Wadi Howar: Paleoclimatic Evidence from an Extinct River System in the Southeastern Sahara

H.-J. Pachur and S. Kröpelin

Field research into the climatic history and shifting of the East Saharan desert has furnished evidence that during Quaternary time the present extremely arid western part of Upper Nubia (northern Sudan) was temporarily linked to the Nile by way of a hitherto unknown 400 kilometer long tributary. From about 9500 to 4500 years ago, lower Wadi Howar flowed through an environment characterized by numerous ground water outlets and freshwater lakes. Savanna fauna and cattle-herders occupied this region, which today receives at most 25 millimeters of rainfall per year. At that period the southern edge of the eastern Sahara was some 500 kilometers further north than today and ground water resources were recharged for the last time.

During the past 10 years paleoclimatic research undertaken in the eastern Sahara has revealed the existence of two major late Pleistocene to mid-Holocene drainage networks that once interrupted the state of internal drainage of this vast region. One network is a 800 km long watercourse in eastern Libya (*1*). This drainage system, however, might have been influenced by increased rainfall in the Tibesti Mountains, which cover an area of some 100,000 km^2 at an average elevation of 2000 m above sea level. For this reason, further fieldwork was conducted in the expanses between the Great Sand Sea of Egypt and the Sahel zone in northern Sudan, which have an elevation of only 500 to 600 m and are located far away from any high mountains (Fig. 1b). The investigations yielded evidence on another major relict drainage system in the southeastern Sahara: lower Wadi Howar.

Wadi Howar issues from the mountainous region between Gebel Marra and Ennedi and traverses the southern fringe of the Sahara for a length of 640 km. All topographic maps of the area show the end of the wadi bed at 17°30′N and 27°25′E south of Gebel Rahib. Here the wadi is already defunct and its course is marked only by linear tree vegetation, sustained by a ground water table some 6 to 10 m below the surface (*2*). Speculations on a possible eastward connection to the Nile during the Tertiary (*3*) and interpretations of satellite imagery (*4*) were verified by ground checks. Evidence was found that the lower Wadi Howar drained this 400 km wide area (present rainfall, 25 mm/year) and entered the Nile between the third and fourth cataracts, opposite Old Dongola (*5*). Thus, Wadi Howar constituted the largest tributary to the Nile from the Sahara between the Mediterranean Sea and the Atbara River, with a length of more than 2700 km.

At Rahib the former riverbed is blocked by a 15-m high and 5-km wide dune barrier (Fig. 1a, locality 3). It overlies a sequence of sandy pebbly alluvium, fossiliferous lake marl, cross-bedded dune sand, and calcrete. The lacustrine deposits at the base gave a radiocarbon date of 9430 ± 85 years ago (Hv 12380), indicating high variability in climate and geomorphology during the early and middle Holocene in this region.

Further to the east the lower Wadi Howar crosses a peneplain with numerous granite outcrops capped by lacustrine calcretes at the old wadi banks. This section, stretching about 185 km, consists of a series of interconnected shallow depressions, which display fossil lake beds up to 10 km in diameter and dated at 5640 ± 70 and 7260 ± 70 years ago (Hv 14434 and Hv 14438) (Fig. 1a, localities marked 4). These deposits indicate pools remaining on the floodplain of the wadi after seasonal flooding and thus enabling an occasional overflow of one sheet

Special Research Project Arid Areas, Department of Physical Geography, Geomorphological Laboratory, Free University, D-1000 Berlin (West) 41, Germany.

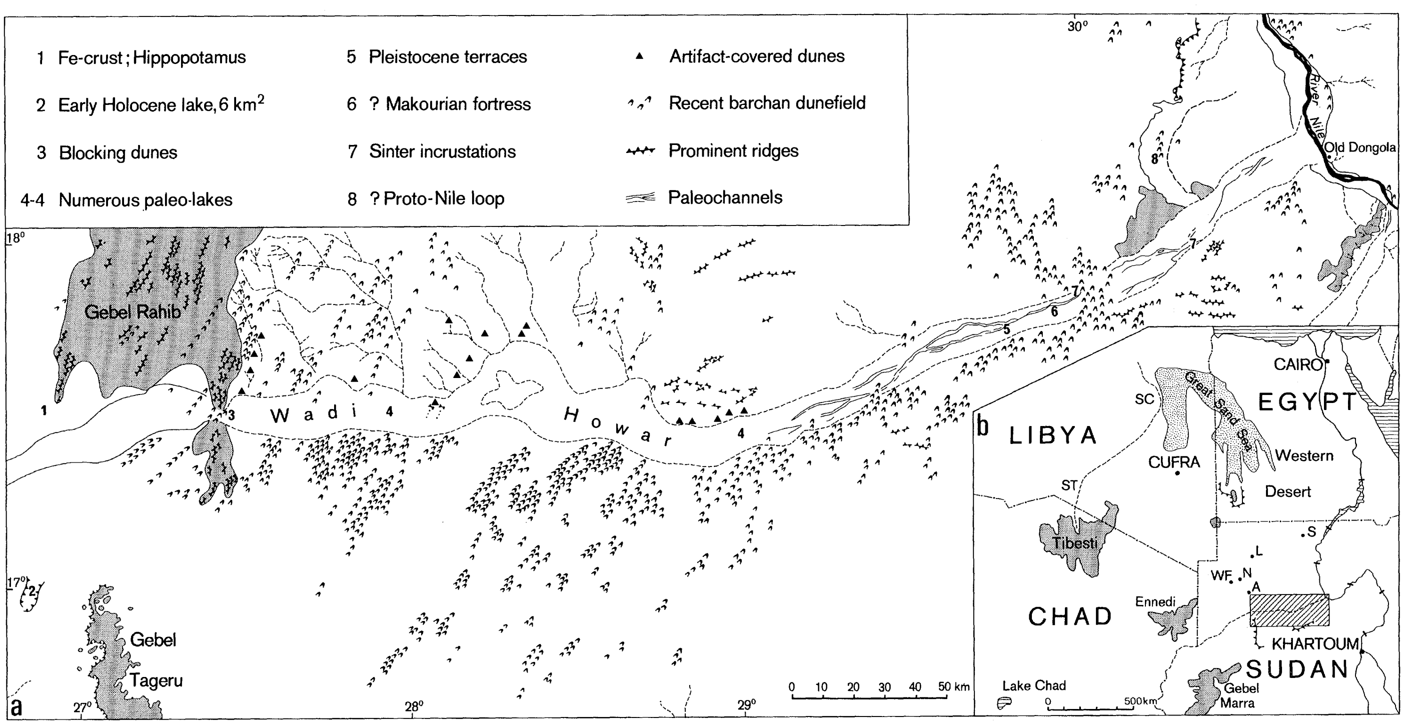

Fig. 1. (**a**) Generalized topographic map of the lower Wadi Howar showing reconstructed paleodrainages and selected features (source of data, LANDSAT imagery and field investigations). (**b**) Outline map of the eastern Sahara indicating mapped area and other localities mentioned in text. ST, Serir Tibesti; SC, Serir Calanscio; S, Selima; L, Laqiya Arbain; WF, Wadi Feshfesh; N, Nukheila; and A, El Atrun.

of water into the next after additional runoff. The lakes were apparently persistent for decades or even centuries and contained freshwater, as judged by sedimentological and mineralogical analysis of the lake chalk deposits and by the spectrum of freshwater Mollusca, including large river bivalves (*Aspatharia arcuta* and *Aspatharia rubens*) up to 13 cm long, freshwater Ostracoda, diatoms, and gyrogonites. The sediments also contain bones of large savanna mammals and amphibious organisms (Table 1). The diversity and widespread distribution of the specimens throughout the entire valley are proof of a stable ecosystem providing animals with optimal living conditions. Remains of domestic cattle are often associated with wild fauna, Neolithic stone implements and pottery, and human bones (*6*).

Near the ancient wadi bed there are numerous, up to 15 m high and several 100 m wide, fossil dunes stabilized by a dense cover of countless Neolithic artifacts. Associated pottery (Early Khartoum) shows that the dunes are older than 8000 years (*7*). The parabolic shape of some of these dunes is attributed to former anchoring by a continuous shrub and grass vegetation maintained by a high ground-water table or lake shore location at the time of the onset of human occupation. Today, these immobilized parabolic dunes with their "horns" trailing toward the trade winds are in sharp contrast with the recent barchan-type dunes migrating with their extremities oriented downwind. Contemporaneous dunes west of Gebel Rahib interfinger with lake sediments [hippopotamus bones dated at 4720 ± 110 years ago (UZ 2168)] and are overlaid by up to 80 cm thick iron crusts that formed at the ground water interface (Fig. 1a, locality 1). Gyrogonites of *Nitellopsis*, a calcareous green algae, found in the lacustrine sediments indicate a low-temperature freshwater lake about 10 m deep (*8*).

Coarse gravel deposits first occur 180 km west of the junction with the Nile inside a wadi section characterized by 5- to 10-m deep channels incised in the bedrock (Fig. 1a, locality 5). The well-rounded quartz cobbles, 10 to 20 cm in diameter, build up terraces 9 m high and several hundred meters wide. Scattered Acheulean bifaces struck from the cobbles establish a minimum age of 50,000 to 200,000 years ago. Some of these presumably early to mid-Pleistocene terrace gravels have been redeposited locally, indicating high kinetic energy transport as late as the Holocene. In the thalweg further downvalley, however, sandy pebbly alluvial deposits and silty sandy playa deposits predominate. A giraffe skull embedded in such semilacustrine sediments provided a radiocarbon age of 3825 ± 115 years (Hv 14433). Lacustrine deposits, however, dated at 6580 ± 100 years ago (Hv 14429), mostly occur as erosional remains on the gentle slopes suggesting subsequent fluvial activity.

Over the last 70 km Wadi Howar approaches the Nile Valley at an apparent low gradient and with no indication of any major incision. Above the level of the Late Quaternary deposits, however, a presumed Proto-Nile riverbed (*9*) has been identified 50 km west of the present-day river (Fig. 1a, locality 8). Its glaring white mantle of quartzose gravels stands out both in the field and on satellite imagery. This probably early Pleistocene Nile loop was as much as 10 km wide and 60 km long. Its chronological position constitutes a maximum age for the major fluvial erosion cutting the banks of the 12 km wide floodplain before the junction with the Nile.

The concept of Wadi Howar as an indicator of a significant shift in the rainfall regime of the eastern Sahara is valid only if proof can be furnished that its lower course was not an exotic river like the modern Nile—that is, a teleconnection from the headwaters, but was fed by substantially increased local rainfall. The following evidence supports this point of view. In the near vicinity of the wadi (Fig. 1a, locality 2) the ground-water table rose considerably, causing the formation of a lake more than 6 km^2 in area; its lake chalk contains both freshwater Mollusca and Ostracoda and was radiocarbon dated to 9195 ± 95 years ago (Hv 13563) at the base and 7985 ± 90 years ago (Hv 13564) at the top. The close network of now defunct tributary wadis with broad gravel belts east of Gebel Rahib likewise points to paleo-discharge characteristics essentially different from those of today. Further evidence is the formation of 50 m wide calcareous sinter incrustations above the wadi bank with a radiocarbon age of 7825 ± 100 years (Hv 13565); they were supplied by springs fed by infiltrated local rainfall (Fig. 1a, localities 7).

Furthermore, the 12-m rise in the water table at El Atrun, 90 km to the north (Fig. 1b), could not have been induced by the upper Wadi Howar. Giraffe bones in the lake chalk were dated at 7370 ± 80 years ago (Hv 13566). The ferrous sulfite–bearing lake mud, laminated at the base and dated at 9180 ± 200 years ago (UZ 2270), is more than 7 m thick at the deepest part of the basin; hence, the lake was probably deeper than 19 m. Also, extensive field studies in February 1985 and January 1986 revealed a 180 km long relict drainage network west of Nukheila Oasis (Wadi Feshfesh, Fig. 1b) that was fed by local rainfall. A more than 10 km wide basin belonging to

Table 1. Vertebrate and invertebrate taxa identified from sites and sections of Holocene age in the lower Wadi Howar between Gebel Rahib and Nile River, Northern Sudan.

Taxa
Savanna* fauna
Addax nasomaculatus (addax)
Alcelaphus buselaphus (hartebeest)
Arvicanthis niloticus (grass rat)†
Bos sp. (big bovide)
Bubalus bubalis (buffalo)
Bufo regularis (toad)†
Crocodylus sp. (crocodile)‡
?*Diceros bicornis* (black rhinoceros)‡
Equus africanus (wild ass)
Gazella dorcas (dorcas gazelle)
Geochelone pardalis (tortoise)
Giraffa camelopardalis (giraffe)
Hippopotamus amphibius (hippopotamus)
?*Hippotigris quagga* (zebra)
Hippotragus equinus (roan antelope)
Loxodonta sp. (elephant)
Phacochoerus aethiopicus (warthog)
Struthio camelus (ostrich)
Tragelaphus sp. (antelope)
Domestic* fauna
Bos primigenius (domestic cattle)
Capra aegragus (goat)
Ovis ammon (sheep)
Gastropoda§ (aquatic snails)
Anisus dallonii
Biomphalaria pfeifferi
Bulinus forskali
Bulinus truncatus
Cleopatra bulimoides
Gabbiella senaariensis
Gyraulus costulatus
Lanistes carinatus
Lymnaea natalensis
Melanoides tuberculata
Pila wernei
Segmentorbis angustus
Valvata nilotica
Gastropoda§ (land-snails)
Curvella sp.
Gastrocopta sp.
Helicidae sp.
Limicolaria flammea
Streptostele sp.
Succinea sp.
Succinea oblonga
Vertigo antivertigo
Zonitoides nitidus
Zootecus insularis
Bivalvia§ (river bivalves)
Aspatharia arcuta
Aspatharia rubens
Caelatura aegyptiaca
Corbicula fluminalis
Mutela nilotica
Ostracoda‖ (freshwater)
Candona sp.
Cypridopsis sp.
Cypris sp.
Darwinula sp.
Encypris sp.
Heterocypris sp.
Metacypris sp.
Strandesia sp.

*Savanna and domestic fauna: determined by Uerpmann, Tübingen. †After (*7*). ‡After (*19*). §Gastropoda and Bivalvia determined by Schütt, Düsseldorf. ‖Ostracoda: determined by Keyser, Hamburg.

this ancient river valley contained a continuous sequence of 3 m thick calcareous diatomite with radiocarbon ages of 7780 ± 90 years at the base and 3805 ± 65 years at the top (Hv 14446 and Hv 14441). This inner Saharan archipelago of brackish to freshwater lakes was possibly linked to the Mourdi depression (*10*).

At Nukheila, only 40 km east of this Holocene river, rhinoceros bones were found in lacustrine marls (*11*). The lake marl terrace here is located 6 m above the present level of the hypersaline ground water fed–lake. The pollen-bearing algal muds of the Oyo complex (*12*) also belong to this archipelago of early to mid-Holocene lakes and correspond to those at El Atrun and Selima. The latter existed between about 9200 and 4500 years ago (*13*). Finally, the fossiliferous lake chalk sequences 80 km northwest of Laqiya Arbain dated between 7500 and 6500 years ago fit into this picture (*14*).

It is now clear that there is substantial evidence of a rainfall regime supporting an early Holocene ground-water recharge and that this evidence culminates in the lower Wadi Howar (18°N). It was surrounded by the early Holocene Sahel zone, which stretched about 500 km further north than today. Since the number of paleoclimatic indicators decreases northward of Wadi Howar, we conclude that rainfall was due to tropical influences from the south. These findings show parallels to paleoclimatic evidence from the central and western Sahara. Lake Chad (14°N) as well as the Mali lakes (21°N) record high levels and humid phases between 9500 and 4500 years ago (*15, 16*).

The extreme summer aridity (*17*) of the Sahara was suspended in early Holocene time. At present it is due to the sinking air masses in the delta of the tropical easterly jet stream, which in turn is caused by high summer temperatures in the central Asian mountains. Should the proposal of a persistent glaciation in the Tibetan mountains during the early Holocene prove correct (*18*), summer paleorainfall in the eastern Sahara could be explained by a continuing weakening of the easterly jet stream.

REFERENCES AND NOTES

1. This Holocene wadi flowed across Serir Tibesti in southern Libya (present rainfall, 2 mm/year) into Serir Calanscio (present rainfall, 20 mm/year) (Fig. 1b). Along its course calcitic lake deposits, radiocarbon dated to 8800 to 5000 years ago, were formed in freshwater lakes. In Egypt's Western Desert however (1 to 2 mm of annual rainfall), silty clayey semi-lacustrine sediments prevail in deflation hollows at numerous sites, mainly at the base of escarpments, during the period between 10,000 and 4,000 years ago; this reflects a west to east decrease in rainfall at a latitude of 23°N in the early Holocene. See H.-J. Pachur, *Berl. Geogr. Abh.* 17, 62 (1974); C. V. Haynes, in *Desert Landforms of Southwest Egypt: A Basis for Comparison with Mars*, F. El-Baz, T. A. Maxwell, Eds. (NASA CR-3611, Washington, DC, 1982), p. 91.
2. K. S. Sandford, *Geogr. J.* **85**, 412 (1935).
3. D. Newbold, *Sudan Notes Rec.* 7, 43 (1924); R. Said [in *The Geological Evolution of the River Nile* (Springer, New York, 1981)] does not even preclude the Wadi Howar as a possible source of the late Pliocene Paleonile about 2 to 4 million years ago.
4. Geological Map of the Sudan 1:2,000,000 (BRGM, Orléans, 1981); B. Meissner and H.-J. Schmitz, *Berl. geowiss. Abh.* (*A*) **47**, 87 (1983). The region under discussion here was not covered by the Columbia Shuttle Imaging Radar (SIR-A) which revealed subsurface valleys in the Selima Sand Sheet about 400 km further north [J. F. McCauley *et al.*, *Science* **218**, 1004 (1982)].
5. The capital of the Early Christian kingdom of Makouria about A.D. 550. On the south bank of Wadi Howar, 150 km west of the Nile, there is a hitherto unknown rectangular fortress about 150 m in diameter with stone walls more than 5 m thick, discovered in 1984 by an archeological expedition from the University of Cologne. We could fix the location by satellite Doppler positioning at 17°48′24″N, 29°59′18″E (Fig. 1a, locality 6). The locations of the capital and this fortification indicate the importance of the lower Wadi Howar as a transit route to Chad as late as the sixth century A.D.
6. It must be emphasized that some of the skeletons found were not buried, but embedded in the completely undisturbed sediment. For that reason death may have been accidental, possibly due to drowning.
7. B. Gabriel, S. Kröpelin, J. Richter, E. Cziesla, *Geowiss. unserer Z.* **3**, 105 (1985).
8. Charophyta were identified by I. Soulié-Märsche, Montpellier.
9. K. W. Butzer and C. L. Hansen, *Desert and River in Nubia* (Univ. of Wisconsin Press, Madison, 1968).
10. The Ptolemaic world map (about A.D. 150) shows marshes inhabited by tortoises in this region. Actually we found tortoise and giraffe remains in calcareous mud deposits reaching thicknesses of about 3 m and containing freshwater Mollusca and Ostracoda. C. V. Haynes [*Natl. Geogr. Res.* **16**, 269 (1985)] refers to part of this abandoned valley calling it "Wadi Mahgour."
11. H.-J. Pachur and H.-P. Röper, *Berl. geowiss. Abh.* (*A*) **50**, 249 (1984).
12. J. C. Ritchie, C. H. Eyles, C. V. Haynes, *Nature (London)* **314**, 352 (1985).
13. The early Holocene lake at Selima was 14 m deep and occupied an area of more than 11.5 km^2. There is a complete sedimentary sequence ranging from lake sands, algal mud, freshwater chalk, rhythmites, aragonitic lake chalk, and diatomite to sulfatic, highly saline sediments.
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15. M. Servant and S. Servant, in *The Sahara and the Nile*, M. A. J. Williams and H. Faure, Eds. (Balkema, Rotterdam, 1980), p. 133.
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20. The investigations were sponsored by the Deutsche Forschungsgemeinschaft and the Free University of Berlin within the framework of the Special Research Project "Geoscientific Problems in Arid Areas." We wish to acknowledge the help given us by the Sudanese colleagues from the Geological and Mineral Resources Department, Khartoum. Fieldwork in Egypt was carried out under the auspices of the General Petroleum Company, Cairo. Special thanks are due to M. A. Geyh, Hannover, for radiocarbon dating. Furthermore, we thank B. Gabriel, Berlin, and R. Said, Washington, DC, who read the manuscript and made useful suggestions.

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Technical Comments

Neuronal Coding and Robotics

Apostolos P. Georgopoulos *et al.* (*1*) present a study of neuronal coding of direction of arm movements in monkeys. They show that a group of neurons exist in the motor cortex which have firing rates that can be combined vectorially to predict the direction of arm movement.

In robotics, an analogous problem exists, called kinematic inversion (*2*). The issue is to decide how to drive the motors of a robot arm so as to drive the hand in a particular direction in Cartesian coordinates. The problem is interesting because the individual joint actuators do not contribute uniquely to any one Cartesian direction. Instead, their contributions are "broad" in the sense of (*1*): several motors contribute to motion along a single Cartesian direction. Furthermore, each motor must, in general, vary its contribution during a motion because the geometric relations between single motor contributions and ultimate hand direction vary as the arm moves and changes shape.

To be more precise, the problem in (*1*) is called the velocity control problem in robotics, wherein the controller must choose velocities for the joint actuators in order to obtain a velocity vector for the hand in Cartesian coordinates. This Cartesian velocity vector corresponds to vector **M** in (*1*). This problem was solved (*3*), as follows: Let X represent a position and V a velocity, respectively, in Cartesian space. Let Θ represent a vector of arm joint positions and Ω a vector of arm joint velocities. We say that Θ and Ω exist in joint coordinates. Then V and Ω are related by

$$V = J(\Theta)\,\Omega \qquad (1)$$

where J is called the Jacobian matrix of the arm and consists of partial derivatives of Cartesian axis motions with respect to joint axis motions. In general, J is 6×6 because Cartesian motions comprise three translations and three rotations, and arms able to make such motions must have at least six joints. The velocity control problem is solved by writing

$$\Omega = J^{-1}(\Theta)\,V \qquad (2)$$

The robot's control computer takes in V commands, reads Θ, calculates J and J^{-1}, and finally calculates Ω and sends it to the motors as individual command velocities.