by Farouk El-Baz

Sand accumulation and groundwater in the eastern Sahara

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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-

Figure 1 Wind patterns of the eastern Sahara showing a flow from north to south and then west (modified from Guy and Mainguet, 1975).

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

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 7.5m/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 (Mojzsis and El-Baz, 1992). In the central region, dry courses of streams trend westward from the Farafrā 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 3 Sand deposits in the Western Desert of Egypt (modified from Gifford et al., 1979).

Figure 4 Landsat image of the western border of the Great Sand Sea, Western Desert of Egypt, showing longitudinal sand ridges with wide, sand-free, inter-ridge corridors (width of image is 50 km).

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 (McCauley 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 5 Close-up view of a trench in a sand ridge in the eastern part of the Great Sand Sea, showing horizontal lamination.

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.

Holocene time, about 10-5 ka. The uranium-series technique was used to date lacustrine carbonates from Bir Tarfawi, Bir Sahara East, Wadi Hussein, Oyo Depression, and the Great Selima Sand Sheet localities (Szabo et al., 1995). Results indicate that five paleo-lake forming episodes occurred at about 320-250, 240-190, 155-120, 90-65 and 10-5 ka. Four of these five pluvial episodes may be correlated with major interglacial stages 9, 7, 5e, and one, the 90-65 ka episode, may be correlated with the interglacial substage 5c or 5a (Szabo et al., 1995).

These results support the previously held contention that past pluvial episodes in North Africa correspond to the interglacial periods farther north. Dating and field relationships suggest that the oldest lake and groundwater-deposited carbonates were much more extensive than those of the younger period, and that the carbonates of the late wet periods were geographically localized within depressions and buried channels (Szabo et al., 1995).

Groundwater implications

The hypothesis brought forth in this paper has far reaching implications to the concentration of groundwater resources in the eastern Sahara. Because the sand was transported by paleo-rivers, the depositional basins would have received vast amounts of fresh water. Much of that water would have seeped into the rocks beneath the sands. Thus, areas that encompass large sand dune accumulations in this part of the Sahara may host vast groundwater resources.

It is well known that the stratigraphic succession of the Nubian Sandstone in the eastern Sahara is mostly porous. It hosts an aquifer

that has been tapped for groundwater for millennia, as indicated throughout recorded history. This is particularly true in the oases of western Egypt, eastern Libya, and northern Sudan.

Concentration of groundwater in topographic basins is particularly illustrated by the case of the Libyan Sahara. Because of the encroachment of sea water into the coastal groundwater aquifers, Libya had to transport sweet groundwater from the southern part of the country to where the population is concentrated along the Mediterranean seacoast. Hundreds of wells were drilled in the course of exploring for groundwater in five basins: Kufra, Sarir, Sirt, Hamra, and Murzuq (El-Baz, 1991).

Similarly, there are indications of a similar geographic setting in the Western Desert of Egypt. Two wells drilled for petroleum exploration near the edges of the Great Sand Sea proved the presence of vast amounts of water. These were drilled south of Siwa Oasis and west of Farafra Oasis to over one-kilometer depth and penetrated thick sandstone sequences that are saturated with groundwater in primary porosity. Water in these wells fountains under artesian pressure up to 40 meters into the air, indicating vast resources at depth.

In addition to the comparatively well-known horizontal aquifers in porous sediments, it is believed that groundwater also exists in fracture zone aquifers (Bisson and El-Baz, 1991). These are extensive, nearly vertical zones in the rock that may contain large amounts of yet untapped resources.

Sediments of the eastern Sahara are highly fractured. The main structural trends are east-west, north-west-southeast, and northeast-southwest. The faults show both vertical and horizontal displacements. The motions causing these faults crushed the rock along the fracture zones inducing secondary porosity. The fractures appear to form networks that would facilitate the transport of water and its storage in fractured rock aquifers.

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) provenience 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

- Bagnold, R. A., 1931, Journey in the Libyan Desert 1929 and 1930. *Geographical Journal*: v. 78, pp.13-39 and 524-535.
- Bagnold, R. A., 1933, A further journey through the Libyan Desert. *Geographical Journal*: v. 82, pp. 103-129.
- Bagnold, R. A., 1941, *The Physics of Blown Sand and Desert Dunes*: Methuen and Co. Ltd., London, 265 pp.
- Bisson, R. A., and El-Baz, F., 1991, Megawatershed exploration model. Proceedings of the 23rd International Symposium on Remote Sensing of Environment. Environmental Research Institute of Michigan: Ann Arbor, v. 1, pp. 247-273.
- Burke, K., and Wells, G. L., 1989, Trans-African drainage system of the Sahara: Was it the Nile? *Geology*: v. 17, pp. 743-747.
- Elachi, D., Brown, W. E., Cimino, J. B., Dixon, T., Evans, D. L., Ford, J.P., Saunders, R. S., Breed, C., Masursky, H., McCauley, J. F., Schaber, G., Dellwig, A., England, A., MacDonald, H., Martin-Kay, P., and Sabins, F., 1982, Shuttle imaging radar: *Science*, v. 218, pp. 996-1003.
- El-Baz, F., 1982, Genesis of the Great Sand Sea, Western Desert of Egypt. Abstracts of Papers, International Association of Sedimentologists: Eleventh International Congress on Sedimentology, McMaster University, Hamilton, Ontario, Canada, 22-27 August 1982, p. 68.
- El-Baz, F., 1988, Origin and evolution of the desert: *Interdisciplinary Science Reviews*, v. 13, pp. 331-347.
- El-Baz, F., 1991, The Great Man-Made River of Libya: Newsletter of the Third World Academy of Sciences, v. 3, n. 4, pp. 11-12.
- El-Baz, F., 1992, Origin and evolution of sand seas in the Great Sahara and implications to petroleum and groundwater exploration, in Sadek, A., ed., *Geology of the Arab World*: Cairo University Press, Cairo, Egypt, v. II, pp. 3-17.
- El-Baz, F., and Mainguet, M., 1981, Dune forms in the Great Sand Sea and applications to Mars: Reports of Planetary Geology Program-1981, NASA Tech. Memo. 84211, pp. 244-246.
- El-Baz, F., and Wolfe, R. W., 1982, Wind patterns in the Western Desert. in El-Baz, F., and Maxwell, T.A., eds, *Desert landforms of southeast Egypt: A basis for comparison with Mars*: NASA CR-3611, pp. 119-139.
- El-Baz, F., Slezak, M. H., and Maxwell, T. A., 1979, Preliminary analysis of color variations of sand deposits in the Western Desert of Egypt. Apollo-Soyuz Test Project Summary Science Report: Volume II: Earth Observations and Photography: NASA SP-412, pp. 237-262.
- Gabriel, B., and Kropelin, S., 1989, Holocene lake deposits in northwest Sudan. in Coetzee, J.A., and van Zinderen-Bakker, E.M., eds, *Paleoecology of Africa and the Surrounding Islands*: Balkema, Rotterdam, pp. 295-299.
- Gifford, A. W., Warner, D. M., and El-Baz, F., 1979, Orbital observations of sand distribution in the Western Desert of Egypt. Apollo-Soyuz Test Project Summary Science Report, Volume II: Earth Observations and Photography: NASA SP-412, pp. 219-236.
- Guy, M., and Mainguet, M., 1975, Les courants de transport éolien au Sahara et leurs manifestations au sol: *Compte Rendue Académie de Sciences*, Paris, v. 281, pp. 103-106.
- Haynes Jr., C.V., 1982, Great Sand Sea and Selima Sand Sheet: *Geochronology of desertification: Science*, v. 217, pp. 629-633.
- Haynes Jr., C. V., 1985, Quaternary studies, Western Desert, Egypt and Sudan-1979-1983 field seasons: *Nat. Geogr. Soc. Res. Rep.* v. 16, pp. 269-341.
- Haynes Jr., C.V., Eyles, C.H., Pavlish, L.A., Rotchie, J.C., and Rybak, M., 1989, Holocene paleoecology of the Eastern Sahara: Selima Oasis: *Quat. Sci. Rev.*, v. 8, pp. 109-136.
- Henning, D., and Flohn, H., 1977, Climate Aridity Index Map: U.N. Conference on Desertification, UNEP, Nairobi, Kenya.
- Kehl, H., and Bornkamm, X., 1993, Landscape ecology and vegetation units of the Western Desert of Egypt. in Meissner, B., and Wycisk, P., eds, *Geopotential Ecology: Analysis of a Desert Region*: Catena, v. 26, pp. 155-178.
- Kropelin, S., 1990, Lower Wadi Howar. *Berl. Geowiss: Abh.*, A, v. 120, pp. 223-234 and 256-259.
- McCauley, J. F., Schaber, G. G., Breed, C. S., Grolier, M. J., Haynes Jr., C. V., Issawi, B., Elachi, C., and Blom, R., 1982, Subsurface valleys and geoarchaeology of the Eastern Sahara revealed by Shuttle radar. *Science*: v. 218, pp. 1004-1020.
- Mainguet, M. M., 1995, *L'homme et la Secheresse*: Collection Geographie, Mason, Paris.
- Manent, L. S., and El-Baz, F., 1980, Effects of topography on dune orientation in the Farafr region, Western Desert of Egypt, and implications to Mars: Reports of Planetary Geology Program. NASA Tech. Memo. 82385, pp. 298-300.
- Maxwell, T. A., 1982, Sand sheet and lag deposits in the southwestern desert. Desert Landforms of Southwest Egypt: in El-Baz, F., and Maxwell, T.A., eds, *A Basis for Comparison with Mars*: NASA Cr-3611, pp. 157-173.
- Mojzsis, S. J., and El-Baz, F., 1992, The Bahariya River: A paleodrainage system in the Western Desert of Egypt. in Sadek, A., ed., *Geology of the Arab World*: Cairo University Press, Cairo, Egypt, v. II, pp. 67-83.
- Pachur, H. J., and Braun, G., 1980 The paleoclimate of the central Sahara, Libya, and the Libyan Desert. in Sarenthim, M., Siebold, E., and Rognon, P., eds, *Paleoeco. Afr.*: v. 12, pp. 351-363.
- Petrov, M. P., 1976, *Deserts of the World*. Wiley & Sons, New York, 447pp.
- Szabo, B. J., McHugh, W. P., Shaber, G. G., Haynes Jr., C. V., and Breed, C. S., 1989, Uranium-series dated authigenic carbonates and Acheulian sites in southern Egypt: *Science*, v. 243, pp. 1053-1056.
- Szabo, B. J., Haynes, Jr., C. V., and Maxwell, T. A., 1995, Ages of Quaternary pluvial episodes determined by uranium-series and radiocarbon dating of lacustrine deposits of Eastern Sahara: *Paleogeography, Paleoclimatology, Paleoecology*, v. 113, pp. 227-242.
- Wendorf, F., and Schild, R., 1980, *Prehistory of the Eastern Sahara*: Academic Press, New York, 414pp.
- Wendorf, F., Close, A. E., and Schild, R., 1987, Recent work on the Middle Paleolithic of the Eastern Sahara. *Afr.: Archaeol. Rev.*, v. 5, pp. 49-63.

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