# The fluvial evolution of the Holocene Nile Delta

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## Abstract

The evolution of the Nile Delta, the largest delta system in the Mediterranean Sea, has both high palaeoenvironmental and archaeological significance. A dynamic model of the landscape evolution of this delta system is presented for the period c.8000–4500 cal BP. Analysis of sedimentary data and chronostratigraphic information contained within 1640 borehole records has allowed for a redefinition of the internal stratigraphy of the Holocene delta, and the construction of a four-dimensional landscape model for the delta's evolution through time. The mid-Holocene environmental evolution is characterised by a transition from an earlier set of spatially varied landscapes dominated by swampy marshland, to better-drained, more uniform floodplain environments. Archaeologically important Pleistocene inliers in the form of sandy hills protruding above the delta plain surface (known as "turtlebacks"), also became smaller as the delta plain continued to aggrade, while the shoreline and coastal zone prograded north. These changes were forced by a decrease in the rate of relative sea-level rise under high rates of sediment-supply. This dynamic environmental evolution needs to be integrated within any discussion of the contemporary developments in the social sphere, which culminated in the emergence of the Ancient Egyptian State c.5050 cal BP.

*Keywords:* Holocene, Palaeogeography, Middle East, Sedimentology, lakes, lagoons & swamps, Deltas, Nile, Geomorphology, fluvial

## 1. Introduction

The present Nile Delta is the latest in a long series of deltaic formations, probably going back to the Miocene (Said, 1981). A large amount of research has been undertaken on the Pleistocene and earlier history of the region, mainly as a result of oil exploration (Abu El-Ella, 1990; Rizzini et al., 1978; Said, 1981, 1971; Schlumberger, 1995), but the Holocene landscape evolution of the area remains quite poorly understood in comparison with the rest of the Nile system. In the upper catchment of the White Nile (Cockerton et al., 2015), Blue Nile (Marshall et al., 2011), at the Nile confluence (Williams et al., 2015) and especially through the Egypt-Sudan desert reach (Honegger and Williams, 2015; Macklin et al., 2013; Vermeersch and Van Neer, 2015; Woodward et al., 2015, 2001), much recent work has reported on Holocene landscape succession, relationships between the changing landscape, human settlement and culture, and the varying roles of climatic and other drivers of change in effecting these changes.

It is only the Holocene evolution of the delta's coastal margin that is understood to a level comparable with the rest of the Nile system (Stanley and Warne, 1993a). The evolution of the extensive fluvial plain (approx. 15,000km$^2$) is less-well known, despite a number of attempts at a delta-wide synthesis over the last century (Bietak, 1975; Butzer, 2002, 1976, 1974; Fourtau, 1915; Hassan, 1997; Said, 1992; Sandford and Arkell, 1939; Stanley and Warne, 1993a,b). This is surprising, given the region's importance in the formative period of the world's first nation state of Ancient Egypt, and its modern-day importance for the nation of Egypt, containing half of the country's agricultural land and population. A better understanding of the mid-Holocene evolution of this area, south of the zone dominated by coastal processes – is urgently needed.

The most recent landscape synthesis of this region (Butzer, 2002) relied solely on lithostratigraphic and chronostratigraphic data collected prior to 1991. Since that time, and especially over the past ten years, numerous teams have carried out geological and geoarchaeological research in the delta, providing a wealth of data on the development of the landscape, none of which has ever been integrated into a delta-wide Holocene landscape synthesis.

This paper incorporates this recent and ongoing research to provide a new and updated perspective on the evolving mid-Holocene landscapes of the delta, a perspective which needs to be integrated into discussions of the emergence of the ancient Egyptian state, and other sociocultural and economic history studies of the region over the longue durée. The vast deltaic plain was the breadbasket of Ancient Egypt, containing the largest amount of cultivateable land in the country, but without a detailed palaeoenvironmental model its landscape history cannot
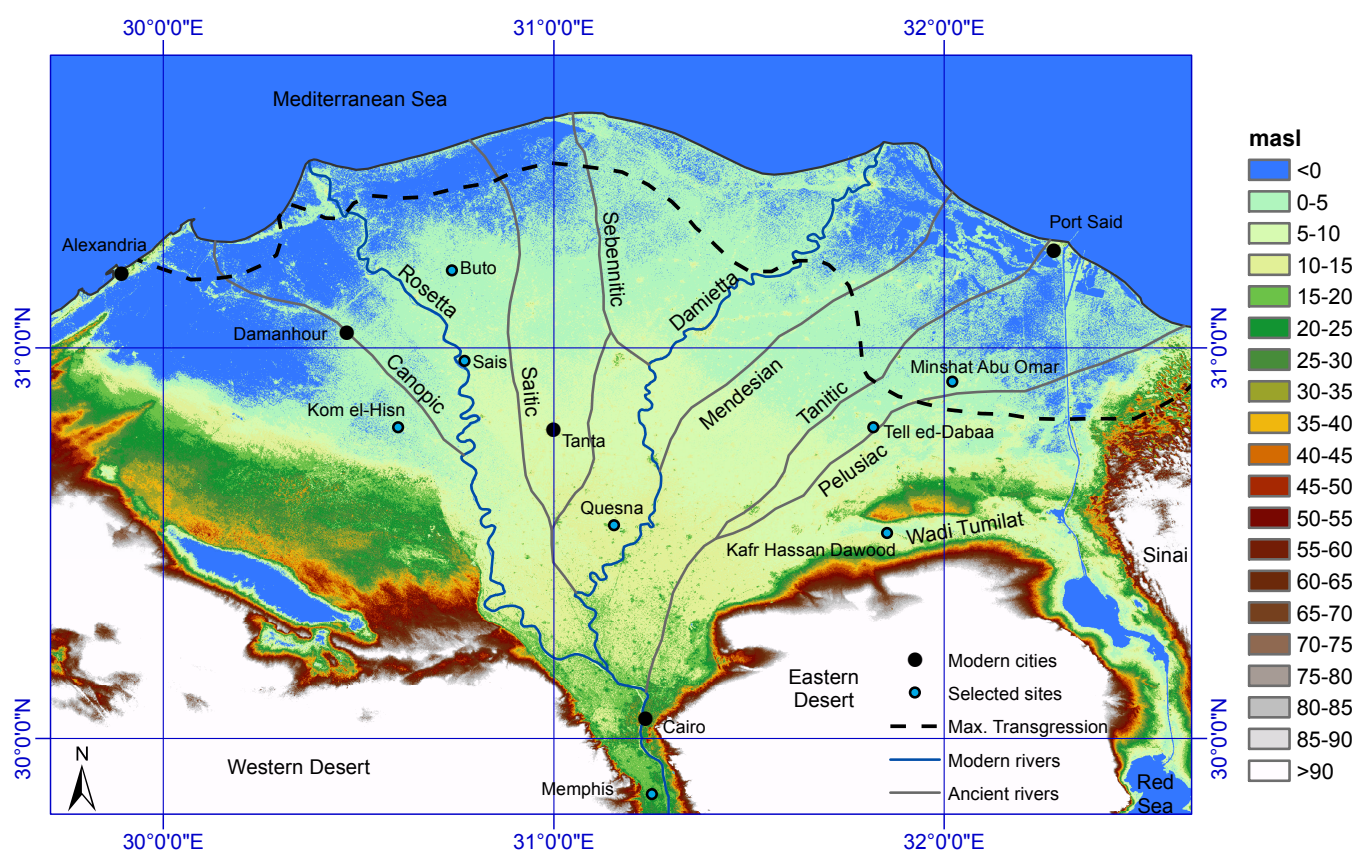
Figure 1: Map of the Nile Delta (SRTM data). The locations of ancient river branches are after Bietak (1975); Butzer (2002); the extent of maximum transgression is as given by Stanley and Warne (1993a). Selected archaeological sites are also shown.

be truly integrated into a geoarchaeological synthesis (Clarke et al., 2016; Hassan, 2010, 2009; Macklin and Lewin, 2015).

The paper focusses on the time period c. 8000 to 4500 cal BP, as this covers the period of greatest geomorphological change, during which sea-level was approaching its modern-day position (Fleming et al., 1998), and the modern Nile hydroclimatic system was being established, as the "African Humid Period" gave way to more arid conditions (Shanahan et al., 2015). This is also a time period without substantial human factors contributing to and complicating the remodelling of the deltaic landscapes, but is an episode crucial for understanding the palaeoenvironmental context of Ancient Egyptian state formation.

### 1.1. Regional setting

The Nile Delta is an alluvial plain in the north of Egypt (Fig. 1) constituting by far the largest continuous expanse of agricultural land in the country. Bounded by desert to both the east and west, its apex is at Cairo, where the river divides into two main distributaries: the Rosetta and Damietta, which discharge over the triangular-shaped alluvial plain and flow north into the Mediterranean. Many more distributaries existed in prior time periods (Butzer, 2002; Hassan, 1997), and the apex of the network was also further south (Bunbury, 2013; Lutley and Bunbury, 2008).

The geology of the alluvial plain is relatively simple. The Holocene deposits are mainly represented by a thin veneer of silty sediments of the Bilqas Formation, which lie unconformably on top of the thick, sandy Mit Ghamr Formation (Rizzini et al., 1978), whose top surface comprises the erosion remnant of a buried alluvial landscape formed under a different hydrological regime (Adamson et al., 1980; Stanley and Warne, 1993a). Some of these remnants protrude above the modern delta surface as sandy hills, known as "turtlebacks", or "gezira" (Judd, 1897).

The plain is densely populated and farmed such that little natural vegetation remains. Almost all the water influx to the region is provided by the river Nile. This river displays pronounced seasonality, related to the differing catchments of its three main tributaries. The Blue Nile and Atbara drain the Ethiopian Highlands and provide the majority of the Nile's annual discharge and sediment flux during the Nile flood between July and October, while the White Nile drains Central Africa, provides minor year round discharge but only accounts for 3% of the sediment flux (Woodward et al., 2015). Since the damming of the river at Aswan the Nile through Egypt has not flooded.

## 2. Towards a unified model for mid-Holocene fluvio-deltaic evolution

The Nile Delta developed during a period of decreasing rates of sea-level rise and high sediment supply within the mid-Holocene. Initially, high rates of relative sea-level rise stimulated high rates of floodbasin aggradation, and gave rise to the associated development of a swampy, wetland landscape dominated by the formation of crevasse splays (Fig. 2). High rates of base-level rise would have resulted initially in a reduction of the river gradient, causing a corresponding decrease in energy to transport sediment, and elevated in-channel aggradation rates. These high rates of in-channel aggradation would have in turn led to channel superelevation, since to maintain constant volumetric flow the channels would have built their margins above the surrounding floodplain (Jerolmack and Mohrig, 2007; Mohrig et al., 2000). Superelevation in turn would have led to widespread crevassing, frequent avulsion, and high rates of floodplain aggradation (Aslan et al., 2005; Jerolmack, 2009; Kraus, 1996; Kraus and Aslan, 1993; Phillips, 2011; Mohrig et al., 2000; Slingerland and Smith, 2004). Rapid floodplain aggradation then inhibited soil formation and resulted in the development of a wetland landscape (Smith and Pérez-Arlucea, 1994; Smith et al., 1989; Willis and Behrensmeyer, 1994). The resulting typical environment (Fig. 2) has been referred to as "Large-Scale Crevassing", or "LSC" (Pennington et al., 2016; Törnqvist, 1993).

Following the mid-Holocene transition to lower rates of relative sea-level rise, lower in-channel aggradation rates would have meant that crevassing and avulsion became relatively less dominant processes of landscape formation, and rivers would have migrated across their floodplain primarily via lateral channel migration and point bar deposition (Brown, 1997; Jerolmack, 2009; Jerolmack and Mohrig, 2007; Pennington et al., 2016). This process would have "swept-up" other channels and so tended to establish a simplified, reduced channel network. With less crevassing, floodplain aggradation rates would have decreased, and soils would have developed. The resulting landscape (Fig. 3) has been referred to as a "Meandering" deltaic environment (Pennington et al., 2016). A summary of the differences between the "LSC" and "Meandering" environments is given in Table 1.

Ultimately, it is the relationship between the rate of vertical aggradation (dominant in LSC) and the rate of lateral migration (dominant in the "Meandering" landscape) that is the main determinant of the character of the landscape. If vertical aggradation is dominant over lateral migration, channel superelevation will occur, leading to the LSC landscape; if lateral migration is dominant this will not be the case. The Mobility Number ($M$) (Jerolmack and Mohrig, 2007), is a dimensionless number that encapsulates this ratio. It is defined (equation 1) as the ratio between the time required for a river to vertically aggrade one-channel height, and the time required for a river to migrate one channel width, and thus expresses whether a river predominantly aggrades vertically or migrates laterally.

$$M = \frac{hV_c}{BV_a} \tag{1}$$

In this equation, $h$ is the river depth at bankfull discharge, $B$ the width, $V_c$ the bank erosion rate and $V_a$ the

Swampy, wetland environments

Reducing environments; enhanced preservation
of organic matter; little soil formation

Stable channel networks, little lateral migration

Frequent large-scale crevassing

Poorly-drained floodbasins

20 m

Narrow channel belts

2 km

Narrow channel belts

River flow to the left

Vertical accretion deposits

Natural levee deposits

Crevasse deposits

Floodbasin deposits

Organic deposits

Substrate

A

High water

Fast floodbasin aggradation

B

0

Low water

Low water

-1

-2

-3

Metres

0

-5

-6

-7

-8

0

250

500

750

Anastomosing, multichannel character

Metres

Complex floodbasin sediments,
highly variable both
laterally and vertically

Vertical accretion channel deposits *(sand)*

Crevasse deposits *(fine sand, sandy-silty clay)*

Natural levee deposits *(sandy-silty clay)*

Floodbasin deposits *(clay)*

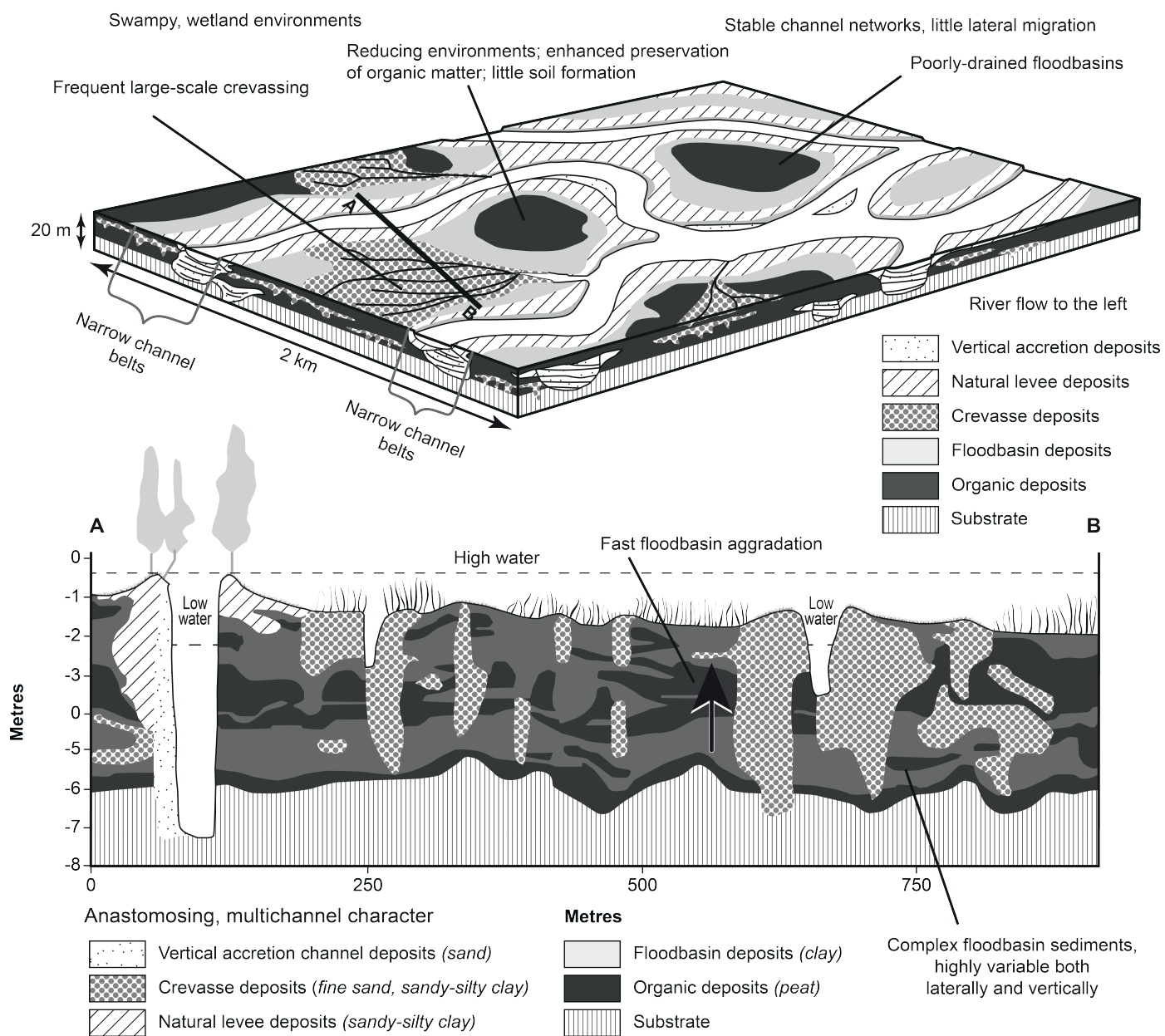Organic deposits *(peat)*

Substrate

Figure 2: The LSC landscape of the early mid-Holocene, in equilibrium with high rates of sea-level rise. Modified after Weerts (1996).
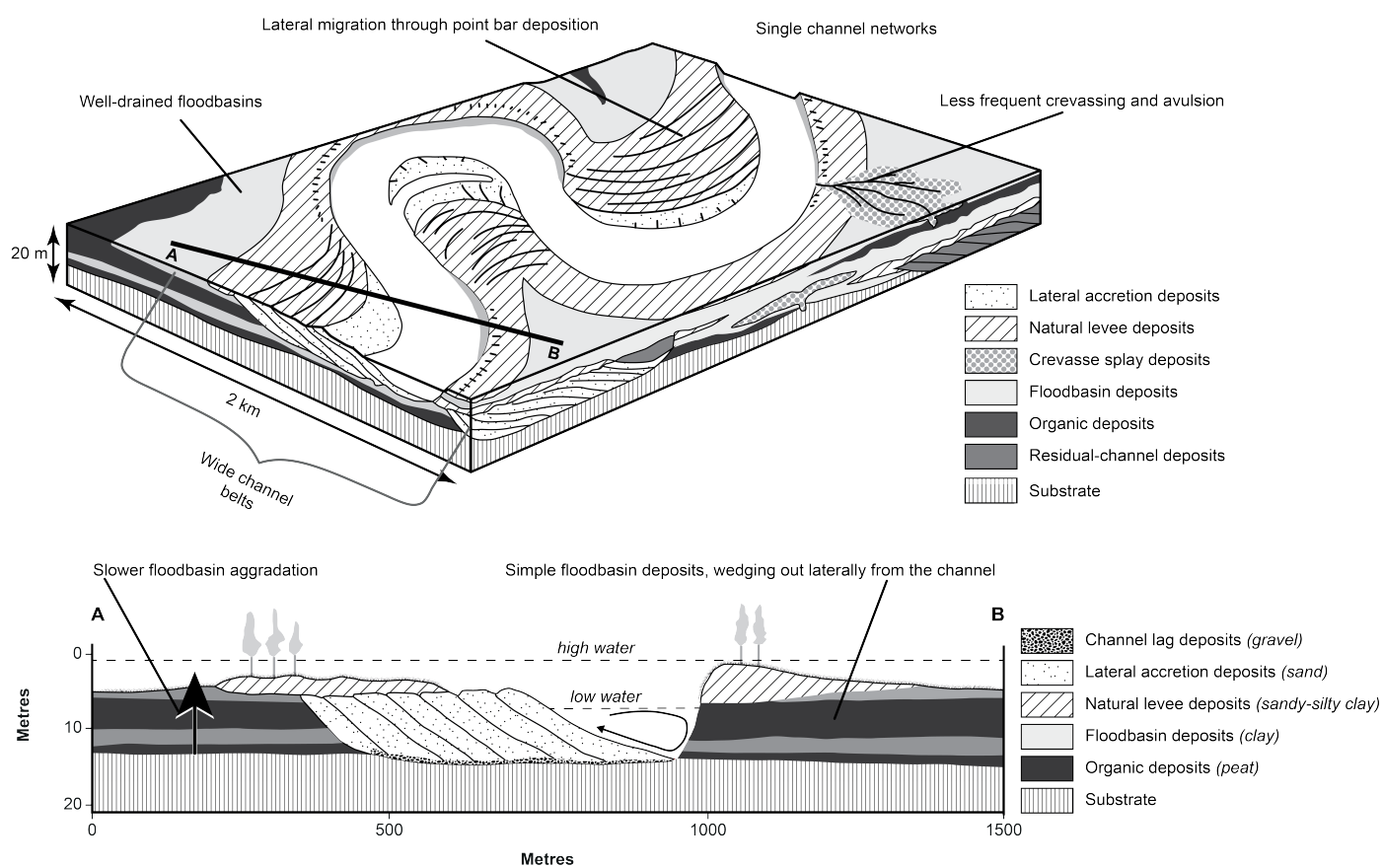
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Figure 3: The "Meandering" landscape of the later mid-Holocene, in equilibrium with lower rates of sea-level rise. Modified after Weerts (1996).

in-channel vertical aggradation rate. Rivers with values of $M{>}10$ are characterised as "single-channel", those $M{<}1$ are "anastomosing" (Jerolmack, 2009). The LSC facies is thus the result of lower $M$ driven by higher $V_a$ during the early Holocene, and the LSC-Meandering Transition was a result of an increase in $M$ driven by lower $V_a$ during the later Holocene. The driving reduction in $V_a$ was forced primarily by decreasing rates of base-level rise, although it could have been further driven by changes in discharge and sediment-supply (see section 7) by analogy with similar shifts in riverine dynamics elsewhere (Macklin et al., 2015, 2013; Woodward et al., 2001).

## 3. Previous work on the Holocene landscapes of the delta

### 3.1. Landscape evolution of the coastal zone

The evolution of the Nile Delta's coastal region, although not the focus of the current study, is fairly well understood (Fig. 4) as a result of research carried out by the Smithsonian Institution's Mediterranean Basin (MEDIBA) survey in the 1980s and 1990s. Building on previous work in the coastal area (Attia, 1954; Sestini, 1976; Sneh et al., 1986), this project drilled 87 radiocarbon-dated cores within the coastal fringe of the delta (Stanley et al., 1996). This work has been built upon by more recent studies of the Holocene sequence (Flaux, 2012; Flaux et al., 2017, 2013, 2011; Marriner et al., 2013, 2012b; Moshier and El-Kalani, 2008) as well as geoarchaeological investigations at specific archaeological sites (Wilson, 2011, 2010; Wilson and Grigoropoulos, 2009).

The general sedimentary sequence in the coastal region is presented in Fig. 5. At the base are Late Pleistocene iron-stained quartz-rich sands and stiff muds ("Sequence I Deposits"). Unconformably above this unit lie quartz-rich sands with a shallow marine fauna ("Sequence II Deposits", or "transgressive sands"), then another depositional hiatus and a variety of lithologies which together comprise "Sequence III Deposits".

The predominantly sandy "Sequence I Deposits" at the base represent terrestrial sedimentation on a partially vegetated braided river-plain (Stanley and Warne, 1993a). These deposits are dated to c.38,000–12,000 cal BP (Butzer, 2002), a time when the coastline was located significantly further north of its current position (Summerhayes et al., 1978). They are correlated regionally as the Mit Ghamr Formation.

The overlying "Sequence II Deposits" record the mid-Holocene transgression, and date from prior to c.8000 cal BP (Stanley and Warne, 1993a). The spatial distribution of the unit thus approximates the extent of the transgression, which was more extensive in the east than the west (Fig. 4).

Finally, the variety of lithologies represented by the deposits of "Sequence III" date from c.7500 cal BP onwards. These sediments record a range of marine, semiterrestrial, coastal, estuarine, lagoonal and in some cases fluvial deltaic environments.

### 3.2. Available lithostratigraphic and chronostratigraphic data from the fluvial zone

The evolution of the fluvially-dominated region of the Nile Delta is less well-understood than the coastal fringe, although this is not necessarily due to a lack of primary data. There are a large number of boreholes known from the region >3m deep (Fig. 6), many of which have been carried out since 1991 and were not included in the most recent synthesis of the delta's evolution (Butzer, 2002). Some of these cores have been drilled and published within a geological framework, but many others have been carried out as part of archaeological research in the area. Isolated studies have also been undertaken and published from within the disciplines of hydrology and engineering. The Supplementary Information contains a list of all the surveys and cores from the fluvial zone that were assessed as part of the current synthesis (1640 borehole records).

## 4. Methods

In order to create an overall palaeogeographic reconstruction of the delta through time, it was necessary to a) collate and rectify all available lithostratigraphic and chronostratigraphic data from the region; b) revise the stratigraphic framework; and c) model the geological data in 3D through time.

### 4.1. Database compilation and stratigraphic revision

A survey of the published literature as well as ongoing fieldwork by the authors provided 1640 relevant core records within the fluvial zone of the delta. Study of these cores allowed for a redefinition of the delta's Late Pleistocene and Holocene stratigraphy (section 5), and the records were input to a stratigraphic database (provided in the Supplementary Information). The available geological information that can be ascertained from these records is of varying quality, and is usually limited to basic sedimentological descriptions. A lack of research focus, coupled with (and partly as a result of) export restrictions have meant that there are few published LOI, magnetic susceptibility or heavy-mineral records, and no published cores from this fluvial region have been studied with XRF techniques, nor with stable isotope analysis.

Most boreholes from the coastal zone of the delta were not input to the database, as palaeogeographic constructions based on these cores are already readily available; the only boreholes which were included from this zone were those of the MEDIBA survey, incorporated only to provide the regional variability in the underlying Mit Ghamr Formation (Marriner et al., 2012b). Neither were cores around the delta apex, due to concerns over local effects.

A complication with the elevations of the borehole records is that they were not all presented with reference to the
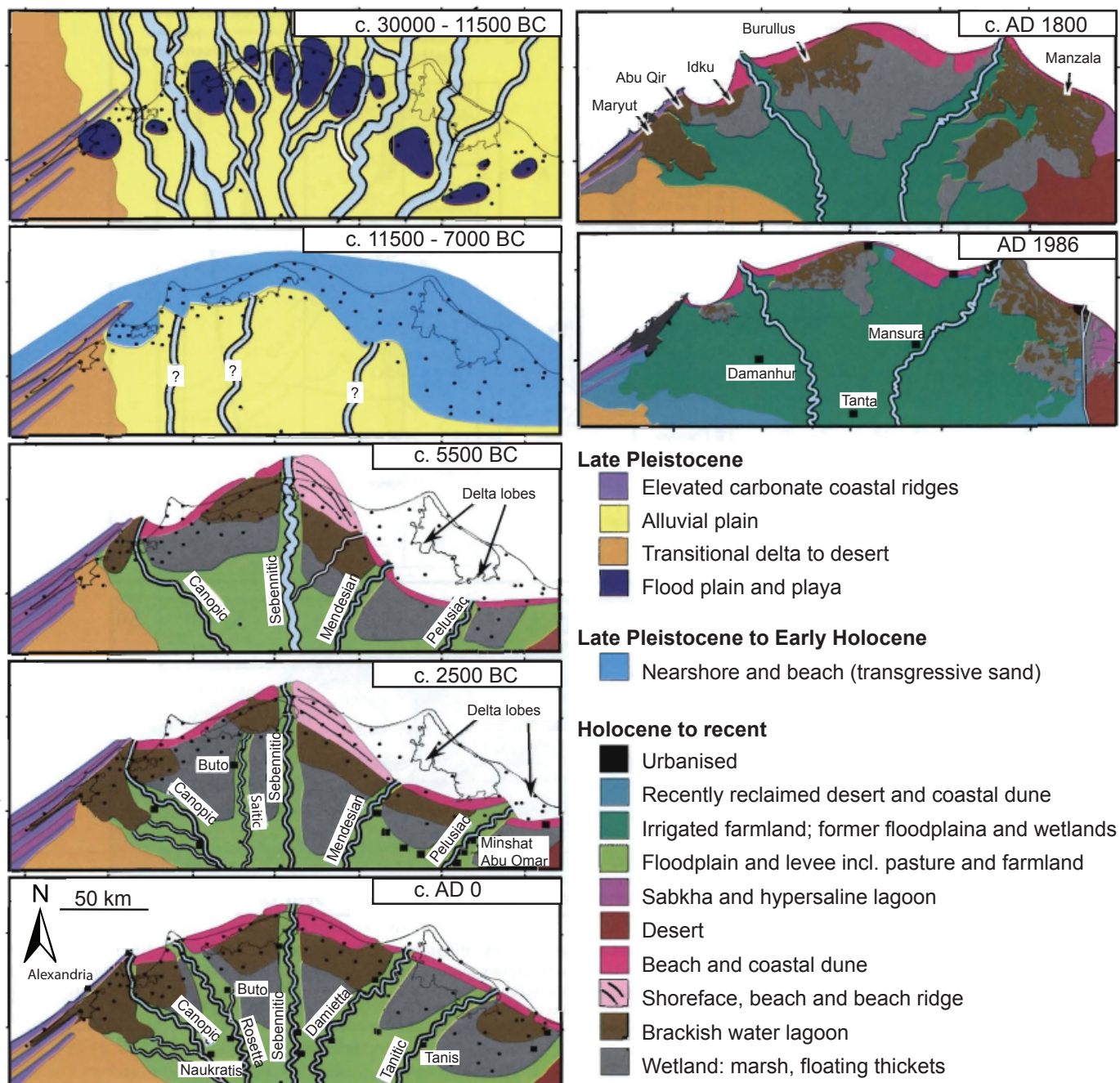
Figure 4: Environmental history of the Nile Delta margin, according to the MEDIBA survey. After Stanley and Warne (1998)
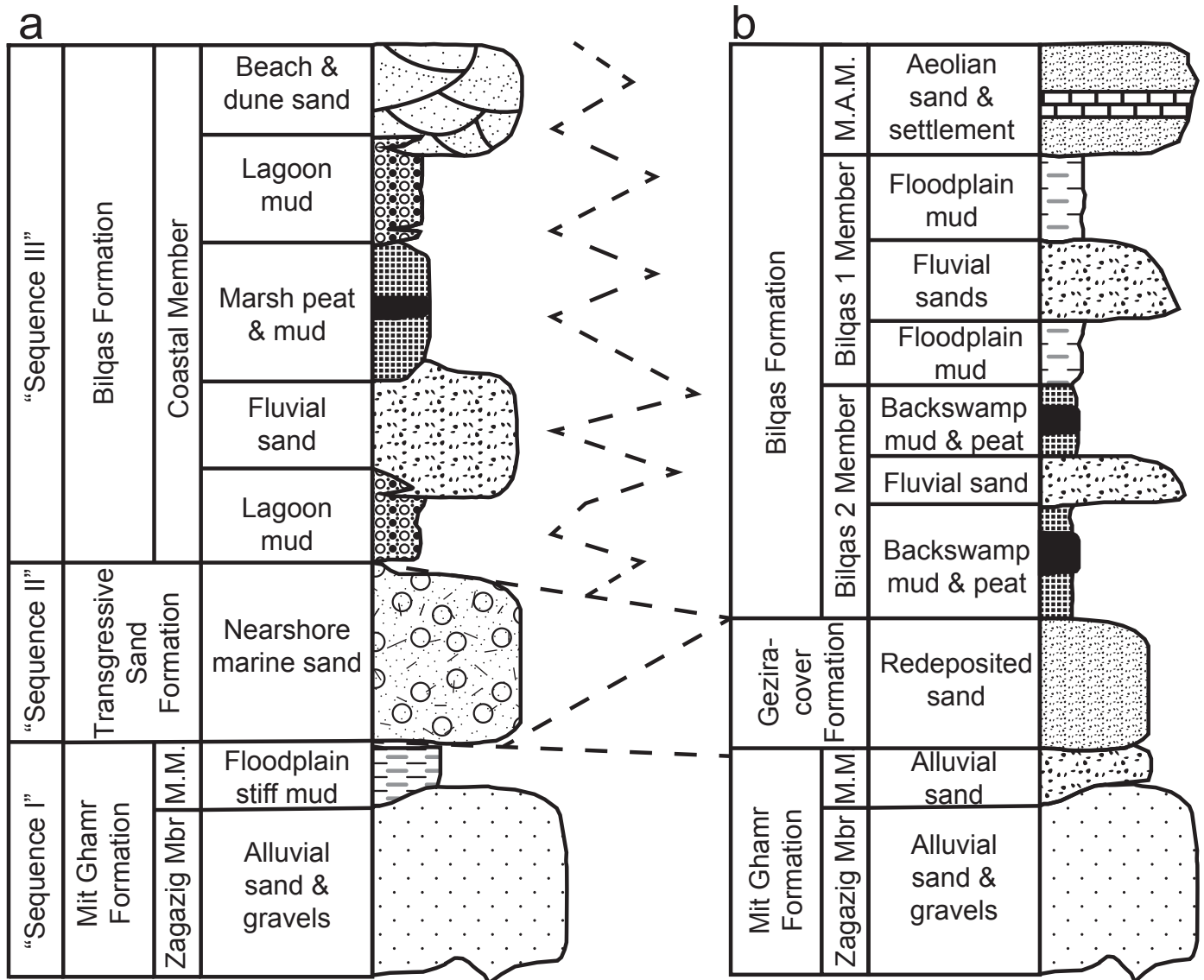.

Figure 5: Representative logs through the a) coastal and b) fluvial zones of the Nile Delta. M.A.M. = Modern Aeolian Member; M.M. = Minuf Member.
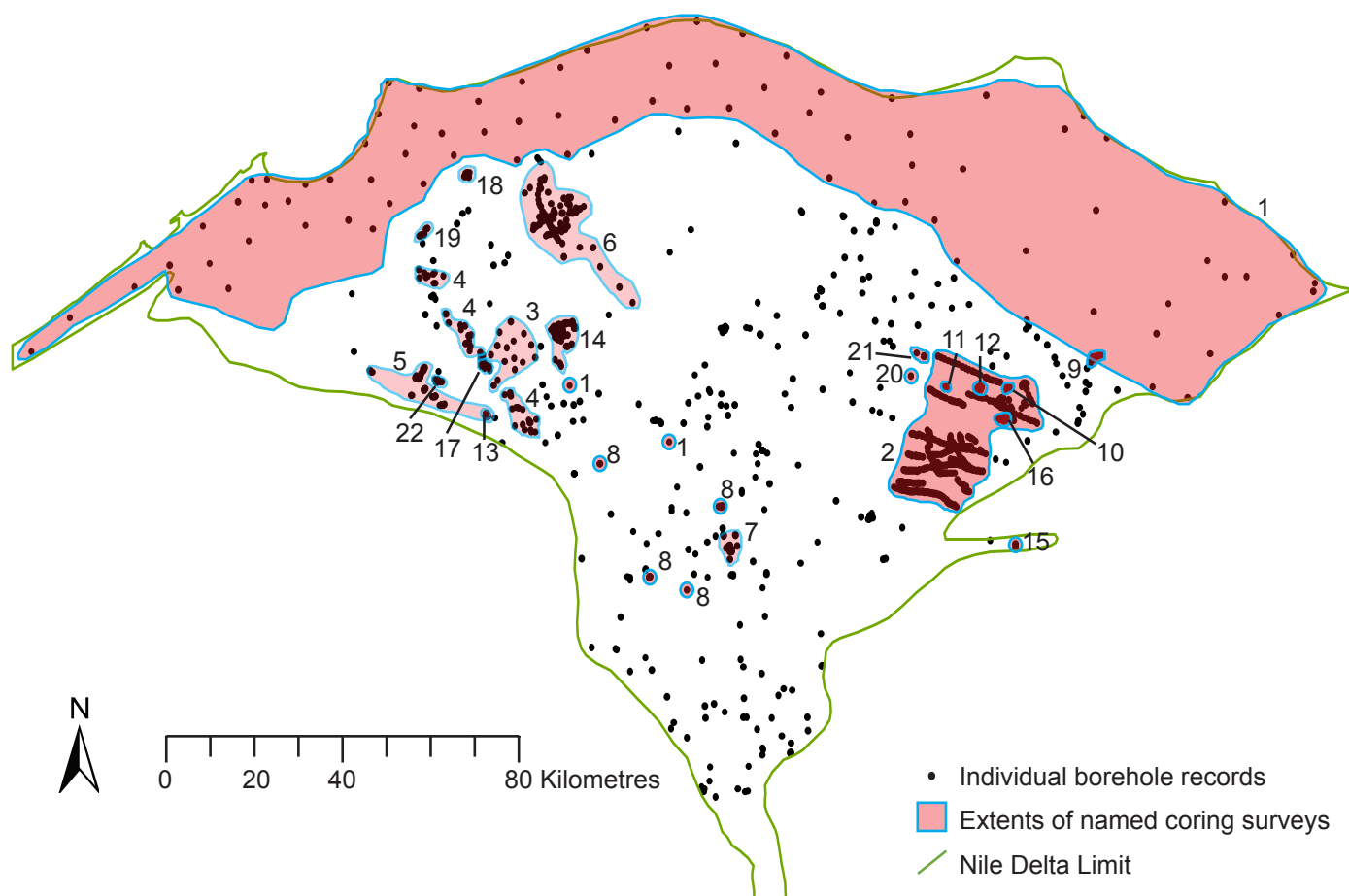
Figure 6: Locations of cores undertaken in the Nile Delta and whose records are available for consultation. Labelled regions represent particular surveys as follows: 1) MEDIBA and other surveys in the coastal zone (not all cores shown); 2) AUSE (Amsterdam University Survey Expedition to the Nile Delta); 3) MUWDS (Mansoura University Western Delta Survey); 4) WDRS (West Nile Delta Regional Survey); 5) WDLP (Western Delta Landscape Project); 6) BRS (Buto Regional Survey); 7) Quesna; 8) Other cores of the MAS (Minufiyeh Archaeological Survey); 9) Minshat Abu Omar; 10) Tell Ibrahim Awad; 11) Tell Gherier; 12) Tell el-Iswid S; 13) Kom el-Hisn; 14) Sais; 15) Kafr Hassan Dawood; 16) Tell ed-Dab$^c$a; 17) Kom Geif; 18) Tell Mutubis; 19) Kom al-Ahmer/Kom Wasit; 20) Tell el-Farkha; 21) Kom el-Khilgan/Tell es-Samara; 22) Kom Firin. Most of the other cores shown were published by the Survey of Egypt.

Table 1: Summary of differences between the LSC and "Meandering" fluvial environments.

| Geomorphological characteristic | LSC | Meandering |
|---|---|---|
| In-channel aggradation rates | High | Low |
| Floodplain aggradation rates | High | Low |
| Channel migration | Little | Substantial |
| Network | Multichannel | Single-channel |
| Alluvial architecture | Narrow sandbodies | Tabular sandbodies |
| Avulsion | Frequent | Less frequent |
| Flooding style | Crevassing | Overtopping |
| Environment | Poorly-drained swamps | Well-drained floodplains |
| Floodbasin sediments | Complex, varying substantially both laterally and vertically | Simpler, wedging out laterally from the channel |

same datum. Most core heights were recorded with reference to the Survey of Egypt datum, which approximates the true geoid more exactly than any other (Dawod and Ismail, 2005), but a small number of cores were expressed relative to EGM2008 (Pavlis et al., 2012). Where no elevations above sea-level were given in the borehole records, approximate heights above sea-level were inferred using SRTM data (Jarvis et al., 2008), which expresses heights relative to the EGM96 geoid (Lemoine et al., 1998). It was necessary to transform the elevations of each core which referenced EGM96 and EGM2008 in order to express them relative to the same datum (see Supplementary Information). The corrections applied by this procedure are significant (up to several metres)

A similar survey of the available literature further reveals 96 stratified radiocarbon, OSL and other dates from within "natural" sedimentary deposits in the fluvial region of the Nile Delta, which were input to a separate chronostratigraphic database (see Supplementary Information). Very few coring surveys collected samples for radiocarbon or other scientific dating, mainly due to restrictions on the export of such material from Egypt. Other projects used very well-correlated sedimentary horizons of identifiable pottery as a (relative) chronostratigraphic marker. Of these 96 dates, 71 were useful for estimating the aggradation history of the floodplain. Others were sourced from within very organic-rich deposits which data suggest have undergone substantial compaction, or were from non-floodplain units. No age-depth information was included in this database from the coastal zone, due to the hypothesised presence of a tectonic hinge-line, north of which the subsidence history is not representative of that further south (Stanley and Warne, 1998).

### 4.2. Geological palaeolandscape and aggradational modelling

In order to create a four-dimensional landscape model for the Holocene evolution of the Nile Delta, the changing spatial extents of the main sedimentary facies and the aggradation history of the delta floodplain had to be established. The changing spatial extents of the different environments in the fluvial zone were mapped through an in-depth analysis of the chronostratigraphic data (sup-

plementary information), by considering the sedimentary units in which each date was hosted. In the coastal zone, the changing environments were copied from previous syntheses that had summarised the work in this region (Stanley and Warne, 1998, 1993a).

The aggradation history of the fluvial sediments was then calculated, which allowed for the mapping of the locations and palaeotopography of the turtlebacks through time. First, minimum-depth geological surfaces of the top surface of each stratigraphic unit were created, using a Kriging algorithm (details in Supplementary Information). This provided a map of the variable height of the "predelta" topography upon which the Holocene delta was laid down (Fig. 7). Then, the spatially and temporally variable aggradation history of the deposits above was established by modelling the data within the chronostratigraphic database. An age-depth diagram for all floodplain sediments of the Bilqas Formation in the fluvial zone of the delta was created (Fig. 8), as well as a series of regionally-specific age-depth diagrams (Fig. 9). The temporal imprecision in these figures was used to create a range of different aggradation models of the Bilqas Formation, the most appropriate of which was selected by using the modelled top surface of the Bilqas 2 Member as an independent estimator of the aggrading height of the floodplain at the time that Bilqas 2 deposition gave way to Bilqas 1 deposits in any particular location.

masl
- -55 - -50
- -50 - -45
- -45 - -40
- -40 - -35
- -35 - -30
- -30 - -25
- -25 - -20
- -20 - -15
- -15 - -10
- -10 - -5
- -5 - -0
- -0 - 5
- 5 - 10
- 10 - 15

mbs
- <1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8 - 9
- 9 - 10
- 10 - 11
- 11 - 12
- 12 - 13

- 13 - 14
- 14 - 15
- 15 - 16
- 16 - 17
- 17 - 18
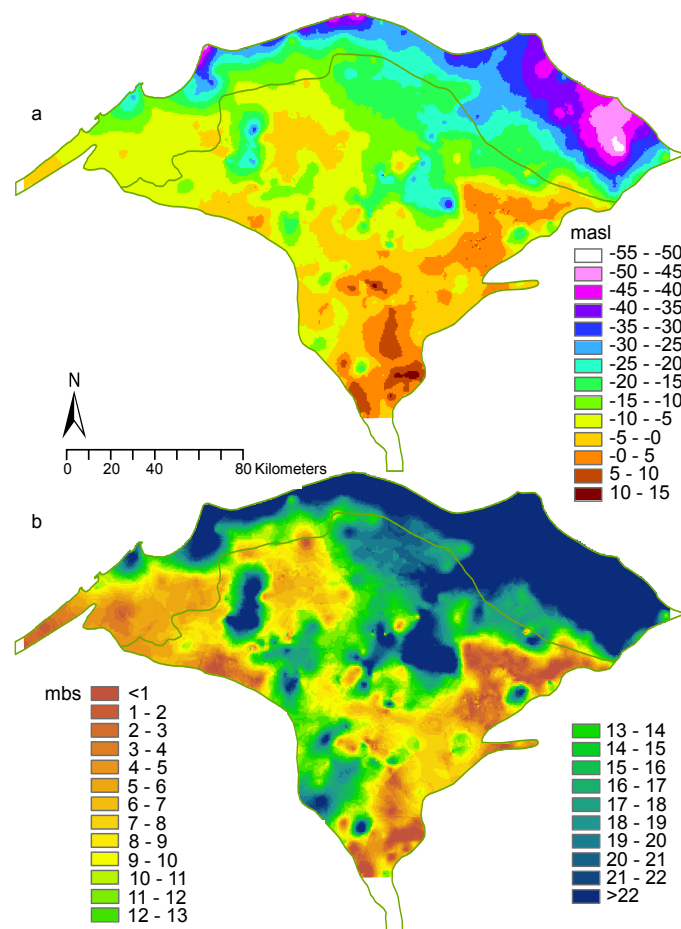- 18 - 19
- 19 - 20
- 20 - 21
- 21 - 22
- >22

Figure 7: "Pre-delta" topographic surface of the combined Mit Ghamr and Geziracover Formations a) in metres above sea level; b) in metres below modern delta surface.
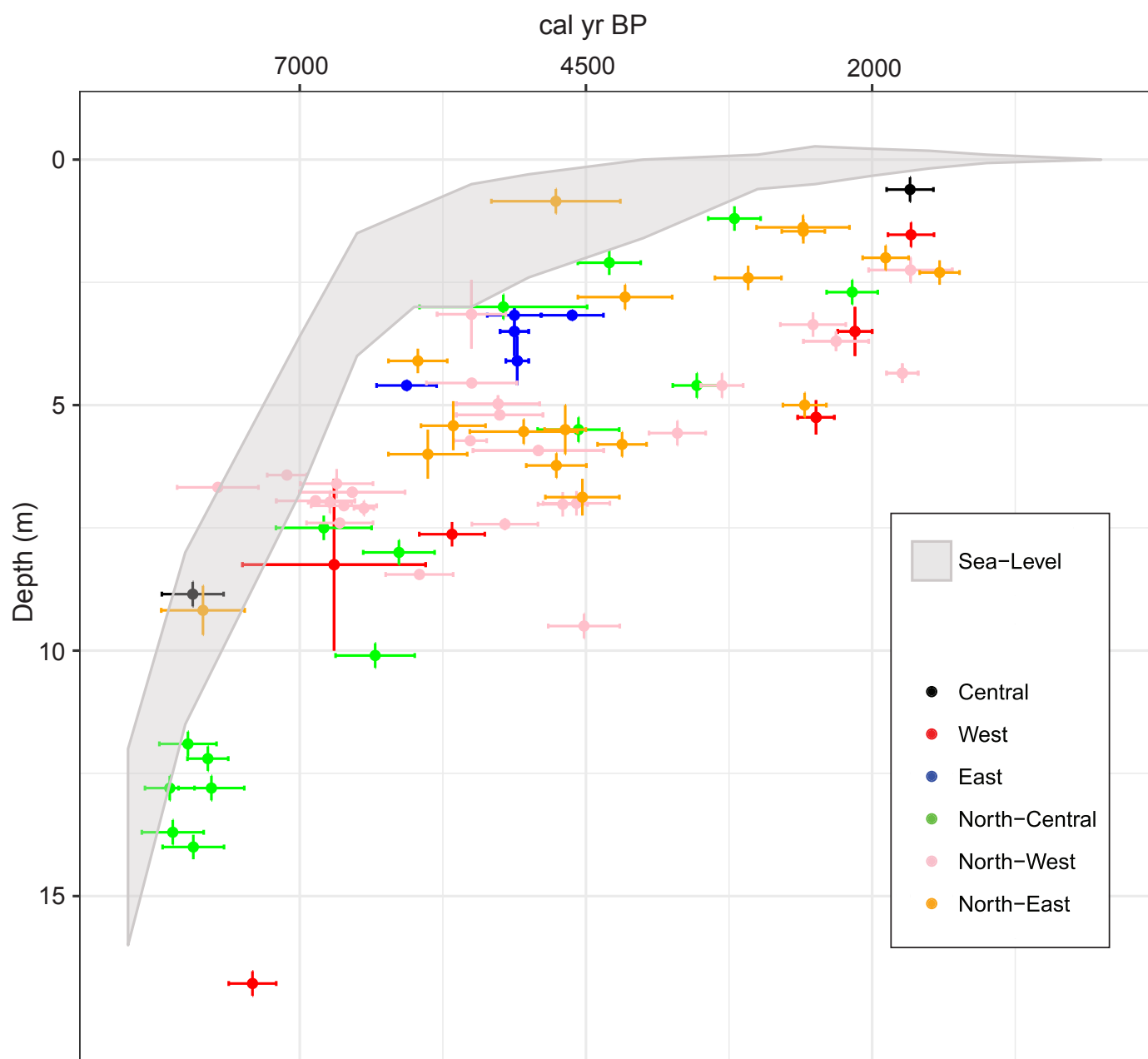
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Figure 8: Age-depth model of stratified dates within the fluvial Nile Delta. Error bars represent 95% probability windows; the shaded region is the sea-level curve for Israel (Sivan et al., 2004, 2001); no more reliable Holocene sea-level curves exist specifically for Egypt.
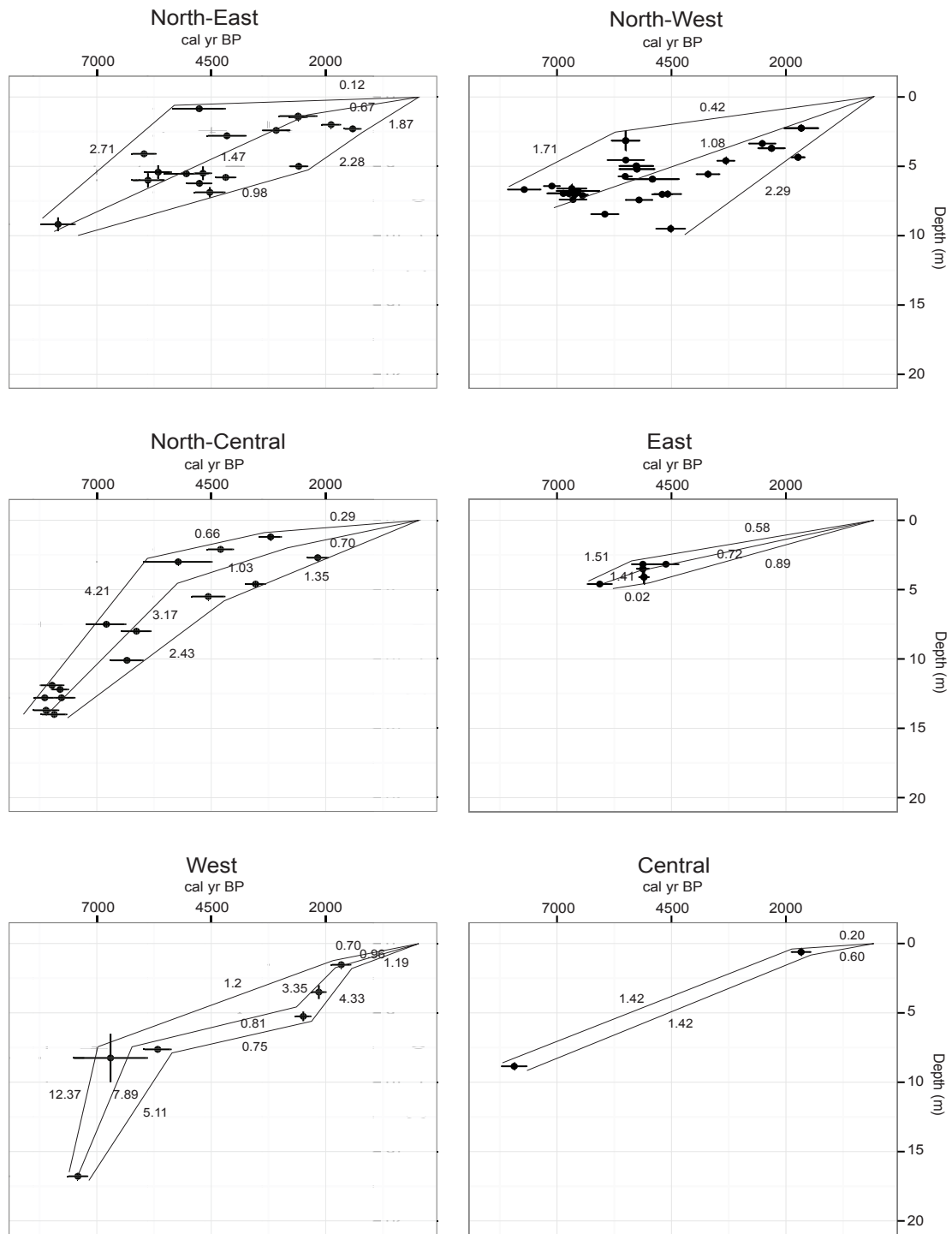
Figure 9: Age-depth models for the six different regions of data for the fluvial Nile Delta. Three sets of line segments are shown for each panel representing the full range of aggradational histories supported by the data. Numbers refer to aggradation rates for each line segment in mm/yr.

## 5. A new stratigraphic framework for the Holocene Nile Delta

A new stratigraphic framework is proposed for the recent deposits of the Nile Delta, which reflects the overall environmental evolution of the area through the Holocene. Eight stratigraphic units within four Formations are defined, displayed in Table 2 and on Fig. 5. The most important conceptual contribution of the present synthesis is that it divides the mid- and late Holocene fluvial sediments of the delta plain into two Members: Bilqas 2 and Bilqas 1, representing the LSC and "Meandering" environments respectively. Standard geological naming conventions are followed for the Pleistocene units, while the Holocene units are named after the facies they represent, except where a previous name already exists (Bilqas).

In no location are all eight units seen in the same core. The Transgressive Sand Formation and Coastal Member are localised to the northern margin of the delta, while the Modern Aeolian Member and Geziracover Formation appear only in certain localities. Fig. 10 shows in which cores each unit was encountered. The results of previous surveys have been reinterpreted within this new stratigraphic framework (Fig. 11), and are discussed below.

### 5.1. The Mit Ghamr Formation

The Mit Ghamr Formation (Rizzini et al., 1978) mainly comprises medium-coarse quartzose sands, containing pebbles of quartzite, chert and dolomite (Rizzini et al., 1978), some autigenic carbonate nodules (El-Awady, 2009), rare gastropod shells (Buck, 1990, p. 80), as well as some finer layers. It can, however, be separated into two different units, with the lowermost unit (renamed here as the Zagazig Member) coarser and mineralogically different to the upper unit (renamed as the Minuf Member). The top of the unit is very uneven, and is often made up of a calcareous white palaeosol some 10–40cm thick (Hamdan, 2003). In other locations the top appears altered in colour to greenish-grey as a result of a reduced iron coating on the sand grains (Andres and Wunderlich, 1991). It is this unit that usually forms turtlebacks where its top surface rises above the modern-day floodplain surface (Butzer, 1959; Fourtau, 1915; Judd, 1897; Kholief et al., 1969; Said, 1981).

#### 5.1.1. Zagazig Member:

The Zagazig Member has been previously known by other names: the "sub-delta formation" (Judd, 1897) or the "Lower Buried Channel" (Sandford and Arkell, 1939). It has also been described as a unit composed of "coarse and fine sands interfingering with pebbly or gravelly beds" (Fourtau, 1915); "several generations of Pleistocene sands and gravels" (Butzer, 1974); or "Mid-Pleistocene coarse sands/cobble gravels" (Butzer, 2002). These sands also usually correspond to the "diluvial deposits" noted by the Survey of Egypt (Attia, 1954).

The material is generally of a grade between $\phi$=2.5 and $\phi$=-5, with a skew to the finer grain sizes (Andres and Wunderlich, 1991; Buck, 1990; Kholief et al., 1969; Rowland and Hamdan, 2012), and is thus often a medium sand with isolated larger clasts, although in some locations may be significantly coarser (Attia, 1954). It is broadly yellow in colour (Buck, 1990; El-Shahat et al., 2005; de Wit and van Stralen, 1988b; Hamdan, 2003; Hamroush, 1987; Kholief et al., 1969; Rowland and Hamdan, 2012). The sediments are moderately-to-poorly-sorted, quite homogenous, and sometimes laminated or cross-stratified with evidence of fining-upwards cycles (Hamroush, 1987; Kholief et al., 1969; Rowland and Hamdan, 2012). The sands are predominantly quartz (80–100%), with some plagioclase feldspar (Zaghloul et al., 1980). The grains themselves have very thin coatings of iron oxide and sometimes carbonate (El-Shahat et al., 1999; Kholief et al., 1969; Stanley and Chen, 1991). Other minerals include iron oxides (magnetite, haematite and ilmenite), hornblende, augite and epidote (El-Hinnawi and El-Shahat, 1969; El-Shahat et al., 2005; Hamdan, 2003; Kholief et al., 1969; Zaghloul et al., 1980). The name given to the unit here comes from the location of the borehole in which it was first recognised (Judd, 1897). The sands are generally correlated with the Qena Prenile sands of Upper Egypt (Said, 1981, p. 56), as well as the Sath Ghorab Formation (Hamdan, 2003).

#### 5.1.2. Minuf Member:

Lying unconformably above the Zagazig Member is another unit within the Mit Ghamr Formation: the Minuf Member. Although the deposits of this unit have been known about for many years as a combination of the "Upper Buried Channel" and "hornblende sands and silts" (Sandford and Arkell, 1939), and together under the name "Fine Nilotic Sands" (Butzer, 1974), they have generally eluded systematic description and correlation with other units in Egypt, and are not discussed at any length in geological syntheses (Said, 1993, 1981; Tawadros, 2011).

The sands within the unit differ from the underlying Zagazig Member by the presence of mica, their less massive character and finer grain size, and their hosting of stiff or compact clayey lenses (Butzer, 2002, 1974; Sandford and Arkell, 1939). These lenses probably originated in fragmented Late Pleistocene floodbasins, especially near the modern-day coastline (Butzer, 2002; Chen and Stanley, 1993). Based on radiocarbon dates of the MEDIBA survey and the Buto Regional Survey (BRS), the deposits appear to have been laid down between c.28,000 and 11,000 cal BP (Butzer, 2002). They most probably comprise a complex set of numerous different minor units of different genetic origin, probably spanning a large age-range (Butzer, 2002), deposited under an earlier, braided Nilotic regime (Adamson et al., 1980). The name given to the unit here is chosen after the location of one of the first boreholes in which the unit was recognised (Fourtau, 1915).

### 5.2. The Geziracover Formation

In a small number of locations, lying unconformably and directly atop the Mit Ghamr Formation are deposits

a     Modern Aeolian Member

b     Bilqas 1/2 undivided

c     Bilqas 1 Member

d     Bilqas 2 Member

e     Coastal Member

f     Transgressive Sand Formation

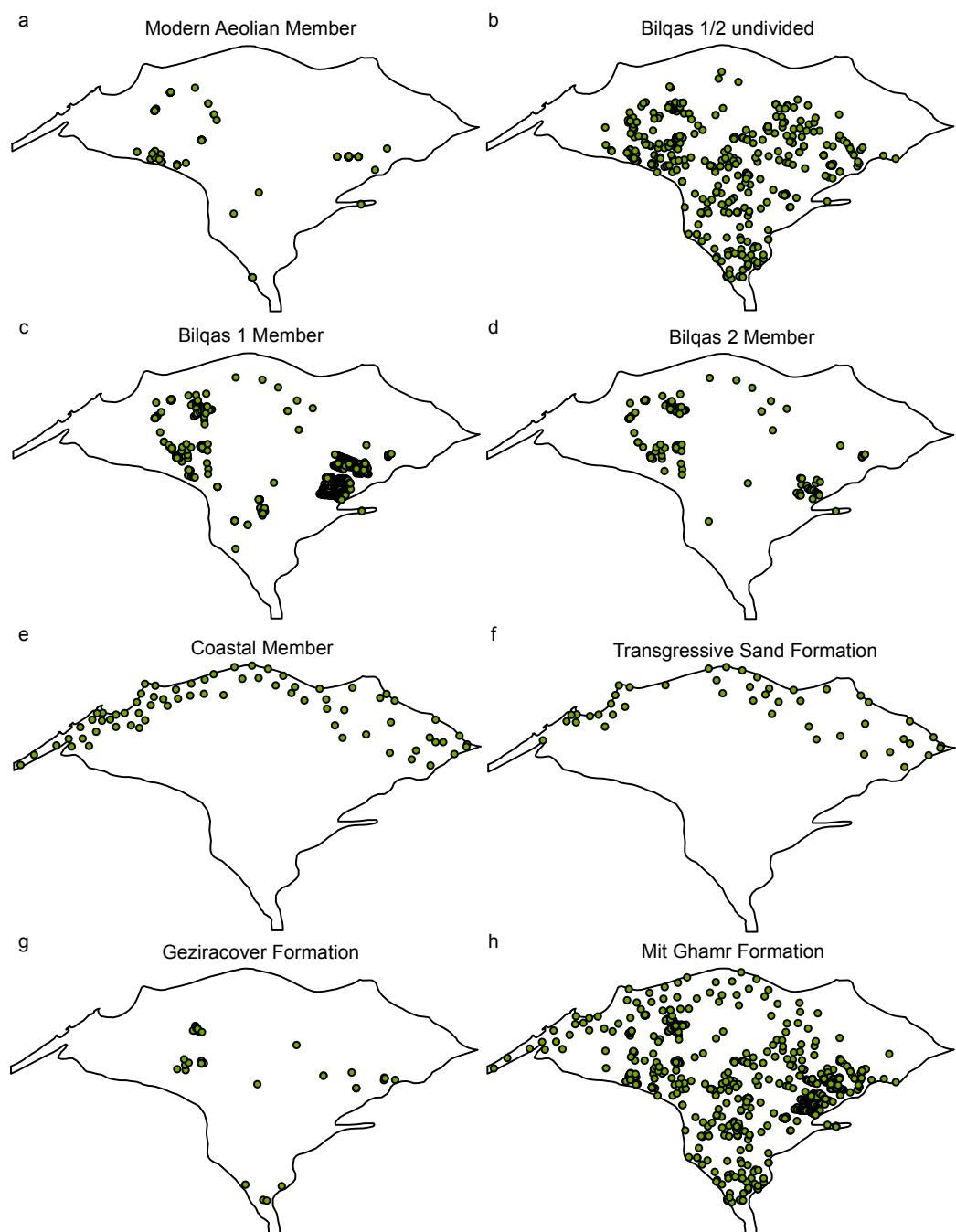g     Geziracover Formation

h     Mit Ghamr Formation

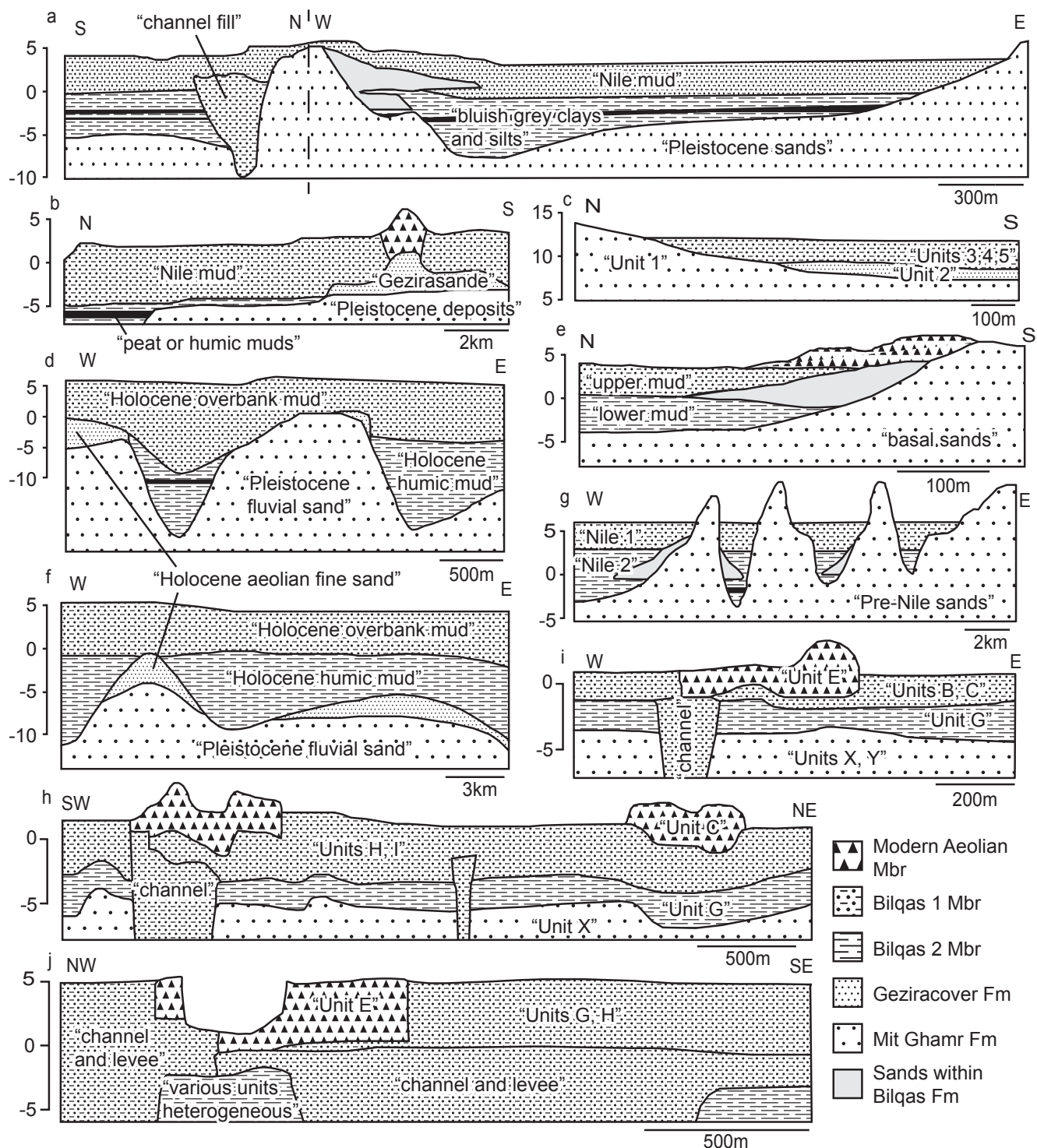Figure 10: Maps showing the distributions of cores containing each unit.

Figure 11: Summary cross-sections of previous localised geoarchaeological/geological surveys in the Nile Delta, reinterpreted within the stratigraphic divisions of the current synthesis. a) Minshat Abu Omar, adapted from Andres and Wunderlich (1992); b) BRS, adapted from Hamdan (2003); c) Quesna, adapted from Rowland and Hamdan (2012); d) Sais, adapted from El-Shahat et al. (2005); e) Kafr Hassan Dawood, adapted from Hamdan (2003); f) MUWDS, adapted from El-Awady (2009). g) AUSE, adapted from Andres and Wunderlich (1992); h) Kom al-Ahmer/Kom Wasit; i) Tell Mutubis; j) Kom Geif. The names of the units given in quotation marks are those from the published literature; the key shows their reinterpretation within the framework of the current synthesis.

Table 2: New stratigraphic framework for Recent Nile Delta deposits. Dashed lines indicate unconformity surfaces; those units in *italics* are new to the current synthesis.

| | |
|---|---|
| *Modern Aeolian Member* | |
| *Bilqas 1 Member* | Bilqas Formation |
| *Bilqas 2 Member* | |
| *Coastal Member* | |
| - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - | |
| Transgressive Sand Formation | |
| - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - | |
| *Geziracover Formation* | |
| - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - | |
| *Minuf Member* | Mit Ghamr Formation |
| *Zagazig Member* | |

which have been interpreted as primarily aeolian reworking of the sands beneath. These are observed, for instance, at Buto (Fig. 11) where there appears to have been a two stage deposition process: first fluvial, then by wind (Wunderlich, 1989). Similar observations were made by Tronchère et al. (2012, 2009) based on microscopic analysis and architectural considerations of a deposit they termed the "pre-Pelusiac transition layer". The unit's presence has also been inferred in other surveys (El-Awady, 2009; El-Shahat et al., 2005; Judd, 1897) where well-sorted, friable, very fine to medium sands at the top of the Mit Ghamr Formation were also attributed to their having been redeposited by wind.

## 5.3. The Transgressive Sand Formation

The "early Holocene transgressive sand" is a sedimentary unit that was defined during the MEDIBA survey (Stanley et al., 1996). The unit is composed of coarse, poorly-sorted, olive-grey to yellowish-brown quartzose sands which contain a high percentage of heavy minerals, as well as mollusc and echinoderm fragments, mica and lithic clasts, plus pelecypods, gastropods, ostracods and foraminifera (Arbouille and Stanley, 1991; Chen et al., 1992; Coutellier and Stanley, 1987; El-Shahat et al., 1999; Stanley et al., 1992). The sands are not stained by iron oxide, in contrast to the Mit Ghamr Formation (El-Shahat et al., 1999). These deposits were probably originally fluvial sediments that incorporated a littoral signature during retrogradation of the shoreline and major reworking by waves and other coastal processes between c.15,000 and 8000 cal BP (Stanley et al., 1992).

## 5.4. The Bilqas Formation

First recognised as a distinctive unit under the name of "terre végétale" (Fourtau, 1915), the Bilqas Formation (Rizzini et al., 1978) makes up the "alluvial mud" of the delta plain. It is divided into four, with the most important conceptual contribution of the current synthesis being the division of the fluvially-dominated delta sediments into two units: Bilqas 2 and Bilqas 1.

### 5.4.1. "Modern Aeolian" Member:

This unit of convenience is represented by sediments which have been deposited by aeolian activity on top of the floodplain; it is also applied to significant quantities of archaeological debris at "tell" sites when encountered in cores from the surface downwards. These deposits of anthropogenic origin originally stood above the floodplain, acting as a trap for windblown material, and also underwent degredation and aeolian reworking *in situ*. The unit usually occurs both at the margins of the delta, and on "tell" sites within the delta.

### 5.4.2. Coastal Member:

This unit represents all sediments interpreted as having being deposited in a coastal, nearshore or marine setting, except for the Transgressive Sand Formation, which is excluded from this grouping as it occupies a very specific stratigraphic position at the base of the Holocene sequence. The Coastal Member, on the other hand, is contemporaneous with much of the deposition of the fluvial units of Bilqas 1 and Bilqas 2. This unit contains marine, semiterrestrial, coastal, estuarine, lagoonal and occasionally sabkha deposits; the spatio-temporal extents of these sedimentary environments have been previously mapped (Arbouille and Stanley, 1991; Chen et al., 1992; Coutellier and Stanley, 1987; Stanley et al., 1992).

### 5.4.3. Bilqas 1 and Bilqas 2 Members:

The recent fluvial sequence is divided into Bilqas 1 and Bilqas 2 Members. In this twofold division, the Bilqas 2 Member is the lower of the two units. It is made up of bluish-black silty-clay to clayey-silt containing a high percentage of organic matter. Peat layers are locally developed, and spatial variations in grain size are rapid and unpredictable, in that (sub-)units do not tend to grade into each other over wide areas. It is thought to represent deposition within the LSC environment discussed in section 2. This is in contrast to the overlying Bilqas 1 Member which is generally brown-grey in colour, less rich in organic material, and very predictable in the lateral variation of its grain size. This later unit represents overtopping of levees and the development of a wide floodplain during the later Holocene, within the "Meandering" environment (section 2).

The contact between the Bilqas 2 and Bilqas 1 units therefore corresponds to the LSC–Meandering Transition, an event suggested by Pennington et al. (2016) to be driven

by the slowing of bulk aggradation rates, driven ultimately by the slowing of sea-level rise within the context of a weakening monsoonal system. This position is revisited and discussed further below in section 7.

The lower, Bilqas 2 unit is first thought to have been observed in the eastern delta by the Amsterdam University Survey Expedition to the Nile Delta (AUSE project), where it was labelled as "Nile 2 deposits". It was described as comprising rapidly-alternating deposits of silt and sand; dark, organic, humic clays; and calcareous clays (de Wit and van Stralen, 1988b) suggesting "permanent water-bearing systems...such as larger rivers, swamps and lakes...[with] no obvious traces of temporal desiccation", in combination with "ephemeral stream sediments...[and] wadi-fed stagnant pools". This lower unit gives way to overlying "Nile 1" facies (Fig. 11), which comprise very different sediments (Bilqas 1 Member): "uniform flood-basin clays, levee silts, channel plugs, and intermittent eolian sandy influxes" (de Wit, 1993).

The rapidly-alternating nature of the deposits of the Bilqas 2 Member in a *lateral* sense suggests deposition in an environment characterised by anastomosing streams with narrow levees surrounding larger floodbasins: an exact picture of the LSC environment. The humic muds would have been deposited within the swamps between these channels. The rapidly-alternating nature of the deposits in a *vertical* sense is the result of the likely very dynamic and changeable landscapes in which they were laid down: again a hallmark of the LSC environment, and in direct contrast to the sediments above.

A very similar sequence was also observed around Minshat Abu Omar (Fig. 11), where a lower unit of "compact dark grey violet mud, rich in organic material" (Krzyzaniak, 1993) gives way to sediments which contain less organic matter, and within which "soil development is documented by calcic nodules, oxic mottles and iron-manganese concretions" (Andres and Wunderlich, 1992, 1991). The lower unit was interpreted as "indicat[ing] the prevalence of semiterrestric environments" (Andres and Wunderlich, 1991), and is correlated here as the Bilqas 2 Member. The upper sediments originate from a much more well-drained setting and are correlated as the Bilqas 1 Member. The whole sequence is underlain by greenish-grey sand deposits, which are coloured as such as a result of reduced iron (Andres and Wunderlich, 1991) – presumably in-situ decomposition of vegetation within the swamps of the Bilqas 2 unit above resulted in reducing environments persisting below the surface.

In the western delta, the same sedimentary sequence has also been observed by the BRS (Wunderlich, 1989; Wunderlich and Andres, 1991), the Mansoura Western Delta Survey (MUWDS) (El-Awady, 2009), around Sais (El-Shahat et al., 2005), and in recent fieldwork at Kom Geif, Kom al-Ahmer/Kom Wasit and Tell Mutubis (Fig. 11). All these coring surveys also divided the Bilqas Formation into two units: a lower unit containing humic muds rich in organic matter (Bilqas 2 Member), sometimes containing peat layers and smelling of hydrogen sulphide, and an upper one (Bilqas 1 Member) which has no peat layers, is browner in colour, contains rhizoconcretions and displays more predictable variations in grain-size. Once again, the substantial lateral inhomogeneity in grain size in the lower unit is taken as an indication of small anastomosing streams separating isolated floodbasins, while the smell of hydrogen sulphide and existence of peat is taken as indicating an organic rich, wetland landscape with standing water and euxinia persisting in the subsurface.

Palynological evidence also supports a division of the sedimentary sequence in two, with the lower unit reflecting more marshy environments than the upper. An undated pollen record from the coastal margin (Saad and Sami, 1967) shows an upwards decrease in semi-aquatic species such as Cyperaceae, Poaceae, Typhaceae and *Jussieua*, and an increase in land plants. Tentative correlation of this core with nearby dated boreholes of the MEDIBA survey suggest this transition could have taken place after 8000–5300 cal BP. A further study (Leroy, 1992) also in general found progressively decreasing amounts of Cyperaceae and other wetland plants, and increasing Poaceae, Amaranthaceae and Chenopodiaceae since c.4000 cal BP. More recent work (Bernhardt et al., 2012; Hennekam et al., 2015) has also found decreasing Cyperaceae c.5000 cal BP, which may reflect the replacement of local wetland landscapes of the Bilqas 2 environment by the Bilqas 1 facies.

## 6. Delta Evolution

Fig. 12 shows the overall modelled landscape evolution of the Nile Delta c.8000–4500 cal BP, characterised overwhelmingly by the genesis and subsequent disappearance of LSC landscapes, represented by deposits of the Bilqas 2 Member, and their replacement by more well-drained floodplains of the Bilqas 1 Member. These landscapes were laid down upon a "pre-delta" topographic surface formed by the Mit Ghamr and Geziracover Formations (Fig. 7). Prior to c.8000 cal BP, the area now covered by the modern delta plain was made up of deposits of the Mit Ghamr Formation and Geziracover Formation. Rivers were incising, redepositing and reworking earlier fluvial material, with aeolian deposition of the Geziracover Formation on some topographic highs.

The onset of Bilqas deposition and the inception of the Holocene alluvial delta plain first occurred around 8000 cal BP in the northern part of the delta (Fig. 12a). Data from the MEDIBA survey (Stanley et al., 1996; cores S38 and S32) as well as from Minshat Abu Omar (Andres and Wunderlich, 1991; core D5) show that around 8000 cal BP deposits of the Bilqas 2 unit were being laid down in the extreme north of the delta. Further south, rivers were still behaving as before, and the Mit Ghamr and Geziracover units were still fully exposed at the surface, as shown by an OSL date from Tell ed-Dab^ca (Tronchère et al., 2012) which comes from within the Geziracover Formation.
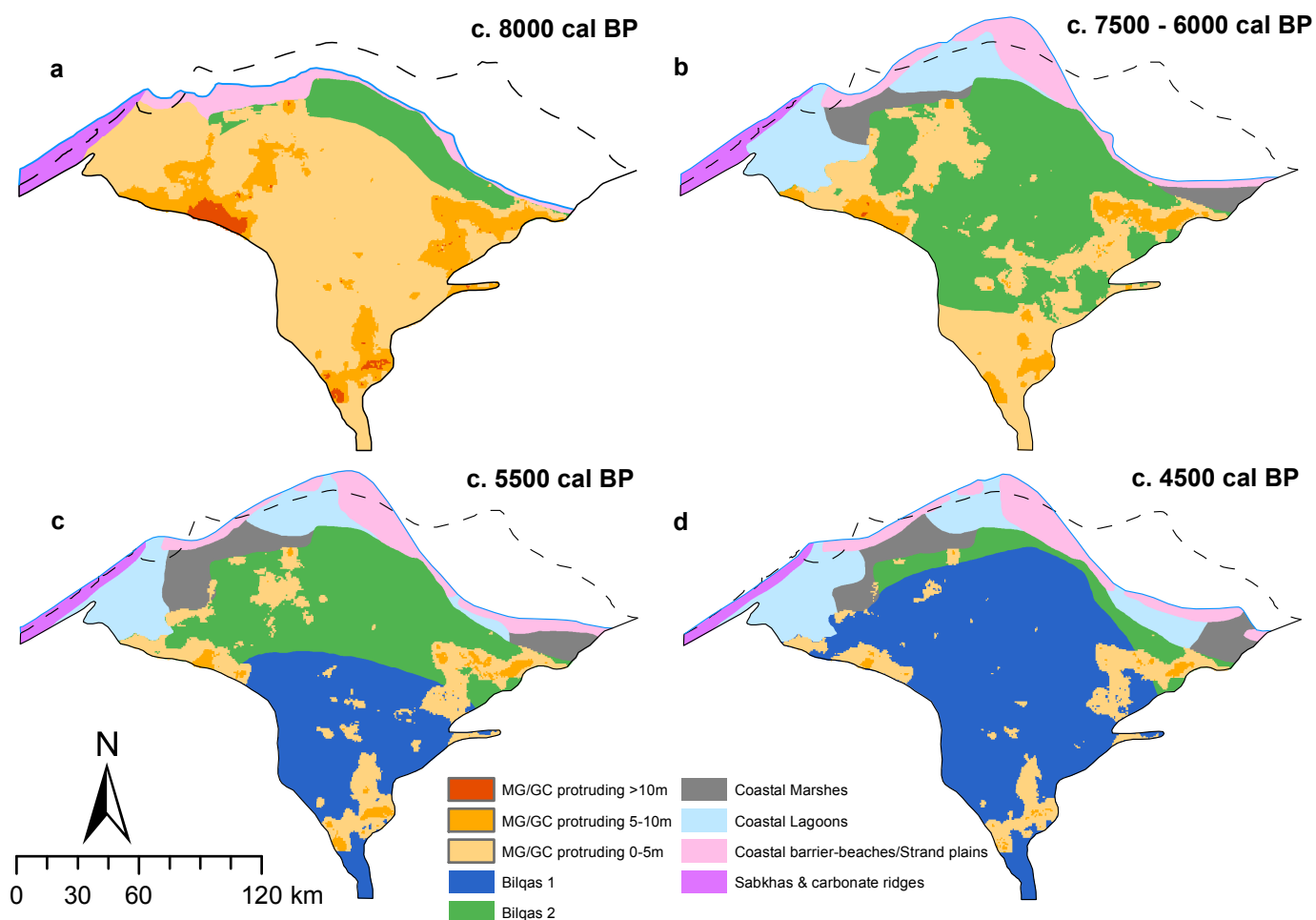
Figure 12: Best estimate maps showing the mid-Holocene evolution of the Nile Delta c.8000–4500 cal BP: a) c.8000 cal BP; b) c.7500–6000 cal BP; c) c.5500 cal BP; d) c.4500 cal BP. The dashed line on each subfigure indicates the modern-day coastline; MG/GC= Mit Ghamr/Geziracover Formation.

The onset of Bilqas 2 deposition in the central, eastern and western delta probably came about at c.8000–7500 cal BP, a date-range constrained by the lowermost date within core S87 of the MEDIBA survey (Stanley et al., 1996), which shows the initiation of Bilqas deposition in the central delta at c.8155–7615 cal BP. Nearby core S86 (Stanley et al., 1996) also corroborates this time-frame, with lowermost dated Bilqas deposits at 7571–7156 cal BP. The lowest AUSE project radiocarbon date (within the Bilqas 2 unit) also points to the onset of Bilqas deposition at some point earlier than c.7250–6750 cal BP (de Wit, 1993); at Sais deposition of the Bilqas 2 unit is also initiated before c. 7450–5850 cal BP (Wilson, 2006b; Wilson et al., 2014).

The topography of the delta at this time was moderately undulating, with hills standing over 5m taller than the floodplain in many locations, especially at the delta fringes (Fig. 12a). The shoreline was situated substantially inland relative to its present position, particularly in the east (Coutellier and Stanley, 1987). Very little is known about the exact character of the coastal margin at this time, although it is probable that barrier-beaches were just beginning to form. The near-offshore was dominated by littoral-zone deposits of the Transgressive Sand Formation (Stanley and Warne, 1993a).

After the onset of Bilqas deposition and until c.6000 cal BP it seems that much of the fluvial part of the delta was experiencing deposition of the Bilqas 2 unit, hosting landscapes characterised by dynamic, anastomosing channel networks and swampy floodbasin facies of the LSC environment (Fig. 12b). Between 7500–6000 cal BP there was extensive peat development of the Bilqas 2 unit at Buto (Wunderlich, 1989), and deposits of the Bilqas 2 unit are also interpreted to have been encountered within some of the MEDIBA cores (Stanley et al., 1996), as well as at Minshat Abu Omar (Andres and Wunderlich, 1991). The southernmost extent of the unit is not known, but it was certainly further south than the AUSE study area, with some cores in the central delta area also suggesting its presence. To the far south deposits of the Mit Ghamr and Geziracover Formations probably still cropped out at the surface. Sandy hills still protruded above the floodplain especially near the delta fringes. The shoreline prograded extensively in the western delta, behind which lagoons were developed (Warne and Stanley, 1993b), while marshy wetlands behind small barrier beaches persisted in the east (Coutellier and Stanley, 1987).

From 6000–5500 cal BP, overall aggradation rates fell (Fig. 8), and the fluvial landscape changed dramatically. While Bilqas 2 sediments, corresponding to dynamic, swampy and marshy environments were still being deposited in the north, deposition of the Bilqas 1 Member appears to have commenced in the southern and central part of the delta (Fig. 12c), characterised by much more extensive, well-drained floodplains, single-channel networks and less marshy landscapes. The second date from the AUSE project, at some c.6000 cal BP, is from within the Bilqas 1 unit (de Wit, 1993); similarly a date within core S86 of

the MEDIBA survey at 5906–5334 cal BP (Stanley et al., 1996) could also be from within the Bilqas 1 unit. This suggests that Bilqas 1 deposition had been initiated by c.6000–5500 cal BP in the central part of the delta.

However, in the north of the delta Bilqas 2 sediments were still being deposited: various cores at Minshat Abu Omar (Andres and Wunderlich, 1991, 1992) still record Bilqas 2 sedimentation, as does core S9 of the MEDIBA survey and a number of cores at Buto. The same overall areas of turtlebacks remained, although they were reduced in size compared to previous time periods. In the coastal area, lagoons persisted in the western and central regions (Warne and Stanley, 1993a), while across the delta fringe a coastal barrier-beach system had clearly been established (Arbouille and Stanley, 1991; Stanley et al., 1992).

Butzer (2002) suggests there is a delta-wide unconformity around 6000 cal BP, based on the fact that at some "tell" sites fans of reworked sandy material appear to extend into the floodplain at this time. However, this is not seen in all studies (see Fig. 11), and the exact stratigraphic relationships of the fans to the sediments above and below is not always clear.

By 4500 cal BP the area of Bilqas 1 deposition had expanded significantly northwards to cover most of the delta (Fig. 12d); Bilqas 2 sedimentation was extremely localised in the far north. However, Bilqas 2 deposition did continue in a number of limited areas in the extreme northeast and north-west delta: cores D71 and D4 at Minshat Abu Omar and MEDIBA cores S55 and S54 to the north of Buto suggest continuing Bilqas 2 deposition in these locations persisting until at least c.4500 cal BP, and possibly much later. The previously substantial turtlebacks were by this time much more limited in extent; the eastern delta was now actively prograding (Coutellier and Stanley, 1987), but extensive lagoons, marshes and barrier beaches remained the main features of the coastal zone (Stanley and Warne, 1993a).

Since 4500 cal BP, the overall landscapes of the Bilqas 1 Member have generally continued to exist until the present day, albeit with significant anthropogenic alteration. They have been modified and exploited as a result of the development of irrigation agriculture, the digging and maintenance of natural and artificial waterways (Butzer, 1976; Cooper, 2014; Hassan, 2010), and most recently through the draining of the coastal lagoons, and the building of the Aswan High Dam which has starved the delta of 95% of its sediments (Stanley and Warne, 1998).

In summary, the data support the initiation of Bilqas 2 deposition at c.8000 cal BP near the shoreline. The spatial extent of the unit and its corresponding environments of swampy floodbasins then expanded upstream until c.6000 cal BP, after which it was replaced by Bilqas 1 sediments and a less swampy landscape from the south. These environments pushed northwards between 6000 and 5000 cal BP. By c.4500 cal BP Bilqas 2 sediments were being deposited in only a limited number of areas; by c.3500 cal BP they had disappeared completely, and the environments of

the Bilqas 1 Member have then dominated to the present day. Turtlebacks – a common landscape feature in the delta prior to some 6000 cal BP – gradually diminished in size and became much more limited in their spatial extent by 4500 cal BP. Importantly these also seem to have been smaller than earlier syntheses suggested (Butzer, 2002, 1976, 1974). The coastline prograded in the west from c.8000 cal BP, and has broadly approximated its modern-day position since 6000 cal BP. In the east, however, an extensive coastal embayment persisted, and the shoreline prograded here only from c.5000 cal BP, reaching its modern position just in the last two thousand years (Coutellier and Stanley, 1987; Goodfriend and Stanley, 1999; Moshier and El-Kalani, 2008).

These landscape changes taking place in the delta were larger than those occurring upstream during this time period. While upstream there was also an early mid-Holocene replacement of sandy sediments by silts (Adamson et al., 1980; Butzer, 1998; Toonen et al., in press) – analogous to the onset of deposition of the Bilqas Formation – the later mid-Holocene period upstream saw no episodes of complete landscape remodelling analogous to the Bilqas 2 – Bilqas 1 transition. The major upstream landscape changes were instead related to periods of floodplain and channel network contraction, possibly associated with decreased discharge, regional aridification and cooling (Macklin et al., 2015).

### 6.1. Aggradation history

Aggradation rates display a decreasing trend through time that correlates with decreasing rates of sea-level rise (Fig. 8). Prior to 5200–5950 cal BP, aggradation rates appear to range approximately between 2.4–12mm/yr; after this time they are lower, generally between c. 0.5–1.5mm/yr (Fig. 9). This decrease in aggradation rates appears to lag the inflexion in the rate of sea-level rise by some 750 years. This lag may be real, or it may be an artefact, since the sea-level curve is not from Egypt but from Israel (no reliable sea-level curves have been constructed for this period for Egypt). In general, however, the fact that aggradation rates decrease through time following the sea-level curve is a strong indication that they are controlled predominantly by downstream factors.

Aggradation rates are not homogenous across the delta, however (Fig. 9). To establish whether these differences are caused by regional east-west faulting patterns (Bosworth, 2008; Hussein et al., 2013; Tingay et al., 2011), the age-depth data was plotted against latitude and longitude (Fig. 13). This figure clearly shows there is no detectable latitudinal trend within the data – points of equal size (equal age) lie along the horizontal – and therefore suggests that east-west regional faulting is not contributing to regional variability in subsidence patterns. It further provides proof that any east-west trending tectonic "hinge-line" of high rates of subsidence (Stanley and Warne, 1993a) lies further to the north than the data considered.

However, there appears to be a longitudinal variation in aggradation rate. Deposits of similar age are buried approximately 2m deeper in the west and north-west regions of the fluvial zone than in the east and north-east (Fig. 13): the west has experienced faster aggradation than the east. Such a trend is also suggested by the modern-day topography, and the depth to "pre-delta" deposits (Fig. 7): turtlebacks are exposed in the east, but not in the west, where they have presumably been buried. Importantly this subsidence is in the opposite direction to that north of the hinge-line, where deposits are more deeply buried in the east (Stanley, 1990).

This deeper burial of deposits in the west could be caused by a variety of factors. It is highly unlikely to be caused by autocompaction within the Holocene deposits, since it is not just the Holocene sediments that are buried at different depths: the subsidence of the underlying "predelta" topography and turtlebacks suggests that the subsidence must have affected the full Quaternary stratigraphy of the delta. It is also probably not due to the influence of the "Pelusium Line" (Said, 1981, p. 56) – a controversial hypothesised transcontinental fault shear system (Neev, 1977, 1975), since even studies that support the existence of this fault system do not place it in a location that could account for the distribution of turtlebacks (Gamal, 2013). Neither is it likely to be as a result of greater original accommodation space in the west, since some of the oldest dated deposits of the Bilqas Formation have been found in the east by the AUSE project; if the western delta were at a lower elevation than the east during the early mid-Holocene then onlap of the Bilqas Formation in the east would have been a later phenomenon. It is therefore more likely a result of a deep control such as differential autocompaction within the full Quaternary or Cenozoic sequence, or longer wavelength patterns of lithospheric flexure.

## 7. Discussion – drivers of landscape evolution

The mid-Holocene landscape evolution of the Nile Delta has been ultimately governed by a decrease in the rate of relative sea-level rise, although subsidence, changes in sediment-supply dynamics driven by a changing monsoonal system and humans have also played major roles.

### 7.1. Sea-level rise

Relative sea-level change (comprising glacio-isostatic, hydro-isostatic and eustatic components) has played the defining role in the landscape evolution of both the coastal and fluvial regions of the Nile Delta throughout the Holocene.

In the fluvial region of the delta, increased base-level initially resulted in a decrease in river gradient and the deposition of the Bilqas Formation (Stanley and Warne, 1994). High rates of sea-level rise then resulted in the development of the LSC landscape as represented by the Bilqas 2 Member in the early mid-Holocene. The decrease
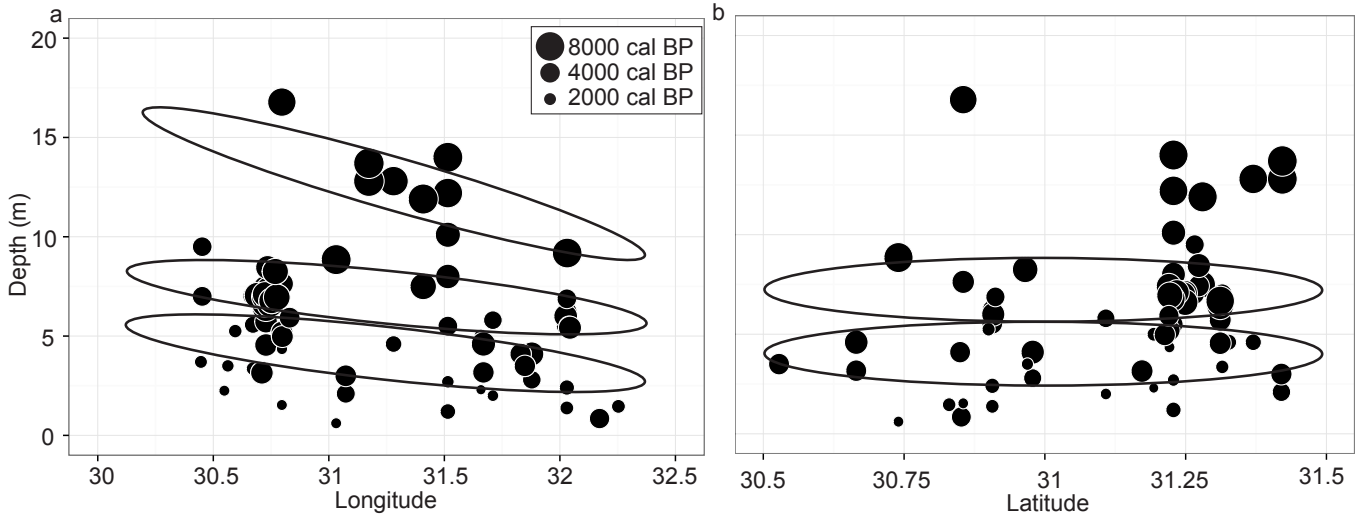
Figure 13: Age and depth of deposits plotted with respect to cardinal directions: a) depth vs longitude; b)depth vs latitude. The size of the bubbles represents age (larger=older).

in the rate of sea-level rise in the later mid-Holocene then ultimately resulted in the LSC-Meandering Transition and the development of the more homogenous floodplains of the Bilqas 1 Member, as described at length in section 2.

Further north, in the coastal zone, the changing landscapes have also been governed by the rate of relative sea-level rise: high rates prior to 7500 cal BP resulted in the marine transgression extending to areas far inland of the present shoreline and the deposition of the Transgressive Sand Formation (Flaux et al., 2013; Stanley and Warne, 1993a). Following the slowing-down of the rate of sea-level rise, sediments were reworked into extensive beach-barrier systems which served to close-up the coastline and halt marine ingression (Stanley and Warne, 1993a). As sea-level rise slowed further the shoreline gradually prograded northwards to its current position.

### 7.2. Subsidence

In addition to this regional sea-level signal, local tectonic effects and subsidence have been important in controlling the spatially heterogeneous evolution of the delta, contributing in the coastal zone specifically to a more extensive transgression (and subsequent progradation) in the east compared to the west. While an east-west trending "hinge-line" has caused high rates of subsidence of Holocene deposits along the coastal margin relative to the area more landward (Stanley and Warne, 1993a), the spatial pattern of subsidence north of this hinge-line is heterogeneous, and is such that lagoonal areas have experienced higher rates of subsidence than the zones in between, with many of the highest rates around the Manzala region in the east (Stanley and Clemente, 2014). These differential patterns in subsidence could be caused by differences in tectonic activity resulting from reactivation of faulted basin structures (Stanley, 1990, 1988; Stanley and Warne, 1997), or lithospheric flexure caused by differences in Holocene

sediment loading, in turn driven by increased autocompaction of lagoonal deposits compared to coarser clastic deposits (Marriner et al., 2012b). Whatever the cause, these patterns of subsidence resulted in a further landward transgression that persisted for longer in the eastern delta compared to the west.

In the fluvial zone, regionally variable subsidence has also occurred: deposits in the west have subsided more than those in the east. This variability does not seem to have been caused by either faulting, subsidence within the Holocene section or the amount of original accommodation space, but may be related to differential autocompaction of Pleistocene or earlier deposits, or longer-wavelength patterns of lithospheric flexure. This heterogeneous pattern of subsidence needs to be considered (for example) when studying the spatial distribution of archaeological sites.

### 7.3. Hydroclimatic changes and sediment-supply

The early and mid-Holocene time periods are also characterised by substantial climatic change and hydroclimatic variability in the Nile Basin. From c.11,000 to 6000 cal BP the region experienced significantly higher precipitation than at present, and the Sahara hosted a savanna ecosystem with permanent lakes (de Menocal et al., 2000; Fleitmann et al., 2003; Gasse, 2000; Kröpelin et al., 2008). The onset of this "African Humid Period" (AHP) was driven by increasing northern hemisphere insolation and concomitant northward movement of the ITCZ in the late Pleistocene; its end was similarly forced by the reverse mechanism during the mid-Holocene (Williams, 2009). Most studies point towards a gradual transition to a more arid climate between c.9000 and 5000 cal BP (Shanahan et al., 2015).

Hydrolological changes associated with these climatic shifts are certainly responsible for aspects of the delta's landscape evolution. As well as being forced by a decrease

in river gradient (section 7.1), the onset of deposition of the Bilqas Formation is also probably related to the onset of the AHP. Increased vegetation and reduced erosion in the Nile catchment likely resulted in the river changing from being dominated by sandy bedload to a silty suspended load, which was deposited across the Nile floodplain (Adamson et al., 1980; Said, 1993).

The subsequent termination of the AHP then contributed to the mid-Holocene landscape changes explored within this paper. The Bilqas 2 to Bilqas 1 transition could have in part also been driven by hydroclimatic shifts. Decreasing rates of sediment-supply probably played a role in forcing the Bilqas 2 – Bilqas 1 transition, through the same mechanism of stimulating lower in-channel aggradation rates. These decreasing sedimentation rates between 7700 and 1200 cal BP are clear from a variety of onshore and offshore records, and have been linked to a decrease in monsoon intensity over the Ethiopian highlands (Blanchet et al., 2014; Marriner et al., 2012a; Marriner et al., 2013; Revel et al., 2015 – although see Krom et al. (2002) for a different view). Decreased discharge could also have played a role in the transition from an anastomosing to a single-channel regime, by analogy with similar changes further upstream (Macklin et al., 2015, 2013; Woodward et al., 2001).

In the coastal zone specifically, a change from a freshwater to a marine system in the Mareotis lagoon around 6750 cal BP (Flaux et al., 2011) has been explained as a consequence of the ending of the AHP, resulting from either a shift in the hydrological budget of the area as a result of reduced Nile discharge (Flaux et al., 2013), or marine influx as a result of the erosion of protective beach-barrier systems due to a reduction in sediment-supply (Marriner et al., 2013).

Overall, it is clear that a variety of hydroclimatic factors contributed to bulk geomorphological change across the delta during the mid-Holocene. These forcing factors are not always easy to disentangle from the primary driver of decreased rates of sea-level rise.

### 7.4. Human impact

Human influences have played a role in the landscape development of the delta plain, but in general probably not to a major extent within the time periods considered within this synthesis. It is only since c.3000–2000 cal BP that variability in the effectiveness of irrigation and canalisation strategies have been shown to have demonstrably had a major impact on the biosedimentary and hydrological budget of the Mareotis lagoon, masking more "natural" changes (Flaux et al., 2012). Pollen records have also shown a much greater human impact on the local environment only over the last 3000 years (Stanley and Bernhardt, 2010). The history of human influences on the delta landscapes over these later periods have been reviewed elsewhere (Cooper, 2014). Most recently, of course, the delta has become intensively farmed, and the reduction in sediment supply caused by the building of the Aswan

High Dam has resulted in fast rates of erosion (Stanley and Warne, 1998), a situation exacerbated further by increased rates of sea-level rise resulting from anthropogenic climate change.

### 8. Conclusions

This paper suggests that the mid-Holocene environmental evolution of the Nile Delta was characterised by the replacement of "Large-Scale Crevassing" environments (dynamic, swampy wetlands with extensive floodbasins and anastomosing channels), by more well drained, less dynamic floodplains hosting single-channel river networks with wide levees. The sediments which record these two different environments are named here as the the Bilqas 2 and Bilqas 1 Members, and sit within an updated stratigraphic framework for the uppermost Nile Delta deposits.

The "Large-Scale Crevassing" environments first existed near the shoreline c.8000 cal BP, before they expanded to cover much of the delta plain for the next two or three millennia. Then, between c.6000–5000 cal BP they were replaced by the later, better-drained floodplain environments. Throughout this time period, topographic highs within the fluvial plain (turtlebacks) also became smaller and less pronounced in their relief, while the contemporaneous development of the coastal zone was marked by the "closing-up" of the shoreline by barrier beaches, subsequent progradation, the development of coastal lagoons and marshes, and the establishment of a clear separation between the marine and fluvial domains. These changes in the landscape were some of the most major environmental shifts taking place in the Nile basin during this time, and were effected primarily by a mid-Holocene decrease in the rate of relative sea-level rise, within the context of weakening Nile discharge due to hydroclimatic changes associated with the ending of the "African Humid Period".

While the landscape models presented in this paper represent the best available synthesis of the Nile Delta's mid-Holocene evolution, they still provide only a general picture of bulk landscape change, at a relatively coarse level of resolution. To move beyond this there is a real need to collect more chronostratigraphic and other data, particularly from the central and southern delta.

However, even as the models stand they are sufficient to begin to be used for site prediction purposes. Archaeological exploration for early sites should focus on the areas of reconstructed turtlebacks, where many Predynastic settlements were founded (Maczyńska, 2011, p. 886). A particular area of note is that around Buto in the north-west delta. Comprising an area of sandy hills but with easy access to large, productive coastal lagoons and wetlands as well as the fluvial floodplain, and having a connection to the sea, this would have been a prime position for early settlement.

The models can also begin to be incorporated into discussions of contemporaneous developments in the human sphere over the longue durée. Relationships exist between

rivers, their environments and channel networks, and societal change (Giosan et al., 2012; Hassan, 1997; Jotheri et al., 2016; Macklin and Lewin, 2015), and social trajectories leading to the emergence of the Ancient Egyptian state c.5050 cal BP need to be considered in light of the environmental evolution presented in this paper. In particular, the delta-wide transformation revealed here between 6000 and 5000 cal BP would have had a significant archaeological impact in relation to agricultural technologies. This time period is one in which the economic basis of (Lower) Egyptian society broadly changed from a mixed strategy involving fishing, hunting, herding and low level agriculture, to a predominantly agrarian mode of subsistence reliant upon floodwater farming of cereals (Hassan, 2010; Tassie, 2014). Such a shift could be interpreted in terms of these changing environments (Pennington et al., in prep.). The dynamic wetland landscapes of the Bilqas 2 Member may not have been so conducive to intensive cereal agriculture, instead affording opportunities centering on the exploitation of aquatic resources (Wilson et al., 2014). The subsequent change to drier floodplains behind levees would have facilitated agricultural expansion and intensification and the move from subsistence activities to the production of a surplus. This could then have funded population growth, leading to the foundations of later social complexity (Castillos, 2011; Hassan, 2010; Kemp, 2006).

Further targeted geoarchaeological and archaeological research at both a local and regional scale within the delta will be able to inform more on specific links between the natural landscape and human culture.

### Supplementary Data

Chronostratigraphic and lithostratigraphic databases for the fluvial zone of the delta Nile Delta, as well as some technical methodological information are provided as supplementary data to this publication.

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Supplementary Information Follows:

| Name | No. of cores | H1 | H2 | H3 | V1 | V2 | V3 | S1 | S2 | S3 | References (see below) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AUSE | 523 | 0 | 131 | 392 | 517 | 6 | 0 | 523 | 0 | 0 | [1] |
| Sais | 276 | 272 | 4 | 0 | 147 | 66 | 63 | 261 | 15 | 0 | [2] |
| SOE | 234 | 0 | 180 | 54 | 230 | 0 | 4 | 71 | 125 | 38 | [3] |
| BRS | 97 | 22 | 73 | 2 | 85 | 5 | 7 | 95 | 2 | 0 | [4] |
| MEDIBA | 87 | 0 | 83 | 4 | 0 | 85 | 2 | 79 | 4 | 4 | [5] |
| WDLP | 63 | 63 | 0 | 0 | 0 | 63 | 0 | 63 | 0 | 0 | [6] |
| Kom Geif | 61 | 61 | 0 | 0 | 61 | 0 | 0 | 61 | 0 | 0 | [7] |
| WDRS | 44 | 44 | 0 | 0 | 32 | 0 | 12 | 44 | 0 | 0 | [8] |
| Isolated municipal & other | 55 | 0 | 15 | 40 | 29 | 0 | 26 | 53 | 2 | 0 | [9] |
| MAS | 40 | 38 | 2 | 0 | 0 | 0 | 40 | 37 | 3 | 0 | [10] |
| Kom el-Hisn | 27 | 0 | 26 | 1 | 27 | 0 | 0 | 27 | 0 | 0 | [11] |
| KA/KW | 26 | 26 | 0 | 0 | 0 | 26 | 0 | 26 | 0 | 0 | [12] |
| Tell Mutubis | 25 | 25 | 0 | 0 | 0 | 24 | 1 | 25 | 0 | 0 | [13] |
| Tell el-Dabᶜa | 24 | 0 | 24 | 0 | 12 | 0 | 12 | 24 | 0 | 0 | [14] |
| MUWDS | 17 | 10 | 7 | 0 | 15 | 0 | 2 | 17 | 0 | 0 | [15] |
| MAO | 15 | 9 | 6 | 0 | 15 | 0 | 0 | 15 | 0 | 0 | [16] |
| Kom Firin | 11 | 11 | 0 | 0 | 11 | 0 | 0 | 11 | 0 | 0 | [17] |

[1] de Wit, (1993); de Wit and van Stralen, (1988b, 1988a); Sewuster and van Wesemael, (1987); van Wesemael and Dirksz, (1986)

[2] El-Shahat et al. (2005); Wilson (2006b,a); Wilson et al. (2014); unpublished cores (Wilson)

[3] Attia (1954); Fourtau (1915); Judd (1897, 1885)

[4] Andres and Wunderlich, 1986; Hartung, 2008; Schiestl, 2012, 2010; Schiestl and Ginau, 2015; Schiestl et al., 2014; von der Way, 1997, p. 42; Wunderlich, 1993, 1989, 1988; Wunderlich and Andres, 1991; Wunderlich et al., 1989

[5] Stanley et al. (1996); Coutellier and Stanley (1987); Arbouille and Stanley (1991); Chen et al. (1992); Stanley et al. (1992)

[6] Trampier (2014); Trampier et al. (2013)

[7] Coulson (1996); Leonard (1997); Pennington and Thomas (2016); Villas (1996); unpublished cores (Pennington)

[8] Wilson (2007); Wilson and Grigoropoulos (2009); unpublished cores (Wilson)

[9] El-Awady (2009); El-Mahmoudi and Gabr (2009); El-Mahmoudi et al. (2005); El-Shahat et al. (2005, 1999); Hamroush (1987); RIGW (1985); Said (1981); Zalat (1995)

[10] Rowland (2007); Rowland and Hamdan (2012); Rowland et al. (2009); unpublished cores (Rowland)

[11] Buck (1990); Hamroush (1987); Kirby et al. (1998); Wenke et al. (1988)

[12] Unpublished cores (Pennington)

[13] Unpublished cores (Pennington; Wilson)

[14] Bietak (1975); Dorner (1999, 1994); El-Beialy et al. (2001); Tronchère et al. (2012, 2009)

[15] El-Awady (2009)

[16] Andres and Wunderlich (1992, 1991); Krzyzaniak, (1993, 1992)

[17] Hughes (2008); Spencer (2007)

TABLE 1: Continued from previous page

| Survey | No. of cores | H1 | H2 | H3 | V1 | V2 | V3 | S1 | S2 | S3 | References (see below) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tell el-Iswid S | 6 | 6 | 0 | 0 | 6 | 0 | 0 | 6 | 0 | 0 | [18] |
| KK/TS | 4 | 4 | 0 | 0 | 3 | 0 | 1 | 4 | 0 | 0 | [19] |
| KHD | 3 | 0 | 3 | 0 | 0 | 0 | 3 | 3 | 0 | 0 | [20] |
| Tell el-Farkha | 2 | 2 | 0 | 0 | 2 | 0 | 0 | 2 | 0 | 0 | [21] |

For each core, the potential error in each of the three data elements (horizontal position; vertical elevation; stratigraphic assignment) was estimated on a 1–3 scale. For the error in horizontal position, a value of "1" (low) indicated a potential error of <5m; a value of "2" (medium) corresponded to a potential error of 5–250m; a value of "3" (high) indicated an error of 250m–2.5km (usually 250–500m). For the error in vertical elevation, a value of "1" indicated a potential error of ±0.15m; a value of "2" corresponded to a potential error of ±0.5m; a value of "3" indicated an error greater than this. The error in stratigraphic assignment was estimated qualitatively.

In some cases, particular surveys have also undertaken many more boreholes than were input. In the majority of cases, the extra boreholes were not included simply because the data has not yet been published. In other cases, where a large number of boreholes have been undertaken in a very small area (sometimes primarily to inform on the depth to archaeological deposits as opposed to geological investigation), only those boreholes useful for informing on the Holocene geological history of the delta were included.

[18] Tristant et al. (2011)
[19] Tristant (2006); Tristant and De Dapper (2009); Tristant et al. (2008, 2007)
[20] Hamdan (2003)
[21] Pawlikowski (2006); Pawlikowski and Wasilewski (2012)

Table 2: Stratified dates from the fluvial zone of the Nile Delta. All radiocarbon dates have been recalibrated according to IntCal13 (Reimer et al., 2013). "Bilqas 1 / Bilqas 2" indicates the contact between the units; Bilqas 1/2 indicates undivided deposits. A small number of dates within this table were excluded from being used to represent an aggradation history for the Nile Delta floodplain as it was thought they did not provide representative fluvial floodplain aggradation rates, if for example they were not located within stratified floodplain facies of the Bilqas Formation or were from very organic-rich sedimentary deposits which data suggest have undergone substantial compaction. These are marked with a "*".

| Core | Zone | Location | Depth (m) | Type | $^{14}$C BP | cal BP | Unit | Reference |
|---|---|---|---|---|---|---|---|---|
| S4 | NC | 31.515E, 31.2283N | 0.95 – 1.45 | $^{14}$C | 2990 ± 90 | 3382 – 2924 | Bilqas 1 | Stanley et al. (1996) |
| S4 | NC | 31.515E, 31.2283N | 2.45 – 2.95 | $^{14}$C | 2150 ± 100 | 2348 – 1901 | Bilqas 1 | Stanley et al. (1996) |
| S4 | NC | 31.515E, 31.2283N | 5.25 – 5.75 | $^{14}$C | 4080 ± 130 | 4872 – 4159 | Bilqas 1 | Stanley et al. (1996) |
| S4 | NC | 31.515E, 31.2283N | 7.75 – 8.25 | $^{14}$C | 5330 ± 120 | 6396 – 5772 | Bilqas 2 | Stanley et al. (1996) |
| S4 | NC | 31.515E, 31.2283N | 9.85 – 10.35 | $^{14}$C | 5510 ± 150 | 6637 – 5946 | Bilqas 2 | Stanley et al. (1996) |
| S4 | NC | 31.515E, 31.2283N | 11.95 – 12.45 | $^{14}$C | 6880 ± 100 | 7931 – 7575 | Bilqas 2 | Stanley et al. (1996) |
| S4 | NC | 31.515E, 31.2283N | 13.75 – 14.25 | $^{14}$C | 7020 ± 120 | 8148 – 7612 | Bilqas 2 | Stanley et al. (1996) |
| S32 | NC | 31.4083E, 31.28N | 7.25 – 7.75 | $^{14}$C | 5880 ± 170 | 7158 – 6323 | Bilqas 1 / Bilqas 2 | Stanley et al. (1996) |
| S32 | NC | 31.4083E, 31.28N | 11.65 – 12.15 | $^{14}$C | 7100 ± 130 | 8177 – 7677 | Bilqas 2 | Stanley et al. (1996) |
| S37 | NC | 31.28E, 31.37N | 4.35 – 4.85 | $^{14}$C | 3260 ± 80 | 3692 – 3272 | Bilqas 1 | Stanley et al. (1996) |
| S37 | NC | 31.28E, 31.37N | 12.55 – 13.05 | $^{14}$C | 6870 ± 170 | 8009 – 7435 | Bilqas 2 | Stanley et al. (1996) |
| S38 | NC | 31.1733E, 31.4217N | 12.55 – 13.05 | $^{14}$C | 7240 ± 90 | 8302 – 7870 | Bilqas 2 | Stanley et al. (1996) |
| S38 | NC | 31.1733E, 31.4217N | 13.45 – 13.95 | $^{14}$C | 7210 ± 130 | 8330 – 7789 | Bilqas 2 | Stanley et al. (1996) |
| S39 | NC | 31.0733E, 31.42N | 1.85 – 2.35 | $^{14}$C | 3840 ± 100 | 4521 – 3972 | Bilqas 1/2 | Stanley et al. (1996) |
| S39 | NC | 31.0733E, 31.42N | 2.75 – 3.25 | $^{14}$C | 4540 ± 290 | 5904 – 4440 | Bilqas 1/2 | Stanley et al. (1996) |
| S44* | NC | 30.9917E, 31.4367N | 0.55 – 1.05 | $^{14}$C | 2570 ± 70 | 2840 – 2379 | Bilqas 1 | Stanley et al. (1996) |
| S44* | NC | 30.9917E, 31.4367N | 2.75 – 3.25 | $^{14}$C | 4870 ± 80 | 5877 – 5330 | Bilqas 1 | Stanley et al. (1996) |
| S44* | NC | 30.9917E, 31.4367N | 3.85 – 4.35 | $^{14}$C | 3980 ± 80 | 4807 – 4159 | Bilqas 1 / Bilqas 2 | Stanley et al. (1996) |
| S44* | NC | 30.9917E, 31.4367N | 4.95 – 5.45 | $^{14}$C | 4870 ± 80 | 5877 – 5330 | Bilqas 2 | Stanley et al. (1996) |
| S44* | NC | 30.9917E, 31.4367N | 7.35 – 7.85 | $^{14}$C | 3260 ± 90 | 3702 – 3252 | Bilqas 2 | Stanley et al. (1996) |
| S44* | NC | 30.9917E, 31.4367N | 10.25 – 10.75 | $^{14}$C | 6370 ± 180 | 7590 – 6857 | Bilqas 2 | Stanley et al. (1996) |
| S44* | NC | 30.9917E, 31.4367N | 1.5 – 2.5 | Pottery | X | 2273 – 1980 | Bilqas 1 | Warne and Stanley (1993) |
| S44* | NC | 30.9917E, 31.4367N | 4 – 5 | Pottery | X | 2614 – 2273 | Bilqas 2 | Warne and Stanley (1993) |
| S44* | NC | 30.9917E, 31.4367N | 9 – 10 | Pottery | X | 3600 – 3500 | Bilqas 2 | Warne and Stanley (1993) |
| S5 | NE | 31.6583E, 31.1933N | 2.05 – 2.55 | $^{14}$C | 1450 ± 80 | 1534 – 1186 | Bilqas 1/2 over Coastal | Stanley et al. (1996) |
| S5 | NE | 31.6583E, 31.1933N | 4.75 – 5.25 | $^{14}$C | 2450 ± 80 | 2730 – 2350 | Bilqas 1/2 over Coastal | Stanley et al. (1996) |
| S6 | NE | 31.71E, 31.1083N | 1.75 – 2.25 | $^{14}$C | 1910 ± 70 | 2033 – 1631 | Bilqas 1/2 over Coastal | Stanley et al. (1996) |
| S6 | NE | 31.71E, 31.1083N | 5.55 – 6.05 | $^{14}$C | 3750 ± 60 | 4349 – 3921 | Bilqas 1/2 over Coastal | Stanley et al. (1996) |
| S7* | NE | 31.8717E, 31.13N | 1.25 – 1.75 | $^{14}$C | 2340 ± 90 | 2707 – 2152 | Bilqas 1/2 over Coastal | Stanley et al. (1996) |
| S7* | NE | 31.8717E, 31.13N | 1.75 – 2.25 | $^{14}$C | 4230 ± 100 | 5044 – 4444 | Bilqas 1/2 over Coastal | Stanley et al. (1996) |
| S7* | NE | 31.8717E, 31.13N | 2.45 – 2.95 | $^{14}$C | 3805 ± 40 | 4404 – 4083 | Bilqas 1/2 over Coastal | Stanley et al. (1996) |
| S7* | NE | 31.8717E, 31.13N | 3.25 – 3.75 | $^{14}$C | 2110 ± 100 | 2332 – 1885 | Bilqas 1/2 over Coastal | Stanley et al. (1996) |

| Core | Zone | Location | Depth (m) | Type | $^{14}$C BP | cal BP | Unit | Reference |
|------|------|----------|-----------|------|-------------|--------|------|-----------|
| S7* | NE | 31.8717E, 31.13N | 4.75 – 5.25 | $^{14}$C | 6300 ± 100 | 7425 – 6979 | Bilqas 1/2 over Coastal | Stanley et al. (1996) |
| S9 | NE | 31.8783E, 30.9783N | 2.55 – 3.05 | $^{14}$C | 3740 ± 150 | 4521 – 3697 | Bilqas 2 | Stanley et al. (1996) |
| S9 | NE | 31.8783E, 30.9783N | 3.85 – 4.35 | $^{14}$C | 5140 ± 80 | 6175 – 5662 | Bilqas 2 | Stanley et al. (1996) |
| S23 | NE | 32.2533E, 30.83N | 1.21 – 1.71 | $^{14}$C | 2490 ± 80 | 2740 – 2363 | Bilqas 1/2 over MG | Stanley et al. (1996) |
| S24 | NE | 32.1717E, 30.8517N | 0.6 – 1.1 | $^{14}$C | 4130 ± 180 | 5276 – 4150 | Bilqas 1/2 over MG | Stanley et al. (1996) |
| S26 | NE | 32.03E, 30.9067N | 1.13 – 1.63 | $^{14}$C | 2500 ± 170 | 2960 – 2148 | Bilqas 1/2 over MG | Stanley et al. (1996) |
| S26 | NE | 32.03E, 30.9067N | 2.16 – 2.66 | $^{14}$C | 2820 ± 120 | 3324 – 2743 | Bilqas 1/2 over MG | Stanley et al. (1996) |
| S26 | NE | 32.03E, 30.9067N | 5.29 – 5.79 | $^{14}$C | 4370 ± 170 | 5465 – 4524 | Bilqas 1/2 over MG | Stanley et al. (1996) |
| S26 | NE | 32.03E, 30.9067N | 5.98 – 6.48 | $^{14}$C | 4210 ± 90 | 4972 – 4446 | Bilqas 1/2 over MG | Stanley et al. (1996) |
| D21 | NE | 32.025E, 30.9019N | 5.5 – 6.5 | $^{14}$C | 5045 ± 125 | 6176 – 5487 | Bilqas 2 | Andres and Wunderlich (1992) |
| D71 | NE | 32.03E, 30.9132N | 6.5 – 7.25 | $^{14}$C | 3975 ± 80 | 4805 – 4158 | Bilqas 2 | Andres and Wunderlich (1992) |
| D5 | NE | 32.0314E, 30.9135N | 8.68 – 9.68 | $^{14}$C | 6900 ± 200 | 8160 – 7431 | Bilqas 2 | Andres and Wunderlich (1991) |
| D4 | NE | 32.0386E, 30.916N | 5 – 6 | $^{14}$C | 4095 ± 30 | 4811 – 4451 | Bilqas 2 | Andres and Wunderlich (1991) |
| D8 | NE | 32.0435E, 30.917N | 4.92 – 5.92 | $^{14}$C | 4870 ± 95 | 5891 – 5327 | Bilqas 2 | Andres and Wunderlich (1991) |
| D22* | NE | 32.0248E, 30.9033N | 3.15 – 3.85 | $^{14}$C | 3175 ± 215 | 3921 – 2854 | Bilqas 1 / Bilqas 2[22] | Andres and Wunderlich (1992) |
| D22* | NE | 32.0248E, 30.9033N | 6.15 – 6.85 | $^{14}$C | 3215 ± 150 | 3836 – 3062 | Bilqas 1 / Bilqas 2[22] | Andres and Wunderlich (1992) |
| D46* | NE | 32.0279E, 30.9125N | 7 – 7.6 | $^{14}$C | 5690 ± 130 | 6791 – 6274 | Geziracover? | Andres and Wunderlich (1992) |
| S54 | NW | 30.7917E, 31.3267N | 4.35 – 4.85 | $^{14}$C | 3080 ± 70 | 3447 – 3077 | Bilqas 1 / Bilqas 2 | Stanley et al. (1996) |
| S55 | NW | 30.6717E, 31.315N | 3.11 – 3.61 | $^{14}$C | 2420 ± 110 | 2752 – 2180 | Bilqas 1 | Stanley et al. (1996) |
| S55 | NW | 30.6717E, 31.315N | 5.32 – 5.82 | $^{14}$C | 3400 ± 100 | 3899 – 3404 | Bilqas 1 / Bilqas 2 | Stanley et al. (1996) |
| S55 | NW | 30.6717E, 31.315N | 6.77 – 7.27 | $^{14}$C | 4170 ± 90 | 4869 – 4437 | Bilqas 2 | Stanley et al. (1996) |
| S66 | NW | 30.452E, 31.266N | 6.75 – 7.25 | $^{14}$C | 4020 ± 100 | 4825 – 4241 | Bilqas 1 | Stanley et al. (1996) |
| S66 | NW | 30.452E, 31.266N | 9.25 – 9.75 | $^{14}$C | 3950 ± 70 | 4780 – 4155 | Bilqas 2 | Stanley et al. (1996) |
| P115 | NW | 30.7281E, 31.3113N | 4.5 – 4.6 | $^{14}$C | 4755 ± 130 | 5844 – 5052 | Bilqas 1/2 | Wunderlich (1989)[23] |
| P115 | NW | 30.7281E, 31.3113N | 5.65 – 5.8 | $^{14}$C | 4755 ± 75 | 5604 – 5317 | Bilqas 2 | Wunderlich (1989) |
| P115 | NW | 30.7281E, 31.3113N | 6.35 – 6.5 | $^{14}$C | 6150 ± 55 | 7235 – 6890 | Bilqas 2 | Wunderlich (1989) |
| P115 | NW | 30.7281E, 31.3113N | 6.65 – 6.7 | $^{14}$C | 6800 ± 200 | 8021 – 7311 | Bilqas 2 | Wunderlich (1989) |
| P87 | NW | 30.7284E, 31.2203N | 7.35 – 7.45 | $^{14}$C | 5970 ± 180 | 6891 – 6310 | Bilqas 2 | Wunderlich (1989) |
| P02* | NW | 30.7305E, 31.2749N | 7.55 – 7.75 | $^{14}$C | 4595 ± 55 | 5467 – 5052 | Bilqas 2 | Wunderlich (1989) |
| P04* | NW | 30.7332E, 31.2749N | 8.7 – 9 | $^{14}$C | 4600 ± 45 | 5306 – 4979 | Bilqas 2 | Wunderlich (1989) |
| P24 | NW | 30.7351E, 31.2734N | 7.3 – 7.55 | $^{14}$C | 4510 ± 90 | 5447 – 4870 | Bilqas 2 | Wunderlich (1989) |
| P24 | NW | 30.7351E, 31.2734N | 8.35 – 8.55 | $^{14}$C | 6140 ± 125 | 6200 – 5610 | Bilqas 2 | Wunderlich (1989) |
| P08* | NW | 30.7259E, 31.2646N | 8 – 8.4 | $^{14}$C | 6135 ± 75 | 7244 – 6800 | Bilqas 2 | Wunderlich (1989) |
| P51* | NW | 30.7033E, 31.2593N | 7.2 – 7.4 | $^{14}$C | 5840 ± 120 | 6954 – 6353 | Bilqas 2 | Wunderlich (1989) |

[22]Two radiocarbon dates come from within channel fill deposits contemporary with the transition from Bilqas 2 to Bilqas 1.

[23]The small number of dates collected on carbonate nodules in this paper were ignored due to concerns over reservoir effects.

| Core | Zone | Location | Depth (m) | Type | $^{14}$C BP | cal BP | Unit | Reference |
|---|---|---|---|---|---|---|---|---|
| P52 | NW | 30.69E, 31.2484N | 6.95 – 7.15 | $^{14}$C | 5720 ± 135 | 6851 – 6278 | Bilqas 2 | Wunderlich (1989) |
| P18 | NW | 30.7225E, 31.2452N | 6.75 – 7.2 | $^{14}$C | 5870 ± 70 | 6877 – 6497 | Bilqas 2 | Wunderlich (1989) |
| P12 | NW | 30.7457E, 31.2492N | 6.3 – 6.9 | $^{14}$C | 6810 ± 140 | 6945 – 6310 | Bilqas 2 | Wunderlich (1989) |
| P13 | NW | 30.724E, 31.2343N | 6.95 – 7.25 | $^{14}$C | 5610 ± 45 | 6477 – 6303 | Bilqas 2 | Wunderlich (1989) |
| P27 | NW | 30.7526E, 31.2267N | 6.7 – 6.85 | $^{14}$C | 5700 ± 175 | 6952 – 6031 | Bilqas 2 | Wunderlich (1989) |
| P39 | NW | 30.7747E, 31.2218N | 6.9 – 7 | $^{14}$C | 5930 ± 120 | 7155 – 6469 | Bilqas 2 | Wunderlich (1989) |
| P37 | NW | 30.7971E, 31.2212N | 4.15 – 4.55 | $^{14}$C | 2765 ± 80 | 1824 – 1548 | Bilqas 1 | Wunderlich (1989) |
| P37 | NW | 30.7971E, 31.2212N | 5.15 – 5.25 | $^{14}$C | 4490 ± 150 | 5582 – 4826 | Bilqas 2 | Wunderlich (1989) |
| P35 | NW | 30.7988E, 31.2128N | 4.8 – 5.15 | $^{14}$C | 4540 ± 150 | 5582 – 4854 | Bilqas 1 | Wunderlich (1989) |
| P34 | NW | 30.8302E, 31.2203N | 5.85 – 6 | $^{14}$C | 4250 ± 185 | 5437 – 4295 | Bilqas 2 | Wunderlich (1989) |
| P121 | NW | 30.7103E, 31.1725N | 2.45 – 3.85 | Pottery | X | 5750 – 5150 | Bilqas 1 | Wunderlich (1993) |
| KA/KW | NW | 30.4465E, 31.1617N | 3.5 – 3.9 | Pottery | X | 2550 – 1980 | Bilqas 1 | Pennington (unpublished)[24] |
| Tell Mutubis | NW | 30.5478E, 31.2831N | 2 – 2.5 | Pottery | X | 1980 – 1250 | Bilqas 1 | Pennington (unpublished)[25] |
| S87 | C | 31.0317E, 30.74N | 0.36 – 0.86 | $^{14}$C | 1720 ± 80 | 1823 – 1414 | Bilqas 1/2 | Stanley et al. (1996) |
| S87 | C | 31.0317E, 30.74N | 8.6 – 9.1 | $^{14}$C | 7030 ± 130 | 8155 – 7615 | Bilqas 1/2 | Stanley et al. (1996) |
| AUSE [26] | E | 31.669E, 30.665N[26] | 3.07 – 3.27 | $^{14}$C | 4079[27] | 4845 – 4297 | Bilqas 1 | de Wit (1993) |
| AUSE[26] | E | 31.669E, 30.665N[26] | 3.07 – 3.27 | $^{14}$C | 4421[27] | 5312 – 4838 | Bilqas 1 | de Wit (1993) |
| AUSE[26] | E | 31.669E, 30.665N[26] | 4.5 – 4.7 | $^{14}$C | 4421[27] | 6279 – 5755 | Bilqas 1 | de Wit (1993) |
| AUSE*[26] | E | 31.669E, 30.665N[26] | ??[28] | $^{14}$C | 4421[27] | 7248 – 6751 | Bilqas 2 | de Wit (1993) |
| AV02AV54* | E | 31.824E, 30.7896N | 3.9 – 4.1 | OSL | X | 8690 – 7030 | Geziracover | Tronchère et al. (2012)[29] |
| AV02AV54* | E | 31.824E, 30.7896N | 4.9 – 5.1 | OSL | X | 13140 – 10940 | Mit Ghamr | Tronchère et al. (2012) |
| AV02AV54* | E | 31.824E, 30.7896N | 6.4 – 6.6 | OSL | X | 16740 – 13540 | Mit Ghamr | Tronchère et al. (2012) |
| TIA | E | 31.83E, 30.8494N | 3.6 – 4.6 | Pottery | X | 5150 – 4950 | Bilqas 1/2 | van den Brink (1992) |
| KHD | E | 31.8483E, 30.528N | 3 – 4 | Pottery | X | 5250 – 4840 | Bilqas 1/2 | Hamdan (2003) |
| S86 | W | 30.7967E, 30.855N | 1.28 – 1.78 | $^{14}$C | 1690 ± 80 | 1811 – 1409 | Bilqas 1 | Stanley et al. (1996) |
| S86 | W | 30.7967E, 30.855N | 7.38 – 7.88 | $^{14}$C | 4910 ± 100 | 5906 – 5334 | Bilqas 1 | Stanley et al. (1996) |
| S86 | W | 30.7967E, 30.855N | 16.53 – 17.03 | $^{14}$C | 6430 ± 110 | 7571 – 7156 | Bilqas 2 | Stanley et al. (1996) |
| Sais | W | 30.7683E, 30.965N | 6.5 – 10 | Pottery | X | 7450 – 5850 | Bilqas 2 | Wilson (2006b)[30] |

[24]Archaeological levels contemporary with early settlement at Kom al-Ahmer persist in the nearby hinterland at 3.5-3.9m below the ground surface.

[25]Archaeological levels contemporary with settlement at Tell Mutubis persist in the nearby hinterland at 2.0-2.5m below the ground surface.

[26]The AUSE radiocarbon dates come variously from cores AUSE1352, AUSE1351, AUSE1440, AUSE1453, AUSE1452.

[27]The AUSE radiocarbon dates were presented by de Wit (1993) as calibrated according to Stuiver and Kra (1986) but with no error estimates; for modern calibrated estimates these were uncalibrated using Oxcal, then recalibrated to IntCal13 with a nominal error introduced of ±100$^{14}$C yr.

[28]No depth was ever given for this date.

[29]Younger dates in this paper were not included as they were from anthropogenically modified contexts.

[30]Neolithic pottery layers were consistently found at these depths.

| Core | Zone | Location | Depth (m) | Type | $^{14}$C BP | cal BP | Unit | Reference |
|---|---|---|---|---|---|---|---|---|
| MUWDS | W | 30.563E, 30.969N | 3 − 4 | Pottery | X | 2250 − 1950 | Bilqas 1/2 | Wilson (2007)[31] |
| Kom Geif | W | 30.595E, 30.9N | 4.9 − 5.6 | Pottery | X | 2600 − 2280 | Bilqas 1 | Pennington (unpublished)[32] |

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[31] Cores Jinbawy-2 and Jinbawy-3 found Ptolemaic pottery around 3m deep; also at Dinshal around 3-4m deep.

[32] Archaeological levels contemporary with Late Period Naukratis persist in the nearby hinterland at 4.9-5.6m below the ground surface.

## DATUM CONVERSIONS:

In order to convert the elevations of cores whose heights were originally presented as referenced to EGM008 or EGM96 into the SOE datum a conversion was applied to each point. The variable geoid heights of EGM2008 and EGM96 over the WGS-84 (NAD-83) ellipsoid were downloaded from NASA (2008; 1998), while a proxy model for the height of the SOE datum over the same ellipsoid (Fig. 1) was created from the EGM2008 geoid model using a conversion derived by Dawod et al. (2010), which adjusted the EGM2008 global geoid model according to equation 1. This "adjusted" geoid model $N^1_{2008}$ performed well in the delta region, with a standard deviation of its residual in the delta area against the "true" geoid (approximated by the SOE datum) that varied by approximately 0.6m.

$$N^1_{2008} = 1.271413252 + 0.897054105 \times EGM2008 \tag{1}$$

## INTERPOLATION OF GEOLOGICAL SURFACES – TECHNICAL DETAILS:

The modelling of geological surfaces was carried out within Rockworks 15, a standard mining industry software package produced by Rockware (2008), using a Kriging algorithm. This Kriging process assumed the semivariogram was gaussian with nugget, used an X–Y–Z node spacing of 664m–664m–0.5m, a spoke spacing of 45°, distance increment of 664m, eight neighbours, a maximum search radius of 8km (the average range of the best-fit semivariograms for the data across the whole delta), as well as high fidelity, densify and decluster tools.

This Kriging process does not use the data to its full extent, in that it necessarily ignores all data from a borehole in the interpolation of a particular unit if that unit is not encountered in the borehole. For example, if a model was run to create the top surface of the Mit Ghamr Formation it would entirely ignore a borehole 8m deep that only penetrated sediments of the Bilqas Formation, even through this borehole contains relevant information, constraining the top of the Mit Ghamr formation at this point to a depth *below* 8m. In order to account for this, second models for each interpolated surface ("Surfaces of Maximum Elevation") were also created by running the same Kriging algorithm but with adjusted borehole data. For this adjusted model, each borehole that did not encounter the Mit Ghamr Formation had its record modified such that the Mit Ghamr Formation was placed with a thickness of 0m at the base of the hole. This produces a a minimum depth (maximum elevation) estimate of the full stratigraphy which would have been encountered had the borehole continued deeper and not terminated within the higher units. Final surfaces were created from a hybrid of the original surface and the surface of maximum elevation: the original surface was used in places where the "Surface of Maximum Elevation" was higher than the original; the "Surface of Maximum Elevation" was used in places where it was lower than the original. This produced a best-estimate maximum elevation model for each surface.

## ABBREVIATIONS WITHIN SUPPLEMENTARY INFORMATION:

AUSE: Amsterdam University Survey Expedition to the Nile Delta
BRS: Buto Regional Survey
KA/KW: Kom al-Ahmer/Kom Wasit
KK/TS: Kom el-Khilgan/Tell es-Samara
KHD: Kafr Hassan Dawood
MAO: Minshat Abu Omar
MAS: Minufiyeh Archaeological Survey
MEDIBA: Mediterranean Basin project of the Smithsonian Institution
MG: Mit Ghamr
MUWDS: Mansoura University Western Delta Survey
SOE: Survey of Egypt
TIA: Tell Ibrahim Awad
WDLP: Western Delta Landscape Project
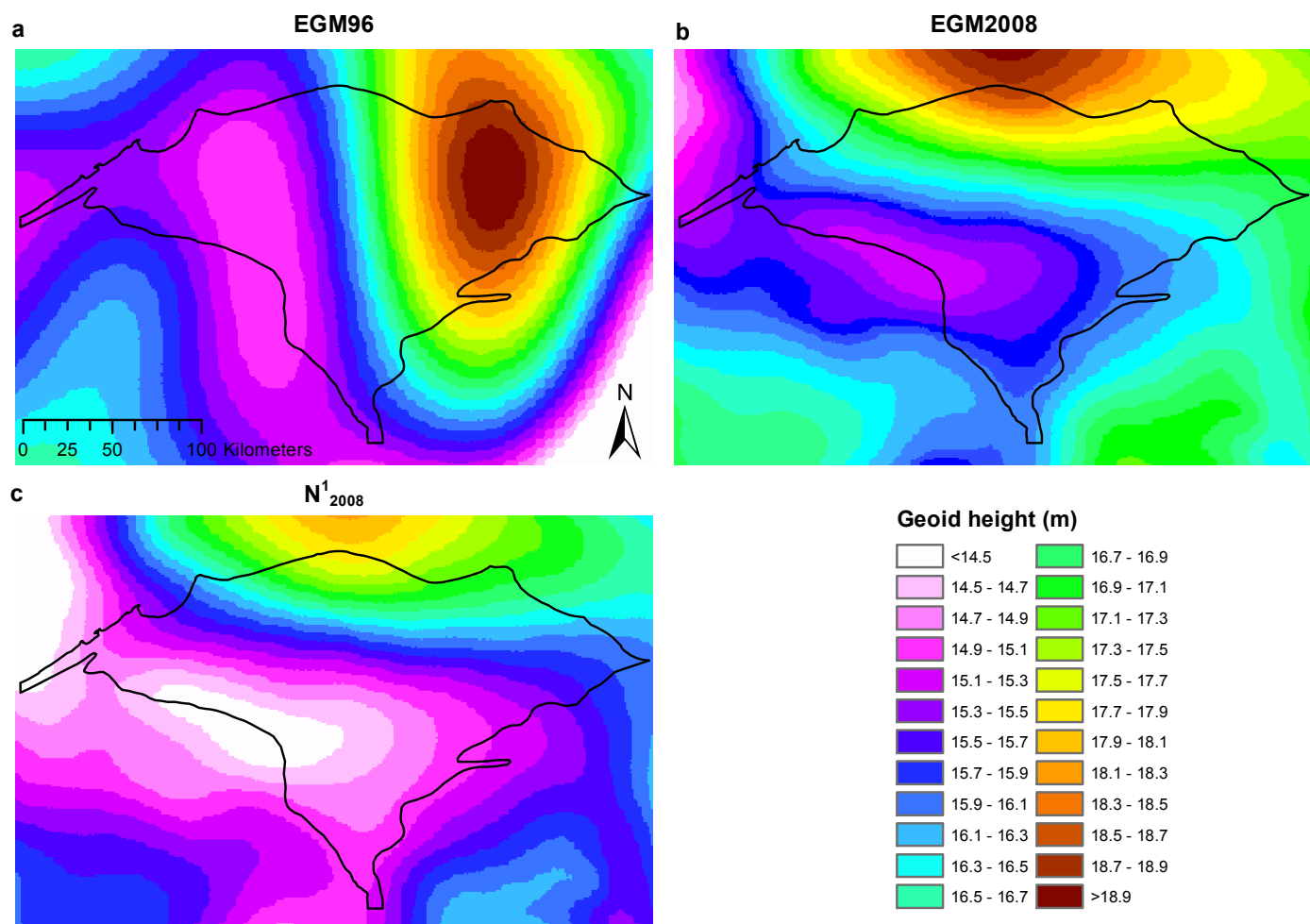WDRS: West Nile Delta Regional Survey

FIGURE 1: Variabilty in geoid models across the Nile Delta, expressed relative to the WGS-84 ellipsoid. a) EGM96; b) EGM2008; c) the proxy Survey of Egypt datum defined by Dawod et al. (2010), and used within the database.