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Nile floods recorded in deep Mediterranean sediments

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Abstract

Clastic mud beds rich in continental organic matter are observed recurrently in the Nile deep-sea turbidite system. They formed during flooding periods of the river similar to those that induce sapropel formation and occurred during periods of increased density stratification of the eastern Mediterranean. The very fine-grained flood deposits are intercalated within pelagic sediments, sapropels and Bouma-type turbidites. These flood deposits form by the successive reconcentrations of surface (hypopycnal) plumes by convective sedimentation, which in turn generate a fine-grained low-energy hyperpycnal flow. Sea-level high stands seem also to favor hypopycnal plume formation and increase clastic mud bed formation. Consequently, these muddy clastic beds provide a direct link between deep-marine sedimentary records and continental climatic change through flood frequency and magnitude.

Keywords: Eastern Mediterranean; Flood-related deposits; Convective sedimentation; Pluvial periods; Sapropels; Nile floods

Introduction

Turbidity currents are gravitational sedimentary processes in which particles are mainly supported by turbulence (Middleton and Hampton, 1973). Turbidity currents include two end-members defined according to flow duration or permanence of sediment supply: turbulent surge and underflow (Lüthi, 1980). Turbidites (deposits resulting from turbidity currents) also show great variability between the classical fining-up Bouma (1962) sequence corresponding to the deposition of a waning depletive flow, i.e. a flow with a decreasing velocity with distance and time (Kneller and Branney, 1995) and the coarsening-up and then fining-up hyperpycnites (Mulder et al., 2002), corresponding to the deposition of a waxing and then waning depletive flow. Turbulent surges usually result from the transformation and differentiation of a sediment failure or of a debris flow. Hyperpycnal flows are in general generated by flooding rivers but also by other mechanisms such as glacial outburst or hypersaline lagoon waters.

Approximately 71% of the world's rivers that directly flow into the ocean are a potential source of hyperpycnal flows (Mulder and Syvitski, 1995). Most of them are small dirty rivers, with average suspended-sediment concentrations >10 kg/m^3 during the year, with a mountainous source according to Milliman and Syvitski's classification (1992), such as the Var River (France) (Mulder et al., 2001). Parsons et al. (2001) showed that the percentage of these rivers responsible for hyperpycnal flows increases to about 84% by taking into account reconcentration processes such as convective sedimentation. In this latter case, hyperpycnal flows result from the sediment reconcentration of a surface (hypopycnal) plume.

The Nile deep-sea turbidite system (NDSTS) is the most important sedimentary accumulation of the eastern Mediterranean. It results from the stacking of terrigeneous sediment of the Nile River over Messinian evaporites. Its present-day morphology and geometry are controlled by gravity spreading of the salt/sediment package, which controls deep-sea sediment dispersal

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by gravity processes. The NDSTS can be subdivided from west to east into four provinces (Fig. 1): (1) the western province, characterized by active turbidite deposition; (2) the central province, characterized by failure scars and fluid-escape structures; (3) the eastern province, with intense salt-related tectonics; and (4) the far eastern province, with important salt-related folding (Loncke, 2002; Mascle et al., 2006).

The eastern Mediterranean water column is composed of three superposed water masses: the Levantine Surface Water (LSW, salinity >39‰; 0–200 m), the Levantine Intermediate Water (39>LIW>38.7‰; 200–600 m) and the Eastern Mediterranean Deep Water (EMDW<38.65‰) (Malanotte-Rizzoli, 2001). Surface current circulation off-shore of the Nile mouth is eastward during winter times and dominated by anticyclonic gyres (among them, the Mersa-Matruh gyre) during summer (Pinardi and Masetti, 2000; Malanotte-Rizzoli, 2001).

Prior to the completion of the Aswan High Dam, the Nile River had a unimodal discharge curve over a year, with summer floods linked to the monsoonal circulation over the Ethiopian highland sources. During summer, the migration of InterTropical Convergence Zone (ITCZ) northward from the equatorial latitude causes heavy rainfall over the headwaters, and especially over the Blue Nile originating in Ethiopian highlands (Gasse, 2000). Several high-magnitude flood periods occurred during the Quaternary and have been correlated with the periodic monsoon intensification, called pluvial periods (Said, 1993; Szabo et al., 1995; Gasse, 2006; Fig. 2), as determined by NE Africa palaeo-lake levels (Szabo et al., 1995; Williams et al., 2000). The last wet period, called the Nabtian Pluvial (Said, 1993), lasted from about 10–12 to 4–6 cal ka BP, depending on latitude (Fig. 2). Said (1993) estimated discharges between 12.5 and 8 cal ka BP from the Nile River were then three to two times larger than modern discharges.

The Nile outflow reduced the salinity of the coastal waters, particularly during floods (Rohling, 1994; Skliris and Lascaratos, 2004), and increased the density stratification of the water column. The presence of low-density water at the surface (from river discharge and/or abundant rainfall) reduced water overturning and generated water-column stagnation. The resultant estuarine circulation brings more nutrients to the surface and increases productivity leading to anoxia in the bottom water and increased accumulation of organic matter in the sediments. This environment has favored the episodic formation of sapropels (organic-rich layers) during the Neogene (Olausson, 1961; Rohling, 1994; Béthoux and Pierre, 1999; Cramp and O'Sullivan, 1999; Jorissen, 1999; Kallel et al., 2000; Struck et al., 2001; Casford et al., 2003; Paterne, 2006; Fig. 2).

In the Nile margin, sedimentation rates are higher during interglacial periods (Marine Isotope Stages 7, 5, 3 and 1), than during glacial periods (MIS 8, 6, 4 and 2) (Ducassou et al., in press). The highest sedimentation rates are measured during sapropel deposition periods (S9 – late Pleistocene to S1 - Holocene) and especially during S7, S5 and S1. These high

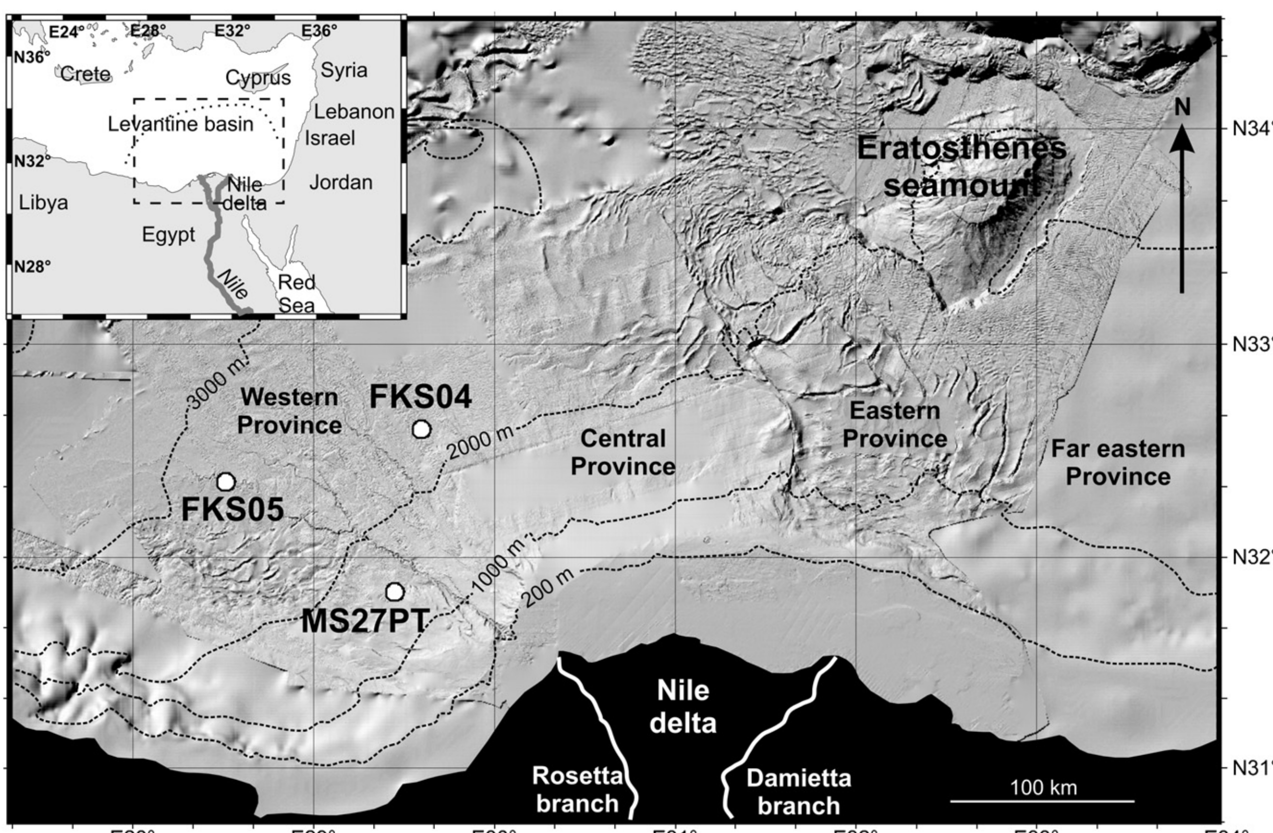

Figure 1. Bathymetric map of the Nile margin with location of cores (white dots) used in this paper. Upper left corner: general map of the eastern Mediterranean showing the studied area (dashed rectangle) off the coast of the Nile delta and the NDSTS limits (dotted line). Bathymetric contours are represented in dashed lines.

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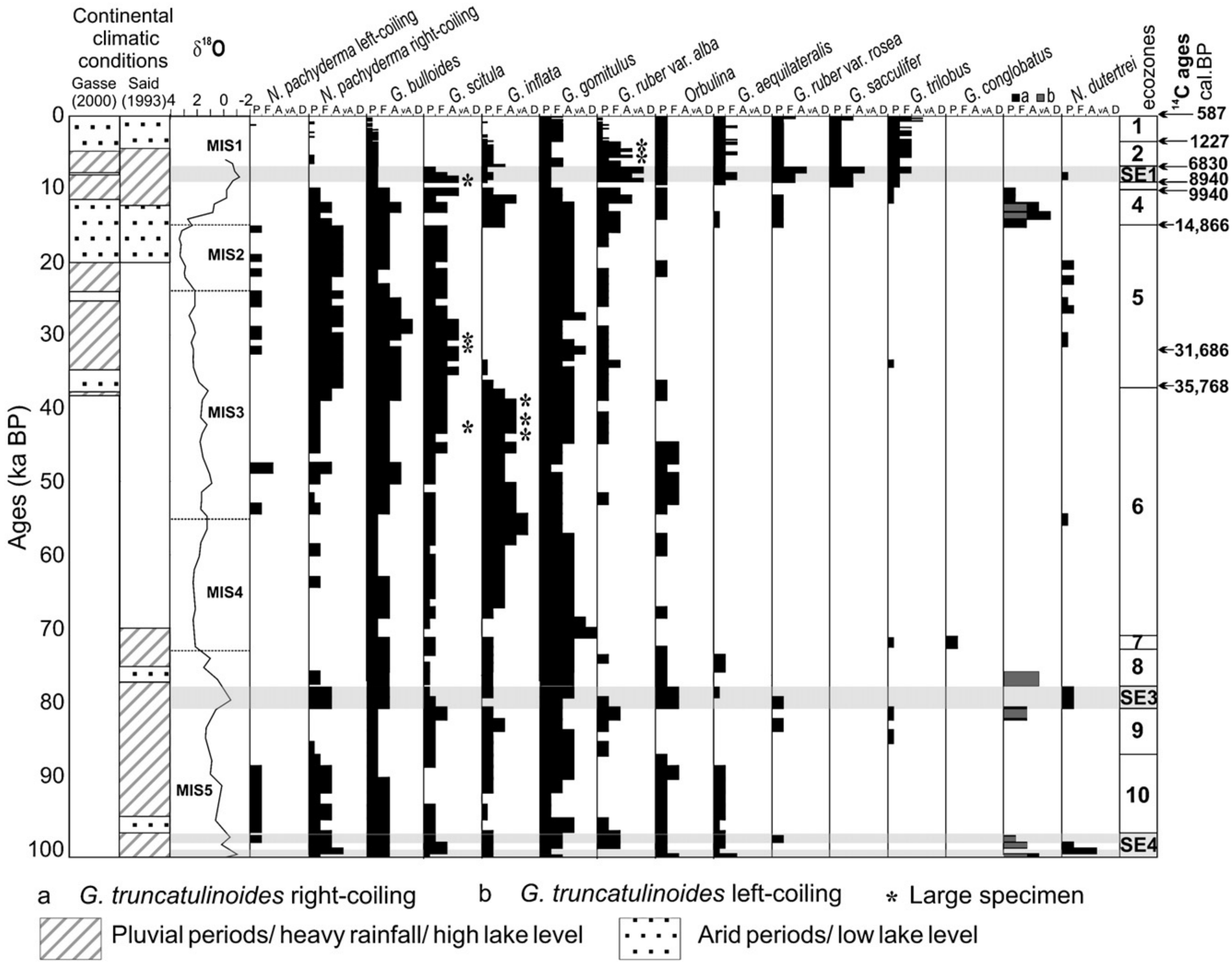

Figure 2. Late Pleistocene–Holocene planktonic foraminiferal ecostratigraphy of the NDSTS area (more details in Ducassou et al., 2007). Ecozone boundaries have been calibrated by ^{14}C AMS radiometric dates and by the stable oxygen isotope record performed on *Globigerinoides ruber* var. *alba* (third column). The two first columns correspond to the climate conditions over the Nile drainage basin after literature citations. Data from Gasse (2000) and Gasse and Street (1978) correspond to Blue Nile source area (Lake Abhé); data from Said (1993), strenghtened with data from Szabo et al. (1995) and Williams et al. (2000) correspond to main Nile and White Nile river records, and deposits from Sudan/Egypt boundary lakes. Pluvial period between ~5 and 12 cal ka BP named Nabtian Pluvial; pluvial period between 70 and 100 ka named Saharian Pluvial. Horizontal shaded stripes show sapropel locations (SE1, 3 and 4: sapropel 1, 3 and 4 ecozones).

accumulation rates are associated with the abundant occurrence of clastic mud beds. In this paper, we focus on specific depositional processes occurring during floods presumed to have resulted from enhanced precipitations witnessed in African palaeoclimatic records. Examples include the S1/ Nabtian Pluvial and beginning of MIS 3 (Gasse and Street, 1978; Servant and Servant-Vildary, 1980; Gaven et al., 1981; Rossignol-Strick, 1985; Said, 1993; Szabo et al., 1995; Johnson, 1996; Rossignol-Strick, 1999; Bar-Matthews et al., 2000; Gasse, 2000; Williams et al., 2000)). We conclude these episodes of anomalous high precipitation are associated with high sediment accumulation rates and clastic mud beds in the Mediterranean deep water zone. Finally we propose a genetic model for the formation of these clastic mud beds.

Materials and methods

Three cores collected in different depositional environments of the western province are used in the present study (Fig. 1). Cores MS27PT (31°47.90′N/29°27.70′E, 1389 m water depth), FKS05 (32°20.37′N/28°29.61′E, 2823 m water depth) and FKS04 (32°34.59′N/29°35.27′E, 2221 m water depth) were collected on an unchannelized upper slope, in a turbidite channel axis and in a sedimentary levee, respectively.

Thin sections were made after induration for sediment observation. Core samples of 30-μm-thick sediment thin sections were dehydrated with a graded series of acetone-water solutions, then impregnated with a solution and desiccated. Image acquisition was made using a digital microscope. Grain-size analyses were done using a Malvern laser granulometer. For reference, d_{90} is 90th percentile diameter on a cumulative weight curve.

The stratigraphic framework was determined using the foraminiferal ecostratigraphy of the NDSTS (Ducassou et al., 2007) constrained in time using the oxygen isotope curve and radiocarbon datings (Fig. 2). All radiocarbon dates were corrected for marine age reservoir difference (400 years) (Siani et al., 2001). The samples presenting conventional AMS ^{14}C ages younger than 21,786 ^{14}C yr BP were calibrated by using CALIB Rev 5.0 program and "global" marine calibration data set (marine 04.14c) (Stuiver and Reimer, 1993; Hughen et al., 2004; Stuiver et al., 2005). Calibrated ages correspond to the median probability of the probability distribution (Telford et al., 2004). ^{14}C radiometric ages older than 21,786 ^{14}C yr BP were calibrated using the polynomial relation of Bard (1998).

The upper part of this stratigraphic scheme is in agreement with the high resolution Holocene biostratigraphy of the eastern Mediterranean (west-southwest of Crete) (Principato et al., 2003). The studied section of core FKS05 was deposited during the Holocene sapropel S1 (between 9 and 6.3 ^{14}C ka BP, Olausson, 1961; Hilgen, 1991; Jorissen et al., 1993; Rohling et al., 1997; and this study) (Table 1 and Fig. 3). The studied section of core MS27PT corresponds to sapropel S1 and early Holocene period (Table 1 and Fig. 4) and the studied sediment interval of core FKS04 was deposited during a period of floods (around 50–60 ka; Rossignol-Strick, 1985) and may correspond to sapropel S2 period observed in the eastern basin (Cita et al., 1977; Muerdter et al., 1984.; Hilgen, 1991; Lourens et al., 1996; Kroon et al., 1998) at the beginning of MIS 3 (Table 1 and Fig. 4). For core FKS05, collected in a channel, the sapropel S1 period is characterized by no bypassing processes, in particular because of the high sea-level stand.

Facies description and interpretation

The clastic mud beds are made of structureless, slightly graded muds dominated by terrigeneous particles (Figs. 3 and 4, facies 4). They consist of clay and fine silt (grain size does not exceed 40 μm) that is dark olive grey to dark grey (Munsell soil color 5Y 3/2 to 5Y 4/1), and these beds contain ligneous fragments and patches of amorphous organic matter. They are almost azoic and without bioturbation. The total carbonate content, mostly composed of reworked Cretaceous nannofossils (Giraudeau, pers.comm.), is less than 1%. The silt fraction includes quartz, biotite, plagioclases, pyroxenes and amphiboles, constituting the typical mineral assemblage from the Nile tributaries (Foucault and Stanley, 1989). These clastic mud beds are unusual because they neither correspond to Bouma (1962) sequences (turbiditic processes) nor to mixture of biogenic and fine terrigeneous particles typical of slow accumulations on the sea floor (hemipelagites).

In some cases, the clastic mud beds are associated with silty laminated beds (Fig. 3, facies 3) showing commonly planar, horizontal or cross stratifications. Their mineralogy is similar to facies 4. They are mostly fine silts (~20–30 μm) and include 2 to 30% clays. Their total carbonate content never exceeds 10%. They also contain large woody fragments and show fining-upward trends, suggesting that they correspond to fine-grained, "base-missing", Bouma-like sequences.

These clastic mud beds are interbedded with two types of pelagic deposits: sapropels (Figs. 3 and 4, facies 2) and classical pelagites (Fig. 4, facies 1). The contact between the clastic mud beds and the other deposits is always sharp but not erosional suggesting that negligible erosion occurred. Sapropels are enriched in red-brown amorphous organic matter. They are organized in discontinuous organic-rich laminae intercalated with pelagic discontinuous laminae. They also contain brown to black continental organic particles (woody fragments) and can be bioturbated at the top. Grain size shows a bimodal distribution with the largest abundance in the clay fraction and a smaller abundance around 200 μm corresponding to planktonic fauna. Their carbonate content ranges up to 30%.

Pelagites are made of beige clay laminae without continental organic matter or ligneous fragments. These deposits, which include nannofossil and foraminifera oozes or marls with sporadic Pteropods, are bioturbated. Grain-size histograms show several modes with a large peak in the clay fraction and a small peak around 100 μm corresponding to planktonic fauna. Their total carbonate content ranges up to 45%.

These foraminiferal-rich pelagic layers are commonly interrupted by clastic mud beds that are also characterized by an abundance (more than 10%) of the species *Neogloboquadrina dutertrei*, which is indicative of low salinity (Table 1). Consequently this taxon is used as a salinity index in the Mediterranean (Ryan, 1972; Cita et al., 1977; Thunell et al., 1977; Vergnaud-Grazzini et al., 1977; Cita et al., 1982). Here, its presence indicates low salinity surface water in the NDSTS during periods of clastic mud deposition due to Nile freshwater plume spreading above salty marine waters (flood season).

A genetic model for the unusual clastic mud beds

The periods of deposition of the clastic muds are synchronous with periods of increased Nile floods. The clastic muds are interbedded either with sapropels that mostly form during flooding periods of the Nile, or with pelagic layers showing evidence of a rapid and large fresh-water input without formation of sapropels. The formation of a fresh-water layer in surface and the resulting increase of water stratification in the eastern Mediterranean suggest that the potential for direct triggering of hyperpycnal flows decreases. The interbedding suggests that mud beds form by along-floor transport and sedimentation. Settling by particle fallout from a hemipelagic plume would induce a complete mixing of sapropelic/pelagic and terrigeneous material. These frequent and high-magnitude floods occurred during pluvial periods. These periods are characterized by a longer duration of the rainfall season and the development of a denser vegetal cover in the Nile source area (Adamson et al., 1980; Williams and Adamson, 1980; Gasse and Van Campo, 1994). The greater cover of erosion-protective vegetation during pluvial episodes, in turn, reduced the relative magnitudes of both mechanical erosion rate in the drainage basin and coarse-particle supply at the river mouth (Williams and Adamson, 1980; Woodward et al., 2001; Krom et al., 2002). This suggests an inverse relationship between water discharge and sediment grain size.

A part of the decrease of coarse clastic-particle supply during pluvial periods is replaced by the increase of both fine-grained particles and organic matter at the river mouth (Williams and Adamson, 1980; Krom et al., 2002). During these periods, the strong Mediterranean water stratification and high densities of surface waters (>1.028 10^3 kg/m^3) prevents the direct formation of hyperpycnal plumes at the Nile River mouth. Consequently, during

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Table 1
Planktonic foraminifer frequency (vA = very abundant (30–40%); A = abundant (15–30%); F = frequent (5–15%); P = present (<5%)) in pelagic samples from cores FKS05, MS27PT and FKS04, and corresponding ecozones from Ducassou et al. (2007)

Core sample	*N. pachyderma* left-coiling	*N. pachyderma* right-coiling	*G. bulloides*	*G. scitula*	*G. inflata*	*G. gomitulus*	*G. ruber* var. *alba*	*Orbulina*	*G. aequilateralis*
FKS05 a			P	P	P	P	A	P	P
FKS05 b			P	P	P	P	A	P	P
FKS05 c			P	F	P	P	A	P	F
MS27PT d			P	P	P	P	A	P	P
MS27PT e			P			P	F		P
FKS04 f			F	F	vA	A			
FKS04 g			F	F	vA	A			

The different core levels studied for ecostratigraphy are indicated by a letter along the X-ray profiles and/or along the core log presented in Figures 3 and 4.

the monsoon-related pluvial periods, high suspended-sediment concentrations generate the formation of large hypopycnal plumes.

The unusual clastic mud beds are enriched in ligneous fragments suggesting a continental source and a direct input from the Nile River. The organic fragments are observed up to 300 km from the river mouth. This, associated with the good preservation of organic matter and the ligneous texture, suggests that the transport process is fast. Rapid sedimentation is suggested by the lack of planktonic fauna and the absence of bioturbation in the associated sedimentation. The frequency of these beds is consistent with a rapid deposition; in core FKS05, more than 40 events are observed during the ~2500 yr of sapropel S1 duration (Fig. 3), in core MS27PT ~800 events are observed during early Holocene (9.94–8.94 cal ka BP; Fig. 4).

The absence of sedimentary structures in the clastic mud beds that are here correlated with Nile floods could be related to the absence of traction at the bed or may result from being too fine-grained to allow formation of dynamic sedimentary structures. The sharp contact between the clastic mud beds and the interbedded pelagic deposits also supports hypothesized short distance transport along the seafloor. Grading of beds from silty laminae to mud suggests that deposition from suspension is the dominant process in the formation of these beds.

The convective sedimentation concept developed by Parsons et al. (2001) represents an appropriate model for explaining fast transfer to the seafloor of the fine-grained sediment supplied by the Nile hypopycnal plumes. This model illustrates how major floods produce flows of warm, fresh and particle-laden water over relatively dense, cold and salty water. In the eastern basin, where present marine waters are as warm as inflowing river waters, Hoyal et al. (1999a) showed that the modest temperature gradient across the boundary between the riverine inflow and the ambient marine water has a minor effect on the sedimentary flux. The surface plumes are subject to a convective instability driven by the combination of a fresh sediment-laden plume with internal particle settling. The experiments of Parsons et al. (2001) and Hoyal et al. (1999b) show that convection occurs at sediment concentrations as low as 1 kg/m^3. It takes the form of millimeter-scale, sediment-laden fingers descending from the base of the surface plume (Fig. 5).

Before the Aswan High Dam construction, the sediment discharge for a summer flood discharge of 9000 m^3/s was 1.6 kg/m^3 (Said, 1993). Said (1993) estimated the discharge during the Nabtian pluvial period to be about two to three times the modern value. Although there are many uncertainties affiliated with quantitative estimates of sediment influxes associated with Nile River floods during prehistoric times, we estimate that between 3 and 5 kg/m^3 occurred during major floods. This estimate is based on the linear relation between discharge and sediment load defined for rivers by Coleman and Wright (1975), Emery and Milliman (1978) and Allen et al. (1979).

The resulting estimates are largely above the threshold value of Parsons et al. (2001) and Hoyal et al. (1999b). If we apply their model to the Nile system, the freshwater hypopycnal plume reconcentrates and forms a mesopycnal flow moving along the LSW/LIW pycnocline. This first mesopycnal flow itself reconcentrates and plunges forming a second mesopycnal flow at the LIW/EMDW pycnocline (Fig. 5). The density stratification of the basin is directly responsible for the spreading and the speed of mesopycnal flows through the water column (Rimoldi et al., 1996). The last convective sedimentation forms a flow that reaches the seafloor (hyperpycnal flow). This is a very low-energy flow, unable to erode the seafloor where it rapidly deposits the observed clastic mud beds that disrupt the pelagic sedimentation or sapropel formation. The low energy and resulting lack of erosional power is due to the small inertia resulting from the fact that the flow did not accelerate on the seafloor of a continental slope and rise, as does a classical turbidity current of a hyperpycnal flow. When sediment input is higher, the convective sedimentation is more intense and reconcentration velocities higher, generating a turbidity surge and the clastic mud beds are replaced by fine "base-missing" turbidites.

In light of information and analyses for the different core locations, two hypotheses are put forward concerning controlling parameters favoring deposition of these clastic mud beds.

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G. ruber var. *rosea*	*G. sacculifer*	*G. trilobus*	*G. conglobatus*	*G. truncatulinoides* right-coiling	*G. truncatulinoides* left-coiling	*N. dutertrei*	Remarks	Ecozones
F	A	F				P	Presence of Pteropods *Limacina*	SE1
F	F	P				P	Presence of Pteropods *Limacina*	SE1
F	F	F				P	Presence of Pteropods *Limacina*	SE1
F	F	P				P	Presence of Pteropods *Limacina*	SE1
P	F	P				P	Presence of Pteropods *Limacina*	3
						P		6
						P		6

The first hypothesis is related to influence of the Nile mouth location on the record of marine sedimentation. Indeed, cores FKS05 and MS27PT both recorded the Nabtian Pluvial period because they are located immediately outward of the Rosetta channel mouth. However the Nabtian Pluvial period is not characterized by clastic mud bed deposition at core FKS04 location, probably because its location was less suitable for receiving hypopycnal plume sedimentation from the Rosetta distributary (Fig. 1). However, core FKS04 recorded clastic mud beds at approximately 55 ka when the core site represented a levee environment on a fan that was active during MIS 4 and 3 (Ducassou et al., in press). Active levee sedimentation at this time suggests that a river mouth probably was located immediately landward and up-fan of core site FKS04 at this time. The absence of clastic mud beds in core MS27PT during, for example MIS 3, suggests that no river mouth then existed upslope of this core location. In core MS27PT, clastic mud beds are thinner for the period represented by Saharian Pluvial than for beds representing the Nabtian Pluvial, and this suggests that the Nile River mouth existed only near the present-day Rosetta channel during the Nabtian Pluvial. This is consistent with a concomitant active deep-sea fan slightly northward of the Rosetta channel mouth (Ducassou et al., in press). These observations inferred from geographical facies distribution support the hypothesized strong link between clastic mud bed extent and palaeoriver mouth location.

A second hypothesis relates the effects of sea-level changes to deposition of clastic mud beds. It is hypothesized that deposition in submarine channelized systems favors hyperpycnal processes during times of low sea level, but involves increased importance of sedimentation by hypopycnal plumes during times of high sea level. High sea levels favor widespread deposition of clastic mud beds across extensive areas of the continental shelf and slope. Note, for example, that three episodes of interstratified mud beds and sapropels in core MS27PT correspond with times of large magnitude floods combined with relative sea-level high stands. The pluvial period between 20 and 35 cal ka BP described by Gasse and Street (1978) and Gasse (2000), especially in Lake Abhé (Blue Nile source area; Fig. 2), is not recorded by clastic mud beds on cores. This possibly is due to the sea-level low stand during MIS 2 and 3. However, Said (1993) did not observe such wet periods along the Nile River during the same time period. Cores FKS05 and MS27PT represent distal and proximal records, respectively, of these flood-related deposits because they are located just seaward of the Rosetta mouth. Very high sediment supply during the early Holocene led to frequent deposition of thin clastic mud beds by unchannelized flows on the upper continental slope (Fig. 4). Turbidite and debrite deposition is restricted in the channel axis (Fig. 3). This can be explained by the connection between fluvial and turbidite systems (Stanley and Warne, 1993; Ducassou et al., in press) favoring bedload transport. During periods where the subaerial and submarine systems are disconnected (e.g., sapropel 1 deposition period) only hypopycnal plumes bring sediment to the deep sea. The facies deposited in proximal locations is the same as the facies deposited during the early Holocene (Fig. 4). On the other hand, more distal sites such as FKS05 record only major floods (wide extent of hypopycnal plumes; Fig. 3).

Sea-level variations are thus important for channelized systems, favoring bedload transport during sea-level low stands and a hypopycnal plume formation during sea-level high stands. Core FKS04 recorded the clastic mud beds at about ~55 ka when turbidity supply on levees temporary stopped (pelagite deposition on levee in Fig. 4). This time period corresponds to the transition between MIS 4 and 3 with a relative low magnitude sea-level rise. This sea-level rise could explain the stop in turbidite activity with a partial and temporary disconnection of fluvial and turbidite systems. Widespread clastic mud beds on the continental shelf and slope are thus preferentially deposited during relative sea-level high stands. During these periods of high stands, the whole continental shelf or at least large parts of the shelf are covered by a surficial water mass (maximum 200 m thick) that rapidly warms and experiences increased evaporation leading to local high salinity values (>39‰). These processes strengthen the stratification of water masses and the density contrast between Nile plumes and salty coastal waters, preventing plume plunging. Sea-level

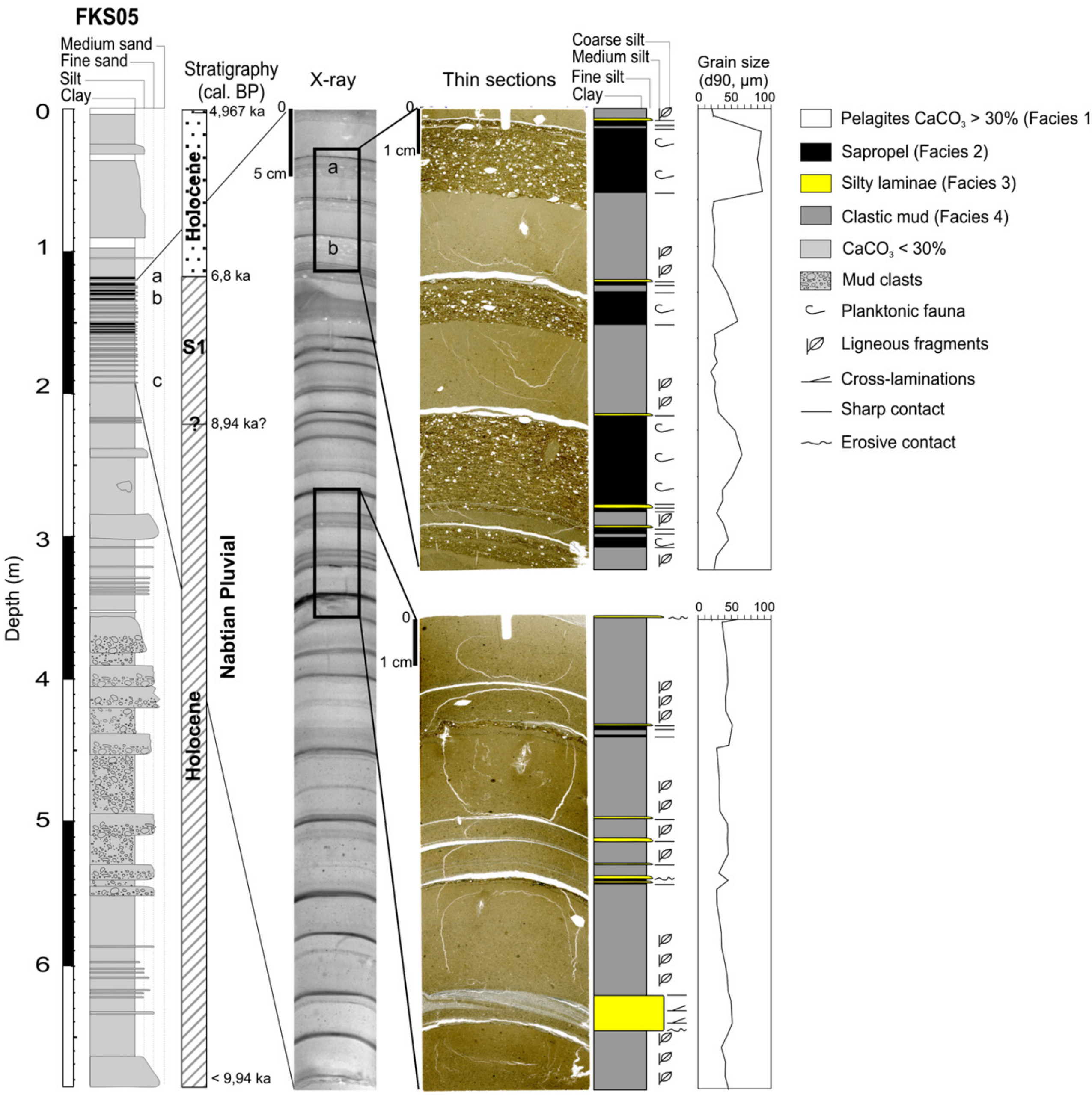

Figure 3. Sedimentary log and stratigraphy of core FKS05. X-ray image, sediment thin section, grain-size and sequence interpretation zooms in clastic mud deposits. Small letters on X-ray images and along the sedimentary log correspond to studied samples for ecostratigraphical dating (a, b and c). The dating results are shown in Table 1.

high stands thus favor hypopycnal plume formation and increased clastic mud bed formation.

Conclusions

In the eastern Mediterranean deep sea, convective sedimentation and clastic mud bed deposition are limited to intensified periods of Nile floods, enhanced water stratification with or without sapropel formation, and sea-level high stands. This mode of deep-marine sedimentation is enhanced by the conjunction of morphologic and the confined basin of the eastern Mediterranean and by the large source of sediment and fresh water from the Nile River. During anomalous wet climate conditions in East Africa, the eastern Mediterranean experiences a strong water stratification that commonly prevents direct hyperpycnal flow formation. The strong stratification of the water column, in turn, favors hypopycnal plumes that contribute to widespread deposition of clastic mud beds on the continental shelf and slope during times of relative high sea levels.

These deposits have a great potential to provide paleoclimate proxy records that link deep-marine sedimentary records from near continental margins to continental climatic changes expressed through long-term variations in flood frequency and magnitude. These unusual clastic mud beds, in the NDSTS, are proxies of Nile palaeofloods and are useful for improved understanding of the Nile River palaeohydrology.

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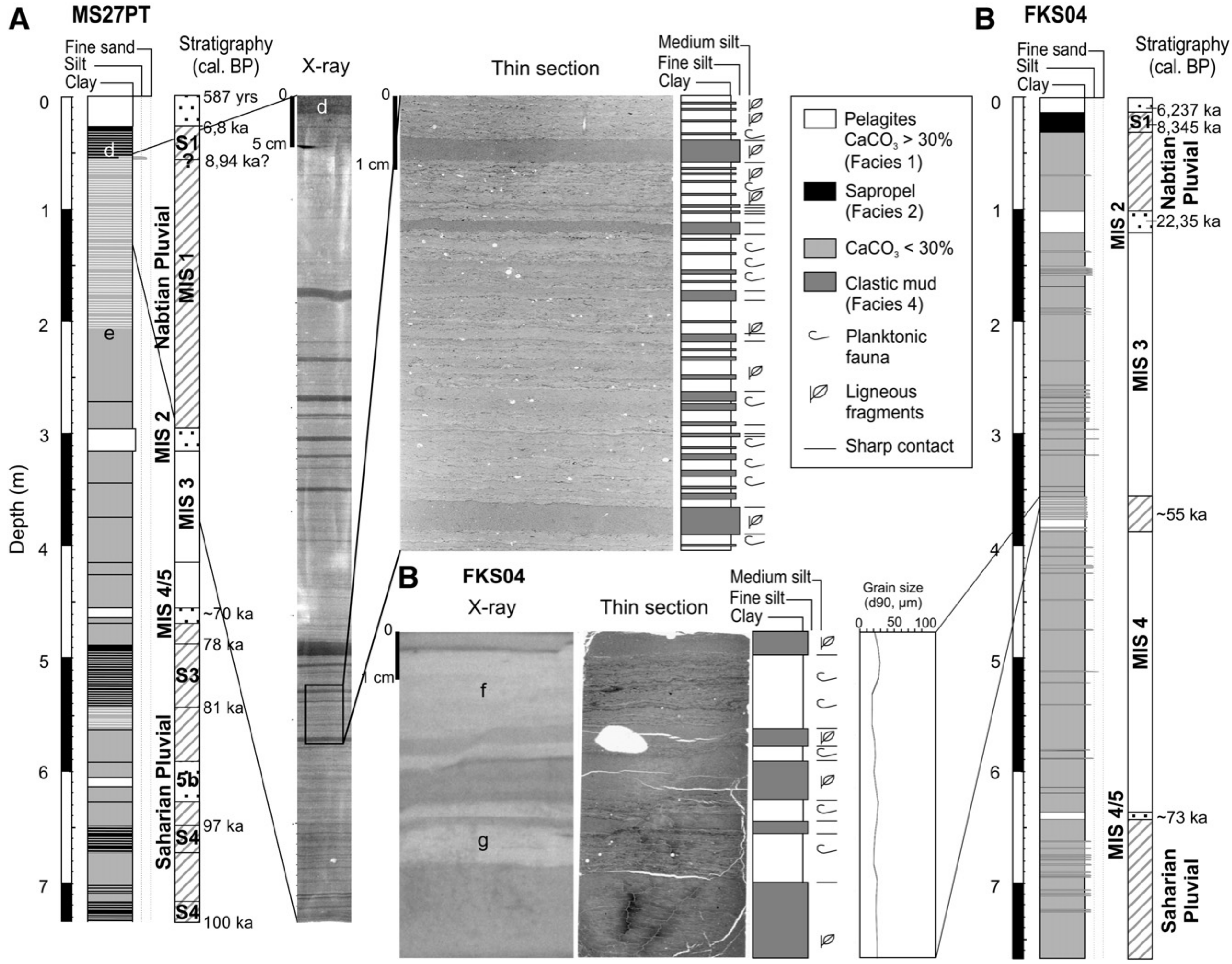

Figure 4. Sedimentary logs and stratigraphies of cores MS27PT (A) and FKS04 (B). X-ray image, sediment thin section, grain-size and sequence interpretation zooms in clastic mud deposits. (A) MS27PT: early Holocene Nabtian Pluvial period; (B) FKS04: period of floods at the beginning of MIS3. Small letters on X-ray images and along the sedimentary log correspond to studied samples for ecostratigraphical dating (d and e in (A), f and g in (B)). The dating results are shown in Table 1.

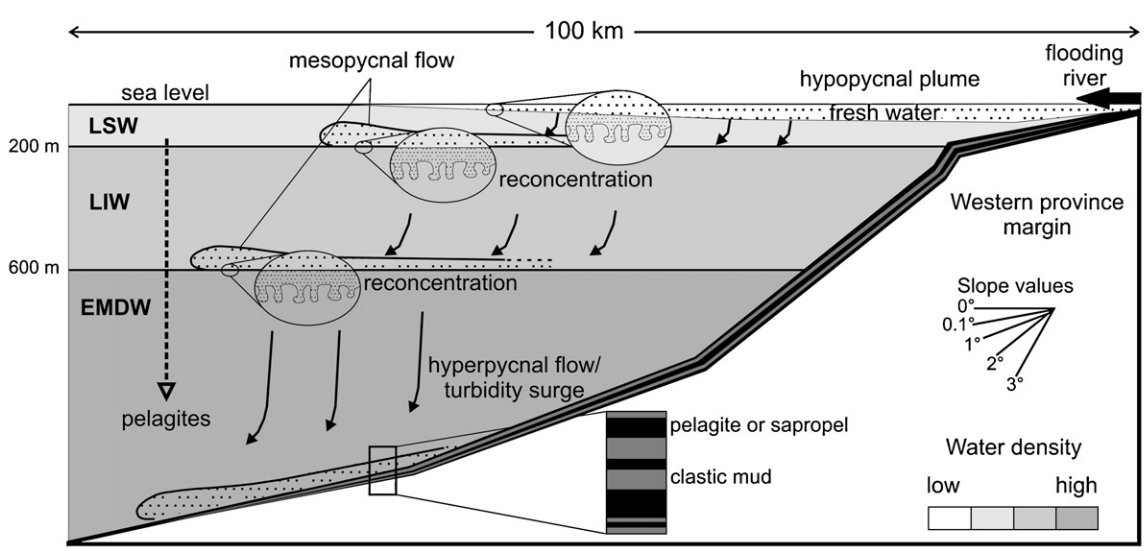

Figure 5. Sedimentation processes occurring seaward of the Nile River mouth during floods. Because of the low particle load of the river, only a hypopycnal plume exists. Convective sedimentation generates mesopycnal plumes moving along the superposed pycnoclines and finally a fine-grained hyperpycnal flow. LSW: Levantine Surface Water; LIW: Levantine Intermediate Water; EMDW: Eastern Mediterranean Deep Water.

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The present study represents one of the first natural observations of sediment reconcentration processes associated with hypopycnal plumes. Prior investigations have emphasized experimental and/or theoretical approaches for understanding this sedimentation process. Present results also demonstrate that hypopycnal plumes and associated convective sedimentation can transport large amounts of terrestrial organic carbon efficiently to the DSTS. These results and observations indicate that the DSTS record of floods and pluvial periods not only provide a basis for assessment of past climate changes, but they also help understand and predict reservoirs and sources of hydrocarbons.

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