

Preliminary Analysis of Color Variations of Sand Deposits in the Western Desert of Egypt

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ABSTRACT

Astronaut observations and photographs of color variations in the Western Desert of Egypt are related to both iron oxide coatings on individual grains and the presence of locally derived material in the sand deposits. The results of four field trips, to Bahariya Oasis, Siwa Oasis, Kharga and Dakhla Oases, and the Great Sand Sea, enable more detailed interpretations of colors photographed during the Apollo-Soyuz mission. The northern region of the Western Desert has the highest percentage of calcareous grains originating from local limestone outcrops. Samples from the central part of the Western Desert contain numerous iron-rich grains originating from the iron deposits of Bahariya and are locally enriched in shale fragments from the Dakhla Shale. Sands of the Great Sand Sea are relatively homogeneous, quartz-rich deposits that vary little in percentage of minor components. Although these results are preliminary, they indicate the need for more detailed field investigations of the causes of color variations; such investigations are currently underway.

INTRODUCTION

Visual observations made by the astronauts of the Apollo-Soyuz Test Project (ASTP) indicated that the colors of desert surfaces varied consider-

ably from place to place (ref. 1). Both mapping- and handheld-camera photographs obtained on the same mission confirmed that these color variations abound on both regional and local scales. It was also shown that these color variations probably reflect compositional variations of the exposed surfaces (ref. 2). For these reasons, an investigation was planned to document the causes of color variations in sand deposits, which are an important component of desert surfaces.

The Western Desert of Egypt was selected for this study because (1) this desert was used as a test site for the investigation of variations in color as seen in ASTP photographs and (2) a team of Egyptian geologists served as team members of the ASTP Earth Observations and Photography Experiment and were able to plan and participate in the collection of field data.

This report must be considered as preliminary. The number of samples reported on here is only a fraction of the samples collected. Additional information is being gathered and analyzed by the research team members at Ain Shams University, Cairo, Egypt. This research is continuing under the auspices of a joint research project between Ain Shams University and the Smithsonian Institution.

GENERAL SETTING

The Western Desert of Egypt is a rocky platform of sandstones and limestones that is interrupted by seven major depressions and that is crossed by roughly north-south-trending parallel belts of sand dunes. The largest concentration of

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dunes occupies the west-central part of the desert and is known as the Great Sand Sea (fig. 1). The origin of all these sand accumulations is not well known.

The largest of the depressions, the Qattara, measures approximately 300 km in length and averages 70 km in width. The depression includes the lowest point in the African continent, 134 m below sea level (ref. 3). Other depressions are smaller, but they enclose the habitable Sîwa, Faiyûm, Bahariya, Farâfra, Dakhla, and Khârga Oases (fig. 1).

The highest areas in the Western Desert of Egypt are in its southwestern corner and include Gilf Kebîr Plateau and Oweinat Mountain. Most of this region is more than 1000 m above sea level. The central and southeastern parts of the desert vary from 200 to 500 m above sea level, and the northwestern and northern parts of the desert reach a maximum elevation of 200 m (ref. 3).

This setting indicates a gentle slope of the terrain from south to north. This northward tilt supports the theory that the sand deposits originated from southern Egypt and northern Sudan. The most likely source for the sand is the Nubian Sandstone Formation (fig. 1). In past wetter climates, fluvial transport by the Nile River and other drainage systems would have been responsible for carrying sand grains from south to north. Also, in addition to the existing Nile Delta, the ancestral delta of the Nile may have contributed much to the accumulation of fluvial sands in the area between the present Nile Delta and the Qattara Depression (fig. 1). (See section entitled "Detection of a Probable Ancestral Delta of the Nile River.") After the fluvial deposition of the sand grains in the north, the winds carried them back southward in the numerous dune belts.

FIELDWORK

The ASTP mission occurred in July 1975. Following a preliminary review of the data, field excursions were planned to check some of the photographic interpretations of studied areas in the Western Desert of Egypt. The senior author took part in four trips that were conducted in the

Western Desert. One trip was supported by the ASTP research project, and the rest were in part sponsored through the joint research program between Ain Shams University, Cairo, Egypt, and the Smithsonian Institution. A brief summary of these trips follows. (See fig. 2.)

Bahariya Oasis

The first field trip, conducted in April 1976, started at Cairo and followed the paved desert road to Bahariya Oasis and El-Gedida iron mines. The terrain from Cairo to Bahariya is basically a rocky desert plain with few prominences. Limestone rocks crop out approximately 90 km southwest of Cairo and continue to the Bahariya Depression. Any sand accumulations observed were predominantly sand shadows in the lee of limestone exposures.

The Qattara dunes are located midway between Cairo and Bahariya, and are composed of dune bundles that are very clearly exhibited on the ASTP photographs. In most cases, these bundles are composed of three to five longitudinal dunes that taper and converge at their southern termini (fig. 3). (See section entitled "Orbital Observations of Sand Distribution in the Western Desert of Egypt.")

Iron deposits abound in the Bahariya Oasis region and are mined at El-Gedida, where hematite occurs as a horizontal bed of considerable thickness (fig. 4). At El-Gedida and other areas in and around the Bahariya Depression, hematite and limonite are exposed on the surface. These occurrences are believed to be important because they provide a source of sand-size iron grains that are mixed with the sand in the Western Desert.

Sîwa Oasis

The field excursion to the Sîwa Oasis (fig. 2) was conducted in December 1976. Field checking of color zones seen in ASTP photographs was done on the 211-km-long desert road from Cairo to Alexandria. (See section entitled "Color Zoning in the Western Desert of Egypt.")

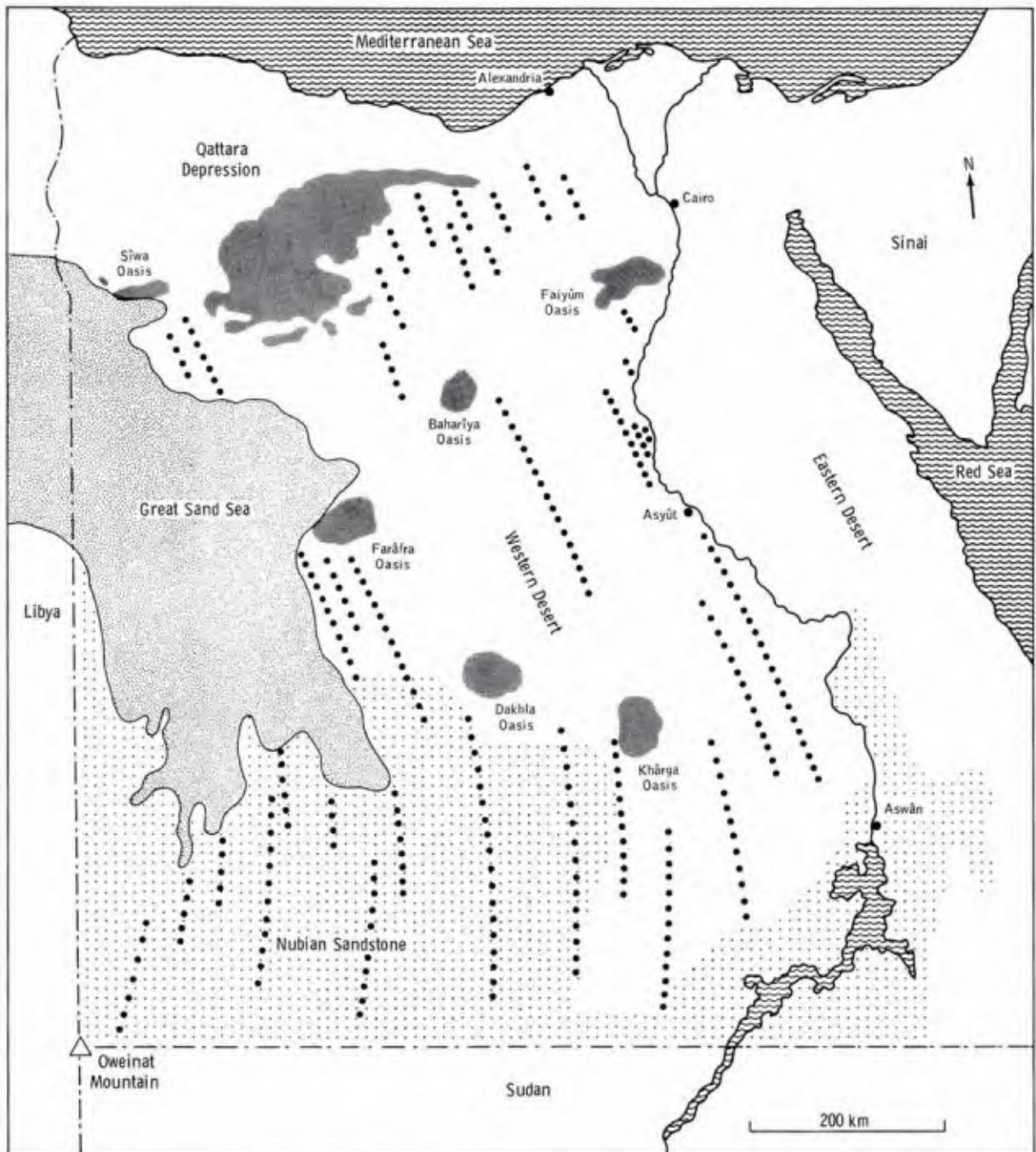


FIGURE 1.—Map of Egypt showing the distribution of depressions (dark areas) and sand dune belts (lines of dots) in the Western Desert. The Great Sand Sea occupies the west-central part of the desert. The Nubian Sandstone, the probable source of most of the sand, is exposed in the southern part of the desert.



FIGURE 2.—Mosaic of false-color Landsat images of Egypt showing color variations in the exposed rock and soil. The tracks of field excursions in the Western Desert are shown with solid lines. The dashed lines indicate the paths of visual observation overflights at 1 to 2 km altitude.

From Alexandria, the field team traveled along a 300-km-long coastal road to Mersa Matrûh, where the pavement ended. From this point, the drive followed a 300-km southwesterly track on unpaved road to Siwa Oasis. The exposed rock was mostly limestone of Oligocene, Miocene, and Pliocene age. The Miocene limestone, locally known as the Marmarica Formation, is characterized by a reddish or pinkish color, and is fossiliferous, sandy, and highly brecciated (fig. 5). This limestone may be represented in the sand samples discussed in this paper by reddish-brown, calcareous sand-size grains.

South and southwest of Siwa Oasis, the northern extremities of the Great Sand Sea were investigated (fig. 1). In this region, the dunes are noticeably smaller than those in the main part of the Great Sand Sea farther south. Unlike the longitudinal dunes photographed by ASTP crewmen in the southern part of the sand sea, the dunes near Siwa are sinuous and form short curving arcs (fig. 6(a)).

The sand color southwest of the Siwa region (fig. 6(a)) is light red. The reddish tint is made more distinctive by the gray color of the crystalline limestone that forms the rock exposures in the area (fig. 6(b)). However, the red color is not prevalent throughout. It appears to be most obvious on active sand surfaces, whereas inactive sand is lighter yellow in color (fig. 6(c) and 6(d)). This observation suggests the possibility of two different sources, although *in situ* reddening may also be important. The sands may have been of mixed origin to start with, or may have been dislodged from the rocky exposures in the area.

Following the investigation of the Siwa area and sampling of the northern part of the Great Sand Sea, desert landforms were studied from an airplane. A flight was made from Siwa 480 km eastward to Faiyûm Oasis and continued southward for approximately 260 km to Asyût (fig. 2). During this flight, the nature of the Qattara dune belts was studied in addition to the sand dunes of the Faiyûm area. Also, it was noticed that sand dunes were encroaching on farmland along the



FIGURE 3.—ASTP photograph of longitudinal dune belts in the Qattara region. The southern tips of the dunes are migrating toward the Cairo-Bahariya Road (AST-16-1254).

western boundary of the Nile Valley from Faiyûm to Asyût (ref. 4). This encroachment is dangerous to the economy of Egypt, a country where the farmland constitutes less than 4 percent of the total area.

Khârga and Dakhla Oases

A preliminary survey of Khârga and Dakhla Depressions was conducted in April 1977. After a flight from Cairo to Khârga, the field investigation was begun.

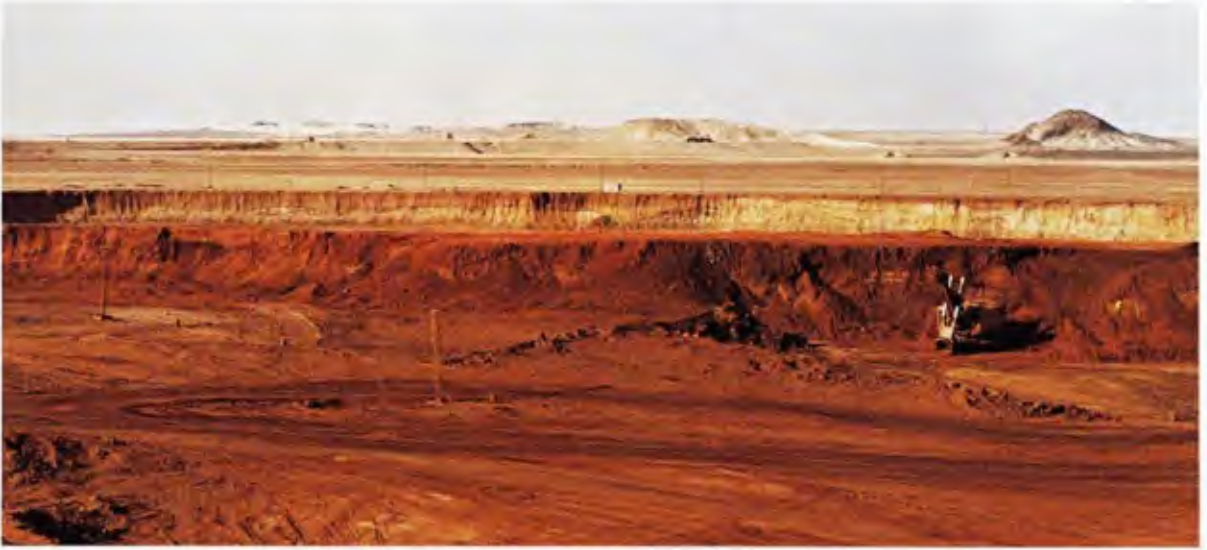


FIGURE 4.—View of the El-Gedida iron mine in the Bahariya Depression. Note that the red iron ore (hematite) occurs near the surface.

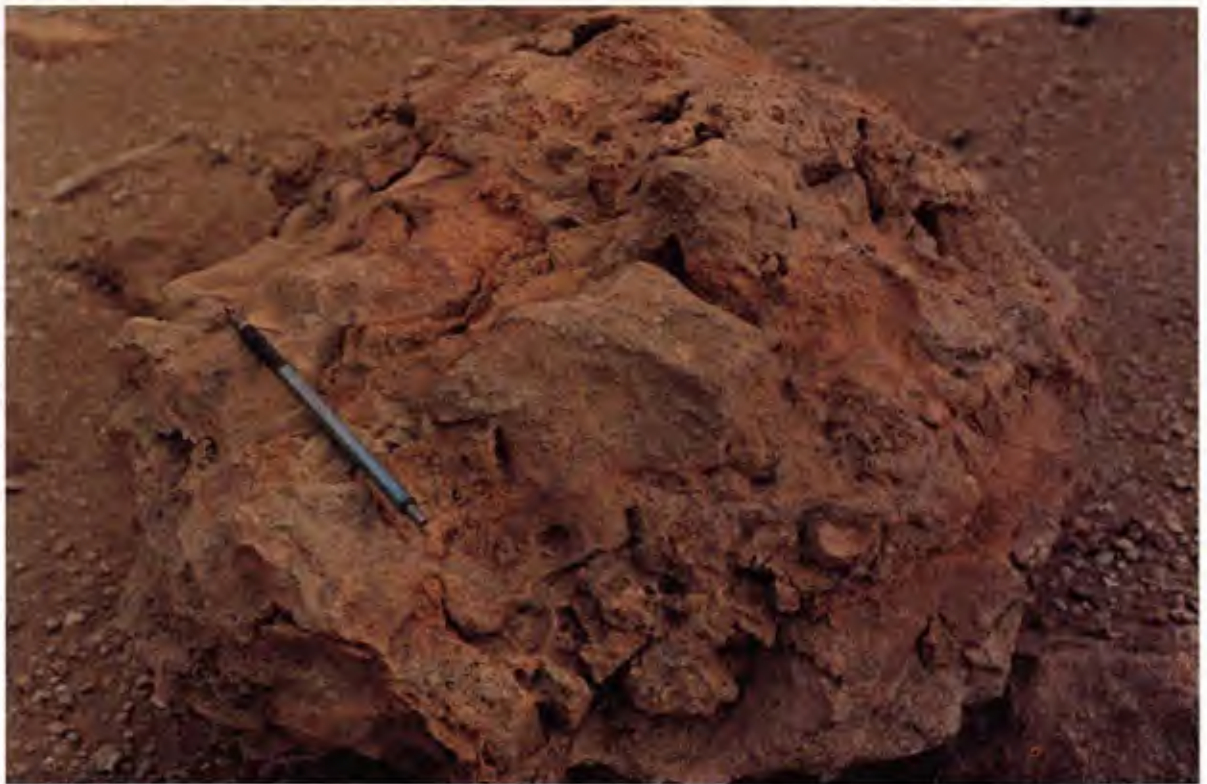


FIGURE 5.—An exposure of the pink-colored, concretionary, and argillaceous limestone north of Siwa Oasis. Pencil at left center is 13 cm long.



FIGURE 6.—Sand color at the northern edge of the Great Sand Sea. (a) A cluster of sinuous dunes as seen from a hill west-southwest of Sîwa Oasis. (b) Reddish sand ripples around a dark-gray, crystalline limestone block. (c) The windward side of a dune that occurs on a limestone hill, approximately 20 m high. (d) The crest of the same dune showing reddish sand on the windward (right) side and a mixture of red and gray sand on the leeward (left) side. The mixing of the two colors is apparently caused by crosswinds on the leeward side, which form several intersecting ripples on the dune surface.

From Khârga, the field party drove north-northeast along a paved road, which was elevated in many places to block advancing dunes. Here, encroachment is so severe that new telephone poles had to be attached to the original ones. Pleistocene lacustrine deposits occur to the north where the road becomes level with the desert surface. These outcrops are consistently streamlined by wind erosion and are parallel in a north-south direction. Sand tails on the leeward side of most of these outcrops range in height from less than 0.3 m to 1.5 m. These forms are small-scale analogs of yardangs streamlined by the action of wind. The last stop north of Khârga was at an enormous compound barchan. The degree of com-

paction varies significantly from the base to the crest of this dune. Near the base of the dune, the sand was hard and closely packed, but in other places, our feet sank several centimeters into the sand. The desert surface in this area is characterized by low and widely spaced sand ridges and by a desert pavement of coarse rounded pebbles and stones.

The trip continued west along the Ghabari Road from Khârga to Dakhla. Just west of Khârga, there is a field of crescent-shaped barchans. The first barchan, 1.3 km west of Khârga, had completely blocked the road so that a bypass road had to be constructed behind the dune. Barchans are the dominant form of dunes

within 20 km west of Khârga and frequently obstruct passage.

On aerial mosaics, the barchan belt west of Khârga is easily identified. The belt widens to the south, and the eastern side of the dune field is remarkably linear. Sand from the field appears to be derived from the plateau north of the scarp bounding the depression. These dunes are probably a continuation of the Abu Muharik dune field. The northern scarp is characterized by a number of parallel, linear wadis filled with sand. A number of barchan chains emanate from these wadis and continue to migrate southward. Fracture patterns in this area are generally east-west and north-south, and the prevailing wind direction is north-south. Therefore, it appears that in the Khârga area, fault and lineament trends control the distribution of sand.

Great Sand Sea

A field excursion was organized in December 1977 to investigate and sample the central part of the Great Sand Sea and to perform detailed studies in areas that were previously visited. This trip included visits to six oases in the Western Desert. It started in Cairo along the desert road to Faiyûm Oasis and then proceeded southward along the Nile Valley to Asyût.

From Asyût, a paved desert road was followed to Khârga Oasis and travel continued farther south on an unpaved road to Bâris Oasis. The route then followed a westerly direction to Dakhla Oasis and from there to the eastern borders of the Great Sand Sea. From that point, the road followed a northeasterly trend through rugged desert terrain and numerous sand deposits toward Bahariya Oasis, and back to Cairo (fig. 2). Upon return, the odometers on the desert jeeps had registered nearly 3000 km.

The investigation of sand color on this trip included comparisons made with the ASTP color wheel. (See section entitled "Comparison of Astronaut Visual Color Observations With ASTP Photographs.") Wherever sand samples were collected, the color of sand was compared to the numbered color chips. In most instances, the color of the active face of a given dune was redder than the slip face (fig. 7).

SAMPLE ANALYSIS

Methods

Both grain size and lithologic components of 31 samples from the Western Desert of Egypt (fig. 8) and of 1 sample from the United Arab Emirates were analyzed. To more fully understand the color variations seen in ASTP photographs, these colors were compared to field and laboratory observations of sand color and texture. The bulk samples collected varied in weight from 61 to 617 g and averaged 305 g. Samples were split into two halves, and one half was sieved for 15 minutes on a Ro-Tap using standard mesh sieves at 0.25 ϕ intervals. After sieving, each size fraction was weighed and recorded. Sediment size-frequency, cumulative-arithmetic (fig. 9), and cumulative-probability curves were plotted for each sample (ref. 5). The analysis of grain composition consisted of examining the second half of the bulk sample under a binocular microscope. In addition to the observation of physical characteristics using the binocular microscope, elemental analyses of randomly selected grains were performed with a scanning electron microscope (SEM). The SEM has an energy dispersive system equipped with a silicon-lithium detector and a multichannel analyzer, which includes a display calibrated for elements of atomic numbers 11 to 32. As a result, it was possible to perform elemental analyses of various grains and of specific areas or points on the grains. Individual grains were identified according to the following scheme, and visual estimates were made of the component percentages of each sample.

Classification Criteria

For this analysis, the components of the sand samples were grouped under the following classification: quartz, reddish-brown calcareous grains, shale, white calcareous grains (dolomitic limestone(?)), heavy minerals (glaucinite, phosphates, and hornblende(?)), ferruginous grains (nodules, limonitic grains, and ferruginous sandstone grains), chalk, marl, gypsum, and calcite. The following criteria were used for identification of the components under the binocular

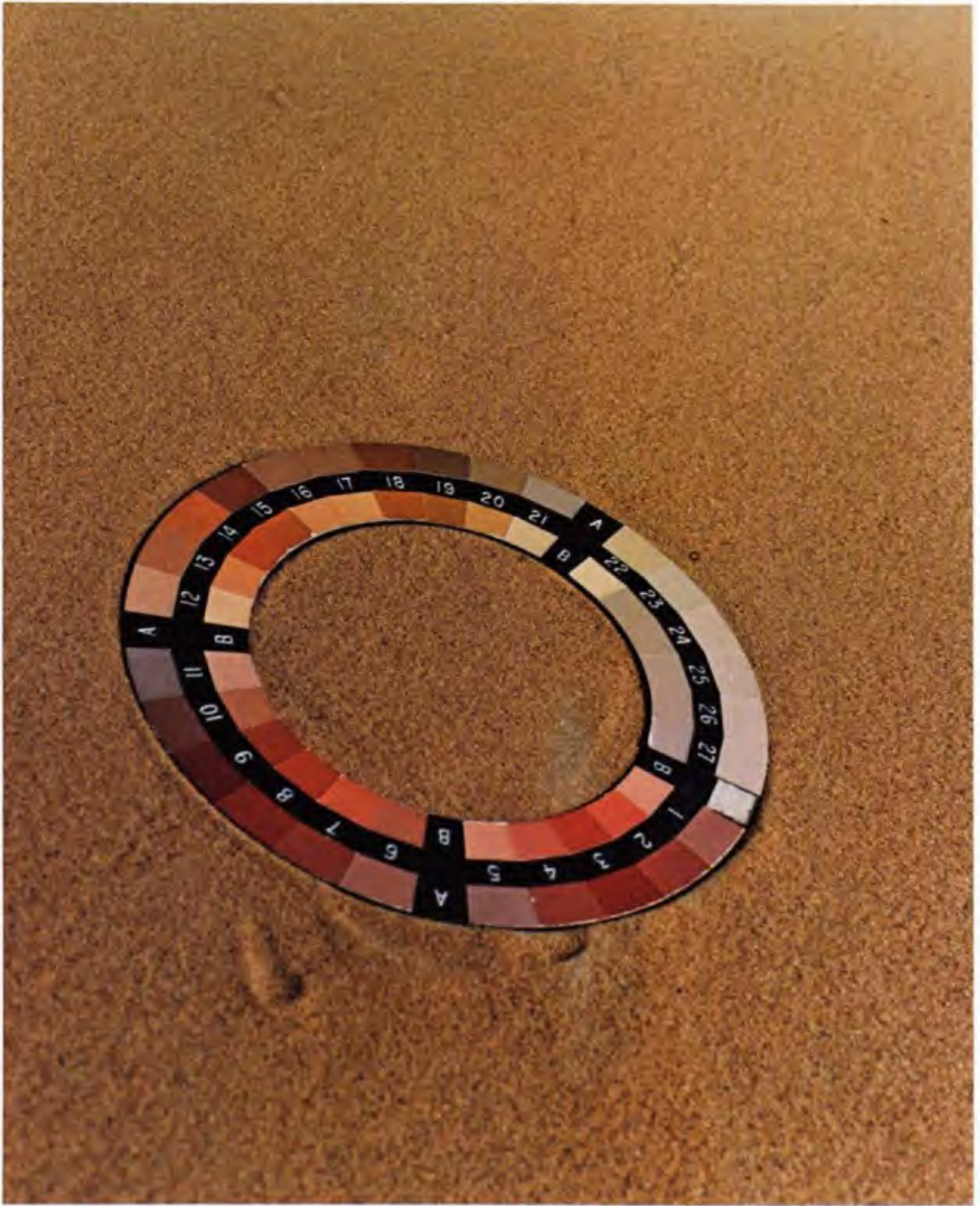


FIGURE 7.—The color wheel used by the ASTP astronauts in orbit is shown near the crest of a dune. The near field is part of the redder, windward side of the dune.

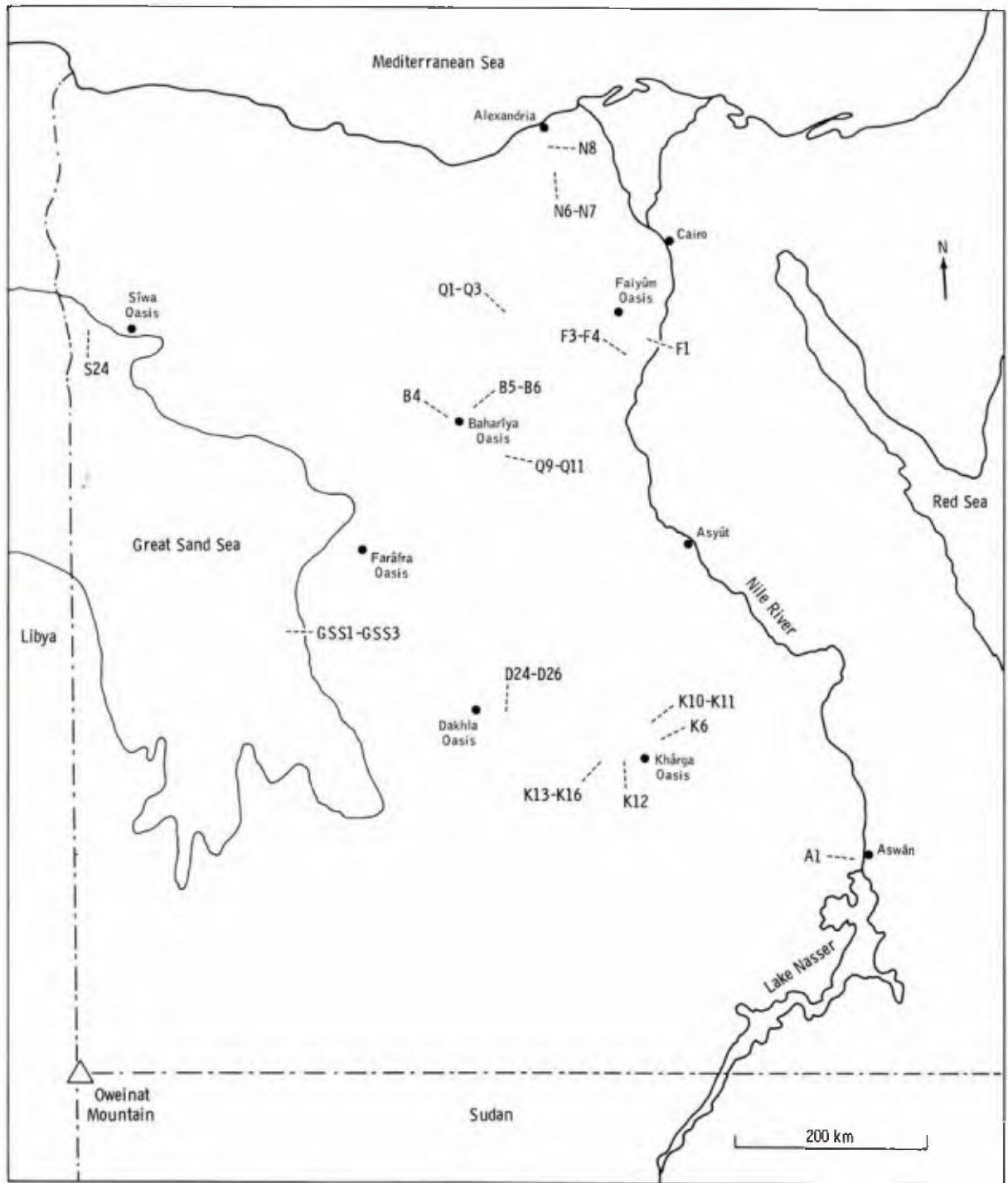


FIGURE 8.—Location of numbered sand samples collected by the senior author on four field trips.

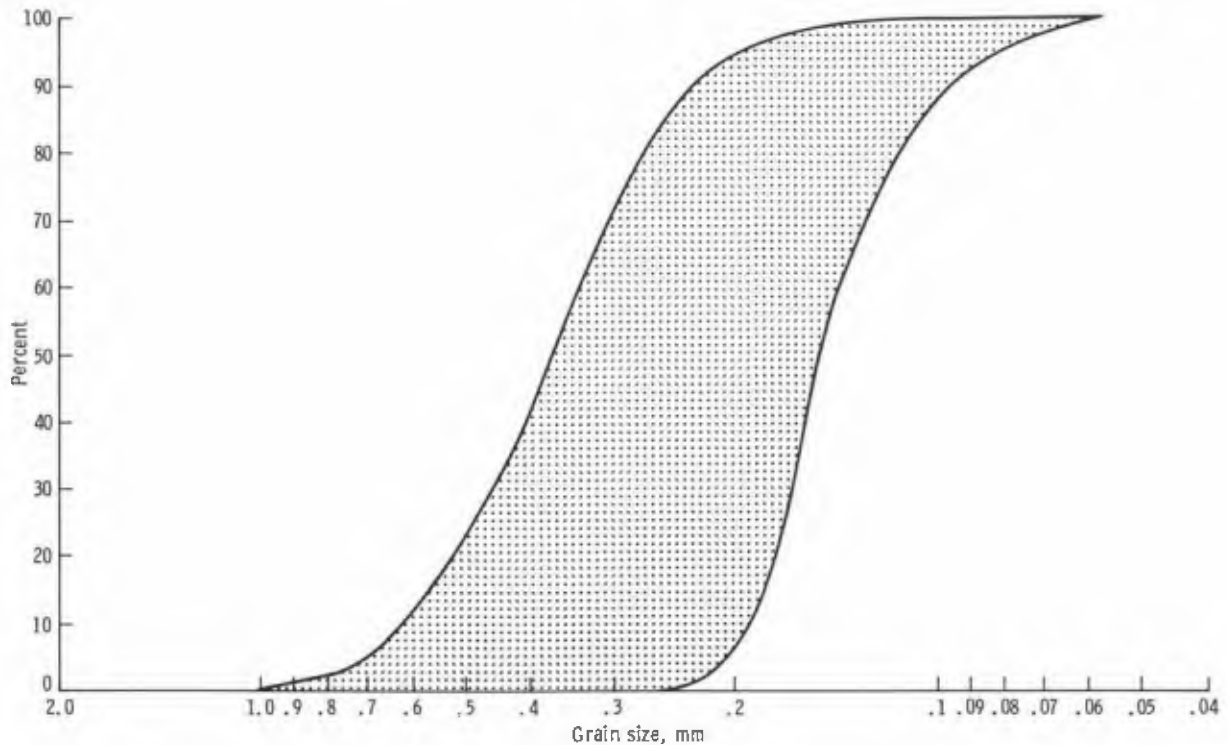


FIGURE 9.—Cumulative size frequency distribution representative of sand samples from the Western Desert. As shown by the steepness of the bounding curves, most samples are well to moderately well sorted.

microscope, supplemented by SEM analysis where noted.

1. *Quartz* was identified by glossy luster, translucence or transparency, lack of cleavage, conchoidal fracture, lack of color, frequent frosting and yellowing, and great hardness.

2. *Reddish-brown calcareous grains* were identified by reddish-brown color, very low hardness, minor crystallinity, and translucence. Supplemental SEM analysis indicates similar composition to white calcareous grains. These two sets of grains vary mainly in color.

3. *Shale* was identified by fissility and very low hardness, and by comparison with grains derived from an Esna Shale rock fragment, collected near Luxor.

4. *White calcareous grains* were identified by white color, very low hardness, minor crystallinity, and translucence, and by SEM analysis.

5. *Heavy minerals*

a. *Glauconite* was identified by high

sphericity, bright- to dark-green color, very low hardness, and high polish, and by SEM analysis.

b. *Phosphates* were identified by comparison of the irregular habit, black color, and interior appearance of the grains with grains derived from a phosphate rock collected from a scarp midway between Dakhla and Kharga Oases.

c. *Hornblende(?)* was identified by SEM analysis.

6. *Ferruginous grains (nodules, limonitic grains, and ferruginous sandstone grains)* were identified by rounded habit and dark reddish-brown or orange color. The ferruginous sandstone grains are aggregates composed of fine angular quartz grains within an iron oxide matrix.

7. *Chalk* was identified by snow-white color and low hardness, and by SEM analysis; soft non-crystalline chalk and microcrystalline limestone have been included under this classification.

8. *Marl* was identified by brown to gray color, low hardness, calcareous composition, and lack of crystallinity. These grains are often composed of

very loosely compacted silt- and clay-size fragments.

9. *Gypsum* was identified by snow-white color and extremely low hardness, by SEM analysis, and by visual comparison with a gypsum and clayey rock fragment collected at Sîwa Oasis.

10. *Calcite grains* were identified by rhombohedral cleavage, lack of color, vitreous luster, and low hardness.

SAMPLE CHARACTERISTICS

Texture and Composition

The mean grain size of most samples falls in the range of fine sand, and the size distribution for all samples is summarized in figure 9. As would be expected from these wind-deposited sands, most samples are well to moderately well sorted, and they generally contain less than 1 percent (by weight) silt and clay.

Because of the survey nature of this study, many local environments were sampled, and textural characteristics for individual samples are shown in table I. Preliminary analyses indicate some dependence on local environment; the crests and windward sides of barchans generally contain coarser grains, although there is no apparent difference in grain size on either side of longitudinal dunes.

Although most samples are composed of more than 50 percent quartz grains, the amount and type of other fragments is the result of local material. Samples from Bahariya, Kharga, and Dakhla Oases contain the largest amounts of local components, consisting of white and reddish-brown calcareous grains and shale. Because the individual sampling sites exert the greatest influence on components other than quartz, representative samples of exposed bedrock are used for comparison with sand samples.

The surface texture of individual grains is predominantly a function of lithology (fig. 10). As determined from high magnification (fig. 10(a)), quartz grains larger than 0.20 mm diameter are well rounded and have frosted surfaces. Iron oxides occur both within fractures of quartz grains and in protected hollows on the grain surfaces.

FIGURE 10.—Photomicrographs of sand grains of various compositions and shapes. (a) Quartz grain with frosted surface; light areas in pits on the surface (A and B) are hematite. (b) High magnification of area A showing minor crystallinity of iron oxides. (c) X-ray fluorescence spectrum of area B; highest peak is located at the iron (Fe) energy level. Other peaks are silicon (Si) and calcium (Ca). (d) Example of angular quartz grains which occur predominantly at smaller grain sizes. (e) Highly spherical glauconite grain. (f) Fissile shale grain. (g) Chalk grain. (h) Marl grain. →

Sample Locations

Because of the regional distribution pattern of the sand deposits, the localities are divided into three parts: (1) the northern region of the Western Desert, including the area west of the Nile Valley (Wâdi el Natrûn), the Qattara dunes, and dunes southwest of the Faiyûm Oasis; (2) the central region, which includes the oases of Bahariya, Kharga, and Dakhla; and (3) the Great Sand Sea, including samples obtained south of Sîwa Oasis and southwest of Farâfra Oasis. Comparisons are made between the samples of the Great Sand Sea with those collected near Aswân in southern Egypt and from the eastern part of Ar Rub' al Khâlî dunes in the United Arab Emirates.

Northern Region

Wâdi el Natrûn.—Samples at Wâdi el Natrûn were taken from a sand sheet that shows a bright pinkish-yellow color with a reddish tint on ASTP photographs (ref. 2). Samples N6 and N7 were taken from the same dune; sample N6 was collected from the more active, windward side, and sample N7 from the slip face.¹ Sample N8 was located in the color zone that appears as a dusty pinkish-gray area with mottled texture in ASTP photographs. (See section entitled "Color Zoning in the Western Desert of Egypt.") Field observations of this zone suggest that it has more clay and carbonate particles than the dune from which samples N6 and N7 were taken.

¹Sample numbers are referred to throughout the text, and locations are indicated in figure 8.

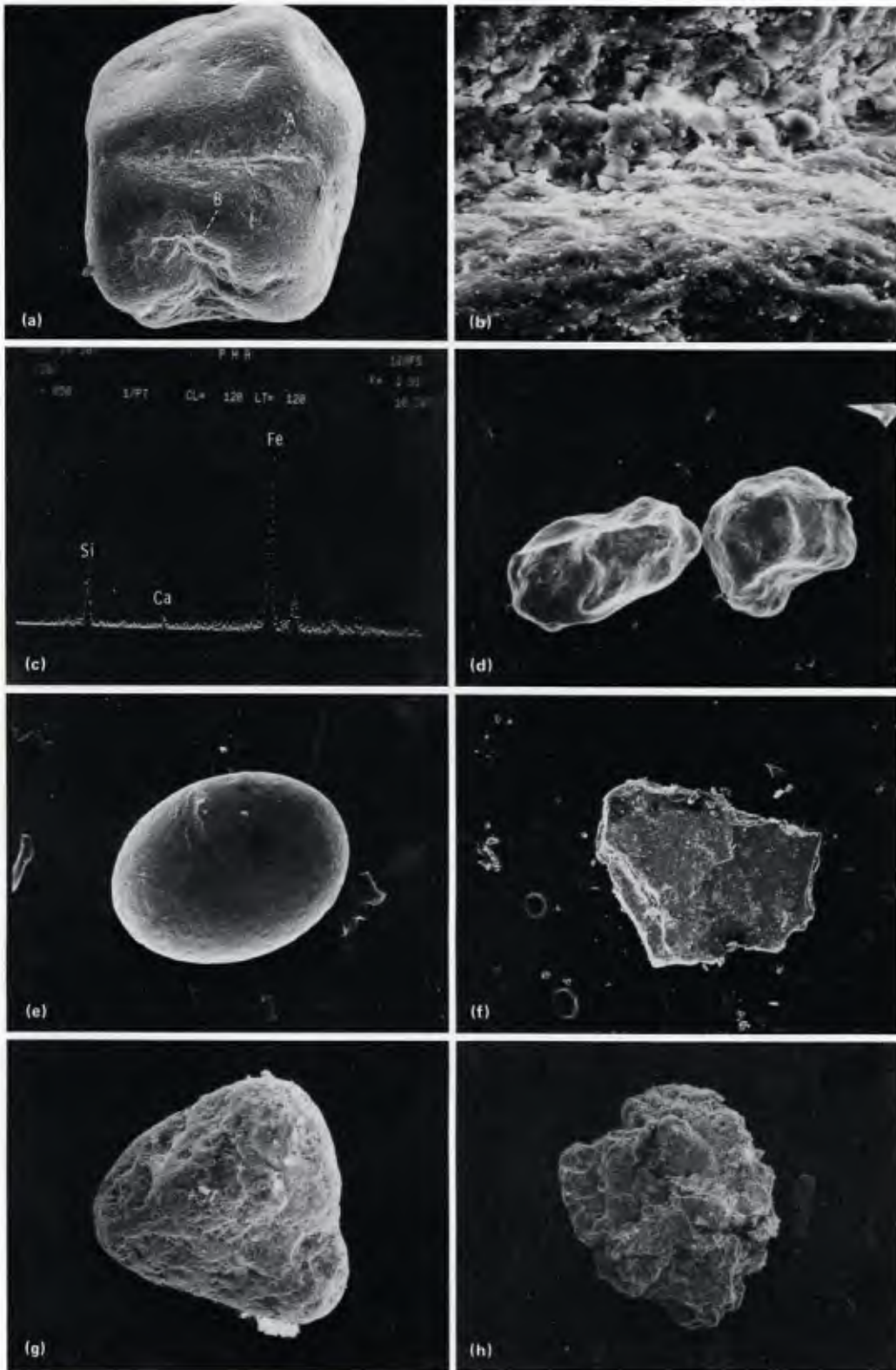


TABLE I.—Summary of Size Analysis Data From Sediment Samples^a

Sample number	Environment	Mean grain Size ^b Mz, ϕ (mm)	Weight % silt and clay (< 4.0 ϕ)	Sorting ^c σ_1 , ϕ	Skewness, ^d SK ₁	Kurtosis, ^e K _G	Munsell color ^f
<i>Wâdi El Natrîn</i>							
N6	Windward side of dune	1.70 (0.32) ^g	1.79	(h)	(h)	(h)	10YR 6/6
N7	Slip face of dune	.40 (.75) ^g	8.27	(h)	(h)	(h)	10YR 6/6
N8	Sand sheet	2.60 (.17) ^g	25.68	(h)	(h)	(h)	10YR 6/4
<i>Qattara dunes</i>							
Q1	Lee side of sand dome	2.30 (0.21)	0.72	0.47	+0.30	1.12	2.5Y 7/6
Q2	Windward side of sand dome	1.86 (.28)	.05	.55	-.13	1.43	2.5Y 7/6
Q3	Lee side of barchan	2.23 (.22)	1.23	.48	+20	1.16	2.5Y 7/6
Q9	Base of longitudinal dune	2.06 (.24)	.19	.85	+07	.93	2.5Y 7/4
Q10	Sinuuous segment of longitudinal dune	1.18 (.44)	.01	.57	+32	1.31	10YR 7/6
Q11	Crest of longitudinal dune	1.78 (.30)	.41	.56	+81	.58	2.5Y 7/4
<i>Faiyûm Oasis</i>							
F1	Sand sheet	0.39 (0.78)	0.84	0.56	+0.62	2.94	2.5Y 7/4
F3	Crest of dune	1.89 (.28)	.84	.56	+46	1.54	2.5Y 7/4
F4	Slope of dune	1.80 (.29)	1.16	.54	+53	1.45	2.5Y 6/4
<i>Bahariya Oasis</i>							
B4	Crescentic dune	2.57 (0.17)	0.21	0.43	+0.15	0.87	2.5Y 7/4
B5	Crescentic dune	2.17 (.22)	.18	.42	+24	1.98	2.5Y 7/6
B6	Crescentic dune	1.87 (.28)	.04	.43	+29	1.36	2.5Y 7/6

^aEquations for size relationships are from Folk (ref. 5).

^bGraphic mean grain size: $Mz = (\phi_{16} + \phi_{50} + \phi_{84})/3$

^cInclusive graphic standard deviation: $\sigma_1 = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$

^dInclusive graphic skewness: $SK_1 = \frac{\phi_{16} + \phi_{84} - 2(\phi_{50})}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2(\phi_{50})}{2(\phi_{95} - \phi_5)}$

^eGraphic kurtosis: $K_G = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})}$

^fColor of bulk sample from comparison with Munsell color chart (ref. 6).

^gMedian grain size (ϕ_{50}) only.

^hSmall sample size did not allow more detailed analysis.

TABLE I.—Concluded

Sample number	Environment	Mean grain Size ^b Mz, ϕ (mm)	Weight % silt and clay (< 4.0 ϕ)	Sorting ^c σ_1 , ϕ	Skewness, ^d SK ₁	Kurtosis, ^e K _G	Munsell color ^f
<i>Khârga Oasis</i>							
K6	Lee side of dune	2.51 (0.18)	1.57	0.67	+0.01	0.94	10YR 6/4
K10	Compound barchan	2.22 (.22)	.35	.77	+1.2	.80	10YR 6/6
K11	Compound barchan	2.20 (.22)	.41	.76	+2.5	.75	10YR 6/6
K12	Base of barchan	2.54 (.18)	.67	.56	-.04	.72	10YR 6/6
K13	Lee side of barchan	2.03 (.25)	.39	.77	-.01	.78	10YR 6/6
K14	Crest of arm of barchan	2.73 (.15)	.07	.28	+1.3	1.06	10YR 6/4
K15	Crest of barchan	2.71 (.15)	.18	.34	+0.1	1.02	10YR 6/4
K16	Windward base of barchan	1.54 (.35)	.08	.74	+1.6	.94	10YR 6/6
<i>Dakhla Oasis</i>							
D24	Base of barchan	2.50 (0.18)	1.11	0.83	-0.34	1.00	10YR 6/4
D25	Surface of barchan (dark sand streaks)	1.46 (.37)	.12	.53	+0.7	1.10	10YR 6/4
D26	Barchan (predominant color)	1.71 (.31)	.09	.48	+0.7	1.04	10YR 6/6
<i>Sîwa Oasis</i>							
S24	Base of windward side of dune	0.70 (0.64)	<0.01	0.81	+0.75	1.38	10YR 6/6
<i>Great Sand Sea</i>							
GSS1	Base of sinuous longitudinal dune	0.74 (0.60)	<0.01	0.45	+0.23	1.02	10YR 6/6
GSS2	Arm of sinuous longitudinal dune	1.82 (.29)	.11	.61	+0.4	.99	10YR 6/6
GSS3	Crest of sinuous longitudinal dune	1.91 (.27)	.97	.39	+1.4	1.33	10YR 6/6
<i>Aswân</i>							
A1	Sand sheet at base of cliff	1.56 (0.35)	3.32	0.77	+0.39	1.54	10YR 6/6
<i>Ar Rub' al Khâir</i>							
UAE1	Red sands at terminus of dune	2.61 (0.16) ^B	0.25	0.39	+0.07	0.91	7.5YR 5/6

Samples N6 and N7 are fairly clean sand. Similar to most of the other samples, N6 consists predominantly of quartz with minor amounts of white calcareous grains, reddish-brown calcareous grains, ferruginous grains (nodules and limonitic grains) and heavy minerals (fig. 11). The heavy minerals in all three samples have been tentatively identified as hornblende. Sample N7 differs from N6 in that it contains more heavy minerals, no calcareous grains, and fewer limonitic grains. The composition of these two samples is a direct result of the local environment, since the leeward side is better sorted compositionally and has a finer mean grain size than the windward side.

Field observations of the color zone from which sample N8 was taken are well substantiated by analysis of the sample. It differs from samples N6 and N7 by containing a higher percentage of calcareous marl grains, minor amounts of gypsum, chalk, and calcite(?) grains, and one or two fossils. In addition, this sample contains the largest amount (25 percent) of silt- and clay-size particles. The composition of this sample is likely influenced by local outcrops, particularly the "small hillocks of marly composition" that appear in this zone. (See section entitled "Color Zoning in the Western Desert of Egypt.")

Qattara dunes.—The Qattara dunes are three parallel belts of longitudinal dunes that cross the rocky, dark-colored desert platform southwest of the Nile Delta (figs. 1 and 2). The tips of some of these dunes have approached the Cairo-Bahariya Road and have even started blocking it (fig. 3). The southern termini of these dunes are characterized by numerous complex crescentic or sinuous dunes.

The southernmost tip is usually characterized by a gently sloping sand dome that is perfectly symmetrical (fig. 12). A clear color difference exists between the windward and the leeward sides of the dome and the crescentic dunes. The windward, more active side appears redder, whereas the leeward side is usually more gray in color.

The southern tip of the dune complex illustrated in figure 12 was sampled to see how much compositional variation exists in the sands at the terminal part of the dune, where mixing with

materials from the surrounding terrain is at its maximum. Sample Q1 was taken from the leeward side of the sand dome, Q2 from the windward side of the same dome, and Q3 from the leeward side of the first barchanlike dune at the tip of the complex. The samples from the leeward sides of both the dome and the barchan are finer grained and contain more silt and clay than the sample from the windward side. However, there is no difference in bulk sample color between the leeward and windward sides. This discrepancy between field and laboratory color designation is not unexpected because samples are from the upper few centimeters, whereas the field color differences are due to a thin veneer of surface sand.

Samples Q1, Q2, and Q3 contain many different components (fig. 11). Sample Q1 consists predominantly of quartz and white calcareous grains, lesser amounts of reddish-brown calcareous grains, heavy minerals (glauconite and hornblende(?)), and ferruginous grains (nodules, limonitic grains, ferruginous sandstone), and contains very low amounts of chalk, marl, and shale.

The composition of sample Q2 is very similar to that of Q1; the ratios of the components of both samples are approximately the same. However, sample Q2 does not contain any shale or marl and has fewer ferruginous grains. Sample Q3 contains less quartz, more white and reddish-brown calcareous grains, and more heavy minerals than do samples Q1 and Q2. This sample also does not include shale or marl in its composition.

These three samples, however, are not characteristic of the longitudinal dunes of the Qattara dune bundles. One of these, known as Ghard Abu Muharik, extends from east of Bahariya Oasis in the north to the Kharga Depression in the south. Three samples were collected from its northern part: Q9 from the base of the dune, Q10 from the leeward side of a sinuous dune segment, and Q11 from the crest of the dune.

Samples Q9, Q10, and Q11 contain fairly high percentages of quartz, particularly Q9 and Q10 (fig. 11). Sample Q9 includes minor amounts of white calcareous grains, heavy minerals (glauconite), chalk, ferruginous grains, marl, and

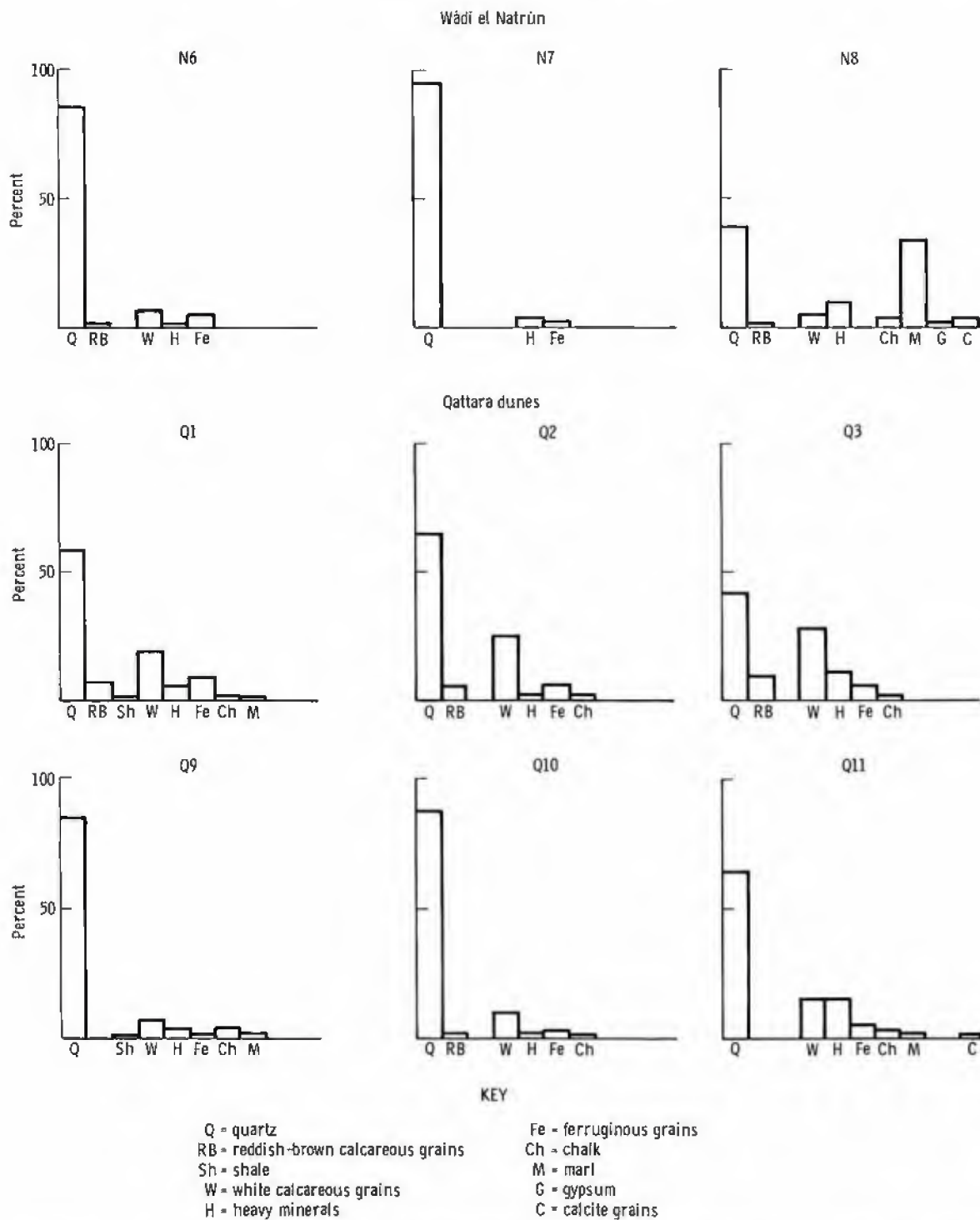
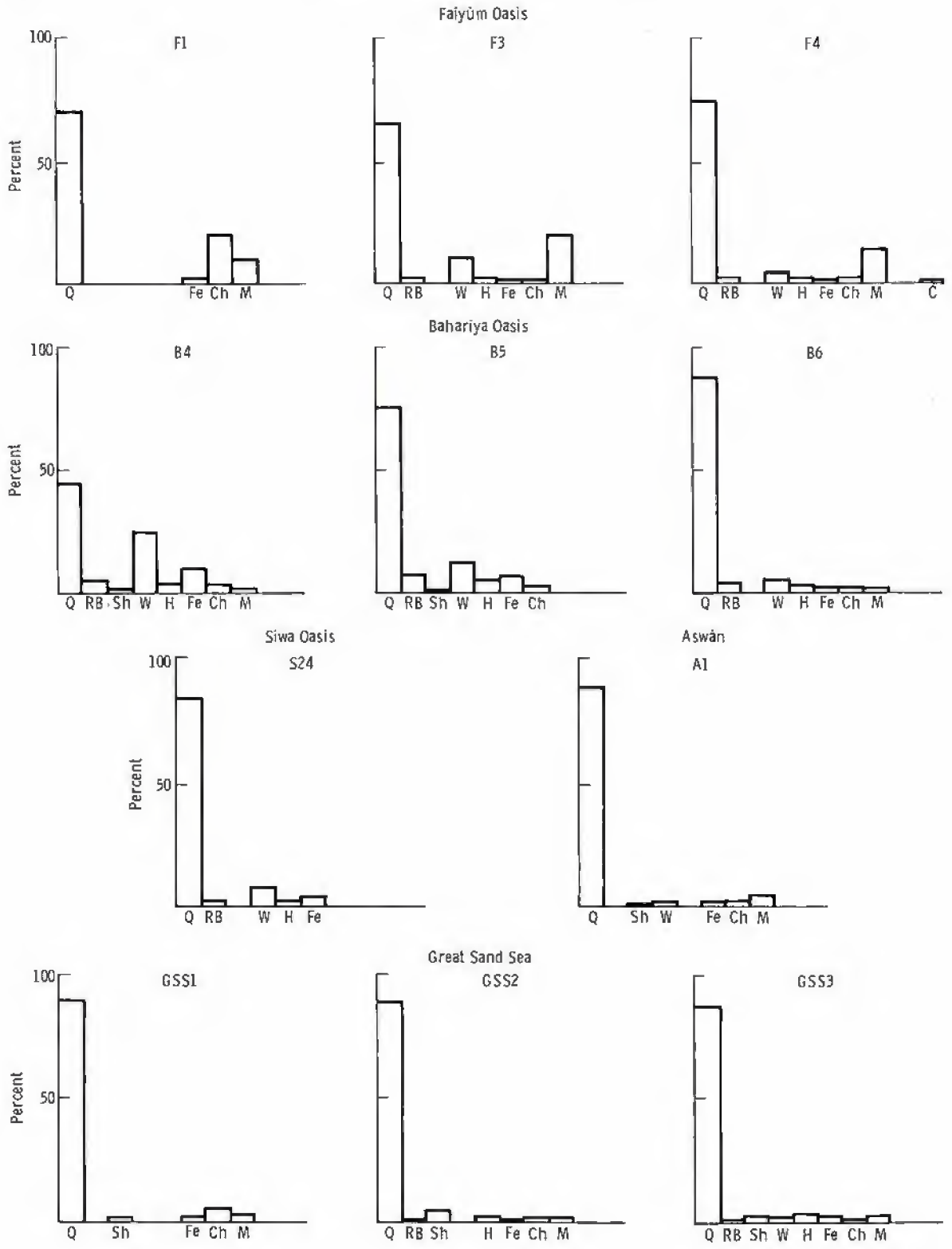
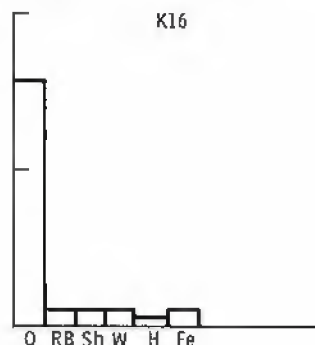
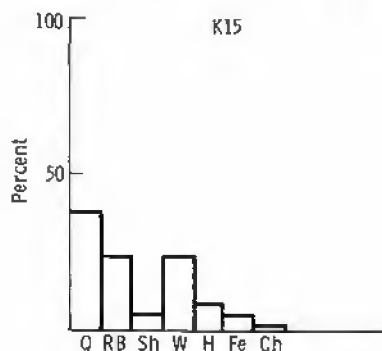
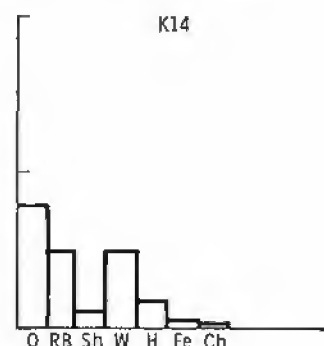
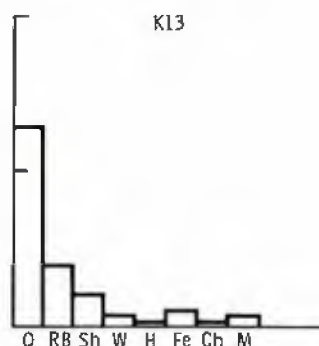
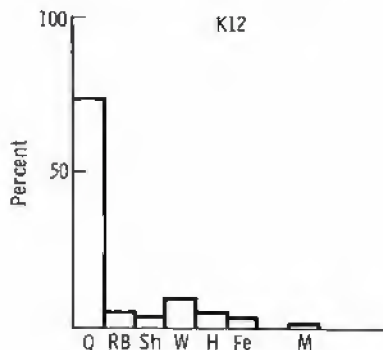
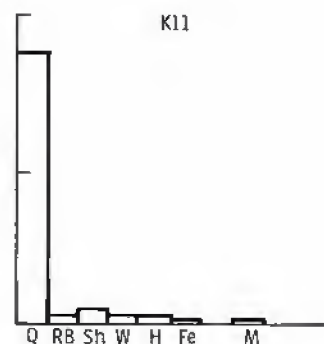
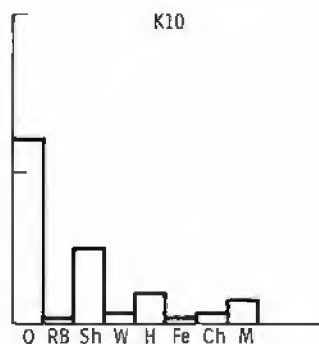
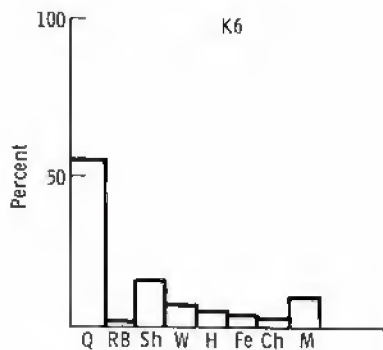


FIGURE 11.—Lithologic frequency histograms indicating visual estimates of individual components in the bulk sand samples. (Continued on following pages.)



Khârga Oasis



Dakhia Oasis

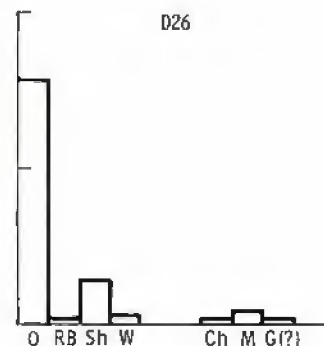
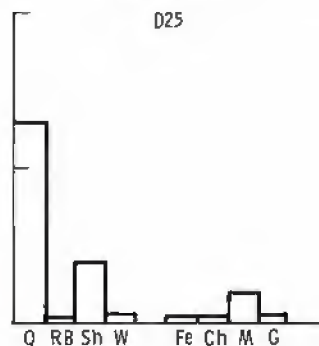
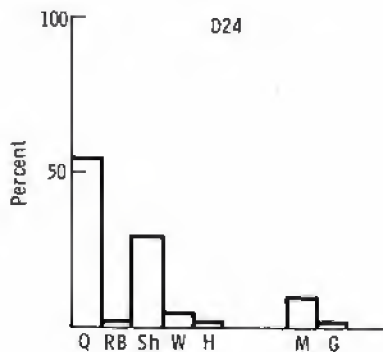




FIGURE 12.—View looking north from the southern tip of the longitudinal dunes photographed by the ASTP astronauts (fig. 3). The foreground of the photograph is occupied by a sand dome; dunes behind this dome are crescentic or complex barchan forms. The dark areas are covered by desert-varnished limestone and chert pebbles.

reddish-brown and green calcareous shale, which could possibly be traced to the variegated shales of El-Hefhuf and Bahariya Sandstone formations in Bahariya Oasis to the north (ref. 3).

Sample Q10 is fairly similar to Q9 in composition, differing mainly in the lack of shale and marl and in the addition of a very minor quantity of reddish-brown calcareous grains. Sample Q10 also contains slightly more white calcareous grains and one or two ferruginous basaltic grains, possibly derived from the dolerite intrusions of Bahariya Oasis (ref. 3).

Sample Q11 differs from both samples Q9 and Q10 by containing higher percentages of white calcareous grains and heavy minerals (mostly glauconite), a lower percentage of quartz, and approximately twice as many ferruginous grains (nodules, limonitic grains, and ferruginous sandstone). This sample also does not contain any reddish-brown calcareous grains or shale, but does include a few calcite grains.

The percentage of white calcareous grains increases from a low value in sample Q9 to a high value in sample Q11.

Faiyûm Oasis.—Sand accumulations abound south of the Faiyûm Oasis. There are two different types of deposits: sand sheets with gentle swells and longitudinal dunes at the beginning of the Wâdi el Ruwayân belt. Sample F1 was taken from a sand sheet that is grayish-yellow (21A on the color wheel (i.e., see section entitled "Comparison of Astronaut Visual Color Observations With ASTP Photographs"), or Munsell 10YR 7/4 (ref. 6)). The color observed in the field differs from that of the sample (see table 1) because the field observation did not include deeper layers of sand.

Two other samples were collected from the sand of the northern part of the Wâdi el Ruwayân dunes. These dunes are enclosed by scarps made primarily of light-colored limestone with marly and chalky intercalations. Sample F3 was taken

from a dune crest and sample F4 from the slope of the same longitudinal dune. As expected from the rapidly shifting leeward and windward sides of a longitudinal dune, both crest and slope have approximately the same mean grain size and cannot be distinguished on the basis of textural characteristics. They also have almost identical compositions, as illustrated by samples F3 and F4, where the only major difference is the appearance of calcite grains in sample F4 (fig. 11). Both samples contain fairly high percentages of marl, presumably derived from the scarps enclosing the dunes.

Sample F1 also contains a high percentage of locally derived chalk as well as marl. Unlike samples F3 and F4, however, it does not contain any white or reddish-brown calcareous grains or heavy minerals. Basalt grains do appear in sample F1, however; they are probably derived from basalt dikes north of Faiyûm (ref. 3).

Central Region

Baharîya Oasis.—Numerous dunes occur within the Baharîya Depression. Because of human activity, many of the dunes have lost their original forms and have become either complex or subdued in shape. One sample (B4) was collected 8 km north of the village of El Bawîti and additional samples were taken 34 km (B5) and 37 km (B6) north of the village. Dune sand from which samples B5 and B6 were obtained appeared similar in both localities, although both sands were lighter in color than the sand from which sample B4 was taken. Based on the mechanical analyses, there is no difference in size characteristics among all three samples. Visual estimations of the bulk sample colors, however, do not support the field observations; sample B4 is lighter in color than either B5 or B6.

In the analysis, these three samples were found to vary considerably from each other (fig. 11). Sample B4 contains the lowest percentage of quartz and the highest percentages of ferruginous grains (nodules and ferruginous sandstone), white calcareous grains, and chalk. This sample also includes smaller amounts of heavy minerals (glauconite and hornblende(?)), shale, marl, and reddish-brown calcareous grains. The iron ore of

Baharîya is very apparent in this sample as the probable source of the large percentage of ferruginous grains.

Sample B5 differs from sample B4 by containing more quartz, fewer white calcareous grains, and slightly fewer ferruginous grains and chalk. It does not include any marl. However, the two samples do contain approximately the same amount of grains tentatively identified as hornblende.

Sample B6 includes in its composition the highest percentage of quartz of the three samples and the lowest percentages of white calcareous grains, ferruginous grains, and heavy minerals. It also contains a very small amount of hornblende(?) and marl.

Khârga Oasis.—The Khârga Depression is elongate in a north-south direction and measures approximately 180 km in length. The habitable areas in the depression lie along a major fault (ref. 3), which is believed to have aided in bringing underground water closer to the surface.

The large longitudinal dunes that cross the limestone plateau north of Khârga divide into smaller dunes as they descend the northern scarp of the depression. These smaller dunes are usually barchans, although some longitudinal forms develop farther to the south.

At the road marker 218 km from Asyût, a large abandoned building is responsible for sand accumulation. Low sand mounds were found on both the windward and leeward sides of the building and within some of the roofless rooms. One sample (K6) was taken from the leeward side of a dune on the north (windward) side of the building. Farther north of Khârga, two samples (K10 and K11) were collected from an enormous compound barchan that is approaching a star-dune shape. Both samples of this barchan are almost identical in size characteristics and are consistent with the rapidly changing shape of the dune.

Just west of Khârga, samples were collected from a field of barchans that are progressively moving southward. One sand sample (K12) was taken 1.3 km west of Khârga near the base of a dune. A group of four sand samples (K13 to K16, fig. 13) was obtained at the last barchan blocking the road 21 km west of Khârga. Sample K13 was taken on the leeward side at the base of the barchan arm, K14 on top of the arm, K15 from the

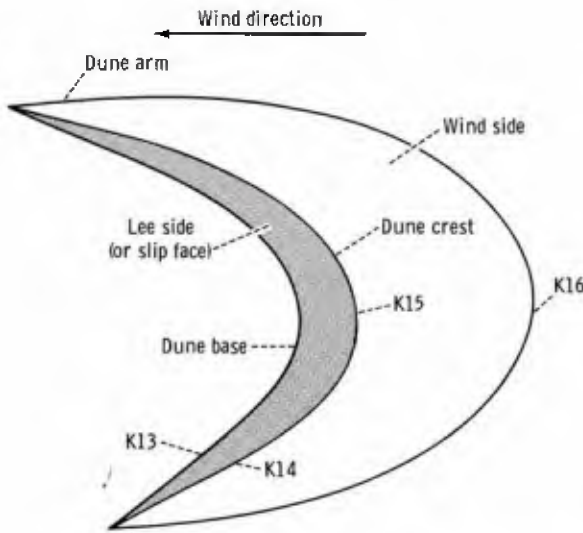


FIGURE 13.—Schematic illustration of the method used in sampling barchan dunes at Khârga and Dakhla Oases. Sample numbers are discussed in the text.

crest of the dune, and K16 from the base of the windward slope. Laboratory analyses indicate that the color of the two samples from the crest is slightly lighter than the color of those from the base of the windward and leeward slopes (10YR 6/4 versus 10YR 6/6; ref. 6). The sand size characteristics of this barchan, however, are consistent with those from Natrûn and Qattara in that the windward side is coarser grained.

All the samples from Khârga Oasis contain the same heavy minerals (glauconite, phosphates, and hornblende(?)) in only slightly varying amounts. Sample K6 is composed of quartz, fairly high percentages of shale and marl, and lesser amounts of white and reddish-brown calcareous grains, chalk, ferruginous grains (nodules and limonitic grains), heavy minerals, and a few fossils.

Samples K10 and K11 are very dissimilar despite the fact that they were collected from the same compound barchan. Sample K10 contains a lower percentage of quartz than does sample K11 and higher percentages of shale, heavy minerals, ferruginous grains (limonitic grains and ferruginous sandstone), and marl. Unlike sample K11, sample K10 includes a small percentage of chalk in its composition.

Of the four samples taken from the same barchan dune (K13 to K16), the samples from the base of the dune (K13 and K16) differ significantly from each other and also from those taken at the crest (K14 and K15). Sample K13 (from the leeward side of the dune) contains a higher percentage of quartz than samples K14 and K15 but a lower percentage than K16. It also includes the highest amount of shale, the lowest percentage of heavy minerals, and the only marl of the four samples. Samples K14 and K15 have virtually the same composition. Of these four samples, K14 and K15 contain the highest percentages of white and reddish-brown calcareous grains in equal amounts, and heavy minerals. They also include the lowest percentages of quartz. Sample K16 contains the lowest percentage of reddish-brown calcareous grains and does not contain any chalk.

Individual grains of the sand deposits in the Khârga Oasis can possibly be traced to formations that outcrop within the oasis and form the surrounding scarps. For example, the shale of the samples has been specifically identified as predominantly Dakhla Shale and minor Esna Shale by visual comparison with the grains derived from collected rock fragments and through published descriptions. The purple and variegated shales are also represented. Similar techniques were used to discover the source of other grains: the chalk grains are presumably derived from the chalk unit and the source of the phosphate grains would be phosphate beds, both of which outcrop within the oasis (ref. 3). Local outcrops therefore contribute significantly to the lithology of the sand deposits.

Dakhla Oasis.—Three sand samples were taken from a barchan blocking the road that connects Khârga and Dakhla Oases. By comparing its position on aerial photographs to its current position, it was found that this barchan has moved 30 m in 3 years. It is an unusual dune because of its poorly sorted sands (as observed in the field) and its mottled colors. Sample D24 was taken from the base of the dune where there was a predominance of calcareous sands. Sample D25 was collected from the black sand streaks on the surface, and sample D26 was obtained from the reddish-yellow sand representative of most of the dune.

Sample D24, from the base of the barchan, has a smaller mean grain size ($2.5\phi/0.18$ mm) than do samples of the surface. It also is slightly gray in color, as is sample D25 (table I).

The microscopic analysis revealed that the three samples are very similar, even though minor differences do exist. All three samples contain relatively high percentages of predominantly gray shale, presumably derived mainly from the Dakhla Shale and to a lesser degree from the variegated shales and from shales in the phosphatic beds (ref. 3). This shale contributes significantly to the grayer colors of samples D24 and D25, as compared to sample D26. Sample D25, in particular, contains a high percentage of coarse shale. Phosphate grains, probably from the phosphate beds that outcrop in the oasis, were found in sample D24. Sample D25 contains the only ferruginous grains (nodules) observed in the three samples.

Great Sand Sea

Sîwa Oasis.—The sample numbered S24 was collected at the base of the reddish, windward side of the Sîwa Oasis dune illustrated in figure 6(c). It is a very clean sample composed of quartz, very minor amounts of white calcareous grains, and a few chert grains.

Great Sand Sea (southwest of Farâfra).—Samples of dune sand on the eastern margin of the Great Sand Sea were collected west of Abu Minqâr, 70 km southwest of Farâfra (fig. 2). Several gently sloping dunes occur in accumulations that resemble those described by Bagnold as "whalebacks." (See section entitled "Color Zoning in the Western Desert of Egypt.") All samples were collected from the first line of longitudinal, sharp-crested dunes that overlie these whaleback dunes.

Three samples are considered in this report: GSS1 was collected from the base of a sinuous dune, GSS2 from an arm of the same dune, and GSS3 from the dune crest. It is significant to note that these samples were taken from the uppermost few centimeters of sand (fig. 14). In this area, the sand grains that form the upper layer are redder than those beneath. The stratification is



FIGURE 14.—Layering in a 30-cm-deep trench that was dug in dune sand of the Great Sand Sea. The surface ripples (top half of photograph) are made of sand that is redder than some of the layers below the surface. The scale is 15 cm long.

similar to that of a large dune field east of Farâfra Oasis in that alternating dark- and light-colored layers are present in both localities.

The three samples were found to be composed mostly of equal amounts of quartz. Differences were observed only in the lithology of the minor components. Reddish-brown calcareous grains and heavy minerals were not observed in sample GSS1, but were found in samples GSS2 and GSS3. Sample GSS1 also contains the lowest percentage of shale and the highest percentage of chalk. Sample GSS3 is the only sample including white calcareous grains in its composition.

Aswân

For comparison with the reddish sands of the Great Sand Sea, a sample collected just west of Aswân (fig. 2), near the base of a cliff, was studied. In this locality, the sand is close to its probable source, the Nubian Sandstone (fig. 1). However, the color of the bulk sample is the same as most of the samples from the Western Desert (fig. 15).

The composition of this sample does not vary significantly from that of other samples collected in the Western Desert. It is composed mainly of quartz, with minor amounts of shale, white calcareous grains, ferruginous grains (nodules and ferruginous sandstone), and marl. Several grains of weathered granite(?) were found in this sample and are presumed to be from the basement complex exposed in the nearby cliff.

Ar Rub' al Khâlî Dunes

For additional comparison with the sands of the Great Sand Sea, one sample was collected from another typically red sand deposit in the United Arab Emirates. This dune sand occurs at the terminus of the great dunes of Ar Rub' al Khâlî (The Empty Quarter) of the Arabian Peninsula. The sample, UAE1, was collected from a relatively low (10-m high) irregular dune mass that was stabilized by natural vegetation south of Abu Dhabi in the United Arab Emirates. The quartz of this sample is very vitreous as compared to the predominantly frosted quartz of the Western Desert of Egypt. The reddish color is due to extensive deposits of iron oxides on the surface of quartz grains.

SUMMARY

Color variations of the Western Desert observed and photographed by the ASTP astronauts can be related to minor compositional variations within the sand deposits. Although the origin of the sand is not well known, the Nubian Sandstone of southern Egypt may have provided a source for much of the sand. As a result of four field trips

FIGURE 15.—Bulk sand samples representative of sand color variations in the Western Desert. (a) Sample N6 from sand sheet at Wâdi el Natrûn that appears bright pinkish-yellow on ASTP photographs. (b) Qattara sample Q3 from the leeward side of a barchan. (c) Sample F3 from the crest of a longitudinal dune at Faiyûm Oasis. (d) Baharîya sample B6 collected 37 km north of El Bawîti. (e) Khârga sample K13 from the leeward side of a barchan. (f) Dakhla sample D25 showing influence of local shale fragments (Dakhla Shale) on the sample color. (g) Sample GSS3 from a longitudinal dune in the Great Sand Sea. (h) Sample A1 from base of cliff in the Aswân area. →

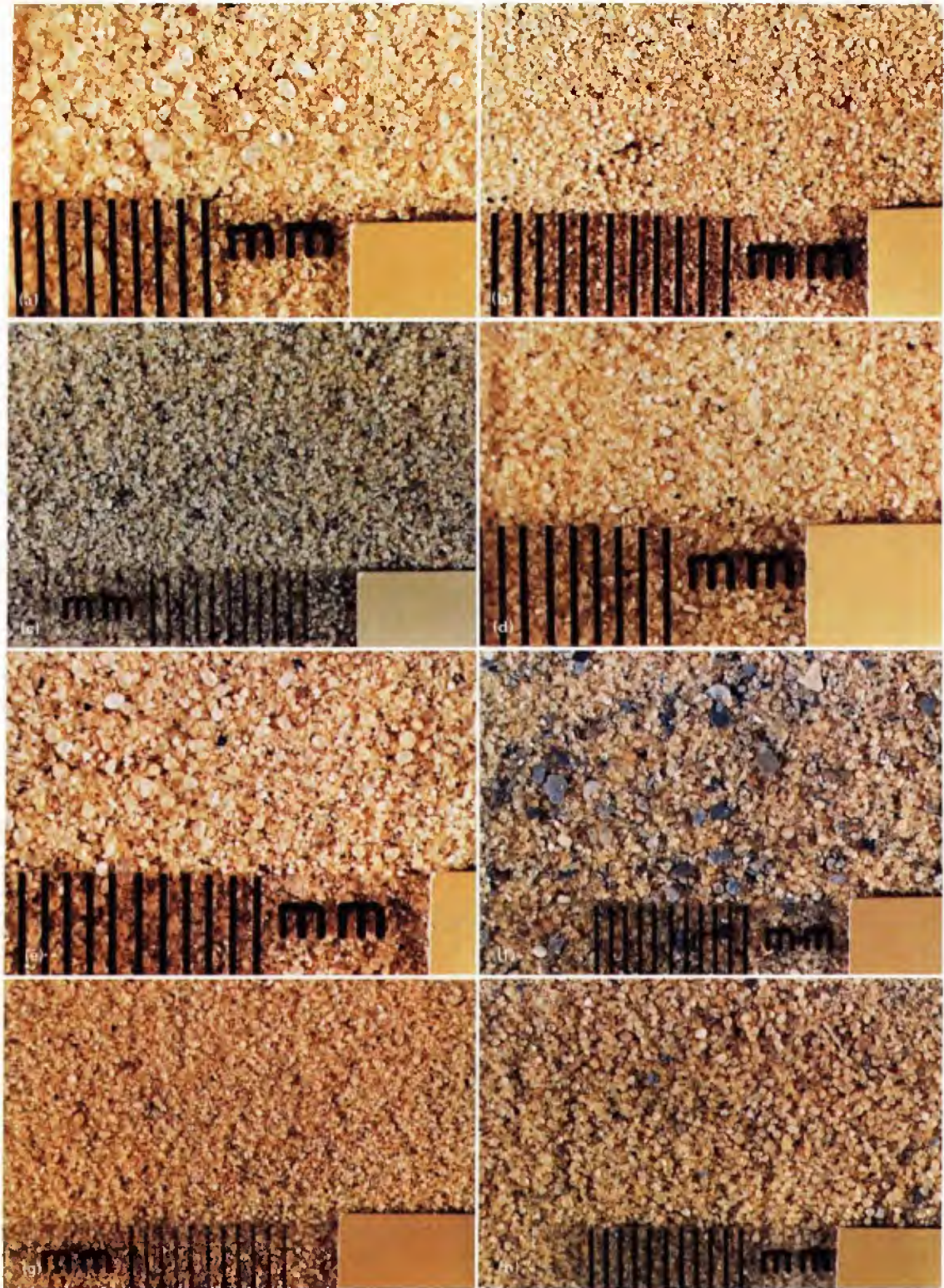
made to check photointerpretations of ASTP data, it was found that sand colors varied greatly on both local and regional scales. Most samples are composed of fine-sand-size grains, and are well to moderately well sorted; and these preliminary results also suggest a dependence on local sampling environment.

Compositional variations in both field and laboratory studies indicate that the major color differences result from the influx of local material and variation in the more regional occurrence of light-colored calcareous fragments. The samples collected from the northern and central regions of the Western Desert are slightly lighter in color and less red than the samples from the Great Sand Sea region. This difference is due primarily to the large percentages of light-colored calcareous grains found in the northern and central samples. Locally, the ferruginous nodules and sandstones at Baharîya and the predominance of shale in Dakhla samples indicate the effect of local material.

Although these results are preliminary, three observations can be made on the basis of this analysis.

1. There is a discrepancy between the color of sand deposits noted by field investigation and that estimated from the bulk samples. This is primarily due to the sampling of sand layers deeper than the thin veneer that is responsible for the color as observed from Earth orbit. More detailed field investigations are currently being planned that will help to account for this source of color discrepancy.

2. The colors of bulk sand samples classified according to the Munsell color chart vary significantly, even within the same color designation. A



more detailed sand color chart for the Western Desert of Egypt is being investigated to provide more accurate ground truth for orbital data.

3. The results presented here suggest that both dune reddening with time and the addition of local material are important to color variations of sand deposits. More detailed field investigations must be made to determine the relative effect of each of these processes before remote observations can be extended to more widespread areas. This need is particularly important in anticipation of the detailed color photographs that will be available from the large format camera to be flown on the Space Shuttle in the next decade.

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