

Orbital Observations of Sand Distribution in the Western Desert of Egypt

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ABSTRACT

Apollo-Soyuz Test Project photographs of the Western Desert of Egypt were studied to discover the usefulness of orbital imagery in delineating sand deposits. A strip of Apollo-Soyuz mapping-camera photographs was used to map sand distribution patterns. Information from this strip was extrapolated to the rest of Egypt using a false-color mosaic of Landsat images.

Sand deposits in the Western Desert were divided into the following 12 areas for observation and discussion: (1) Wâdi el Natrûn, (2) Qattara, (3) Baharîya, (4) north Sitra, (5) south Sitra, (6) Great Sand Sea, (7) El-Quss Abu Said, (8) Farâfra, (9) Dakhla, (10) Khârga, (11) Oweinat, and (12) Faiyûm. Each area shows a distinct pattern of sand deposition and dune formation that is closely related to topography and wind patterns.

In general, the dunes of the Western Desert trend in a clockwise pattern around a center near Kufra Oasis in Libya. The dune orientations change from north-northwesterly in the northern desert to north-northeasterly in the south. The dunes are intimately associated with scarps that bound numerous depressions in the Western Desert. This relationship is believed to result from the interactions between sand-carrying winds and scarps and other topographic variations.

The sand distribution pattern also reveals areas where dune movement presents a threat to cultivated land. Examples of these areas are on the

western side of the Nile Valley, where the Faiyûm dune field in particular is encroaching on fertile land, and in several of the Western Desert oases.

INTRODUCTION

Although as much as a third of the world's landmass can be called arid and as much as 20 percent has been classed as desert, only approximately 4 percent is actually covered by sand (refs. 1 and 2). The distribution of these sand deposits, whether single dunes, dune fields, sand drifts, or the more amorphous sand sheets, is a far from random phenomenon. The factors controlling the occurrence and morphology of sand deposits are complex; they include the wind direction, strength, and duration; the nature, extent, and rate of erosion at the sediment source; the distance from the source; the grain and fragment size; the underlying and surrounding topography; the nature of the surface (rough or smooth); the amount and type of vegetation; and the amount of rainfall (refs. 2 and 3). Although a number of studies have dealt with these factors, a thorough understanding of the mechanisms governing sand movement and deposition is still lacking.

Recently, though, the desertification of what were once arable lands has resulted in an increasing emphasis being placed on general desert studies. Because spreading sands are both a result of and an element in the process of desertification, two of the aims of these studies are (1) to map sand distribution and (2) to determine the direction of sand movement (ref. 4). For this investigation of sand distribution, the Western Desert of

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Egypt was chosen because it contains a variety of desert landforms and because excellent photographs of it were obtained during the Apollo-Soyuz Test Project (ASTP).

During the past decade, orbital photography has emerged as a useful tool in the study of large, inaccessible, and remote desert regions. Because of their large regional coverage and their ability to depict temporal distributions, space photographs can provide a new way of observing features of the desert environment, particularly sand distribution. With this fact in mind, the ASTP Visual Observations Team selected photographic targets over eight desert regions including the Western Desert of Egypt (ref. 5).

The ASTP photographs of Egypt were studied to ascertain (1) the usefulness of orbital photographs and satellite images in mapping the distribution of sand deposits; (2) the types of images and the resolutions needed for such mapping; and (3) the varieties of fieldwork and other supporting data needed. The Western Desert of Egypt was studied using both ASTP photographs and Landsat images, which were complemented by collateral data in the form of aerial photographs, field observations, and ground photographs. In addition, attempts were made to correlate these various types of data for the purpose of determining the direction of sand movement and the provenance of the sand.

STUDY AREA

In the Western Desert, explorers and scientists working in various disciplines have "rubbed shoulders" for years in attempts to decipher secrets of the ancient past and also in performing field studies in geology, meteorology, and biology. Much of the basic research on dune classification and sand movement by wind has been performed in the Western Desert. Bagnold (ref. 6) did work there that led to his classic study of sand movement and dunes. Geological works include the pioneering studies of Ball (ref. 7), Beadnell (refs. 8 to 10), and Sandford (ref. 11), as well as more recent work (e.g., ref. 12).

Deserts have traditionally been remote places of mystery, and the Western Desert still retains

this mystique, even though it is perhaps one of the best studied desert areas in the world. The Western Desert includes all the land in Egypt west of the Nile River (fig. 1). It has an area of 681 000 km², approximately 27 percent of which is actually covered by sand. It is essentially a low-elevation plateau consisting of expanses of rocky terrain interrupted by a series of scarp-bounded depressions and crossed in numerous places by parallel belts of sand dunes and extensive deposits of relatively flat sand sheets (ref. 12).

The regional geology of the Western Desert is characterized by great thicknesses of sedimentary rocks that dip gently to the north (ref. 12). Rocks exposed at the surface include the Cretaceous Nubian sandstone in the south; Cretaceous and Eocene limestones in the central part; and, farther north, Miocene marly limestones and calcareous sandstones. The great oases (Sîwa, Bahariya, Farâfra, Dakhla, and Khârga) are all located in scarp-bounded depressions that occur at the boundaries between these formations. The generally sedimentary character of the Western Desert plateau is disturbed in the southwestern corner of Egypt by a number of volcanic cones and by the plutonic massifs of Gebel Arkenu, Gebel Oweinat, and Gebel Kissu. Only the northeastern flanks of Gebel Oweinat are actually within Egypt; Gebel Arkenu lies in Libya and Gebel Kissu in Sudan.

PHOTOGRAPHIC DATA

The ASTP photographs of Egypt include (1) a strip of 15 overlapping mapping frames taken with a bracket-mounted 70-mm Hasselblad data camera (HDC) and (2) a series of 40 handheld-camera photographs taken with a 70-mm Hasselblad reflex camera and a 35-mm Nikon camera. A color-sensitive film (SO-242) especially selected for desert photography was used for the HDC mapping pass (ref. 5). The accurate depiction of color variations in deserts was regarded as essential because the color tones that delineate sand bodies could provide information on the chemical makeup and relative age of desert sands. (See section entitled "Color Zoning in the Western Desert of Egypt.") Additional informa-

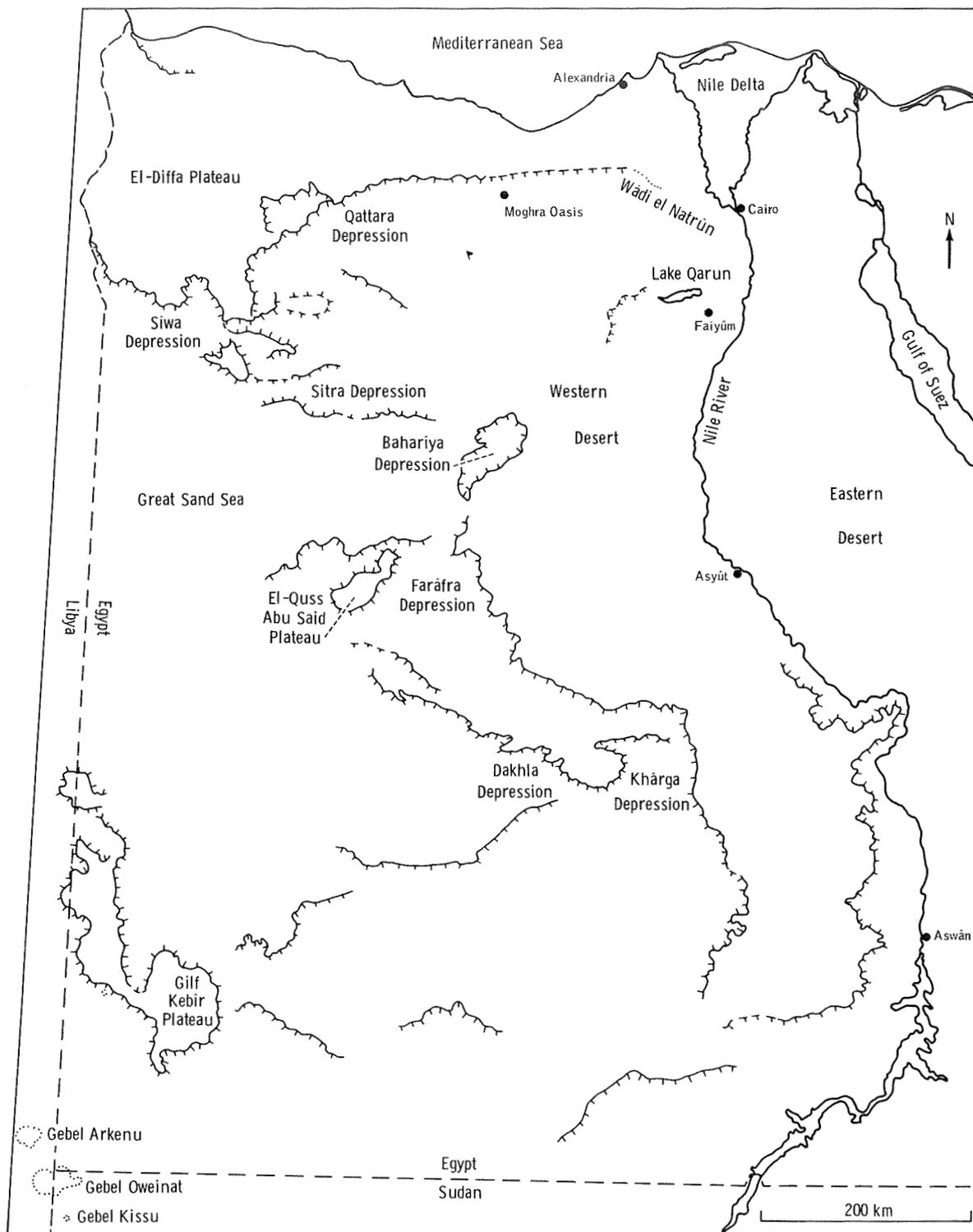


FIGURE 1.—Sketch map of the Western Desert of Egypt showing the location of features and places mentioned in the text.

tion on the ASTP photographs is given in NASA publication number TM 58218, a catalog of ASTP Earth photographs.

Figure 2 is a color mosaic of the ASTP mapping pass of Egypt. This mosaic extends from the Egyptian-Libyan border (latitude 26° N and longitude 25° E) to the Mediterranean Sea (latitude 32° N and longitude 31° E). A variety of desert landforms are clearly shown in these photographs. At the western end, a sharp color difference marks the boundary between the reddish gravel plains associated with the Gilf Kebîr sandstone plateau and the yellow sands of the Great Sand Sea. Within this sand sea, long linear dune features trending northwest-southeast are visible. Other sand features evident in these photographs include dune fields south and northeast of Sitra Depression, the northern limits of three dune belts bordering Bahariya Depression, and an extensive series of parallel dunes south of the northern scarp of Qattara Depression. In addition, the northeastern boundary of the Western Desert is easily distinguished by the contrast between the dark-green, fertile Nile Delta and the yellow, barren desert plain. In this area, an interesting pattern is revealed in the relation of sand deposits and cultivated land. West of the Nile Delta, the mottled sand/vegetation pattern is caused by an increase in cultivated land. (See section entitled "Temporal Changes as Depicted on Orbital Photographs of Arid Regions in North Africa.") As will be discussed later, this is in contrast to the situation 250 km south of the delta (cf. plate 2 in ref. 13), where a similar pattern is caused by dunes encroaching on the narrow strip of farmland bordering the Nile River.

Knowledge gained from studies of orbital photographs of one area can often be used for correlations with other spatially removed but geographically similar regions. To extend the usefulness of the ASTP data to the entire Western Desert, as well as to other desert regions of the world, an attempt was made to extrapolate from the orbital photographs to Landsat satellite images. A false-color mosaic of 65 Landsat images of Egypt was prepared (fig. 3). Each false-color image is a combination of band 4 (0.5 to 0.6 μm), band 5 (0.6 to 0.7 μm), and band 7 (0.8 to 1.1 μm) data. In these Landsat color composites, vegeta-

tion appears red; rocks and soils are shades of yellow and brown; deep, clear water is black; and sediment-laden water has blue tones. An effort was made to match the desert colors on the Landsat images with the colors on the ASTP photographs to facilitate the recognition of sand deposits. (See section entitled "Color Zoning in the Western Desert of Egypt.")

SAND DISTRIBUTION

The Landsat mosaic provided a useful photobase on which to map sand distribution for all of Egypt. Figure 4 is a thematic map showing the location of sand deposits in the Western Desert. This map was prepared from the Landsat mosaic and the ASTP photographs. A comparison of the usefulness of the two types of data will be discussed later.

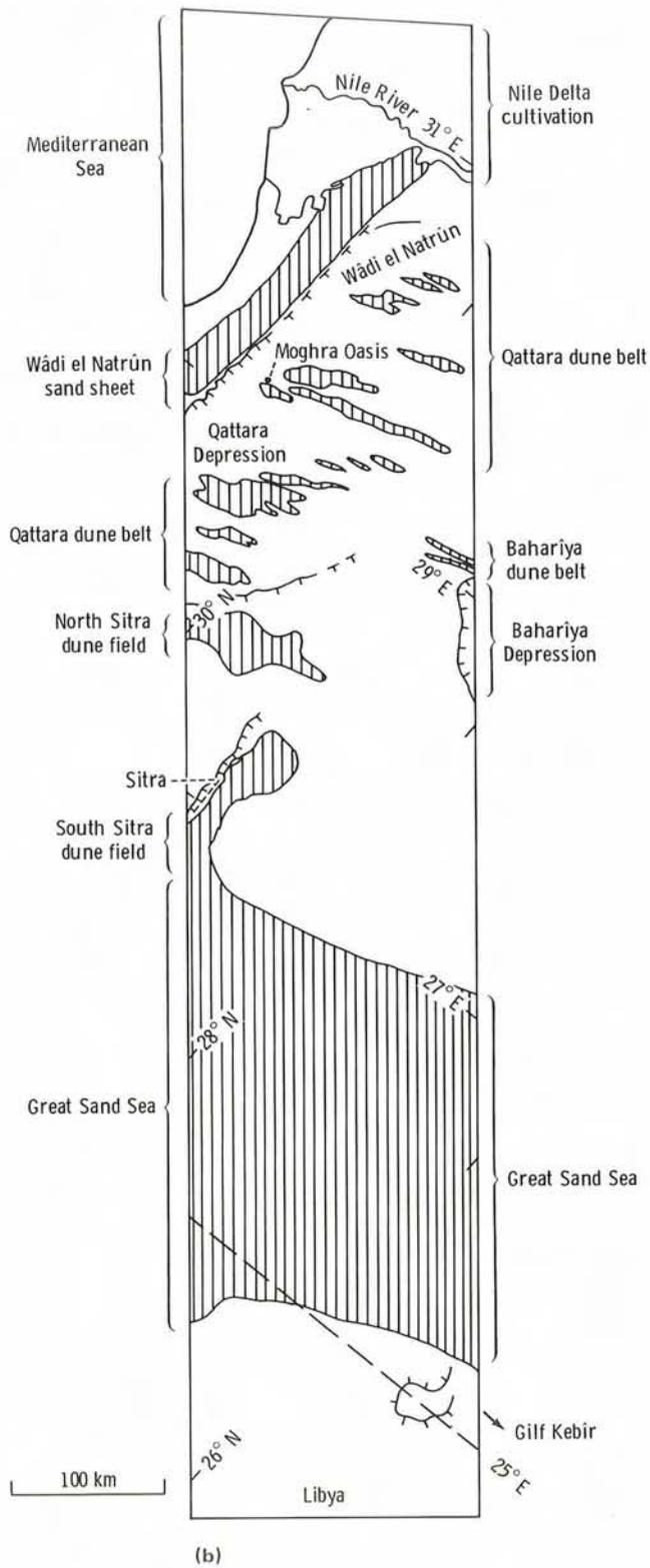
The pattern of sand distribution depicted in figure 4 reveals several distinctive features. Of particular interest is the orientation of the major dune trends. Ball (ref. 7, p. 128) points out that the dune trends in the Western Desert probably afford a very exact index to the general wind direction. The overall dune pattern is one of clockwise veering of trend around a point near Kufra Oasis in Libya (latitude 24.5° N, longitude 23° E). This pattern has already been documented (refs. 6, 7, and 14), and it implies a change in the prevailing wind direction from north-northwest in the northern desert to north-northeast in the southern desert near Gebel Oweinat.

Another interesting feature is the association of sand deposits and the depression-bounding escarpments previously described. Three types of relationships can be noted. First, in many places, sand dunes and sheets lie south of the east/west-trending scarps. In some areas, such as Qattara, Sitra, and Sîwa, there is a sand-free area at the foot of each scarp, and the sand deposits do not start until farther south. This can perhaps be attributed to the occurrence of wetlands (sebkhas) or lakes

FIGURE 2.—Area covered in the ASTP mapping pass over Egypt. (a) Color mosaic of ASTP photographs (AST-16-1246 to AST-16-1257). (b) Sketch map showing the major physiographic features. →



(a)



(b)



FIGURE 3.—False-color mosaic of 65 Landsat images of Egypt. (Prepared by the General Electric Company for the Smithsonian Institution.)

at the bases of the scarps; sand deposition does not occur until farther away, where it is dry enough for dunes to form. In other areas, it appears that the sand actually starts at the bases of the scarps. This mode of sand deposition can be attributed to a rapid decrease in the velocity of the prevailing northwesterly winds as they meet the scarps. This decrease is concomitant with a decrease in the sand-carrying capacity of the winds and results in sand deposition on descending slopes (ref. 15).

A second sand/scarp-related feature is seen where a large dune, a series of dunes, or a sand sheet is moving from one direction (usually from the north) and meets a scarp trending perpendicular (generally east-west) to the direction of sand movement. The effect of the scarp in this case is to break up the sand bodies and split the dunes into stringers, which sometimes recombine to continue as dunes downwind of the scarp. This is particularly true in the case of the Khârga scarp.

A third association of sand deposits and scarps



FIGURE 4.—Map showing the location of sand deposits in the Western Desert. These deposits are designated (1) Wâdi el Natrûn, (2) Qattara, (3) Baharîya, (4) north Sitra, (5) south Sitra, (6) Great Sand Sea, (7) El-Quss Abu Said, (8) Farâfra, (9) Dakhla, (10) Khârga, (11) Oweinât, and (12) Faiyûm.

occurs when a depression is enclosed not only on the north but also on the east and/or west by steep north/south-trending escarpments. Sand blown into the depression from the north is channeled southward. In the depression, the prevailing northerly winds and the north/south-trending scarps reinforce each other as factors in sand deposition.

Another type of relationship is seen in places where sand meets a rise in topography. This results in a change in the direction of sand movement. An example is seen in the Oweinat region, where the sand is diverted around protruding igneous masses that lie in the path of regional sand movement. Places where the topography rises more gently also seem to have the effect of halting or rerouting sand.

This study of sand distribution also helped pinpoint areas where moving sands constitute a threat to cultivated lands. The encroachment of dunes on fertile land represents a danger to the economy of Egypt, particularly because less than 4 percent of the land area of Egypt is presently cultivated; the rest is barren desert.

DISCUSSION OF SPECIFIC AREAS

The sand deposits mapped from ASTP photographs and Landsat images were divided into 12 areas for observation and discussion. These are designated (1) Wâdi el Natrûn, (2) Qattara, (3) Bahariya, (4) north Sitra, (5) south Sitra, (6) Great Sand Sea, (7) El-Quss Abu Said, (8) Farâfra, (9) Dakhla, (10) Khârga, (11) Oweinat, and (12) Faiyûm (fig. 4, table I). Areas 1 to 6, 11, and 12 were covered by ASTP photographs; supporting data in the form of Landsat images and aerial photographs provided information on the remaining areas.

Figure 5(a) is a mosaic of five ASTP mapping photographs showing the area between Sitra and the Nile River. Just west of the Nile Delta, three broad color zones in the desert can be seen; on a mosaic of Landsat images of the same area (fig. 5(b)), only two of these zones could be detected (ref. 13). (See section entitled "Color Zoning in the Western Desert of Egypt.") One of the color zones was tentatively identified as a sand sheet

because of its bright yellow color and uniform tone (fig. 4). This sand sheet has been designated area 1, Wâdi el Natrûn. This zone runs roughly east-west and is approximately 22 km in width.

Aerial photographs of area 1 were examined to substantiate the ASTP findings. These photographs show a dune field northeast of Wâdi el Natrûn (fig. 6). The dunes are simple and compound crescentic forms; their slip faces indicate prevailing easterly winds and dune movement to the west. Near the outer western margin of the dune field, the dune forms dissipate into a sand sheet. The aerial photographs therefore confirm the ASTP interpretations, although the resolution of the orbital photographs was not sufficient to discern individual dunes.

Five other areas of sand dunes were depicted in the ASTP mapping strip; these are Qattara (area 2), Bahariya (area 3), north Sitra (area 4), south Sitra (area 5), and the Great Sand Sea (area 6). Unfortunately, some of the photographs over the Great Sand Sea were overexposed, and only dune forms near the northeastern and southwestern borders of area 6 could be identified. In areas 2 to 5, however, sand distribution and regional sand patterns were easily mapped and were found to be intimately related to topographic scarps.

Qattara Depression is bounded by a steep northern and western escarpment. The lowest elevations in the depression (134 m below sea

TABLE I.—Areal Extent of Major Sand Deposits in the Western Desert of Egypt

Dune belt designation	Area, km ²
1. Wâdi el Natrûn	3 000
2. Qattara	18 000
3. Bahariya	4 500
4. North Sitra	4 000
5. South Sitra	2 100
6. Great Sand Sea	72 000
7. El-Quss Abu Said	800
8. Farâfra	10 000
9. Dakhla	2 700
10. Khârga	8 000
11. Oweinat	31 500
12. Faiyûm	2 400

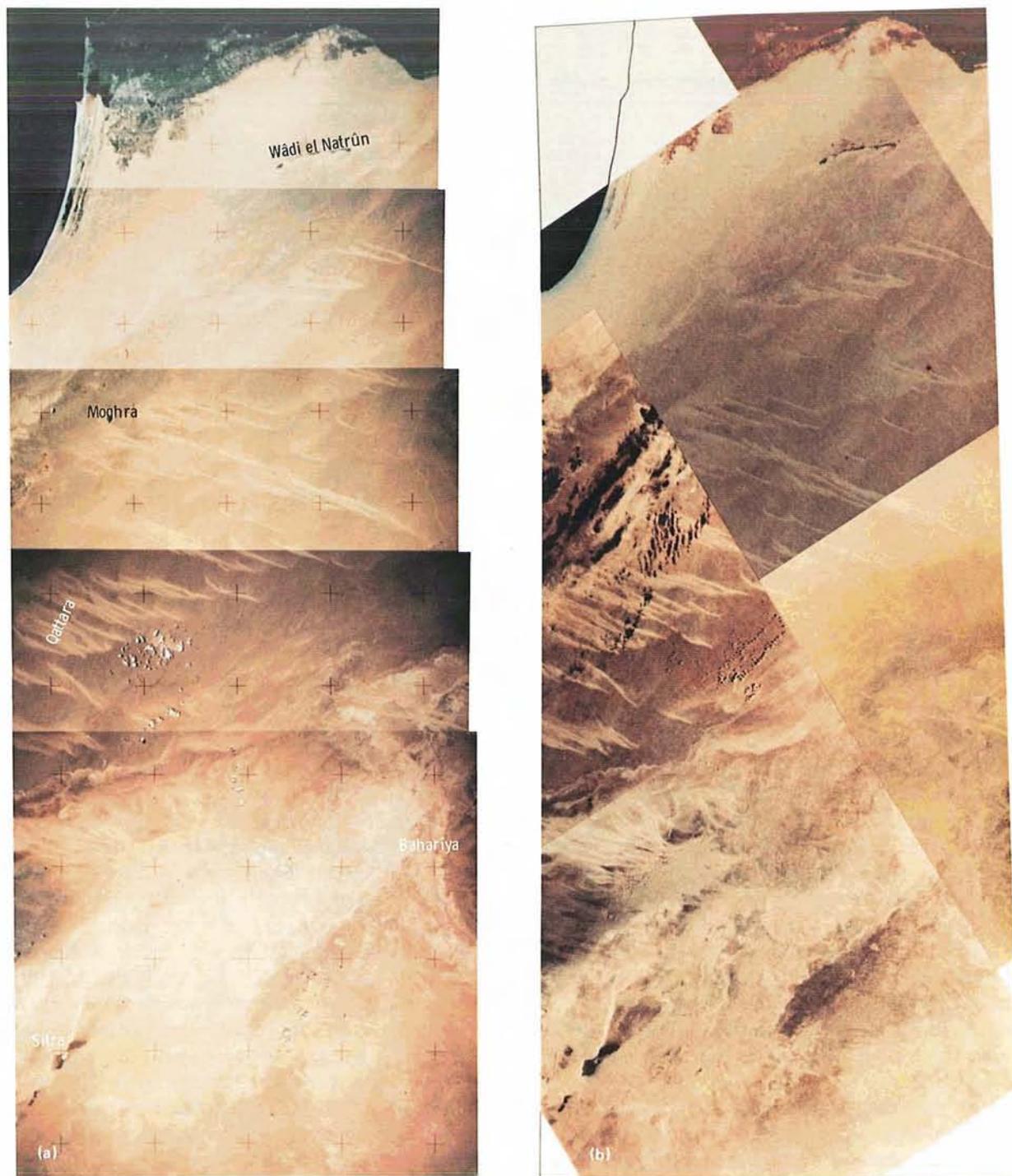


FIGURE 5.—Photomosaics of area between Sitra and the Nile River. (a) ASTP mapping photographs (AST-16-1252 to AST-16-1256). (b) Landsat false-color images.

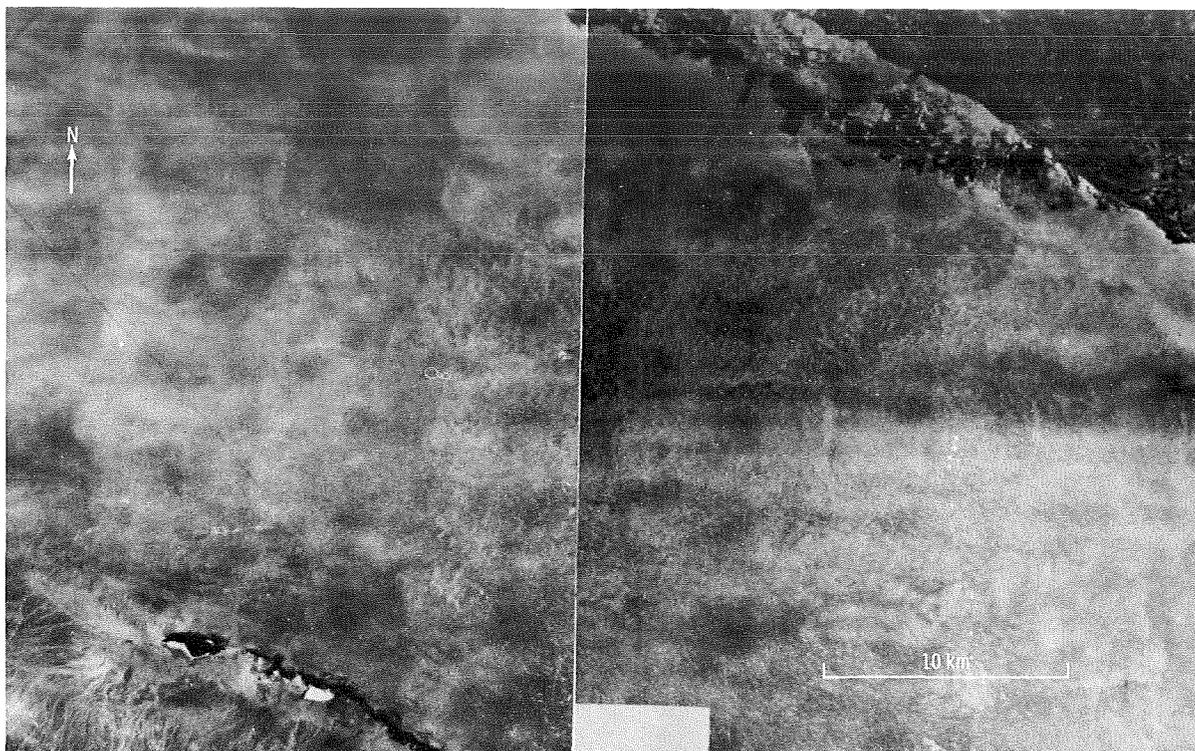


FIGURE 6.—Mosaic of two aerial photographs of the Wâdi el Natrûn area. Part of the Nile Delta is visible in the upper right corner. Wâdi el Natrûn is the elongated dark area in the lower left corner. A field of crescentic dune forms is visible northeast of Wâdi el Natrûn. (Photograph from the Military Survey, Egypt.)

level) are located at the foot of the northern scarp and are characterized by sebkhas. Toward the south and east, the depression is more open and its floor rises gradually to the general level of the desert surface (ref. 16). Because of this, the sea level contour is usually chosen to mark the southern and eastern limits of the depression on topographic maps. The northeastern border of Qattara is usually placed near Moghra Oasis, one of two oases within the depression. However, on the ASTP photographs, a continuation of the northern scarp, although poorly defined, can be traced at least to Wâdi el Natrûn, 140 km east of Moghra.

Large quantities of material have been removed from Qattara Depression by wind deflation, and sand-sized particles are blown to the south-southeast, where they are deposited as long chains of sand dunes (ref. 16). The Qattara dunes (area 2) begin south of the sebkhas and extend to the south-southeast; their lengths vary from 10 to

40 km (fig. 5(a)). The Qattara dunes have been referred to in the literature as seif dunes (ref. 17). They are characterized on the orbital photographs by diffuse northern ends and tapering southern termini. These dunes are subparallel, but they are not equally spaced along the desert surface. In fact, the ASTP photographs show that these dunes are clustered in bundles; in some cases, two or more dunes may join at the southern ends to produce a "spearhead" (ref. 18). Dune density increases to the west and, on the photographs, it is difficult to identify individual dunes within these westernmost bundles. In contrast, however, dunes in the eastern part of area 2 appear better defined. This variation within area 2 can perhaps be attributed to the effect of the northern Qattara scarp on the prevailing northwesterly winds. As the scarp increases in height to the west, crosswinds might become more prevalent. This possibility is confirmed by an examination of aerial photographs, which reveal crescentic forms concen-



FIGURE 7.—Aerial photograph of dunes in the western part of Qattara dune field. (Photograph from the Military Survey, Egypt.)

trated at the northern ends of these westernmost dunes (fig. 7). The orientation of these crescentic slip faces indicates crosswinds normal and oblique to the direction of the prevailing wind.

Baharîya Oasis lies 170 km southeast of Qattara in a scarp-enclosed depression excavated in a plateau of Eocene limestones (ref. 12). Details of the northern ends of three large dune belts north-

east of Bahariya (area 3) are revealed in the ASTP mapping strip (fig. 5(a)). The three dune belts are oriented south-southeast and are named Ghard Ghorabi, Ghard El-Qazzun, and Ghard Abu Muharik. The last dune belt is the longest measured dune line in Egypt, extending approximately 300 km from the northeastern tip of Bahariya Depression to Kharga Depression.

On ASTP photographs, the Bahariya dunes are similar in appearance to the Qattara dunes (fig. 5(a)); on a Landsat image of the same area, these dunes are much more difficult to distinguish (fig. 5(b)). To extend the ASTP data and to determine the southern limits of the Bahariya dunes, aerial photographs and Landsat images were examined. Aerial photographs indicate that to the southeast of Bahariya, the dunes diffuse into a broader belt of sand sheets and longitudinal dunes (ref. 18). On the corresponding Landsat images, it is extremely difficult to distinguish these sand deposits from the surrounding terrain on the basis of color. In this area, where the bedrock units have not been well mapped (ref. 19, p. 22), fieldwork is necessary to determine whether color variations are due to different bedrock units or to various ground coverings such as sand.

The north Sitra dune field (area 4) provides a good illustration of how dune form is influenced by local relief. Stereoscopic examination of two ASTP mapping photographs shows that the dune field is bounded on the west by a topographic high and on the northeast by a poorly defined scarp that marks the southern limit of Qattara Depression. The dunes do not start at the foot of the scarp (fig. 5(a)). For this reason, the dark mottled tones occurring at the base of the scarp have been interpreted as sebkhas. In the northern half of the dune field, long slightly curving dune forms seem to converge toward the south where a break in slope coincides with a change in dune form. Examination of a Landsat image of this area revealed a change in size, spacing, and orientation of dune forms at this break in slope (fig. 5(b)). In this case, the quality of the Landsat image was better than that of the ASTP photograph, a fact probably attributable to Sun elevation angle (37° for the Landsat image and 80° for the ASTP photograph).

The south Sitra dune field (area 5) lies in Sitra Depression, which is bounded on the north and

south by east/west-trending scarps (fig. 5(a)). Lakes and sebkhas occur directly south of the northern scarp, and the dune field lies south of these wetlands. In this area, the identification of sand deposits was facilitated by the color contrast between the sand and the interdune surfaces. It seems likely that in the north Sitra and south Sitra dune fields, variations in topography increase the complexity of the wind regime. Both factors (topography and deviations in wind strength and direction) have an effect on dune geometry.

The western end of the south Sitra dune field grades into the Great Sand Sea (area 6). The Great Sand Sea is the largest dune field in Egypt. It begins just south of the oases that border the southern edge of El-Diffa Plateau in Libya and Egypt. The sand sea then continues south for 600 km before the dunes are deflected by the Gilf Kebir Plateau and associated topographic highs. Although most of the ASTP mapping photographs of the Great Sand Sea were overexposed, linear seif dunes of tremendous lengths can be seen at the southern border of the sand sea. Landsat images provided more detail and revealed a change in form from large seif dunes with sinuous crests (called "whalebacks" by Bagnold, ref. 6) (fig. 8) in the northern part of the Great Sand Sea to narrow linear seifs in the south.

Areas 7 to 10 were not covered by ASTP photographs but were examined on Landsat images. These areas are similar to Qattara, Bahariya, and Sitra in that they provide further illustrations of the relationships between sand deposits and scarps.

Two dune belts occur in Farafra Depression. Both a small field on the north side of El-Quss Abu Said Plateau (area 7) and a relatively large field filling a major part of the main depression (area 8) are visible on Landsat images, but dune forms cannot be well defined. The former field is interesting because the trend of its longitudinal dune forms is normal to the trend of the dunes in the Great Sand Sea, which borders the El-Quss Abu Said group on the west. The details of this dune field do not show well on Landsat images but are confirmed on aerial photographs. These photographs also reveal the interesting fact that these dunes converge and taper to the northeast and are more widely spaced to the southwest.



FIGURE 8.—Sinuous dunes at the northern edge of the Great Sand Sea. Top: numerous dunes that start at the southwesternmost edge of Siwa Oasis. Bottom: view from the top of one of the sinuous dunes; the vehicle near the base of the dune gives scale. (Photographs by Farouk El-Baz.)

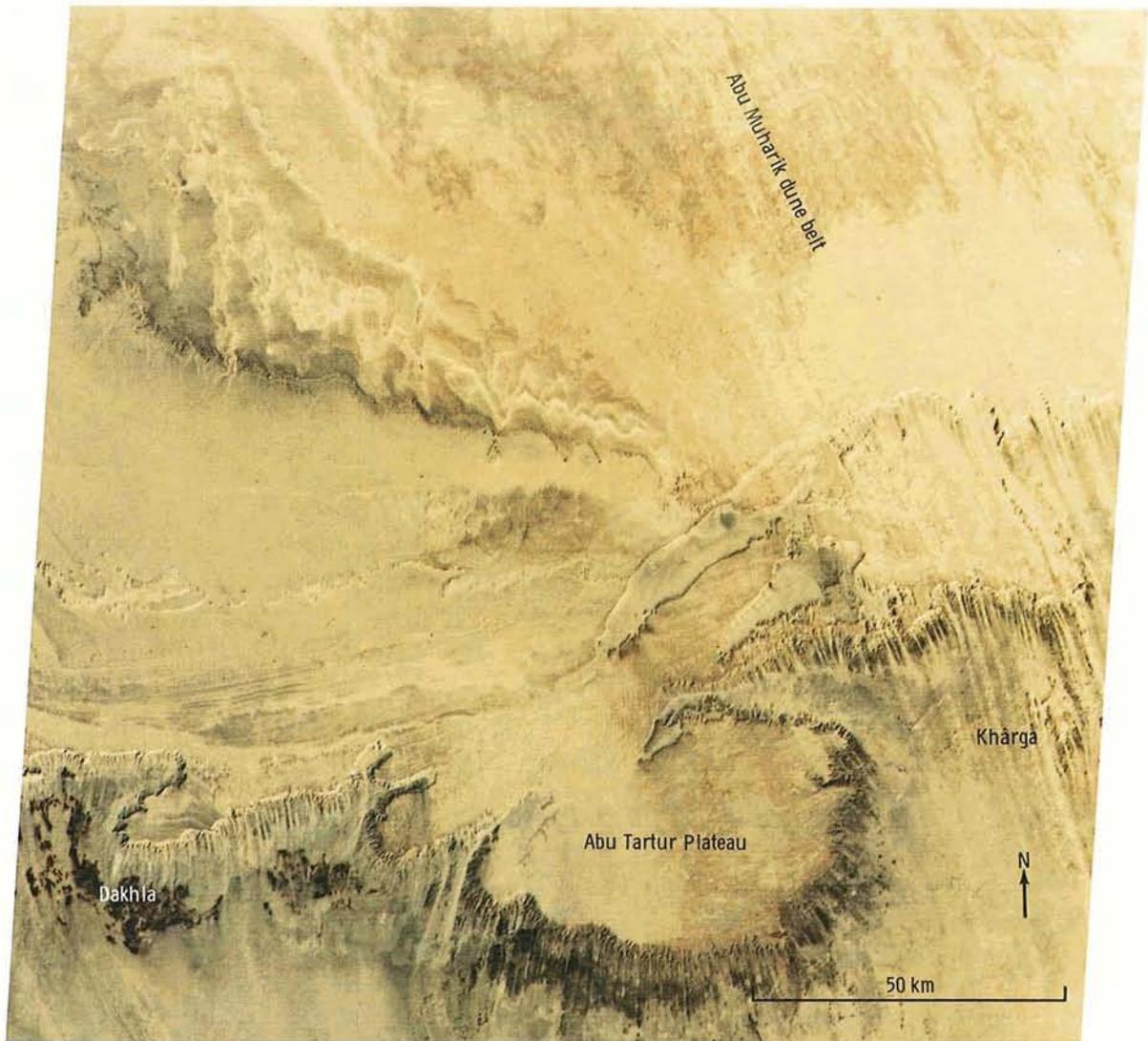


FIGURE 9.—Landsat false-color image of the Dakhla-Khârga area. Vegetated areas on the floor of these depressions appear in red tones (E-1165-08014).

Other dunes previously discussed (e.g., the Qatara dune bundles) converge to the southeast. The unusual patterns are probably attributable to wind deflection caused by the presence of scarps (ref. 19).

To the south, where the eastern north/south-trending Farâfra scarp veers to head east-west, the Farâfra dune field (area 8) spreads out to the east and south. Sand in the southern part of area 8 is channeled down the Dakhla scarp along wadis and then moves onto the flat floor of Dakhla Depres-

sion (fig. 9). Aerial photographs show that the Dakhla dunes (area 9) are barchans.

The occurrence of the barchan dunes in Khârga Depression (area 10) is similar to the situation in Dakhla. Sand is derived from the Abu Muharik dune field on the plateau north of Khârga Depression (fig. 9). The northern scarp is characterized by a number of remarkably linear sand-filled wadis that may be structurally controlled. A number of barchan chains begin at the mouths of these wadis and continue to move southward.



FIGURE 10.—Oblique ASTP photograph showing the patterns of sand distribution around topographic highs in the Oweinat region. Gebel Arkenu is approximately 15 by 20 km (AST-2-127).

Perhaps the best example of topographic control of sand deposits is in the area around Gebel Oweinat in the southwestern corner of Egypt (area 11). Excellent orbital photographs of this area are available (fig. 10). In the southwestern quadrant of the Western Desert, the prevailing

wind direction becomes northeasterly; this is reflected by the major trends of sand movement and deposition. Another major feature in this area is the presence of several protruding topographic highs with sand-free areas on their leeward sides. Sand deflected around the hills and mountains



FIGURE 11.—Aerial view of sand dunes encroaching on the cultivated land of the Nile Valley south of Cairo. Direction of sand movement is indicated by arrow. (After El-Baz, ref. 20.)

coalesces downwind to form dunes and stringers of sand reaching into Sudan to the south and Libya to the west.

The areas discussed up until now have been studied to show the relationships between sand, wind, and topography. Of equal interest are areas where sand movement constitutes a threat to cultivated land. The problem of sand dune encroachment on vegetated land has lately been the subject of much concern (ref. 13). An excellent example of the advance of dunes onto farmland is shown by ASTP and Landsat images of the Faiyûm dune belt (area 12). These dunes begin on the floor of the flat desert surface southwest of Faiyûm and stretch south-southeastward until they meet the western border of the Nile Valley. As segments of the dune field come into contact with vegetated lands, they diffuse around patches of wetter ground and produce a spotty, frayed edge to the sand/vegetation border (fig. 11, ref. 20). Dune encroachment on cultivations is

also observed in many of the Western Desert oases, particularly in Dakhla, Khârga, and Baharîya. This phenomenon shows up extremely well on Landsat false-color composites, where small vegetated spots appear as red islands in an ocean of yellow sand waves.

CONCLUSIONS

This study shows the usefulness of orbital images in mapping sand distribution patterns in the Western Desert of Egypt. The ASTP photographs and Landsat images were used to recognize and map the individual dunes, dune bundles, dune fields of various shapes and sizes, and relatively homogeneous sand sheets. However, the resolution and other qualities of these photographs and images fall short of allowing detailed study of the sand accumulations and their relationship to surrounding topography.

To enable clear delineation of dunes and other sand deposits from the surrounding bright sediments, orbital photographs must have the following characteristics:

1. Natural color: The brightness and the color of surface features are often important diagnostic characteristics in the recognition of sand deposits. Therefore, a highly color-sensitive film helps in the delineation of dunes and sand deposits. Also, variations in color within the same sand field or between different fields are usually meaningful (ref. 13). For these reasons, it is important to obtain a film record of the true colors of the surface.

2. Stereo overlap: Dune form is significant in determining prevailing wind directions and dune migration. Therefore, stereo coverage with the greatest possible vertical exaggeration is important to the study of sand distribution patterns.

3. High resolution: The resolutions of ASTP photographs (50 m at best) and Landsat images (80 m at best) are not adequate to clearly identify dunes and sand fields. The resolution required to achieve this identification is approximately 10 m.

4. Low-Sun-angle illumination: At relatively high Sun angles, the sand deposits appear washed out and it is very difficult to distinguish sand dunes from the surrounding sediments that appear equally bright. Low-Sun-angle illumination provides shadows that clearly delineate the dunes. A Sun angle of close to 30° is ideal for enhancing dune relief because this is approximately equal to the angle of repose of loose sand.

In the 1980's, the Space Shuttle will enable the acquisition of orbital photographs of the Earth by means of a 305-mm f/6 "large-format camera" that has a 40° by 74° field of view. This camera will provide an orthographic (vertical) perspective and large areal coverage. It will also provide stereoscopic photographs with as much as 80 percent overlap and high photographic resolution (10 to 20 m from a 260-km altitude).

The first Space Shuttle missions on which the large-format camera is used will have a relatively low orbital inclination of 28.5°. These missions will cover the Earth's equatorial regions and will thus be suitable for studying desert belts north of the Equator. This will enable a complete survey of the characteristics of sand accumulation to be made from Earth orbit.

Finally, in addition to detailed study of orbital photographs, subsidiary data are required. In the case of the ASTP photographs and Landsat images, both aerial photographs and field studies were necessary to clarify some of the orbital observations. With increased resolution of orbital images, aerial photographs and ground checks will be necessary in places to confirm the photo-geologic interpretations.

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