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ANCENE-47; No. of Pages 6

ARTICLE IN PRESS

Anthropocene xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Anthropocene

journal homepage: www.elsevier.com/locate/ancene

Short communication

Evolution of Chilia lobes of the Danube delta: Reorganization of deltaic processes under cultural pressures

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ARTICLE INFO

Article history:
Received 12 June 2014
Received in revised form 20 July 2014
Accepted 23 July 2014

Keywords:
Deltas
Avulsion
Land use
Ottoman Empire
Columbian Exchange

ABSTRACT

The growth of Chilia deltaic lobes reflects a drastic reorganization of the Danube delta that accompanied its rapid expansion in the late Holocene. Using new cores collected at the apices of the two older Chilia lobes, together with historical maps and satellite photos, we find that a partial avulsion since ~1500 years BP led to a gradual rejuvenation of the Chilia distributary. This process led to the successive infilling of a lake and a lagoon and subsequently to the construction of an open coast lobe at the Black Sea coast. The Chilia branch became the largest Danube distributary, reaching its maximum sediment load in the last 300 years as the southernmost St. George branch lost its previous dominance. Here, we propose that the intensive deforestation of Danube's lower watershed leading to this delta reorganization has historical cultural causes: an increase in sheep and timber demand associated to the Ottoman Empire expansion in Eastern Europe followed by the adoption of maize agriculture as a result of the Columbian Exchange. Rapid industrialization-driven damming during the Communist Era led to the current generalized sediment deficit for the Danube. Under these conditions, the modern Chilia lobe is rapidly remodeled by waves and may join the Sulina coast to impede navigation on the Sulina canal.

Human impacts in the Danube delta

Watershed deforestation over the last two millennia led to the rapid expansion and morphological diversification of the Danube delta (Fig. 1) coupled with a complete transformation of the ecosystem in the receiving marine basin, the Black Sea (Giosan et al., 2012). During this period the central wave-dominated lobe of Sulina was slowly abandoned and the southernmost arm of the Danube, the St. George, was reactivated and started to build its second wave-dominated delta lobe at the open coast. Simultaneously, secondary distributaries branching off from the St. George branch built the Dunavatz bayhead lobe into the southern Razelm lagoon (Fig. 1). This intense deltaic activity accompanied drastic changes in Danube's flow regime. Many small deltas had grown during intervals of enhanced anthropogenic pressure in their watersheds (Grove and Rackham, 2001; Maselli and Trincardi, 2013). However, finding specific causes, whether natural or anthropogenic, for such a sweeping reorganization of a major delta built by a continental-scale river like Danube requires detailed reconstructions of its depositional history. Here we provide a first look at the Danube's deltaic reorganization along its main distributary, the Chilia, and discuss potential links to hydroclimate, population growth and cultural changes in the watershed. For this reconstruction, we used sediment core-based depositional histories together with a morphological analysis of historical cartographic material and recent satellite photography (see complete methods in Supplementary data).

History of Chilia delta lobes

The Chilia arm, which flows along the northern rim of Danube delta (Fig. 1), has successively built three lobes (Antipa, 1910) and it was first mapped in detail at the end of the 18th century (Fig. 2a). The depositional architecture of these lobes was controlled by the entrenched drainage pattern formed during the last lowstand in the Black Sea, by the pre-Holocene loess relief developed within and adjacent to this lowstand drainage and by the development of Danube's own deltaic deposits that are older than Chilia's (Ghenea and Mihailescu, 1991; Giosan et al., 2006, 2009; Carozza et al., 2012a). The oldest Chilia lobe (Fig. 2b and c) filled the Pardina

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http://dx.doi.org/10.1016/j.ancene.2014.07.003
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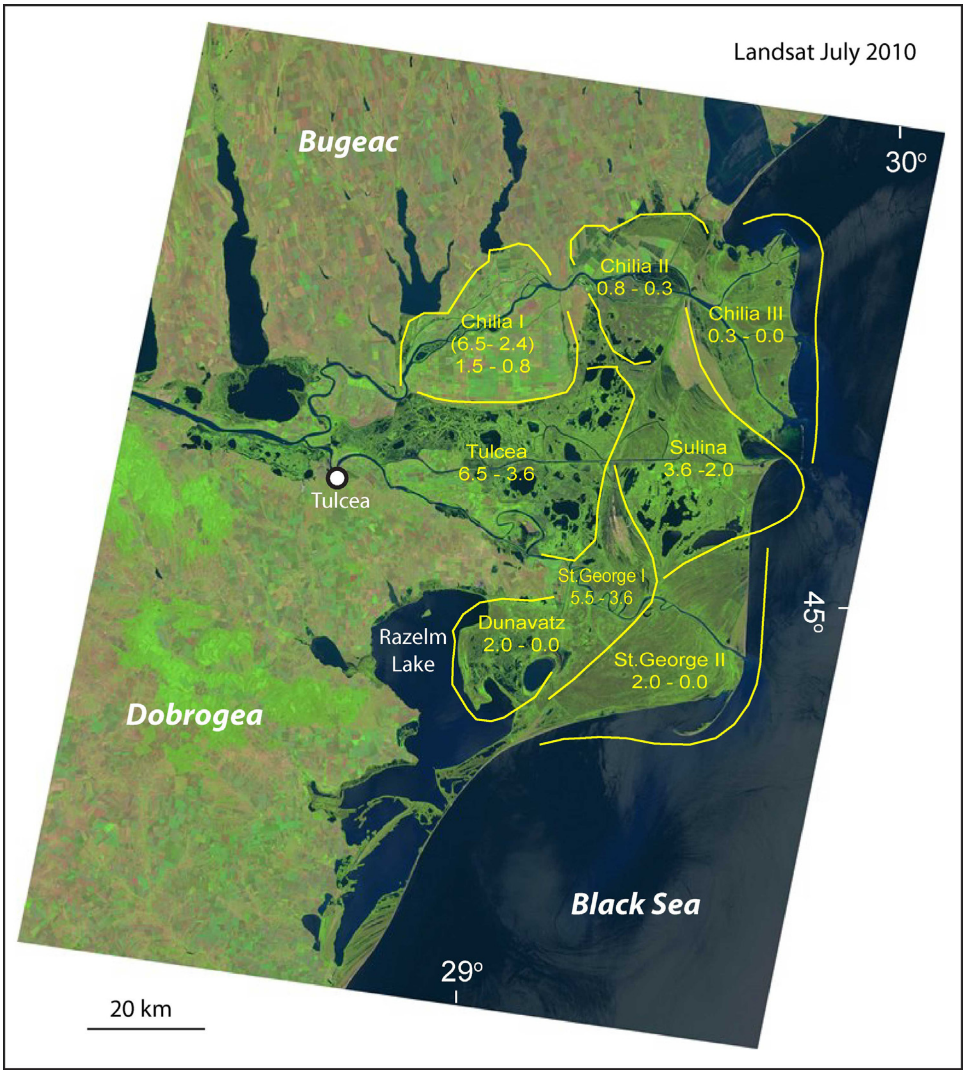

Fig. 1. Danube delta geography and its evolution phases (modified from Giosan et al., 2013). Yellow lines delineate delta lobes in the order of their build-up (Giosan et al., 2006, 2009 and results herein): (1) Tulcea, (2) Chilia I, (3) St. George I, (4) Sulina, (5) St. George II, (6) Dunavatz, (7) Chilia II, and (8) Chilia III. Estimated ages for the development of each lobe (Giosan et al., 2006, 2012 and present study) are given below each lobe name in cal. ka BP.

basin, which, at the time, was a shallow lake located at the confluence of two pre-Holocene valleys (i.e., Catlabug and Chitai) incised by minor Danube tributaries. This basin was probably bounded on all sides by loess deposits including toward the south, where the Stipoc lacustrine strandplain overlies a submerged loess platform (Ghenea and Mihailescu, 1991). Because most of the Chilia I lobe was drained for agriculture in the 20th century, we reconstructed the original channel network (Fig. 2b) using historic topographic maps (CSADGGA, 1965) and supporting information from short and drill cores described in the region (Popp, 1961; Liteanu and Pricajan, 1963).

The original morphology of Chilia I was similar to shallow lacustrine deltas developing in other deltaic lakes (Tye and Coleman, 1989) with multiple anastomosing secondary distributaries (Fig. 2b). Bounded by well-developed natural levee deposits, the main course of the Chilia arm is centrally located within the lobe running WSW to ENE. Secondary channels bifurcate all along this course rather than preferentially at its upstream apex. This channel network pattern suggests that the Chilia I expanded rapidly as a river dominated lobe into the deepest part of the paleo-Pardina lake. Only marginal deltaic expansion occurred northward into the remnant Catlabug and Chitai lakes and flow leakage toward the adjacent southeastern Matita-Merhei basin appears to have been minor. Secondary channels were preferentially developed toward the south of main course into the shallower parts of this paleo-lake (Ghenea and Mihailescu, 1991). As attested by the numerous unfilled ponds (Fig. 2b), the discharge of these secondary channels must have been small. All in all, this peculiar channel pattern suggests that the Chilia loess gap located between the Bugeac Plateau and the Chilia Promontory (Fig. 2b) already existed before Chilia I lobe started to develop. A closed Chilia gap would have instead redirected the lobe expansion northward into Catlabug and Chitai lakes and/or south into the Matita-Merhei basin.

The growth chronology for the Chilia I lobe has been unknown so far. Our new 6.5 m long KP1/K1 vibracore collected in a drained pond near the apex of the Chilia I lobe shows two cycles of interdistributary fine grained deposits (Fig. 3). In the first cycle between 6250 ± 250 and 2600 ± 250 years BP, sedimentation was slower (~1 m/ka) compared to the second cycle after 1470 ± 60 years BP (~2 m/ka). This depositional history shows that the Chilia I lobe developed in two phases. A smaller proto-Chilia distributary started the lobe growth after 6500 years BP in the same time as the Tulcea bayhead lobe grew adjacently to the south (Carozza et al., 2012b).

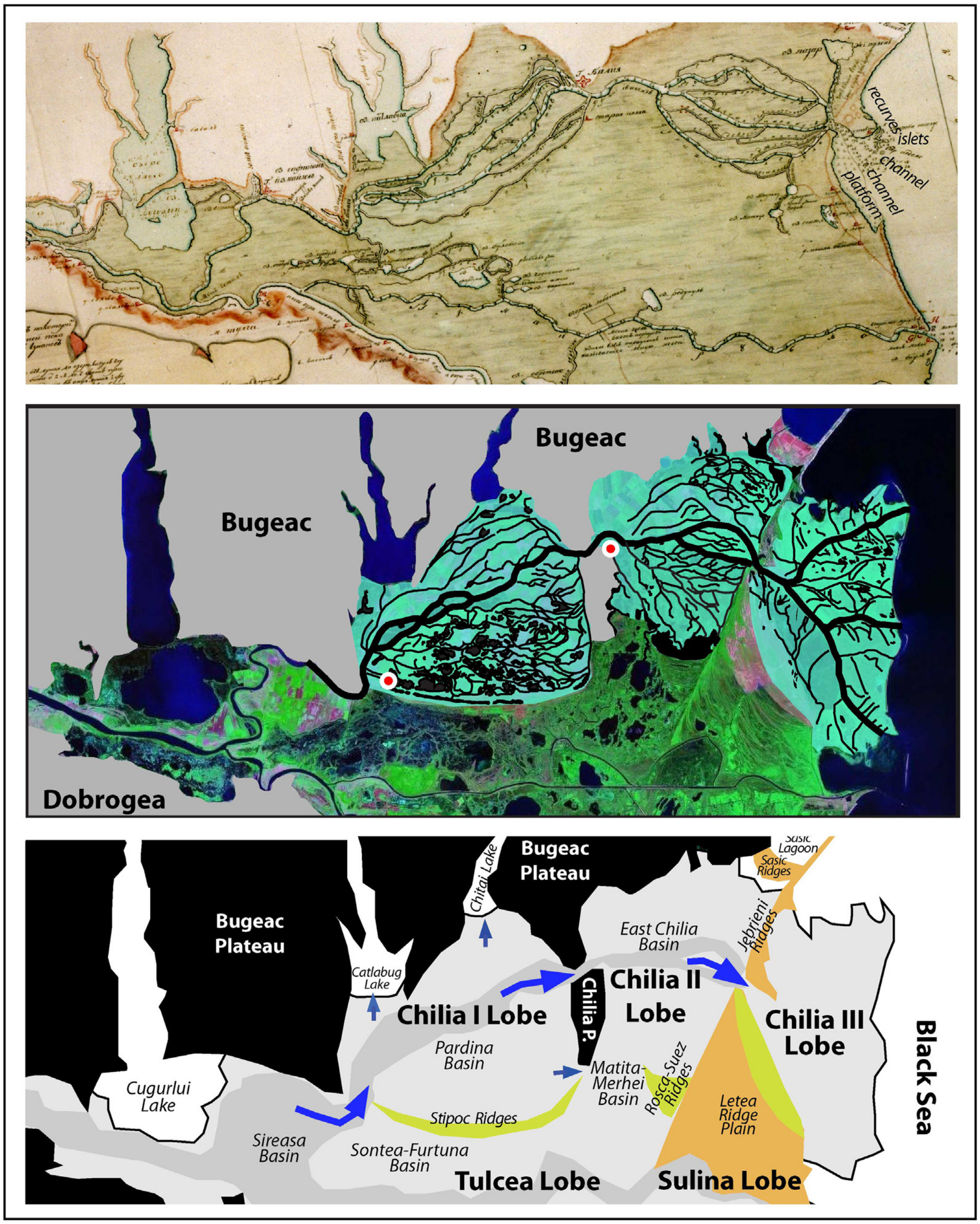

Fig. 2. The Chilia delta lobes. Upper panel (a): the Chilia I and II lobes and the incipient wave deflected Chilia III lobe in a map from 1771. Annotations indicate the main morphological features at the Chilia mouth (see main text). Middle panel (b): the channel network and pond distribution for the three Chilia lobe. Locations of new cores discussed are shown with red dots. Lower panel (c): generalized morphology of Chilia lobes and adjacent bounding features: hinterland (in black); levees and meander belts for the main Danube distributaries (in dark gray); interdistributary basins (light gray); beach ridges (Danubian sediments in light brown and non-Danubian or mixed sediments in dark brown). Larger blue arrows indicate the main course of the Chilia branch through major gaps in antecedent relief whereas smaller arrows show minor flow leakages. (For interpretation of the references to color in this text, the reader is referred to the web version of the article.)

Occurrence of benthic foraminifera (i.e., *Ammonia* sp.) at the base of our core indicates that the Pardina basin was connected to the sea at the time. Because contemporary deposits of the Tulcea lobe to the south record only freshwater fauna (Carozza et al., 2012b) this connection of the Pardina basin to the Black Sea was probably located at the Chilia loess gap. The hiatus between the two deltaic cycles (Fig. 3) indicates that the proto-Chilia distributary diminished its discharge or ceased to be active after ~2600 years BP and was reactivated or rejuvenated after ~1500 years BP. By the time that this new distributary began to build a new lobe beyond the Chilia loess gap, the growth of Chilia I lobe was probably largely completed.

Chilia II lobe presents a typical bayhead delta morphology (e.g., Bhattacharya and Walker, 1992) with multiple distributaries bifurcating primarily at its apex at the Chilia loess gap (Fig. 2b). This channel network pattern, along with a lack of interdistributary ponds, suggests that the new lobe developed by filling the East Chilia basin in a sweeping and rapid west-to-east migration. Although most of the Chilia water flows now along several central anastomosing channels, natural levee deposits are less developed than in the older upstream lobe. Lack of secondary channels intruding into the basins south or north of the East Chilia basin (Fig. 2c) suggests that the basin was completely confined as the Chilia II lobe grew. The Letea strandplain and the Jebrieni spit

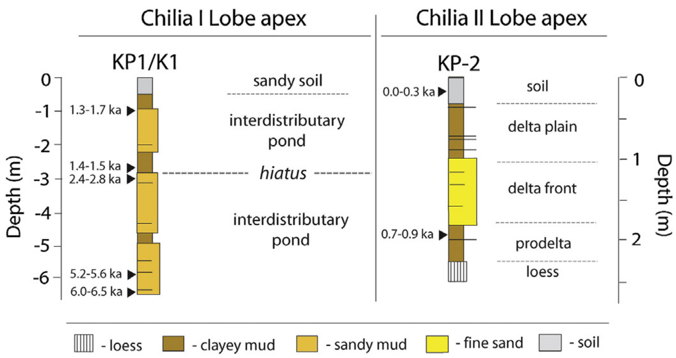

Fig. 3. Interpreted logs of cores KP1/K1 and KP2 from near the apices of Chilia I and II lobes respectively. Ages are from radiocarbon ages on articulated molluscs in cal. ka BP.

separated the East Chilia basin from the Black Sea whereas the Tulcea lobe extension into the Matita-Merhei basin along with the Rosca-Suez strandplain confined the basin in the south and the lagoonal Sasic strandplain confined it in the north.

The presence of marine fauna such as foraminifera (*Ammonia* sp.) and bivalves (*Cardium edule*) above loess deposits at the base of our core collected at the apex of the Chilia II lobe (Fig. 2) indicates that the East Chilia basin was initially a lagoon connected to the Black Sea. Above the fine grained lagoon sediments, the deposits of the Chilia II lobe exhibit a typical but thin succession of fine prodelta deposits and delta front sands with interstratified muds that are capped by organic-rich fines of the delta plain and soil. A radiocarbon date at the base of the delta front deposits indicates that the Chilia II lobe started to grow at this proximal location at 800 ± 130 years BP (Giosan et al., 2012). Once it filled the East Chilia basin, the rejuvenated Chilia distributary began to flow directly into the Black Sea building its third lobe.

The Chilia III lobe begun developing at the open coast sometimes around 1700 AD (Mikhailova and Levashova, 2001). Although still primitive, the earliest realistically detailed map of the Danube delta region dating from 1771 (Fig. 2a; Panin and Overmars, 2012) provides important information about the earliest growth phase of the lobe. Its wave-dominated deflected morphology (*sensu* Bhattacharya and Giosan, 2003) is evident. Two thalwegs at the mouth separated by a submerged middle-ground bar are oriented southward in the direction of the dominant longshore drift. Updrift of the mouth, the offshore-recurving shape of the contemporary Jebrieni beach plain ridges clearly indicates that the submarine deltaic deposition was already significant. Only a few islets were emergent on the updrift side of the submarine channel, but a shallow submerged depositional platform appears to have developed on its downdrift side (Fig. 2a). Subsequently, as recorded in numerous maps and charts since 1830 (Fig. 4a), the Chilia III lobe evolved as a typical river-dominated delta in a frictional regime, which has led to repeated bifurcations via formation of middle-ground bars (Giosan et al., 2005).

The influence of the longshore drift, expressed as a southward deflection of main distributary of Old Stambul, remained noticeable until the end of the 19th century as documented by a survey in 1871 (Fig. 4a). The isometric shape of the lobe acquired after that time resulted from the infilling of the shallow bay left between the deflected part delta plain and the mainland (Fig. 4a). Throughout the history of Chilia III growth, deltaic progradation was favored at northern Oceacov mouth, which advanced into the dominant direction of the waves, and the southern Old Stambul distributary mouth, which grew in the direction longshore drift. Slower progradation is evident along the central coast (Fig. 4a) fed by eastward directed distributaries that had to contend with the strong longshore drift removing sediments southward (Giosan et al., 2005). The decrease in new fluvial sediment delivered per unit shoreline as the lobe grew larger and advanced into deeper water resulted in progressively slower growth of the entire lobe in the 20th century (Fig. 4a). By 1940, clear signs of erosion were apparent, and a general erosional trend continues until today leading to a wave-dominated morphology characterized by barrier islands and spit development (Fig. 4b and c).

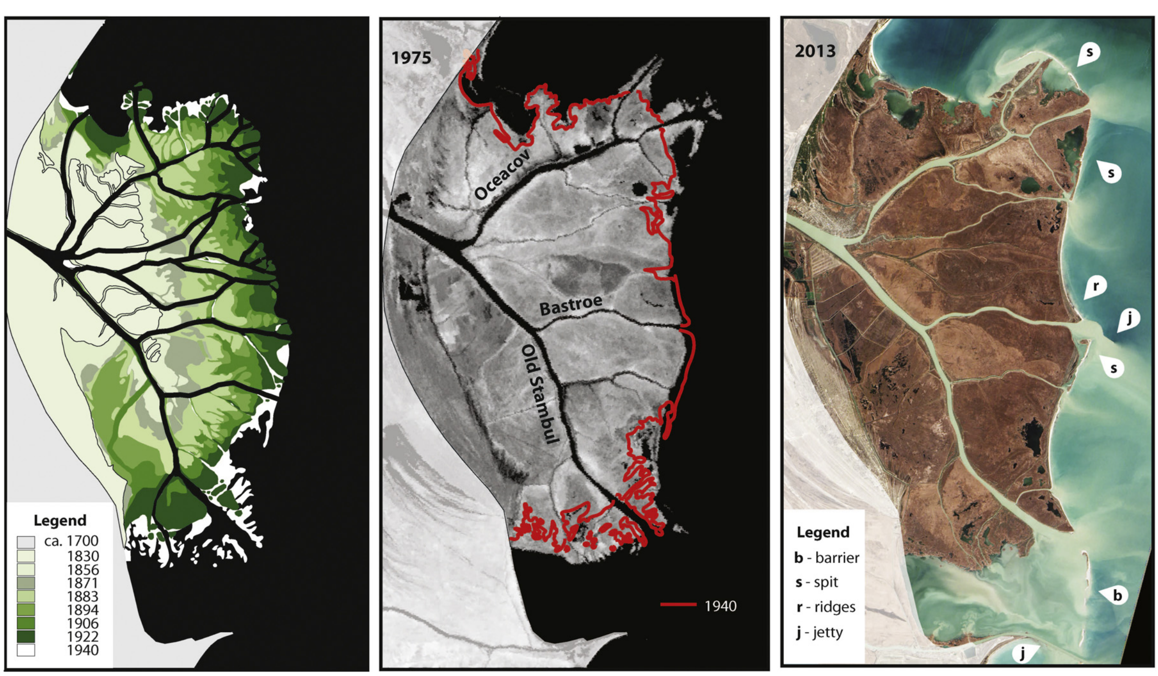

Fig. 4. Evolution of the modern Chilia III lobe. Left panel (a): the pattern of lobe growth between 1830 and 1940 (after Giosan et al., 2005); middle panel (b): changes at the coast of Chilia III lobe under wave dominance between 1940 and 1975 (the main secondary distributaries of Oceacov, Bastroe and Old Stambul discussed in text are indicated; right panel (c): marked current wave controlled features of the lobe (beach ridges, barrier spits and islands) are indicated together with jetties built at Bastroe and Sulina mouths. In the lower right corner the Musura barrier is indicated by "b" and Sulina jetties by "j".

Please cite this article in press as: Filip, F., Giosan, L., Evolution of Chilia lobes of the Danube delta: Reorganization of deltaic processes under cultural pressures. Anthropocene (2014), http://dx.doi.org/10.1016/j.ancene.2014.07.003

Causes for Danube delta reorganization

Our reconstruction of the Chilia lobe evolution supports the idea that the rapid Danube delta growth in the late Holocene (Giosan et al., 2012) led to its radical reorganization via flow redistribution across the delta. Initially the southernmost St. George branch was reactivated around 2000 years BP and constructed the bulk of its wave-dominated open coast lobe (Fig. 1) in the last 1000–1500 years (Giosan et al., 2006, 2012), which is roughly the same time that the Chilia distributary was reactivated. Assuming that the first Chilia lobe was partially built during its first depositional cycle, the estimated rate of sediment deposition for the entire lobe must have been less than 5.9 MT/year (see Supplementary data). Subsequently, during the Chilia II lobe growth to completion, the depositional rate remained similar at ~4.5 MT/year but it increased by an order of magnitude to over 60 MT/year during the open coast Chilia III lobe growth phase (Table 2 in Supplementary data). Thus, Danube's partial avulsion that reactivated the Chilia branch was gradual since the 8th century BC and its discharge reached its maximum only around 1700 AD.

This sustained increase in sediment load brought down by the Danube to the delta was explained by Giosan et al. (2012) by an increase in erosion in the lower watershed. Ecological changes in the Black Sea best constrain the age of the maximum sediment load to the last 700–600 years, when an upsurge in soil-derived nutrients (i.e., Si, N) lead to the makeover of the entire marine ecosystem (Giosan et al., 2012; Coolen et al., 2013). Past hydroclimate changes in the lower Danube basin are currently little known but detailed reconstructions in the Alps (Glur et al., 2013) document repeated intervals of higher precipitation in the last thousand years associated with cooler periods in Central Europe (Büntgen et al., 2011). Stronger and higher floods during this period may help explain the successive Danube avulsions, first toward the St George, and then toward the Chilia branch. However, the lack of a strong sensitivity to changes in discharge in a large river like Danube (McCarney-Castle et al., 2012) leaves the dramatic increase in sediment load unexplained without a late deforestation of the lower watershed (Giosan et al., 2012), which provides the bulk of the Danube's load (McCarney-Castle et al., 2012). Similar increased sensitivity to land use for continental scale rivers have been documented in other cases, whether through modeling (e.g., for Ebro River by Xing et al., 2014) or field-based studies (e.g., Rhine by Hoffmann et al., 2009). However, climate variability expressed as floods probably contributed to this intense denudation as the erosion sensitivity of landscapes increases on deforested lands (Lang et al., 2003).

What could explain the rapid deforestation in the lower Danube basin since the 15th century (Giurescu, 1976), hundreds of years later than in the upper watershed of Central Europe (Kaplan et al., 2009)? The Columbian Exchange (Crosby, 2003), which led to the adoption of more productive species such as maize probably led to "*a demographic revival*" (White, 2011), which certainly required the expansion of agricultural lands. However, this alone cannot explain the extensive clearing of forest in agriculturally marginal highlands of the Carpathian and Balkan mountain ranges (e.g., Feurdean et al., 2012). Furthermore, the rapid population increases in Romania and northern Balkans began at the end of 17th century (McEvedy and Jones, 1978; Murgescu, 2010) and postdate the augmentation in sediment load on the Danube by over two centuries.

We propose instead a cultural explanation for this late deforestation: the expansion of the Ottoman Empire in Bulgaria (1396), Romanian Principalities (1417 for the Wallachia; 1498 for Moldavia; 1526 for Transylvania) and Serbia (1455). The Ottoman-ruled Bulgaria and Serbia and especially the vassal Romanian principalities provided a significant part of the empire's resource provisioning including "*wheat, honey, timber, and above all, sheep*" (White, 2011). We propose that deforestation of highly erodible alpine settings that led to the five-fold increase of sediment load on the Danube (Giosan et al., 2012) reflects this increased demand for timber and especially for sheep by the Ottoman Porte. Indeed, zooarchaeological evaluations for medieval Moldavian towns (Stanc and Bejenaru, 2013) shows that before the Ottoman expansion in the region, cattle and pig dominated the local diet. In a short time, by the end of the 16th century, Moldavia alone may have provided 300,000 sheep to Constantinople (Istanbul), out of an estimated 400–500,000 sent by the entire northern Balkans and Romanian principalities (White, 2011). Such radical changes in animal husbandry suggest that the region adapted to meet the religious dietary requirements and the huge demand of the suzerain Islamic empire by deforesting alpine lands for pasture.

Future of Chilia lobes

Currently, despite a 70% sediment deficit accrued after extensive damming in the watershed during the Communist industrialization of Romania in the late 20th century (McCarney-Castle et al., 2012), Danube delta is better positioned compared to other deltas to withstand in the short run the ongoing rise in sea level (e.g., Cazenave et al., 2002). This is due to a combination of reduced subsidence and anthropogenically-augmented sediment trapping on the delta plain (Giosan et al., 2013). That holds true in large part for the internal lobes of Chilia I and II; furthermore, ongoing and planned restoration measures such as dike removal (e.g., Schneider et al., 2008) may re-establish sediment retention and ecological functions even for their sectors that were drained for agriculture or diked for fisheries.

On the other hand, the open coast Chilia III lobe coming under increased wave dominance due to the sediment deficit has become the most dynamic coast of the entire Danube delta (Fig. 4c). Besides the Old Stambul mouth that advances into a shallow lagoon, the only other stable stretch of the coast is linked to the construction of a protecting jetty at the Bastroe mouth, built as a part of a large navigation project. This led to updrift beach ridge progradation as the southward longshore drift is trapped by the jetty and downdrift spit extension under a reversed drift in the lee of the jetty (Fig. 4c). However, intense erosion has remodeled the northern Oceacov mouth into flying barrier spits and led to the emergence of Musura barrier island in front of the southern Old Stambul mouth (Giosan et al., 2005). This erosive regime straightens the coast and steers a large southward longshore drift to the Sulina mouth. If the elongation of the Musura barrier will connect it to the northern protective jetty of the Sulina navigation canal, the fluvial sediment load of the main secondary distributary, the Old Stambul, may be redirected from the shallow infilling lagoon behind the barrier toward the offshore. In such conditions, an eventual depositional merging of the Chilia lobe with the Sulina shipping canal can be envisioned with dramatic consequences for maintaining navigation access at the Sulina mouth.

Acknowledgements

This project benefited funding from various sources including a Romanian doctoral grant for F.F. and a WHOI Coastal Ocean Institute grant to L.G. We thank colleagues from WHOI (Jeff Donnelly and Andrew Ashton) and University of Bucharest, in particular Emil Vespremeanu and Stefan Constatinescu, for their support and are grateful for discussions with Sam White and Bogdan Murgescu on the cultural and agricultural histories of the Ottoman Empire and the Romanian Principalities.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:10.1016/j.ancene.2014.07.003.

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