Nearly all sand dune fields in the eastern Sahara are located within topographic depressions. The sand, mostly composed of quartz grains, occurs south of limestone plateaus that border the Mediterranean seacoast, over which the wind blows southward. The source of the sand is the “Nubian Sandstone,” which is exposed throughout the southern part of the eastern Sahara. Satellite images, particularly radar data, reveal that sand-covered, northward-trending courses of dry rivers end at the depressions. The sand appears to have been deposited, most likely in lake beds, during wet climates. Alternating dry climatic episodes resulted in sculpturing these deposits into sand dunes and sheets by southward flowing wind. The depressions must have hosted great volumes of surface water during the wet climates. Much of that water would have seeped into the underlying rock through primary and/or secondary porosity. It follows that areas of large accumulations of sand may host vast groundwater resources.

Introduction

The eastern Sahara of North Africa is one of the driest regions of the Earth, where the received solar radiation is capable of evaporating over 200-times the amount of rainfall (Henning and Flohn, 1977; Kehl and Bornkamm, 1993). In some parts of the Western Desert of Egypt, where rainfall is extremely variable and unpredictable, it rains only once in 20 to 50 years. This condition necessitated a complete dependence on groundwater resources for human consumption and agricultural activities. Groundwater levels have decreased and the known resources are becoming scarce in most of the Western Desert oases. Population growth and attendant food and fiber requirements threaten to exacerbate the situation in the future. Therefore, the need exists to pursue innovative approaches for the location of additional groundwater resources.

In this paper, the regional setting of the Western Desert as part of the eastern Sahara is considered in terms of potential application to groundwater resources. Although this region is now hyperarid and subjected to the action of strong winds from the north, geological and archaeological evidence indicate that it hosted much wetter climates in the past. Surface water during moist climates appears to have been responsible for the erosion, transportation and deposition of sand into inland basins. It follows that these basins would have stored most of the water in the underlying porous “Nubian Sandstone” rocks. Aeolian activities resulted in the formation of sand dunes and sandsheets (Maxwell, 1982) during dry conditions that alternated with the wet climate episodes.

To illustrate these relationships, the author used digital images from space including multi-spectral data of the Landsat Thematic Mapper (TM) as well as radar images from the Spaceborne Imaging Radar (SIR) of the American Space Shuttle and the Radarsat spacecraft of the Canadian Space Agency. These data provide unique perspectives that allow the recognition of regional influences on groundwater concentration, as well as the necessary information for detailed evaluation of the groundwater potential in a given area.

In addition to the primary porosity of the sandstone in the eastern Sahara, structural stresses causing the formation of faults induce porosity along fracture zones. The latter appear to have significant control on the trends of exposed and sand-buried drainage lines, thus, on the enhancement of groundwater recharge into the substrate. Therefore, it would be prudent to apply the concept of fracture zone aquifers (Bisson and El-Baz, 1991) to the exploration for groundwater in this desert. It is hoped that the ideas presented in this paper will influence the strategy of groundwater exploration in the eastern Sahara and similar desert regions worldwide.

Wind regime

The wind regime of the eastern Sahara trends in an arcuate pattern that emanates from the coastal zone of the Mediterranean Sea. The pattern changes from southward in the northern part of the desert to westward along the borders with the Sahel (Figure 1). Weather satellite images such as those of Meteosat of the European Space Agency (ESA) helped greatly in deciphering the details of this regional pat-
tern (Mainguet, 1995), which was first detected by Bagnold (1941, p. 235). Erosional scars throughout the desert suggest that this wind regime was effective during much of the Pleistocene.

To evaluate the effects of the wind on particle transport and the formation, shape and orientation of dunes, it is necessary to analyze data on wind velocity and direction. In the case of the eastern Sahara, surface wind data were summarized for 42 meteorological stations between 15° and 35° N latitude and 15° and 41° E longitude (El-Baz and Wolfe, 1982). Summaries presented as wind rose diagrams and sand-drift potential resultants agree with the basic pattern of a net southward direction of sand transport.

Thus, the sand-carrying wind in this desert moves toward the south during most of the year, except where it is locally affected by topographic prominences (Manent and El-Baz, 1980). Seasonal winds from the south do occur, particularly in the Spring, but these are not significant transporters of sand. Haynes (1989) found a remarkably consistent rate of dune migration of 7.5 m/yr to the south over the preceding 57 years, in the southern part of the desert.

Two other observations must also be accounted for. The first is that sand accumulations in the eastern Sahara occur within or near topographic depressions (Manent and El-Baz, 1980). Seasonal winds from the south do occur, particularly in the Spring, but these are not significant transporters of sand. Haynes (1989) found a remarkably consistent rate of dune migration of 7.5 m/yr to the south over the preceding 57 years, in the southern part of the desert.

Two other observations must also be accounted for. The first is that sand accumulations in the eastern Sahara occur within or near topographic depressions. This must be explained in any theory regarding the origin of the sand and the evolution of the dune forms in space and time. The second is that the dune sand is composed mostly of well rounded quartz grains. The exposed rocks to the north of the sand seas are mostly limestones of Eocene or younger ages. The limestones could not have been the source of the vast amounts of quartz sand.

These two observations discount the possibility of the origin of the majority of the sand by wind erosion and transportation from the north. The sand appears to have formed by fluvial erosion of sandstone rocks in the south. Therefore, it is more likely that the areas presently covered by dune sand were relatively low areas that received sediments from northward flowing stream channels in the geological past. When the conditions of climate changed, the wind sculptured these sand accumulations into the various dune forms and sandsheets and ridges seen today.

**Dune accumulations**

Although as much as 40% of the world’s landmass may be called arid to semi-arid, and as much as 20% has been classified as desert, only about 4% is actually covered by sand (Petrov, 1976). The eastern Sahara, in particular, encompasses the largest number of sand fields in any desert (Figure 2). The Western Desert of Egypt, for example, covers an area of 681,000 km², of which 159,000 km² (over 23% of the total area) is covered by sand (Gifford, et al., 1979).

Dune fields of the Western Desert of Egypt have been mapped (Figure 3) since the original dune classification work by Bagnold (1931, 1933 and 1941). The distribution and dune patterns of these fields have also been studied in detail from satellite images (Gifford, et al., 1979).

The Great Sand Sea, which covers 72,000 km², is the largest dune field in this desert. It is a relatively low area bounded in the north by the escarpment of the Siwa Oasis and in the south by the Gilf Kebir Plateau and the Oweinat Mountain (El-Baz and Mainguet, 1981). Numerous dry wadis run northward from the southern part of the desert (Mojsis and El-Baz, 1992). In the central region, dry courses of streams trend westward from the Farafra Oasis toward the area of the Great Sand Sea. Topographically, the lowest area in the region is a sand-free, flat playa just south of the extension of the Great Sand Sea into Libya. To the north of this playa, the dunes are densely distributed in complex forms; to the southeast, the dunes are linear forms with wide interdune corridors (Figure 4).

The patterns of dunes in the Great Sand Sea in particular support the present theory (El-Baz, 1982). The largest linear forms (Figure 4) were called “whaleback” dunes by Bagnold (1941) who theorized that they grew so large that they no longer could move. Dunes, however, move when individual sand grains are dislodged by the wind, as Bagnold himself noted. Furthermore, cross-sections made into these dunes show that the sand is horizontally laminated (Figure 5) rather than curved parallel to dune profiles as in the case of the nearby barchans and other wind-formed dunes (El-Baz et al., 1979). This suggests that what Bagnold named whaleback dunes are residual sand ridges of horizontally laminated sand, left behind as the

![Figure 2 Major dune fields of the eastern Sahara (modified from Mainguet, 1995).](image)

![Figure 3 Sand deposits in the Western Desert of Egypt (modified from Gifford et al., 1979).](image)
wind preferentially eroded the sand in what we see today as sand-free, interdune corridors. 

According to Gifford et al. (1979, p. 219), “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.”

It was recently further realized that the single most important characteristic of areas with high concentrations of sand dunes, is the location within topographic depressions (El-Baz, 1982, 1988, and 1992). Of twelve sand covered areas in the Western Desert of Egypt (Figure 3), ten occur in topographic basins; in the other two cases the sand emanates from low areas and is driven to level ground downwind.

Fluvial history

El-Baz (1982) proposed that the dune sand originated by fluvial erosion of sandstone rocks such as those of the Nubian Sandstone to the south of, or close to, the dune fields of the Western Desert of Egypt. Rounding of the grains must have occurred in turbid water as the particulate matter was transported during humid phases in rivers and streams (El-Baz, 1992).

The sediment load must have been deposited in low areas at the mouths of these channels. As the climate became drier, the particulate matter was exposed to the action of wind, which locally mobilized and sculptured the sand into various dune forms, depending on the amount of available sand and the prevailing wind directions. At the height of each arid period, it is likely that winds from the north and southward aeolian transport dominated, as they do today.

This hypothesis is supported by archaeological evidence in the Western Desert of Egypt, where earlier periods of greater effective moisture are evident from archaeological sites associated with remnants of playa or lake deposits (Haynes, 1982 and 1985; Szabo et al., 1995). An early Holocene pluvial cycle is well documented by geoarchaeological investigations at Neolithic playa sites in Egypt (Wendorf and Schild, 1980; Pachur and Braun, 1980; Gabriel and Kropelin, 1989; Haynes et al., 1989; Kropelin, 1990). Late Pleistocene lake deposits with associated early and middle Paleolithic archaeological sites are best known from work in the Bir Tarfawi area of southwestern Egypt (Wendorf et al., 1987). Similar associations occur in northwestern Sudan (Haynes, 1985; Haynes et al., 1989).

This undisputed archaeological evidence of previous human habitation, coupled with remains of fauna and flora, suggests the presence of surface water in the past. Indeed, remains of lakes and dry river and stream channels are exposed throughout the eastern Sahara.

Furthermore, in November 1981, the Shuttle Imaging Radar (SIR-A) acquired images of a variety of features including faults, outcrops and dunes (Elachi et al., 1982). Among the revealed features are channels of ancient river and stream courses that are buried beneath up to five meters of sand in the southwestern part of the Western Desert of Egypt near the border with Sudan (McCueley et al., 1982; El-Baz, 1988; Burke and Wells, 1989).

Calcium carbonate deposits associated with some of these buried river channels are believed to have precipitated in the upper portions of the zone of saturation during pluvial episodes, when water tables were higher. The only method available for determining the age of the deposits of the radar-revealed paleo-rivers, other than archaeological estimation, was uranium-series analysis applied to samples of groundwater-deposited carbonates. Based on such analysis, Szabo et al. (1989) recognized four periods of widespread carbonate deposition.

These findings increased the interest in both the search for additional evidence of sand-buried river channels and better documentation of the ages of the fluvial episodes. The Spaceborne Imaging Radar (SIR-C) instrument that was flown on the Space Shuttle in April and October of 1994 revealed numerous rivers and streams in the region, particularly to the south of Kufra Oasis in southeastern Libya (Figure 6). This encouraged additional measurements of the ages of previous wet climatic episodes in this hyper-arid desert.

The radiocarbon dating and geoarchaeological investigations subsequently carried out show that the eastern Sahara experienced a period of greater effective moisture during early and middle
Figure 6 Spaceborne Imaging Radar (SIR-C) view of southeastern Libya. The radar waves penetrated desert sands to reveal the dry courses of two major rivers, one on the left leading to the Kufra Oasis (at 0), and a wider channel leading to one-kilometer in diameter circular irrigation farms northeast of the oasis.

Conclusions

The hypothesis presented in this paper suggests that groundwater resources may be inferred from large accumulations of sand in the eastern Sahara. It is based on the study of satellite images followed by field work to confirm interpretations of the space-borne data. This hypothesis is supported by: (a) the topographic confinement of the sand seas in depressions; (b) the consistent wind direction from the north during dry climates throughout the Pleistocene; (c) the quartz composition of the sand whose source is most likely a sandstone that is exposed only in the south, whereas rocks to the north are mostly limestones; (d) the ample archaeological proof of wet climates in the past as indicated by the evidence of prehistoric habitation by plants, animals and humans; and (e) the recognition, particularly in radar images, of sand-buried courses of paleo-rivers that lead to the aforementioned depressions.

The hypothesis relates the origin of the sand to fluvial erosion of the Nubian Sandstone, which is exposed in the southern part of the desert. It involves the down-gradient transport of the sand grains toward the north. This occurred in the courses of ancient rivers that led to inland depressions, where the sand was deposited in horizontal laminae. The water that accumulated in the depressions during wet climate episodes would have seeped through the underlying rocks to be stored as groundwater. As dry climates set in, the wind mobilized the sand and shaped it into various dune forms. Thus, the hypothesis implies that sand was born by water and sculptured by the wind.
Validation of this theory will depend on future research into: (a) the detailed topography of the desert, today and during the Quaternary; (b) provinence studies of the sand and its correlation with the Nubian Sandstone; (c) additional investigations into the lamination of sand ridges, particularly in the Great Sand Sea; and (4) exploratory drilling within the sand-filled depressions to confirm the presence of the groundwater. It is hoped that the theory is tested in the rest of North Africa and similar deserts in Asia, particularly the large sandy expanses of China.

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References


Dr. Farouk El-Baz is Director of the Center for Remote Sensing at Boston University. He established, and from 1873 to 1982 directed, the Center for Earth and Planetary Studies at the Smithsonian Institution, Washington, DC. From 1967 to 1972 he participated in the training of the Moon-bound astronauts and the selection of landing sites for the Apollo missions. His research concentrates on the origin and evaluation of arid landforms using satellite images. He has lectured widely on the topic at universities throughout the world.