of supplying the observed increase in atmospheric CO_2, when the ocean surface is warmed by an amount typical of the southern oscillation (El Niño) cycle. A simple equilibrium model calculation (*14*) predicts about one-half the observed amplitude, which is probably sufficiently close agreement.

The problem with the sea-surface temperature explanation of the atmospheric CO_2 response to the southern oscillation is that upwelled water is rich in CO_2. The equatorial upwelling region appears to be a large and persistent source of CO_2 to the atmosphere. Measurements of the partial pressure of CO_2 exerted by surface sea-water (pCO_2) in the upwelling region are above the atmospheric CO_2 partial pressure by as much as 80 parts per million (ppm) (*15*), presumably because of the recent upwelling of the surface water. Reduced upwelling might be expected to reduce the atmospheric CO_2 concentration, exactly opposite to the observations.

If equatorial sea-surface temperature change is the cause of the connection between the southern oscillation and atmospheric CO_2 concentration, then pCO_2 must be lower in the colder but presumably CO_2-richer water at an SOI maximum than during an SOI minimum. This could probably be accounted for if vertical water exchange and thermal balance were introduced into the model, in addition to CO_2 balance.

Biotic processes may also be important (*16*). Recently upwelled water is rich in the nutrients nitrogen and phosphorus, in addition to CO_2. A plankton bloom in response to these nutrients would be expected to reduce pCO_2 at an SOI maximum.

The hypothesis that pCO_2 is lower in Pacific equatorial water during an SOI maximum than during an SOI minimum should be tested. A time series of pCO_2 measurements in the Pacific equatorial upwelling region could be obtained during an El Niño cycle. The El Niño need not be fully developed; a study conducted during one as weak as the 1975 El Niño would do much to resolve the question of the mechanism by which the southern oscillation influences atmospheric CO_2.

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14. The size of this region [as indicated by the area where the NS1 of Weare *et al.* (*12*) is large] is approximately 18×10^6 km², about 1/20th of the area of the world's oceans. The change in sea-surface temperature associated with the southern oscillation is about 5°C [(*12*); R. E. Newell, personal communication]. A model consisting of a surface ocean layer with an area 1/20th that of the oceans and a depth of 100 m, in equilibrium with the entire atmosphere, would lead to the prediction that a temperature change of 5°C would correspond to an atmospheric CO_2 change of 0.4 part per million [equation 8 in (*11*)]. The observed total anomaly amplitude is about 1 part per million.
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Geochronology of Wadi Tushka: Lost Tributary of the Nile

Abstract. *The Sadat Canal, now under construction, is designed to drain excess water from Lake Nasser to the Western Desert by way of Wadi Tushka, a sand-filled, dry-wash tributary of the Nile 34 kilometers north of Abu Simbel. Core-drilling logs made by the Aswan High Dam Authority prior to excavation of the Sadat Canal and along 48 kilometers of its axis reveal as much as 33 meters of unconsolidated sand and gravel over Mesozoic bedrock and under surficial dune sand and playa muds of Holocene age. Excavation of the canal revealed Acheulean artifacts 6.7 meters below the surface in fluvial sediments capped by a buried, red calcic paleosol. These data are interpreted as evidence for the existence of a major tributary of the Nile during the late middle Pleistocene. The tributary drained the Kiseiba-Dungul Depression and possibly the Kharga Depression as well. Chalcedony-armored mudstones in the depressions are believed to be saline lake deposits possibly related to a lake that drained to the Nile by way of Wadi Tushka, thus entrenching the divide between the depression and the valley. Gross correlations with Pleistocene deposits of the Nile Valley and the Kharga Depression are based upon archeological evidence only until more precise geochronology can be applied to the problem.*

Between the desert spring of Dungul at the south end of the Eocene plateau of Egypt and Bir Kiseiba, 200 km to the west-southwest, there is an irregularly shaped, internally drained basin about 17,000 km² in area that lies at an elevation below 180 m (Fig. 1). This area, which I shall call the Kiseiba-Dungul Depression, has been described as a pediplain (*1*, *2*) and is separated from the Nile Valley by a broad sandstone ridge with high points between 200 and 300 m. Thirty-four kilometers northeast of the restored temples at Abu Simbel a dry stream bed called Wadi Tushka heads on the divide between the Kiseiba-Dungul Depression and the Nile Valley. Close to the divide, the wadi becomes inconspicuous. A number of long-inactive mud pans (playas) at an elevation between 174 and 180 m extend farther northwestward across the inconspicuous divide.

The Aswan High Dam can retain Lake Nasser at a maximum level of 183 m, but, by excavating a spillway along the axis of Wadi Tushka, the High Dam Authority plans to be able to divert excess water from any rise above 178 m to the Kiseiba-Dungul Depression for irrigation agriculture. Thus the Sadat Canal project can be an effective means of conserving irreplaceable groundwater if care is taken to avoid the accumulation of salt in an environment where evaporation rates (*3*) are among the highest known.

More than 50 years ago John Ball asked whether the Nile, or a branch of it, ever flowed through the Libyan Desert to the Mediterranean. After reviewing

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the development of this concept in relation to newly determined elevations in the Western Desert, he concluded (*4*, p. 28) that "neither the Nile nor any branch of it ever passed through the Libyan Desert to the sea." However, he suggested, on the basis of contour maps, that a tributary stream "may formerly have drained the southwestern faces of the great plateau in which the depressions of Dakhla and Kharga form bays, and have entered the Nile somewhere between Aswan and Halfa" (*4*, p. 32), but he considered all evidence to have been obliterated. Recent borings along Wadi Tushka, in conjunction with the construction of the Sadat Canal, indicate that Ball's suggestion of a former tributary was correct.

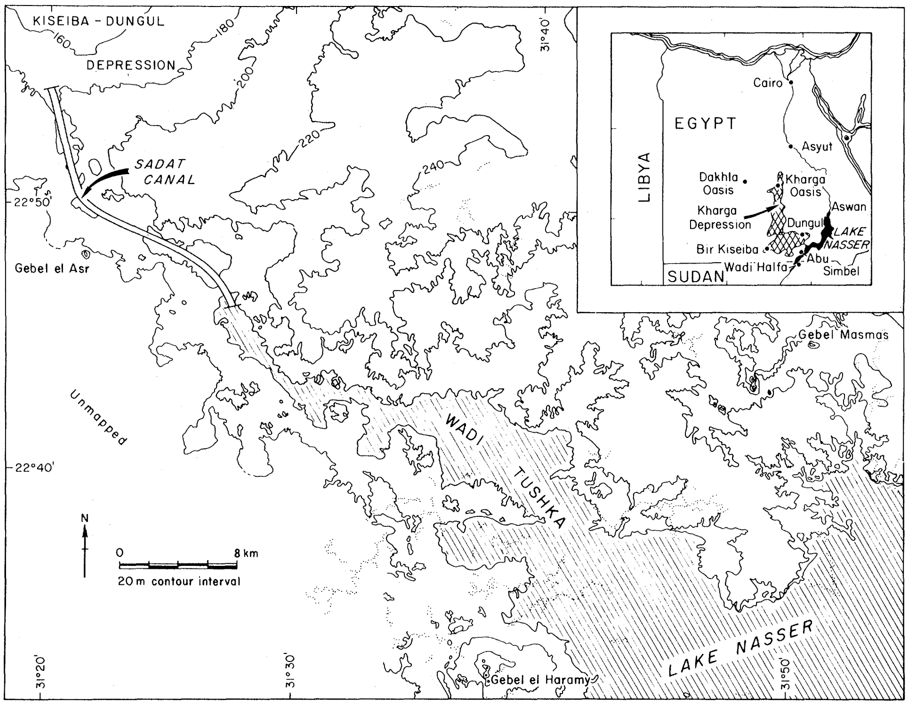

Fig. 1. Maps of the Western Desert, Egypt, showing the Kharga and Kiseiba-Dungul depressions and the Sadat Canal in the Wadi Tushka area. Dotted lines show ancient stream channels (inverted wadis) after Giegengack (*11*).

Thirty-eight cores from holes drilled approximately along the 48-km axis of the spillway provide a longitudinal geological profile which reveals as much as 33 m of unconsolidated sediments over bedrock. These sediments have been logged as clay, loam, and gravel, with two holes penetrating volcanic rock interbedded with the sediment (*5*). Only four of the boreholes reached bedrock, the deepest contact being at an elevation of 123.0 m. This is not likely to be the deepest part (thalweg) of channel cross section.

Groundbreaking for construction of the canal began in February 1978, and a year later parts of the canal had been excavated to the design depth of 7 m. The fresh exposures revealed 0.6 m of yellowish-brown, clayey, fine-to-medium sand and a playa deposit over at least 7 m of yellowish-brown, calcareous, pebbly sand with two distinct white calcic horizons (calcretes 0.6 and 0.9 m thick) centered about 1.7 and 4.5 m below the surface. A reddish-brown, medium-to-coarse pebbly sand in the lower 2 m of the section displays root casts of weakly cemented sand where freshly exposed surfaces have been wind-abraded. Approximately 8 km down the canal from the eastern end, which is about 75 km from the Nile, a crude Acheulean hand ax (Fig. 2a) was found in situ in the middle of this unit at a depth of about 6.7 m. Approximately 1 km southeast of a water control gate at the entrance to the canal spillway, another hand ax, well made, fresh, and obviously of Late Acheulean tradition (Fig. 2b), was found in spoil dirt 2 to 3 m below the surface from a low-water irrigation ditch excavated to the base of the upper calcrete.

From matrix adhering to the hand ax and two other nondiagnostic flake artifacts, it is clear that they came from the upper part of the calcareous alluvium and below the overlying Holocene playa deposit. From their freshness (lack of abrasion), it is reasonable to assume that they were contemporary with deposition of the upper part of the calcareous alluvium. The hand ax found at the lower depth is slightly abraded, and so some degree of redeposition cannot be precluded. A single hand ax is insufficient evidence to permit the assignment of the cruder specimen to Middle or Early Acheulean types, but its cruder, more primitive form is consistent with its stratigraphic position with respect to the Late Acheulean level. Absolute dates for these Old Paleolithic traditions are few and unknown for Egypt, but 200,000 years is probably a minimum for Late Acheulean artifacts (*6*). On this basis, the alluvial deposits are probably no younger than early Upper Pleistocene.

Several geological studies of Quaternary deposits of the Nile Valley have been made, mainly in conjunction with archeological investigations [see figure 3 of (*7*)]. Deposits older than 40,000 years before the present (B.P.) are dated by archeological content only, which is grossly imprecise but the only basis presently available. Therefore, the channel deposits of the Sadat Canal may correlate with the Dandara silt and the Qena sand of Wendorf and Schild (*8*), the Proto Nile Group of de Heinzelin (*9*), the Wadi Korosko gravel of Butzer and Hansen (*10*), and the Early Nile gravel of Giegengack (*11*), or possibly earlier deposits. Butzer and Hansen described a sequence of pediment gravels in the Tushka–Abu Simbel area that reach elevations between 190 and 160 m (*10*). Some of these could have been graded to either the ancestral Wadi Tushka or the Nile. Giegengack mapped numerous inverted wadi gravels reaching elevations ranging from 140 m (4 km west of the river) to 270 m along the divide between the Nile Valley and the Kiseiba-Dungul Depression (*11*). Some of these at lower and intermediate elevations contain Acheulean hand axes and could have been graded to the ancestral Wadi Tushka–Nile system. The higher inverted wadi gravels predate this drainage system because projected gradients to the buried sedimentary column of the Sadat Canal would be unusually steep as compared to gradients reconstructed from the channel remnants.

The deepest contact with bedrock in the boreholes along the Sadat Canal is 123 m, and the thalweg is probably lower. The historic bed of the Nile before the dams were built was 118 m at Tushka; the nearest low point in the Kiseiba-Dungul Depression is 148 m in a subbasin 25 km west-northwest of the weir site at the west end of the canal. Thus, the ancestral Wadi Tushka channel was probably graded to a lower Nile channel, which, if true, supports Chumakov's belief that the entrenched channel of the Nile extends south of Kalabsha (*12*).

Near Gebel Nabta, inverted wadi

gravels at an elevation of 200 m (75 km southwest of the weir site) stand topographically above, and are older than, carbonate deposits that are clearly older than Late Acheulean artifacts that lie on their wind-eroded surfaces. Relatively fresh undersides of some of the artifacts suggest that they have not been significantly moved downward by deflation from their original positions. From this and similar occurrences of hand axes near Bir Kiseiba, it is apparent that the main topographic features of the Kiseiba-Dungul Depression had been attained before Late Acheulean times, and the inverted wadi gravels in the Nabta area may have a part of the ancestral Wadi Tushka drainage system.

No geologist with experience in the hyperarid parts of the Sahara would seriously dispute the significant role of wind in forming the major depressions of the Western Desert, and ample evidence for aeolian origin of the Kiseiba-Dungul Depression exists there (*13*). If the depression existed before the ancestral Tushka channel was cut into bedrock, as seems likely, then the channel can best be attributed to the overflow of an ancient lake occupying the depression. Possible evidence for such a lake exists as isolated remnants of chert-bearing, lacustrine mudstones armored by chert nodules (*13*). These may be the oldest Pleistocene deposits recognized so far in the Western Desert.

Beadnell was the first to point out the occurrence of chalcedony nodules south of Kharga Oasis (*14*), and geologic mapping by Issawi revealed a large area between Bir Murr and Beris covered with irregular, lobate to spherical, white chalcedony nodules extending along the ancient caravan route called the Darb el Arba'in, in other areas around Gebel Nabta, and near Dungul Oasis north of the Sadat Canal site (*1*, *15*). I found similar deposits north of Kharga near Qasr el Gyb.

Close inspection of the nodules, some as much as 18 cm in diameter, reveals a zonation from white cryptocrystalline quartz (chalcedony) in outer layers to clear, crystalline quartz toward the inside; interior cavities are lined with euhedral quartz crystals overgrown by celestite in a few places. The surfaces of most exposed nodules are wind-abraded with irregular protrusions, but some nodules show a coarse reticulate pattern similar to that displayed on chert derived from hydrous sodium silicates in ultraalkaline lakes (*16*). Test pits revealed the nodules to be dispersed in a maroon, conchoidal amorphous claystone with

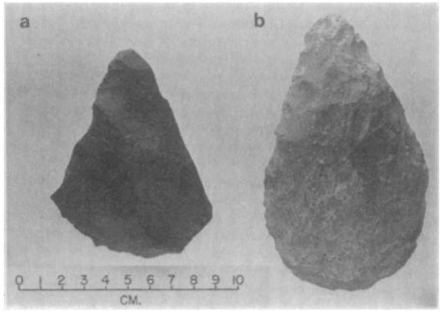

Fig. 2. Acheulean hand axes found in sediments exposed by the Sadat Canal. (a) The more primitive specimen, found 6.7 m below the surface. (b) A Late Acheulean specimen, from the spoil pile of upper excavations and 2 to 3 m below the surface.

associated anhydrite and halite. There seems little doubt that the silica nodules formed in the bottom muds of former saline lakes. Like the inverted wadis, these deposits are topographically inverted because there is a large concentration of nodules armoring the claystone from further deflation.

The age of the chalcedony lake beds is unknown, except that some of the chalcedony occurs as clasts in the inverted wadi gravels that predate Late Acheulean deposits of the Gebel Nabta area. Therefore, the lake beds are significantly older than the Late Acheulean occupation of the area and older than the stream gravels that are likely to have been part of the ancestral Tushka drainage system.

Throughout the Western Desert there are numerous playa-lake deposits of early Holocene age with associated archeological sites, but these deposits are being rapidly obliterated by wind (*17*). Remnants of older lacustrine deposits, mainly marls associated with Mousterian-Aterian and Late Acheulean artifacts, are rare (*13*, *18*). Older yet are the lacustrine claystones with authigenic chert, and their preservation is entirely due to the lag concentrations of chert that greatly reduced their rate of erosion. Were it not for the chert armor, no evidence of the former presence of these sediments would exist today. Even shore features of all but a few of the Holocene lakes appear to have been blown away, but a vast expanse of fine-to-coarse pebble sheet occurs along the southeastern side of the depression and smaller patches are scattered elsewhere. These could be lagged remnants of former wadis, but some, particularly the large expanse of residual gravel, could be remnants of former beaches, bars, and spits. These hypotheses will have to be tested in future work and much of the depression has yet to be explored for Quaternary deposits, but from the remnants that are known it is clear that times when lakes existed in the Western Desert have alternated with times of hyperaridity (*19*).

Rather drastic changes in climate characterized the Western Desert during the last half of the Pleistocene and probably the earlier half as well. From the geologic and archeological record, it is clear that today's hyperaridity (less than 1 mm of precipitation per year) was preceded by a pluvial climate that lasted from 10,000 to 6,000 ^{14}C years B.P. During this period the landscape was dotted by a large number of playa lakes in subbasins wind-scoured during the preceding hyperarid period (*17*). Earlier cycles appear to have been more intense and of longer duration than the last (*19*). It is not unreasonable, therefore, to suggest the possible prior existence of large lakes in the major depressions, one of which, the Kiseiba-Dungul Depression, overflowed into the Nile Valley.

As the lake drained through Wadi Tushka, the channel would eventually have become graded to the floor of the depression, and drainage networks would have extended headward, as long as adequate precipitation continued, until an integrated system was established. Inverted wadis of the Nabta area might represent this stage. It is not clear whether the saline lakes represented by the chalcedony and claystones resulted from the evaporation of water from several subbasins left parched as the proposed lake drained through Wadi Tushka, or from the earlier evaporation of a single large lake 17,000 km^2 in area or twice that size if it was integrated with the Kharga Depression (*20*).

In the Kharga area two major Pleistocene pluvials have been proposed on the basis of sheet gravels and tufas indicating episodes of stream and spring discharge (*21*); tufas I and II of Kurkur Oasis are tentatively correlated with these by Butzer and Hansen (*10*). The earliest sheet gravels are without artifacts, whereas Late Acheulean artifacts are found in the early part of the later sequence of gravels and tufas. The Kharga sequence needs to be reexamined in the light of newer knowledge, but, if the twofold division is retained, Wadi Tushka may be shown to have been cut during the earlier pluvial, which is believed to have been the wetter of the two, and filled during the transition to the later pluvial when discharge may have been inadequate to degrade the channel. Instead, aggradation with fluvial sand and gravel and reworked aeolian sand took place during Acheulean occupation of the Western Desert. Each calcrete layer formed at the end of an aggradational phase, either by evaporation from a capillary fringe or by pedogenic processes. In either case, the climate was characterized by more effective moisture than it is today.

Eventually Wadi Tushka became fluvially inactive and filled with aeolian sand during Late Pleistocene time. During the Holocene pluvial event, interdunal depressions along the former watercourse held playa lakes around which prehistoric people lived between 9350 ± 400 ^{14}C years B.P. (UCR-831) and 4530 ± 100 years B.P. (SMU-746) (*22*). Wind erosion has removed part of these deposits over the past 4000 or 5000 years, and today the movement of heavy construction equipment has obliterated most if not all surface archeological sites along the canal area.

Ancestral Wadi Tushka is real, but its origin is uncertain. Further testing of the hypotheses presented here will depend upon continued investigations like those in progress, both geological and archeological, to establish a paleoclimate chronology for the Western Desert. The outcrops are limited, the area is vast, and water is scarce, but it is today one of the least explored areas remaining on the earth.

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20. Today there is no topographic separation between the Kiseiba-Dungal Depression and the Kharga Depression to the north. Instead, the 170-m contours connect the two depressions between a series of hills northeast of Bir Murr. In fact, it would be entirely possible, with careful engineering, to allow Nile water to flow by way of the Sadat Canal all the way to Kharga, some 400 km to the northwest, where the floor of the depression is only a few meters above sea level. It is possible, therefore, that a hypothetical lake extended over the Kharga Depression as well. Such extensions are at present based on tenuous hypotheses at best, because of the degree to which erosion has changed the details of the topography over the several hundred thousand years that have elapsed since the time of the pluvial proposed on the basis of the inverted playas.
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22. From my visit to the canal site as groundbreaking got under way in February 1978, it was apparent that numerous prehistoric archeological sites were going to be destroyed by the construction equipment. With the help of the High Dam Authority, D. L. Johnson and I spent 2 days determining the stratigraphy of playa deposits exposed by the limited excavations and collecting radiocarbon samples from associated archeological sites (D. L. Johnson and V. C. Haynes, in preparation). The radiocarbon analyses were made by E. R. Taylor, University of California, Riverside (UCR), and H. Haas, Southern Methodist University (SMU), Dallas.
23. This work was supported by grants from the National Geographic Society, grant EAR-77-10109 from the National Science Foundation, and Smithsonian Foreign Currency Program grants FC 80140100, 90247700, and 90878700; this research is a part of the Combined Prehistoric Expedition of Southern Methodist University, the Institute for the History of Material Culture of the Polish Academy of Sciences, and the Geological Survey of Egypt. Additional assistance was provided by the American Research Center, Cairo; D. L. Johnson, University of Illinois; P. J. Mehringer, Jr., Washington State University; and B. Issawi and El S. Zaghloug, Geological Survey of Egypt. Borehole data and permission to visit the Sadat Canal excavations were provided by engineers A. Hassanein and K. Amin, High Dam Authority. Engineers F. Takla, R. Saad, and G. R. Kishk, Behera Construction Company, provided for our needs at the canal site.

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Changes in Endolymphatic Potential and Crossed Olivocochlear Bundle Stimulation Alter Cochlear Mechanics

Abstract. *Mechanical nonlinearity in the cochlea produces acoustic distortion products that can be measured in the ear canal. These distortion products can be altered by changes in the endolymphatic potential as well as by stimulation of the crossed olivocochlear bundle, which provides efferent innervation to cochlear hair cells.*

The origin of the exquisite sensitivity and frequency selectivity of mammalian auditory nerve fibers has been a topic of great interest in auditory physiology. A number of experimental manipulations (cochlear efferent stimulation, anoxia, drugs, loss of outer hair cells, and changes in perilymph composition) have been shown to alter the sensitivity and selectivity of auditory nerve fibers (*1, 2*). These changes may be the result of changes in cochlear mechanics, since Rhode has shown that the tuning of the basilar membrane is physiologically vulnerable (*3*).

Within the past few years, considerable attention has been drawn to nonlinearities in both auditory nerve responses and cochlear mechanics that seem to be intimately associated with normal cochlear function (*3–5*). Mechanical nonlinearity in the cochlea will distort the incoming sound waveform, and the resulting distortion products will propagate along the length of the cochlea. The finding that the mechanically propagated distortion products measured in the ear canal and in the response of auditory nerve fibers are altered by hair cell damage and fatigue suggests that the hair cells play an important role in cochlear mechanics (*5*). I have shown that the generation of propagating distortion products as measured with the cochlear microphonic depends on the electrical potential (EP) of the endolymph (*6*) bathing the hair cell cilia (*7*). This potential is normally positive 80 to 90 mV with respect to the extracellular fluid at the bottom of the hair cells.

The purposes of the experiments reported here are (i) to confirm that the effect of EP is indeed mechanical and (ii) to test the hypothesis that the effect is mediated by the outer hair cells.

Pigmented guinea pigs (200 to 700 g) were anesthetized with urethane (1.4 mg per gram of body weight) supplemented with ketamine as needed. The bulla was exposed and opened through the use of a ventrolateral approach. For experiments in which the EP was altered, a small hole was made in the cochlea over the stria vascularis of the first turn and a 5- to 8-μm KCl-filled pipette was inserted into the scala media. An optically coupled