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# Palaeogeographical and palaeoenvironmental reconstruction of the Medjerda delta (Tunisia) during the Holocene

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ABSTRACT

The progradation of the Medjerda delta has been the subject of many studies since the 19th century. The scale and the rapidity of this phenomenon interested researchers in various fields early on, such as geomorphology, geology, palaeogeography, history, archaeology, or geoarchaeology. Indeed, the delta prograded by around 10 km over 3 millennia. At the time of its foundation supposedly at the end of the 12th century BC, the Phoenician city of Utica was located on a promontory bathed by the sea, but the sediments carried by the Medjerda progressively sealed the bay, leaving the tip of the Utica promontory now 10 km inland. This area is therefore an exception to the general pattern along the Tunisian coast, since as over the same period everywhere else there is a regression of the coastline, owing to a sea level rise of several decimeters. Based on multi-proxy analyses of two coring transects, this paper aims to reconstruct the palaeoenvironments and the palaeogeography of the Medjerda delta's progradation since the mid-Holocene, some aspects of which are described in ancient sources. The results highlight in particular an episode of high-intensity flooding around the 4th century AD, which is consistent with episodes of high floods and an increase in sedimentation rates recorded in the watershed at the end of the Roman period. The gradual abandonment of the city of Utica can certainly be related to the activity of the Medjerda River, but our results show that it is because of an increase of fluvial sediment contribution in connection with an erosive crisis in the headwaters, and not because of the change of course of the river, which had occurred long before.



## 1. Introduction

Since the 19th century, the progradation of the Medjerda (called *Bagrada* during ancient times) delta and the resulting landscape changes have interested many researchers because of their historical implications for the fate of the city of Utica. Several hypotheses have been advanced regarding the chronology of the progradation of the delta. A first chronological evolution of the infilling of the former Utica gulf (*Sinus Uticensis*) was deduced from ancient texts by Tissot (1884; 1888). Archaeology combined with morphological field observations then allowed Bernard (1911), Reyniers (1951) and Lézine (1956; 1966; 1968; 1970; 1971) to enrich the corpus of data and propose new hypotheses of evolution. Pimienta (1959) and Jauzein (1971) carried out important geological studies of the delta. Based on photo-interpretation and surface prospecting, geo-archaeological research then provided some clarification and

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permitted a partial review of the chronological framework (Chelbi et al., 1995; Oueslati et al., 2006; Paskoff, 1994; 1985; Paskoff and Trousset, 1992; Slim et al., 2004). More recently, Delile et al. (2015a; b) used manual coring inside the ancient city of Utica and GIS analysis to clarify this framework. But so far, no stratigraphic data on the scale of the delta has validated these hypotheses of evolution. For this reason, a coring campaign was organized, oriented along two main transects (Fig. 1). The objective was threefold: (1) to understand the maximum marine transgression of the mid-Holocene, (2) to estimate the rate of deltaic progradation and finally, (3) to make the link between the Medjerda delta and its watershed.

Beyond the regional geomorphological and geographical approach, this work sheds new light on the history of the foundation of the city of Utica and the occupation of its territory. Indeed, the most controversial question concerns the chronology of the passage of the river Medjerda into the “northern compartment”, through the corridor formed by the promontories of Utica and Kalaat El Andalous (Fig. 1). This question is crucial both to our understanding of the reason for the establishment of the Phoenicians in this area, and for the location of Utica’s Phoenician and Roman harbours (Pleuger et al., 2019). This problem is also essential for the understanding of the decline of Utica, because the progradation eventually led to the complete isolation of the port city from the sea.

Given the complexity of the progradation process and the difficulty in combining all factors, this paper presents an interdisciplinary study aimed at understanding the Medjerda delta development during the Holocene.

## 2. Regional setting

### 2.1. Geological context

Tunisia is located in a dynamic tectonic context, at the convergence between the African and Eurasian tectonic plates (Ben Ayed and Oueslati, 1988). The compression movements toward Africa led to the formation of Pliocene folds and inverse faults, including the anticline of Utica (Coque, 1955; Mejri et al., 2010; Pimienta, 1959). Abrupt contact between Pliocene sandstones and Quaternary potsherd-rich silts attests the Late Pleistocene–Holocene activity of the Utica fault, which might be illustrated by the destructive earthquake of AD 408 (Fentress and Wilson, 2019; Mejri, 2012; Mejri et al., 2010; Paskoff et al., 1991). Nevertheless, this catastrophic earthquake episode has been challenged by some researchers (Vogt, 1993, 1992).

The Medjerda is one of the most important rivers in the Maghreb and the only perennial one in Tunisia. It is 460 km long and drains a watershed of the order of 23,700 km$^2$. The Medjerda takes its source in eastern Algeria, follows the chain of the Atlas from SW to the NE, and then flows into the Mediterranean. Along its course, it crosses Tertiary evaporites, marls and dolomite, Oligocene to Lower Miocene sandstones and claystones and Jurassic marbles, with diapirs of Numidian flyschs and Cretaceous marls and limestones (Moldenhauer et al., 2008). Fluvial activity corresponds with Pliocene, Pleistocene and Holocene flood deposits. An average discharge of 30 m$^3$/s is measured at the entrance to the delta with strong seasonal contrasts, from 1 m$^3$/s during dry periods to 80 m$^3$/s during the winter rainy season (Jauzein, 1971; Moldenhauer et al., 2008; Oueslati et al., 2006; Paskoff, 1994). The Medjerda is characterized by a regime of high-intensity

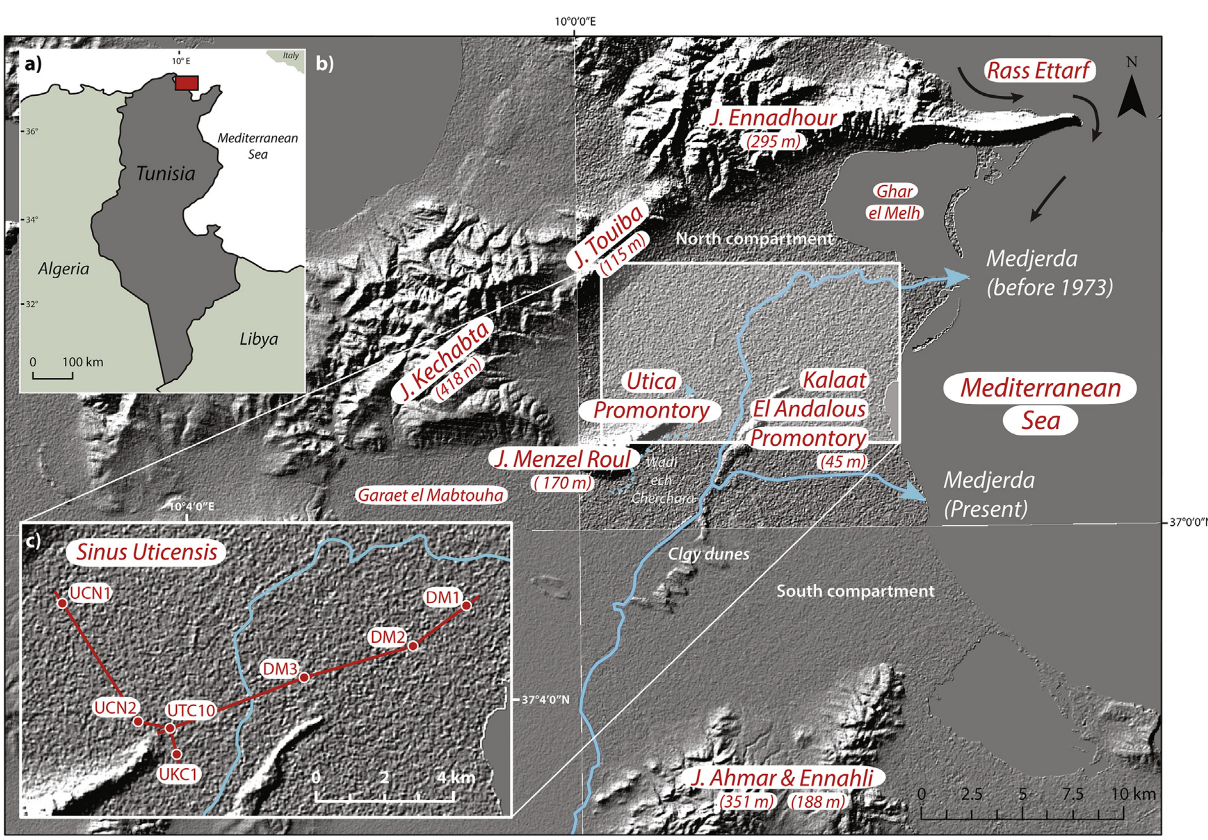


**Fig. 1.** a) General map of Tunisia. b) Map of the Medjerda delta. Hillshade from Jarvis et al. (2008). Black arrows indicate the direction of the dominant swell, deviated by the promontory of Rass Ettarf. c) Detail of map b: Location map of the 7 coring points, following two transects.

progradation capable of generating forms such as alluvial cones (Delile et al., 2015a, 2015b). The high-energy meandering could be explained by the fineness of the deposits and the strong cohesion of the banks (Delile et al., 2015b; Nanson and Croke, 1992; Zielhofer et al., 2008). This model of evolution is close to that of the Mississippi, but with a specific torrential dynamic (Baulig, 1949; Delile et al., 2015a, 2015b).

The deltaic plain of the Medjerda is characterized by Quaternary flood deposits carried by the river. It is bounded on the south and north by anticlinal structures. The northern alignment of folds (Jebels Annadhour and Kechabta) is dominated by Mio-Pliocene sandstones and Pliocene marls. On the south, the petrography is older (Jebels Ahmar and Ennahli), composed essentially of Cretaceous clayey to calcareous formations. This synclinal area is divided in two by the faulted anticlinal ripple of the Jebel Rhoul to the west of Utica and that of the small horst of Kalaat El Andalous, which support the city of Kalaat El Andalous. The latter is made by Pliocene sandstones and clays. Other hills correspond to ancient clay dunes formed during the Upper Quaternary (Oueslati et al., 2006; Paskoff and Trousset, 1992).

The land gained from the sea over the entire Medjerda delta is estimated at 450 $km^2$. For instance, the deposition of a clayey and silty layer of ~10 cm of thickness over 470 $km^2$ was observed during the flood of 1973 (Bomer and Naoui, 1990; Claude et al., 1977; Naoui, 1995). This is an interesting example of the enormous alluvial intake and the resulting aggradation. Since that time, the Medjerda has passed south of the Kalaat El Andalous promontory, using the floodway which was built to manage excess floodings of the river. Today the delta is drained and cultivated, reflecting the adaptation of humans to environmental changes (Paskoff, 1994; Paskoff and Trousset, 1992).

### 2.2. Climate and vegetation

The northeastern Tunisian coast is characterized by a Mediterranean semiarid climate (Csa-type according the Köppen classification system), with a sub-humid nuance since the average annual rainfall is around 500 mm, mainly concentrated over a period spanning between September and April (Oueslati et al., 2006). The topography is rugged and characterized by steep slopes. The high runoff generated by the torrential rains causes strong erosion of the watershed substratum, made up of clays, marls and sandstones (Oueslati, 1995; Paskoff, 1994). In addition, the delta has been affected by the exploitation of its watershed by man over the centuries (Arnould et al., 1979; Brun, 1983; Brun and Rouvillois-Brigol, 1985; Delile et al., 2019; Oueslati, 1995; Paskoff et al., 1991; Paskoff and Oueslati, 1988; Zielhofer, 2006; Zielhofer and Faust, 2003). Subsequently, the anthropic pressure on the landscape is quite important. The combination of all these factors involved changes in the morphology of the coastal landscape, sometimes aggradation, sometimes digging of sebkhas and lagoons. The most frequent winds come from the northwest, but winds from the east, south-east and south can be active in summer and spring (Oueslati et al., 2006).

### 2.3. Coastal morphology

The local reliefs are traversed by a dense network of wadis, adding to the water supply of the Medjerda in the plain. The northwest dominant swell is deflected by the promontory of Rass Ettarf. It arrives weakened from the northeast, controlling the general orientation of the coast and the meandering loops of the river over the centuries. Episodically, a strong swell may come from the southeast. The Medjerda delta has been built from coastal cords delineating lagoons that have been sealed by decantation (Delile et al., 2015b; Oueslati et al., 2006; Paskoff, 1978; Paskoff and Trousset, 1992; Pimienta, 1959).

### 2.4. Sea level

Two phases of evolution of the Tunisian coast were highlighted by Oueslati (1995) and Paskoff and Oueslati (1988). First, an important progradation took place during the Punic/Roman period. On the basis of archaeological markers, Anzidei et al. (2011) situate the Roman sea level (150 ± 50 AD) at 0.58 ± 0.3 m below the local mean sea level (LMSL; Anzidei et al., 2011). Secondly, after the end of the Roman era, a sea level rise is observed, expressed by the advance of the sea at the expense of the shoreline. The increase in sea level and the decrease in alluvial inputs after the Roman period generated salinization of the land and the creation of sebkhas and chotts, except on the wadi side, as here in the Medjerda delta, where progradation continued (Oueslati, 1995). First conclusions linked the post-Roman decrease of the erosive crisis solely with the transition from intensive agriculture to extensive pastoralism (Paskoff et al., 1991), but more recent researchproves that late Holocene fluvial dynamics in Northern Tunisia were mainly driven by climate, intensified or attenuated by anthropogenic impact (Faust et al., 2004; Zielhofer, 2006).

### 2.5. Archaeological context

The deltaic plain of the Medjerda has been occupied throughout the Punic, Roman, and Muslim periods. The human impact on the delta evolution must therefore be taken into account. More than 54 sites around the former gulf of Utica were reported on the maps of Ariana and Porto Farina in the archaeological Atlas of Tunisia (Cagnat and Merlin, 1932), and in the survey reports carried out by Chelbi et al. (1995). The most important of these occupations is the city of Utica, supposedly founded by the Phoenicians in 1101 BC according to the ancient texts, although no archaeological remains have been found earlier than the 9th century BC (López Castro et al., 2016; Monchambert et al., 2013). The city was installed on the eastern end of a promontory, then bathed by the sea. The ruins of the later city cover some 100 ha, suggesting an estimate for the maximum population of the city between 15,000 and 30,000. The city was a port, but we know little of its harbour infrastrucure, and indeed our most recent environmental reconstruction suggests that for much of the Roman period there was a sheltered anchorage on the north side of the city, protected by the prograding delta to the east, rather than a closed or constructed harbour (Delile et al., 2015a; Pleuger et al., 2019).

The promontory of Kalaat El Andalous (ancient *Castra Cornelia*) lies about 4 km east of Utica. *Castra Cornelia* was a military camp established by Scipio during the Second Punic War (218-201 BC) Livy, XXIX, 35, 13-14), and was also used by Curio during the Civil Wars (49 BC) (Caesar, *De Bello Civili* II.24). Caesar describes the places in the 1st century BC as "a straight ridge, projecting into the sea, steep and rough on both sides, but the ascent is gentler on the part that lies opposite Utica" (Caesar, *De Bello Civili* II.24). This place was known as a vast and safe winter anchorage accessible to the largest ships. Utica and *Castra Cornelia* were, according to Caesar, separated from each other by a vast swamp of brackish waters (Caesar, *De Bello Civili* II.24) (Mannert, 1812; Tissot, 1884).

## 3. Material and methods

### 3.1. Coring

The study of palaeoenvironments and sedimentary processes is carried out through the mechanical extraction of cores (15–20 m deep) to reach the early Holocene levels. The drilling holes were protected by casing to prevent contamination by the stratigraphic units above. This technique is a good compromise for collecting samples in a delta area, avoiding the problems of the water table (Goiran et al., 2014). After recording the stratigraphy of the cores, sediment samples are selected in order to cover each unit previously determined and then studied in the laboratory, using different and complementary approaches. All coring points were positioned in x, y, z using a DGPS Trimble geoXT 6000. For the sake of concordance with the ancient and current sea levels, a measurement was also taken in the Kalaat El Andalous lagoon to correct the elevation of each coring, and the unit depths are reported in absolute elevations above or below present sea level (a.s.l. and b.s.l.).

Two transects of core drillings were carried out: the SW-NE (UTC10, DM3, DM2, DM1 cores) and the NW-SE (UCN1, UCN2, UKC1 cores) (Fig. 1).

Four cores were taken along the SW-NE transect. The UTC10 core is located within the archaeological site of Utica, adjacent to the area currently excavated by the Tunisian-Spanish team (López Castro et al., 2016). It is located about 40 m north of a hot water source (Bouzourra et al., 2015). The three other points (cores DM1 to DM3) define a transect between Utica and the current coastline, which is required to reconstruct the rates of the delta progradation.

For the NW-SE transect, cores UCN1 and UCN2 were drilled in a marshy area, north of the “northern compartment” of the delta, to determine if this area could have been a marine bay during the occupation of Utica. The UKC1 core is particularly sensitive since it definitively elucidates the passage of the Medjerda into the northern compartment.

### 3.2. Magnetic susceptibility

Magnetic susceptibility (MS) was used to help to confirm the different stratigraphic units of each core. It is measured by a Bartington MS2E and is expressed in SI. Moreover, in a deltaic environment, MS reflects the terrigenous flux derived from fluvial processes (Delile et al., 2016). MS was measured three times using a Bartington MS2E1 (Dearing, 1999).

### 3.3. Particle size analysis

Particle size analysis is used in order to determine depositional and transport processes. The texture analysis is carried out from a fraction of 30 g of dry sediment. The samples are wet-sieved and the residues are weighed to obtain the percentages of the different fractions, i.e. coarse fraction (>2 mm), sands (2 mm-63 μm) and silts/clays (<63 μm). Laser granulometry was performed using a Malvern Mastersizer 2000 (Inorganic and structural chemistry, Department of Chemistry, University of Liège). This technique allows one to obtain the distribution of the sample's particle size. It uses the principle of diffraction and diffusion of a laser beam encountering a particle, which is suspended in water. It allows the acquisition of the granulometric distribution, the particle size histogram with its cumulative curve, and parameters like the median grain (D50), which provides hydrodynamic information (Bertrand et al., 2005).

### 3.4. Biological indicators

Ostracoda, small bivalve crustaceans, are valuable palaeoenvironmental indicators in marginal marine environments and archaeological settings (Mazzini et al., 2017). Salinity is the main factor controlling the occurrence of ostracods in brackish waters (Ruiz et al., 2005). Whenever possible, 30 valves were handpicked under a stereomicroscope and each species frequency was normalized to 1 g of dry sample. Information about the environment such as depth, occurrence of vegetation and water flow could be inferred through the auto-ecological analyses of the dominant species (Carbonel and Purser, 1982; Lachenal, 1989; Meisch, 2000). The ostracod assemblages were separated into four ecological groups: shallow marine, brackish marine, euryhaline, freshwater to low brackish (Goiran et al., 2010; Mazzini et al., 2017, 2011). In marginal marine environments, the boundary between these groups is indistinct and can only be determined by analysing the dominant association.

The determination of the mollusc shells makes it possible to reconstitute biocenotic assemblages and thus to identify the conditions that prevailed during the development of these species (biotopes) (Pérès and Picard, 1964). Shells and shell fragments were collected after wet sieving using 2 mm, 1 mm and 500 μm mesh sieves. In Mediterranean marine environments, the assemblages of malacofauna correspond to biocenoses which are distributed in littoral environments in a staged fashion: (1) the supra-littoral stage, emerged, sometimes influenced by sea spray; (2) the medio-littoral stage, corresponding to the tidal and wave zone and (3) the infra-littoral stage, characterized by constant immersion but which receives sunlight. To these stages must be added the euryhaline and eurythermal lagoonal biocenoses and the terrestrial gastropods (Goiran et al., 2014, 2011; 2009; Salomon, 2013).

### 3.5. Mineralogical characterisation

Mineralogical characterisation of the sediment is used to understand the genesis of the sediments, identifying the transport mechanisms, and deducting past limnologic, hydrologic and climatic conditions (Last and Smol, 2002). Bulk mineralogy was carried out by X-ray diffraction (XRD), using a Bruker AXS D8 Advance diffractometer (Cu-Kα radiation, 40 kV and 25 mA), equipped with a linear detector (LINXEYE XE). Dry samples were crushed in an agate mortar to reach a diameter of less than 150 μm and mounted in a PVC support, following the “back-side” method (Brindley and Brown, 1980). These non-oriented powder samples were then passed through X-ray diffraction between 2 and 45° 2θ. Mineral characterisations were determined with the EVA 3.2 software and their abundance were calculated in a semi-quantitative way (±5%) following Cook et al. (1975). For each mineral, intensity of the main diffraction peak was measured and corrected by a multiplicative factor (Boski et al., 1998; Cook et al., 1975).

### 3.6. Loss-on-ignition

Loss-on-ignition (LOI) was performed to estimate the organic and carbonate content of the sediment. Organic content tends to increase when the hydrodynamic energy slows down. After oven-drying at 105 °C during 12 h, samples are placed in a muffle furnace at 550 °C during 4 h to determine the organic content and then at 950 °C during 2 h to determine the carbonate content (Heiri et al., 2001).

### 3.7. Radiocarbon datings

The AMS radiocarbon dating was performed at the Centre de datation par le Radiocarbone (Lyon, France) and the Gliwice Radiocarbon Laboratory (Gliwice, Poland). The results are reported in Table 1.

The dates were calibrated with the OxCal 4.3 calibration program (Bronk Ramsey, 2009) using the atmospheric IntCal13 or Marine13 calibration curve (Reimer et al., 2013) according to the nature of the dated material. Younger dates were calibrated using

**Table 1**
Radiocarbon datings. The AMS radiocarbon datings were calibrated with the OxCal 4.2.4 calibration program (Bronk Ramsey, 2009) using atmospheric IntCal13 or Marine13 curve (Reimer et al., 2013), and reported at the 95% confidence level (2 sigma). The age-models are available in the Supplementary materials.

| Core | Depth below soil surface (cm) | Depth (cm) relative to the MSL | Laboratory code | Material | $\delta^{13}C$ (AMS) | Calibrated age range AD/BC (95.4% probability): $^{14}C$ age (B.P.) | Atmospheric curve cal. age (Reimer et al., 2013; 95.4%) or Hua et al. (2013) | Marine curve cal. age (Reimer et al., 2013; 95.4%) | Modelled age (95.4%) | Comment |
|---|---|---|---|---|---|---|---|---|---|---|
| DM1 | 249–252 | | GdA-3698 | Posidonia ? | −24.9 | 215 ± 25 | AD 1645–1935 | | AD 1645–1800 | |
| DM1 | 475–477 | −421 to −423 | GdA-3699 | Plant material | −24.9 | 515 ± 25 | AD 1400–1445 | | AD 1410–1440 | |
| DM1 | 502–504 | −448 to −450 | GdA-3700 | Plant material | −22.5 | 540 ± 25 | AD 1320–1435 | | AD 1385–1430 | |
| DM1 | 533 | −479 | GdA-3701 | Plant material | −25.35 | 480 ± 25 | AD 1415–1445 | | AD 1295–1430[a] | Outlier - too young; removed from the age-depth model; age reversal gives unrealistic sedimentation rate |
| DM2 | 1142 | −892 | GdA-3697 | Plant material | −24.5 | 1895 ± 25 | AD 55–210 | | | |
| DM3 | 685 | −285 | GdA-3682 | Shell | −11.7 | 32,010 ± 145 | | 33950–33120 BC | | Redeposited shell |
| DM3 | 720–723 | −320 to −323 | GdA-5021 | Plant material | −19.8 | 1700 ± 30 | AD 255–405 | | | |
| DM3 | 793–795 | −393 to −395 | GdA-3683 | Plant material | −19.1 | 1810 ± 25 | AD 130–320 | | | |
| DM3 | 946 | −546 | GdA-3684 | Plant material | −26.5 | 1770 ± 25 | AD 145–340 | | | |
| DM3 | 1146 | −746 | GdA-3685 | Plant material | −26.6 | 1765 ± 25 | AD 215–375 | | | |
| DM3 | 1257–1262 | −857 to −862 | GdA-5022 | Plant material | −25.3 | 1750 ± 25 | AD 230–380 | | | |
| DM3 | 1338–1343 | −938 to −943 | GdA-5023 | Charcoal | −24.2 | 1650 ± 35 | AD 260–535 | | | |
| DM3 | 1505–1507 | −1105 to −1107 | GdA-3686 | Plant material | −17.7 | 1755 ± 30 | AD 215–385 | | | |
| UTC10 | 288–290 | +170 to +172 | Lyon-12628 | Peat | −20.67 | 1460 ± 30 | AD 550–650 | | AD 565–650 | |
| UTC10 | 498–501 | −038 to −041 | Lyon-13581 | Plant material | | 1600 ± 30 | AD 400–540 | | AD 395–530 | |
| UTC10 | 600–603 | −140 to −143 | Lyon-13582 | Plant material | | 1725 ± 30 | AD 245–390 | | AD 255–390 | |
| UTC10 | 739–742 | −279 to −282 | Lyon-12629 | Wood | −20.9 | 1640 ± 30 | AD 335–535 | | AD 110–255[a] | Outlier - too young; removed from the age-depth model; age reversal gives unrealistic sedimentation rate |
| UTC10 | 860–865 | −400 to −405 | Lyon-13583 | Plant material | | 1940 ± 30 | 20 BC–AD 130 | | 20 BC–AD 130 | |
| UTC10 | 1616–1619 | −1156 to −1159 | Lyon-12630 | Charcoal | | >44,000 | | | | |
| UCN1 | 539–542 | −300 to −303 | Lyon-12621 | Plant material | −10.98 | 1675 ± 30 | | AD 660–780 | AD 660–785 | |
| UCN1 | 792 | −553 | Lyon-12622 | Wood | −25 | 1640 ± 30 | AD 336–535 | | AD 350–535 | |
| UCN1 | 989–995 | −761 to −767 | Lyon-12623 | Posidonia | −10.96 | 2040 ± 30 | | AD 255–425 | AD 233–400 | |
| UCN1 | 1117–1119 | −900 to −903 | Lyon-13710 | Plant material | −11.3 | 4390 ± 30 | | 2700–2470 BC | 2700–2468 BC | |
| UCN1 | 1300–1306 | −1061 to −1067 | Lyon-12624 | Plant material | −13.09 | 6890 ± 30 | | 5520–5370 BC | 5520–5367 BC | |
| UCN2 | 447 | −17 | GdA-5017 | Plant material | −25.8 | 1160 ± 25 | AD 775–965 | | AD 775–970 | |
| UCN2 | 1047–1050 | −617 to −620 | GdA-5019 | Plant material | −25.4 | 2090 ± 25 | 180–45 BC | | AD 130–650[a] | Outlier - too old, caused by remobilisation of older organic matter by fluvial sediment inputs; removed from the age-depth model |
| UCN2 | 1670–1674 | −1240 to −1244 | GdA-5018 | Posidonia | −13 | 2095 ± 25 | | AD 190–570 | 200–500 BC | |
| UCN2 | 2242–2246 | −1812 to −1816 | GdA-5020 | Plant material | −26.8 | 3525 ± 30 | 1935–1760 BC | | 1940–1760 BC | |
| UKC1 | 124–127 | +473 to +476 | Lyon-13589 | Wood | | 105,4 ± 0,26 pMC | AD 1956–1957 (3.0%)<br>AD 2007–… (92.4%) | | AD 2008–2009 (89.3%) | |
| UKC1 | 203–206 | +397 to +394 | Lyon-13705 | Plant material | | 102,99 ± 0,25 pMC | AD 1955–1958 | | AD 1956–1957 | |
| UKC1 | 218–221 | +382 to 379 | Lyon-13706 | Plant material | | 103,99 ± 0,26 pMC | AD 1956–1957 (58.8%)<br>AD 2008–2010 (36.6%) | | AD 1956–1957 | |
| UKC1 | 318–321 | +282 to +279 | Lyon-13707 | Charcoal | | 1500 ± 30 | | AD 430–640 | AD 430–640 | |
| UKC1 | 681–684 | −081 to −084 | Lyon-13708 | Charcoal | | 2105 ± 30 | 200–45 BC | | 190–55 BC | |
| UKC1 | 739–742 | −500 to −503 | Lyon-13709 | Charcoal | | 2140 ± 30 | 355–55 BC | | 340–100 BC | |
| UKC1 | 760–763 | −160 to −163 | Lyon-13592 | Charcoal | | 2045 ± 30 | 165 BC–AD 25 | | 270–150 BC[a] | Outlier-too young; poor agreement index with neighbouring data; insignificant age reversal, but leads to underestimation of model uncertainty |
| UKC1 | 778–781 | −178 to −181 | Lyon-13591 | Charcoal | | 2185 ± 30 | 360–170 BC | | 350–160 BC | |
| UKC1 | 812 | −212 | Lyon-12625 | Charcoal | −22 | 2140 ± 30 | 355–55 BC | | 355–170 BC | |
| UKC1 | 939–942 | −339 to −342 | Lyon-12626 | Posidonia | −11.84 | 4495 ± 30 | | 2855–2630 BC | 2850–2630 BC | |
| UKC1 | 987–990 | −387 to −390 | Lyon-13593 | Wood | | 4905 ± 30 | 3760–3640 BC | | 3760–3640 BC | |
| UKC1 | 1360–1364 | −760 to −764 | Lyon-12627 | Wood | −24 | 6930 ± 30 | 5885–5740 BC | | 5840–5730 BC | |
| UKC1 | 1378–1381 | −778 to −781 | Lyon-13590 | Plant material | | 6895 ± 35 | 5845–5715 BC | | 5850–5730 BC | |

[a] Age calculated from the age-depth model for the sampled depth.

the post-bomb curve for NH1 zone (Hua et al., 2013). The results are reported at the 95% probability level (corresponding to 2 sigma) (Table 1).

For the cores, except the DM3 site, the age-depth models were calculated using *P_Sequence* function in OxCal, with a variable *k* parameter (Bronk Ramsey, 2008; Bronk Ramsey and Lee, 2013). The details about model outputs, excluded outliers, model options, agreement indices, are included in Table 1.

## 4. Results

The stratigraphic logs of the cores are described from bottom to top and the depths are expressed as metres below the current sea level (b.s.l.) or above the current sea level (a.s.l.). Both raw and calibrated radiocarbon dates are given in Table 1; in the discussion below, the calibrated date range at 2σ (95.4% probability) is given. Detailed results about biological indicators, granulometry and mineralogy are given in the Supplementary Materials.

### 4.1. Transect SW-NE

#### 4.1.1. UTC10 core

Core UTC10 (Fig. 2) is located within the archaeological site of Utica. This core consists of an alternation of clays, fine sands and gravels, with a peat layer between 1.53 and 1.69 m a.s.l. Unit A (between 12.40 and 11.80 m b.s.l.) is composed of a homogeneous layer of finely laminated grey clays. From 11.80 to 4.40 m b.s.l. (unit B), an alternation of sandy and clayey subunits dating from the Pleistocene (over 44,000 BP, to about 11.40 m b.s.l.) is observed. A compact, carbonated and concretion-rich layer of badly sorted grains is visible from 4.40 to 4.07 m b.s.l. (Unit C). Then (from 4 m b.s.l. to 1.53 m a.s.l., unit D), alternating sandy and clayey subunits are visible, with some plant fragment remains. Radiocarbon dates span the period between the 1st century BC and the 6th century AD. The top of the peat layer between 1.53 and 1.69 m a.s.l. (unit E) has been dated to cal. AD 545–650. The next unit is homogeneous, composed of ochre clays.

#### 4.1.2. DM3 core

DM3 (Fig. 2) was taken in an area northwest of Kalaat El Andalous, at the junction between the road to Utica and a track to the south. The altitude of the coring point, with respect to the current sea level, is +4.01 m. It presents an interesting alternation of clays, fine sands and coarse sands containing fragments of marine shells, about 20 m deep. The basal unit A (15.99–12.89 m b.s.l.) is composed of grey clays. Unit B (12.89–2.99 m b.s.l.) is made by an alternation of grey clays and fine sands. Radiocarbon datings on plant material and charcoal give ages between the 2nd and the 6th centuries AD. The heterogeneous unit C (2.99–1.89 m b.s.l.) is formed of several subunits with a coarse particle size and shell sands. It contains fragmentary remains of marine shells and rolled gravel. Radiocarbon dating on a marine shell gives 33,950-33125 cal. BC at 2.85 m b.s.l. Unit D (1.89 m b.s.l.-2.76 m a.s.l.) is composed of an alternation of beige fine sands and grey clays. The uppermost unit (E, 2.76–4.01 m a.s.l.) is composed of compact ochre clays.

#### 4.1.3. DM2 core

The core (Fig. 2) was taken in a cultivation zone located about 5–10 m from a tributary or dead arm of the river Medjerda (wadi es

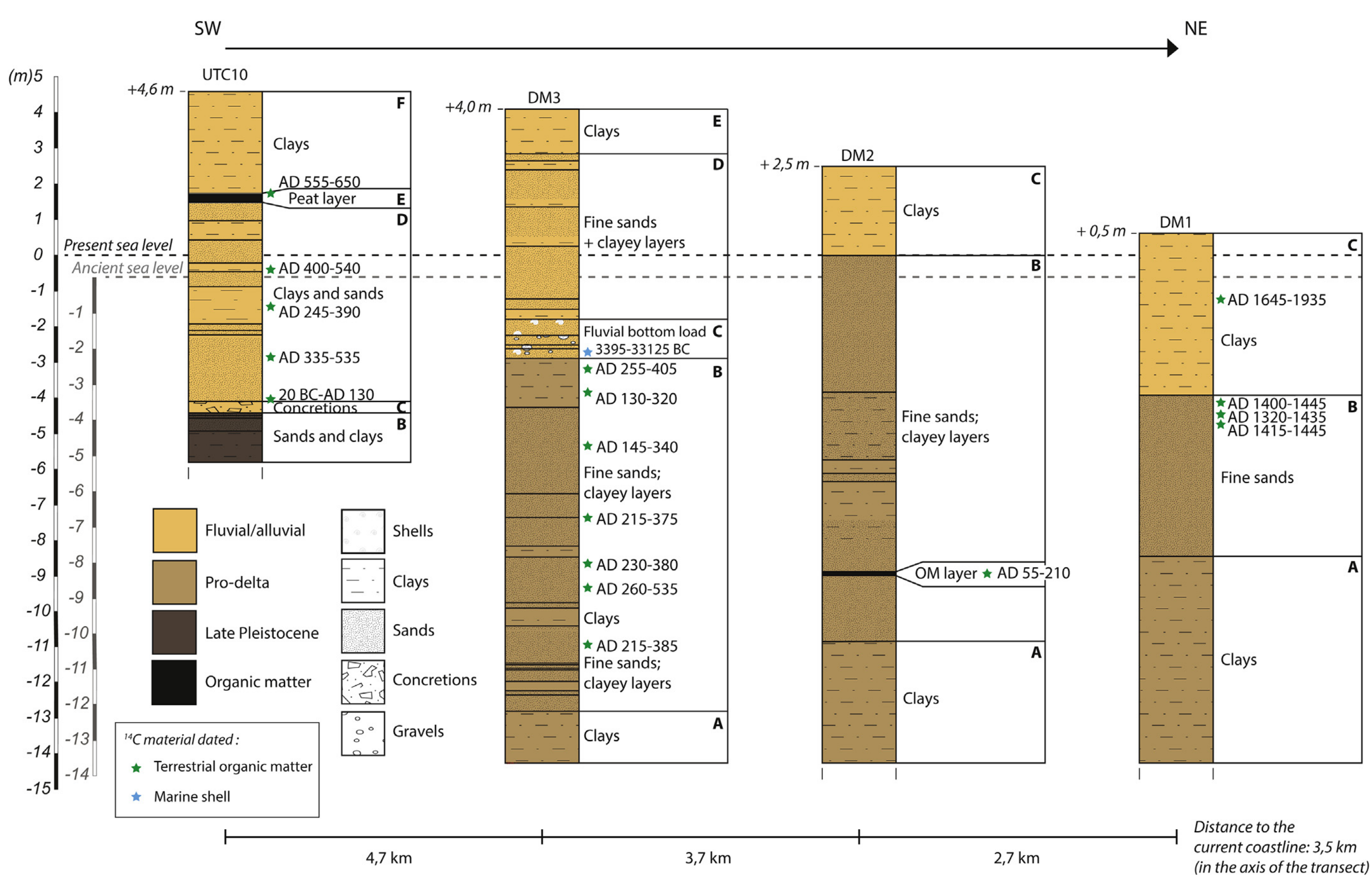


**Fig. 2.** Cross-section of the corings carried out for the SW-NE transect.

Semara). It is composed of an alternation of clays and fine sands, over 20 m depth. The altitude of the top of the core is 2.5 m. Unit A (17.50–10.80 m b.s.l.) is composed of homogeneous grey clays. Unit B (10.80–0 m b.s.l.) consists of an alternation of fine sands and grey clays. A thin layer of organic matter appears at 8.92 m b.s.l. Between 3.80 and 1.90 m b.s.l., fragments of shells are visible among the sands. Radiocarbon dates cover the period between the 1st century AD and the 18th century AD.

#### 4.1.4. DM1 core

The DM1 core (Fig. 2) is located within a sebkha, south of the Ghar el Melh lagoon. The elevation of the site is 0.54 m above the current sea level. This core has large sequences of clays and sands, over a depth of 20 m. Unit A (basal unit; 19.46–14.46 m b.s.l.) is composed of heterogenous compact grey clays. Unit B (8.46–3.96 m b.s.l.) is composed of grey sands, laminated in the top of the unit. These beddings are interspersed with thin layers of organic matter. Radiocarbon dates give an age around the 14th-15th centuries AD. Finally, unit C (3.96 m b.s.l.-0.54 m a.s.l.) is composed of compact ochre clays and is dated from the 17th-20th centuries AD.

### 4.2. Transect NW-SE

#### 4.2.1. UCN1 core

The core UCN1 (Fig. 3; 4) was drilled in a marshy area, north of the "northern compartment" of the delta. The altitude of the coring point UCN1 is +2.4 m. The core is 15 m deep and can be divided into five units according to the main sedimentological features (granulometry, structure and color). The UCN1 core is characterized by an abundant ostracod association, with 20 taxa recognised in 54 samples. Unit A (from 10.55 to 9 m b.s.l.) is mainly characterized by yellow compact clays, laid down at the latest during the first half of the Holocene. The base of unit B (from 9 to 5.65 m b.s.l.) is dated from 5520 to 5375 cal. BC. A second date gives 2700-2470 cal. BC at 6.73 m b.s.l. The unit is essentially composed of grey clays (from 60.5 to 99.5% of particles < 63 µm), mixed with *Posidonia* plant remains and shells, starting from 7.55 m b.s.l. The base of unit C (from 5.65 to 3.55 m b.s.l.) is dated cal. AD 255–425. It consists of laminated compact grey silty clays. The base of the unit D (from 3.55 to 0.75 m b.s.l.) is dated cal. AD 335–535 (2.94–2.97 m b.s.l.) and the top is cal. AD 660–780. It is constituted by grey clays with 80–100% of fraction <63 µm. Unit E (from 0.75 m b.s.l. to 4.45 m a.s.l.) consists of fine sediments (up to 100% at < 63 µm), ochre clays.

#### 4.2.2. UCN2 core

Core UCN2 was taken at an elevation of +4.3 m in the northern compartment, north of the Utica promontory (Fig. 4). It is 24 m deep and can be divided into four units. Unit A (from 19.70 to 16.70 m b.s.l.) is composed of laminated grey clays, dated from 1935 to 1755 cal. BC at 18.12–18.16 m b.s.l. Unit B (from 16.70 to 12.40 m) is composed of fine beige sands, mixed with shell fragments and *Posidonia* fibers. The top of this unit is dated cal. AD 190–570 at 12.40–12.44 m b.s.l. Unit C (from 12.40 to 0.62 m b.s.l.) is composed of an alternation of laminated grey clays and beige fine sands, with fine layers of organic matter. This unit is dated 180-45 cal. BC at 6.17–6.20 m b.s.l. Unit D (from 0.62 m b.s.l. to the top) is composed of beige clays and sands. This unit is dated cal. AD 775–965 at 0.17 m b.s.l.

#### 4.2.3. UKC1 core

The core UKC1 (Fig. 4; 5) was extracted south of the archaeological remains of Utica, in the corridor formed by the Utica and the

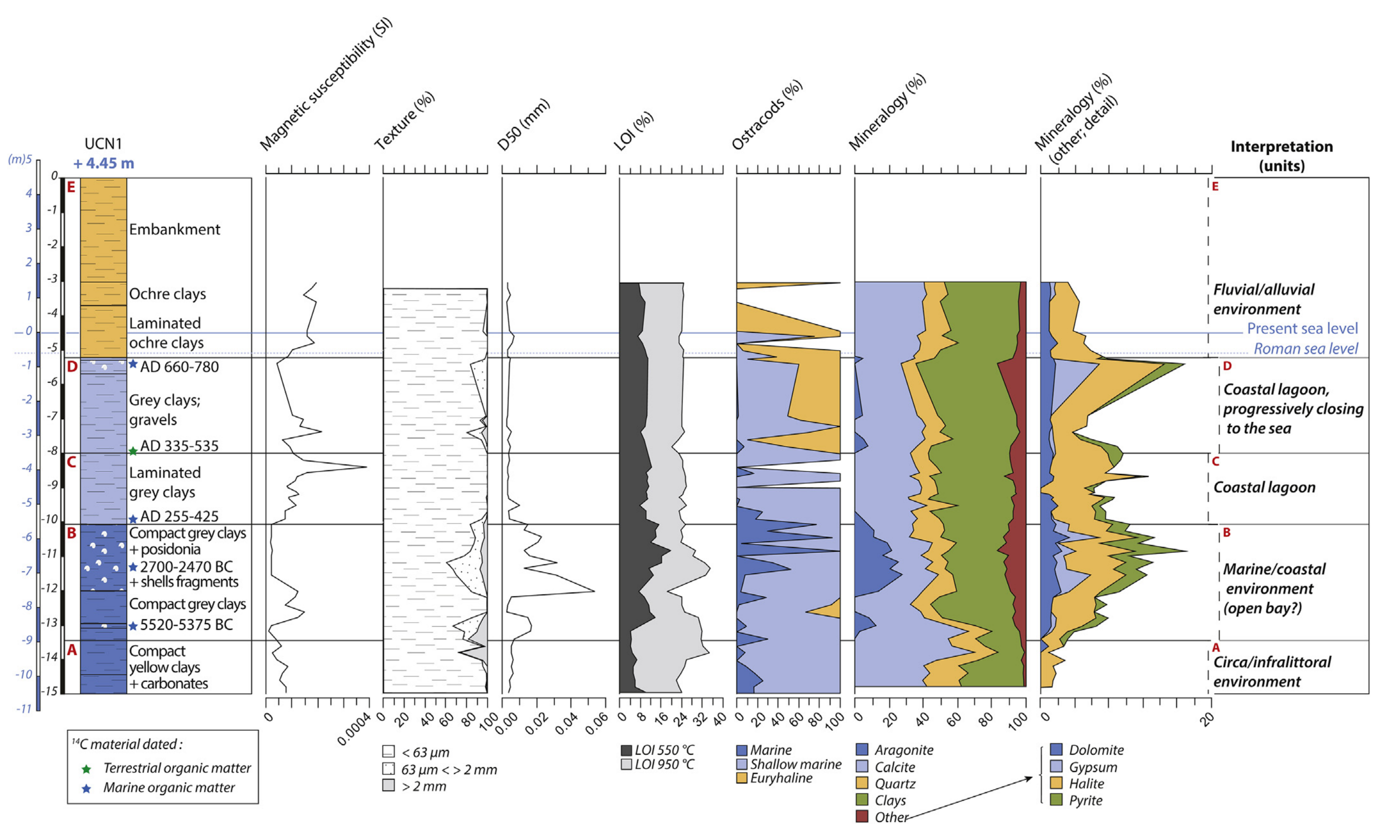


**Fig. 3.** Stratigraphic log of the UCN1 core and interpretation of the units. Methods are described in section 4.

Kalaat El Andalous promontories. The altitude of the coring point is +6 m. The UKC1 core, also 15 m deep, can be subdivided into five units. The UKC1 core is characterized by a scarce but diverse ostracod fauna. Twenty-four taxa have been recovered in the 24 ostracod-bearing samples. The basal unit (A) is composed of compact yellow/grey clays (9–7.80 m b.s.l.), laid down at the latest during the first half of the Holocene. Sediments of unit B (from 7.80 to 3.25 m b.s.l.), are fine grey sands with many shells and *Posidonia* fibers. The base of this unit is dated from the early 6th mill. BC and its top from the 3rd mill. BC. Unit C (from 3.25 to 3 m b.s.l.) is composed of laminated ochre and grey clays. Unit D (3–0.62 m b.s.l.) consists of fine grey sands interspersed with clayey layers. The first subunit, D1, is characterized by laminated yellow fine sands. The second subunit (D2; 2.18 to 0.62 m b.s.l.) contains a large number of artifacts (ceramic, mortar), but also animal bone fragments and charcoal. The radiocarbon datings cover the period between the 4th century BC and the 1st century AD. Unit E (0.62 b s.l. to 6 m a.s.l.) consists of an alternation of sub-units of clays and fine ochre sands, with some marine shells observed between 2.58 and 2.82 m a.s.l. The level 2.79–2.82 m a.s.l. was dated cal. AD 430–640 (charcoal). The three other radiocarbon datings at 3.82–3.79, 3.97–3.94 and 4.73–4.76 m a.s.l. give modern datings.

## 5. Interpretation and discussion

### 5.1. Palaeoenvironmental reconstruction based on bio-indicators and mineralogy

Cores UCN1 (Fig. 3) and UKC1 (Fig. 5) are the cores that have yielded the most complete results. They provide an overall view of the area since they cover the northern compartment of the delta.

Ostracods in unit A of the core UCN1 (*Cytheropteron spp; Leptocythere ramose; Loxoconcha gibberosa*) are typical of a coastal area and indicate a circumlittoral/infralittoral environment. The presence of broken valves of marine ostracods typical of deeper environments ($\simeq$120 m) around 12 m b.s.l. can be interpreted as the signal of a storm. This clayey unit contains a lot of carbonate nodules, which are usually produced in a deep clayey mud with pressure and temperature (Boulvain, 2010). The absence of marine fauna in unit A of the core UKC1 could suggest an interpretation as a pre-transgressive facies. The occurrence of pyrite and aragonite in the upper part of this unit might be the result of the growing

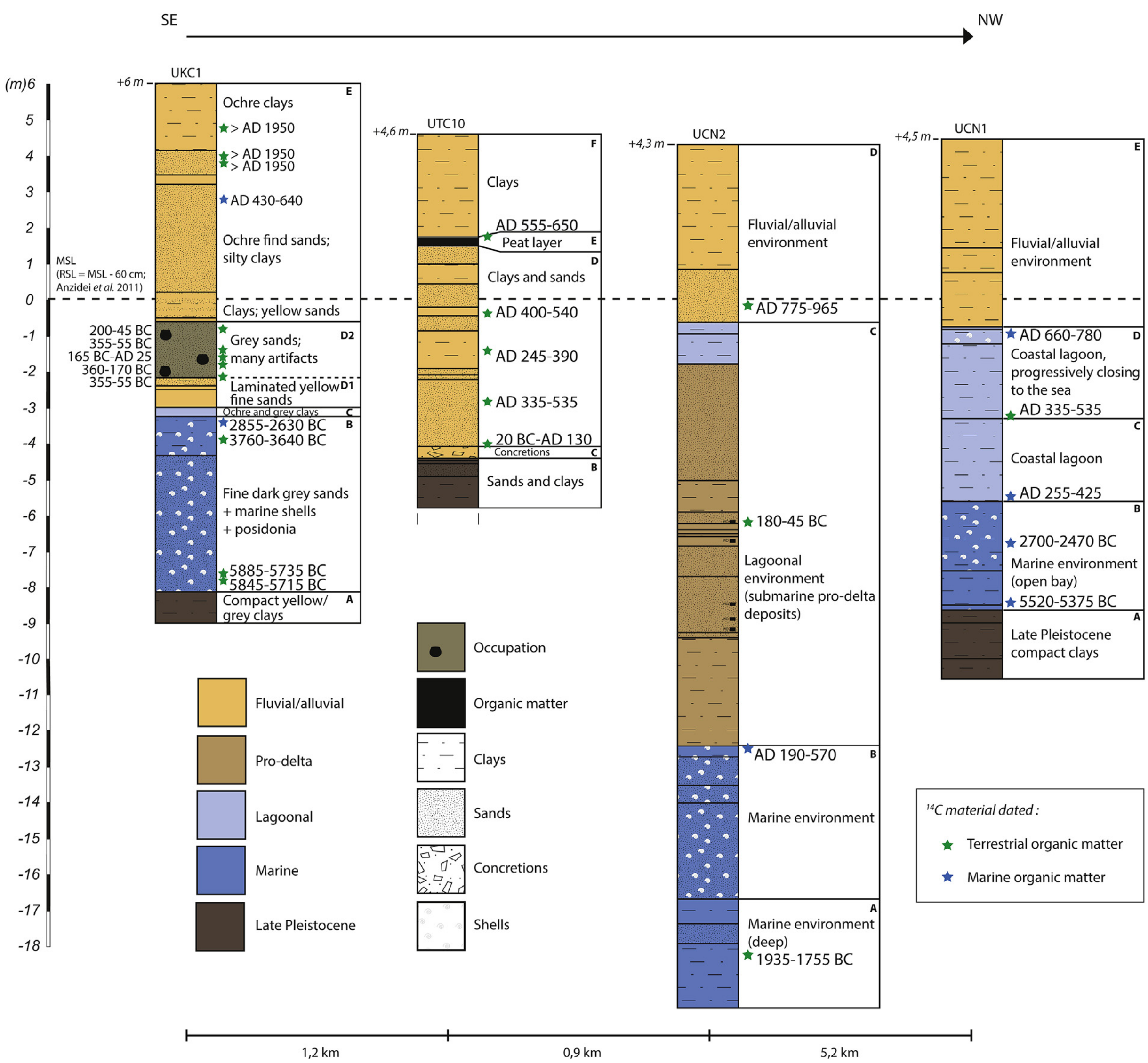


**Fig. 4.** Cross-section of the corings carried out for the NW-SE transect.

influence of the sea.

The ostracod assemblage of the unit B of UCN1 is characteristic of a marine/coastal environment. Its base is dated from 5520 to 5375 cal. BC, which corresponds to a deceleration in the relative sea level rise related to decreasing melting of the major ice sheets (Anthony et al., 2014; Morhange et al., 2001; Stanley and Warne, 1993). The ostracods are typical of a coastal area, open to the sea, with some vegetation (*Xestoleberis aurantia*) and marine inputs (*Callistocythere bacescoi; Semicytherura* spp.*; Cytherois fischeri*). Gypsum and halite are signs of an evaporitic environment, and pyrite was formed following organic matter enrichment, probably linked with the abundance of *Posidonia oceanica* fibers. Aragonite seems to be related to the abundance of shells and occurrence of *Cladocora caespitosa* fragments. Fragments of *C. caespitosa* that occur in this unit had already been noticed in the former “Utica Sea” by Pimienta (1953). Signs of evaporation and organic matter enrichment are also visible in the ostracod assemblage around 10.20 m b.s.l., reflecting a probable lagoon closure (occurrence of *Cyprideis torosa* and lack of truly marine forms). Unit B of UKC1 (6th mill.-3rd mill. BC) is typical of a marine environment, rich in macrofauna living in *P. oceanica* meadows, algae, sands or fixed on the rocks. The ostracods show a shallow-brackish marine environment between 7.62 and 6.84 m b.s.l., and then the passage to a brackish environment characterized by flowing waters, and finally a shallow lagoonal environment. Flowing waters can be corroborated by quartz inputs and terrestrial gastropods. This phenomenon could be related to the growing influence of the irregular flows of the river Medjerda, as the progradation of the delta progresses, or to the wadi ech Cherchara evoked by Bernard (1911). From 3.98 to 3.40 m b.s.l. the fauna is typical of a shallow marine environment with *P. oceanica* meadows. The presence of aragonite, gypsum and pyrite is one more element marking the predominance of the marine environment (Boulvain, 2010).

The evolution is then different between the two cores, testifying to the fact that the mouth of the river advanced, while passing in the corridor between the two promontories.

Unit C of UKC1 marks a rather brutal transition to a pro-deltaic environment. This homogenous layer of clays is typical of pro-delta muds, witnesses of the presence of the river mouth not far upstream. The only adult valves of ostracods imply that they are probably displaced. Laminated yellow fine sands observed in subunit D1, still for UKC1, are the witnesses of the progress of the pro-delta. Combined with the pro-deltaic muds of unit C, they form a sequence in inverse granulometry, characteristic of the creation of a new meander by avulsion. These are followed in subunit D2 (4th century BC-1st century AD) by an important layer of artifacts indicating an anthropogenic presence, interspersed with clayey layers. This unit seems to be constituted by the successive layers of a dumping area, at the southern end of the city. This coring point is effectively outside the maximal extension of the city proposed by Lézine (1966), but recent geophysical research has proved that the street grid, probably laid out around the middle of the 2nd century BC, extended not far from this area (Hay et al., 2010). The “artificiality” of this layer is particularly clear in the curves of sedimentation rates (Fig. S7). Indeed, this peak is only visible in UKC1 and not in the other cores. The laminated composition of this unit tends to prove that natural processes continue to interact with anthropogenic process. High percentages of carbonates and organic matter seem to be related respectively to the important presence of lime and animal bones, and charcoal within this dumping layer. The top of the subunit D2 corresponds to the Roman sea level. In this unit D, the ostracods are very scarce and a palaeoenvironmental reconstruction is not easy. Moreover, the ostracod assemblage includes freshwater (*Ilyocypris* spp.) and marginal marine forms (*Palmoconcha turbida*). Their scarcity and poor preservation, together with the almost contradictory palaeoenvironmental signal, could imply that there was a displacing process most likely linked to human activity.

The base of unit C in UCN1 is dated to the 3rd-5th century AD. The ostracod assemblage indicates a coastal setting where *Loxoconcha elliptica* is the dominant species accompanied by *Leptocythere castanea*. *L. elliptica* is a brackish marine species that withstands extreme swings in salinity and is associated with algae and mud (Athersuch et al., 1989). Found only in estuaries, it is a very common species in Europe (Yassini, 1969). It is a periphytal species (Carbonel, 1980) that predominates in channels and channel margins with fine sediment and low-velocity tidal currents (Ruiz Muñoz et al., 1996). Barren samples and broken valves from 6.60 m b.s.l. upwards seem to indicate a rather unstable environment. Unit C reflects a coastal lagoon environment. The base of unit D (UCN1) is dated to the 4th-6th century AD and its top to the 7th-8th century AD. The ostracod assemblage indicates a coastal lagoon environment (*C. torosa*; *L. elliptica*), progressively closing to the sea, with shallow water body (*X. aurantia* and *Leptocythere spp.*) and marine inputs (*Bythocythere sp.* and *Costa batei*), linked most likely to tidal or storm influence.

Unit E is characterized in both cores UKC1 and UCN1 by ochre fine sands and silty clays related to a fluvial environment, sometimes influenced by marine inputs, corroborated by the presence of marine ostracod. A scarce ostracod assemblage is recorded, only represented by the euryhaline *C. torosa* in UCN1. The lack of ostracod valves in some levels can be related to high-energy fluvial input. The considerable drop in gypsum, aragonite, pyrite and halite tends to support the hypothesis of a fluvial/alluvial environment, showing the aggradation of the alluvial plain.

### *5.2. Palaeogeographical evolution of the delta landscape over the mid-Holocene*

According to Paskoff et al. (1991) and Paskoff and Trousset (1992), the filling of the western and southern parts of the delta occurred before the Punic period. Indeed, Punic occupation was found on clay dunes formed on the deltaic plain, to the south of the Kalaat El Andalous promontory (Paskoff et al., 1991; Paskoff and Trousset, 1992). We will not revisit this hypothesis here, because our research has focused on the question of the passage of the Medjerda in the northern compartment of the delta.

#### *5.2.1. 6th mill. — ~2600 BC: a marine bay (Fig. 7/1)*

The base of the marine layer found in the UKC1 and UCN1 cores confirms the hypothesis that the Gulf of Utica formed during the postglacial transgression around the 6th mill. BC (Figs. 7—1). This is in concordance with the datings obtained for the region and for the Mediterranean coast (Stanley and Warne, 1993; Stock et al., 2013; Zaara Ben Mosbah et al., 2010). The Holocene marine trangression peaked around 3550 - 4050 B for southeastern Tunisia (Jedoui et al., 1998; Lakhdar et al., 2006; Lakhdar and Soussi, 2009; Marzougui et al., 2013; Morhange and Pirazzoli, 2005; Paskoff and Sanlaville, 1983), and more generally in the Mediterranean (Kayan, 1999; Kraft et al., 2007). A shallow marine environment is corroborated by the fauna in the corridor between Utica and *Castra Cornelia*, and there seems to have been a shallow open marine bay in the vicinity of core UCN1. The interface between units A and B of the core UKC1 (7.80 m b.s.l.) corresponds to the mean sea level at this time (6th mill. BC). With the rising sea level (Antonioli et al., 2007), sediments were accumulated. During this period, the sedimentation rates were very low (0.14 cm/yr for UKC1 and around 0.05 cm/yr for UCN1). In UKC1 the presence of substantial *P. oceanica* meadows and epiphytic marine fauna is attested. Ostracods show that freshwater supplies nevertheless happened in the corridor during

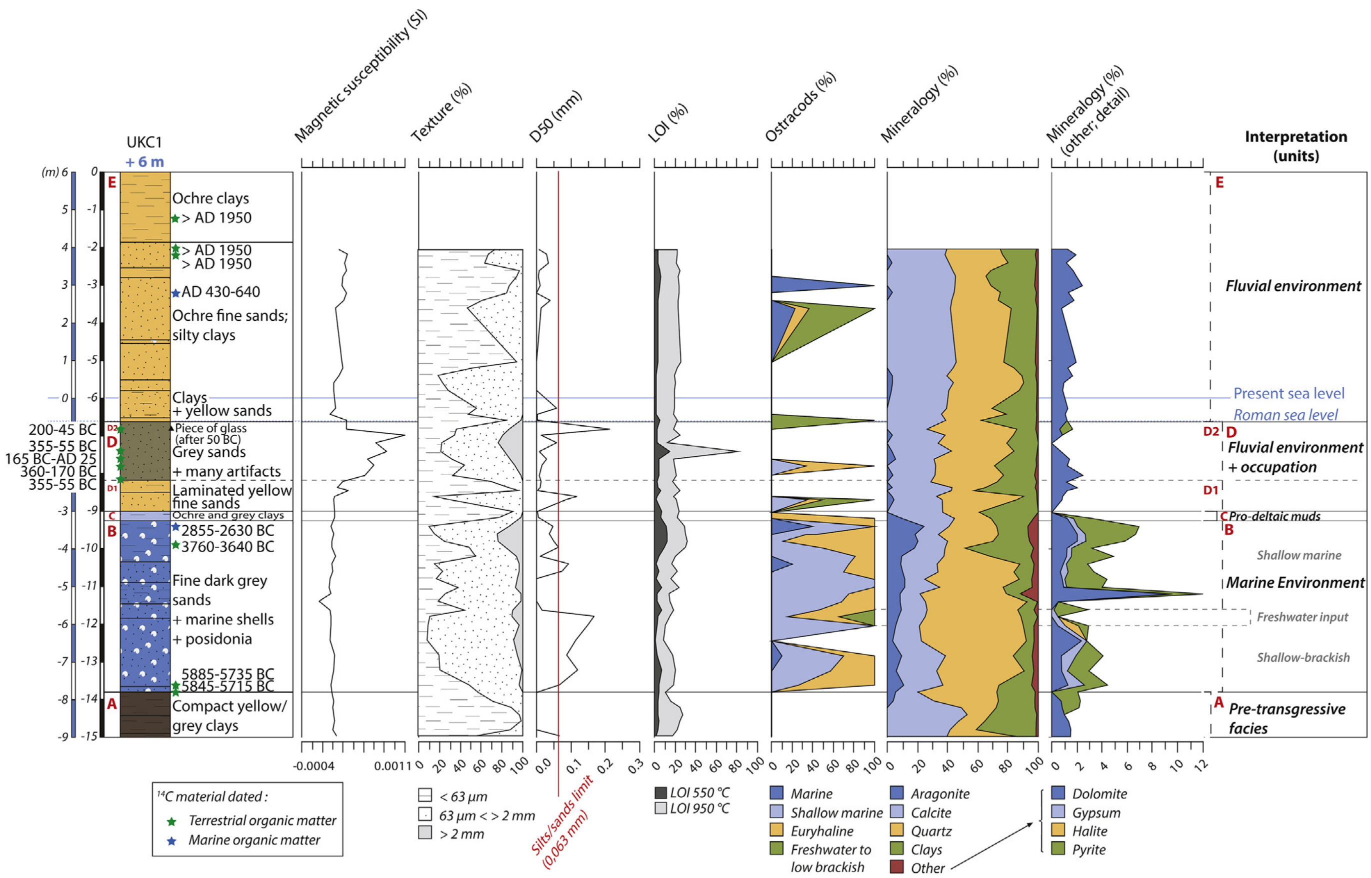


**Fig. 5.** Stratigraphic log of the UKC1 core and interpretation of the units. Methods are described in section 4.

this period, witnessing the growing influence of the floods of the river Medjerda.

### 5.2.2. ~2600 BC – 1st century BC: progressive filling of the corridor (Fig. 7/2)

While a deep marine bay (~20 m b.s.l.; UCN2; Fig. 4) is attested on the northern façade of the Utica promontory in the 2nd mill. BC, the top of the marine layer in the UKC1 core shows that fluvial influence began to be felt after around 2600 BC in the corridor, due to the first pro-deltaic sediments recorded at this time (Fig. 5). The pro-deltaic muds (unit C) and the sands carried by its floods (unit D1) attest to this dynamic change (Figs. 7–2). According to the radiocarbon dates and the age model of UKC1 (Fig. S1), the sedimentation rate for units C and D1 (between ~2400 BC and ~4th century BC) is around 0.05 cm/yr. This weak accumulation rate can be explained by a period of low hydrodynamic energy, allowing the establishment of the Phoenician settlement without fear of the threat of the river at the end of the 12th century BC, or in the 9th century BC according to the oldest archaeological remains. This is contrary to the hypothesis of Chelbi et al. (1995), who argued that the threat of the river supported the idea that the corridor between the two promontories was completely filled before the foundation of Utica, and that the river must have retreated by avulsion south of the promontory of Kalaat El Andalous, allowing Phoenicians to settle without fear of siltation in their marine anchorage.

The delta has been affected by the exploitation of its watershed by man over the centuries (Arnould et al., 1979; Brun, 1983; Brun and Rouvillois-Brigol, 1985; Oueslati, 1995; Paskoff et al., 1991; Paskoff and Oueslati, 1988). Indeed, the vegetation cover has been degraded since the Punic period by human actions such as overgrazing, significant clearing for agriculture and a use of wood as fuel or timber (Stambouli-Essassi et al., 2007). The cultivation of the olive tree in particular was practised from the Punic period in northern Tunisia, and then intensified during the Roman period (Brun, 1989). But the weak sedimentation rates show that for the period between ~2400 BC and ~4th century BC, human activity did not have a major impact on the geomorphological processes.

Potsherds, fragments of lime, animal bones and charcoal found in unit D2 of the core UKC1 (Figs. 4 and 5) could be evidence for the use of this point as a dumping or backfilling area. The radiocarbon dates obtained are quite contemporaneous (between the 4th century BC and the 1st century AD), suggesting that this area was filled in a short period of time. Artifacts are not water-worn, which is a further element in favour of a rapid and artificial filling, probably in order to clean up the ground and make it practicable. Indeed, the altitude of this unit implies that this area must have been swampy. This hypothesis is corroborated by Caesar's mention of a vast swamp separating the two promontories of Utica and Castra Cornelia (Caesar, *De Bello Civili* II.24). The peak in sedimentation rate observed only for this core tends to prove that it was an artificial event, human-induced (Fig. S7). Furthermore, geophysical results tend to prove that this sector is close to the southern end of the city (Hay et al., 2010). The scarcity and poor preservation of the ostracods, combined with their quite contradictory palaeoenvironmental significance, could also imply that they were displaced, most likely linked to human activity.

Captain Bernard (1911) thought that the corridor was silted up and almost filled in the 7th-6th centuries BC by the wadi ech Cherchara, a natural channel that served as an overflow to the flooded area of Garaet el Mabtouha. Reyniers (1951) also believed that this corridor was filled early on from 650 BC, making Utica a fluvial harbour at the mouth of the river at the end of the 1st century BC. According to Paskoff (1994) and Chelbi et al. (1995), by the mid 4th century BC, the clogging of the corridor must have been completed because potsherds dating from this period were found in the alluvial plain around Utica. They also point to a passage in Livy, who, referring to the expedition of Scipio (2nd century BC), mentions that one side of the city was washed bathed by the sea (Livy, XXIX, 35). Based on a comparison of the depths of archaeological datings from Chelbi et al. (1995), the ancient sea level and the current elevation of this area, as well as manual cores, Delile et al. (2015a; b) concluded that the passage of the Medjerda into the northern compartment would have occurred between the 12th and 4th centuries BC. In view of our results, it seems that a change of direction of the river took place after 2600 BC, but that dry land had not yet emerged. We are thus not yet talking about the passage of the river into the northern compartment.

#### 5.2.3. 1st century BC – 4th century AD: passage of the river into the northern compartment (Fig. 7/3)

According to the age model of UKC1 (Fig. S1), land emerged above the sea level from the 1st century BC in the corridor, suggesting that the river definitely changed its course and began to fill the northern compartment of the delta. This contradicts the hypothesis of Paskoff (1994), according to whom the Medjerda no longer passed between the two promontories between the middle of the 3rd century BC and the end of Antiquity. Based on texts of Polybius, Caesar, and Appian, about events that took place during the Civil War, Tissot (1884) also situated the Medjerda south of Kalaat El Andalous around the 1st century BC. Contrary to the hypothesis of Chelbi et al. (1995), our results tend to prove that the Medjerda did not leave the corridor between the 3rd century BC and late antiquity, because fluvial activity is observed in cores UKC1, UTC10, and DM3 during this period. The textual and archaeological indications advanced by Chelbi et al. (1995) are too tenuous to say that the Medjerda changed its course at that time and no longer passed through the corridor. The division of the main river into several active arms simultaneously operating in the north and in the south of the Kalaat El Andalous promontory is a possible hypothesis, as suggested by Reyniers (1951). It is even the most plausible solution to combine the different hypotheses, but a parallel study in the southern compartment of the delta could provide new information on that question.

At that time, the marine bay north of Utica still existed, which is confirmed by the study of unit B in core UCN1. Indeed, ostracods of this unit gave a typical coastal assemblage and mineralogy revealed an evaporitic environment (gypsum, halite) influenced by organic matter (pyrite) (Strechie et al., 2002) and marine fauna (aragonite).

Between the 1st century AD and the 5th century AD, a progradation rate of 286 m per century (2.9 m per year) can be deduced from the dates combined with the location of emerging terrain. The low sedimentation rates in the alluvial records are also registered in the Medjerda watershed, suggesting a stable fluvial dynamic until AD 250 (Faust et al., 2004; Zielhofer and Faust, 2003). This period of stability can be explained by wetter conditions, highlighted in particular by palynological data. According to Faust et al. (2004), landscapes become more stable ecologically and socially when the humidity increases. Despite the intensive use of the area by the Romans, the sedimentological results show a geomorphic stability, perhaps due to the techniques used. Late Holocene Medjerda fluvial dynamics in northern Tunisia were thus maybe mainly shaped by climate, and geomorphic processes were slightly modified by anthropogenic impact (Faust et al., 2004). Contrary to what Paskoff concludes, that an erosive crisis took place during antiquity because of the clearings started since the Punic period, we do not see any signs of important sedimentary transport before the 4th century AD, or the end of antiquity.

#### 5.2.4. 4th – 7th century AD: increase of the fluvial contribution (Fig. 7/4)

From the 3rd-4th century AD, the fluvial influence becomes indisputable. Pro-deltaic muds and sands from the Medjerda floods are found in the stratigraphy of all the cores. An impressive increase in the sedimentary accumulation rates is observed in all of the age models (Fig. 6 and Figs. S1–S5). It is particularly clear in the stratigraphy of the cores UCN1 and UCN2, where the sedimentation rate goes from respectively 0.04 and 0.26 cm/yr to c. 2 cm/yr (Fig. S7). During this period, the submarine pro-deltaic progradation became visible in the north of the Kalaat El Andalous promontory, since unit D of the core UTC10 and unit B of the core DM3 could correspond to deposits of a submarine pro-delta, taking into account the very fine texture of the sediment and the fact that these deposits lie several meters lower than the Roman sea level. The development of a lagoon still open to the sea is visible in the UCN1 core at this time (4th-7th centuries AD), which shows that the alluvia carried by the river began to isolate the northern compartment from the sea under the effect of progradation. Between the 5th and the 11th century AD, a progradation rate of 746 m per century (7.4 m per year) can be deduced, that is 2.6 times the rate before the 5th century.

The passage of the river to the north of the Kalaat El Andalous promontory is inferred from the core DM3, after cal. AD 315–405. Indeed, unit C displays fragmentary remains of marine shells and rolled gravel, coarse granulometry, poorly sorted; probably a river bottom charge. Radiocarbon dating on a marine shell gives 33,950-33125 cal. BC at 2.84 m b.s.l., suggests a remobilisation of old marine material upstream by a strong current. The presence of halite in all the preceding units (up to 3.59 m b.s.l.), and its later disappearance, may reflect freshwater inputs owing to the passage of the river into the northern compartment. The appearance of aragonite may be due to a reworking of marine elements by the floods of the river.

These results are consistent with the post-Roman crisis highlighted in the middle Medjerda valley (Faust et al., 2004; Zielhofer et al., 2003). Indeed, episodes of high floods and increase in the sedimentation rates are recorded in the watershed at the end of the Roman period (Fig. 6). This enhanced geomorphic activity is the result of a combination of climatic and anthropogenic factors. Palynological records and salinity data from Lake Ichkeul show an aridification of the conditions (Stevenson et al., 1993). This period of enhanced aridity coincides with a Northern Hemisphere cooling event in Late Antiquity (Bond et al., 2001) (Fig. 6). A steppisation process began at the end of the Roman era, and continued following an increase in aridity, until at least the 13th–14th centuries. The landscape is marked by both nomadic and sedentary traditions in Tunisia, and by the various conquests, including the invasion of the Vandals in the 5th century (Brun and Rouvillois-Brigol, 1985; Stambouli-Essassi et al., 2007). This erosive crisis is also found in areas not affected by human activities in southern Tunisia, and can thus be attributed to climatic variations (Paskoff et al., 1991), but probably intensified by anthropogenic impact in the Medjerda watershed (Faust et al., 2004).

This increase in the fluvial sediment contribution is probably what prompted Bernard (1911) to think that the Medjerda would "have recovered its previous bed" between the two promontories at the end of antiquity, a hypothesis supported by Chelbi et al. (1995). Charles Tissot (1884) also proposed that the passage of the Medjerda into the northern compartment would have been later than the 4th century AD, as suggested by the Peutinger Table and the writings of Ptolemy (*Geogr.* IV, 3, 2). This last change of the river's

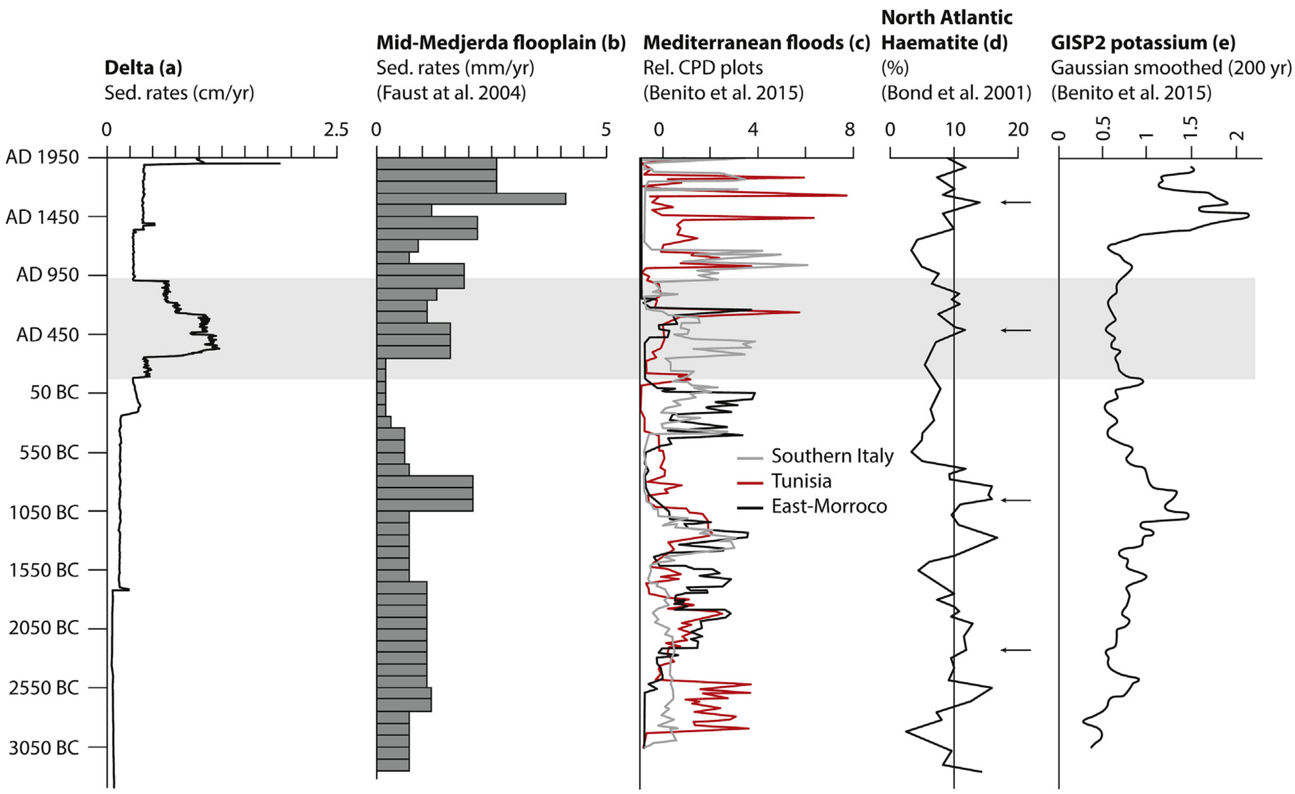


**Fig. 6.** Correlation figure between: (a) average sedimentation rates for the delta (this study); (b) average sedimentation rates for the middle Medjerda floodplain (Faust et al., 2004); (c) relative CPD plots showing floods and extreme fluvial episodes at different Mediterranean regions (Benito et al., 2015); Holocene North Atlantic cooling (Bond et al., 2001); Gaussian smoothed (200 yr) GISP2 potassium (K+; ppb) ion proxy for the Siberian High (Benito et al., 2015).

course would have been fatal to Utica, and would have caused its abandonment in the 7th century AD (Paskoff and Trousset, 1992). Actually, the city progressively lost its access to the sea from the 5th century AD, since a peatbog developed along the ancient maritime façade of Utica at this time (Fig. 4). This fact is consistent with At the same time (4th or early 5th century AD; Modéran, 2003), Julius Honorius speaks of the Bagrada river as like “scattered hair in the vicinity of the city of Utica”, testifying to a deltaic advance ramified in contact with the sea, and a “Mississipian-type” river mouth (Chelbi et al., 1995; Paskoff and Trousset, 1992; Pellissier, 1853) with particular specificities (Delile et al., 2015a, 2015c). The gradual abandonment of the city of Utica can certainly be related to the activity of the Medjerda River, but our results show that it is because of an increase of fluvial sediment contribution in connection with a late antique erosive crisis, and not because of the change of course of the river, which had occurred well before that.

#### *5.2.5. 7th century – 10th century AD: Utica is definitely isolated from the sea (Fig. 7/5)*

Between the 5th and 10th centuries AD, the development of a peatbog is attested along the northern facade of the Utica promontory, as is seen in the stratigraphy of UTC10 (Figs. 2 and 4). The age is consistent with peat layers found in two other cores carried out in this area, dated between the 5th and 10th centuries AD (Delile et al., 2015a; Pleuger et al., 2019). Between the 4th and 8th centuries AD, the coastal lagoon in the north of the ancient *Sinus Uticensis* progressively closed to the sea, favoring the development of a euryhaline environment. By the 8th century AD, the northern compartment was fully and definitively clogged. After the 8th century AD, no further marine influence is visible in the northern compartment, except for occasional storms. The accumulation of alluvium seems fairly constant and no significant change appears.

#### *5.2.6. 10th-15th centuries AD: complete sealing of the northern compartment (Fig. 7/6)*

Around the 10th century, a radical change in the environmental conditions in the northern facade of the Utica promontory is attested by the cessation of the vertical accretion of the peat, which is covered by fluvial clays. At the same time, strong fluvial activity is recorded in the watershed (Faust et al., 2004). Important fluvial inputs are also recorded in the core DM1 during the 15th century (three dates around the 15th century over a thickness of 60 cm). After these stages, the sedimentary accumulation continues, following the floodings of the Medjerda (Figs. 7–5).

#### *5.2.7. 15th-18th centuries AD: the river gradually gains ground on the sea (Fig. 7/7)*

The withdrawal of the coastline in the northern part of the Gulf of Utica took place during the Middle Ages and Modern times, the lagoon of Ghar el Melh being the last vestige (Paskoff et al., 1991; Paskoff and Trousset, 1992; Slim et al., 2004). In the 15th century, the configuration of the delta seems to have been close to that of the present. No major change is visible in the core stratigraphies, and the sedimentation rate for the core DM1 after the 15th century is 0.46 cm/yr (Figs. S5 and S7). For the period between the 11th century and the 17th century, a progradation rate of 672 m/century (6.7 m/yr) was calculated. Progradation thus slows down and sedimentary inputs decrease over the following centuries. Paskoff (1994) suggested a decrease in the rate of progradation linked to a more sustainable exploitation of the watershed. But according to the study of Faust et al. (2004), after AD 1550 the Medjerda catchment area faced catastrophic episodic floods, leading to strong

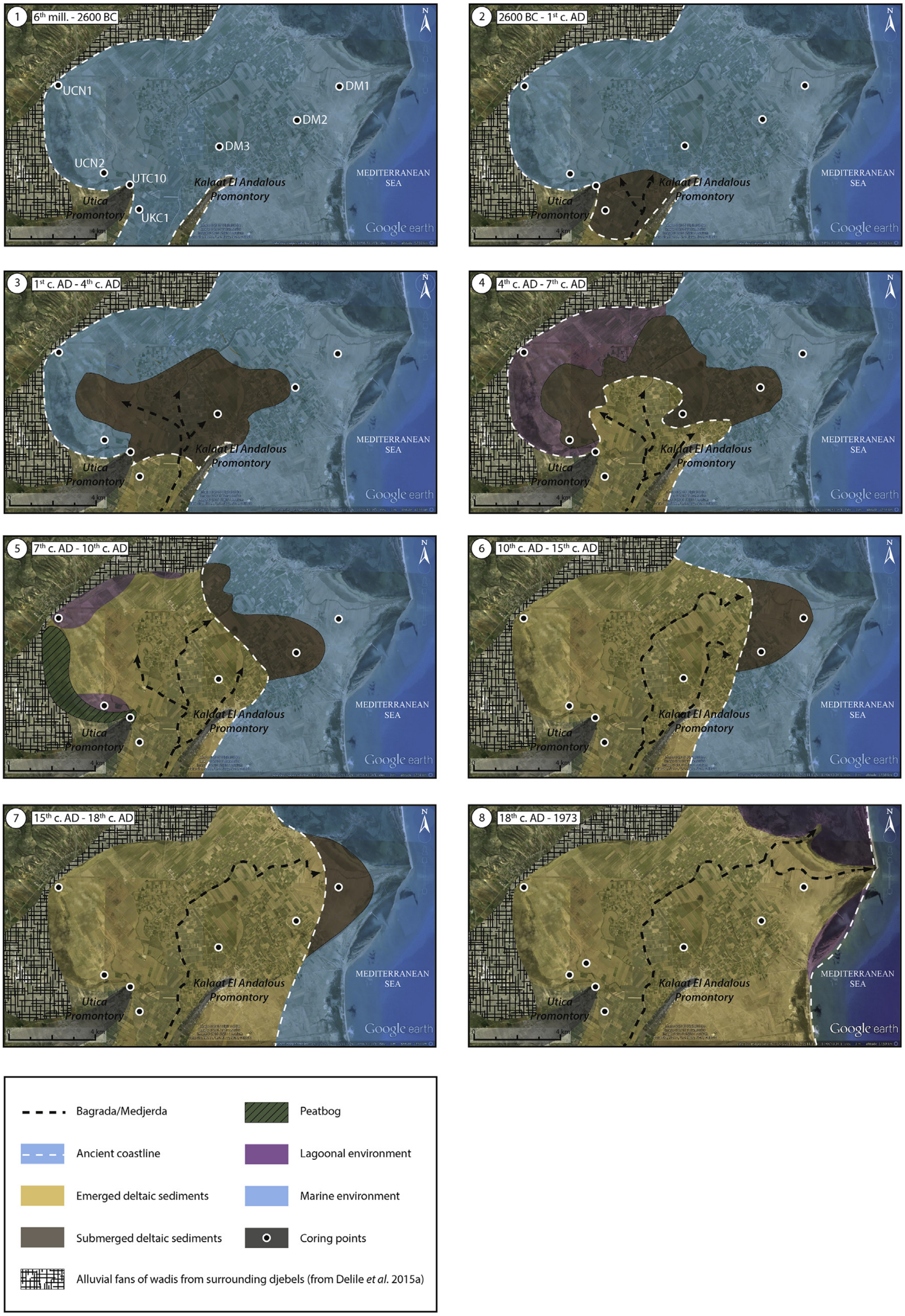


**Fig. 7.** Geomorphological evolution of the Medjerda delta. (1) 6th mill. - 2600 BC: The sea covered the northern compartment and the corridor; (2) 2600 – 1st century BC: The river begins its passage through the corridor (change of course); (3) 1st century BC – 4th century AD: The delta is prograding; passage of the Medjerda into the northern compartment; sediments carried by the river isolate an arm of the sea; (4) 4th century AD – 7th century AD: The north marine bay gradually shrinks; sediments carried by the river isolate a lagoon; (5) 7th – 10th centuries AD: A peatbog develops west of the ancient marine bay; Utica is definitely isolated from the sea; (6) 10th – 15th centuries AD: Complete sealing of the northern compartment; (7) 15th – 18th centuries AD: Progradation of the delta; (8) 18th century AD - 1973: Configuration of the northern compartment of the delta before the flood of 1973.

erosion and downstream aggradation, but this crisis is not specifically recorded in the present research. Before the 18th century, the river flowed into the present lagoon of Ghar el Melh and ended in a mouth with a pointed beak.

*5.2.8. Until 1973 (Fig. 7/8)*

The modification of the delta continued after the 18th century to reach the current configuration. Radiocarbon dating and the age model for DM1 (Fig. S5) show that this point emerged at the beginning of the 19th century. At that time, the river changed its course for a new mouth south of Ghar el Melh lagoon, resulting in a long spit named "Foum el Oued" (Paskoff, 1981). Between the 17th and the 20th centuries, a progradation rate of 818 m per century (8.2 m per year) is estimated. During the great flood of 1973, the Medjerda spilled into a diversion canal which was dug after the Second World War as a relief channel for the river's floods. This major change of the river bed and the creation of numerous dams upstream resulted in a reduction of the terrigenous inputs, and the beak of the river's mouth became less pronounced over the years (Paskoff, 1994, 1978). With regard to previous work on the delta, Lézine (1956) thought that the passage of the Medjerda into the northern compartment could have been after the 18th century AD, depending on the writings of travellers affirming that the sea was still near the western frontage of Utica at that time. Until that time, the city would have kept a sea front, which cast doubt on the idea that alluviation was the main cause of the decline of the city of Utica (Paskoff and Trousset, 1992). This hypothesis is obviously now definitively rejected, given the results described above.

## 6. Conclusions

This interdisciplinary study has reconstructed the spatio-temporal pattern of the landscape evolution of the northern compartment of the former *Sinus Uticensis* in northern Tunisia over the last millennia. It permitted us to understand the maximum marine transgression of the Mid-Holocene and to propose a chronological map of the deltaic progradation, which reached 10 km in 3 millennia. Indeed, our study demonstrates that there was a large and deep bay around the promontory of Utica since the 6th mill. BC, which was progressively sealed by the alluvium carried by the Medjerda from the 1st century BC with a progradation rate of 6.7–8.2 m/century.

The reconstruction of regional morpho-sedimentary evolution provides fundamental elements to improve our understanding of the site of foundation of the Phoenician city of Utica and one of the reasons for its decline. Indeed, it seems that the corridor was not completely sealed before the foundation of the city, given the fact that at the point of the core UKC1 land emerged only around the 1st century BC, but the formation of the delta began to be felt in this sector after 2600 BC. These results tend to prove that when the Phoenicians established a settlement at Utica, the mouth of the river was not far upstream. The founders were therefore aware of the threat of the river. The filling process was already under way at the time of the foundation of the city of Utica, and was strengthened by changing climate and occupational practices. Our results tend to prove that the Medjerda did not leave the corridor between the 3rd century BC and late antiquity, because fluvial activity is observed in cores UKC1, UTC10, and DM3 during this period. Nevertheless, the division of the main river into several active arms simultaneously operating at that time is a possible hypothesis.

The filling of the northern compartment is therefore to be attributed to a change in the course of the river, but the isolation of the city of Utica from the sea is rather linked to a change in water flow and sediment supply generated by climatic factors, perhaps also combined with anthropogenic factors. Indeed, the comparison with the sedimentation rates in the middle Medjerda valley at the end of Antiquity and the late Holocene North Atlantic coolings allows us to make the link between the evolution of the Medjerda delta and that of the fluvial dynamics in its watershed.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2019.07.017.

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