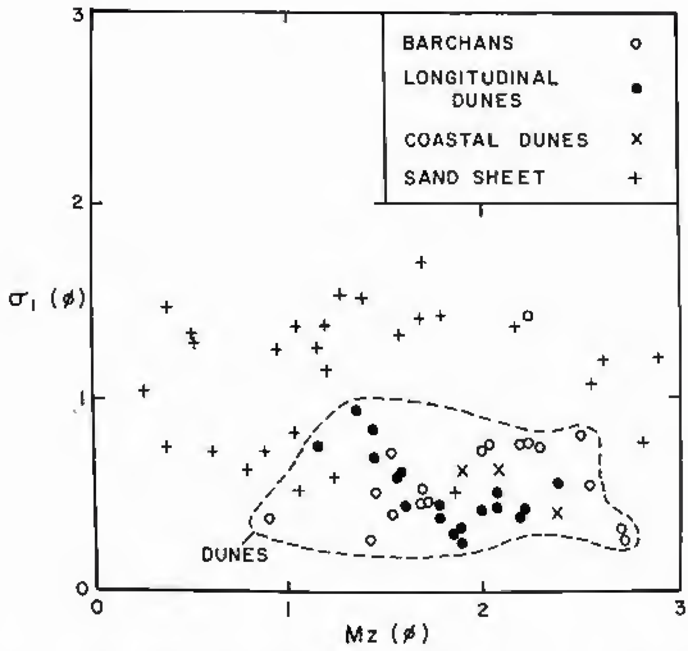

Figure 12.5 Relationship between sorting (σ_I) and mean grain size (Mz) for Western Desert sands. Poor values of sorting are characteristic of even the sand size fraction of sand sheet sands.

Skewness Versus Mean Grain Size

Although several early studies of dunes and associated eolian deposits suggested that positive skewness is characteristic of eolian sands (Mason and Folk, 1958; Friedman, 1961; Folk, 1971), more recent analyses of dune sands suggest that positive skewness is not a universal phenomenon (Bigarella, 1972; Friedman, 1973; Ahlbrandt, 1979). Results of the present study support the latter view, since one-third of the Western Desert dune samples are negatively skewed (Fig. 12.6). There is a lack of distinct fields of dunes and sand sheet sands on a plot of skewness versus mean grain size, although the larger mean size of the sand sheets provides a slight separation (Fig. 12.6). Coarse-grained sand sheet sands tend to have both positive and negative skewness values, and several of the samples fall in the field defined by dune sands, further suggesting that this pair of graphic parameters may not be the best for separation of environments.

Ahlbrandt (1975; 1979) found that for dune samples in the Killpecker Dune Field in Wyoming, and for interdune and serir deposits from various deserts, skewness was dependent on mean grain size. By using both coarse lag and sand-size material as one sample in the calculation of graphic parameters, however, this "dependence" naturally results from the bimodal nature of the sample. Positive (fine) skewness will result from a relatively coarse sand with another mode in the fines, whereas negative skewness will result from a sample with a finer mean grain size with an admixture of lag grains. As shown by the present study, there is no tendency for a grain-size

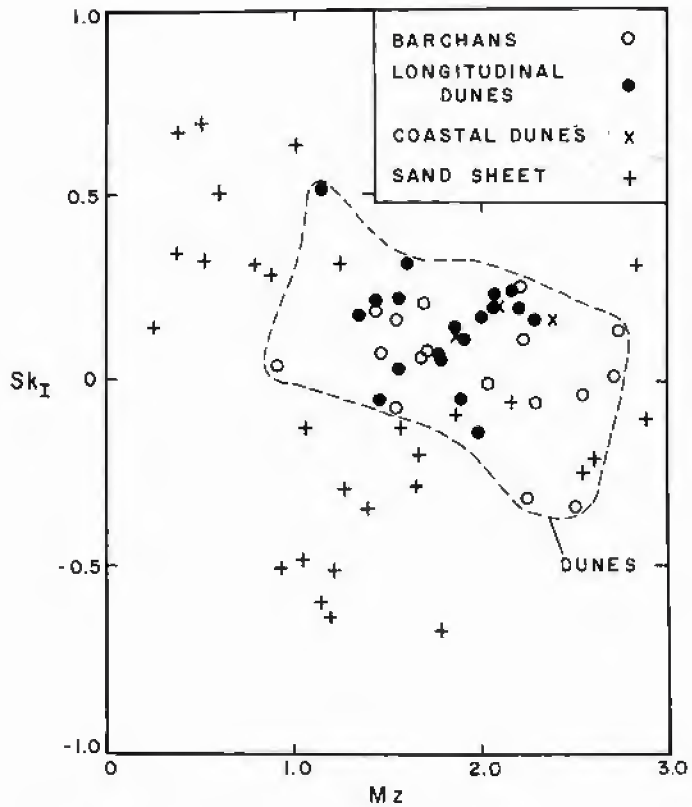

Figure 12.6 Relationship between skewness (SK_I) and mean grain size (Mz) for Western Desert sands. Note the negative skewness values for several dune sands, and more than half of the sand sheet sands.

dependence of skewness within the sand fraction of sand sheet deposits.

Skewness Versus Sorting

The combination of skewness and sorting provides the best separation of environments for Western Desert sands (Fig. 12.7). Separation is due primarily to the characteristic poor sorting of sand sheet sands, but it is aided by the narrow range of skewness of dune sands (-0.2 to +0.6). A similar grouping of inland dune sands is presented in Figure 5 of Moiola and Weiser (1968), although they found it difficult to separate dune from river sand on the basis of these parameters. The data of Folk (1971) would compare well in the dune field; Simpson Desert dunes have an average skewness of +0.09, and sorting values from 0.32 ϕ to 0.71 ϕ . The better sorting values and narrower skewness range for his reg samples, however, would cause his reg field to fall just to the right of the dune field outlined in Figure 12.7. Considering the number of variables involved in both source and transport on two different continents, the agreement is much better than would be expected.

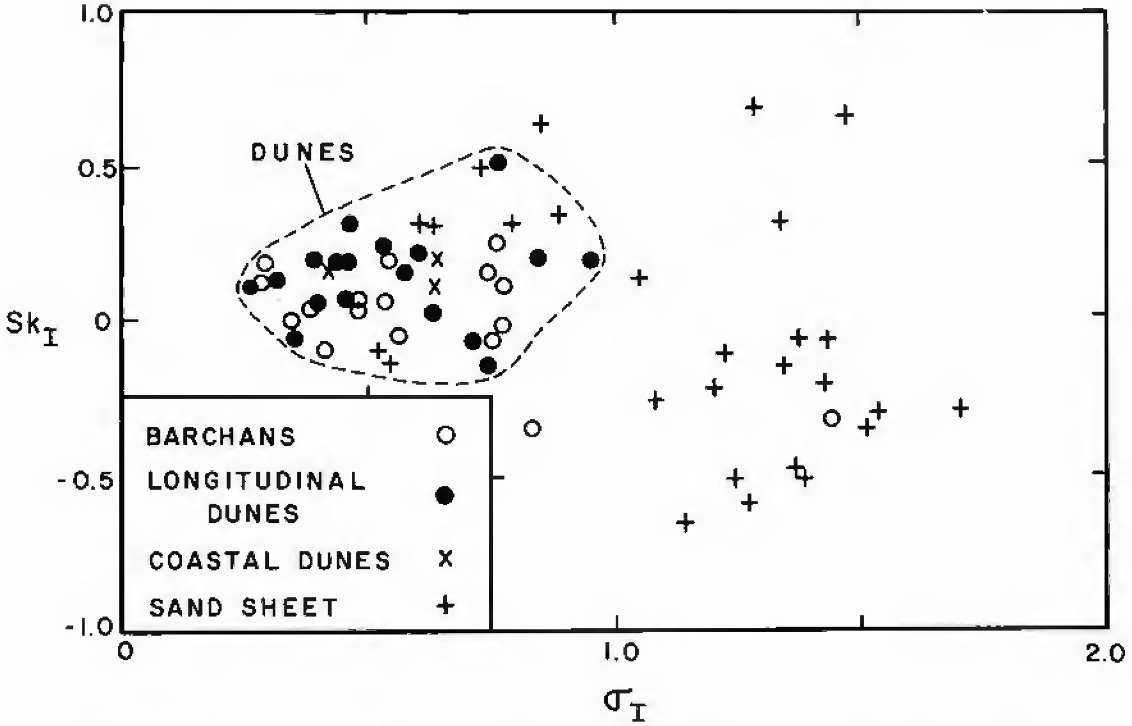

Figure 12.7 Skewness (SK_I) versus sorting (σ_I) for Western Desert sands. The combination of poor sorting of sand sheets and a relatively narrow range of skewness for dune sands suggest that these parameters are the most useful for distinguishing these environments.

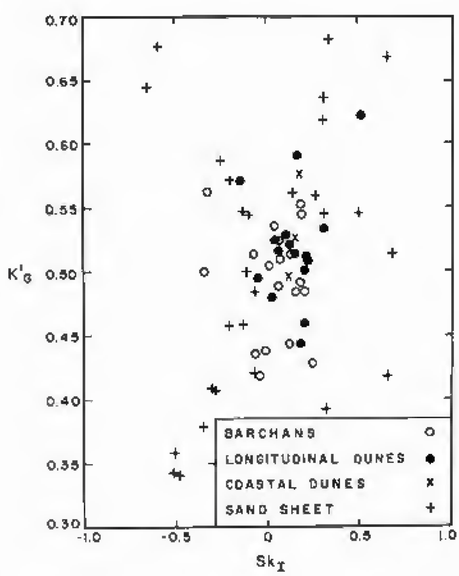

Figure 12.8 Kurtosis (transformed Kurtosis, KG/(1 + KG) versus skewness (SK_I). Although specific fields are not well-defined, there is a tendency for the more platykurtic sand sheet samples to be characterized by negative values of skewness.

Skewness Versus Kurtosis

Since neither skewness nor kurtosis values individually exhibit any consistent variation with environment, the plot of these two parameters (Fig. 12.8) shows the expected high degree of scatter. Western Desert sands reveals more extreme variations in both SK_I and K_G than sands of the Simpson Desert (Folk, 1971), or eolian sands of Mustang Island, Texas (Mason and Folk, 1958). There is a general trend for platykurtic sand sheet sands to be negatively skewed, which is consistent with the polymodality and presence of the coarse grained fraction in these samples.

DISCUSSION

As shown by the present and previous studies of dune sands, no distinction has been made between the size and sorting characteristics of sands from different dune types, although a few studies have noted the textural differences between desert floor and dune sand. R. A. Bagnold provided the initial physical rationale for sand sheet sand, noting that "a desert surface is never composed entirely of fine dune sand, unprotected by a layer of coarser grains" (Bagnold, 1941; p. 168). Once deposited, the stability of sand sheets was thought to be maintained by the increased drag produced by the pebbles. Consequently, Bagnold regards the pebble surface as a reservoir in which sand is stored during periods of gentle wind, and removed in sudden storms (Bagnold, 1941, p. 169).

Recently, modifications of this basic theory have been proposed. Folk (1968) has proposed that selective removal of the saltation size fraction (1.5 to 4.0 ϕ ; .35 to 0.63 mm) is responsible for bimodal sands of the desert floor. Coarser grains from 1.0 to -1.0ϕ which are too heavy for saltation would move primarily by rolling. This gave rise to Folk's (1971) "quantum theory" of eolian deposition, in which reg sediments were thought to be a combination of several populations, each having a normal distribution.

In contrast, Warren (1972) proposed that bimodal sands could not be explained by invoking high threshold velocities needed to move fine sands. Fine sands would be as likely to move because of bombardment by coarser grains. Therefore, Warren's (1972) "protectionist theory" involved a modification of previous selective transport models. According to this theory, the slightly coarser fraction of the saltation load would be too large to fit in the inter-particle voids of the surface creep fraction, and thus would be kept in transport to eventually end up as dunes.

The results of each of these methods for sand sheet development should be manifested in the size distribution of the sand fraction. According to Bagnold's (1941) near-surface drag theory and Folk's (1971) quantum theory, the mean grain size of the sand fraction should be highly variable, having been deposited by the less frequent, strong winds capable of disturbing the lag surface. However, if selective removal of the saltating, dune-forming fraction has occurred (Folk, 1968; Warren, 1972), then that size should be deficient in sand sheet deposits. As a group, the widely distributed values for mean grain size of Western Desert sands suggest that selective transport, if it has occurred, has not been an efficient means of modifying the size distribution of sand sheets. The poor sorting of the sand-size fraction makes it difficult to single out any individual size populations within the sand sheets. The wide range of grain sizes present in the Nubia sandstone (Issawi, 1973b; Klitzsch and others, 1979) indicates that a continuum of source material in the Western Desert overrides any eolian sorting into "quanta." On a local scale, however, selective transport is supported by observations within the Abu Hussein dune field. Here, the mean grain size of the sand sheet is 2.83 ϕ (.14 mm; sand fraction alone), finer than the 1.79 ϕ (.29 mm) sand of the surrounding terrain.

INFERENCES FOR SURFICIAL DEPOSITS ON MARS

As shown in Mariner and Viking images of the surface of Mars, dunes and other eolian features have suggested the presence of a significant population of saltation-size particles that are available for eolian transport (Cutts and Smith, 1973; Greeley and others, 1974b). In addition, observations of the duststorms indicate that material in the 1 μm range is extensively redistributed on a planet-wide scale (Arvidson, 1972). In contrast to these observations, however, Viking lander images indicate an apparent deficiency of surficial material in the 1.75 - 2.5 ϕ (.30 - .18 mm) size range (Patterson and others, 1977), and theoretical calculations of wind velocities needed for eolian entrainment both suggest that sand-size material should not be an important constituent in the martian eolian regime. According to Greeley (1979a), three possible explanations for the presence of sand on the martian surface are: 1) the dunes are remnants of a previous episode of a denser atmosphere, 2) the calculations suggesting the need of sand are incorrect, or 3) the eolian features may be formed of agglutinates of smaller grains that act as sand-size material during transport. Based on the size characteristics of sediments from the Western Desert, however, it is also possible that these seemingly conflicting lines of evidence are the result of the heterogeneity of eolian depositional environments.

Source materials for many present-day terrestrial deserts are found in previously consolidated sedimentary deposits, subjected to fluvial reworking during Pleistocene and Recent times (Folk, 1968). Eolian sands of the Western Desert are one example of this process, in that they were derived from highlands to the south, and transported northward by rivers only to be blown back southward by the prevailing winds (El-Baz and Maxwell, 1979a). In the southwestern desert, however, there is an additional local source of sand grains in the widespread Nubia sandstone that underlies the surficial deposits (Issawi, 1973b; Klitzsch and others, 1979). Consequently, there is likely to be a continuum of particle sizes present that are available for eolian sorting. The characteristics of source materials for martian deposits are much more difficult to specify. The effects of impact, thermal and chemical weathering, and possible fluvial erosion may all play an important role in generation of sand- and silt-size material. Because of our limited knowledge on the nature of martian bedrock, however, the grain size of source materials on that planet still remains unknown.

On both Earth and Mars, the resultant size distribution of wind-transported material can be divided into two fractions: 1) Unimodal, saltation-sized grains that are the dune-forming population, and 2) A bimodal population of sand sheet, interdune and desert-pavement type of deposits. Locally, material derived from an immediate source will modify both populations in the form of large fragments let down from eroded outcrops. As indicated by the comparison of textural parameters, the deposits of dunes can be distinguished from those of sand sheets on the basis of textural parameters. Although both the gravity and the atmosphere differ on Mars, the basic processes of eolian sorting are likely to be the same. Differences in the martian environment suggest that the size of the saltation fraction may be greater than that of the Earth (Sagan and Bagnold, 1975), but that both wind speeds and net sediment transport rates are greater (Arvidson, 1972; White, 1979). Because of the differing modes of sand sheet deposition, it is likely that these environmental effects may be represented more by sand sheet and associated deposits rather than the relatively homogeneous dune deposits.

Unfortunately, data from the Viking landers are inconclusive with respect to particle size variations at the two locations on the martian surface. Limitations on pixel size and sampling rate of the lander cameras make it impossible to see surface particles finer than about 2.5 ϕ (.18 mm). Based on an absence of false low frequency components in surface imaging, Patterson and others (1977) suggested that there is a deficiency in the medium to fine sand size range (1.75 to 2.3 ϕ, .30 to .20 mm). On the basis of grain counting in the footpad of Viking Lander 2, Zimmer and others (1977) also suggested a depletion of fragments less than -1 ϕ (2 mm) in diameter. Consequently, there is an apparent bimodal sediment distribution among the $<$ 5 mm size material at both sites. Grains greater than a few millimeters are abundant on the surface, with finer material (less than about 2.5 ϕ ;.18 mm) forming intervening areas and possibly the drifts.

The deficiency of sand-size material has been attributed to particle break-up due to reduced atmospheric density (the so-called "Kamikaze" particles of Sagan and others, 1977), or a debris-flow origin or material near the landers (Shultz and others, 1979). Based on sorting characteristics of Western Desert sands, however, it is also possible to consider this size distribution as the result of the sand-sheet mode of deposition transferred to the martian environment. On Mars, the larger gap between the modes of fine sand and silt versus clay material may be the result of the much higher wind speeds and wind speed variations present at the martian surface.

CONCLUSIONS

Different dune types studied in the Western Desert of Egypt are indistinguishable from each other on the basis of textural parameters. However, the median grain sizes of the sand fraction of sand sheet deposits are coarser than those of dunes, and there is a much wider range of mean sizes for sand sheets than for dunes. On an individual sample basis, this is consistent with both the poor sorting of the sand fraction of sand sheets as opposed to the good sorting of dune sand.

The combination of skewness and sorting provides the best means of separating dune from sand sheets on the basis of the sand size fraction alone. Separation is due to the poor sorting of the sand sheet sands (even within the sand fraction alone) and the relatively narrow range of skewness of the dune sands. Although the selective transport of sand sheet sand may be represented on a local scale, the influences of a continuum of grain sizes present in the Nubian sandstone source is consistent with deposition of sand sheet sand from sporadic high winds that are needed to disturb the lag surface.

The presence of fine and coarse deposits, and apparent absence of a sand-size component at the Viking Lander sites is suggestive of eolian modes of deposition similar to those of terrestrial sand sheet deposits. It may be possible that the great variation of martian wind velocities is responsible for a greater spread between the coarse and fine sediment populations on the martian surface.

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