Egypt's Nile Delta in Late 4000 Years BP: Altered Flood Levels and Sedimentation, with Archaeological Implications

Author: Stanley, Jean-Daniel

Source: Journal of Coastal Research, 35(5) : 1036-1050

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/JCOASTRES-D-19-00027.1

Journal of Coastal Research	35	5	1036–1050	Coconut Creek, Florida	September 2019

www.JCRonline.org

REVIEW ARTICLES

www.cerf-jcr.org

Egypt's Nile Delta in Late 4000 Years BP: Altered Flood Levels and Sedimentation, with Archaeological Implications

Jean-Daniel Stanley

Mediterranean Basin (MEDIBA) Program
Smithsonian Institution
Adamstown, MD 21710, U.S.A.

ABSTRACT

Stanley, J.-D., 2019. Egypt's Nile Delta in late 4000 years BP: Altered flood levels and sedimentation, with archaeological implications. *Journal of Coastal Research,* 35(5), 1036–1050. Coconut Creek (Florida), ISSN 0749-0208.

Compositional and textural attributes of dated fluvial and coastal to offshore deposits of the Nile delta in northern Egypt provide a means to determine whether, when, and to what extent climate change modified sedimentation of the Nile about 4000 years ago. This mid-Holocene period has been interpreted by climatologists and earth scientists as one of increased aridity, evaporation, and salinization, along with diminished rainfall and decreased Nile flood levels. Egyptologists also consider this as a time of major historic change from the end of the pharaonic Old Kingdom to the First Intermediate Period. Attention here is paid to diverse assemblages of mineralogical, geochemical, palynological, and faunal components, as well as to grain size, in numerous sediment core samples that became significantly altered within a 200- to 300-year period between 4300 and 4000 years before present (BP). This is the approximate time of the well-recognized climatic event of *ca*. 4200 years BP recorded in Eastern Mediterranean and Levant regions. In some core sections, such compositional changes are also identified but over a somewhat longer period that overlaps timewise with those of the shorter 200- to 300-year phase; these are attributed to the same major climatic event around 4300 to 4000 years ago. Some seemingly older dates and highly variable sediment textural types likely result from a stop-and-go downslope fluvial transport process involving repeated sequences of alternating sediment storage and subsequent erosional events that occurred during seaward flow along this extensive fluvial system. Findings summarized herein pertaining to the Nile's response to marked changes in climate and environmental conditions about 4000 years BP are needed to better decipher Egypt's evolving societal history at that time.

ADDITIONAL INDEX WORDS: *Archaeological interpretations, aridification, environmental stress, First Intermediate Period, Nile flow, Old Kingdom, rainfall, salinization, stop-and-go transport.*

INTRODUCTION

A synthesis of mid-Holocene sediment attributes in Egypt's Nile delta records the effects of climatic events in this region, especially during the last centuries of the fifth millennium before present (BP). Climate change at that time influenced a considerable geographic expanse, from the Atlantic eastward across extensive sectors of the Mediterranean and Europe and to the Middle East and Asia. Research has revealed how and when this event influenced that region, including Syria, Lebanon, and farther south to the Eastern Mediterranean, Israel, and northern Red Sea (Kaniewski *et al*., 2018). This climatic phase has been associated with an estimated 30 to 50% drop in rainfall in sectors of the Levant (Weiss, 2016; Weiss and Bradley, 2001; Weiss *et al*., 1993). Reviews of what is generally termed the *ca*. 4200 years BP event and its effects on the Levant have been compiled by specialists of diverse professions, including archaeologists, climatologists, geographers, and geologists (Kaniewski *et al*., 2008, 2018; Weiss, 2016). Fewer studies, however, have focused on potential effects of intensified aridity, altered rainfall patterns, salinization, and associated diminished Nile river flood levels at that time on the sediment depositional record in the Nile delta of NE Africa (Finné *et al*., 2011). It has been proposed that changes of Nilotic hydrology and sedimentation in Egypt are attributed to millennial-scale southern displacement of the Intertropical Convergence Zone that resulted in a weakening of the Ethiopian monsoon's intensity (Macklin *et al*., 2015; Marriner *et al*., 2012; Said, 1993). On submillennial timescales, significant changes to the delta were probably also induced by events associated with variations of El Niño Southern Oscillation.

Summarized herein are attributes of Nile delta sediments transported from east-central Africa and Ethiopia northward across the Sudan and Upper Egypt and then to the Nile delta and adjoining Mediterranean Sea (Figure 1) around the end of the fifth millennium BP (Hamdan *et al*., 2018; Krom *et al*., 2002; Marriner *et al*., 2012; Pennington *et al*., 2019; Stanley and Warne, 1998). It has been proposed in scientific studies of Egypt's evolution that altered climatic and associated environ-

DOI: 10.2112/JCOASTRES-D-19-00027.1 received 10 March 2019; accepted in revision 26 April 2019; corrected proofs received 5 June 2019; published pre-print online 24 June 2019.
Corresponding author: stanleyjd0@gmail.com

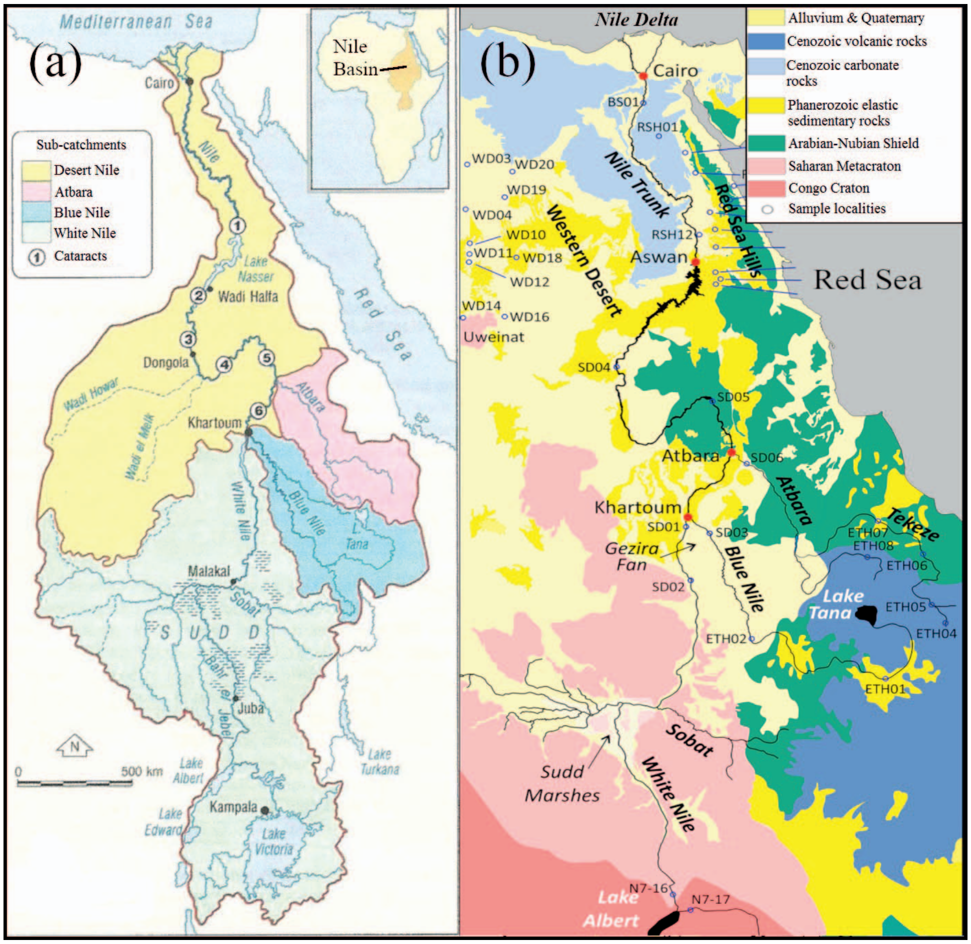

Figure 1. The Nile Basin (inset in a) covers about 3.3 million km^2 and *ca*. 10% of the African landmass; the Nile flows through 11 countries. (a) Four major tributary and subcatchment basins of the modern Nile are delineated (Woodward *et al*., 2015). (b) Modern channels of the three major tributaries of the Nile (White Nile, Blue Nile, and Atbara) and their hinterland geology are shown (Fielding *et al*., 2016).

mental conditions likely led to reduced Nile flood levels during that period (Butzer, 1976, 1984, 2012; Marriner *et al*., 2012; Said, 1993; Stanley *et al*., 2003). Until the end of the 20th century, most archaeological research on pharaonic Egypt conveyed that environmental conditions were probably associated in some manner with marked new political and societal developments occurring during the final centuries of the fifth kilo annum (ka) BP. Concurrence of these events was believed to have induced a significant change of direction in Egypt's human history, especially from about the end of the Old Kingdom (OK) through much of the First Intermediate Period (FIP). During the past two decades, however, some archaeologists have reevaluated the nature and significance of political and societal changes during this period and express reservations, or reject, the role of contemporary environmental impact on Egypt's evolving history at that time (Seidlmayer, 2000).

Of interest in the present study are observations that indicate a period of increased aridity and reduced rainfall patterns that likely would have induced changes in the Nile's hydrography and sediment dispersal about 4200 to 4000 years ago as far northward as the Nile delta. It is postulated here that a period of lower Nile floods at that time would be recorded by sediment loads of altered composition and texture derived from southern headwaters and other source areas. An attempt is made to determine whether such influences could be identified and traced to distal sectors of sediment dispersal as far as the lower Nile valley and Egypt's delta positioned at the Mediterranean margin (Figures 2 and 3). For this, numerous and diverse compositional databases identified in deltaic deposits are reviewed herein. These include mineralogical, geochemical, palynological, faunal, and other components that record temporal changes in sediment transported by the Nile and released in the delta and coastal margin around the end of the fifth ka BP.

DATABASES CONSULTED

Information presented herein is derived largely from study of sediment drill cores collected between 1985 and 2002 in the Nile delta, primarily along its northern margin (85 borings) and in the central delta (2 borings), as shown in Figure 4a, as

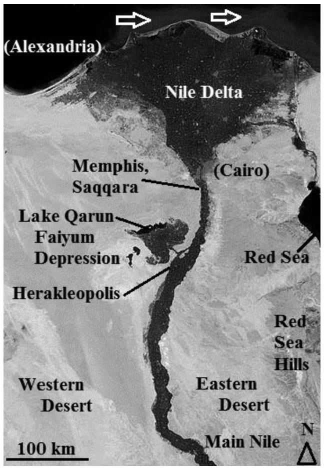

Figure 2. Satellite image of the delta and northern main Nile system showing its meandering flow pattern between Egypt's Eastern and Western Deserts, the site of Herakleopolis near the Faiyum depression and Lake Qarun, and the centers of Memphis-Saqqara west of the Nile and south of the delta's apex. Wave and coastal currents driven from the northwest mix fluvial sediments from the Nile with offshore deposits, and transport these toward the east (white arrows).

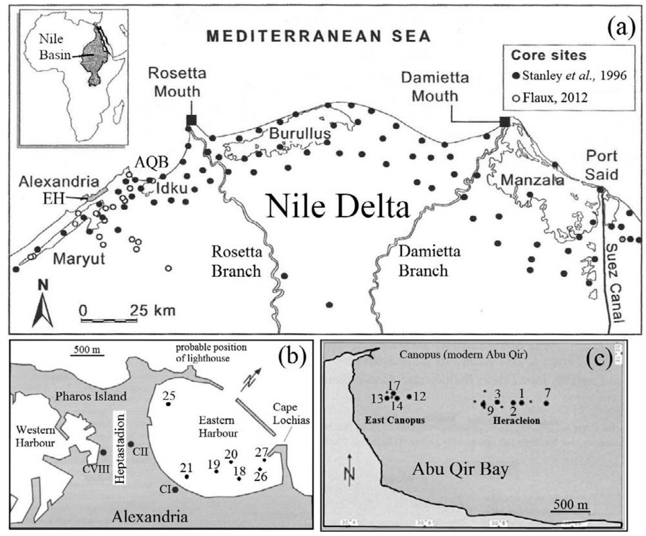

Figure 4. Nile delta core sites: (a) northern and central delta (Marriner *et al*., 2013), (b) Alexandria's Eastern Harbor (Stanley and Landau, 2010), and (c) Abu Qir Bay (Stanley *et al*., 2007).

well as offshore in Alexandria's Eastern Harbor and Abu Qir Bay (24 vibrocores), as shown in Figure 4b,c. These subsurface materials were obtained as part of the Mediterranean Basin (MEDIBA) Program, initiated in 1985 at the Smithsonian Institution's National Museum of Natural History in Washington, D.C., to interpret the late Pleistocene and Holocene to recent evolution of the lower Nile sector and its coastal region. Cores recovered on land range in length from approximately 20 to 60 m, and those recovered offshore range from 1.0 to 5.5 m. Studies of the 87 cores collected on land in the northern and central delta include textural and compositional data from more than 2500 sediment samples, including information on the relative amounts of petrological, faunal, plant, and other

Figure 3. Aerial photographs showing the mouths of the (a) Rosetta distributary along the NW delta coastline and (b) Damietta distributary at the NE delta coast. Observed are coastal wave-driven patterns oriented toward the east and, landward in the distance, the last of numerous meanders (vertical arrows) before the Nile branches reach the Mediterranean (Bertinetti, 2002). Dams recently emplaced on these two branches close to the coast (Stanley and Warne, 1998; Waterbury, 1979) preclude fresh water and Nile sediment from escaping the delta to the sea at these two coastal localities.

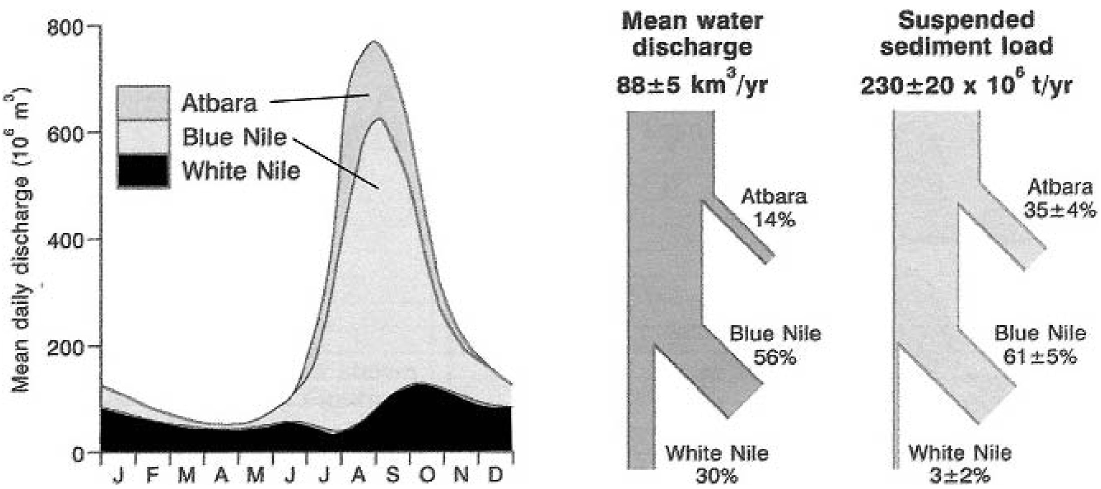

Figure 5. Flow regime of the modern Nile showing the relative contributions from the Atbara River, Blue Nile, and White Nile during the 12 months of the year; mean daily flow increases markedly from July to October and is highest in August and September. The present mean annual water discharge and suspended sediment load from these three main tributaries are also indicated (Foucault and Stanley, 1989; Woodward *et al*., 2015).

components of sand size (>63 μm) or larger. These data, along with 87 core logs and their geographic locations, are compiled in a volume that summarizes core materials examined during the period from 1985 to 1994 (Stanley, McRae, and Waldron, 1996). Approximately 350 radiocarbon-14–dated core samples from sequences of the late Pleistocene (*ca*. 35,000 years BP) to upper Holocene are shown along the lithological logs in that compendium and in subsequent studies. More detailed information based largely on samples from these cores are recorded in published works, several of which are cited in the next two sections of this paper. These and some additional articles by others, based on analyses from 1986 to present, provide information on petrology, mineralogy, geochemistry, pollen, fauna, and radiocarbon-14 dates for the region and period of interest here. Data from coastal to offshore materials (Figure 4b,c) include those adjacent to the city of Alexandria (Flaux, 2012; Flaux *et al*., 2013; Goiran, 2001; Stanley, McRae, and Waldron, 1996), 7 cores (Figure 4b) in Alexandria's Eastern Harbor (Stanley and Landau, 2010), and 17 cores (Figure 4c) in Abu Qir Bay (Stanley *et al*., 2007). Also cited here for comparison are data on sediments from studies south of the delta compiled by others.

Baseline mineralogical information used to interpret the provenance of MEDIBA and other core deposits is provided by studies of surficial sediment collected from the two major upper Nile sources (Shukri, 1949, 1951) in the Ethiopian highlands (for Blue Nile and Atbara River transport) and in east-central Africa (White Nile). Studies of Holocene sediments transported downslope by the Nile across the Sudan desert (Fielding *et al*., 2016; Woodward *et al*., 2015) and to the lower Nile and its delta, as discussed herein, are helpful for interpretation. Other consulted studies identified other components derived from formerly active fluvial tributaries, now dry wadis, that once flowed across sectors of adjacent basin regions to the main Nile (Red Sea hills to the east and arid to desert sectors to the east and west), and additional windblown sand and silt from adjacent and distal desert terrains (Figure 2). Reaching the Nile, some of these materials were then displaced farther downslope across Egypt to the sea (Hamdan *et al*., 2018; Hassan, 1976; Pennington *et al*., 2019; Siegel *et al*., 1995; Stanley and Chen, 1991; Stanley and Wingerath, 1996; Williams *et al*., 2010; Woodward, Macklin, and Welsby, 2001; Woodward *et al*., 2015). These and other published reports on compositional materials in the Nile basin (Figures 1 and 5) shed light on the complexity of the multisourced provenance of minerals, chemical elements, isotopes, biological components, and grain size attributes in Holocene samples collected in delta and offshore cores.

The two subsequent sections in the present study summarize findings reported in published articles by the MEDIBA Program team and by other groups that have also examined diverse compositional attributes of mid-Holocene sediment core sequences in the delta and adjacent areas, both to its north and to its south. Information pertaining to samples examined, their locations, methodologies applied, results obtained, and interpretations of findings are presented in published articles cited later. This first section identifies sediment samples presenting distinct changes in composition that occurred primarily during a relatively brief period in the late fifth ka BP; these are called group I. The section that follows it summarizes those samples with altered attributes but recorded over a somewhat longer period (identified as group II), some from as early as about the mid–fifth ka BP and others with dates extending to the early fourth ka BP.

CHANGES OF SHORT DURATION IN LATE 4000 YEARS BP

Group I sediment samples derived from studies cited below and listed in Literature Cited identify compositional and textural components in Nile delta sediment that record changes occurring within a period from approximately 200 to

300 years or less, with most occurring primarily from before the end of the period 4000 years ago.

Pollen Analysis, Charcoal Content, and Fauna

A distinct change in pollen content, including a decrease in sedges (Cyperaceae), is recorded around and shortly after 4195 years BP in a core (Goiran-II) dated by calibrated radiocarbon-14 samples collected in the coastal city of Alexandria and adjacent to the Eastern Harbor (Goiran, 2001). In the same core and at the same period, that author identifies changing proportions of ostracod, pelecypod, and gastropod faunas.

A core positioned in the northern delta along the western margin of Burullus lagoon and dated by calibrated radiocarbon-14 provides a record of altered terrestrial vegetation *ca*. 4200 years BP (Bernhardt, Horton, and Stanley, 2012). A marked decrease here in sedges (Cyperaceae in Figure 6a), as was found in the previously cited pollen study in the Alexandria region by Goiran (2001), suggests that increased aridity prevailed at that time. This shift in pollen content was accompanied by an increase in relative abundance of microscopic charcoal (Figure 6a), perhaps a marker of an increased number of fires that prevailed during the period of accentuated aridity.

In cores collected offshore in Alexandria's Eastern Harbor, Bernasconi, Melis, and Stanley (2006) identified molluscan and foraminiferal faunas that indicate altered environmental conditions where they lived. This involved a switch from a slightly confined marine setting to a more open marine vegetated one, comprising less confined biofacies *ca*. 4300 years BP. These modified conditions are associated with reduced Nile freshwater inflow and increased influence of intense reworking by coastal current and wave flow along the delta's marine margin and offshore shelf, much as at present (Figures 2 and 3; *cf*. Frihy and Dewidar, 2003). Another study, also focusing on less confined biofacies but in a modern setting of Manzala lagoon, provided similar information that helps interpret the late fifth ka BP record. Reinhardt, Stanley, and Patterson (1998) found that strontium (Sr) isotope records in these deposits show an increase in marine input associated with saltwater intrusion into the Nile's delta plain. This finding is attributed to a phase of decreased Nile fluvial discharge and sediment input that reached the delta's coastal margin in the recent past. Measurements of concurrent paleontological and Sr isotope changes in this modern setting indicate that the earlier mid-Holocene salinity changes at Alexandria's nearshore locale *ca*. 4300 years BP (Bernasconi, Melis, and Stanley, 2006) could also have been a response to disruption, reduction, or both of former Nile freshwater flow to the coast.

Strontium and Titanium/Aluminum Ratios, Instrumental Neutron Activation Analysis, and Trace Elements

Samples in three cores, one from the northeastern delta coast and two from middelta, examined ^{87}Sr:^{86}Sr and titanium (Ti)/aluminum (Al) ratios and recorded distinct changes between *ca*. 4500 and 4200 years BP. High Sr values characterize sections older than 6000 years BP; in time, this was followed by a rapid decrease of this ratio and then by fluctuating values between *ca*. 4350 and 4000 years BP (Krom *et al*., 2002; Stanley *et al*., 2003). A minimal isotopic ratio of similar age (*ca*. 4200 years BP) is also noted in core S-21 (Figure 6b). Moreover, split core sections in the two middelta cores reveal visually distinct layers of reddish brown silt and iron oxide concentrate that formed between *ca*. 4250 and 4050 years BP. A similar change was noted *ca*. 4000 years BP when Sr isotope ratios were examined in a separate core study on the western delta margin (Marriner *et al*., 2013).

Dated core samples (two from the eastern delta and one from the north-central delta) were analyzed using instrumental neutron activation analysis of rare-earth and other trace elements of the light-mineral fraction of sand-size (>63 μm) sediments (Allen, Hamroush, and Stanley, 1992; Hamroush and Stanley, 1990). Analyses of chromium/scandium ratios (Figure 6c) recorded decreased values *ca*. 4000 years BP, suggesting a reduction at that time of Blue Nile and Atbara sediment derived from the Ethiopian plateau. Moreover, a concurrent increase of lanthanum/lutetium ratios in these core samples indicates a relatively higher White Nile sediment contribution from the East African system.

Sediment Grain Size Variability

A range of textural types as defined by Folk (1961) comprise the bulk of samples in 48 cores around the end of 4000 years BP (Stanley, McRae, and Waldron, 1996). These are as follows: 0.5 to 57% sand (62.5–2000 microns), 6 to 86% silt (4–62.5 microns), and 7 to 93% clay (1–4 microns). Sedimentologists would define samples from this period as including sand, silty sand, sandy silt, silt, sandy silty clay, silty-clay sand, and clay. This broad assemblage of grain size categories records highly variable fluvial transport regimes, ranging from high fluvial channel energy to low channel and overbank or delta plain deposition.

Thus, it appears that both coarser-grained sandy bedload and finer-grained suspended loads were distributed during this time span, largely because of variable transport and depositional mechanisms involved during various phases of sedimentation. An example of bulk sample textures in core S-53 (~4.5-m depth dated *ca*. 4000 years BP) is defined as silty clay by proportions of its grain size: 12% sand, 36% silt, and 52% clay. This sample coincides with a stratum of decreased sedge pollen and increased charcoal (Figure 6a), indicating deposition in a relatively low-energy setting in the northern delta sector.

Changes Recorded South of the Delta

Numerous mineralogical, geochemical, and palynological changes in the Nile alluvium are identified at Saqqara, south of the delta (Figure 2), from *ca*. 4400 to 4100 years BP (Hamdan *et al*., 2018). Examination of the pollen record in particular shows distinct differences occurring at that time.

The sedimentary record at Moeris Lake (now named Qarun Lake) in the Faiyum depression, about 100 km south of the delta and Cairo (Figure 2), has also responded to changes of Nile flood levels during the mid- and late Holocene. Lake levels fluctuated largely as a function of the Nile's sill elevation and height of Nile floods (Hassan, 1986, 2005); thus, this lacustrine setting provides a useful measure of times of pronounced high and low Nile flow events. If cut off from the Nile, for example, the once 73-m deep lake could be desiccated in only about 42 years. Hassan's geographic surveys and dating of the lake's shifted beach sediment at different positions in the Faiyum

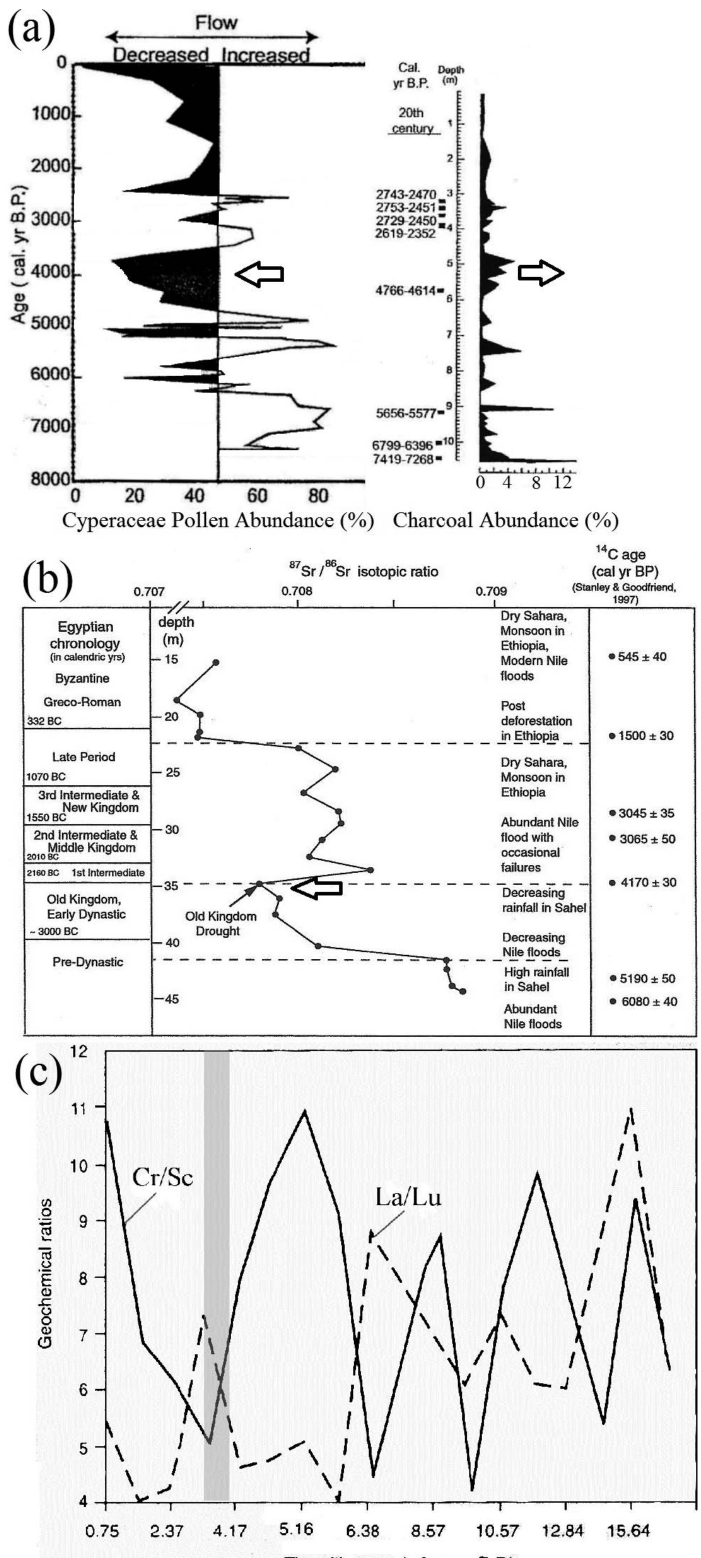

Figure 6. Examples of compositional changes in the Nile delta's mid-Holocene sediments around the end of 4000 years BP. Shown are (a) concurrent decrease of relative abundance of Cyperaceae in the pollen record and increased abundance of microscopic charcoal in core sediment near Burullus lagoon (Bernhardt, Horton, and Stanley, 2012); (b) decrease of strontium (^{87}Sr:^{86}Sr) ratios around the end of the Old Kingdom (OK) to the First Intermediate Period (FIP) in core sediment near the coast, east of the Suez Canal (Stanley *et al.*, 2003); and (c) decrease of the chromium/scandium (Cr:Sc) ratio and increase of the lanthanum/lutetium (La:Lu) ratio using instrumental neutron activation analysis on core sediment (Allen, Hamroush, and Stanley, 1992; Hamroush and Stanley, 1990).

depression serve as useful markers of changing lake levels. Some occurred abruptly, such as the one that is dated at the end of the fifth ka BP.

Using numerous radiocarbon-14 and optically stimulated luminescence (OSL) dates, Macklin et al. (2015) identify mid-Holocene phases of Nile channel and floodplain contractions south of Egypt along the desert Nile in the Sudan (Figure 1a). These occurred as early as *ca*. 4700 to 4550 years BP and were followed by years of further reduction in Nile river flows and floodplain contractions *ca*. 4300 to 4200 years BP.

SEDIMENTARY CHANGES OF LONGER DURATION

This section focuses on results of various analytical methods applied to dated mid-Holocene deposits that identify periods of increased climatic aridity and altered, usually diminished, Nile flood stages dated after *ca*. 5000 to 4500 years BP and others continuing to 4000 years BP. These core samples comprise group II. Like the group I samples described in the prior section, those listed later are indicative of transport by decreased Nile flows but range in age for a period longer than approximately 200 to 300 years. However, most samples in this group II partially overlap timewise with those of group I that are of shorter duration at the end of the 4000 years BP period.

Sr Isotopes, Trace Elements, and Water-Soluble Ions

Fourteen major and trace elements in Nile delta bulk sediment samples from two cores in the northeastern delta margin near Manzala lagoon were investigated (Dominik and Stanley, 1993). The boron (B)/beryllium (Be) ratio helps record the onset of arid conditions in this region *ca*. 5000 to 4000 years BP. Analyses of sulfur content and B:Be ratios also denote a change *ca*. 4500 years BP.

A progressive hydrological shift from a Nile-dominated lacustrine to a marine-dominated lagoon from *ca*. 5500 to 3800 years BP is recorded by the Sr isotope for a core from Maryut lake at the westernmost margin of the delta (Figure 4a). This extended period ranges from the African Humid Period to one of increased regional aridity (Flaux *et al*., 2013). The measured ^{87}Sr:^{86}Sr ratios denote timewise changes from fresh and low-salinity water (Nile provenance) to seawater (Mediterranean origin). The present ^{87}Sr:^{86}Sr ratios of Nile water and sediment measured in this area indicate a Blue Nile signature, with Sr data marking the period from *ca*. 4000 to 3000 years BP as one of lower Nile flows.

Analyses of samples from the Faiyum depression south of the delta (Figure 2), using Ti:Al and other ratios (Sun *et al*., 2018), record an increasingly arid climate in this Nile basin region from *ca*. 5000 to 4000 years BP; the titanium dioxide content of samples also increased during that time. Another core collected on the floor of Qarun Lake (Marks *et al*., 2017) indicates this depression became partly desiccated at a time of reduced freshwater discharge when Nile flow levels became lower and were then cut off from the lake. Paleosalinity conditions are determined by measurement of water-soluble ions in lake floor sediment. Both ion content and diatom assemblages in lake floor sediment record environmental changes associated with its transition from freshwater, to brackish and saline conditions, and then to a dry phase that appears to have occurred from about 4400 years to 3000 years BP.

Sand-Size Minerals

Two studies of heavy minerals in the sand-size fraction of radiocarbon-14–dated core sections in the northeastern delta near Manzala lagoon do not reveal a distinct temporal or source-related mineralogical change after *ca*. 4500 years BP (Foucault and Stanley, 1989; Stanley, Sheng, and Pan, 1988). These components record a mixed derivation from several headwater Nile source areas that reached the delta in the mid-Holocene. Moreover, some light mineral types such as feldspars may have been introduced laterally into the Nile from formerly active tributary rivers flowing from both east and west (Figure 7). Proportions of sand-size heavy minerals (range from 0 to 13%) and mica grains (from 0 to 47%) in bulk samples of that period are highly variable, largely the result of low- to high-energy transport-depositional processes involved during this period of low Nile floods. In addition, some iron-coated quartz grains were likely displaced by aeolian processes from desert terrains (Figure 1a) rather than only from distant upriver source areas to the south.

Fauna, Pollen, and Microscopic Charcoal

Ostracoda assemblages in a suite of cores recovered along the delta's northeastern margin appear to have been responsive to climatic oscillations trending to drier conditions from about 4000 to 3500 years BP (Pugliese and Stanley, 1991). At that time, a marked change in environmental conditions in shallow marine environments near Manzala lagoon (Figure 4a) is indicated by the decreased number of species able to colonize the shallow seafloor at the delta-front and nearshore settings. This faunal change is interpreted as a response to an increase in salinity conditions that coincided with a wet-to-drier climate shift, accompanied by lower volumes of fresh Nile water reaching the northeastern delta and its coastal margin.

Samples of core AL-19 recovered in Alexandria's Eastern Harbor (Figure 4b) record marked changes in pollen assemblages and an increase in microscopic charcoal (Stanley and Bernhardt, 2010). This occurs in sections dated from *ca*. 4200 to *ca*. 2700 years BP and is similar to observations made in some cores recovered on adjacent land in Alexandria examined by Goiran (2001). Perhaps those of older age are indicative of climatic change, while younger ones (since *ca*. 4 ka BP) in this semienclosed marine body close to land may record an increased input of wastewater released by human activities such as irrigation and municipal usage.

Human Remains from Egypt

The oxygen isotope composition of teeth and bones from 48 human mummies was analyzed to trace oxygen-18 evolution and other possible responses to effects of climate fluctuations during an extended period, from *ca*. 5500 to 1500 years BP (Touzeau *et al*., 2013). The authors assumed that materials tested in this study were from individuals who likely would have drunk water from the Nile during that time. The results showed an increased mean oxygen isotope composition of tooth enamel during this period, especially one increasing somewhat more rapidly between *ca*. 4500 and 3800 years BP.

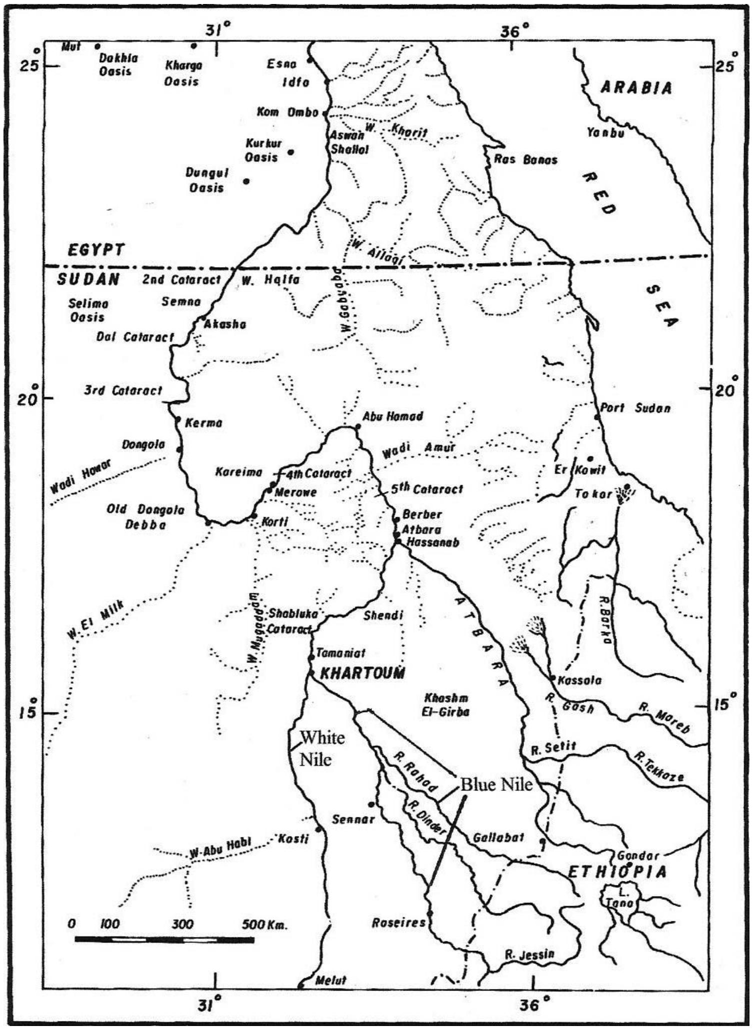

Figure 7. Map of the Nile system in Ethiopia, Sudan, and upper Egypt, along with its numerous former fluvial tributaries (Said, 1993). The latter (shown by dotted lines) are now mostly dry wadis that had stopped transferring water and sediment to the main Nile by the end of 4000 years BP.

INTERPRETATION OF DATA

Hydrological attributes of the Nile river, the world's longest at 6853 km, were detailed before emplacement of the High Aswan Dam in 1965 (Hurst, 1957) and after that time (Said, 1993; Sutcliffe and Parks, 1999; Waterbury, 1979). Some river flow characteristics during Egypt's early history were initially recorded by carvings on rocks and steles. This was followed, as early as *ca*. 3050 years BP, by systematically collected information using nilometers, *i.e*. gauges serving as the instruments of choice to denote variations of Nile levels through time. Nilometer readings recorded seasonal water-level variations at different stations along the Nile during the year and thus denoted flow-level fluctuations increasing from low to high in summer to early fall and then returning to low in subsequent seasons (Figure 5). These gauges also identified natural fluctuations that occurred from year to year and some for longer periods.

It has been recognized that monsoonal rainfall patterns, especially affecting the Ethiopian highlands, result in markedly increased input of Blue Nile and Atbara River flows in summer and early fall in recent time (Figure 5) and serve as the major annual sources of river water and sediment transported downriver from volcanic, metamorphic, and sedimentary terrains to the delta (Figure 1b). This annual shift in flow pattern substantially modifies the volumes of water, sediment loads, and types of sediment annually displaced downslope, as highlighted by Hurst (1957), Said (1993), Shukri (1949, 1951), Waterbury (1979), and others. The causes of longer-term, markedly altered fluctuations of sediment composition in the past, as summarized in the two previous sections, also have been interpreted as a function of more powerful, regionally important climatic changes that affected the Nile basin. Marked fluctuations of flood levels about 4000 years ago that occurred during periods of less than a decade to ones of longer extent, lasting off and on during a century or more, are receiving better definition. Their regional effects, superposed on the annual seasonal fluctuations of Nile flow, are of the most interest here.

Sediment components summarized in the previous two sections provide insight into two overlapping age ranges recorded by core samples of group I and II recovered in and adjacent to the delta. Those in group I record varied Nile depositional patterns that occurred within a relatively short time span (approximately 200 to 300 years), and primarily during the final centuries of the fifth ka BP. This period correlates well with the *ca*. 4200 years BP event in lower Egypt explored by the MEDIBA team and other groups; this is associated with effects of regionally marked climate change episodes that affected Nile flows at that time (Hamdan *et al*., 2018; Kaniewski *et al*., 2018; Krom *et al*., 2002; Marriner *et al*., 2012, 2013; Stanley *et al*., 2003). These included primarily increased aridity, evaporation, salinization, and altered monsoonal rain patterns inducing lower Nile flows (Figure 2.12 of Said, 1993) that altered sediment transport and composition patterns identified in the lower Nile basin. It is proposed that these changing climate-related factors leading to diminished Nile flows were largely responsible for modified compositional and textural attributes noted in samples of groups I and II.

Dating Delta Samples

Useful for correlating mid-Holocene changes of Nile sediment provenance in delta cores are measurements of East African lake levels in upriver source and catchment areas (Figure 1), including Victoria and Tana Lakes, that supply Nile waters (Adamson *et al*., 1980; Gasse, 2000; Gillespie, Street-Perrott, and Switsur, 1983; Street-Perrott and Perrott, 1993). Hydrological shifts with reduced Nile flow and channel contraction appear to correlate well with times of lower water levels in these two lakes dated from *ca*. 4400 to 4140 years BP. Lake Turkana's level, near the catchment of the White Nile, reached a minimum *ca*. 4400 years BP (Owen *et al*., 1982), and lakes Abhe and Ziway-Shala near Blue Nile and Atbara River sources show a decline in water levels, reaching a minimum *ca*. 4200 years BP (Gillespie, Street-Perrott, and Switsur, 1983). Among useful component markers of climate change and sediment provenance of group I delta samples of that age examined in the present study are pollen, charcoal, and distinctive trace elements and isotopic components (Figure 6). Among the latter are those indicative of increased proportions derived from volcanic terrain sources (Blue Nile and Atbara River) in the Ethiopian highlands or those from metamorphic and other sources (White Nile) in East Africa.

Although not of as brief an age as those in group I, most samples of group II tend to overlap timewise to some extent with those of group I. Some group II samples are dated earlier, usually after the period of increased aridification from *ca*. 4500 years BP, while others extended to and/or somewhat after 4000 years BP. A difference of dates between the two groups may result at least partly from some limitations of the radiocarbon-14 method that is commonly applied and, in this case, insufficiently close spacing of accelerator mass spectrometry dates and total number of samples collected. In addition, another limitation with regard to the *ca*. 4200 years BP event occurs at a plateau at that time on the radiocarbon curve.

When used to determine ages of fluvial sediment, radiocarbon dates obtained have been found to be reliable to within approximately 50 years in some cases but only to within one or two centuries in others. This disparity in dates depends partly on the dating method used (*cf*. Dee, 2017), including Bayesian modeling (Bronk Ramsey, 2009); the materials tested; and on particular aspects of fluvial sediment transport style of the Nile, as discussed in the following section. Other dating methods, such as OSL, could perhaps additionally be used. OSL is a chronometric measurement that presumably records the time a sample was last exposed to sunlight, before the deposit was finally buried. Most helpful for interpreting dates are those fairly rare occasions on which identifiable and datable anthropogenic materials are recovered in core sections along the delta margin (Robinson and Wilson, 2010; Stanley, Arnold, and Warne, 1992).

Repeated Stop-and-Go Sedimentation

Both markedly changing seasonal flux and longer-term climatic effects on Nile floods help identify a stop-and-go sediment transport process that has prevailed along the lengthy and meandering downslope fluvial pattern of the Nile. In play are the river's numerous straight stretches alternating with bends along the thousands of kilometers of flow between the upriver sources and the distal delta coast (Figures 2 and 3). Complete downriver displacement of sediment occurring as one single event during the time of a flood, from source area to depositional site thousands of kilometers to the north, would be the exception rather than the rule in most cases. Downslope transport of fluvial material to as far as the delta and adjacent marine shelf has more likely involved a variable number of repeated temporary depositional storage events. Each displaced deposit that is stored along the river's course, such as meanders, may then be removed subsequently by more powerful erosive fluvial events.

If the process is repeated several times downslope, this would result in an increasingly older depositional mix shifted seaward (Stanley, 2001). Effects of this process have been recognized in several of the world's major deltas (Stanley and Chen, 1991, 2000; Stanley and Hait, 2000). The number of times a sediment is subject to displacement as it moves downslope to its burial at a distal delta site, and the time involved in total overall transport, would help explain why it could: (1) comprise material of unexpected mixed texture ranging from sand and silt to clay, or the reverse; (2) include a diverse composition of confusing multiple provenance rather than of a single major source origin; and (3) record an age that is older, or possibly younger, than expected. Therefore, it is postulated that delta samples of group II, with dates of longer duration (>300 years) but overlapping in age with those of group I, are not necessarily of either older or younger in age and may be nearly contemporaneous to samples of group I.

Evidence for this proposed multiple stop-and-go transport process is provided by studies of the numerous core sections recovered from the delta. It was noted earlier that the grain size of core sediments dated *ca*. 4000 years BP were highly variable, neither consistently fine or coarse, as would be expected with this type of multiphase and extensive displacement seaward. In addition, sediment strata recorded with dates are inverted as one proceeds upward in a core's section, *i.e*. where sediment strata with dates of older age are sometimes positioned directly above those of younger age (Stanley, 2001; Stanley, McRae, and Waldron, 1996). Radiocarbon-dated delta bulk samples that are sometimes considerably older than reasonably expected in group II also suggest that some radiocarbon-14–deficient old carbon may have been incorporated into and preserved in Nile sediment that are of younger age. This may be the result of repeated sequences of erosion → displacement → redeposition of sediment downslope along the river, suggesting a somewhat earlier or later time of transport, as is the case with group II samples, until their final burial in distal lower Nile sites.

Multisourced Provenance of Sediments

Material transported downriver by the Nile is derived from several major source areas (Figures 1 and 5), *i.e*. primarily the Blue Nile and Atbara River with headwaters in the Ethiopian highlands, and diverse geological terrains traversed by the White Nile headwaters in east-central Africa (Fielding *et al*., 2016; Shukri, 1949, 1951). Findings suggest increasing sediment discharge at times from the Blue Nile and Atbara River that carries volcanic sediment from the Ethiopian Highlands and that tends to be rich in Ti and magnetic minerals, some fixed in silt. The aridity phase intensifying after *ca*. 5000 to 4500 years BP is associated with declining monsoon rainfall caused by the lower southward retreat of the Intertropical Convergence Zone. More frequently overlooked in the mix of components in Lower Egypt are possible added proportions of sediment transported to the Nile valley by windblown processes such as sand and silt from shifting proximal desert terrains and finer silt and clay from more distal sources. Also added may be material carried into the Nile by fluvial flow from previously active fluvial tributaries that became dry wadis after about 4000 years ago (Figure 7); these sediments that had entered the main Nile system earlier, especially in the Sudan, could have been displaced subsequently farther downslope. Among the former active tributaries are those originating in the Red Sea Hills to the east and those flowing from western Nile basin areas (Woodward *et al*., 2015). These authors, focusing on sediments along the desert to the south between Atbara River and Lake Nasser and using ^{87}Sr:^{86}Sr and neodymium isotopes, indicate that the climate in that area became drier after 4500 years BP. The mixing of different proportions of this multisourced material of different ages tends to complicate precise resolution of dates and provenance in delta sediments released farther downriver.

Other Factors Affecting Delta Sedimentation

Once transported to the delta proper during the mid-Holocene period, additional processes could have further altered dispersal of both Nile water and sediment. Among these are the role of displacement by Nile distributaries flowing from the delta's apex in different northward directions toward the coast. Although only two such channels remain active (Rosetta and Damietta; Figure 4), others (eight or perhaps even more branches; Figure 8) existed earlier that released freshwater and sediment across the delta plain, some all the way to the coast (Bietak, 1975; Butzer, 1976; Sestini, 1992; Toussoun, 1925). It is probable that decreased flow along the main Nile valley likely led to a reduction in discharge of water and sediment moved through active distributaries approximately 4200 to 4000 years ago. Envisioned at that time are changes in channel, overbank, and delta plain deposition along the laterally migrating and meandering patterns of active distributaries that then generally dispersed reduced amounts of both water and sediment.

Even during the relatively short period of a century or two of reduced Nile flows, the overall distribution of mid-Holocene depositional sequences, now buried beneath the delta plain surface, would have been further modified (Butzer, 1976; Stanley and Warne, 1998). Two major factors came into play. The first is active neotectonic motion produced by a system of earthquakes and faults (Figure 9a,b) that displaced deltaic strata vertically and laterally, much as at present (EGAS, 2015; El-Sayed, Korrat, and Hussein, 2004; Gamal, 2013; Kebeasy, 1990). The second is active subsidence that lowered strata north of an E-W trending hinge line in the northern delta and offshore (Figure 9c); this is recorded by submerged deltaic and coastal deposits, along with once-active ancient ports, that have sunk and are preserved at depths beneath the seafloor (Robinson and Wilson, 2010; Stanley and Clemente, 2017; Stanley and Warne, 1998). These phenomena would have altered the three-dimensional configuration and lowered the mid-Holocene sequences and coastal archaeological sites (Stanley, Arnold, and Warne, 1992) underlying the delta and its offshore shelf margin independently of climate change.

Anthropogenic activity at that time of lower Nile flow would also have included effort, albeit limited, for water extraction, diversion, and irrigation for agricultural and municipal purposes. This was not only a time of increased aridification but also one leading to greater evaporation and salinization and probably to altered nutrient levels and less nitrogen-rich silt deposition (Avnaim-Katav *et al*., 2019; Burn, 2018; Butzer, 1976, 1984). It is assumed that agricultural activities continued in floodplains where possible at that time, although such areas became fewer in number and of more limited size, while seasonal pastoral activities likely increased in relative importance. How rulers and inhabitants of delta towns and centers with small populations responded to such environmental challenges annually and longer term during the *ca*. 4200 to 4000 years BP period remains to be defined. It appears that Memphis lost its long-held starring role as the capital of Egypt around the end of the OK and during much of the FIP, a period of fluctuating but overall diminished availability of the Nile's freshwater. Breasted wrote as recently as 1937 that "after the death of Pepi II all is uncertain, and impenetrable obscurity veils the last days of the Sixth Dynasty."

ARCHAEOLOGICAL IMPLICATIONS

More reliable age dating applicable to the period under study has been obtained by Egyptologists, and timelines for some major events in some instances can be narrowed to 50 or fewer years for older pharaonic phases such as those at the end of the OK. Dates of accession and rule of pharaohs in some instances can be determined to within several decades and thus likely provide a more accurate temporal correlation among climate

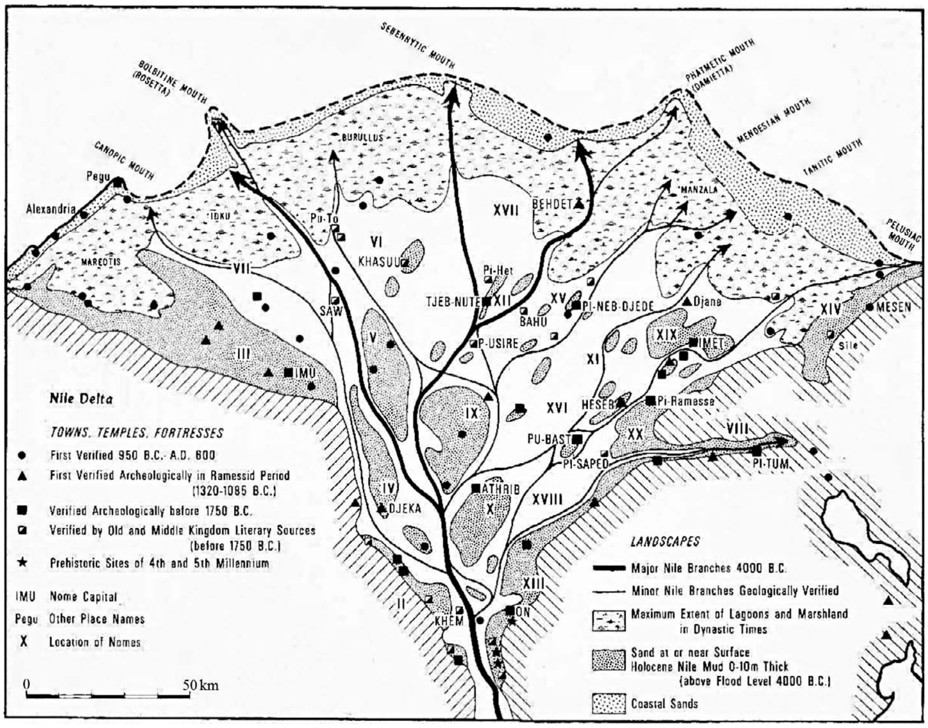

Figure 8. Landscape and settlement map of the Nile delta (Butzer, 1976). Locations of some archaeological sites that predate *ca*. 3750 years BP are shown by solid black or black-and-white squares. Also depicted are several early Nile distributaries that migrated across the delta plain. Other early sites and channels are yet to be discovered, especially those buried by thickened Holocene sediment sequences of the northern delta plain and others submerged offshore.

change, the Nile's altered hydrographic history, and Egypt's political–societal evolution. Based on the work of Breasted (1937), the late fifth millennium BP has been interpreted as a period of turmoil that involved environmental effects leading to drought and perhaps even famine (Bell, 1971; Butzer, 1976, 1984, 1997; Hassan, 2007; Said, 1993; Vandier, 1936). This view is based on early written records and texts, the exact ages of which have remained poorly defined, including some likely compiled long after the climate-related events discussed therein would have occurred (Schneider, 2017; Seidlmayer, 2000). Nevertheless, Egyptologists who had long consulted these texts inferred that Egypt and its people *ca*. 4200 to 4000 years ago experienced a period of chaotic change. Until the turn of the present century, this so-called dark age (Bell, 1971) involved not only major political, societal, and economic changes but also environmental effects. These diverse events were believed to have occurred from the time of Dynasty VI at the end of the OK to Dynasty VII, and possibly to Dynasty X and early in Dynasty XI, during the FIP.

The OK, dated from *ca*. 4700 to 4181 years BP (chronology based on Bard, 2008) was mostly a time of remarkable societal progress and advancement, flourishing artistic development, and impressive pyramid and other major construction. It ended shortly after the long reign of the pharaoh Pepi II. This was followed by the shorter FIP dated from *ca*. 4181 to 4055 years BP. Dynasty VI to early Dynasty XI is generally envisioned by historians as a phase of marked political change that included pronounced weakening of the central administration, rule, and power at Memphis, long the capital of Egypt. Memphis and Saqqara, the famous necropolis in its proximity, were positioned west of the Nile and just south of the delta's axis (Figure 2). Toward the end of the OK, the reign of an all-powerful pharaoh was replaced by a series of concurrent governors, or nomarchs, each becoming responsible for administering a different geographic sector (or nome) from south to north of Egypt (the latter shown in Figure 8).

It has been suggested that following the rule of Pepi II, Egypt was beset by insufficient supplies of cereals and other crops, some of which in earlier pharaonic time would have been stored and distributed as needed by the population in seasons following harvests (Butzer, 1976). During prior years of the OK, this storage system had become a practical solution to feed populations after periods of one or a few lean years of reduced cultivation and poor harvests. Based on findings presented herein, one would expect that populations living in the northern part of the country and largely depending on an agricultural–pastoral economy would have been affected by one or several periods of extended aridity and salinization, lower rainfall, and Nile floods between *ca*. 4200 and 4000 years BP. These conditions could have led to droughts, poor subsistence, and perhaps even starvation around the end of the OK and lasting during at least some years of the FIP. The population of the delta *ca*. 4000 years BP is estimated to be around 650,000 to 700,000 people, and they occupied perhaps approximately 8000 km^2 of cultivated land of the approximately 22,000 km^2 total delta area (based on data in Butzer, 1976).

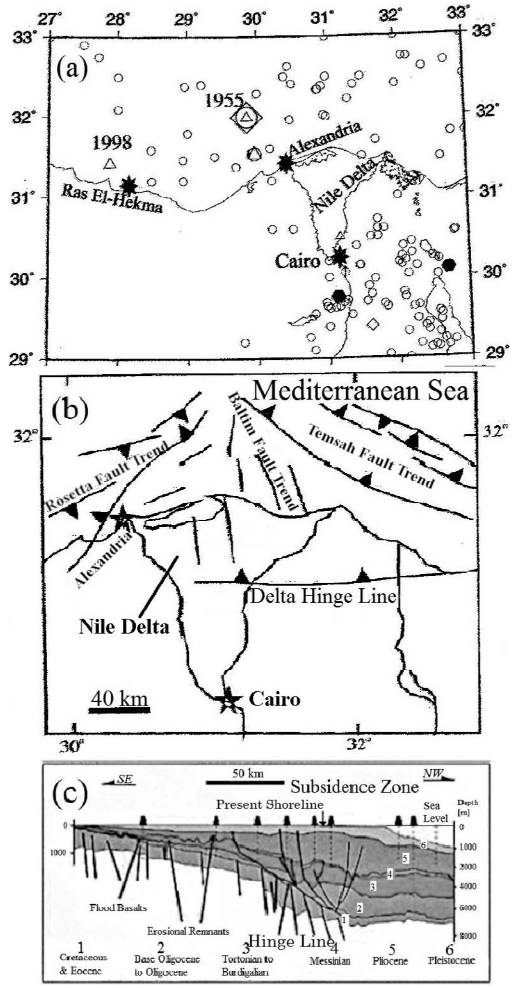

Figure 9. The Nile delta is positioned on Egypt's northern neotectonically active platform. Its Holocene to present mobility results from frequent subsurface to surface earth disturbances, including (a) earthquakes, some powerful and destructive, and (b) fault motion (El-Sayed, Korrat, and Hussein, 2004). (c) A SE-NW transect across the delta depicts subsidence (sinking) of the northern delta, its contiguous offshore sector underlain by compressible Holocene and Pliocene sediment, and fractures in deeper consolidated strata at depths underlying the hinge line (Stanley and Clemente, 2017).

Some villages may well have been reduced to smaller hamlets or perhaps were even abandoned as water depletion became the norm in some regions, as has been similarly suggested for the Levant at that time (*cf.* Weiss, 2016; Weiss and Bradley, 2001). There has been limited documentation or in-depth discussion of moderate to massive human migrations taking place in Egypt, including in the delta proper. Nevertheless, Memphis, just south of the delta axis, no longer retained its former distinctive status as a powerful political center during and after the periods of marked aridity and lower Nile flood conditions indicated in this study. Recorded are some changes in political centers and population shifts southward to Herakleopolis Magna, near the Faiyum depression in northern Middle Egypt (Figure 2), and farther south to Thebes, formerly a provincial town in a nome of lesser significance in Upper Egypt, that then grew in importance (Bunbury, 2010; Seidlmayer, 2000).

Recently, some Egyptologists have expressed doubts as to the development of trying environmental conditions such as drought, hunger, and starvation that could have led to turmoil during the period of interest here. Suggested instead are that political, economic, and societal conditions evolved during the late 4000 years BP, and these factors are viewed as having been considerably, or entirely, more influential than environmental ones (Moeller, 2005; Moeller and Marouard, 2018; Moreno Garcia, 2015; Seidlmayer, 2000). These newer archaeological interpretations of history during this period apparently provide no firm evidence that argues against an extended, climatically altered phase. However, the present summary citing the numerous physical changes induced by the Nile in Egypt's delta at this critical time leads the author of the present article to envision a lower, or even extremely reduced, freshwater supply; this likely would have led to a situation that negatively affected essential agricultural productivity in the delta. What happened with regards to probable diminished water and food supplies available for Egypt's population during this period constitutes a significant problem that now needs renewed attention and improved resolution.

CONCLUSIONS

Mid-Holocene depositional sequences examined in the Nile delta and its coastal margin indicate that the proportions of compositional components in sediments released there were altered during a relatively brief historic period toward the end of the fifth millennium BP. Similar changes around that time have been recorded south of the delta in the Memphis-Saqqara area, the Faiyum depression, and along the desert Nile in the Sudan. The numerous altered sediment compositional and textural patterns in lower Egypt that are reviewed here are attributed largely to lower Nile flood levels *ca*. 4200 to 4000 years BP that responded primarily to a period of increased aridity, altered rainfall patterns, and reduced Nile flows that affected NE Africa.

Altogether, the findings summarized here and collected in diverse surveys by scientists of varying disciplines are indicative of the increased importance of changing environmental events affecting the delta during this relatively short period and likely occurred around the same time as the one termed the *ca*. 4200 years BP event in the Eastern Mediterranean and the Levant. The observations made in Lower Egypt are most closely associated with a regional change, a factor supported by numerous scholars, including climatologists, geographers, and archaeologists, who independently have studied the mid-Holocene physical conditions and history of northern Egypt. The stances recently taken by some Egyptologists that minimize, or discount, the potentially important influence of climate and other environmental effects during this late 4000 years BP period in Egypt thus warrant further testing and evaluation. Intensified collaborative exploration of both Nile sedimentary sequences and proximal archaeological sites that date from the late OK and FIP may help answer some as yet unresolved but pertinent questions. Egypt's population in the delta and along much of the Nile was directly in need of a critical factor of vital importance to continue developing their remarkable civilization: availability of sufficient amounts of the Nile's fresh water to cultivate and maintain at least a minimal food supply for its population.

Having recognized herein evidence for the Nile's fluctuations in the delta, questions should be raised as to whether and how changes to this critical source of water in the late 4000 years BP would have affected the southern upriver source sectors and populations in the East African highlands and central reaches of the desert Nile in the Sudan. It would be useful to determine whether the populations in upper, middle, and lower sectors of Egypt were similarly affected, to the same extent, and/or at the same time. It is probable that comparative and multidisciplinary examination of all three sectors of Egypt could yield new information to help resolve remaining major aspects of this remarkable period of paleoclimatic change and its effects on sociopolitical evolution. In closing, quoting Butzer (1976, p. 56) seems appropriate: "it has become difficult to ignore the possibility that major segments of ancient Egyptian history may be unintelligible without recourse to an ecological perspective."

ACKNOWLEDGMENTS

Most fieldwork in Egypt and a considerable number of laboratory analyses leading to the present synthesis were funded by the Smithsonian Institution's National Museum of Natural History in Washington, D.C. The author expresses his sincere thanks and gratitude to the numerous participants of the MEDIBA Program from Egypt, Europe, Israel, China, India, Canada, and the United States with whom he worked, studied, and learned from 1985 to 2018. The present summary is an outgrowth of this long-term collaborative effort. Appreciation is also expressed to S. Wedl for assistance in preparing the manuscript, to N.A. Ellis and S. Wedl for its initial review, and the two outside reviewers for their useful suggestions.

LITERATURE CITED

Adamson, D.A.; Gasse, F.; Street, F.A., and Williams, M.A.J., 1980. Late Quaternary history of the Nile. *Nature,* 288(5786), 50–55.

Allen, R.O.; Hamroush, H., and Stanley, J.-D., 1992. Impact of the environment on Egyptian civilization before the pharaohs. *Analytical Chemistry,* 65(1), 32A–43A.

Avnaim-Katav, S.; Almogi-Labin, A.; Schneider-Mor, A.; Crouvi, O.; Burke, A.A.; Kremenetski, K.V., and MacDonald, G.M., 2019. A multi-proxy shallow marine record for mid-to-late Holocene climate variability, Thera eruptions and cultural change in the Eastern Mediterranean. *Quaternary Science Reviews,* 204, 133–148. doi:10.1016/j.quascirev.2018.12.001

Bard, K.A., 2008. *An Introduction to the Archaeology of Ancient Egypt*. Maulden, Massachusetts: Blackwell Publishing, 400p.

Bell, B., 1971. The dark ages in ancient history. *American Journal of Archaeology,* 75(1), 1–26.

Bernasconi, M.P.; Melis, R., and Stanley, J.-D., 2006. Benthic biofacies to interpret Holocene environmental changes and human impact in Alexandria's Eastern Harbour, Egypt. *The Holocene,* 16(8), 1163–1176.

Bernhardt, C.E.; Horton, B.P., and Stanley, J.-D., 2012. Nile delta vegetation response to Holocene climate variability. *Geology,* 40(7), 615–618.

Bertinetti, M., 2002. *Egypt from the Air*. New York: Barnes & Noble, 288p.

Bietak, M., 1975. *Tell El-Dab'a II: Der Fundort Im Rahmen Einer Archäologisch-Geographischen Untersuchung Über Das Ägyptische Ostdelta*. Österreichische Akademie Der Wissenschaften. Vienna, Austria: Denkschriften Der Gesamtakademie, 236p.

Breasted, J.H., 1937. *A History of Egypt*. New York: Charles Scribner's Sons, 634p.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon,* 51(1), 337–360.

Bunbury, J., 2010. The development of the River Nile and the Egyptian civilization: A water historical perspective with focus on the First Intermediate Period. *In:* Tvedt, T. and Cooper, R. (eds.), *A History of Water. Series 2.2: Rivers and Society from Early Civilizations to Modern Times*. London: I.B. Tauris, pp. 52–71.

Burn, J.W., 2018. A river in drought: Consequences of a low Nile at the end of the Old Kingdom. *Environment and Ecology Research,* 6(5), 446–460.

Butzer, K.W., 1976. *Early Hydraulic Civilization in Egypt*. Chicago: University of Chicago Press, 134p.

Butzer, K.W., 1984. Long-term Nile flood variation and political discontinuities in Pharonic Egypt. *In*: Clark, J.D., and Brandt, S.A. (eds.), *From Hunters to Farmers: The Causes and Consequences of Food Production in Africa*. Berkeley, California: University of California Press, pp. 102–112.

Butzer, K.W., 1997. Sociopolitical discontinuity in the Near East c. 2200 BCE: Scenarios from Palestine and Egypt. *In*: Dalfes, H.N.; Kukla, G., and Weiss, H. (eds.), *Third Millennium BC: Climate Change and Old World Collapse*. NATO ASI Series, 149. Heidelberg: Springer-Verlag, pp. 245–296.

Butzer, K.W., 2012. Collapse, environment, and society. *Proceedings of the National Academy of Sciences,* 109(10), 3632–3639.

Dee, M.W., 2017. Absolute dating climatic evidence and the decline of Old Kingdom Egypt. *In*: Holfmayer, F. (ed.), *The Late Third Millennium in the Ancient Near East*. Chicago: University of Chicago, pp. 324–331.

Dominik, J. and Stanley, J.-D., 1993. Boron, beryllium and sulfur in Holocene sediments and peats of the Nile delta, Egypt: Their use as indicators of salinity and climate. *Chemical Geology,* 104(1–4), 203–216.

EGAS, 2015. EGAS concessions map and 2015 international bid round blocks. *Ministry of Petroleum and Mineral Resources Technical Report, Cairo, Egypt,* 1(8), 1–5.

El-Sayed, A.; Korrat, I., and Hussein, H.M., 2004. Seismicity and seismic hazard in Alexandria and its surroundings. *Pure and Applied Geophysics,* 161(5–6), 1003–1019.

Fielding, L.; Najman, Y.; Millar, I.; Butterworth, P.; Ando, S.; Padoan, M.; Barfod, D., and Kneller, B., 2016. A detrial record of the Nile river and its catchment. *Journal of the Geological Society,* 174(2), 301–317.

Finné, M.; Holmgren, K.; Sundqvist, H.S.; Weiberg, E., and Lindblom, M., 2011. Climate in the Eastern Mediterranean and adjacent regions, during the past 6000 years—A review. *Journal of Archaeological Sciences,* 38(12), 3153–3173.

Flaux, C., 2012. Holocene Paleoenvironments of the Maryut Lagoon in the N.W. Nile delta, Egypt. Aix-en-Provence, France: Université Aix-Marseille, Ph.D. dissertation, 413p.

Flaux, C.; Claude, C.; Marriner, N., and Morhange, C., 2013. A 7500-year strontium isotope record from the northwestern Nile delta (Maryut Lagoon, Egypt). *Quaternary Science Reviews,* 78, 22–33. doi:10.1016/j.quascirev.2013.06.018

Folk, R.L., 1961. *Petrology of Sedimentary Rocks*. Austin, Texas: Hemphills, 154p.

Foucault, A. and Stanley, J.-D., 1989. Late Quaternary paleoclimatic oscillations in East Africa recorded by heavy minerals in the Nile delta. *Nature,* 339(6219), 44–46.

Frihy, O.E. and Dewidar, K.M., 2003. Patterns of erosion/sedimentation, heavy mineral concentration and grain size to interpret boundaries of littoral sub-cells of the Nile delta, Egypt. *Marine Geology,* 199(1–2), 27–43.

Gamal, M.A., 2013. Truthfulness of the existence of the *Pelusium megashear* fault system east of Cairo, Egypt. *International Journal of Geosciences,* 4(1), 212–227.

Gasse, F., 2000. Hydrological changes in the African tropics since the last glacial maximum. *Quaternary Science Review,* 19(1), 189–211.
Gillespie, R.; Street-Perrot, F.A., and Switsur, R., 1983. Post-glacial arid episodes in Ethiopia have implications for climate prediction. *Nature,* 306(5944), 680–683.
Goiran, J.-P., 2001. Recherches Géomorphologiques dans la Région Littorale d'Alexandrie en Egypt. Aix-en-Provence, France: Université de Provence, Ph.D. dissertation, 264p.
Hamdan, M.A.; Hassan, F.A.; Flower, R.J.; Leroy, S.A.G.; Shallaly, N.A., and Flynn, A., 2019. Source of Nile sediments in the floodplain at Saqqara inferred from mineralogical, geochemical, and pollen data and their paleoclimatic and geoarchaeological significance. *Quaternary International,* 501(Part B), 272–288. doi:10.1016/j.quaint.2018.02.021
Hamroush, H.A. and Stanley, J.-D., 1990. Paleoclimatic oscillations in East Africa interpreted by analysis of trace elements in Nile delta sediments. *Episodes,* 13(4), 264–269.
Hassan, F.A., 1976. Heavy minerals and the evolution of the modern Nile. *Quaternary Research,* 6(3), 425–444.
Hassan, F.A., 1986. Holocene lakes and prehistoric settlements of the western Faiyum, Egypt. *Journal of Archaeological Science,* 13(5), 483–501.
Hassan, F.A., 2005. A river runs through Egypt: Nile floods and civilization. *Geotimes,* 50(4), 22–25.
Hassan, F.A., 2007. Droughts, famine, and the collapse of the Old Kingdom: Re-reading Ipuwer. *In*: Hawass, Z.A. and Richards, J. (eds.), *The Archaeology and Art of Ancient Egypt*. Cairo: Publications du Conseil Suprème des Antiquités de l'Egypte, pp. 357–379.
Hurst, H.E., 1957. *The Nile,* 2nd edition. London: Constable, 326p.
Kaniewski, D.; Marriner, N.; Cheddadi, R.; Guiot, J., and Van Campo, E., 2018. The 4.2 ka BP event in the Levant. *Climate of the Past,* 14(10), 1529–1542.
Kaniewski, D.; Paulissen, E.; Van Campo, E.; Al-Maqdissi, M.; Bretschneider, J., and Van Lerberghe, K., 2008. Middle East coastal ecosystem response to middle-to-late Holocene abrupt climate changes. *Proceedings of the National Academy of Sciences,* 105(37), 13941–13946.
Kebeasy, R.M., 1990. Seismicity. *In*: Said, R. (ed.), *The Geology of Egypt*. Rotterdam, The Netherlands: A.A. Balkema, pp. 51–59.
Krom, M.D.; Stanley, J.-D.; Cliff, R.A., and Woodward, J.C., 2002. Nile river sediment fluctuations over the past 7000 years and their key role in sapropel development. *Geology,* 30(1), 71–74.
Macklin, M.G.; Toonen, W.H.; Woodward, J.C.; Williams, M.A.; Flaux, C.; Marriner, N.; Nicoll, K.; Verstraeten, G.; Spencer, N., and Welsby, D., 2015. A new model of river dynamics, hydroclimatic change and human settlement in the Nile valley derived from meta-analysis of the Holocene fluvial archive. *Quaternary Science Reviews,* 130(12), 109–123.
Marks, L.; Salem, A.; Welc, F.; Nitychoruk, J.; Chen, Z.; Blaauw, M.; Zalat, A.; Szymanek, M.; Chodyka, M.; Toloczko-Pasek, A.; Sun, Q.; Zhao, X., and Jiang, J., 2017. Holocene lake sediments from the Faiyum Oasis in Egypt: A record of environmental and climate change. *Boreas,* 47(1), 62–79.
Marriner, N.; Flaux, C.; Kaniewski, D.; Morhange, C.; Leduc, G.; Moron, V.; Chen, Z.; Gasse, F.; Empereur, J.Y., and Stanley, J.-D., 2012. ITCZ and ENSO-like pacing of Nile delta hydro-geomorphology during the Holocene. *Quaternary Science Reviews,* 45, 73–84. doi:10.1016/j.quascirev.2012.04.022
Marriner, N.; Flaux, C.; Morhange, C., and Stanley, J.-D., 2013. Tracking Nile delta vulnerability to Holocene change. *PLoS One,* 8(7), e69195.
Moeller, N., 2005. The First Intermediate Period: A time of famine and climate change? *Ägypten und Levante/Egypt and the Levant,* 15, 153–167. http://www.jstor.org/stable/23788258
Moeller, N. and Marouard, G., 2018. The development of two early urban centres in Upper Egypt during the 3rd Millenium BC, the examples of Edfu and Dendara. *In*: Budka, J. and Auenmüller, J. (eds.), *From Microcosm to Macrocosm. Individual Households and Cities in Ancient Egypt and Nubia*. Leiden, The Netherlands: Sidestone Press, pp. 29–58.
Moreno Garcia, J., 2015. Climatic change or sociopolitical transformation? Reassessing late 3rd millennium BC in Egypt. *In*: Meller, H.; Arz, H.W.; Jung, R., and Risch, R. (eds.), *2200 BC—A Climatic Breakdown as A Cause for the Collapse of the Old World?*, Volume 13. Halle: Landesamt für Denkmalpflege und Archäologie Sachsen-Anhalt—Landesmuseums für Vorgeschichte, pp. 79–94.
Owen, R.B.; Barthelme, J.W.; Renaut, R.W., and Vincens, A., 1982. Palaeolimnology and archaeology of Holocene deposits north-east of Lake Turkana, Kenya. *Nature,* 298(5874), 523–529.
Pennington, B.T.; Hamdan, M.A.; Pears, B.R., and Sameh, H.I., 2019. Aridification of the Egyptian Sahara 5000–4000 cal BP revealed from x-ray fluorescence analysis of Nile delta sediments at Kom al-Ahmer/Kom Wasit. *Quaternary International*. In press. doi:10.17632/dj4zk7cbj8.1
Pugliese, N. and Stanley, J.-D., 1991. Ostracoda, depositional environments and Late Quaternary evolution of the eastern Nile delta, Egypt. *Il Quaternario,* 4(2), 275–302.
Reinhardt, E.G.; Stanley, J.-D., and Patterson, R.T., 1998. Strontium isotopic-paleontological method as a high-resolution paleosalinity tool for lagoonal environments. *Geology,* 26(11), 1003–1006.
Robinson, D. and Wilson, A. (eds.), 2010. *Alexandria and the North-Western Delta*. Oxford Centre for Maritime Archaeology, Monograph 5. Oxford, United Kingdom: University of Oxford, 282p.
Said, R., 1993. *The River Nile: Geology, Hydrology, and Utilization*. Tarrytown, New York: Pergamon Press, 320p.
Schneider, T., 2017. The First Intermediate Period from an epistemological perspective. *In*: Höflmayer, F., (ed.), *The Late Third Millennium in the Ancient near East*. Oriental Institute Seminars No. *11*. Chicago: University of Chicago, pp. 311–322.
Seidlmayer, S., 2000. The First Intermediate Period. *In*: Shaw, I. (ed.), *The Oxford History of Ancient Egypt*. Oxford, United Kingdom: Oxford University Press, pp. 118–147.
Sestini, G., 1992. Implications of climatic changes for the Nile delta. *In*: Jeftic, L.; Milliman, J.D., and Sestini, G., (eds.), *Climatic Change and the Mediterranean*. London: Edward Arnold, pp. 535–601.
Shukri, N.M., 1949. The mineralogy of some Nile sediments. *Quarterly Journal of the Geological Society,* 105(1–4), 511–534.
Shukri, N.M., 1951. Mineral analysis tables of some Nile sediments. *L'institut Fouad I du Désert,* 1(2), 39–67.
Siegel, F.R.; Gupta, N.; Shergill, B.; Stanley, J.-D., and Gerber, C., 1995. Geochemistry of Holocene sediments from the Nile delta. *Journal of Coastal Research,* 11(2), 415–431.
Stanley, J.-D., 2001. Dating modern deltas: Progress, problems and prognostics. *Annual Review of Earth and Planetary Sciences,* 29(1), 257–294.
Stanley, J.-D.; Arnold, D., and Warne, A.G., 1992. Oldest Pharaonic site yet discovered in the north-central Nile delta, Egypt. *National Geographic Research and Exploration,* 8(3), 264–275.
Stanley, J.-D.; Bandelli, A.; Bernasconi, M.P.; Jorstad, T.; Melis, R.; Pugliese, N.; Schnepp, G., and Warne, A.G. (eds.), 2007. *Underwater Archaeology in the Canopic Region in Egypt. Geoarchaeology,* Monograph 2. Oxford, United Kingdom: Oxford Centre for Maritime Archaeology, 128p.
Stanley, J.-D. and Bernhardt, C.E., 2010. Alexandria's Eastern Harbor, Egypt: Pollen, microscopic charcoal, and the transition from natural to human-modified basin. *Journal of Coastal Research,* 26(1), 67–79.
Stanley, J.-D. and Chen, Z., 1991. Distinguishing sand facies in the Nile delta, Egypt, by stained grain and compositional component analyses. *Journal of Coastal Research,* 7(3), 863–877.
Stanley, J.-D. and Chen, Z., 2000. Radiocarbon dates in China's Holocene Yangtze delta: Record of sediment storage and reworking, not timing of deposition. *Journal of Coastal Research,* 16(4), 1126–1132.
Stanley, J.-D. and Clemente, P.L., 2017. Increased land subsidence and sea-level rise are submerging Egypt's Nile delta coastal margin. *Geological Society of America Today,* 27(5), 4–11.
Stanley, J.-D. and Hait, A.K., 2000. Deltas, radiocarbon dating, and measurements of sediment storage and subsidence. *Geology,* 28(4), 295–298.
Stanley, J.-D.; Krom, M.D.; Cliff, R.A., and Woodward, J.C., 2003. Nile flow failure at the end of the Old Kingdom, Egypt: Strontium

isotopic and petrologic evidence. *Geoarchaeology: An International Journal,* 18(3), 395–402.

Stanley, J.-D. and Landau, E.A., 2010. Early human activity (pre-332 BC) in Alexandria, Egypt: New findings in sediment cores from the Eastern Harbour. *In*: Robinson, D. and Wilson, A. (eds.), *Alexandria and the North-Western Delta,* Monograph 5. Oxford, United Kingdom: Oxford Centre for Maritime Archaeology, pp. 35–52.

Stanley, J.-D.; McRae, J.E., Jr., and Waldron, J.C., 1996. *Nile Delta Drill Core and Sample Database for 1985–1994: Mediterranean Basin (MEDIBA) Program*. Smithsonian Contributions to the Marine Sciences *37*. Washington, D.C.: Smithsonian Institution Press, 428p.

Stanley, J.-D.; Sheng, H., and Pan, Y., 1988. Heavy minerals and provenance of Late Quaternary sands, eastern Nile delta. *Journal of African Earth Sciences,* 7(4), 735–741.

Stanley, J.-D. and Warne, A.G., 1998. Nile delta in its destruction phase. *Journal of Coastal Research,* 14(3), 794–825.

Stanley, J.-D. and Wingerath, J., 1996. Nile sediment dispersal altered by the Aswan High Dam: The kaolinite trace. *Marine Geology,* 133(1–2), 1–9.

Street-Perrott, F.A. and Perrott, R.A., 1993. Holocene vegetation, lake levels and climate in Africa. *In*: Wright, H.E., Jr.; Kutzbach, J.E.; Webb, T., III; Ruddiman, W.F.; Street-Perrott, F.A., and Bartlein, P.J. (eds.), *Global Climates since the Last Glacial Maximum*. Minneapolis, Minnesota: University of Minnesota Press, pp. 318–356.

Sun, Q.; Liu, Y.; Salem, A.; Marks, L.; Welc, F.; Ma, F.; Zhang, W.; Chen, J.; Jiang, J., and Chen, Z., 2018. Climate-induced discharge variations of the Nile during the Holocene: Evidence from the sediment provenance of Faiyum Basin, north Egypt. *Global and Planetary Change,* 172, 200–210. doi:10.1016/j.gloplacha.2018.10.005

Sutcliffe, J.V. and Parks, Y.P., 1999. *The Hydrology of the Nile*. IAHS Special Publication No. 5. Wallingford, Oxfordshire: International Association of Hydrological Sciences Press, 179p.

Toussoun, O., 1925. *Mémoire sur l'histoire du Nil*. Mémoire de l'Institut d'Egypte Series 8–10. Cairo, Egypt: Imprimerie de l'Institut Français d'Archéologie Orientale, 543p.

Touzeau, A.; Blichert-Toft, J.; Amiot, R.; Fourel, F.; Martineau, F.; Cockitt, J.; Hall, K.; Flandrois, J.-P., and Lécuyer, C., 2013. Egyptian mummies record increasing aridity in the Nile valley from 5500 to 1500 y before present. *Earth and Planetary Science Letters,* 375(1), 92–100.

Vandier, J., 1936. *La Famine dans l'Egypte ancienne*. Recherches d'Archéologie, de Philologie et d'Histoire, Volume 7, Cairo, Egypt: Institut Français d'Archéologie Orientale, 176p.

Waterbury, J., 1979. *Hydropolitics of the Nile Valley*. Syracuse, New York: Syracuse University Press, 301p.

Weiss, H., 2016. Global megadrought, societal collapse and resilience at 4.2–3.9 ka BP across the Mediterranean and west Asia. *Pages Magazine,* 24(2), 62–63.

Weiss, H. and Bradley, R.S., 2001. What drives societal collapse? *Science,* 291(5504), 609–610. doi:10.1126/science.1058775

Weiss, H.; Courty, M.A.; Wetterstrom, W.; Guichard, F.; Senior, L.; Meadow, R., and Curnow, A., 1993. The genesis and collapse of 3rd millennium north Mesopotamian civilization. *Science,* 261(5124), 995–1004.

Williams, M.A.J.; Williams, F.M.; Duller, G.A.T.; Munro, R.N.; El Tom, O.A.M.; Barrows, T.T.; Macklin, M.; Woodward, J.; Talbot, M.R.; Haberlah, D., and Fluin, J., 2010. Late Quaternary floods and droughts in the Nile Valley, Sudan: New evidence from optically stimulated luminescence and AMS radiocarbon dating. *Quaternary Science Reviews,* 29(9–10), 1116–1137.

Woodward, J.C.; Macklin, M.G., and Welsby, D., 2001. The Holocene fluvial sedimentary record and alluvial geoarchaeology in the Nile Valley of northern Sudan. *In*: Maddy, D.; Macklin, M.G., and Woodward, J.C. (eds.), *River Basin Sediment Systems: Archives of Environmental Change*. Rotterdam, The Netherlands: A.A. Balkema, pp. 327–355.

Woodward, J.; Macklin, M.; Fielding, L.; Millar, I.; Spencer, N.; Welsby, D., and Williams, M., 2015. Shifting sediment sources in the world's longest river: A strontium isotope record for the Holocene Nile. *Quaternary Science Reviews,* 130, 124–140. doi:10.1016/j.quascirev.2015.10.040