Research Article

The Geoarchaeology of Utica, Tunisia: The Paleogeography of the Mejerda Delta and Hypotheses Concerning the Location of the Ancient Harbor

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Although the ancient site of *Utica* has been studied since the 19th century, the location of its harbors remains unresolved as they were buried under sediments as the Mejerda delta prograded and left *Utica* 10 km inland. Using relief data and a coring survey with sedimentological analysis, we identify the dynamics of the delta's progradation, which produced a double system of alluvial fans. These show that the ancient bay of *Utica* silted up faster and earlier than was thought, probably before the end of the Punic period. Combined with the radiocarbon dates from coring, this suggests that the harbor lay on the northwestern side of the *Utica* promontory, communicating with the sea by a marine corridor west of the northern compartment of the delta. As the infilling of the ancient bay progressed, this corridor narrowed until it disappeared completely in the early 5th/mid-6th century A.D., when a peat bog developed on the northern side of the promontory, sealing the fate of *Utica* as a port. This relative environmental stability ended in the 9th–10th century A.D. when about 4 m of sediment, probably of fluvial origin, covered the peat bog, leaving the site more than 4.5 m above the local sea level.

INTRODUCTION

The progradation of the Mejerda delta in the ancient bay of *Utica*, the *Sinus Uticensis*, has been the subject of numerous studies since the end of the 19th century. This infilling of sediment has been studied through the written sources (Tissot, 1884), then by means of archaeology (Reyniers, 1951; Lézine, 1966, 1970) and geology (Pimienta, 1959; Jauzein, 1971) and most recently using geoarchaeology (Paskoff, 1985, 1994; Paskoff, Slim, & Trousset, 1991; Paskoff & Trousset, 1992; Chelbi, Paskoff, & Trousset, 1995; Slim et al., 2004; Oueslati, Charfi, & Baccar, 2006). These studies have involved developing a spatiotemporal outline for the many changes of course (avulsions) to which the Mejerda has been subjected during its advance toward the sea. Thus, the periods of activity of the different channel beds of the Mejerda have been more or less well identified, ending in the infilling of the *Utica* gulf along a south-west/north-east orientation. The point of convergence of all these studies concerns the infilling of the area between the promontory of Kalaat el-Andalous (*Castra Cornelia*) and peninsula of *Utica*

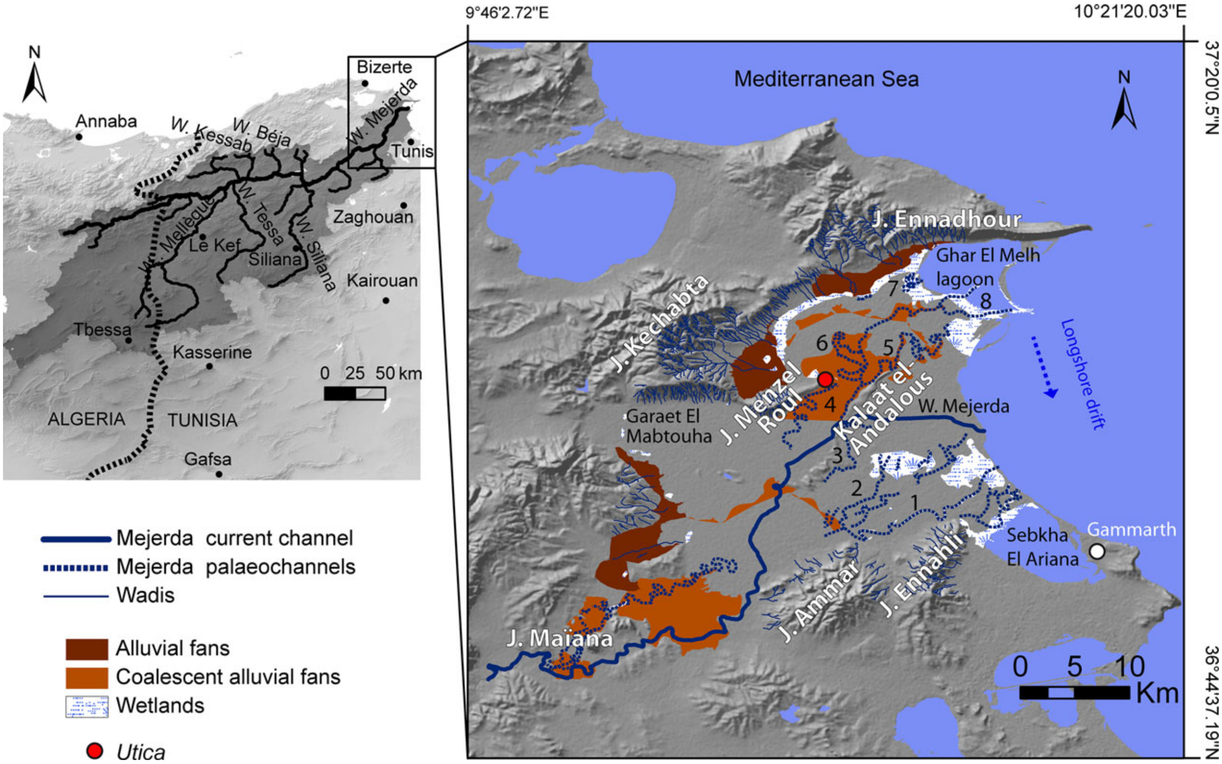

Figure 1 General location maps of the Mejerda catchment and delta. The numbers correspond to those of the Mejerda paleochannels.

(Figure 1). It is through this sector that the Mejerda reaches the northern compartment of the delta. Our research is also concerned with this transition zone, because it holds the key to understanding the choices involved in establishing the first settlements of the Phoenician city and thus the location of its harbor basins, today buried under the alluvium. Harbor geoarchaeology has made great strides in recent years, using coring techniques to investigate the ancient harbor basin at Marseille (Morhange, 1994) and to discover lost harbors at Tyre (Marriner, 2007) and the riverine harbor of Ostia (Goiran et al., 2014). By contrast, a coring program has shown that the harbor at *Cumae* could not have lain to the south of the acropolis (Morhange et al., 2001). Our fieldwork has applied similar techniques to the question of where the harbor of Utica was located.

On the basis of textual and archaeological evidence and from analysis of satellite images (Paskoff & Trousset, 1992), the latest research situates the harbor basins of the city in the north-western part of the peninsula of *Utica* (Figure 2). Without investigations beneath the present ground surface, these hypotheses cannot be confirmed or rejected. The infilling of the harbor would have begun following the Mejerda's avulsions to the northern part of the delta before the end of Antiquity (Paskoff & Trousset, 1992; Chelbi, Paskoff, & Trousset, 1995; Slim et al., 2004), leading to the progressive abandonment of the city by the 7th century A.D. (Paskoff, 1994; Chelbi, Paskoff, & Trousset, 1995).

Using a geographic information system (GIS) that includes digital elevation data, as well as topographic and geological maps and geo-referenced aerial photographs (taken in 1947, 1954, 1956, and 1962), and an initial series of borehole cores, we propose a hydrogeomorphological rereading of the Mejerda delta progradation, in which the hydro- and morphosedimentary processes can be identified. The geoarchaeological implications of our results provide new insights concerning the location of these harbor basins.

Furthermore, the knowledge of the relative sea level (RSL) of the Roman period will provide information both on the approximate position of the harbor deposits within the stratigraphy and the rate of sea level rise for about 2000 years. Anzidei et al. (2011) have evaluated at different archaeological sites of Punic–Roman age the change in sea level since about 2000 years ago along the coasts of Tunisia and Libya. They relied on archaeological markers of Punic–Roman age, such as ancient fish tanks, piers, slipways, quarries, and harbors, which are presently submerged. Their estimation of the sea level rise over the last

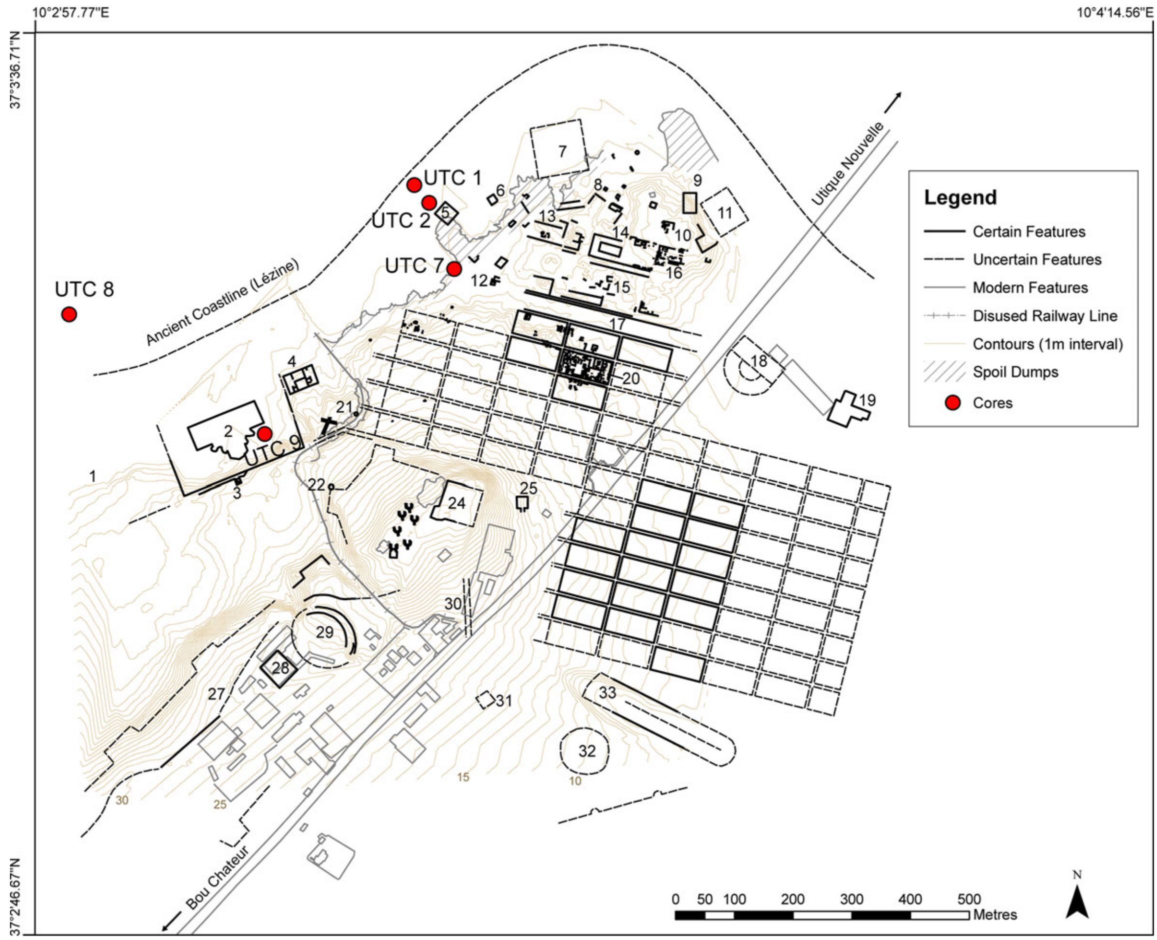

Figure 2 Plan of Utica, with main buildings, and locations of the five cores taken in 2012. (1) Location of possible circus. (2) Large Baths. (3) Columbarium. (4) Possible temple. (5) Vaulted structure. (6) Mosaic and ornamental fountain. (7) Public square, or reservoir? (8) Temple? (9) House with *intarsia*. (10) Staircase or ramp. (11) Public square? (12) Mortared rubble foundation. (13) Fish-salting vats. (14) Basilica. (15) Forum. (16) House of the Grand Oecus. (17) Colonnaded Street. (18) Theatre. (19) Baths. (20) Houses excavated in 1950s. (21) Punic kiln. (22) Limekiln. (23) Feature supposed by Lézine to be ramparts; actually natural break of slope. (24) Citadel. (25) Early Church. (26) As 23. (27) Aqueduct. (28) Reservoir cisterns. (29) Amphitheatre. (30) Street going uphill. (31) Roman necropolis. (32) Small amphitheatre? (33) Stadium or circus. Source: Kallala et al. (2010), Figure 11.

2000 years is between 0.2 and 0.5 m on these coasts. A similar method has been employed on Roman fish tanks at Fréjus by Morhange et al. (2013) who estimated a RSL rise of 40 ± 10 cm since Roman times. These results, which are consistent with those of Oueslati (1995) and Slim et al. (2004), show significant variability in the rise in the sea level at different sites. The rise in sea level is part of a global process resulting from both eustatic and glacio-hydro-isostatic changes in the Mediterranean since the end of the last glacial maximum, but the local variation is explained by tectonic vertical movements of the land, such as subsidence, causing higher values in some areas, such as Gammarth, where RSL around ~A.D. 200 (±50 years) stood at 0.58 ± 0.3 m below the local mean sea level (LMSL; Anzidei et al., 2011).

SETTING

Geological and Geographical Background

The delta of the Mejerda is the outlet for the water and sediment discharges of Tunisia's largest river, which drains along its course of 460 km the waters of a basin oriented south-west/north-east that has a surface area of 23,700 km² (Figure 1). The source of the Mejerda lies in Algeria in the high mountains (1300 m) of the semi-arid Tell Atlas formed by Eocene and Senonian limestones, from which the river flows in torrents up to the Tunisian–Algerian border (David, 1956). The lower course of the river, 340 km in length, begins east of the frontier where the widening of the alluvial plain results in the development of wide meanders, mainly fed by the wadis Béjà, Kessab, Tessa, Seliana, and Mellègue (Figure 1).

The regime of the Mejerda includes contrasting seasonal flows with summer discharges of 1 m^3/s, associated with a period of drought (Jauzein, 1971; Oueslati, Charfi, & Baccar, 2006). On the other hand, the winter rainy season produces high flows and floods are a normal occurrence between October and March with a discharge above 80 m^3/s. The deltaic plain of the Mejerda has developed in a subsiding synclinal structure, delimited by an assemblage of small anticlinal reliefs such as the recent hills (jebels) of Ennadhour and Kechabta to the north and the older jebels Ammar and Ennahi to the south. The deltaic plain of the Mejerda is divided into two compartments, north and south, either side of the anticlines of Menzel Roul and Kalaat el-Andalous (Figure 1). Tunisia's location at the convergence of the African and Eurasian tectonic plates results in compression movements toward Africa, which led to the formation of Pliocene folds, including the anticline of *Utica* (Paskoff & Oueslati, 1988). Recent research has highlighted abnormal contact between the sandstones of the Pliocene and Quaternary silts containing potsherds. These data show the Late Pleistocene–Holocene activity of the Utique Fault. An example of this active faulting is the destructive earthquake of A.D. 412 in *Utica* (Paskoff, Slim, & Trousset, 1991; Vogt, 1993; Mejri et al., 2010, Mejri, 2012).

The annual deposition of sediment in the gulf of Tunis, estimated at ~22 million tons (Oueslati, Charfi, & Baccar, 2006), has resulted in the construction of a delta of 450 km² since the early Holocene. In this lower valley of the Mejerda, all the major hydrogeomorphological units of a delta are present. The lowest levels are the humid zones such as marshes, sebkhas (sebkha of El Ariana), and ancient (lagoon of Garaet El Mabtouha) and modern lagoons (lagoon of Ghar El Melh). The latter are delimited by a coastal belt constructed by longshore drift. This favors the construction of dune ridges that fit together and are parallel, particularly visible at the present river mouth. The delta of the Mejerda also contains a network of paleochannels (Figure 1), evidence of the complex construction of this lower plain.

The delta shoreline is washed by shallow waters, with the 5 m isobath sometimes located more than 1.5 km offshore (Oueslati, Charfi, & Baccar, 2006). These shores are also fairly well protected from the western strong winds by the hills that form an almost continuous chain along the northern edge of the plain. The most frequent winds from the north, particularly the north-west, form a swell in the same direction; the swell caused by the northwest winds is diffracted by the promontory of Rass Ettarf (Oueslati, Charfi, & Baccar, 2006). The southward longshore drift thus created provides an estimated coastal transfer of 30,000 to 40,000 m^3 of sediment per year (Paskoff, 1985). The tide is weak, fluctuating between 0.1 m at low tide and 0.3 m at high tide.

Historical and Archaeological Background

The foundation of the Phoenician city of *Utica* is traditionally said to date to 1101 B.C., predating Carthage, although the earliest known archaeological remains are from the 8th century B.C. The early city occupied a small promontory on the western side of the Mejerda estuary, with its cemeteries to the south. Over time, the city expanded southward over rising ground. Following Rome's defeat of Carthage in 146 B.C., *Utica* became the seat of the provincial governor of the new province of Africa. During the Civil Wars the city was besieged by Curio in 49 B.C., though not before 200 merchant ships had left the harbor to go over to the besieging side (Caesar, *De Bello Civile* II.25); and the Younger Cato famously committed suicide there in 46 B.C., following Caesar's victory at Thapsus. The capital was transferred to Carthage in the reign of Augustus, after the refoundation of that city, but *Utica* evidently prospered, first as a *municipium* and then, from the reign of Hadrian, as a *colonia*. Over the first two centuries A.D., it acquired the full range of public buildings one would expect in a major Roman city: a civil basilica, aqueduct and reservoir cisterns, public baths, theatre, amphitheatre, and a stadium or circus, although the site and nature of the harbor are unknown (Figure 2). Much of the city was laid out on a rectangular street grid, fringed to the south-west by a suburban zone of pottery and lime kilns and cemeteries. Private houses with lavish mosaics evidently flourished into the 4th century A.D., although there is a notable decrease in activity in the late Roman period, particularly in the area of the forum, where we find no pottery later than the 4th century. Overall the ruins cover some 100 ha, including cemeteries, and the population of the city at its peak might have been between 15,000 and 30,000. Recent archaeological work suggests that the civil basilica was demolished in the late Roman period, and later an early Islamic village grew up over the ruins (Kallala et al., 2010; Fentress et al., 2012).

MATERIALS AND METHODS

GIS Design

This study is based in part on analysis using a GIS consisting of topographic (topographic map of the Mejerda delta at 1:25,000 and 1:50,000 scales) and geological maps (geological map of the Mejerda delta at 1:50,000 scale) and aerial photographs (archives from the Department of the French Air Force). After having georeferenced all these data, we proceeded to study the topography of the delta by defining contour lines and altimetric points on the geological map at 1:50,000.

Measurement of the Current Sea Level

Because of the infilling of the *Utica* gulf since Antiquity, the remains of the ancient harbor are buried deep under the alluvia. Only borehole cores, by which the thickness of the alluvia may be measured, can enable determination of the altitude of the ancient installations. However, comparison between the absolute altitudes indicated on the plans of A. Lézine in the 1960s and those determined in 2011 based on the WGS84 system of reference established with a differential GPS by the British mission in 2010 shows differences of the order of 1.7 m, which makes the interpretation of the cores difficult. To avoid all uncertainty, it was decided to measure the local sea level with respect to the global mean sea level (MSL) that serves as the reference basis for the GPS system used by the British team (differential GPS, in UTM projection zone 32 North based on a WGS84 geodesic system).

A 10-km-long transect (27 relays) between the archaeological site and the nearest maritime point, in the lagoon of Ghar el Melh, enabled us to establish that the sea level today lies 1.60 m below the new reference zero point or global MSL. These measurements correspond, within about 10 cm, to those of A. Lézine.

This difference is explained by the utilization of two different geodesic systems—a local system used by A. Lézine and the global standard geodesic system, WGS84, used by the British team. Although the WGS84 system defines an MSL with respect to which altitudes are calculated, in reality sea level is not constant, and the variations across the globe amounting to as much as a hundred meters. Here the difference is of the order of 1.60 m. It is of course the local sea level and not the global MSL that one needs to consider when investigating the harbor structures of *Utica*, and we therefore need to add 1.60 m to the altitudes given by the GPS to give altitudes relative to the LMSL.

The measurement of the current local sea level is crucial for two main reasons. The first is that it enables us to compare the stratigraphy of the different cores. Indeed, the coring areas show some important discontinuities in elevation that, without this accurate measurement of the elevation of the cores, would induce stratigraphic offsets between boreholes. In addition, this measure of the local sea level is also the only way to position in the stratigraphy the RSL of the Roman period that has recently been estimated at Carthage and Gammarth by Anzidei et al. (2011). We have therefore represented it in Figure 3 using data provided by Anzidei et al. (2011) for Gammarth.

Cores and Radiocarbon Dating

In order to compare the results from the GIS study with the actual composition of the deposits beneath the surface, in October 2012 we extracted five cores using a manual auger (Figure 2). These cores, whose lengths are between ~2.80 and ~6.60 m, also provide an efficient means of testing the location of the harbor basins (Goiran & Morhange, 2003). This coring season was aimed at investigating a possible location for the harbor on the north-western side of the promontory of *Utica* (cores UTC 1 and UTC 2), and investigating the supposed coastal edges of the Roman city next to the present marsh (core UTC 7) and in the sector of the Large Baths (core UTC 9). Core UTC 8 was extracted north of the Large Baths, in what was presumed to be the area of the Roman coastline, near an alluvial fan of the Mejerda.

Radiocarbon dating was performed on peat and shell samples from cores UTC 2 and UTC 1. Only the peat samples were dated, owing to the lack of organic materials in the other sedimentary units or their advanced state of degradation. The laboratories of Oxford and Gröningen carried out the analyses using the AMS dating method. The ^{14}C (B.P.) dates were converted into calibrated B.C. and A.D. dates using the continental and marine curves of Reimer et al. (2009) by means of the Clam software (Blaauw, 2010). Errors on raw radiocarbon ages B.P. are reported at the 95% confidence level (2σ). The radiocarbon ages are shown in Table I and Figure 3.

Samples and Analytical Techniques

We sampled cores UTC 2 and UTC 8, which we analyzed for grain-size distributions (see Delile et al., 2014, for analytical details) in order to characterize hydrodynamic and sediment conditions (Marriner, Morhange, & Goiran, 2010). The interpretation of granulometric curves was based on the CM diagram (also called the Passega image), which uses the median (D50) and the coarsest percentile (D99) to determine depositional and transport processes (Passega, 1957; Bravard & Peiry, 1999; Salomon et al., 2012; Delile et al., 2015). The cores were analyzed in the OMEAA laboratory in Lyon.

Magnetic susceptibility (MS) measurement was performed on samples to detect variations in ferrimagnetic mineral contents in sediments, mostly Mn and Fe oxides, hydroxides, and oxyhydroxides (Dearing, 1999). In a deltaic environment, MS reflects the terrigenous flux derived from fluvial processes. MS was measured three times using a Bartington MS2E1 (Dearing, 1999).

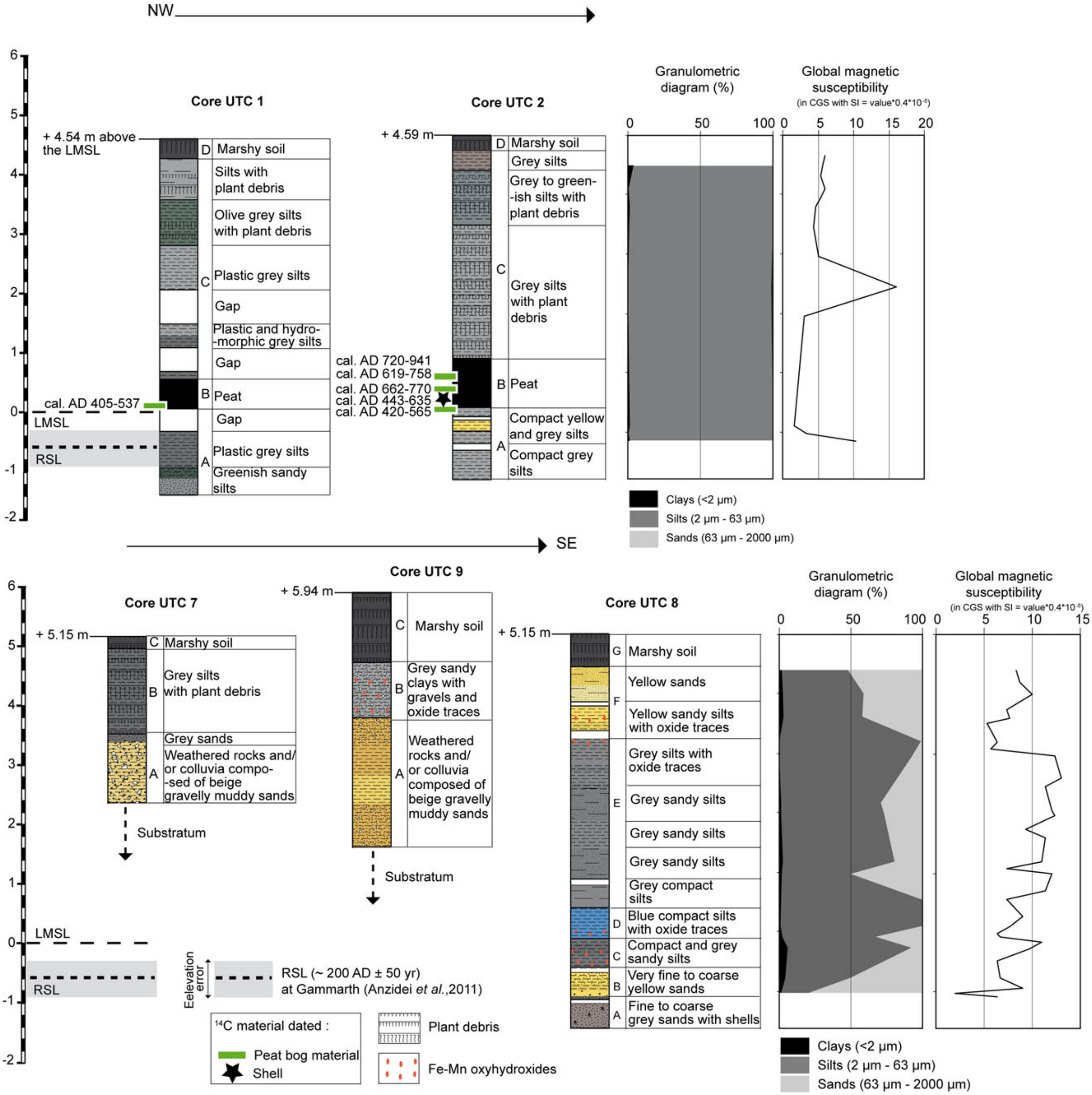

Figure 3 Descriptions of the stratigraphic units of the five cores.

We did not measure the degree of compaction of the peat layers because this type of analysis is intended for studies of sea-level variations throughout the Holocene, where the succession of coastal peats in the stratigraphy is considered as an indicator of former sea levels (Vella & Provansal, 2000; Lampe et al., 2010). In this case, knowledge of the top of the peat is indispensable to properly assess the maximum sea level rise. Since ancient sea level is not calculated in this study, the intensity of its compaction is not a relevant factor.

RESULTS

We describe here only the results related to the cores and the dating. The figures produced using the GIS

Table I ^{14}C dating of samples from the peat unit (B) in cores UTC 2 and UTC 1.

Core	Depth (cm)	Depth (m) relative to the LMSL	Laboratory code	Material	$\delta^{13}C$	^{14}C age (B.P.)	Calibrated age (Reimer et al., 2009; 2σ)
UTC 1	440–450	0.14–0.04	OxA-29185	Peat	−27.31	1599 ± 26	A.D. 405–537
UTC 2	413–416	0.46–0.43	OxA-28614	Peat	−26.13	1362 ± 26	A.D. 619–758
UTC 2	413–416	0.46–0.43	Lyon-10289(GrA)	Peat	NA	1195 ± 30	A.D. 720–941
UTC 2	437–444	0.22–0.15	Lyon-10288(GrA)	Peat	NA	1295 ± 30	A.D. 662–770
UTC 2	444–447	0.15–0.12	Lyon-10291(GrA)	Shell*	NA	1860 ± 35	A.D. 443–635
UTC 2	456–461	−0.02–0.03	Lyon-10290(GrA)	Peat	NA	1560 ± 30	A.D. 420–565

Ages were calibrated according to the IntCal09 and the Marine09 (marked by an asterisk) radiocarbon calibration curves (Reimer et al., 2009).

(Figures 4, 6, 7) support the interpretation of the results in section 5.1. A complete discussion of these results is presented in Delile et al. (2014). In all cases the stratigraphic units are described from bottom to top in each core.

Stratigraphic Description of the North-western Side of the *Utica* Promontory Provided by Cores UTC 1 and UTC 2

Cores UTC 1 and UTC 2 were taken from a marshy zone, on the north-western side of the promontory of *Utica* (Figure 2). Paskoff and Trousset (1992) considered this the most probable location of the ancient harbor basins of *Utica*. Cores UTC 1 and UTC 2 have a length of ∼6 m and are similar in their stratigraphy. The altitudes of the two points of coring, in relation to the LMSL, are +4.54 m for UTC 1 and +4.59 m for UTC 2 (Figure 3). Based on the stratigraphy and dating, cores UTC 1 and UTC 2 can be divided into three major units: unit A corresponds to the prepeat environment, unit B is a typical peat environment, and unit C corresponds to the postpeat state (Figure 3). Unit D is similar in all the cores; it corresponds to the present marshy ground level.

Unit A: Prepeat environment

According to the radiocarbon dates from cores UTC 2 and UTC 1 (Figure 3 and Table I), this unit A is earlier than the Byzantine period and should thus correspond to the Roman period. The thickness of this unit A is approximately 1.40 m in core UTC 1, and 1.20 m in core UTC 2.

Unit A in the core UTC 2 is dominated by compact gray silt sediments (∼99%). The base of core UTC 1, some 20 cm deeper than core UTC 2, presents a small proportion of fine sands between 0.96 and 1.46 m below the LMSL.

Unit B: Peat environment

Unit B corresponds to a peat layer situated between the depths of 0.01 m below and 0.49 m above LMSL in core

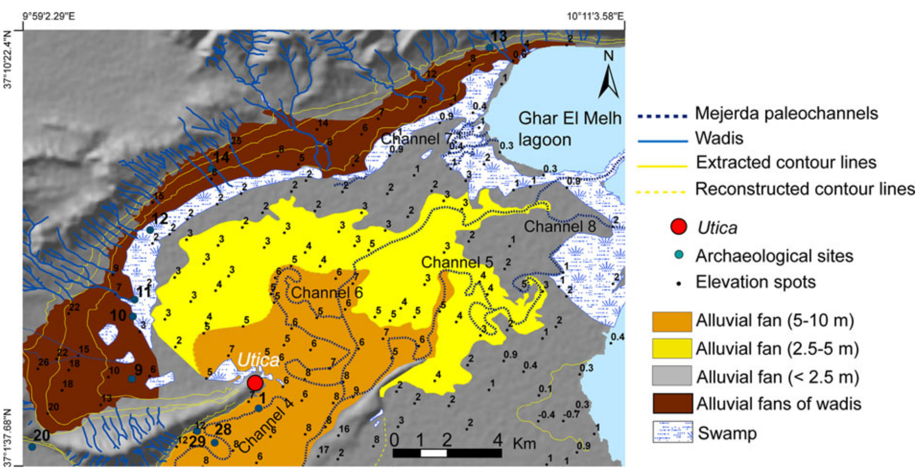

Figure 4 Main hydrogeomorphological units of the northern part of the Mejerda delta.

UTC 1 and between the depths of 0.01 m below and 0.84 m above LMSL in core UTC 2 (Figure 3). It has produced six radiocarbon dates (Table I). These show that the peat bog developed between the end of the Roman period (~A.D. 500) and end of the High Middle Ages (~A.D. 900). In this chronological interval, an average rate of accretion of the peat bog can be estimated at ~0.22 cm/yr. The base of this peaty level is situated at the same elevation as the LMSL. Thus, this peat bog developed slightly above the supposed medieval sea level, presumed to lie between the RSL (Anzidei et al., 2011) and present sea level.

Unit C: Postpeat environment

This sedimentary unit presents generally the same characteristics as unit A, in which silts and light-gray clays dominate the texture of the sediment. The only differences observed from unit A are the presence of plant debris and fine chromatic variations in the deposits. While the texture is dominated by compact dark silts (>99%) in the core UTC 2, deposits between 1.80 and 2.30 m above the LMSL show a slight enrichment of sands (~1%), meaning that the MS values are higher than in lower units. A rate of sedimentation of ~0.33 cm/yr can be calculated—that is, 50% higher than for the peat.

Stratigraphic Description of the Coring Sectors by the Large Baths (Core UTC 9) and Colonnaded Street (Core UTC 7)

Cores UTC 7 and UTC 9 were extracted from a marshy zone on the northern margins of the ancient city, UTC 7 situated at +5.15 m by the edge of the marsh near the western end of the "Colonnaded Street," and core UTC 9 in the area of the Large Baths (Figure 2). In the 19th century, and even until the mid-20th century, some scholars thought the area of the Large Baths held the harbor of *Utica* (Daux, 1869; Reyniers, 1952), although this idea was rejected late 19th century onward (e.g., Torr, 1894a:46–47; Torr, 1894b) and comprehensively refuted by Picard in 1953. In order to investigate the ancient topography of this zone, and definitively refute this assumption with another method, we extracted core UTC 9 situated at +5.94 m above LMSL (Figure 3). Both cores UTC 7 and UTC 9 show comparable stratigraphy, which can be divided into two major units.

Unit A

Unit A consists of an alteration level of the substratum and/or colluvia, from the erosion of the *Utica* promontory slopes by runoff, in which are intermixed yellowish-to-beige silty and gravelly sands. This level is found between 2.35 and 3.35 m above LMSL in core UTC 7 and between 1.64 and 3.84 m above LMSL in core UTC 9. We could not drill more deeply because we hit the substratum at these depths, which firmly excluded any idea that a Phoenician harbor could have existed within the area later occupied by the Roman baths.

Unit B

Unit A is surmounted by unit B, which is silty and gray in color, and is situated between 3.5 and 4.95 m above LMSL in core UTC 7 and between 3.84 and 4.74 m above the LMSL in core UTC 9. A rapid comparison of this unit shows that it is slightly coarser in core UTC 9 (presence of sands, gravels, and oxyhydroxides of Fe and Mn) than in UTC 7, where it contains plant debris, not observed in core UTC 9.

Stratigraphic Description of an Alluvial Fan, from Core UTC 8

Core UTC 8 was extracted in a zone to the north-west of the Large Baths that was probably constructed by an alluvial fan (Figure 1). This fluvial form is characterized initially by a relatively high topographic level, situated at 5.15 m above LMSL. There is, thus, an altitudinal difference of ~60 cm with the potential harbor sector investigated by UTCs 1 and 2. Overall, the more sandy stratigraphy of this core is evidence of a more sustained hydrodynamism in this zone.

Unit A

This deposit, situated between 1.45 and 0.95 m below LMSL, consists of medium-to-coarse gray sands. Unidentified shell debris was also found in this unit.

Unit B

Unlike unit A, this sandy deposit (50–80%) located between 0.95 and 0.55 m below LMSL is yellow in color and contains no shell. This unit is situated at the same depth as the RSL determined at Gammarth (Anzidei et al., 2011).

Unit C

Unit C (0.55 m below to 0.05 m above LMSL) incorporates fine particles that give a compact aspect to this gray silty deposit (>87%). Its intermediate position between the two sea levels (RSL and the present LMSL) could

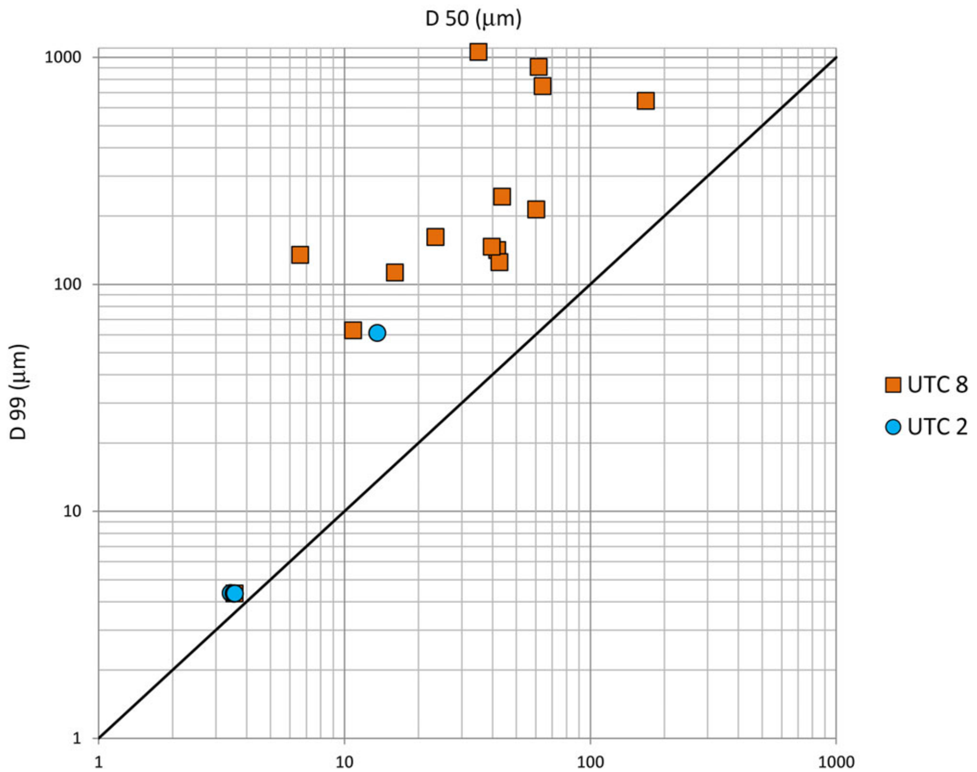

Figure 5 C/M diagram for cores UTC 2 and UTC 8.

explain the presence of oxyhydroxides of Fe and Mn resulting from fluctuations of the water table.

Unit D

Unit D is a light-blue extremely compact silty deposit (65–99%), also containing traces of Fn and Mn oxides, that contrasts strongly with the color of the main body of the deposit. This unit is situated between depths of 0.55 and 0.05 m above LMSL.

Unit E

Unit E is the largest unit in this core as it extends from the depths of 0.55 to 3.4 m above LMSL. More or less enriched in silts (~99–48.6%), sands (0 to ~50%) are well represented in this grayish deposit. This enrichment of the sandy fraction is also seen in a corresponding increase in the MS values for this unit.

Unit F

Between 3.4 and 3.95 m above LMSL, this unit is composed of more or less sandy yellow silts flecked with traces of Fe and Mn. These disappear in the upper part of the unit, between 3.95 and 4.65 m above the LMSL, where the texture of the sediment becomes coarser with yellow silty sands. Once again, the sand fraction (41.5–52%) is accompanied by an increase in the MS values.

INTERPRETATION AND DISCUSSION

The Progradation of the Delta and its Effect on the Harbor of *Utica*

At the scale of the delta we have identified a series of low-angle alluvial fans (Figures 1, 4), more or less coalescent depending on the site, characterized by an elevated and rounded topography resembling lobes. These forms follow the different beds of the Mejerda, occurring particularly at the ancient sites where the river avulsions occurred. This observation is as valid for the southern part of the delta, for the zone at the foot of jebel Maïana and at the level of the divergence points of river beds 1, 2, and 3 (Figure 1), as it is for the northern part with beds 4, 5, 6, 7, and 8 (Figure 4). Based on these observations, we can propose the hypothesis of a regime of high-intensity deltaic progradation capable of constructing such forms, on which the ancient avulsions of the Mejerda probably operated.

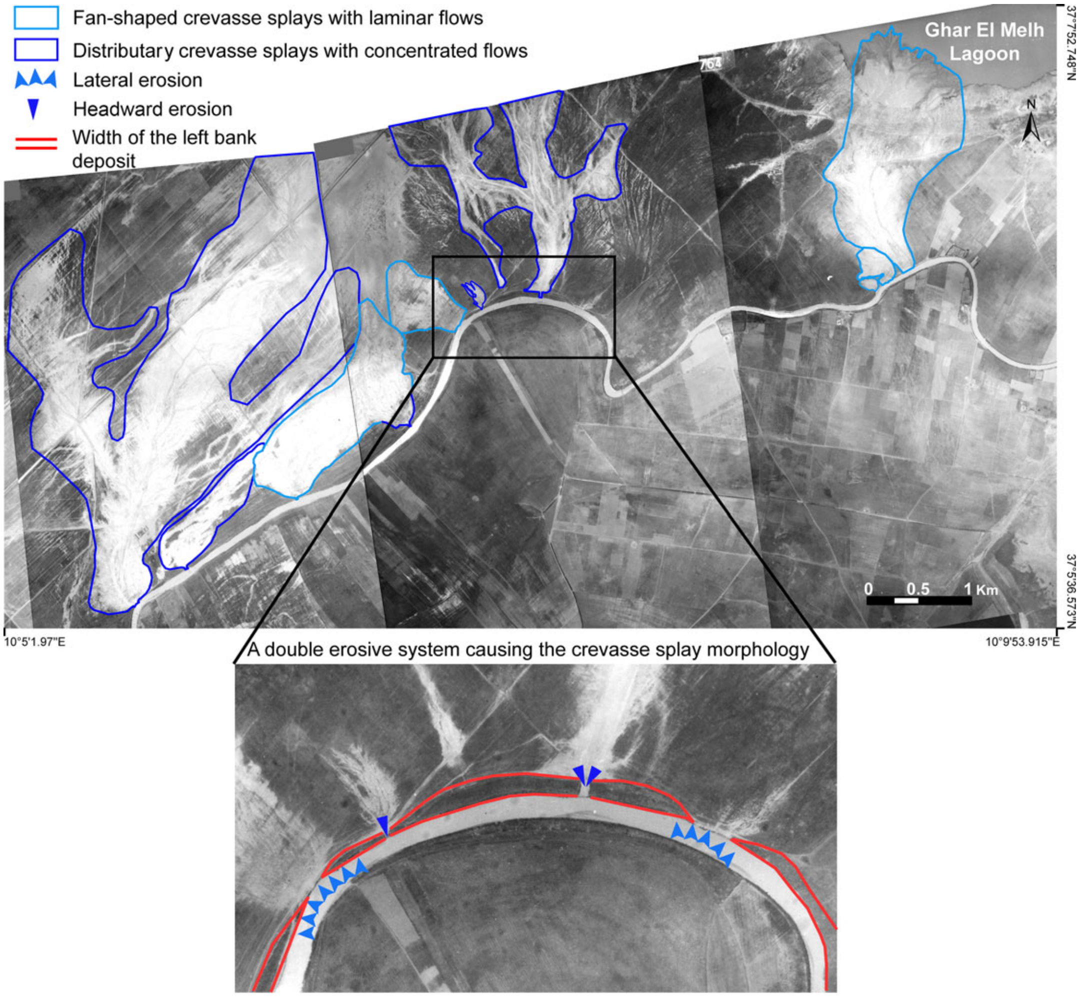

Figure 6 Crevasse splay morphologies caused by erosion: the example of the flood of June 25, 1954. With the authorization of the Service historique de la Défense du département de l'armée de l'air française.

The CM diagram (Figure 5) supports this interpretation because the deposits of the core UTC 8, located on an alluvial fan, were created by graded suspension processes, unlike backswamps. Indeed, sediments of the core UTC 2 were deposited by decantation processes related to low-intensity flows. This variability in fluvial hydrodynamism is also reflected in the MS values, which are both high on the alluvial fan of the core UTC 8 and relatively weak in the marshy zone of the core UTC 2. The very well-sorted deposits in cores UTC 2 and UTC 8 (close to the C = M straight) and the MS values support a fluvial origin for the hydro- and morphosedimentary dynamics of the delta progradation.

Systematic calculation of the slopes of the alluvial fans identified in the delta provides an average value of 1% as the crow flies and 0.7% along the line of the river. If we relate these longitudinal slopes with the highest flow of 800 m^3/s within the river channel of the Mejerda (Leca et al., 1954; Jauzein, 1971), we observe that the river should behave almost like a braided river if these parameters are placed on the model of Leopold and Wolman (1957). This graph was devised by leading American hydrogeomorphologists to predict how and why rivers assume particular changes of fluvial style (e.g., meandering, braiding, anastomosing) in relation to specific characteristics (slopes, discharges, velocities, etc.). This is a particular case of very high-energy meandering that is reflected in the fine-grained nature of the deposits and by the high cohesion of the channel banks.

According to the aerial photographs taken at the end of June 1954 (Figure 6), the avulsions began with tentacular crevasse splays, formed by regressive erosion on the levees in periods of flooding, which favor the concentration of flows. As the channels became established and the flows more and more concentrated, a main channel emerged (Morozova & Smith, 2000; Morozova, 2005). At the end of its course in the distal parts of the delta, this channel formed a subdelta in the shape of a crow's foot (Figure 6), whose distal part was shaped by the distributary bars of the river mouth. Then, the subdelta rose progressively to form a true deltaic alluvial fan (Fisk, 1944; Coleman & Gagliano, 1964; Saucier, 1994; Coleman, Roberts, & Stone, 1998), the phases of construction occurring during high-energy hydrological events (Delile et al., in press). If this model of the Mejerda delta progradation is transposed onto the paleogeographic reconstruction of the delta in the sector of the city, some hypotheses can be proposed concerning the possible location of the harbor of *Utica* and the configuration of its communication with the sea, as well as its development.

Review of the Ancient Coastline and the Paleogeographical Evolution of the Northern Part of the Mejerda Delta

At the exit of the bottleneck between the promontories of *Utica* and Kalaat El Andalous, the top of these coalescent alluvial cones lies between 6 and 10 m above LMSL (Figure 4). This sedimentary thickness would thus have buried the paleochannels responsible for the infilling of this ancient arm of the sea and of the northern compartment. In other words, beds 4, 5, and 6 (Figures 1, 4), visible on the surface and classically held responsible for this infilling (Jauzein, 1971; Paskoff, 1985, 1994; Paskoff, Slim, & Trousset, 1991; Paskoff & Trousset, 1992; Chelbi, Paskoff, & Trousset, 1995; Slim et al., 2004; Oueslati, Charfi, & Baccar, 2006) cannot be responsible because their altitude is too high. This appears to be confirmed by the fact that the sea level in the Punic–Roman period was lower by several decimeters than the present LMSL (Figure 3; Oueslati, 1995; Slim et al., 2004; Anzidei et al., 2011).

Encroachment of the Mejerda delta in the northern part of the ancient bay of Utica (12 to 4th century B.C.)

These conclusions appear to be confirmed by the archaeological surveys carried out on the delta in the 1990s (Chelbi, Paskoff, & Trousset, 1995). These revealed in particular an archaeological site that had been occupied from the Punic period (site no. 1 in Figure 4), only a few decimeters beneath the surface. We can thus definitively exclude our predecessors' hypothesis of a silting-up of the northern compartment in late Antiquity by the paleochannels visible on the surface (Paskoff & Trousset, 1992; Chelbi, Paskoff, & Trousset, 1995). Instead of this traditional short chronology, we propose a longer chronology in which the passage of the Mejerda into the northern part occurred at the latest before the end of the Punic period and perhaps even before the legendary foundation of *Utica* at the end of the 12th century B.C. (map A in Figure 7). Indeed, the Punic–Roman levels dated earlier than the 4th century B.C. (site no. 1 in Figure 4), and situated at an altitude of more than 6 m in the corridor formed by the jebels Menzel Roul and Kalaat El Andalous, show that the line of the coast in this period must have been positioned in the northern part of the delta. This altitude of more than 6 m is definitively too high to imagine the Roman–Punic coastline in this sector because shorelines are found around sea level. Thus, the harbor basins that are today preserved under the alluvia can only be situated on the northern side of the peninsula of *Utica* (Figure 7), as previous studies have suggested (Paskoff et al., 1991; Paskoff & Trousset, 1992; Paskoff, 1994; Chelbi, Paskoff, & Trousset, 1995; Slim et al., 2004), and not on the eastern side.

Infilling from east to west of the northern part of the Utica bay (4th century B.C. to 6th century A.D.)

The communication between the harbor and sea would thus have been through a marine corridor situated between the coastal alluvial fans to the west and those of the Mejerda to the east. The latter fans developed in the northern compartment during the Roman period (map B in Figure 7). This major result contrasts with previous studies (Chelbi, Paskoff, & Trousset, 1995; Paskoff & Trousset, 1992; Paskoff, 1994) that located the coastline at the exit of the bottleneck between the promontories of *Utica* and Kalaat El Andalous (map B in Figure 7). The hypothesis of a communication between the harbor and sea by this western arm of the sea is so probable that we suggest, contrary to the position of previous workers, that the passage of the Mejerda toward the north would not have constituted a threat of infilling by alluvia to the harbor basins. In fact, at the exit of the bottleneck the alluvial fans probably developed in an east–west orientation, because of the coastal drift oriented toward the south (Pimienta, 1959; Delile et al., in press).

Development of the peat bog in the ancient arm of the sea (6 to 10th century A.D.)

As the alluvial fans filled in the northern part of the bay, this marine corridor progressively shrank during the Roman period. This situation definitively isolated the city from the sea by the 6th century A.D. at the latest, as in the Middle Ages a landscape of peat bogs became established

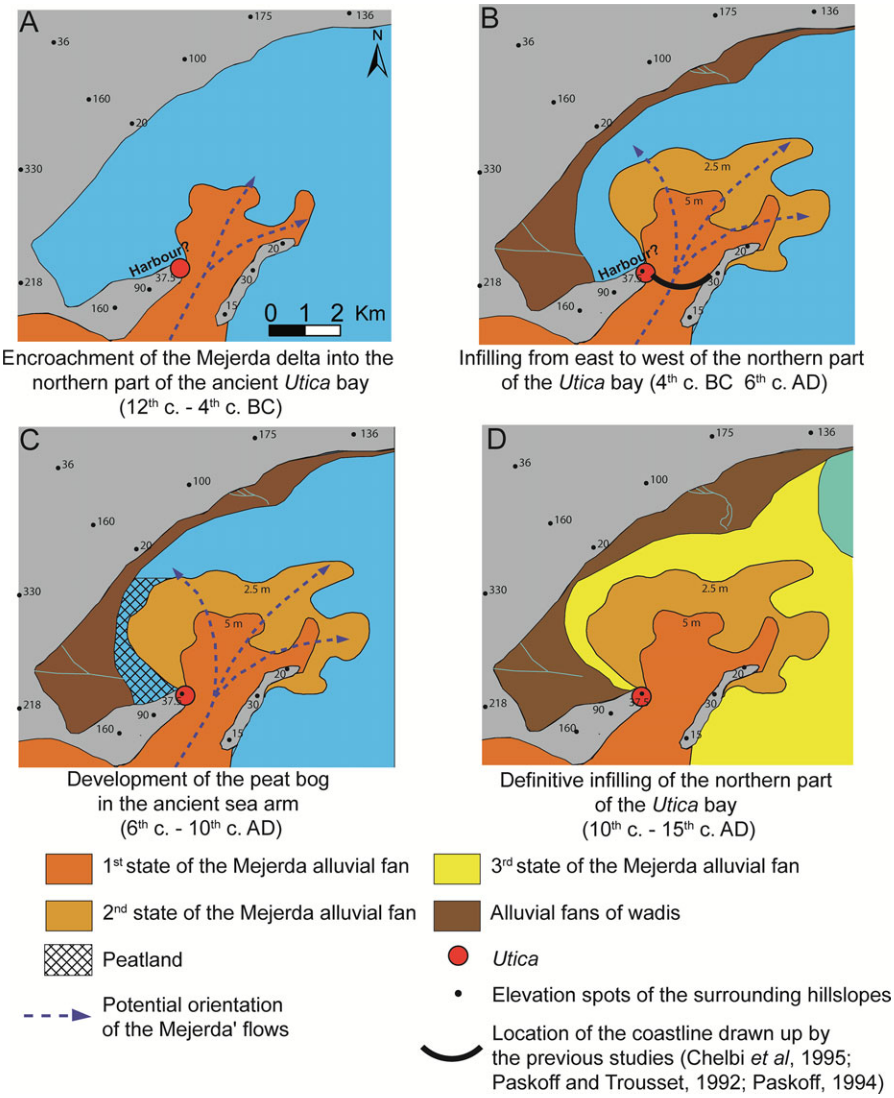

Figure 7 Four maps showing the paleogeographical evolution of the northern part of the Mejerda delta. The outline of these maps is the same as that of Figure 4.

on the northern side of the promontory of *Utica* (map C in Figure 7). The development of this landscape, starting in the early 5th/mid-6th century A.D., coincides generally with the date of abandonment of the late Roman city, perhaps in the 6th century A.D. In other words, if the harbor was situated on the northern side of the peninsula of *Utica*, it was definitively sealed off at the end of Antiquity. The disappearance of this arm of the sea and its replacement by a peat bog could also have had an influence on the occupation of archaeological sites numbers 9 to 14 (Figure 4), as they were all abandoned during the 6th and 7th centuries A.D., while they had been occupied generally since the 2nd century A.D. (Chelbi, Paskoff, & Trousset, 1995).

Definitive infilling of the northern part of the Utica bay (10 to 15th century A.D.)

At the beginning of the second half of the Middle Ages, a new change in environmental conditions took place in which the vertical accretion of the peat ended, giving way to deposits that were probably of fluvial origin. The gray plastic mud represented in unit C of cores UTC 1 and UTC 2 was deposited at least ~1.50 m above the sea level of this period. Moreover, the rate of sedimentation being more rapid by half than the accretion of the peat could indicate a new phase of rapid construction of the delta, with alluvial fans edging more and more closely to the northern side of the *Utica* promontory. In this period, it is probable that the northern compartment of the delta was mostly infilled (map D in Figure 7) as suggested by Jauzein (1971); Paskoff, Slim, and Trousset (1991); Paskoff and Trousset (1992); Paskoff (1994); and Chelbi, Paskoff, and Trousset (1995). This dynamic led to a rapid aggradation of this sector, causing the site to be ~+4.50 m above the LMSL. This proximal fluvial influence may be clearly seen in core UTC 8, taken from a relic of an alluvial fan, which has recorded a sustained period of active fluvial processes seen in the volume of sand in all its stratigraphy.

The Ancient Harbors

Definitive rebuttal of the earlier theories on the location of a pre-Roman harbor in the Large Baths and Colonnaded Street sectors

While Beulé (1861), Daux (1869), and Reyniers (1952) thought that the area of the Large Baths hosted the ancient harbor of *Utica* (Figure 2), with a basin enclosing a central island like the harbor of Carthage, the ruins here were first identified as Roman baths by Torr (1894a,b) and later studies demonstrated that they had nothing to do with a supposed Phoenician or Punic harbor (Martin, 1915; Gsell, 1920; Cintas, 1951; Picard, 1953; Lézine, 1966, 1970). In order to remove all ambiguity concerning earlier theories for the location of a pre-Roman harbor in this zone, we extracted core UTC 9 within the sunken esplanade of the baths area. The stratigraphy of this core shows very clearly that a harbor could not have been located in this zone. Likewise, core UTC 7 extracted near the western end of the colonnaded street showed that the wide linear depression later occupied by the street could never have been an arm of the sea. Indeed, unit A shows that the substratum outcrops in this sector, with its alteration levels and/or the colluvia lying only 2 m beneath the present ground surface, and over 3 m above the modern sea level, and even more above the RSL. This was solid ground in antiquity.

Hypothesis that the harbor was located on the north-west side of the Utica promontory

The paleogeographic reconstruction presented in the previous section corresponds perfectly with the information that we have concerning this sector in late antiquity. If the harbor basins were located to the northwest of the promontory, they would have been permanently out of use in this period because the peat indicates an environment in the process of silting up. Our observations thus correspond with what is known about the site for this period.

The position of this coastal peat, whose altitude is close to LMSL, indicates that the sea level rise from the Roman period reached the LMSL around late antiquity according to the peat bottom dates. Indeed, littoral peat formation occurs approximately at the same level as the sea due to its link with the phreatic system (Triat-Laval, 1978; Vella & Provansal, 2000; Lampe et al., 2010). Moreover, the location of the RSL coupled with the peat bottom dates indicate that the hypothetical levels of the harbor deposits should be found under the peat. The fact that these deposits that are earlier than the end of the Roman period are found at ~1 m under the RSL (base of the cores) indicates a draft equivalent to a maximum of ±1 m. Such a shallow depth of water renders navigation possible only for small craft, less than 50 tons (Boetto, 2010). If we extend these results toward assumptions needing to be confirmed by future research, as a result, small craft would have been needed to transfer goods between the city and the largest ships anchored in the open sea, unless the harbor also possessed constructed moles running out into deeper water.

The absence of dating for the sedimentary unit (A) beneath the peat means that the hypothesis that merchandise was transferred by lighters cannot be chronologically proven. With the caution due to the age-depth model, if we extrapolate the rate of sedimentation of 0.33 cm/yr calculated for U.S. C uniformly to unit A of core UTC 2, we obtain a model age of A.D. 130 for the base of the core. In view of what has been stated in the preceding paragraph, this would signify that if the harbor of *Utica* was located here, it started to be filled in in the 2nd century A.D. This date echoes the interpretation made by Braemer (1992) of the opening of a direct route, dated by military milestones of the reign of Hadrian (2nd century A.D.), linking the harbor of Tabarka (on the northern coast of Tunisia) to the quarry of Simitthus (ancient Chemtou) for the distribution of marble. Braemer thinks that this road was opened in the 2nd century A.D. to remedy the inevitable loss of the harbor of *Utica* which, according to the evidence of a stone-paved road linking the quarries of Simitthus to the left bank of the river (Khanoussi, 1994), originally provided a regional outlet for the products coming from the upper valley of the Mejerda. However, without any direct dating from the base of the cores, it is difficult to conclude that the harbor was no longer in use by the time of the High Roman Empire. Consequently, these assumptions concerning the location and the depth of the harbor basin require more investigations, and in particular deeper cores need to be taken on the northwest side of the Utica promontory.

CONCLUSIONS

This geoarchaeological and geo-historical study of the delta of the Mejerda provides a basis for the reconstruction of the processes involved in the deltaic progradation of this river, whose avulsions leading to the formation of deltaic alluvial fans appear to be the principal cause. The combination of the processes acting on these deltaic alluvial fans and the archaeological data available suggests that the passage of the Mejerda into the northern compartment of its delta occurred at the latest before the Punic period and possibly even before the legendary founding of *Utica* in the 12th century B.C. For this reason, the harbor basins of *Utica* could only have been located on the northern side of the *Utica* peninsula, where communication with the sea would have been through an ancient sea corridor located to the west of the northern part. In other words, it is unlikely that the harbor of *Utica* could have been located on the southeast side of the peninsula. As the alluvial fans at the mouth of the river thickened and progressively filled the northern part of the *Utica* Bay, this ancient sea corridor became narrower in the Roman period and completely disappeared in the early 5th/mid-6th century A.D. In this period a peat bog developed on the northern side of the *Utica* promontory and thus sealed the fate of *Utica* as a maritime harbor.

The series of cores taken have excluded the idea of a location for the harbor in the sunken esplanade around the Large Baths, because of a substratum that outcrops at less than 2 m from the present ground surface, above RSL. However, the sector slightly to the north has shown that the deposits situated under the medieval peat could be those of the harbor levels, because the bases of cores UTC 1 and UTC 2 suggest a draft of ± 1 m, which is enough for small sea craft. This last hypothesis could be tested by future research based on a new coring campaign, and by modeling of currents and sedimentary processes (Millet, Tronchère, & Goiran, 2014; Seeliger et al., 2014). Nevertheless, for the first time, these GIS and geoarchaeological approaches have improved our understanding of the northwest side of the *Utica* promontory, both inside and outside the marshes.

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REFERENCES

Anzidei, M., Antonioli, F., Lambeck, K., Benini, A., Soussi, M., & Lakhdar, R. (2011). New insights on the relative sea level change during Holocene along the coasts of Tunisia and western Libya from archaeological and geomorphological markers. Quaternary International, 232, 5–12.

Beulé, C.-E. (1861). Fouilles à Carthage. Paris, France: Imprimerie impériale.

Blaauw, M. (2010). Methods and code for "classical" age-modelling of radiocarbon sequences. Quaternary Geochronology, 5, 512–518.

Boetto, G. (2010). Le port vu de la mer: L'apport de l'archéologie navale à l'étude des ports antiques (pp. 112–128). Presented at the XVII International Congress of Classical Archaeology, Vol. special issue. Roma: Bolletino di Archeologia On line.

Braemer, F. (1992). Les gisements de pierres à l'époque romaine. Méthodes, état de la question. (pp. 227–234). Presented at the 117e Congrès National Société Savante. Clermont-Ferrand, Paris: CTHS.

Bravard, J.-P., & Peiry, J.-L. (1999). The CM pattern as a tool for the classification of alluvial suites and floodplains along the river continuum. In Floodplains: Interdisciplinary Approaches (pp. 259–268), Vol. 163. London: S.B. Marrott and J. Alexander.

Chelbi, F., Paskoff, R., & Trousset, P. (1995). La baie d'Utique et son évolution depuis l'Antiquité: Une réévaluation géoarchéologique. Antiquités Africaines, 31, 7–51.

Cintas, P. (1951). Deux campagnes de fouilles à Utique. Karthago. Revue d'archéologie africaine, 2, 5–88.

Coleman, J.M., & Gagliano, S.M. (1964). Cyclic sedimentation in the Mississippi River deltaic olain. Gulf Coast Association of Geological Societies Transactions, 14, 67–80.

Coleman, J.M., Roberts, H.H., & Stone, G.W. (1998). Mississippi River delta: An overview. Journal of Coastal Research, 14, 698–716.

Daux, A. (1869). Recherches sur l'origine et l'emplacement des emporias phéniciens dans le Zeugis et le Byzacium (pp. 1–145). Paris: Impr. Imperial (Pairs).

David, L. (1956). Etude géologique des monts de la haute Medjerda. Alger: Service de la carte géologique de l'Algérie.

Dearing, J.A. (1999). Environmental magnetic susceptibility. Using the Bartington MS2 System (pp. 32–54). Kenilworth: Chi Publishing.

Delile, H., Goiran, J.-P., & Bravard, J.-P. (In press). Contribution du SIG à la reconstitution des processus de progradation de la Majerda: Quels enjeux pour le port d'Utique? In Actes du premier colloque organisé par l'Association pour l'Étude du Quaternaire en Tunisie (p. 23). Presented at the ATEQ First Meeting. Tunis.

Delile, H., Mazzini, I., Blichert-Toft, J., Goiran, J.-P., Arnaud-Godet, F., Salomon, F., & Albarède, F. (2014). Geochemical investigation of a sediment core from the Trajan basin at Portus, the harbor of ancient Rome. Quaternary Science Reviews, 87, 34–45.

Delile, H., Blichert-Toft, J., Goiran, J.-P., Stock, F., Arnaud-Godet, F., Bravard, J.-P., Brückner, H., & Albarède, F. (2015). Demise of a harbor: A geochemical chronicle from Ephesus. Journal of Archaeological Science, 53, 202–213.

Fentress, E., Ghozzi, F., Quinn, J., & Wilson, A. (2012). Excavations at Utica by the Tunisian-British Utica Project 2012 (pp. 1–27).

Fisk, H.N. (1944). Geological investigation of the alluvial valley of the lower Mississippi River (p. 170). Vicksburg, M S: Mississippi River Commission.

Goiran, J.P., & Morhange, C. (2003). Géoarchéologie des ports antiques de Méditerranée: Problématiques et études de cas. Topoï, 11, 645–667.

Goiran, J.-P., Salomon, F., Mazzini, I., Bravard, J.-P., Pleuger, E., Vittori, C., Boetto, G., Christiansen, J., Arnaud, P., Pellegrino, A., Pepe, C., & Sadori, L. (2014). Geoarchaeology confirms location of the ancient harbour basin of Ostia (Italy). Journal of Archaeological Science, 41, 389–398.

Gsell, S. (1920). Histoire ancienne de l'Afrique du Nord, vol. 2. L'état carthaginois. Paris: Librairie Hachette.

Jauzein, A. (1971). Les agents de la morphogenese: Document évolution récente du delta de la Medjerda (Tunisie), Vol. 5. Paris: Travaux du laboratoire de géologie de l'ENS.

Kallala, N., Fentress, E., Quinn, J.C., & Wilson, A. (2010). Survey and excavation at Utica.

Khanoussi, M. (1994). Note préliminaire sur le praesidium. In Der Tempelberg und das römische lager, Simitthus III (pp. 241–247). Mainz: DAI et INP.

Lampe, R., Endtmann, E., Janke, W., & Meyer, H. (2010). Relative sea-level development and isostasy along the NE German Baltic Sea coast during the past 9 ka. Quaternary Science Journal, 59, 3–20.

Leca, A., Valiron, F., Rolland, L., Cintas, J., & Tron, M. (1954). La mise en valeur de la vallée de la Medjerda. Tunis: Imprimerie La Rapide.

Leopold, L.B., & Wolman, M.G. (1957). River channel patterns: Braided, meandering, and straight. Washington: U.S. Govt. Print. Off.

Lézine, A. (1966). Utique: Notes de topographie (Mélanges d'archéologie et d'histoire offerts à André Piganiol., Vols. 1-1). France.

Lézine, A. (1970). Utique, Vols. 1-1. Tunis, Tunisie: Société tunisienne de diffusion.

Marriner, N. (2007). Paléoenvironnements littoraux du Liban à l'Holocène - Géoarchéologie des ports antiques de Beyrouth, Sidon et Tyr 5000 ans d'interactions nature-culture. Université Aix-Marseille I.

Marriner, N., Morhange, C., & Goiran, J.-P. (2010), Coastal and ancient harbour geoarchaeology. Geology Today, 26(1), 21–27.

Martin, J. (1915). Reconnaissance des antiquités préhistoriques de Chaouach: Dédicace romaine à Thala; fouilles à Utique. Bulletin archéologique du Comité des travaux historiques et scientifiques: xcvi-xcviii. Monchambert, J.-Y., Jerbania, I.B., Belarbi, M., Bonadies, L., Bricchi-Duhem, H., Jonghe, M.D., Gallet, Y., Nacef, J., Sghaïer, Y., Tekki, A., Thébault, E., Vermeulen, S., 2013. Utique. Rapport préliminaire sur les deux premières campagnes de fouilles de la mission franco-tunisienne, 2011 et 2012. Chronique des activités archéologiques de l'École française de Rome 57.

Mejri, L. (2012). Tectonique Quaternaire, paléosismicité et sources sismogéniques en Tunisie Nord-orientale: Etude de la faille d'Utique. Université Toulouse 3 Paul Sabatier et Université de Tunis El Manar.

Mejri, L., Regard, V., Carretier, S., Brusset, S., & Dlala, M. (2010). Evidence of quaternary active folding near Utique (Northeast Tunisia) from tectonic observations and a seismic profile. Comptes Rendus Geoscience, 342(11), 864–872.

Millet, B., Tronchère, H., & Goiran, J.-P. (2014), Hydrodynamic modeling of the Roman harbor of Portus in the Tiber Delta: The impact of the north-eastern channel on current and sediment dynamics. Geoarchaeology, 29, 357–370.

Morhange, C. (1994). La mobilité récente des littoraux provençaux: Eléments d'analyse géomorphologique. Université de Provence, Aix-en-Provence.

Morhange, C., Vecchi, L., Stefaniuk, L., Goiran, J.P., Bui Thi Maï, B.M., Carbonel, P., & Oberlin, C. (2001). Il problema della localizzazione del porto greco antico di Cuma: nuovi metodi e risultati preliminari. Cuma, Nuove forme di intervento per lo studio del sito antico, Atti della Giornata di Studio, Napoli, 12, 153–165.

Morhange, C., Marriner, N., Excoffon, P., Bonnet, S., Flaux, C., Zibrowius, H., Goiran, J.-P., & Amouri, M.E. (2013). Relative sea-level changes during Roman times in the Northwest Mediterranean: The 1st century A.D. fish tank of Forum Julii, Fréjus, France. Geoarchaeology, 28, 363–372.

Morozova, G.S. (2005). A review of Holocene avulsions of the Tigris and Euphrates Rivers and possible effects on the evolution of civilizations in lower Mesopotamia. Geoarchaeology, 20, 401–423.

Morozova, G.S., & Smith, N.D. (2000). Holocene avulsion styles and sedimentation patterns of the Saskatchewan

River, Cumberland Marshes, Canada. Sedimentary Geology, 130, 81–105.
Oueslati, A. (1995). The evolution of low Tunisian coasts in historical times: From progradation to erosion and salinization. Quaternary International, 29–30, 41–47.
Oueslati, A., Charfi, F., & Baccar, F. (2006). Presentation of the Tunisian site: La basse vallée de l'oued Majerda et la lagune de Ghar El Melh (p. 26). Presented at the Wadi project, Water Demand Integration, Fifth International Meeting, Tunis.
Paskoff, R. (1985). Les littoraux. Impact des aménagements sur leur évolution (Masson). Paris.
Paskoff, R. (1994). Le delta de la Medjerda (Tunisie) depuis l'Antiquité. Etudes Rurales, 133, 15–29.
Paskoff, R., & Oueslati, A. (1988). Acquisitions récentes à propos du quaternaire supérieur des côtes de la Tunisie. Méditerranée, 64(2), 79–84.
Paskoff, R., & Trousset, P. (1992). L'ancienne baie d'Utique: Du témoignage des textes à celui des images satellitaires. Mappemonde, 1, 30–34.
Paskoff, R., Slim, H., & Trousset, P. (1991). Le littoral de la Tunisie dans l'Antiquité: cinq ans de recherches géo-archéologiques. Comptes-rendus des séances de l'Académie des inscriptions et belles-lettres, 135, 515–546.
Passega, R. (1957). Texture as characteristic of clastic deposition. American Association of Petroleum Geologists, 41, 1952–1984.
Picard, G.C. (1953). Un pretendu port à Utique. Revue Archéologique, 52, 105–106.
Pimienta, J. (1959). Le cycle pliocène-Actuel dans les bassins paraliques de Tunis. France: Université de Paris.
Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., vander Plicht, J., & Weyhenmeyer, C.E. (2009). IntCal09 and Marine09 radiocarbon age calibration curves, 0–50000 years cal BP. Radiocarbon, 51, 1111–1150.
Reyniers, F. (1951). Note sur le comblement de la Basse Medjerdah. Tunis, Tunisie: Saliba.
Reyniers, F. (1952). Port à Utique. Alger, Algérie.
Salomon, P., Delile, H., Goiran, J.-P., Bravard, J.-P., & Keay, S. (2012). The Canale di Comunicazione Traverso in Portus: The Roman sea harbour under river influence (Tiber delta, Italy). Géomorphologie, 75–90.
Saucier, R.T. (1994). Geomorphology and quaternary geologic history of the Lower Mississippi Valley (p. 414). Vicksburg, M S: U. S. Army Corps of Engineers.
Seeliger, M., Brill, D., Feuser, S., Bartz, M., Erkul, E., Kelterbaum, D., Vött, A., Klein, C., Pirson, F., & Brückner, H. (2014). The purpose and age of underwater walls in the Bay of Elaia of Western Turkey: A multidisciplinary approach. Geoarchaeology, 29, 138–155.
Slim, H., Trousset, P., Paskoff, R., & Oueslati, A. (2004). Le littoral de la Tunisie, Etude géoarchéologique et historique (CNRS, p. 308). Paris.
Tissot, C.J. (1884). Géographie comparée de la province romaine d'Afrique (S. Reinach, Ed.). Paris, France.
Torr, C. (1894a). Les ports de Carthage. Revue Archéologique, 20, 32–47.
Torr, C. (1894b). Les ports de Carthage. Revue Archéologique, 20, 294–307.
Triat-Laval, H. (1978). Contribution pollenanalytique à l'histoire tardi-and postglacaire de la végétation de la Basse vallée du Rhône. Université d'Aix-Marseille III.
Vella, C., & Provansal, M. (2000). Relative sea-level rise and neotectonic events during the last 6500 yr on the southern eastern Rhone delta, France. Marine Geology, 170, 27–39.
Vogt, J. (1993). Further research on the historical seismicity of Tunisia. Terra Nova, 5, 475–476.

