

# Eolian Features in the Western Desert of Egypt and Some Applications to Mars

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Relations of landform types to wind regimes, bedrock composition, sediment supply, and topography are shown by field studies and satellite photographs of the Western Desert of Egypt. This desert, which lies at the core of the largest hyperarid region on earth, provides analogs of Martian wind-formed features. These include sand dunes, alternating light and dark streaks, knob 'shadows,' and yardangs. Surface particles have been segregated by wind into deposits (dunes, sand sheets, and light streaks) that can be differentiated by their grain size distributions, surface shapes, and colors. Throughgoing sand of mostly fine to medium grain size is migrating southward in longitudinal dune belts and barchan chains whose long axes lie parallel to the prevailing northerly winds, but topographic variations such as scarps and depressions strongly influence the zones of deposition and dune morphology. Sand from the longitudinal dunes on the plains is commonly redistributed into barchans in the depressions. These barchans are generally simple crescents that are morphologically similar to many of the dunes seen on Viking orbiter pictures of the north polar sand sea on Mars. Light streaks are depositional features consisting of dune belts and elongate sheets of coarse to medium sand and granules. Intervening dark streaks are erosional features consisting of strips of desert-varnished bedrock and lag gravel surfaces exposed between the sand deposits. The shape of both light and dark streaks is controlled by wind flow around topographic highs. Dark zones (shadows) in the lee of mountains, hills, and knobs are erosional products from the topographic highs; they change shape only in response to movement of the adjacent lighter-colored sand deposits. Streamlined yardangs carved in crystalline limestone constitute one of the largest yardang fields on earth. Yardangs occur also in sandstone of the Nubian Series and in lacustrine sediments. The variables that affect the patterns of wind erosion and deposition in the Western Desert are topographic effects on wind velocities and directions, resistance of the bedrock, sand supply, and climatic change with time; vegetation is essentially absent and is not a controlling factor.

## INTRODUCTION

In Egypt the Western Desert extends from the Libyan border to the Nile River and from the Mediterranean Sea to the border of Sudan at latitude 22°N. The desert occupies 681,000 km<sup>2</sup>, more than two thirds of the total area of Egypt. The region consists of gently northward dipping sandstone and limestone that have been eroded to an eolian peneplain and veneered with windblown debris. The remarkably flat terrain is broken by numerous escarpments that bound depressions, by scattered inselbergs, and in the southwest corner, by the Gifl Kebir Plateau and the isolated, circular mountains centered around Uweinat (Figures 1 and 2).

Much of the basic research on dune classification and sand movement by wind has been carried out in the Western Desert of Egypt, where 'the free interplay of sand and wind has been allowed to continue for a vast period of time, and [where] if anywhere, it should be possible in the future to discover the laws of sand movement and growth of dunes' [Bagnold, 1933, p. 121]. Early geomorphic descriptions include those of Beadnell [1910], King [1918], Ball [1927], Bagnold [1933, 1939], Kádár [1934], Sandford [1935], Peel [1939], and Mitwally [1953]. Bagnold's [1941] classic treatise on the physics of sand movement by wind is based largely on observations made in the Western Desert. Sand flow patterns in the Sahara, including western Egypt, have been mapped by Wilson [1971, Figure 5] from the 'sand storm resultants' of Dubief [1952] and from barchan dune orientations as shown on topographic maps [Wilson, 1971, p. 187]. Recent work in Egypt is

summarized by Said [1962] and Smith [1963]. However, the work of the wind in hyperarid regions such as western Egypt remains largely unrecognized among geologists whose experience has been limited to the semiarid deserts of the American southwest [McCauley *et al.*, 1977a, p. 1.4]. Although the Western Desert of Egypt is still relatively unexplored, it has recently been the subject of comparative planetology studies through the use of earth orbital photographs in combination with multidisciplinary field investigations [El-Baz *et al.*, 1979].

Despite recurrent episodes of lesser aridity than the present, as evidenced by Paleolithic and Neolithic artifacts found in parts of the Western Desert [Murray, 1951; Haynes, 1978, also oral communication, 1978], wind excavation of the surface may have begun as early as Pliocene or even post-middle-Miocene time [Murray, 1951; Said, 1960, p. 14, 1962, pp. 43-44]. 'Although the frequency of rain must have been greater than today, rainfall of the Pleistocene fluvial phases was ineffective in producing drainage lines or vegetative cover' [Said, 1962, p. 43]. The Western Desert is a 'desert peneplain' [Sandford, 1933] in which most of the geomorphic features are primarily due to wind action [Said, 1960, p. 12]. Vegetation is essentially absent. Fluvial processes in that part of Egypt no longer play an effective role in modifying the landscape. As on Mars, wind is the dominant agent of erosion, transportation, and deposition.

The Landsat mosaic of Egypt (Figure 1) shows the regional patterns of large-scale eolian features in the Western Desert, including fields of sand dunes, alternating light and dark streaks, dark knob 'shadows,' and yardang fields. Many of these features are morphologically similar to wind forms observed on Mariner 9 and Viking orbiter pictures of Mars.

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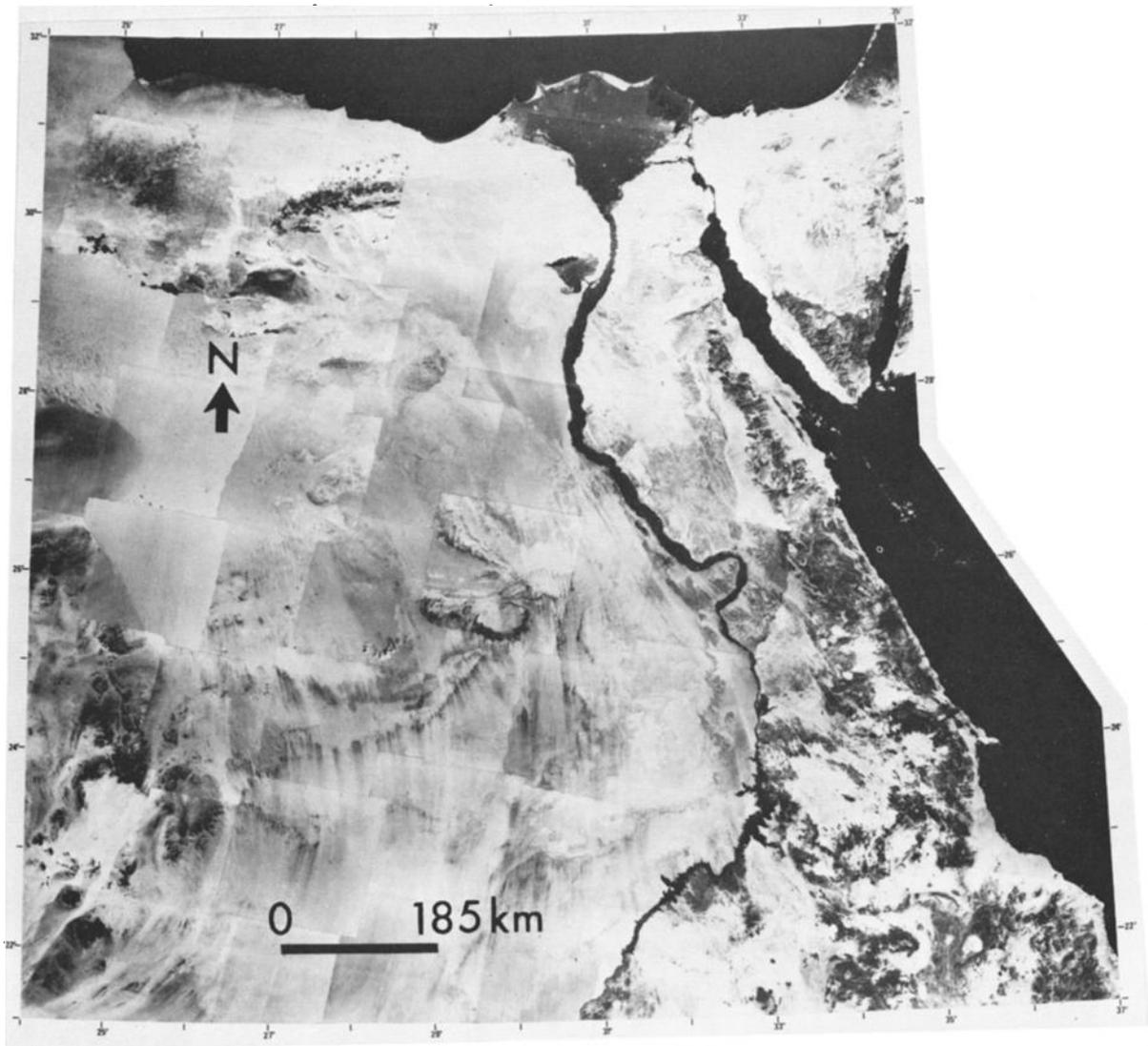


Fig. 1. Mosaic of 65 Landsat images of Egypt, showing the distinct difference of the landforms in the Western Desert from those in the Eastern Desert (east of the Nile, Figure 2). Light-colored eolian deposits in the form of dunes, sand sheets, and streaks cover most of the Western Desert. In contrast to the Eastern Desert, few traces of fluvial processes remain in the Western Desert [Haynes, 1978], and the landscape is dominantly wind formed.

#### SAND DUNES

One of the largest accumulations of dune sand in North Africa is the Great Sand Sea of Libya and Egypt. In Egypt the sand sea occupies the west central part of the Western Desert (Figure 2), beginning just south of the Siwa Depression and continuing uninterrupted for 600 km to the Gilf Kebir Plateau. The main sand mass consists of subparallel arrays of enormous compound linear dunes. These are broad whalebacks ('plinths') surmounted by sharp-crested longitudinal ('seif') dunes [Bagnold, 1941, pp. 230–232, Plate 13; El-Baz, 1976]. The whalebacks are relatively static, whereas the longitudinal dunes are actively migrating southward under the prevailing winds.

East of the Great Sand Sea, numerous other belts of longitudinal dunes are migrating southward across the Western Desert. The largest array of dunes extends south-southeast from the Qattara Depression (Figure 2). This wind-excavated

basin [Ball, 1927; Said, 1962], the largest depression in Egypt, occupies an area of approximately 19,500 km<sup>2</sup> below sea level. The depression's northern and western margins are marked by a steep scarp capped by limestone of the Mamarican Formation of Miocene age, which are underlain by the friable sand and silt of the Moghra Formation of Miocene age [Said, 1960]. The southern and eastern margins of the depression rise gradually into the flat plain that stretches unbroken to the Bahariya Depression (Figure 2). Nearly 5800 km<sup>2</sup> of the floor of the Qattara Depression is covered by sebkha (water-saturated salt that is thinly mantled with sand). The remainder consists of exposed bedrock and deposits of sand, pebbles, and clay.

Enormous volumes of sedimentary rock debris have been removed from the Qattara Depression by deflation [Said, 1960; Squyres and Bradley, 1964]. Winds have transported the sand-sized particles southward in belts of long, compound, longitudinal sand dunes. As depicted in the Apollo-Soyuz photographs (Figure 3), the dunes south of Qattara are char-

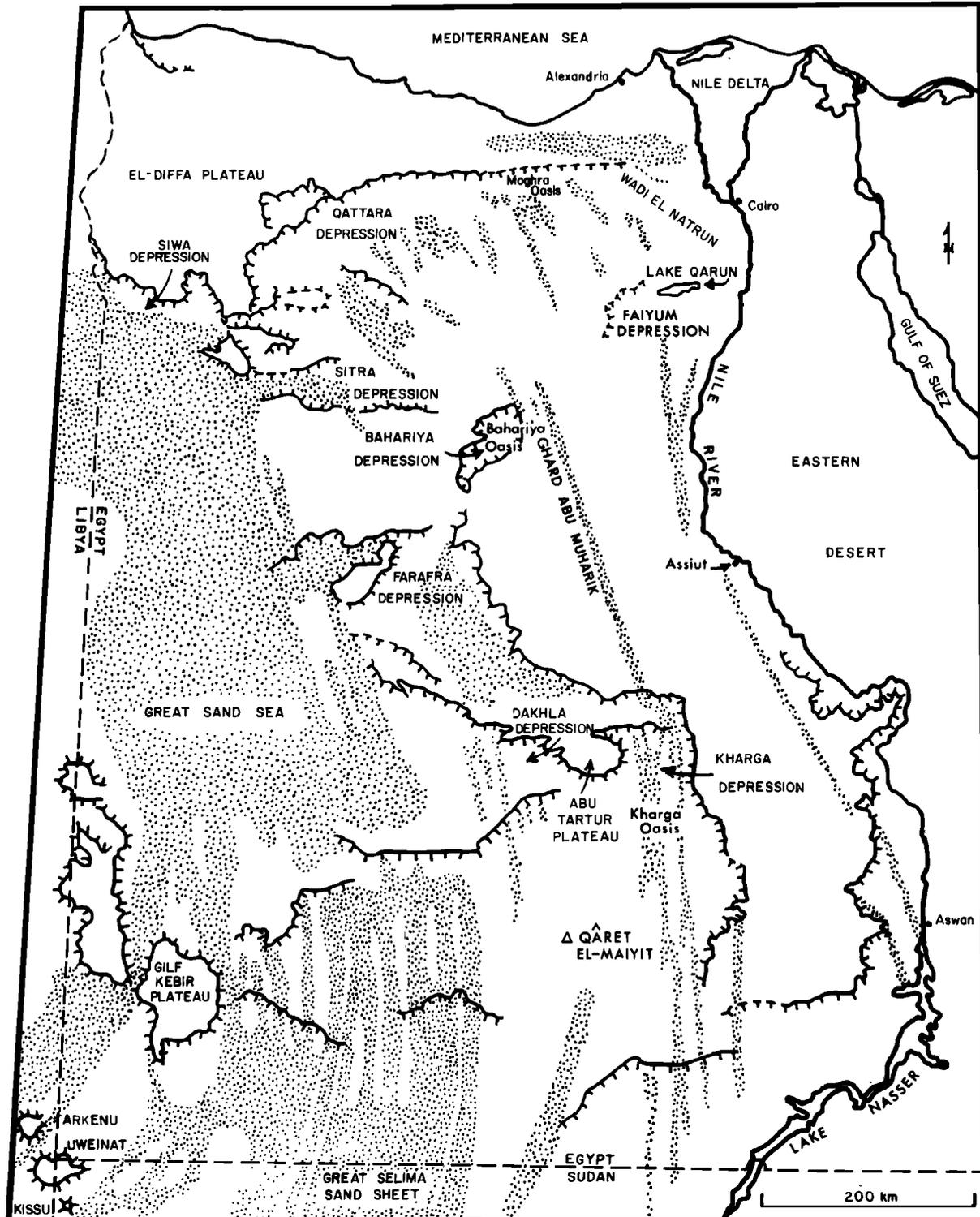


Fig. 2. Map of the Western Desert of Egypt showing the distribution of major sand deposits in relation to the numerous scarps that bound the major depressions (modified from Gifford et al. [1979]).

acterized by diffuse northern ends and tapering southern ends, and they join together downwind, producing a 'spearhead' appearance.

South of Qattara the dunes increase in number to the west, and on orbital photographs it is difficult to identify individual dunes within these westernmost belts. This variation in dune density has been attributed [Gifford et al., 1979] to topographic

effects of the east-west Qattara scarp on the prevailing north-northwesterly winds; as the scarp increases in height to the west, it forms a barrier to the prevailing winds that may enhance the relative effectiveness of winds from other directions. This effect is also suggested by patterns on aerial photographs showing crescentic forms concentrated at the northern ends of the westernmost dunes. Slip face orientations on the crescentic

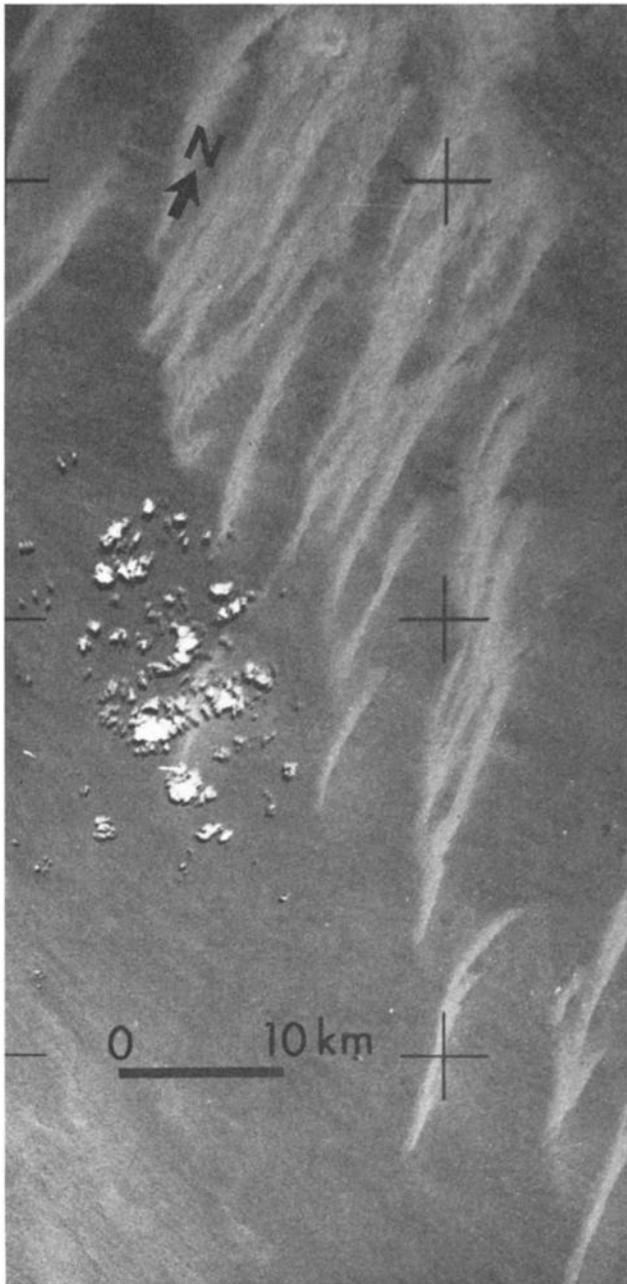


Fig. 3. Compound longitudinal dunes just south of the Qattara Depression in the northern part of the Western Desert of Egypt (part of Apollo-Soyuz photograph AST-16-1253).

forms indicate transverse winds normal and oblique to the direction of the prevailing north-northwest wind.

Crescentic dunes (barchans and barchanoid ridges) occur mostly in the seven depressions that lie 100–200 m below the average elevation of the Western Desert. Where belts of longitudinal dunes cross escarpments and spill into the depressions, they commonly break up into fields of crescentic dunes. These dunes tend to run southward in chains whose long axes lie parallel to the long, bounding north-south scarps on the east side of the Kharga Depression and just south of the Faiyum Depression. The barchans move rapidly through the depressions, inundating roads, telephone lines, and more impor-

tantly, agricultural fields [El-Baz, 1978], thus creating significant problems because less than 4% of the land area of Egypt is presently used for agriculture.

The Kharga Depression is bounded on the north by a 200-m-high scarp capped by limestone of Eocene age, but it is open to the south and southwest. Oases and villages lie in its center, along a north trending fault that provides access to groundwater. Downwind extensions of large compound longitudinal dunes enter the depression from the limestone plateau to the north. The largest of these is the Ghard Abu Muharik, which begins just east of the Bahariya Depression and extends downwind to the Kharga Depression more than 300 km to the south-southeast (Figure 2). This dune reaches the edge of the depression north-northeast of Kharga, and as sand from this dune descends the escarpment, it is redistributed into fields of barchans and barchanoid ridges. The transition in dune type is apparently due to the effect of the abrupt change in slope on the oncoming sand-moving winds. Vegetation is virtually absent except in oases and villages in the center of the depression, along a north trending fault that provides access to groundwater, and thus is not associated with dunes of either longitudinal or crescentic type. The idea that the presence or absence of vegetation controls dune morphology, first proposed to explain the distribution of dune types in semiarid deserts of North America [Hack, 1941], does not seem to apply to the development of dune types in the hyperarid Egyptian desert.

The barchans in the Kharga Depression (Figure 4) are simple crescentic forms that range in length from 30 to 650 m, in width from 25 to 540 m, and in height from 0.5 m to 25 m [Embabi, 1970–1971]. Their rate of movement (20–100 m per year) is roughly inversely proportional to their height (N. S. Embabi, oral communication, 1976). Barchans of similar appearance are seen on Viking orbiter pictures of the north polar sand sea on Mars, for example, at latitude 71°N, longitude 50° [McCauley et al., 1979; Breed et al., 1979a]. The Martian barchans grade poleward into fields of closely spaced, large crescentic dunes ridges that are morphologically very similar to the megabarchanoid or transverse variety of crescentic dunes that typically occur in topographically closed basins in terrestrial deserts [Breed et al., 1979a]. Crescentic dunes of this variety are also common in the crater floor dune fields on Mars [Breed, 1977]. In the closed basins of the Sahara, oncoming sand-laden winds deposit their load in typically massive crescentic dune ridges that act as sand traps; such dunes may, as in the Marzūq Basin of Libya, accumulate sand to depths of 300 m or more [Glennie, 1970, Enclosure 4]. In the Egyptian depressions that are open at their downwind ends, however, dune sand is not trapped but rather continues its southward migration in the form of throughgoing barchan chains. Differences in growth habits between these two common varieties of crescentic dunes in the Sahara thus seems to be related, at least in part, to topographic controls on the migration versus the accumulation, in place, of windblown sand. Variations in the shapes of dunes on Mars may also reflect similar topographic controls on the transportation and deposition of particles capable of saltation.

Numerous workers have studied the variables of atmospheric pressure, wind velocity, particle size and composition, and the nature of 'sand' sources on Mars that would account for the presence there of dunes that are morphologically simi-

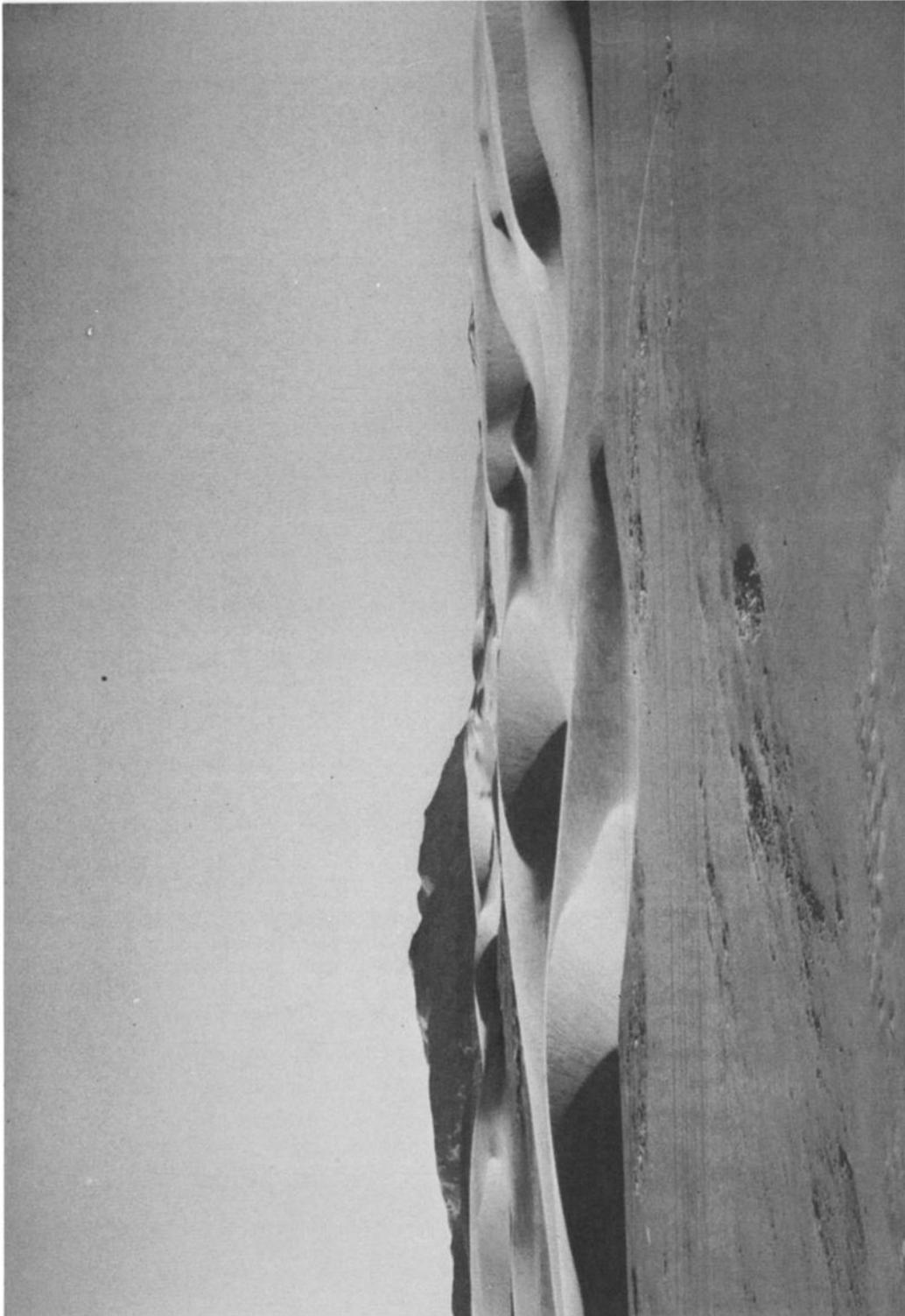


Fig. 4. View north at the oncoming slip faces of barchans in the Kharga Depression.

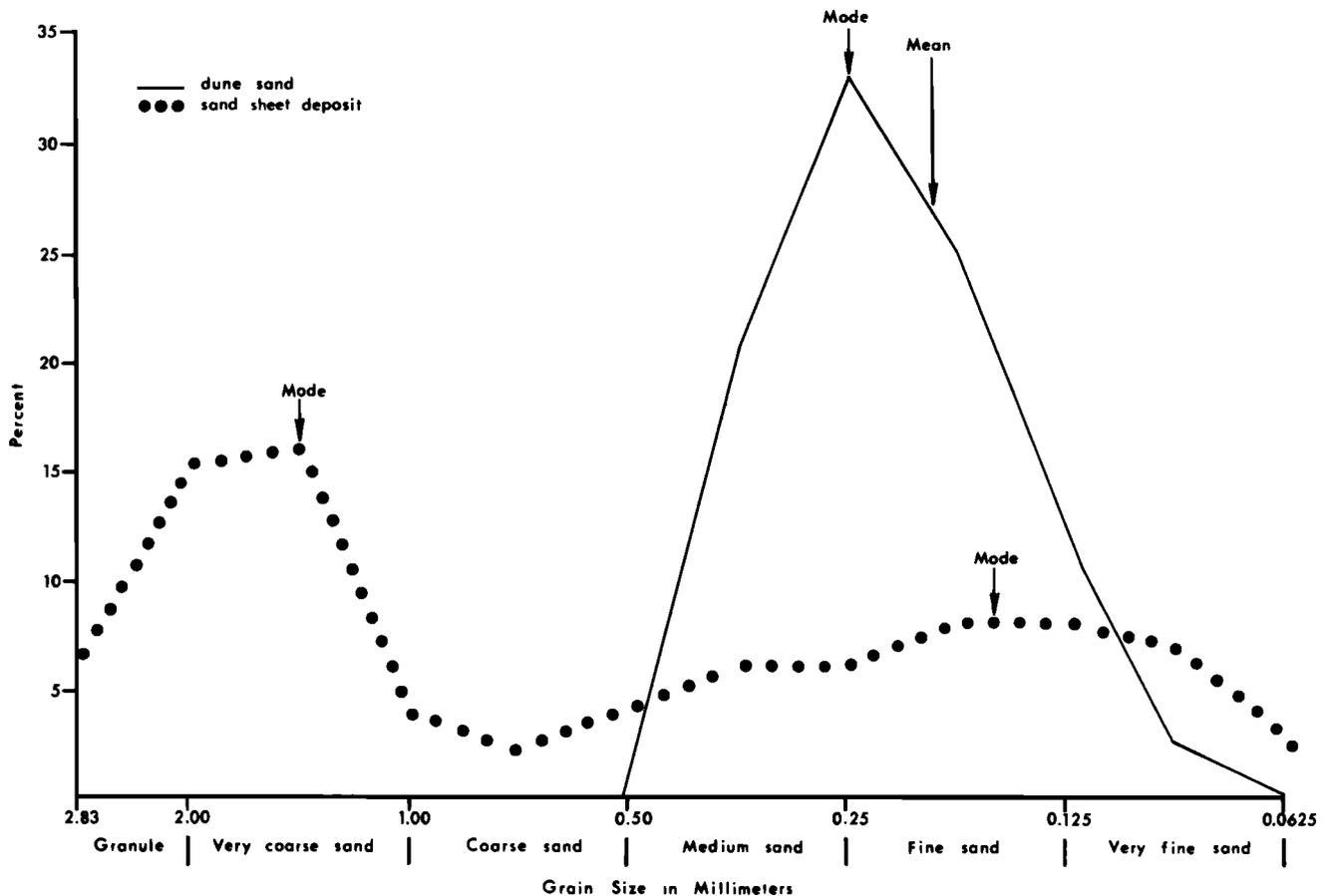


Fig. 5. Frequency curves showing differences in grain size distribution between dune sand and sand sheet deposits on the 'sand plain' south of the Abu Tartur Plateau at about latitude 23°N, longitude 30°E in the Western Desert of Egypt. The sand sheet deposit forms the flat surface of the eolian sand plain, which extends for hundreds of square kilometers in the central part of the desert. In the sampled area, most of the fine to medium sand is concentrated in dunes. The dune sand shown on the graph is from an active, 150-km<sup>2</sup> barchan field that is migrating southward across the sand plain. The coarsest particles on the graph are quartz lag granules that armor the surface of the sand sheet deposit against deflation. This lag surface is stable in winds of at least 32 km/h, which is above the threshold velocity observed in the field for movement of the dune sand by saltation [Breed *et al.*, 1979a].

lar to common varieties of crescentic dunes on Earth [e.g., Greeley, 1968, 1979; Greeley *et al.*, 1977b; Sagan *et al.*, 1977; Arvidson *et al.*, 1978; Pollack, 1978; White *et al.*, 1979; Krinsley and Leach, 1979; Krinsley *et al.*, 1979]. Interpretations differ, particularly as to the composition and source of particles subject to saltation on Mars and as to possible implications of climate change, but most agree that within the constraints of the present Martian atmospheric conditions the particles most easily moved by saltation are of 0.16-mm size. For comparison the sand collected from dunes throughout the Western Desert of Egypt has a mean size of 0.25 mm (fine to medium sand).

Dunes of the Western Desert consist mostly of rounded to well-rounded grains of detrital quartz derived from primary sources, including sedimentary rocks such as the Tertiary formations exposed in the Qattara Depression to the north [Said, 1960, p. 42] and the Nubian Series of Mesozoic age to the south, and from secondary sources such as sediments in abandoned wadis. In order to relate dune deposits to source areas better, and to define patterns of wind erosion, transportation, and deposition in the Western Desert, numerous sand samples

were taken, both from the northern (upwind) part of the desert, near Bahariya Oasis, and from the southern part, or Nubian Desert, between the Kharga Depression and the Gilf Kebir. Directions of potential sand migration were calculated, according to the method devised by Fryberger [1978], for each station where winds have been recorded [Wolfe and El-Baz, 1979].

Mechanical analyses of the dune sands show that in most of the sampled localities, grain sizes within the dunes are unimodally distributed and have peak diameters in the fine to medium sand categories (0.125–0.50 mm). Nearly all of the dune sands are well to moderately well sorted, with two exceptions. Sand from a dome dune (incipient barchan) east of the Gilf Kebir [Breed *et al.*, 1979b] is poorly sorted, with modes at 0.50 mm (medium to coarse sand) and 0.0625 mm (very fine sand to coarse silt). Sand from the Ghard Abu Moharik, near Bahariya Oasis, is poorly sorted and bimodal, with peak diameters at 0.50 (coarse to medium sand) and 0.088 mm (very fine sand).

The grain size distribution, composition, and color of sand in dunes sampled in the northern part of the desert differ from

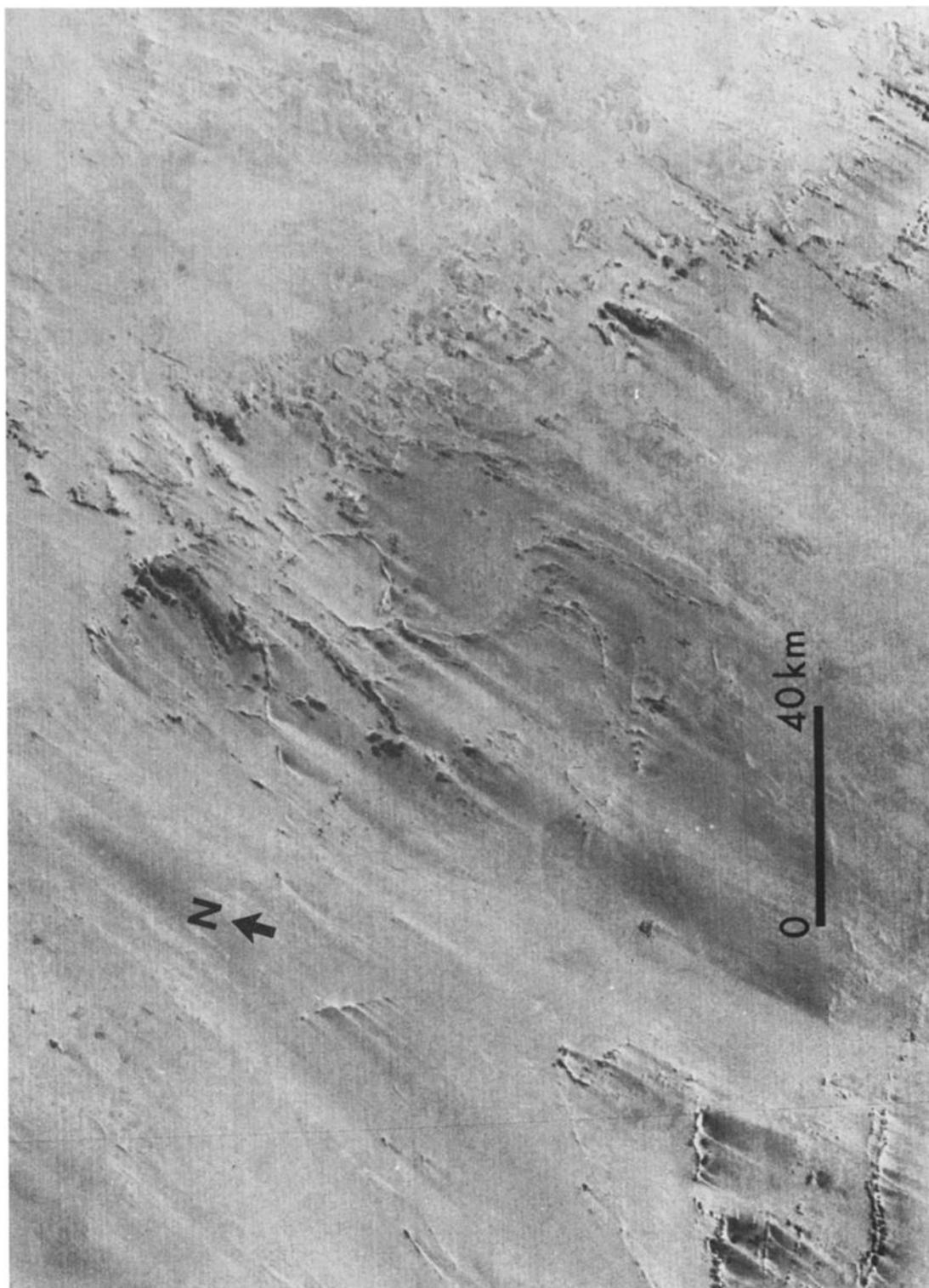


Fig. 6a. Landsat image of the Western Desert showing light and dark streaks.

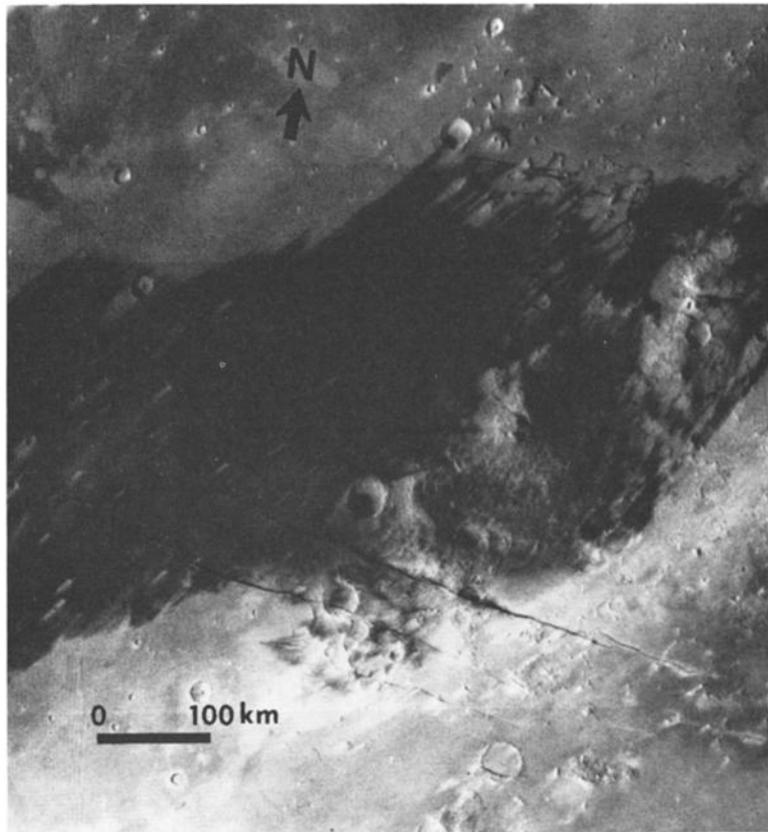


Fig. 6b. Viking orbiter picture of the Cerberus region of Mars (latitude 10.5°N, longitude 202°) showing light and dark streaks in the lee of craters and hills.

those farther downwind. Sand from the Ghard Abu Moharik and other longitudinal dunes near Bahariya Oasis consist of both quartz and carbonate grains with a relatively large admixture of heavy minerals. Thin iron oxide coatings are visible, with a hand lens, on less than half of the quartz grains. These dunes are yellow (10 YR 8/6) on the Munsell Soil Color Charts. Sand from longitudinal dunes near the Gilf Kebir are well to moderately well sorted and highly unimodal, with peak diameters of 0.25 mm (fine to medium sand). They consist almost entirely of quartz grains, with very few heavy minerals. Iron oxide coatings are developed on most of the quartz particles and are readily visible to the naked eye. These dunes are reddish-yellow (5YR 6/8) on the Munsell Soil Color Charts.

Analysis of Landsat, Skylab, and Apollo-Soyuz color pictures of major terrestrial deserts, verified by field work in central Australia [Breed and Breed, 1979] and Western Egypt [El-Baz, 1978] have shown that many of the color zones visible on the satellite pictures are related to the abundance of desert-varnished pebbles armor the surface, the composition and grain sizes of the surface materials, and the thickness of iron oxide coatings on individual sand grains. Recent studies [Breed *et al.*, 1979a] indicate that in areas of uniform climate and sand source materials, relative redness can be a useful criterion for distinguishing younger, active dunes from relatively older, less active forms. Field investigations show that in the Western Desert, sand dunes actively encroaching on arable land of the Nile Valley, south of Faiyum, are less red than the

more stable and older dunes of the central Western Desert [El-Baz, 1978]. Previous workers in deserts of the southwestern United States [Norris, 1969], southern Africa [Logan, 1960], North Africa [Alimen, 1957], and Australia [Twidale, 1972] have suggested that relative redness of sand increases with age of the dunes. The progressive reddening of desert sands, due to the weathering of heavy mineral grains and ferruginous clay particles, first to yellow limonite and then to red hematite, has been described by Folk [1976].

The reddest dunes observed by the 1979 expedition to the Western Desert [El-Baz *et al.*, 1979] are the climbing and falling dunes that are trapped in the lee of wadi cliffs in the Gilf Kebir Plateau. Scanning electron microscope analysis of sand from one of these dunes revealed coatings, 2–5  $\mu\text{m}$  thick, of hematite mixed with a clay mineral, on the quartz grains [Prestel and El-Baz, 1979]. The deep yellowish-red color of the sands in the topographically trapped dunes (hue 5YR 5/8 on the Munsell Soil Color Chart) contrasts markedly with the much yellower hue (7.5 YR 7/6) of sands in the active barchans about 170 km to the east, on the sand plain.

Marked differences in grain size distributions were found between windblown sediments in the dunes and in the widespread, essentially flat sand sheet deposits in the southern part of the Western Desert. A typical comparison (Figure 5) shows that the dune sand is well sorted and rather narrowly distributed within the very fine to medium grain size categories, whereas the sand sheet deposits are very poorly sorted and bimodal and include particles with a wide range of sizes. These

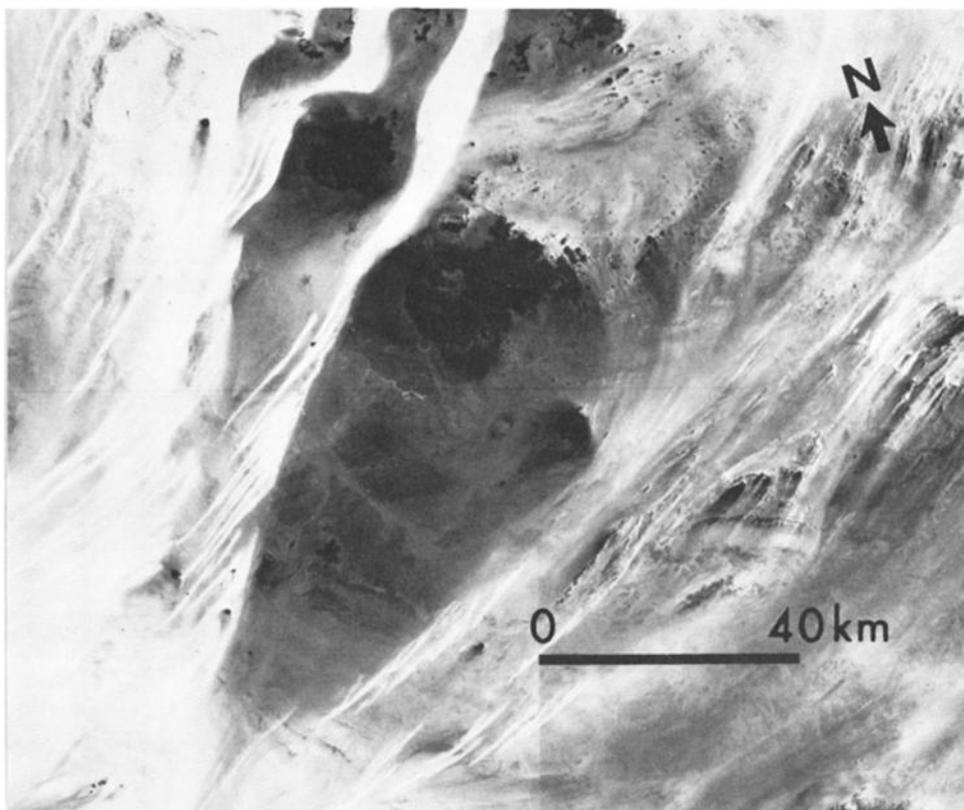


Fig. 7. Landsat view of the dark, spindle-shaped streak in the lee of Uweinat Mountain at the borders between Egypt, Libya, and Sudan. The light streaks are longitudinal (seif) dunes.

analyses indicate that the wind has selectively sorted the surficial debris into distinctly different deposits that can be distinguished not only by differences in topographic expression but also by their different grain size populations, although the composition of the dunes and sand sheets (mainly quartz particles) is the same [Breed *et al.*, 1979a]. Breed *et al.* [1979b] suggest that a similar segregation of particles by grain size may have occurred on Mars and that such grain size differences within the Martian resistates may account for some of the differences in surface characteristics on that planet, such as those observed by Kieffer and Palluconi [1978]. In contrast to the abundance of detrital quartz particles in Egypt, however, they suggest that the sand derived from the mechanical disintegration of basaltic rocks on Mars may be sparse.

Interpretations of the relations of wind regimes to grain size distributions, composition, and color variations among eolian deposits in the Western Desert are based on work that is still in progress. However, the early findings indicate that wind depositional patterns are more complex than those described by Bagnold [1933] and depicted on the generalized sandflow map by Wilson [1971, p. 5]. The mobility of particles in areas subject to the same regional wind pattern is strongly dependent on local topographic controls on the sand supply and on the directions of sand-moving winds. Topographic effects include deflection of the winds by hills and scarps and the channelling of sand-laden winds through depressions and local wind gaps. Erosion of the bedrock outcrops also adds locally derived particles to the sandflow.

#### LIGHT AND DARK STREAKS

The Landsat mosaic of the Western Desert of Egypt (Figure 1) shows numerous alternating light and dark streaks. On Mars, orientations of streaks associated with craters have been used to map global wind circulation patterns [Sagan *et al.*, 1973; Ward, 1978], and streaks have been successfully modeled in wind tunnel experiments [Greeley *et al.*, 1974].

On the basis of Mariner 9 data, calculations of the density of the Martian atmosphere suggest that much higher wind velocities and a smaller mean sediment size than on earth would be the most important constraints on the eolian regime of Mars [Arvidson, 1972]. It was also suggested [Sagan *et al.*, 1973; Arvidson, 1974; Mutch *et al.*, 1976; D'Alli, 1977] that whereas light streaks are most probably areas of deposition of fine-grained material, the dark streaks may be areas of non-deposition, erosion, or bedrock surfaces. These hypotheses have been tested in wind tunnel experiments [Greeley *et al.*, 1974].

Although particle entrainment size and wind speeds on earth may be substantially different from those on Mars, the southwestern part of the Western Desert contains a range of grain sizes, wind orientations, and natural topographic barriers of circular shape that simulate conditions of the Martian surface probably better than elsewhere on earth. The high-quality Viking orbiter images allow detailed studies of the Martian eolian regime on both a local [Greeley *et al.*, 1977a] and a regional [Veverka *et al.*, 1977] basis. However, the relations of large-scale streak patterns to topography and wind re-

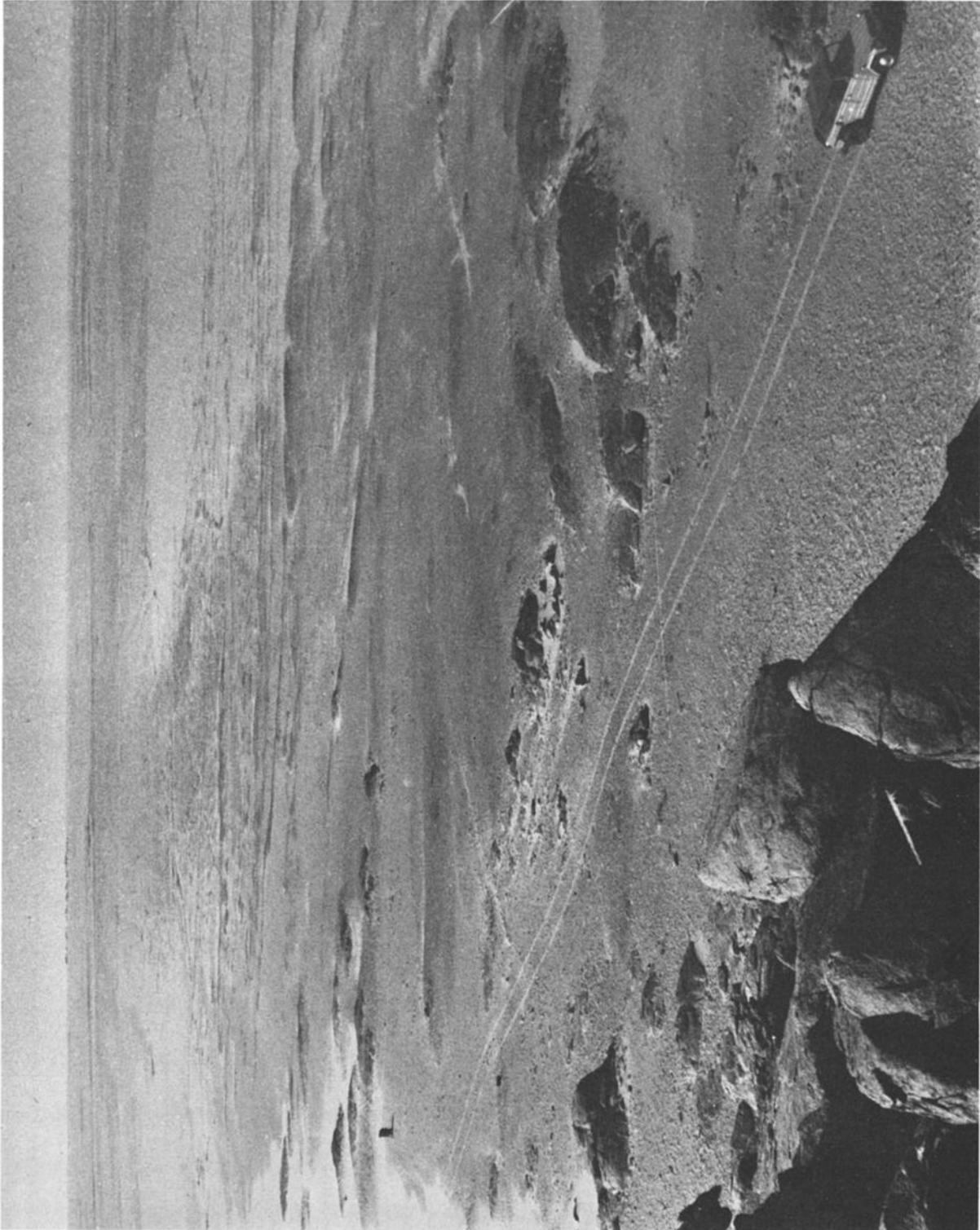


Fig. 8. View southeast from the top of Qâret el Maiyit hill at about latitude  $23^{\circ}\text{N}$ , longitude  $29^{\circ}\text{E}$  in the Western Desert. Vehicle tracks indicate the scale of the dark streak formed by debris eroded from the granitic hill. The dark color of the streak is emphasized by the lighter windblown sand deposits on either side.

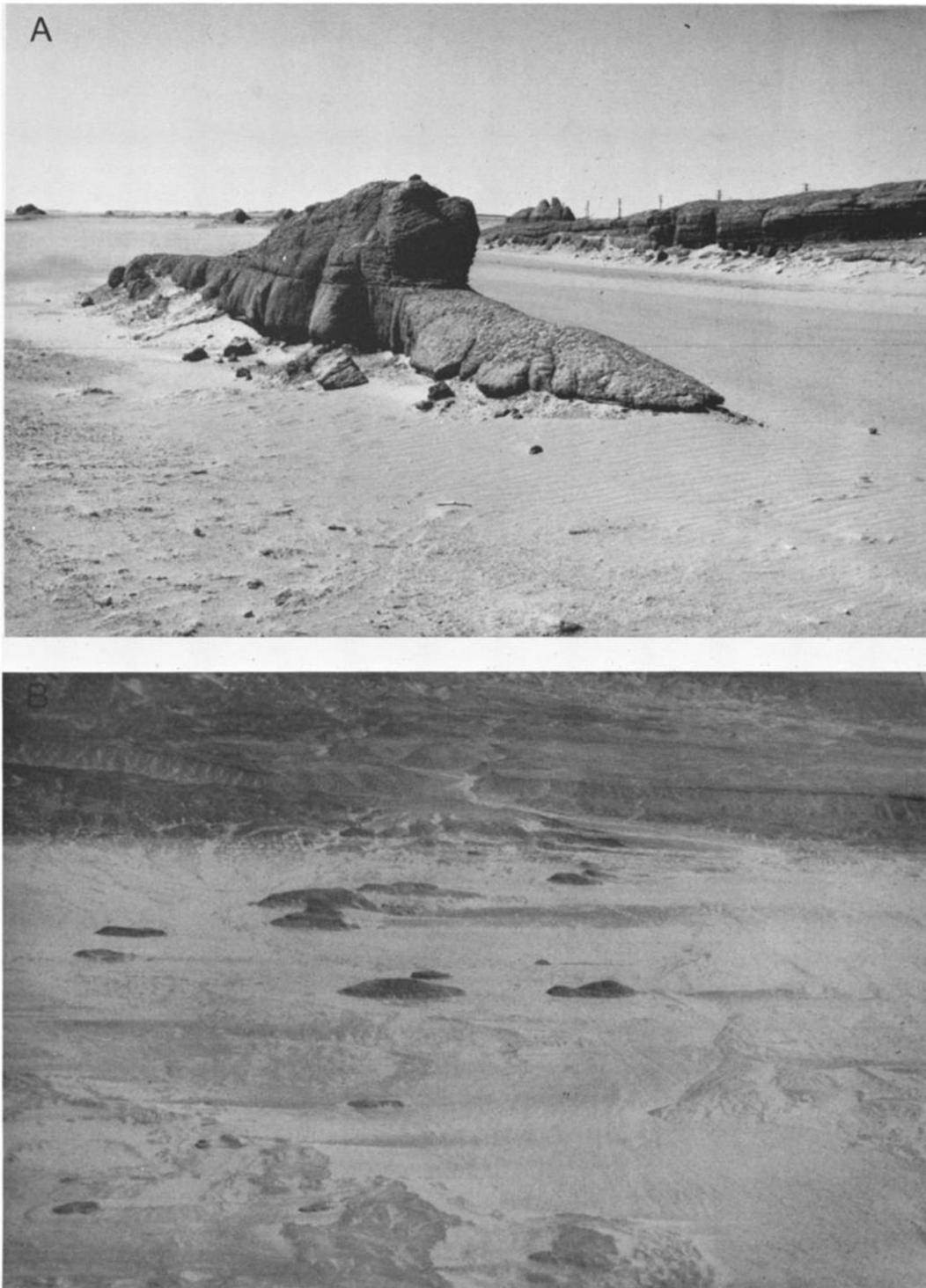


Fig. 9. (a) Small yardang (30 m long, 3 m high, and 1.5 m wide) in bedded and cross-bedded Quaternary deposits about 9 km north of Kharga in the Western Desert. Blunt head and tapering proboscis give the hill a sphinxlike appearance facing into the northerly wind. The blocks that lie alongside were loosened from the side slopes by deflation. (b) Yardangs hundreds of meters long eroded in the Nubian Sandstone of Cretaceous age exposed in the floor of the Kharga Depression. North is to the left. The variations of streamlined form are controlled by rock type and structure. These features strongly resemble some of the yardangs in the Ica Valley, Peru [McCauley *et al.*, 1977a, Figures 64, 65].

gimes in terrestrial deserts have not yet been studied in detail. In particular, the southwestern desert of Egypt, which includes both light and dark streaks accessible to field studies, provides a natural laboratory for the study of features similar in scale to those on Mars.

Recent studies of satellite images of the Sahara [Breed *et al.*, 1979b] show that light streaks are typically elongate sand sheet deposits in which bedforms (dunes) generally cannot be discerned at the resolution of space images. Such light streaks are characteristic features of regions of high wind energy such

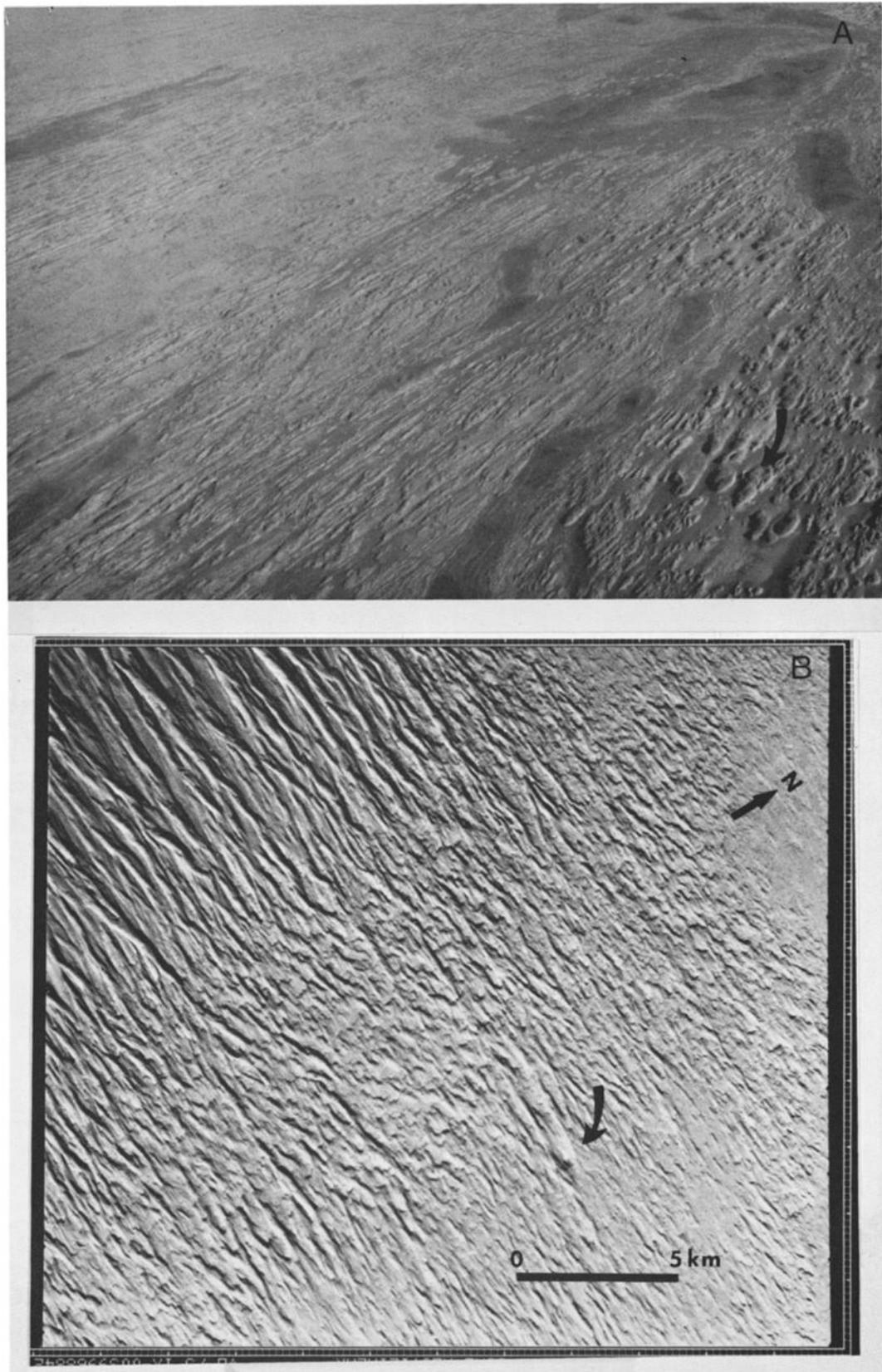


Fig. 10. (a) Oblique aerial view of the yardang field a few kilometers north of the Kharga Depression, Egypt. Kilometer-scale streamlined hills of silicified limestone and couloirs are aligned parallel to the northerly wind (north is to the left front). Joints control the crosscutting alignment. Compare the blunt-nosed hill (arrow) with the similar feature indicated by the arrow in Figure 10b. (b) Yardangs in the Biblis Patera region near the Martian equator. The sun illuminates the north slopes of the streamlined hills (Viking orbiter image 732A61).

as the border region between western Algeria, Chad, and Mauritania, where the streaks grade into belts of longitudinal dunes [Breed *et al.*, 1979b]. Field observations in the southeastern Gilf Kebir area show that light streaks are formed both by dunes and by elongate sheets of coarse, highly reflective quartz granules without dune forms. The wind has concentrated both the finer, reddish dune sand and the coarser, nearly white lag particles into parallel deposits that appear as streaks on photographs.

As first proposed by Bagnold [1933], the orientation of the light streaks in the Western Desert suggests a clockwise rotation of the prevailing wind about a center near Kufra Oasis in southeastern Libya (latitude 24.5°N, longitude 23°E). Deviations from this pattern, particularly at the southwest corner of Egypt, are controlled by local topography. Here in the Uweinat region, changes in streak orientations and patterns over the past few years have been studied by comparing an Apollo 9 photograph (AS9-23-2533) taken in 1969 with four Apollo-Soyuz photographs (AST-2-126, 127, 129, and 130) taken in 1975 [Slezak and El-Baz, 1979]. The average change in the positions of the sand streaks, particularly in relation to the surrounding slopes, was found to be 2.5 km over the 6-year period. These and similar measurements provide data for comparison with temporal changes of Martian streaks following dust storms.

Mariner 9 and Viking orbiters photographed numerous streaks on Mars, particularly in the Cerberus and Elysium Mons regions (Figure 6b). The uplifted rims of impact craters on Mars play a major role in shaping the streak directions, and the turbulence in the lee of craters is most likely responsible for some streak patterns there. An arcuate vortex of high surface stress in the lee of craters has been presented as one model responsible for the characteristic patterns of erosion and deposition [Greeley *et al.*, 1974]. Clusters of volcanic craters occur along with discontinuous scarps (Figure 6a) in southwest Egypt. Streaks there, as on Mars, emanate from crater rims and isolated knobs (Figure 6b), and the knobby material protrudes through the surrounding terrain on a line that is oblique to the prevailing wind [El-Baz and Maxwell, 1979a, b].

#### DARK KNOB SHADOWS

Circular granitic mountains abound in the extreme southwestern corner of Egypt near the borders with Libya and Sudan (Figures 1 and 2). The largest and highest (1893 m) of these mountains is Uweinat. East and west of it are several mountains and smaller hills that, like Uweinat, display dark areas resembling shadows. In all cases the dark zone occurs in the lee of the topographic barriers; the largest streak is southwest of Uweinat itself (Figure 7). This mountain stands 1200 m above the surrounding sandy plain. Under the prevailing wind from the north-northeast it creates a flow pattern that is similar to those generated by laboratory experiments to simulate the flow of wind around Martian craters [Greeley *et al.*, 1974].

As observed in the field, the northern part of the Uweinat dark streak is strewn with irregular chips or flakes of dark rock a few centimeters in size. They appear to be fragments from the Uweinat Mountain rocks. Smaller, lighter-colored fragments and sand grains occur between the dark chips. However, the color of the larger fragments dominates, giving the area a dark color both on the ground and on space pictures. The derivation of the streak material confirms the con-

tribution of local sources to dark streaks in southwestern Egypt.

Veverka [1975] has cited temporal variations of light and dark streak patterns observed during the 1971 dust storm on Mars as evidence that dark streaks have an erosional origin. The rapidly changing form of dark streaks over a short period of time suggests that there is not a large quantity of material being redistributed [Veverka, 1975]. Figure 8 shows an erosional dark streak extending southward in the lee of a granite knob (Qâret el Maiyit) about halfway between Kharga and the Gilf Kebir. This inselberg is a remnant of basement rocks that protrudes about 15 m above the surrounding eolian plain. The streak is composed of reddish soil veneered by a lag pavement of 5- to 7-mm granitic pebbles and granules eroded from the hill. This lag surface has been deflated to a depth of about 2 m lower than the surrounding plain. It is bordered on both the east and west by a light-colored sand sheet. Because the pebbles on the surface of the streak are not likely to be shifted about by the frequent sand-moving winds, the shape of the streak will probably change mainly in response to the shifting of the light-colored sand on both sides [El-Baz and Maxwell, 1979a].

#### YARDANGS

The barren surface of the Western Desert is broken here and there by hills, which include yardangs, inselbergs, and volcanic cones. Yardangs and inselbergs are among the most spectacular erosional landforms in the Western Desert. Whereas inselbergs are outliers eroded from escarpments and thus require the existence of sufficient relief for their formation, yardangs are hills or hillocks left standing above troughs that are excavated by the wind. Their shape differs from that of inselbergs in that yardangs are streamlined by the wind and their length greatly exceeds their width—by a ratio of 3:1 or more,—whereas inselbergs are roughly equant. The occurrence of yardangs does not require the presence or former presence of an escarpment, and they are restricted to the most arid parts of deserts, where wind erosion dominates in molding the landscape [McCauley *et al.*, 1977a, b]. Yardangs are eroded in both soft and hard rocks by a combination of abrasion and deflation. Their most obvious prerequisites are strong, unidirectional or reversing winds and great fetch over barren continuous rock exposures or over the surfaces of poorly consolidated sediments. In the southern part of the Western Desert these conditions are met on the limestone plateau between Assiut and the Kharga Depression, on the floor of the Kharga Depression, and wherever lacustrine or sebkha deposits occur.

One of the largest fields of small yardangs in soft lacustrine deposits occupies the floor of the Kharga Depression east of Kharga. It is easily accessible along the paved highway to Assiut, a few kilometers north of Kharga. The lacustrine deposits consist of slightly indurated, brownish sand and clay that unconformably overlie harder and older rocks. They are furrowed by wind and sand into a multitude of elongated hummocks, which are 3–5 m high, a few meters wide, and tens of meters long [Beadnell, 1909, p. 111]. The rate at which the lacustrine deposits are deflated varies from layer to layer according to slight differences in resistance to weathering and erosion: degree of cementation and bedding and jointing patterns are among the controlling factors. The resulting landform is known under a variety of evocative names such as

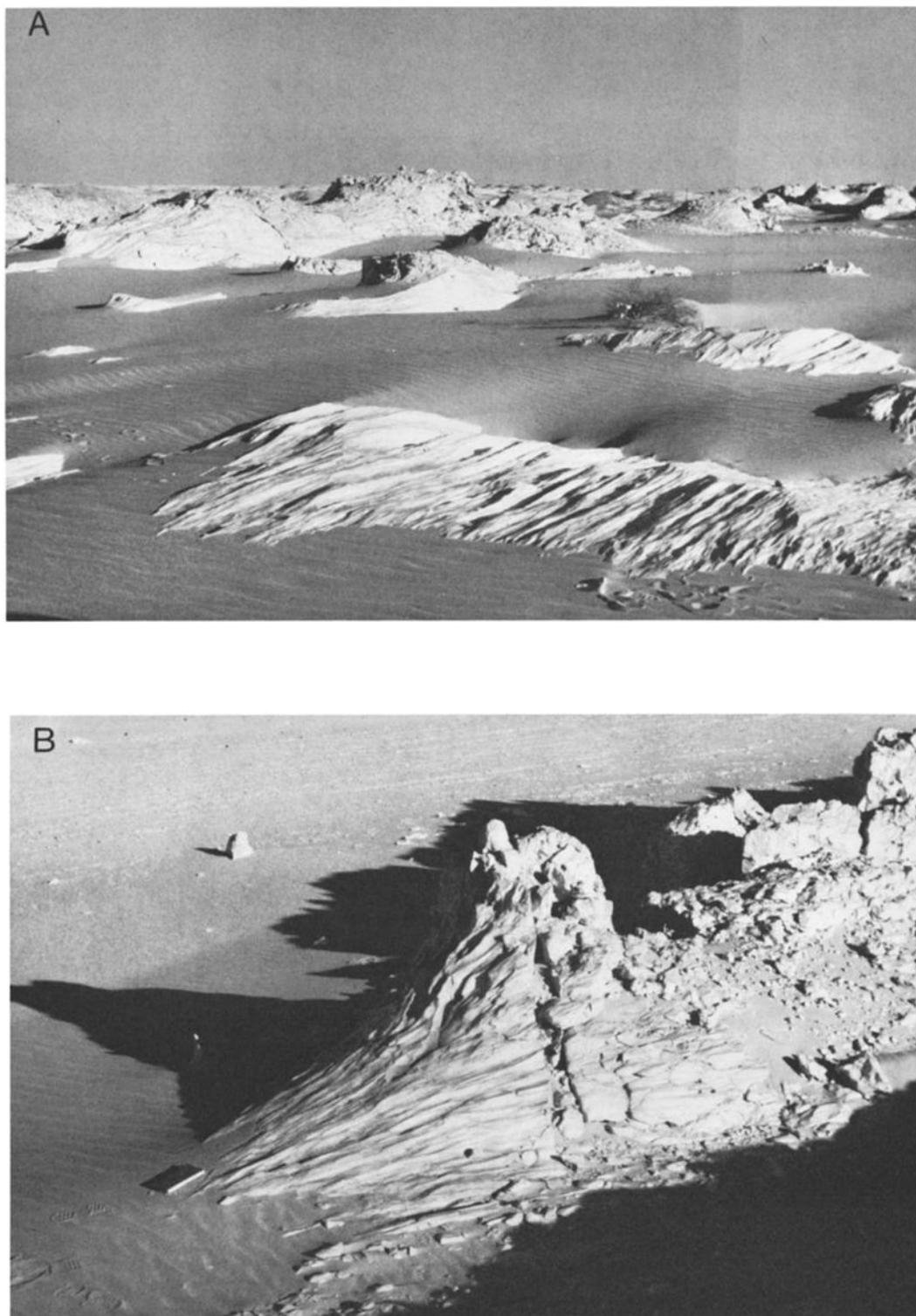


Fig. 11. (a) Ground view of typical kharafish terrain, about 20 km north of the Kharga Depression. Streamlined limestone hillocks, with fluted prows pointing into the direction of the northerly wind, rise a few centimeters to a few meters above sand-choked couloirs. Flutes are parallel to one another on the gently sloping limestone surfaces (foreground) and vertical side slopes. The limestone rubble on top of the yardangs indicates the upper limit to active wind abrasion. The orientation of sand and granule streamers is controlled by irregularities along the yardangs. The bush at center right of the photograph is about 1 m across. (b) Close-up view of an 'artichoke head' or prow in the yardang field shown in Figure 10. Flutes diverge upward and sideways from a 'node' located at couloir level, a few centimeters upwind from the prow. The prow points into the direction of northerly wind. Limestone rubble downwind from the prow is being abraded and deflated along bedrock joints normal to the direction of the northerly wind. Notebook at lower left for scale.

mud lion, recumbent lion, sitting sphinx, and sphinx hill (Figure 9a).

The yardangs are separated by long and shallow troughs, or 'couloirs' [Mainguet *et al.*, 1974], which bear no morphological evidence of fluvial erosion. The long axes of both yardangs and couloirs are parallel to the prevailing northerly wind. Fields of well-developed mud lions also occur south of Kharga [Embabi, 1972]; in the southern part of the Western Desert, southwest of Kharga [Bagnold, 1933, p. 105, 1939, p. 283]; and on the floors of shallow depressions along Bagnold's 1932 and 1938 routes to the Gilf Kebir. One of these fields of 'mud' deposits was illustrated by Shaw [1936, p. 198].

Besides mud lions, yardangs have also been carved out of the much more resistant Nubian Sandstone of Cretaceous age within the Kharga Depression (Figure 9b). Outside of the depression a very large field of yardangs has been eroded in the dense, crystalline Thebes Limestone of early Eocene age, which caps the plateau that extends from the Nile valley to the edge of the Kharga Depression (Figure 10a). These limestone yardangs and those in the Nubian Sandstone within the depression were first sighted and photographed during our flight from Cairo [Grolier *et al.*, 1979].

The Thebes Limestone was previously reported to be furrowed by the wind into a very rough surface which was called 'kharafish' [Beadnell, 1909, p. 35]. Kharafish topography as originally described consists of innumerable sharp-ridged hill-locks separated by troughs that are partly buried with sand. Hillocks and troughs lie parallel to the direction of prevailing winds. This type of terrain was considered by Gautier and Mayhew [1935, pp. 112–113] to be similar to that in western China, where yardangs were first described by Hedin [1905], but the general impression left by these early explorers was that these wind erosion forms were small features.

In the flights to and from Kharga we realized that the kharafish topography represents only a small part of a far more extensive field of large yardangs (Figure 10a). This field of streamlined hills and couloirs is approximately 150 km long and at least tens of kilometers wide. Westward, it extends at least as far as the Ghard Abu Moharik as observed by Bagnold [1933, pp. 104–105] and Sandford [1933, p. 214]. Bagnold [1933] states: 'We kept to the dune edge . . . , with the result that we became entrapped in a series of parallel wind-scored corridors in the rock, which led straight for the brink of the precipitous cliffs of the depression.' Farther south, Hobbs [1917, p. 349] had observed the wind-eroded, flat-topped hill-locks and associated siliceous concretions ('melons') from the railroad track (now abandoned) leading from the Nile valley to Kharga. Forty-five years ago, P. A. Clayton photographed a field of similar siliceous concretions on the Darb el Arbain road south of Assiut [Murray, 1951].

The innumerable hillocks reported by Beadnell [1909] are only the smallest of the limestone yardangs in the Kharga area. Countless larger yardangs, which occur isolated and in clusters, are hundreds of meters long and tens of meters high (Figure 11a), but like the yardangs of the Takla Makan in western China and unlike the larger yardangs of the Lut Desert in Iran [McCauley *et al.*, 1977a, b] they are detectable only as faint and very fine grooves at Landsat images (Landsat image 1110–07561, November 10, 1972).

One day's ground reconnaissance of these features showed the irregular tops of the larger yardangs on the plateau to be mantled by a grayish-pink residual material described by Haynes [1978] as terra rossa. It is similar to the terra rossa so

commonly found on limestone terrain in much of the Mediterranean region. Terra rossa extends downward into cracks and irregular cavities within the limestone. The upper part of the Thebes Limestone—the part that is furrowed by the wind—is silicified, and it is unusually hard and resistant. Siliceous concretions—the melons of British geologists and 'bat-tikh' of Egyptian geologists—are common erosional remnants on the windswept surface of the kharafish terrain. The chemical changes implied by terra rossa, by silicification, and by solution features such as interconnecting cavities suggest that a wetter climate had prevailed over the region for a long time prior to the conditions of extreme aridity that must have prevailed during the carving, by the wind, of the limestone yardangs. A general outline of the Quaternary climatic fluctuations in this region is described by Murray [1951].

The smaller streamlined rock exposures typical of the kharafish terrain are intensely fluted into the wind, in the lee of the wind, and also on side slopes. They resemble artichoke heads or the prows of heavy ships, with the stern or the prow pointing into the wind (Figure 11b). The wind-fluted and polished crystalline limestone glistens in the sun in an interval of several meters high above the couloirs, which are choked with ripples of abrading sand and granules. Unlike sharp-crested, keel-shaped yardangs of other deserts these are commonly flat topped and retain some of the weathered surface that predates wind erosion. Thus these yardangs seem less mature than the sharp-crested variety, and the tops may mark a surface below which the depth of wind erosion can be estimated. The relation of yardang development to rock types and climate changes will be an important component of our future investigations. The discovery and preliminary description of these wind features in bedrock of the Kharga area was one of the major results of our expedition. A detailed study of the extraordinarily large yardang field in the Thebes Limestone may lead to a better understanding of the extensive yardang fields seen on Mars (Figure 10b), first on Mariner 9 images [McCauley, 1973, Figure 2c] and in more detail on the recently acquired Viking orbiter images [Ward, 1978, this issue].

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