Nile Delta's sinking past: Quantifiable links with Holocene compaction and climate-driven changes in sediment supply?

Nick Marriner[1]*, Clément Flaux[2], Christophe Morhange[2], and David Kaniewski[3]
[1]CNRS, CEREGE UMR 7330, Europôle de l'Arbois, BP 80, 13545 Aix-en-Provence cedex 04, France
[2]Université Aix-Marseille, CEREGE UMR 7330, Europôle de l'Arbois, BP 80, 13545 Aix-en-Provence cedex 04, France
[3]Université Paul Sabatier-Toulouse 3, EcoLab (Laboratoire d'Ecologie Fonctionnelle), Bât 4R1, 118 Route de Narbonne, 31062 Toulouse cedex 9, France

ABSTRACT

The Nile Delta is a subsiding sedimentary basin that hosts ~66% of Egypt's population and 60% of the country's food production. Projected sea-level-rise scenarios for the coming decades have sharpened focus on the delta's potential resilience to rapid changes in accommodation space. We use chronostratigraphic data from 194 organic-rich peat and lagoon points to quantitatively reevaluate the drivers of Nile Delta surface dynamics during the Holocene. Reconstructed subsidence rates range from 0.03 to 4.5 mm/yr, and are highest in the Manzala, Burullus, Idku, and Maryut lagoons, areas that correspond to deep late Pleistocene topography infilled with compressible Holocene strata; 88% of the subsidence values are <2 mm/yr. We suggest that during the Holocene two significant but previously underestimated contributors to changes in Nile Delta mass balance have been sediment compaction and orbitally forced changes in sediment supply. Between 8000 and 4000 calibrated (cal) ^{14}C yr B.P., spatially averaged sedimentation rates were greater than subsidence, meaning that delta aggradation was the dominant geomorphological process at the regional scale. Since ca. 4000 cal yr B.P., a sharp climate-driven fall in Nile sediment supply, coupled with the human-induced drainage of deltaic wetlands, has rendered the depocenter more sensitive to degradation by sea-level rise and extreme flood events.

INTRODUCTION

It is now widely accepted that the world's deltas have been subsiding at a wide range of of temporal and spatial scales (Syvitski et al., 2009), a phenomenon that has been variously attributed to dewatering, compaction, isostatic adjustment, and neotectonics (Törnqvist et al., 2006). Recent natural disasters (e.g., Hurricane Katrina) have underscored how negative land-level changes in coastal areas are a significant environmental problem because they increase the risk of flooding, saltwater intrusion, shoreline retreat, and wetland loss. Within this context, the Nile Delta in Egypt has attracted considerable research interest as the possibility of subsidence and the Intergovernmental Panel on Climate Change (IPCC) projected sea-level rise potentially threaten one of Egypt's most valuable economic resources (63% of national agricultural land; Hereher, 2010) and the future livelihood of more than 50 million people (Becker and Sultan, 2009). It is one of just three deltas assigned to the IPCC "extreme" category of vulnerability hotspots (Nicholls et al., 2007).

Because the Nile Delta has a well-investigated late Quaternary record (Wunderlich, 1989; Stanley and Warne, 1993; Stanley et al., 1996; Flaux et al., 2011; Flaux, 2012), a spatially extensive and robust chronostratigraphic framework is now available to probe millennial-scale changes in its mass balance. Previous research has elucidated geographically variable land-level changes of 0.5–5 mm/yr operating at the Holocene time scale, largely attributed to liquefaction, lithospheric flexure, and neotectonics in an active rift context (Stanley, 1988; Warne and Stanley, 1993; Stanley and Toscano, 2009). Studies of the Mississippi Delta (United States) have highlighted the contributions of compaction (Meckel et al., 2006; Törnqvist et al., 2008) and long-term changes in sediment supply (Kulp, 2000; Blum and Roberts, 2009) as being important drivers of deltaic surface dynamics. Nonetheless, the role of these variables on the Nile Delta is largely equivocal. Given this knowledge gap, we have analyzed a chronostratigraphic database of 194 radiocarbon and archaeological dates from organic-rich peat and lagoon deposits to quantitatively explore the possible role of compaction and millennial-scale sediment supply in driving changes in the delta's Holocene mass balance.

METHODS

From a large chronostratigraphic database of >90 cores studded across the Nile Delta plain, we isolated a subset of 194 radiocarbon dates deriving from organic-rich peat and lagoon deposits (Wunderlich, 1989; Stanley and Warne, 1993; Stanley et al., 1996; Stanley and Toscano, 2009; Flaux et al., 2011; Flaux, 2012; Fig. 1). Because of the large altitudinal uncertainties associated with prodelta muds and sublittoral sand deposits, we omitted these from our analyses. Peat and lagoon deposition is assumed to have occurred near historic mean sea level for each specimen. These delta points have been attitudinally benchmarked relative to present mean sea level using GPS and topographic maps. Radiocarbon determinations were calibrated using Oxcal (Bronk Ramsey, 2000) with the IntCal09 and Marine09 data sets (Reimer et al., 2009).

To probe changes in Holocene delta elevation we obtained age-dependent predictions for the relative sea level of each point using model data from Sivan et al. (2001, 2004). For given points in time, it is assumed that eustatic and glacial hydroisostatic signals have been spatially uniform across the delta. Elevation residuals were calculated as being the difference between the

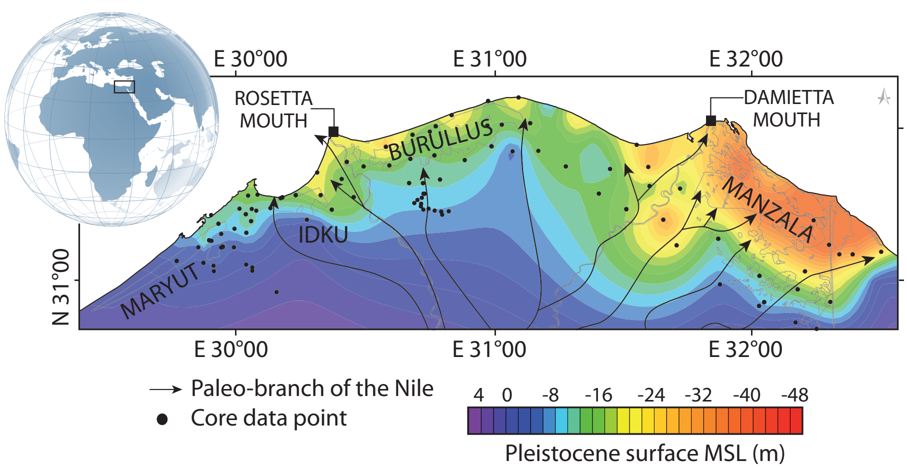

Figure 1. Geography of Nile Delta Pleistocene surface and location of core sites. MSL—mean sea level.

*E-mail: marriner@cerege.fr.

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age of dated peat and lagoon deposits and concomitant modeled relative sea level, yielding 194 residual estimates for the magnitude of subsidence since deposition of the radiocarbon-dated point. We have also considered changes in deltaic surface dynamics to be dependent upon (1) the thickness of sediment overburden, and (2) Holocene changes in sediment supply. Spatially averaged Nile Delta sediment loadings derive from Marriner et al. (2012). Estimates of the delta's Holocene accretionary status were calculated by subtracting spatially averaged sedimentation rates from the sum of Holocene averaged subsidence and modeled sea-level rise (see the GSA Data Repository[1]). Because subsidence values are temporal (Holocene) and spatial averages, we stress that they are conservative (<2 mm/yr). For example, Becker and Sultan (2009) used radar interferometry to reconstruct modern subsidence rates of as much as 8 mm/yr around the Damietta mouth. We used a battery of statistical analyses to probe the strength of correlations, and to compare and contrast these Nile data with other regional proxy records. Data have been represented cartographically to facilitate a detailed understanding of spatial patterns. All isopach maps were produced using Kriging interpolation.

RESULTS AND DISCUSSION

Figure 2A plots the present altitude of radiocarbon points below mean sea level, categorized into archaeological, lagoon, and peat environments. The deposits have present elevations of 1.3–22 m below mean sea level, with corrected ages of deposition spanning 953 ± 188 to 8060 ± 121 calibrated (cal) yr B.P. Despite the scatter in points, the data cloud reveals an upward relative sea-level trend during the past 8000 yr, with a clear plateau since ca. 6000 cal yr B.P., consistent with the stabilization of sea level since that time (Morhange et al., 2001; Sivan et al., 2001). This implies that at no point during the Holocene has sea level risen above present. Because many of the samples come from thick sediment sequences, we suggest that the scatter observed in Figure 2A is partially related to compaction of deltaic sediments. To test this hypothesis, we plotted elevation residuals against the depth of sediment overburden (Fig. 2B). Sediment compaction of the peat and lagoon deposits is corroborated by the statistically significant correlation ($r = 0.68$) using a linear robust multiarray model ($P = 5.14\ 10^{-9}$). The strength of this signal was confirmed by a kernel density (Gaussian function) with a 1000 × 1000 bootstrap and multivariate allometry (95% confidence level;

[1]GSA Data Repository item 2012314, Figures DR1–DR3 and additional methods, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

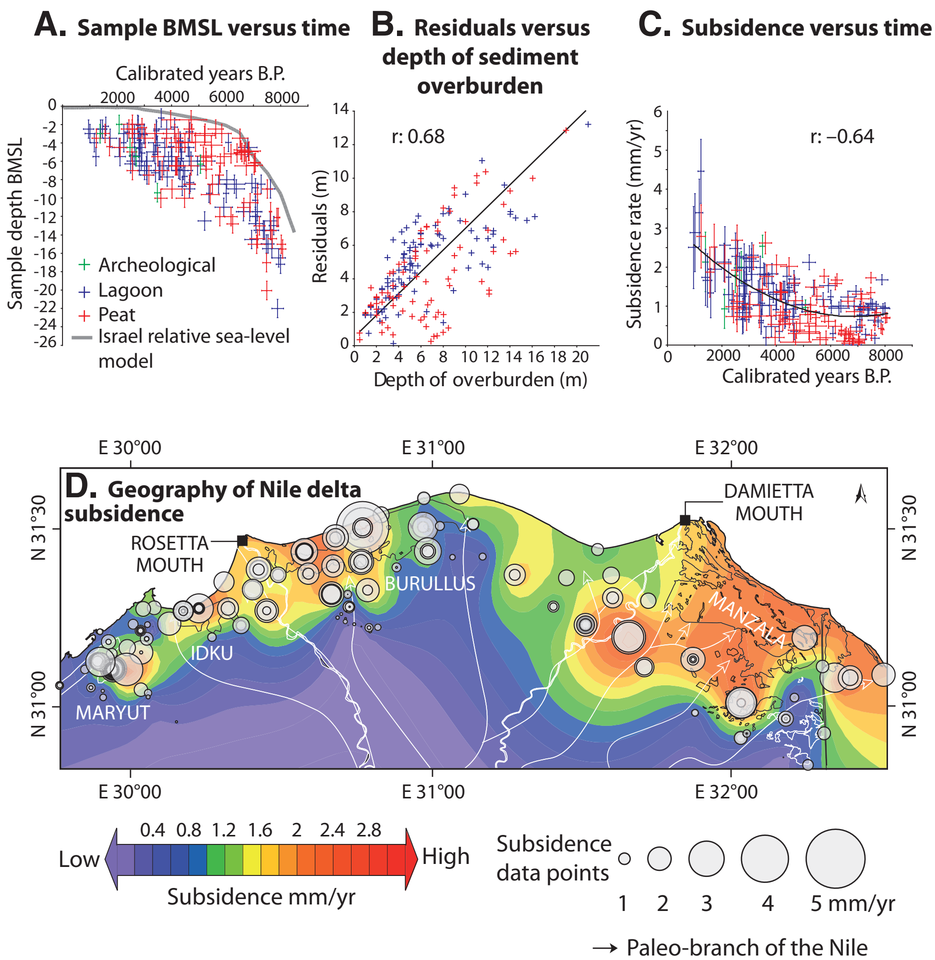

Figure 2. Data plots analyzing Nile Delta subsidence and geography during Holocene. A: Sample depth below mean sea level (BMSL) versus time (dates are ^{14}C). B: Data residuals versus depth of sediment overburden. C: Subsidence versus time (dates are ^{14}C). D: Geography of subsidence rates (in mm/yr).

Figs. DR1 and DR2 in the Data Repository). Residuals vary between 0.11 m and 13.37 m, with considerable local variability. The values reflect mechanical (e.g., rearrangement of the clastic sediment matrix, dewatering) and chemical processes (e.g., oxidation of organic-rich sediments) that are linearly correlated to the depth of the sediment overburden. The scatter can be attributed to disparities in sediment composition, water and organic content, and depositional history. The importance of sediment compaction in base-level depocenters such as deltas and estuaries has been highlighted by a number of studies (Törnqvist et al., 2008; Horton and Shennan, 2009).

Spatially, the subsidence rates are characterized by complex areal patterns, with a range spanning 0.03–4.5 mm/yr (Fig. 2D). The maximum rates occur in the present lagoon areas that show greater subsidence compared to more inland core sites located close to or above the 2 m isopach. This pattern appears to translate (1) flexural depression of the lithosphere brought about by high sediment loading (Blum et al., 2008), and (2) the inherited Pleistocene landscape. Much of the space available for sediment accommodation was created by valley incision during the Last Glacial Maximum (Butzer, 1997), when the Nile Delta comprised a seasonally active alluvial plain with braided stream channels and local wadis (Said, 1993; Stanley and Warne, 1993; Fig. 1). The incised late Pleistocene topography seems broadly consistent with more active consolidation around the deeper areas of the depocenter at Burullus, Manzala, Idku, and Maryut. For example, the late Pleistocene paleotopography of the Manzala lagoon, supplied by sediments from the Tanitic and Mendesian paleobranches of the Nile, has yielded >40-m-thick sections of compressible Holocene deposits that began accreting ~8000 yr ago (Stanley, 1988). By contrast, the coastal fringe between Burullus and Manzala presents lower subsidence rates consonant with the less-compressible nature of the sand ridges that constitute the stratigraphic architecture of this area (Stanley and Warne, 1993). Juxtaposed on this pattern is a dynamic geomorphology of fluvial branch avulsions and diversions, which have varied in space and time during the Holocene.

Our analysis also revealed a negative correlation between subsidence rates and time (r = –0.64). This trend is characterized by rapid compaction of the latest Holocene deposits with progressive decline with increasing age of sediments. Subsidence rates are generally <2 mm/yr in strata that are older than 3000 yr, but are considerably higher (to 3.5–4.5 mm/yr) in deposits <1500 yr old (Fig. 2C); this invites future analysis of compaction decay rates. A priori, the mechanistic explanation for this pattern appears consistent with the rapid compaction of the youngest delta sediments that undergo the most important phase of volume loss during earlier periods following deposition (Becker and Sultan, 2009). This is generally linked to dewatering and oxidation of organic material. These findings are in close agreement with research from the Mississippi Delta; Meckel (2008) showed that radiocarbon-based subsidence rates averaged for the Holocene are similar to numerically modeled compaction. One possible source of error is that longer term rates incorporate a plethora of sedimentation parameters, including hiatuses (Sadler, 1981). This is notably the case of the Maryut, where one of us (Flaux, 2012) described an ~2000 yr sediment hiatus that extends across large tracts of the paleolagoon.

A millennial-scale decrease in Nile flow and sediment supply to the delta area appears to have been significant in accentuating land-level changes (Fig. 3). We have previously reported a gradual long-term decrease in sedimentation rates for the study area, from a maximum of 355 mm/100 yr ca. 7700 cal yr B.P. to a minimum of 138 mm/100 yr ca. 1200 cal yr B.P. (Marriner et al., 2012). Over a 6500 yr period, this represents a 61% reduction in spatially averaged sediment loadings that significantly affected the mass balance of the delta system. These relationships mesh with the idea that the Nile's hydrosystem has responded to a gradual precession-driven shift in the mean boreal position of the Intertropical Convergence Zone (ITCZ) (Gasse, 2000). After 5000 cal yr B.P., a more southern ITCZ (mean summer maximum ~15°N) increased the proportion of subequatorial rains over the White Nile, to the detriment of the Blue Nile and Atabara catchments, both of which generate 97% of the Nile's suspended load (Williams, 2009). Negative elevation changes in the delta surface were emphasized because the newly created accommodation space was not offset by significant floodplain aggradation (Blum et al., 2008; Blum and Roberts, 2009). Furthermore, the regionally attested ebb in Nile flow (Marriner et al., 2012) would have been important in accentuating subsidence through interstitial water loss. This is clearly illustrated in the radiocarbon data for the past 4000 yr that persistently plot ~2 m or more below the rela-

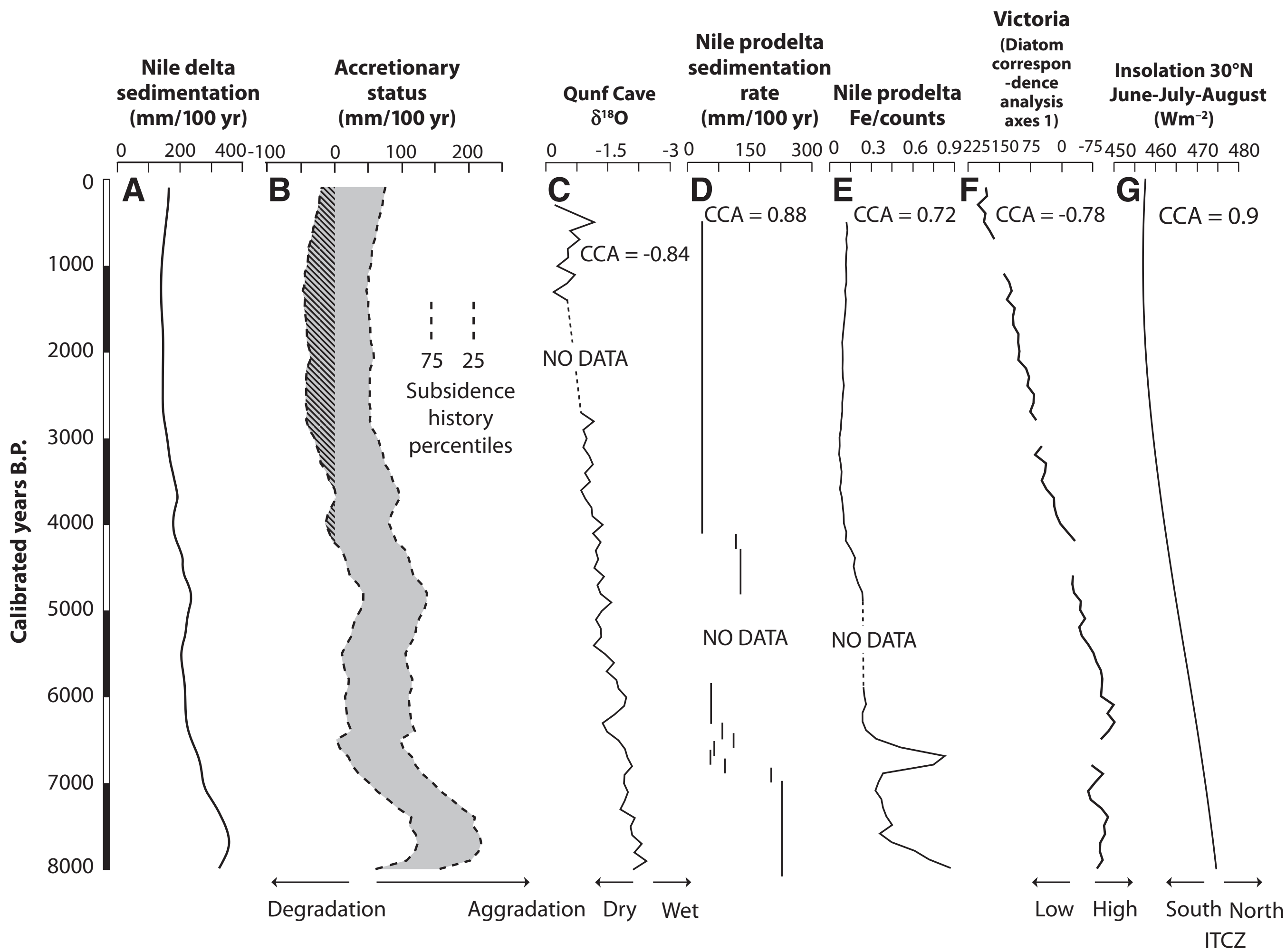

Figure 3. Nile Delta time series versus other climate proxies since 8000 calibrated ^{14}C yr B.P. A: Spatially averaged Nile delta sedimentation (mm/100 yr). B: Accretionary status (mm/100 yr). C: Qunf Cave isotope record (Fleitmann et al., 2003). CCA—cross-correlation analysis. D: Nile prodelta sedimentation rate (mm/100 yr; Revel et al., 2010). E: Nile prodelta Fe counts (Revel et al., 2010). F: Victoria lake-level record (CAST1; Stager et al., 2003). G: June-July-August insolation at 30°N. CCAs are relative to Nile Delta accretionary status (B). Cluster analyses demonstrate that all proxies are strongly correlated, confirming that position of Intertropical Convergence Zone (ITCZ) has been significant in modulating source to sink sediment fluxes in Nile valley (Fig. DR3; see footnote 1).

tive sea-level curve (Fig. 2A). Also, this period corresponds to the widespread canalization and drainage of the delta's wetlands by human societies (Said, 1993), reinforcing volume loss of late Holocene deposits by groundwater lowering and microbial oxidation of organic-rich sediments. We suggest that ancient drainage technologies, in a context of decreasing Nile flow, were significant in accentuating the negative trajectory of the delta's surface dynamics after ca. 4000 cal yr B.P.

CONCLUSIONS

Nile Delta surface dynamics during the Holocene reflect the juxtaposition of several natural and anthropogenic driving mechanisms that act at different depths, times, and spatial scales. The elucidated geochronological framework, subsidence history, sea-level record and climate-change archives show that orbitally forced modifications in sediment supply have been key to driving shifts in the Nile Delta mass balance during the past ~8000 yr. In particular, sharp reductions in sediment supply during the later Holocene, linked to the southward migration of ITCZ rains, have rendered the delta more sensitive to high-magnitude floods and sea-level rise. We suggest that during the past ~4000 yr, human-induced drainage of the Nile's coastal wetlands has further accentuated subsidence. These new data analyzing sediment mass balance of the Nile Delta are important in understanding surface processes, stratigraphy, climate, and sea-level change, and archaeology and Egyptian history.

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