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Human influence and the changing geomorphology of Mediterranean deltas and coasts over the last 6000 years: From progradation to destruction phase?

Edward J. Anthony [a,*], Nick Marriner [b], Christophe Morhange [a]

[a] Aix Marseille Université, Institut Universitaire de France, CEREGE, UMR 34, Europôle Méditerranéen de l'Arbois, B.P. 80, 13545 Aix en Provence Cedex, France
[b] CNRS, Laboratoire Chrono-Environnement UMR 6249, Université de Franche-Comté, UFR ST, 16 route de Gray, 25030 Besançon, France

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ABSTRACT

The present geomorphology of the Mediterranean's coasts is largely a product of an intricate long-term relationship between Nature and human societies. A cradle of ancient civilisations, the Mediterranean has seen its shores occupied by Humans since Prehistory, and is, therefore, a particularly pertinent unit of analysis. The morphotectonic context and other forcing agents (e.g., climate) shaped out a highly diversified coastal morphology and generated a sediment-supply regime potentially favourable to the formation of numerous open-coast deltas and bay-head deltas in infilled rias as sea level stabilised during the mid-Holocene. This supply of riverine sediment has also been the key agent in mediating human occupation of the Mediterranean's clastic coasts. Expressions of this relationship have been extensively archived in clastic coastal deposits, including base-level deltaic and estuarine sedimentary sinks, which comprise records to explore the interactions between geosystems and the human environment. The stratigraphic sequences in these coastal sedimentary archives comprise, in many places, a clearly identified anthropogenic signature, notably in ancient harbours, some of which underwent extremely rapid silting up due to massive sediment sourcing generated by new agricultural practices from the Neolithic onwards. Increasing human influence, especially over the last 3000 years, has been, in turn, an important driver of changes in sediment supply, strongly modulating deltaic development. Pulses of sediment supply from catchments rendered vulnerable by human perturbations during the Roman period resulted in a new cycle of inception of many other deltas and in rapid delta growth (e.g. the Ebro, the Po, the Arno and the Ombrone). Another progradation dynamic during the Little Ice Age, at a time of strong rural population growth, river discharge increases, technological developments, and urbanisation, further consolidated delta growth. Understanding the life cycle of these deltas since their initial formation is, in turn, key to unravelling the relative role of natural and anthropogenic forcing agents. Rapid climate changes are deemed to have contributed through both the stripping of landscapes rendered fragile by human activities and active fluvial sediment transport to the coast, but disentangling climate change effects from human impacts in the Mediterranean remains a challenge. The patterns of subsequent deltaic growth and delta morphodynamics reflect adaptations to pulsed sediment supply, river discharge variations, the microtidal, fetch-limited context of the Mediterranean, and direct engineering interventions. The progradation dynamic of the Roman period and Little Ice Age contrasts markedly with the situation of common coastal destabilisation over the last two centuries, particularly well documented for the last 50 years. This period has been characterised by reduced sediment flux to base-level geosystems due to catchment reforestation, retenion within reservoirs, fluvial regulation and dredging, resulting in the erosion of deltas and barrier–lagoon and beach–dune systems. Large stretches of shoreline and narrow coastal plains have been massively engineered for coastal defence and protection against erosion, but also for the construction of marinas, leisure harbours and artificial beaches, resulting in the emergence of veritable artificial seafronts. These interventions have, collectively and progressively, raised societies to a pervasive and overarching position in the geomorphic stability–instability of the Mediterranean's coasts, a situation that will be exacerbated by pressures from sea-level rise, paving the way for rampant coastal erosion and delta destruction.

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* Corresponding author.
E-mail address: anthony@cerege.fr (E.J. Anthony).

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1. Introduction

The subject of the influence of past and present societies on the geomorphology of the coasts of the Mediterranean is very large, and is embedded in fundamental changes in the relationship between natural processes and human activities that have occurred over the course of the Holocene period (van Andel, 1989), marked by the transition from a strongly nature-dominated to an increasingly human-dominated environment (Marsh, 1864; Desjardins, 1876; Sherlock, 1922; Churchill Semple, 1932; Delano-Smith, 1979; Horden and Purcell, 2000; Berger and Guilaine, 2009; Walsh, 2013). The Mediterranean, therefore, stands out as one of the most pertinent geographical zones to look at the nature and trajectories of these interactions. One of the cradles of ancient civilisations, the Mediterranean has seen its shores occupied by societies since Prehistoric times, and the geomorphology of large sectors of the Mediterranean's coasts is a heritage of this relationship between Nature and Humans. Expressions of this relationship are diverse and affect both the bold rocky coasts and low-lying depositional coasts of the Mediterranean. The effects are most clearly evident, however, and increasingly more pervasive, on the latter coasts, especially those formed by river deltas, which have sequestered rich sedimentary archives to probe Holocene change and human impacts.

The aim of this paper is to present a review of the geomorphic human imprint on the coasts of the Mediterranean at different spatial and temporal timescales within the time frame of the Holocene. The evolution of non-deltaic coastal barriers and of many Mediterranean deltas and their adjacent downdrift coastal sectors has been reconstructed using multiproxy analyses of core data, palaeogeographical or geomorphological reconstructions, and coastal archaeology, providing material for the review. This review comes at a time when human impacts are leading to increasing coastal instability, providing a potential framework for exacerbating the effects of climate-induced change and sea-level rise. The overview provided here is both a daunting and necessarily incomplete task, given: (1) the long and complex relationship between the Mediterranean's coasts and societies, (2) the vast range of human interventions, both directly on the coast, and indirectly via modifications of river catchments that supply sediment, and therefore condition, the stability of depositional coasts, (3) the difficulty of disentangling human influence from the effects of commonly rapid changes in climate and vegetation dynamics, (4) the sometimes fragmentary and time-transgressive nature of many large deltaic sediment records, and (5) the overarching geographical and geomorphological diversity of the Mediterranean's clastic coasts. Salient elements of this relationship and the way human societies have profoundly modified the Mediterranean's coasts are highlighted through focus on clastic non-deltaic barriers and river deltas and their associated deposits. These coastal morphosedimentary archives record the temporal progression of human impacts, starting from dispersed coastal strongholds, related mainly to ancient harbours and maritime commerce, through larger-scale indirect impacts on the hinterlands that back the waterfront, and onto the modern era of direct significant anthropogenic transformations of the coast. It must be stated at the outset that direct quantification of the balance between human impacts and natural changes affecting the background environment and the coasts of the Mediterranean is not feasible. However, quantifying river discharge variation and changes to coastal sediment budgets provides an indirect measure of the importance of human activity over the last 200 years.

Following the introduction (Section 1), Section 2 briefly describes the setting and characteristics of the Mediterranean. Section 3 provides an overview of the coasts and deltas of the Mediterranean, including the recently emerged trend of massively engineered and artificial shores. Section 4 deals with ancient harbours and coastal palaeo-engineering works, several of which provide a distinct record of sedimentation reflecting a growing anthropogenic signature. Section 5 briefly describes the morphogenesis of non-deltaic coastal barriers for which identified anthropogenic signatures are lacking. Section 6 concerns an appraisal of the morphogenesis and morphodynamics of Mediterranean deltas hinged on the classic relationship between these deposits and relative sea-level stabilisation, as initially postulated by Stanley and Warne (1994), whereas Section 7 considers Mediterranean river delta inception in terms of the postulate of these deposits being largely man-made constructs generated by land-use changes related to the flourishing of classical civilisations, as initially proposed for deltas in Tuscany, Italy (e.g. Marinelli, 1926 in Pranzini, 1989; Fabbri, 1985; Innocenti and Pranzini, 1993) and in Spain (Vita-Finzi, 1975; Guillén and Palanques, 1997). Sections 8 and 9 focus, respectively, on the massive modifications of river catchments over the last two centuries (Section 8) and direct human interventions on the Mediterranean's coasts that are strongly reflected in the current fragile status of large stretches of the depositional non-deltaic barriers (Section 9). Section 10 provides an overview of delta morphodynamic changes associated with variations in sediment supply and direct and indirect human interventions on river catchments and river mouths. Following these sections, Section 11 discusses the difficulty of disentangling human impacts and changes in the geomorphic functioning of the Mediterranean's coasts from those of rapid climate changes in the course of the Holocene, debouching on a synthesis that warns against a simplistic view of Mediterranean river deltas as human constructs. Section 12 proposes conclusions and perspectives on the future of the Mediterranean's deltas and coasts, against a background of destabilisation by Humans under the overarching framework of sea-level rise and climate change. The review shows a strong imbalance in favour of the literature published since 2000. Much of the post-2000 literature provides more updated and comprehensive coverage of coastal geomorphic changes documented in many pre-2000 publications, especially given the greater attention being paid to deltas in the current circumstances of increasing delta vulnerability (Ericson et al., 2006; Syvitski et al., 2009; Anthony, 2014a). Much of the literature reviewed also reflects the increasing impacts of human activities inventoried over the last 15 years or so.

2. Setting and characteristics

The Mediterranean has been subjected to an array of interconnected, yet discrete, orogens that have been traditionally considered collectively as the result of an “Alpine” orogeny, but that are, instead, the result of diverse tectonic events spanning some 250 Ma, from the Triassic to the Quaternary (Cavazza and Wezel, 2003). The Mediterranean zone thus forms a present-day geodynamic analogue for the final stages of a continent–continent collisional orogeny. This has involved a complex suite of events dominated by subduction and partial obduction of the Eurasian and African–Arabian plates, except for the Ionian basin and the southeastern Mediterranean, and the formation of new oceanic domains. The resulting crustal context is characterised by active and passive margins and by isostasy and tectonics that have imprinted marked variations in relief (Fig. 1), and in present-day tectonics and coastal geomorphic diversity.

Regarding the recent tectonics of the Mediterranean's coasts, the Marine Isotope Substage (MIS) 5.5 highstand (~125 Ka) has been used by Ferranti et al. (2006) to draw a picture of vertical displacements affecting coasts of the Central Mediterranean since the Late Pleistocene. Stewart and Morhange (2009) concluded that the general tendency for MIS 5.5 marine terraces to lie within a few metres of present-day sea level was an indication of general long-term land stability throughout most of the circum-Mediterranean region, notwithstanding the complex geodynamic history. Marked variability in terrace elevation has been a result of local (basin-bounding) rather than regional tectonics (e.g. Ferranti et al., 2006), an aspect that also comes out in Holocene and modern tide-gauge records from the Mediterranean (Emery et al., 1988; Flemming, 1993; Pirazzoli, 2005). The sea-level data from these studies suggest that most of the Mediterranean coast is submergent, albeit at generally low rates (<1.2 mm/yr, Emery et al., 1988). Zones of little or no sea-level change correspond to the coastal tracts between Gibraltar and Genoa in the west and along southern Turkey in the east, whereas mobile coasts are mostly on or immediately inboard of the Hellenic and Calabrian arc areas of the Central northern Mediterranean (e.g. Vött, 2007; Pavlopoulos et al., 2012), which are zones of high earthquake activity (e.g. Pirazzoli et al., 1996; Stewart et al., 1997; Shaw et al., 2008) and/or active volcanism (e.g. Dvorak and Mastrolorenzo, 1991; Firth et al., 1996; Stiros, 2000; Morhange et al., 2006). This gives an overall image of considerable variation in the amount and sense of vertical coastal movements along the Mediterranean's coasts (Stewart and Morhange, 2009; Brückner et al., 2010).

The Mediterranean drainage basin comprises more than 160 rivers with a catchment area >200 km^2. Only six of these are larger than 50,000 km^2 (Table 1), an observation that brings out the abundance and importance of small rivers in supplying sediment to the coast (Poulos and Collins, 2002). Dedkov and Mozzherin (1992) concluded from data on rates of catchment disturbance and erosion across the world that Mediterranean mountain streams are among those with the highest anthropogenic contribution of any climatic zone. Together with the Alpine mountainous catchments, the Mediterranean zone shows the highest catchment sediment yields in Europe (Vanmaercke et al., 2011). Small Mediterranean rivers with catchments of 1000–10,000 km^2 show relatively high sediment yields with regards to annual runoff that are comparable to similar-sized rivers from tectonically active margins (Fig. 2) in western North America, Japan, Taiwan, Indonesia, the Philippines and New Zealand (Milliman and Farnsworth, 2011). Notwithstanding, river discharge is highly variable both spatially and temporally as a result of climatic disparities within and across catchments, and this variability has been diversely exacerbated by human transformations of Mediterranean fluvial systems especially over the last 200 years (Poulos and Collins, 2002; Milliman and Farnsworth, 2011). This marked spatial and temporal variability of Mediterranean fluvial regimes also creates problems for measurement, monitoring and assessment of effects (Hooke, 2006). It also renders difficult the distinction of human impacts in river sediment supply from those of background climate and vegetation changes. The discharge regime shows marked seasonality, dominated by winter–spring high flow conditions and low flow in summer–autumn, but

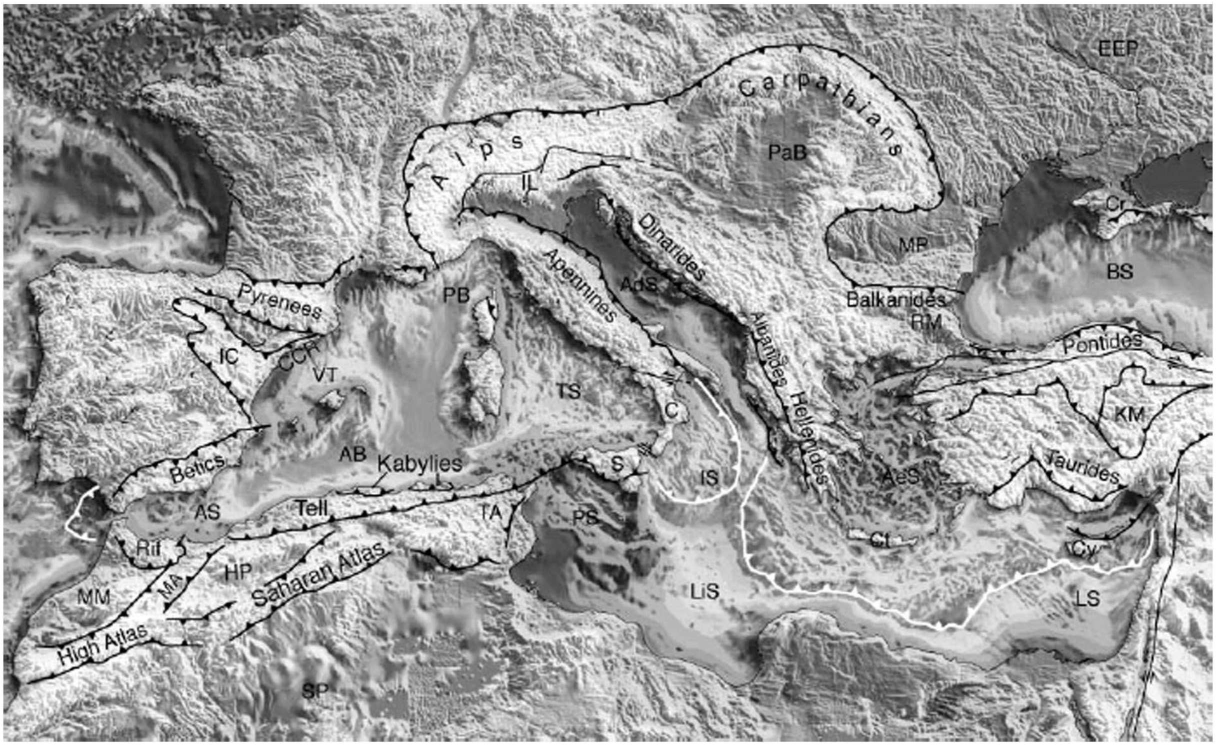

Fig. 1. Digital terrain model of the Mediterranean showing major, simplified geological structures. White thrust symbols indicate the outer deformation front along the Ionian and Eastern Mediterraean subduction fronts. AB: Algerian basin; AS: Alboran Sea; AdS: Adriatic Sea; AeS: Aegean Sea; BS: Black Sea; C: Calabria-Peloritani terrane; CCR: Catalan Coast Range; Cr: Crimea; Ct: Crete; Cy: Cyprus; EEP: East European Platform; HP: High Plateaux; KM: Kirsehir Massif; IC: Iberian Chain; IL: Insubric line; IS: Ionian Sea; LS: Levant Sea; LiS: Libyan Sea; MA: Middle Atlas; MM: Moroccan Meseta; MP: Moesian Platform; PB: Provençal Basin; PaB: Pannonian Basin; PS: Pelagian Shelf; RM: Rhodope Massif; S: Sicilian Maghrebides; SP: Saharan Platform; TA: Tunisian Atlas; TS: Tyrrhenian Sea; VT: Valencia Trough. From Cavazza and Wezel, 2003.

Table 1
Basin area, length and delta area of a selection of Mediterranean rivers.

River	Country	Basin area (km^2)	River length (km)	Delta area (km^2)	Ratio of delta to basin area
Nile	Egypt	2,900,000	6825	12,512[a]	0.004
Rhône	France	96,000	812	1740[a]	0.018
Po	Italy	74,000	382	13,398[a]	0.181
Ebro	Spain	87,000	928	624[a]	0.007
Moulouya	Morocco	54,500	600	30[b]	0.0005
Evros	Greece	53,500	480	180[b]	0.003
Buyukmenderes	Turkey	25,000	548	276[b]	0.011
Axios	Greece	23,750	380	220[b]	0.009
Seyhan	Turkey	21,000	560	900[b]	0.042
Drini	Albania	19,600	160	250[b]	0.012
Tiber	Italy	17,000	405	80[b]	0.004
Neretva	Croatia	10,380	230	120[b]	0.011
Acheloos	Greece	6395	217	300[b]	0.046
Llobregat	Spain	5045	163	80[c]	0.015
Ombrone	Italy	3500	161	70[b]	0.02
Guadalhorce	Spain	3180	154	5[d]	0.001
Ter	Spain	2990	212	8.5[c]	0.002
Var	France	2800	135	8[b]	0.002
Andarax	Spain	2160	74	9.5[d]	0.004
Guadiaro	Spain	1490	101	5.8[d]	0.003
Guadalfeo	Spain	1312	72	8.6[d]	0.006
Besos	Spain	1030	52	8.3[c]	0.008
Fluvia	Spain	1008	104	19.4[c]	0.019

[a] From Coleman and Huh (2004).
[b] This study.
[c] From Liquete et al. (2005).
[d] From Liquete et al. (2009).

variability can be high at timescales ranging from intraseasonal to multi-annual. Conditions are much more arid in the southern and eastern flanks (Poulos and Collins, 2002; Milliman and Farnsworth, 2011), which also display coasts of lower elevation, and where pulses of fluvial sediment supply to the coast evince consistent irregularity at seasonal to decadal timescales. The geographical difference is manifested by the limited development of large rivers in the latter sector, with the notable exception of the Nile, and by the common occurrence of episodically functional wadis, compared to a much higher density of rivers in the more humid former sector. Such differences in fluvial sediment supply, have, together with climate variations, contributed to the coastal diversity imprinted by the complex morphotectonic context.

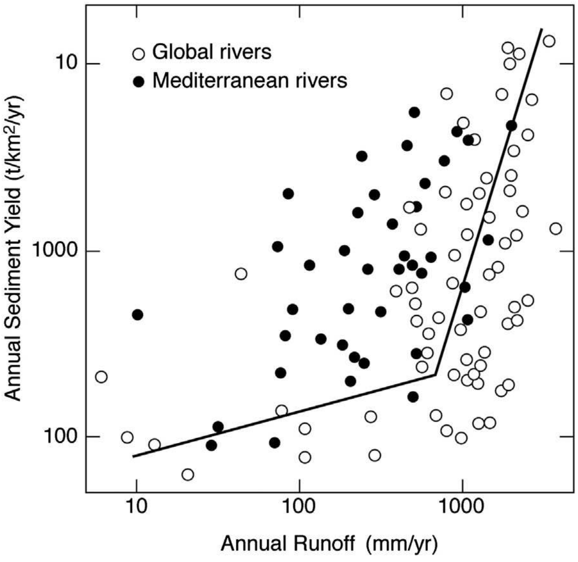

Fig. 2. Sediment yields of small Mediterranean rivers with catchments of 1000–10,000 km^2 compared to those of similar-sized rivers from tectonically active margins but with larger runoff.
From Milliman and Farnsworth (2011).

Apart from the eastern seaboard of Tunisia and the Adriatic Sea, the Mediterranean continental shelf is relatively narrow (a few km to about 50 km), resulting in weak tidal amplification and in a microtidal regime (mean spring tidal range of 0.5 to 1 m). Along the steep Alpine margins of the Western Mediterranean, the shelf is dissected in many areas by deep fossil canyons inherited from the Messinian Salinity Crisis (Clauzon et al., 1996; Bachea et al., 2009). The wave climate is dominated by short-fetch wind waves (periods of 4–6 s) with very variable directions depending on location, sometimes intermixed with longer waves (8–9 s) where fetch conditions are favourable. The intricate shoreline of the Mediterranean and these relatively fetch-limited wave conditions result in a potentially large directional apportionment of the wave energy, a factor liable to favour sequestering of fluvial sediment in the vicinity of river mouths and therefore favouring delta construction. Storms can attain, however, extreme intensities (Lionello et al., 2006; Dezileau et al., 2011; Shah-Hosseini et al., 2013), despite the limited fetch context. Destructive historical and pre-historical tsunamis have been reported (e.g. Shaw et al., 2008).

3. Mediterranean coasts and river deltas

The total length of the Mediterranean coastline, including the numerous islands, is about 46,000 km (Poulos and Collins, 2002; Stewart and Morhange, 2009). Less than half (46%) consists of depositional shores, the rest comprising rocky coasts that commonly exhibit cliffs cut into a variety of lithologic terranes, notably carbonate formations. Bold, rocky coasts in the Mediterranean have become increasingly occupied by settlements, especially in the modern era of world tourism, but their morphology has remained relatively intact, in contrast to low-elevation clastic coasts, the sediment dynamics and budgets of which have been strongly affected by human interventions, especially where climatic and other environmental conditions have been favourable to massive urbanisation.

The clastic coasts of the Mediterranean comprise sand, and locally, gravel barriers that either fringe consolidated rock formations or bound lagoons. Barrier–lagoon systems are also common to the numerous river delta systems that have developed in the strongly wave-influenced microtidal Mediterranean context. Non-deltaic barrier systems are generally bay barriers of various lengths (10 to >100 km) between bedrock headlands or between river mouths that have not developed into deltas. Examples include the Gulf of Lions coast in France, and much of the semi-arid to arid southern and southeastern Mediterranean seaboard. The functional linkage involving alongshore sediment transfers from deltas and estuaries to distant coastal barriers is particularly pertinent in the Mediterranean where many such barriers are remotely sourced in sand by rivers. The Mediterranean seaboard being relatively steep, the propensity for its coasts to benefit from sediment supply from the nearshore shelf is limited, in contrast to many oceanic coasts facing broad continental shelves (Anthony, 2009). As a result, alongshore supply of riverine sediment has been fundamental to the geomorphic development of these open-coast barrier systems where coastal morphology and wave fetch conditions favour unimpeded longshore drift. Barrier development in these cases has generally been sourced by rivers episodically subject to floods strong enough to flush sediments to the nearshore zone, forming a sedimentary reservoir for wave-induced alongshore supply to adjacent beaches. Some of the river mouths associated with these barrier systems may be diverted hundreds of metres alongshore by longshore currents, and even blocked during periods of low river discharge, and many are ephemeral (e.g., Lichter et al., 2010). Along the relatively arid southern and eastern shores of the Mediterranean, aeolian activity has commonly generated dune systems. These dune systems are rather poorly developed on the western shores of the Mediterranean.

In addition to these open-coast barriers, the Mediterranean comprises a plethora of more or less deeply embayed shores of all lengths (<10 m to 10 km) locked between bedrock headlands. These variably indented embayments are associated with dominantly rocky shores and are rimmed by rocky bluffs and/or sandy/gravelly pocket beaches or barriers. These embayments commonly have limited accommodation space for sediments and limited sediment supply but some are sourced by episodic inputs from ephemeral streams, especially on high-relief coasts (Pranzini et al., 2013) in the Western Mediterranean. Pocket beaches and barriers generally show little or no progradation, as a result of this limited sediment supply, although exceptions exist, as in the case of the prograded beach–ridge complex of the Gulf of Almería, in Andalusia, sourced by gravel supplied through longshore drift from both the nearby Adra river delta and eroding cliffs cut into last interglacial marine terraces (Goy et al., 2003). Other embayments formed rias in which fluvio-deltaic progradation has occurred since sea level stabilised in the mid-Holocene, such as the bay-head deltas of Ionia in present-day western Turkey (Brückner, 1997; Brückner et al., 2002). Offshore islands and, in some cases, submerged sand banks formed in zones of longshore drift convergence have also favoured the development of dispersed spits and tombolos (e.g. Marriner et al., 2012a).

High fluvial sediment supplies, sand- and gravel-rich bedload and locally impeded longshore drift between bedrock headlands have favoured an abundance of infilled bay-head deltas in rias and open-coast deltas (Fig. 3), especially in the Central and Western Mediterranean. Mediterranean river deltas range from protruberances of a few km^2 in area associated with small catchments (tens to hundreds of km^2) to major subaerial delta plains associated with the larger rivers, the most important of which are those of the Po, the Nile, the Ebro and the Rhône (Table 1). Small deltas are particularly abundant on the steep, and relatively bare mountain ranges bordering the Mediterranean coast of Spain (Liquete et al., 2005, 2009). On the 400 km coast of Andalusia in southeastern Spain, Liquete et al. (2005) identified no less than 26 rivers ranging in basin size from 3120 km^2 (the Guadalhorce) to 3.8 km^2 (the Dos Hermanas), all with deltas. Ratios of delta area to river basin area vary widely, however, as a function of geological setting and inheritance, climate, exposure to waves, and human influence. The Po subaerial delta, which has an area of about the same size as that of the Nile, stands out with an exceptionally high ratio, fed by a large supply of sediment from its steep Alpine setting, and located in an area that excludes strong wave export of sediment (Table 1).

Significant deltas (apart from the Nile) have not developed on the relatively dry to arid southern margins of the Mediterranean, even with rivers having relatively large catchments such as the Cheliff in Algeria (35,000 km^2) and the Medjerda in Tunisia (22,000 km^2). However, the Mediterranean coast of Morocco is studded with small deltas at the mouths of sediment-charged steep-gradient wadis that drain the Atlas Mountains. Here and elsewhere, fluvial sediment supplied by flash floods has been redistributed alongshore to source the growth of adjacent coastal barrier and lagoon systems. Many small rivers throughout the Mediterranean, commonly with drainage basins not exceeding 1000 km^2, lack deltas, as stated above, especially where they drain low-elevation terrain and debouch in long open bays subject to strong wave-generated longshore currents that sweep sediment to feed adjacent barriers.

Coastal engineering has generated, especially in the Western Mediterranean, entirely new shores, where the original shore type and morphology have been totally transformed by humans (Anthony, 1994; Di Pippo et al., 2008). Such 'artificial' shores are mainly associated with major commercial or industrial ports, and with various tourism-related structures: leisure harbours, land reclamations, marinas, and artificial beaches, the construction of which took a significant upswing in the Mediterranean in the 1980s. Reclamation fill structures and marinas tend to combine residential and tourism facilities, but can also serve as transport infrastructure, as in the cases of the reclaimed Tiber and Var deltas, both of which host airports. Artificial shores generally blend entirely with urban fronts. Despite this modern context of increasing human modification of the coasts of the Mediterranean, rocky shores have been relatively well preserved, direct engineering intervention on these 'hard' shores being generally limited to short enclaves offering suitable locations for leisure harbour development or providing foundations for the construction of small artificial beaches. In some ways, the high costs of physically modifying rocky shores is a factor that fosters their preservation, but that has also contributed to bringing pressure to bear on the more accessible, depositional coasts (Anthony, 2014b). The breath-taking views offered by bold rocky coasts have contributed to the attractiveness of the Mediterranean, especially along the mountainous western margins, which are commonly untransformable. This has, in turn, increased the development pressures on the more accessible adjacent clastic coasts. Bold picturesque rocky shores are, however, becoming increasingly exposed, in turn, to pressures from housing and tourist infrastructure. Limited sectors of soft rocky shores have also been significantly affected by human intervention, as on the Apulian coast of southeast Italy (Andriani and Walsh, 2007).

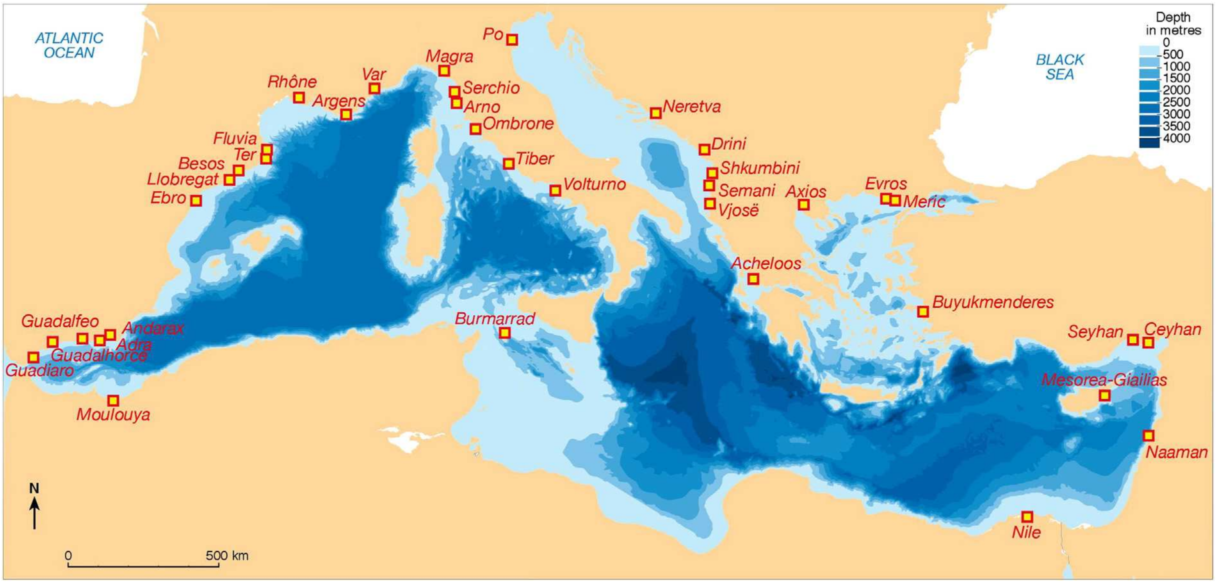

Fig. 3. Rivers deltas of the Mediterranean mentioned in the text.

4. Ancient harbours, palaeo-coastal engineering, and the anthropogenic signature

Anthropogenic modification of sedimentary patterns and processes constitutes both adjustments to natural sedimentary environments (e.g. delta irrigation, coastal reclamation) and the creation of novel sedimentary environments articulated around man-made structures. Although the Mediterranean river delta, epitomised by the Nile, stands out as an iconic example of the long-standing relationship between Humans and the coast, this relationship started in sheltered fluvial, estuarine and low wave-energy coastal settings that served as sites for the establishment of settlements built on maritime trade. Leaving aside the potential influence of the Neolithic "Revolution" on the sediment budgets of drainage systems via new agricultural practices in the Mediterranean Basin (Guilaine, 1991; Foley et al., 2013), one significant manifestation of this long relationship between societies and the coast is recorded in the deposits of numerous ancient harbours throughout the Mediterranean (Fig. 4), the stratigraphic signatures of which have been the object of numerous studies (Reinhardt and Raban, 1999; Morhange et al., 2003; Marriner and Morhange, 2006; Stanley and Bernasconi, 2006; Marriner and Morhange, 2007; Marriner et al., 2008a,b; Goiran et al., 2010; Bony et al., 2011; Sarti et al., 2013; Seeliger et al., 2013; Stock et al., 2013; Goiran et al., 2014). These studies provide well-documented cases of shore processes, human impacts and coastal sedimentation in ancient times, highlighting a clear pattern of millennial anthropogenic forcing in the coastal stratigraphy. Work has demonstrated that different harbour technologies have well-defined chronostratigraphic parallels, beginning with the exploitation of semi-protected natural environments during the Bronze Age through to the completely artificial infrastructure of the Roman and Byzantine periods (e.g. Marriner et al., 2014). The stratigraphic sequences generated in these ancient harbours reflect the superposition of deposits that give rise to a distinct sedimentary suite. Ancient harbour facies are quintessentially lagoonal in terms of the sedimentary signatures and biological assemblages, marked by an artificial fining-up sequence, and comprise low energy silts and fauna typical of anthropogenically-favoured sedimentation in protected settings (Fig. 5). Marriner and Morhange (2007) and Marriner and Morhange (2006), Marriner et al. (2008a, 2008b) have documented the development of these ancient harbours in the Levant towards the end of the Late Bronze Age and the Early Iron Age, under the pressures of expanding trade (Marcus, 2002). Some of these ancient harbours were located in prograding river-mouth settings in protected embayments where incident wave energy was low as a result of significant refraction, diffraction and nearshore dissipation. Examples include Frejus (Forum Julii), at the mouth of the Argens River in southeastern France (Devillers et al., 2007: Bertoncello, 2010; Gébara and Morhange, 2010), and the mouth of the Mesorea/Gialias river system in Cyprus (Devillers, 2008). In such settings, rapid silting up has commonly led to harbour displacement, mirrored in a number of well-studied ria systems, including the text-book examples of Ionia's deltas (Brückner, 1997; Brückner et al., 2002; Seeliger et al., 2013; Stock et al., 2013). These changes reflect the effects of profound human modifications of river catchments throughout the Mediterranean (Bintliff, 2002; Butzer, 2005; Dusar et al., 2011).

The deposits archived in these harbours undoubtedly provide some of the most thoroughly documented cases of human influence on shore processes and coastal sedimentation in ancient times. On the basis of strongly converging data from chronostratigraphy, biological indicators, geomorphology and geoarchaeology, Marriner and Morhange (2006, 2007) have shown that the unique chronostratigraphic and biosedimentary similarities common to these ancient Mediterranean harbours have generated a human-modified parasequence which they defined in terms of a new working model (Fig. 6): the *Ancient Harbour Parasequence* (AHP), different from the Coastal Progradational Parasequence (CPP). The preservation of thick transgressive sequences in the semi-artificial depocentres of ancient Mediterranean harbours renders the AHP a rich geoarchaeological archive.

Although harbours generally took advantage of sheltered enclaves along the coast, notably embayments and quiescent river mouths, their implantation and development have not always been passive accompaniments of site geomorphic characteristics naturally advantageous to harbours. Many harbours developed in the lee of spits and tombolos that were subsequently engineered to ensure harbour protection. Marriner et al. (2008b) demonstrated that the tombolos of the ancient port cities of Tyre in Lebanon and Alexandria in Egypt are the heritage of a long history of natural morphodynamic forcing since

Fig. 4. Ancient harbours in the Mediterranean, grouped according to how they have been preserved in the geological record. From Marriner and Morhange (2007).

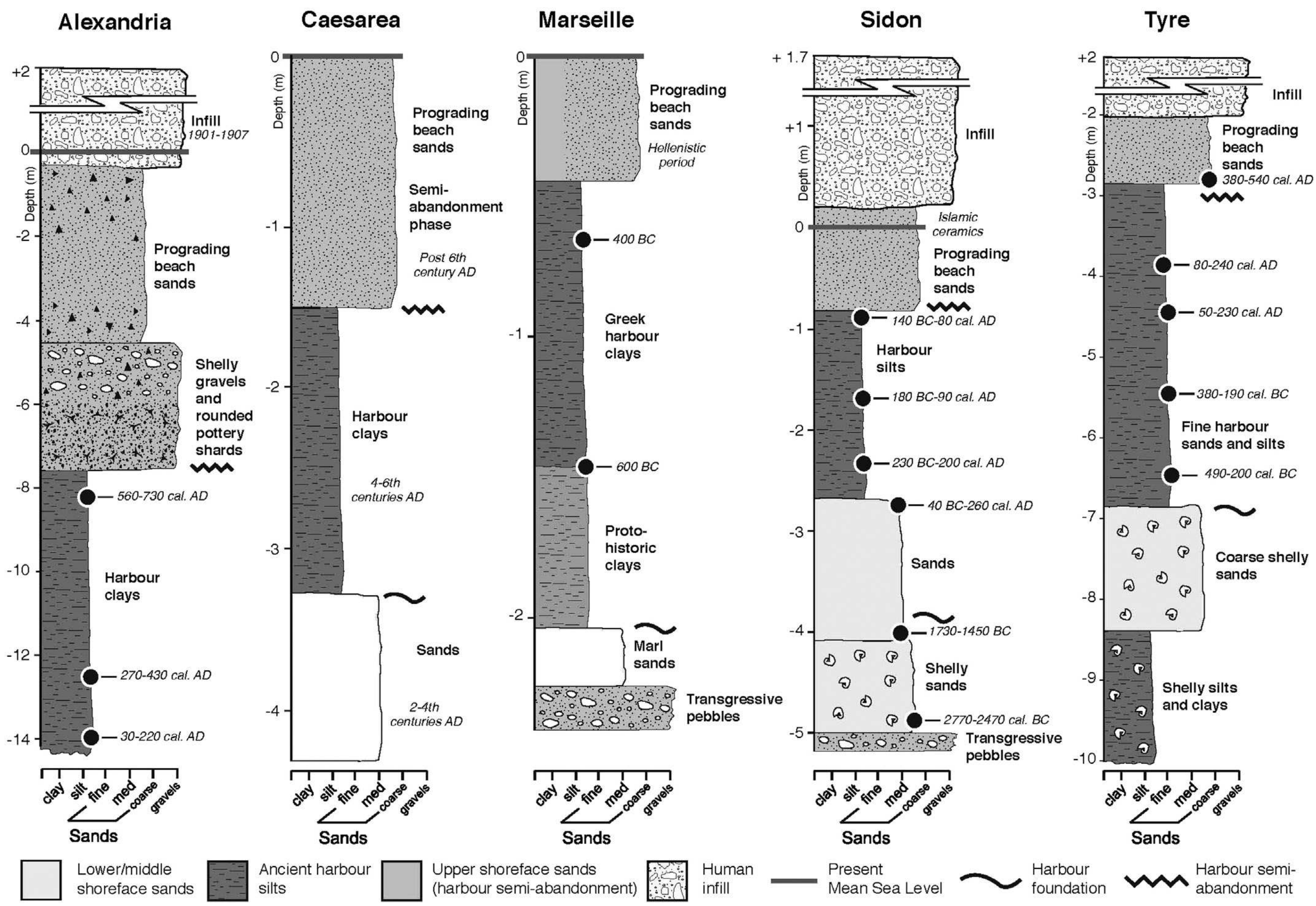

Fig. 5. Examples of stratigraphic successions in ancient Mediterranean harbours (see Fig. 4 for harbour locations.

8000 cal. BP and human intervention since Hellenistic times (Fig. 7). The tombolo at Tyre was a submerged sand bank, formed by longshore drift convergence, that was cleverly exploited in 332 BC by Alexander the Great's engineers, following a seven-month siege of the city, enabling their leader to seize the island fortress (Marriner et al., 2008b). The Tyre and Clazomenae causeways served as prototypes for Alexandria's Heptastadion, built a few months later by Alexander the Great (Goodman et al., 2009).

In another example from the Levantine coast, recent work on the Ras Ibn Hani peninsula (Syria) has elucidated a largely analogous morphosedimentary evolution and suggests that there is a great deal of predictability to tombolo geomorphology at the regional scale (Marriner et al., 2012a). Two broad periods can be identified in the formation of Levantine tombolos. During the first phase, between ~4000 and ~1000 cal. BC, the sediment records attest to low accretion, implying that tombolo development was relatively limited. Despite abundant accommodation space, this finding appears consistent with three factors: (1) rapidly exhausted shelf sediment supply following the end of the Holocene marine transgression; (2) low sediment inputs by local fluvial systems within the context of well-vegetated catchments; and (3) a partitioning of base-level sediment sinks, whereby sediment was preferentially sequestered in proximal depocentres (e.g., estuaries and deltas) during the mid-Holocene. This latter idea is widely supported by the Levant's archaeological record, which shows an abandonment of estuarine harbours and settlements during the late Bronze Age and their relocation at more distal coastal sites (Raban, 1990; Morhange et al., 2005). The situation appears to have changed, however, during the Late Bronze Age/Early Iron Age, with the switch from a ‘neutral’ to a positive sediment budget concurrent with a pulse in alluvium. Fronted by the island barriers, the combination of high terrigenous sediment yield and low-energy wave processes permitted the rapid accretion of the sand banks at both Tyre and Ras Ibn Hani. This rapid accretion pulse led to aggradation of the sublittoral sand banks on the leeward coasts and accentuated the efficiency of sediment trapping by positive feedback mechanisms involving the formation of two drift cells (Marriner et al., 2012a).

Goiran (2001) and Stanley and Bernasconi (2006) similarly identified in Alexandria's eastern harbour, the major port in the southeast Mediterranean, sediments comprising important hiatuses (time gaps) that record the episodic influence of storms, seismic tremors, and possible tsunamis, but also the influence of human activity after about 2400 years BP, following development of Alexandria by the Ptolomies and their successors, the Romans. These findings are mirrored in lead isotope analyses used to reconstruct the history of human-induced palaeo-pollution (Véron et al., 2006; Stanley et al., 2007; Véron et al., 2013). Researchers have attributed development of important mud-rich deposits from about 2200 to 1800 years BP in part to construction of the Heptastadion, the large causeway and aqueduct system built to connect Alexandria with Pharos Island to the north. It has also been suggested that structures such as breakwaters have modified sedimentation patterns, blurring the distinction of deposits from natural processes from those of human-related activities (Millet and Goiran, 2007).

5. Morphogenesis and evolution of non-deltaic coastal barriers

Although the Mediterranean currently shows a relatively high density of river deltas, many of its barrier–lagoon systems are morphological expressions of sediment sourcing by river mouths that did not evolve

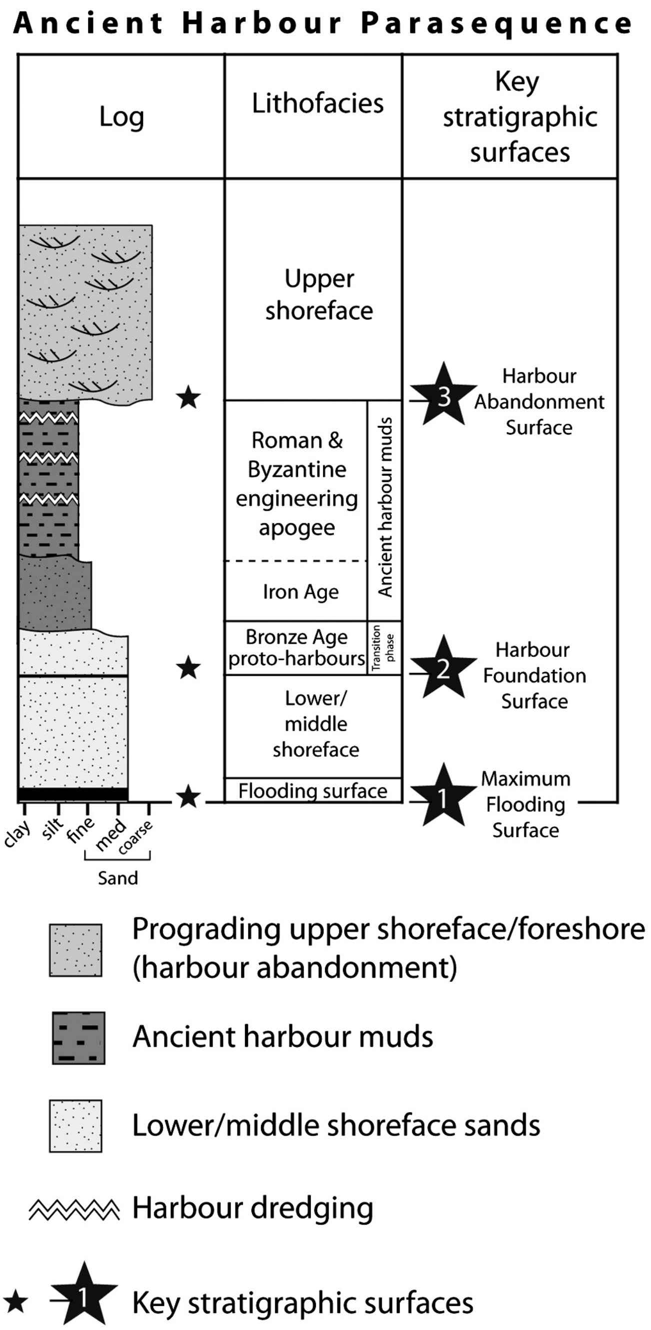

Fig. 6. Illustration of the impact of human palaeoengineering on coastal deposition in Mediterranean harbours and their vicinity, resulting in distinct lithofacies and key stratigraphic surfaces composing the Ancient Harbour Parasequence.
From Marriner and Morhange (2006, 2007).

into deltas, probably as a result of moderate sediment supplies from small catchments of low elevation. In consequence, barrier systems associated with non-deltaic coasts have commonly showed moderate to no progradation. The patterns of development of these barriers remote from deltas are much less known than the strandplains and associated lagoonal systems of deltaic coasts. Although the morphosedimentary development of non-deltaic barriers may have been indirectly affected by human-generated fluctuations in river sediment supply, only a few sedimentary archives of these barrier systems have been probed, and direct anthropogenic influence on barrier sedimentation and morphology, as in the previously described cases of tombolos, for instance, has not been identified or reported. Some barriers have variably prograded as a function of the supply and alongshore redistribution of fluvial and cliff-derived sediment by waves, as on the Gulf of Almería coast (Goy et al., 2003), whereas others are narrow and have been dominantly 'stationary' (in the sense of Thom, 1984), as in the Gulf of Lyons, after having migrated to their current positions with the final phases of Holocene sea-level rise (Barusseau et al., 1996; Raynal et al., 2009). Goy et al. (2003) identified 6 strand-plain units dating back as far as 7400 BP for which they associated phases of beach–ridge progradation and inter-ridge swale deposition with relative sea-level and sediment supply variations.

The narrow barrier systems of the Gulf of Lyons bound infilling lagoons and are devoid of tidal inlets as a result of the nearly tideless environment. Raynal et al. (2009) have estimated that one of these sandy barriers was established around 7500 cal. yr BP 1 km seaward from its present position, and according to Dezileau et al. (2011) there has been no change in the morphology and position of this barrier over the last 300 years. The history of these stationary barriers appears to have hinged on a combination of fluctuations in sediment supply from the rivers and direct storm impacts and overwashing (Sabatier et al., 2008). Research on the back-barrier lagoonal deposits has demonstrated that the barrier systems were significantly affected by numerous phases of storminess during the past 7000 years (Sabatier et al., 2012), most recently during the Little Ice Age (Dezileau et al., 2011). Storm overwash played an overarching role in the morphodynamics of these systems, generating lagoonal infilling, rather than barrier storage of sand. Along the relatively arid southern shores of the Mediterranean, where aeolian activity has commonly generated dune systems, these storm and overwash impacts may be less common, but research on Holocene records from these shores are unfortunately lacking.

6. Early morphogenesis of river deltas and human impacts

The formation of Mediterranean river deltas may be envisaged in two broad successive stages. The first corresponds to the delta inception scenario tied to sea-level stabilisation (Stanley and Warne, 1994), and the second (Section 7) to relatively synchronous delta formation over the last 2500 years, especially in the Western Mediterranean, associated with the rise of classical civilisations and population dynamics, a theme that has been well documented by researchers in Italy (e.g. Fabbri, 1985; Pranzini, 2001) and Spain (Vita-Finzi, 1975), and recently echoed by Maselli and Trincardi (2013). In both stages, delta morphogenesis and subsequent morphodynamics have been more or less strongly mediated directly and indirectly by human activities.

The most deeply incised palaeo-valleys became sites for the formation of some Mediterranean deltas around 8500 years ago when deceleration in sea-level rise favoured the accumulation of extensive sediment tracts in coastal depocentres (Stanley and Warne, 1994). Nile delta sedimentation began at about this time as the rising post-glacial sea level drowned the incised Pleistocene topography, essentially shaped by local wadis and the Nile's braided stream channels during the sea-level lowstand of the Late Glacial Maximum (Stanley and Warne, 1993; Flaux, 2012). Recent research suggests that morphogenesis of the Nile delta has been modulated by a gradual ~60% decrease in sedimentation rates between the early and late Holocene (Marriner et al., 2012c). The Nile's sediment supply, sea-level change and subsidence histories, which have collectively mediated deltaic growth, have been used to reconstruct a delta accretion model (Fig. 8). Following the early to mid-Holocene growth of the Nile's deltaic plain, sediment losses and pronounced decay are first recorded around 4000 years ago, driven by falling sediment supply from the catchment and an intensification of anthropogenic impacts. Channelling and drainage of the wetlands for agriculture altered sediment and water routing through the delta, with further implications for human-accentuated subsidence of organic-rich deltaic sediments. These changes in Nile flow and sediment supply mediated a shift at about 4000 cal BP from a river-dominated delta to a more wave-influenced delta. One further consequence of the millennial-scale ebb in Nile flow and human channelling of the delta

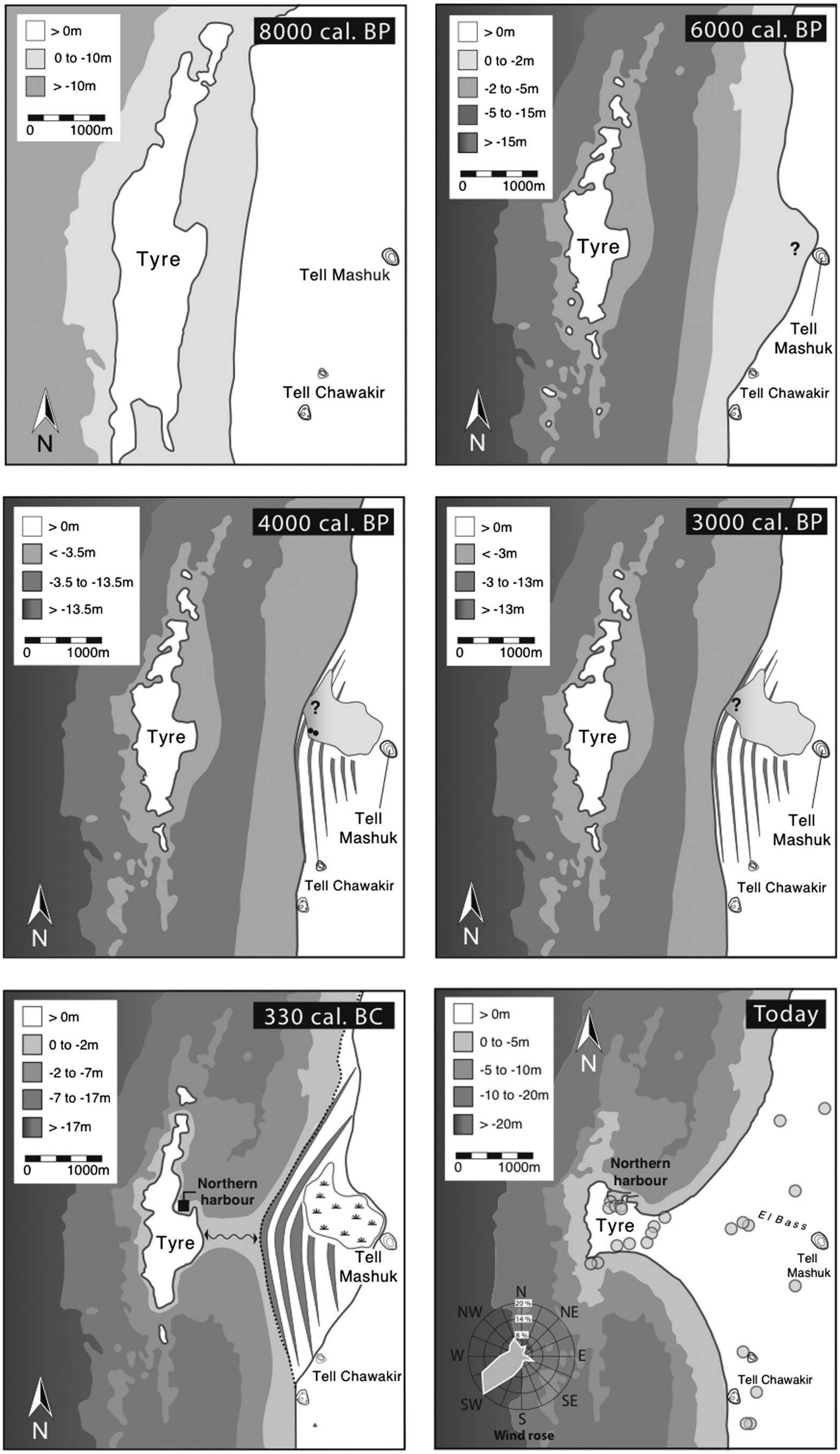

Fig. 7. Environmental evolution of the Tyrian coast during the past 8000 years, showing the morphodynamics of tombolos associated with the ancient harbour of Tyre (adapted from Marriner et al., 2008a, 2008b). Tyre lies on the distal southern margin of the Litani delta, which was key to supplying sediment for the formation of the city's tombolo. Note the progressive evolution from an indented to a regularised coastline during the period.

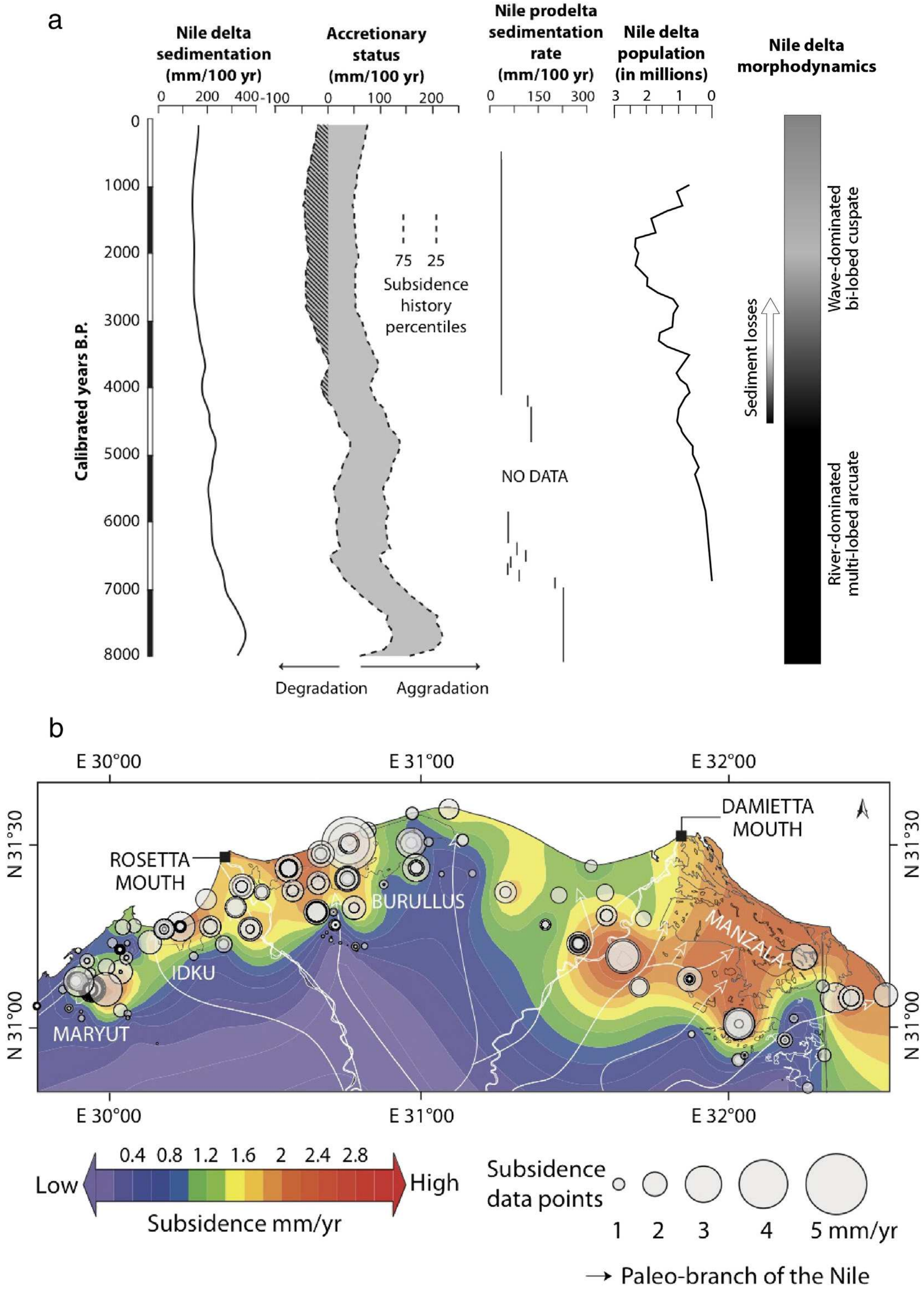

Fig. 8. The geomorphic and sedimentary status of the Nile delta in the course of the Holocene (adapted from Marriner et al., 2012d), and comparison with human population growth. (a) Spatially averaged Nile delta sedimentation (i, ii, iii), and estimation of human population (iv). (b) Geography of Nile delta subsidence rates. Nile prodelta sedimentation rate from Revel et al. (2010), and population estimate for Nile valley in Egypt from Butzer (1976).

was a gradual reduction in the number of fluvial branches from seven in early Antiquity to just two at present (Stanley and Warne, 1993). Whilst no Holocene analogue exists for the current sediment-starved deltaic system, the reconstruction suggests that the coastal fringe of the deltaic plain, parts of which have been prone to the highest subsidence rates (Fig. 8d) has a particularly long history of vulnerability to extreme events and relative sea-level rise.

Build-up of the Rhône delta plain similarly began about 7000 years ago and took place in several stages which are still visible in the present morphology, which includes prodelta deposits, palaeochannels, sandy beach ridges, dunes and spits (Vella et al., 2005; Amorosi et al., 2013a). The subsequent history of the Rhône delta echoes the influences of both climatic changes and human interventions that were especially notable during the Roman era and the Little Ice Age (Arnaud-Fassetta and Provansal, 1999; Bruneton et al., 2001; Arnaud-Fassetta, 2002, 2003; Provansal et al., in press). In the smaller Tiber delta, multi-proxy investigations around the river mouth and the Roman town of Ostia have shown an evolution pattern involving three distinct phases over the last 5000 years (Bellotti et al., 2011). In the first stage (5000–2700 yr BP) a cuspate delta was built at the river mouth, which was located north of the present outlet. Subsequently, between 2700–1900 BP, an abrupt southward migration of the river mouth led to the abandonment of the previous cusp and the progradation of a new one. The third step, which is still in progress, has been strongly mediated by human impacts (Section 7) and marked by the appearance of a complex cusp made up of two distributary channels.

Several other recently documented examples illustrate the interplay between societies and the geomorphological onset and early growth of deltaic plains in the Mediterranean following sea-level stabilisation. Such growth commonly occurred in the form of bay-head deltas in low-energy embayments where a small accommodation space was rapidly infilled by pulses of sediment supply mediated by human activities. Many embayments thus underwent coastal metamorphosis during the mid Holocene, evolving from transgressed rias to prograding deltaic plains (Kayan, 1999). On the island of Malta, early Holocene deforestation by human societies began around 7300 years ago and appears to have significantly impacted upon sediment pulsing to coastal lowlands with a reduction in the island's ria dimensions (Gambin, 2004, 2005). For instance, in the ria of Burmarrad, deltaic progradation reduced the area of the embayment by up to 40% between the Neolithic period and the Bronze Age (Marriner et al., 2012b). Data from coastal Sicily show that humid conditions, to flush sediments from source to coastal sink areas, persisted in the region until around 4500 years ago (Tinner et al., 2009; Magny et al., 2011). A sparse tree cover would have rendered the sediment-generating catchments particularly sensitive to soil erosion during the flash flood-type events that are typical of the Maltese islands and the Central and Eastern Mediterranean (Djamali et al., 2012). Similar scenarios played out in the rias of Ionia (Brückner et al., 2002; Kraft et al., 2006) and the Gialias of Cyprus (Devillers, 2008). On the Gialias delta, for instance, a vast marine embayment formed during the early Holocene marine ingression. The ensuing growth of the deltaic plain significantly impacted upon the human geographies of coastal occupation, as manifested by the landlocking of three ancient harbour sites: Early/Middle Bronze Age Kalopsidha, Middle/Late Bronze Age Enkomi, Graeco-Roman Salamina and finally Medieval Famagusta on the distal margin of the palaeo-ria. Similarly, recent research by Kaniewski et al. (2013) looking at pollen records from the Namaan delta demonstrates that coastal societies around Akko (Haifa Bay) began significantly modifying vegetation and coastal environments between around 4000 and 3300 cal. BC, expressed by transition from a densely forested landscape to a shrub-steppe. These human-induced changes generated significant sediment pulsing to the Levant's coasts from the Bronze Age onwards and drove rapid changes on downdrift coasts (e.g. Marriner et al., 2008b).

In the Patras Gulf of Greece, the Acheloos delta is a peculiar example of human–environment interactions because the delta has landlocked the former Oeniades archipelago (Vött et al., 2007). The military harbour of Oeniades in Trikardo Island is presently landlocked 9 km from the coast and demonstrates the considerable coastal changes since Antiquity (Fig. 9). Based on sedimentary and archaeological evidence, Vött et al. (2007) have found that around 3000 cal. yr BC, during early Helladic times, an anchorage existed on the swampy lagoonal shore in the southeast. High fluvial discharge between 1300–1000 cal yr BC resulted in efficient offshore sediment flushing and a fall in siltation rates, and created ideal anchoring conditions. During Classical-Hellenistic to Roman times—when the shipsheds were in use—the northern harbour experienced ongoing water inflow from the Acheloos River and communicated with the sea via a lagoon. During Roman to Byzantine times, a river harbour existed near a palaeo-Acheloos meander flowing near the southeastern fringe of Trikardo. In a context of stable sea level, the changes in sediment supply and in frequency of flooding, rapid shoreline advance and subsidence associated with these deltas in embayed settings have had, in turn, considerable meso-scale consequences, notably the decline and demise of many harbours and cities (Brückner, 1997; Arnaud-Fassetta et al., 2003; Stefaniuk and Morhange, 2005; Ghilardi et al., 2008; Fouache et al., 2010; Goiran et al., 2011; Ghilardi et al., 2014).

7. Classical civilisations and the waxing and waning of river deltas

A corollary of the rise of classical civilisations and the spread of new agricultural technologies was a significant increase in demographic pressures (e.g. Kaniewski et al., 2013), with concomitant deforestation throughout much of Europe and the circum Mediterranean (Kaplan et al., 2009). The waxing and waning of many deltas in the Western Mediterranean has been correlated with the rise and fall of the Roman civilisation as well as with subsequent demographic changes in Europe (e.g. Büntgen et al., 2011). The postulate of an overaching anthropogenic influence on the formation and subsequent dynamics of Mediterranean deltas has been most vigorously applied in Peninsular Italy (the Po: Fabbri, 1985; Marchetti, 2002; Simeoni and Corbau, 2009; the Arno and Ombrone: Pranzini, 2001, 2007; Amorosi et al., 2013b; the Tiber: Bellotti et al., 2007), where it has given rise to the increasingly employed concept of 'man-made deltas' (Maselli and Trincardi, 2013).

The Po River catchment area is only 10% that of the Nile catchment area, but the subaerial delta of the Po grew extremely rapidly over the last 2000 years (Fig. 10a) to become the largest in the Mediterranean. Marchetti (2002) has claimed that human influence on the fluvial dynamics of the Po, especially since the Roman Age, has prevailed over climate, tectonics, and vegetation changes. This active growth has been purportedly driven essentially by human deforestation of the catchment (Simeoni and Corbau, 2009). From the 1st to 3rd centuries AD, land grants to Roman war veterans caused almost complete deforestation and generalised soil erosion, resulting in maximum progradation of the Po delta. This pattern of rapid deltaic growth over the last few millennia is mirrored by various other river deltas in Tuscany, notably the Arno and Ombrone (Fig. 10b,c), reportedly formed only over the last 2500 years, following large-scale deforestation of the catchment hillslopes, and which have prograded by up to 7 km over this time span (Pranzini, 2001, 2007). In addition to land-use changes, embanking of these rivers by Roman engineers has also been considered as having enhanced the progradation of their deltas. On the coastal plain formed by the Arno and Serchio Rivers, Amorosi et al. (2013b) have documented the gradual upswing in anthropogenic influence and the way this is embedded in the coastal–plain stratigraphy, culminating in the city of Pisa (Fig. 11). The transition from early Holocene transgressive conditions to the middle to late Holocene relative sea-level highstand phase is characterised by a regressive, shallowing-upward, stratigraphic succession of lagoonal, paludal and then poorly drained floodplain facies derived from sediments supplied by the two rivers. This coastal progradation under nearly stable sea-level conditions was interrupted by widespread swamp development close to the Iron-Etruscan Age transition. The meandering Arno and Serchio Rivers generated vast, low-lying floodplain swamps that strongly influenced the early Etruscan culture (7th–5th centuries BC) in terms of human settlement and societal behaviour. The subsequent ascendancy of human influence on this environment is attested at the transition to the Roman age (from the 1st century BC onwards), when the wetlands were drained and the modern delta plain started to form. Amorosi et al. (2013b) indicate that their palaeoenvironmental reconstruction fits in with the original geographical descriptions mentioned in Strabo's Chronicles.

A similar history of important progradation at the end of Antiquity resulting from land-use changes has also been reported from the deltas of the Tiber (Bellotti et al., 2007) and the Magra (Bini et al., 2012). The oldest archaeological evidence for human occupation at Ostia on the

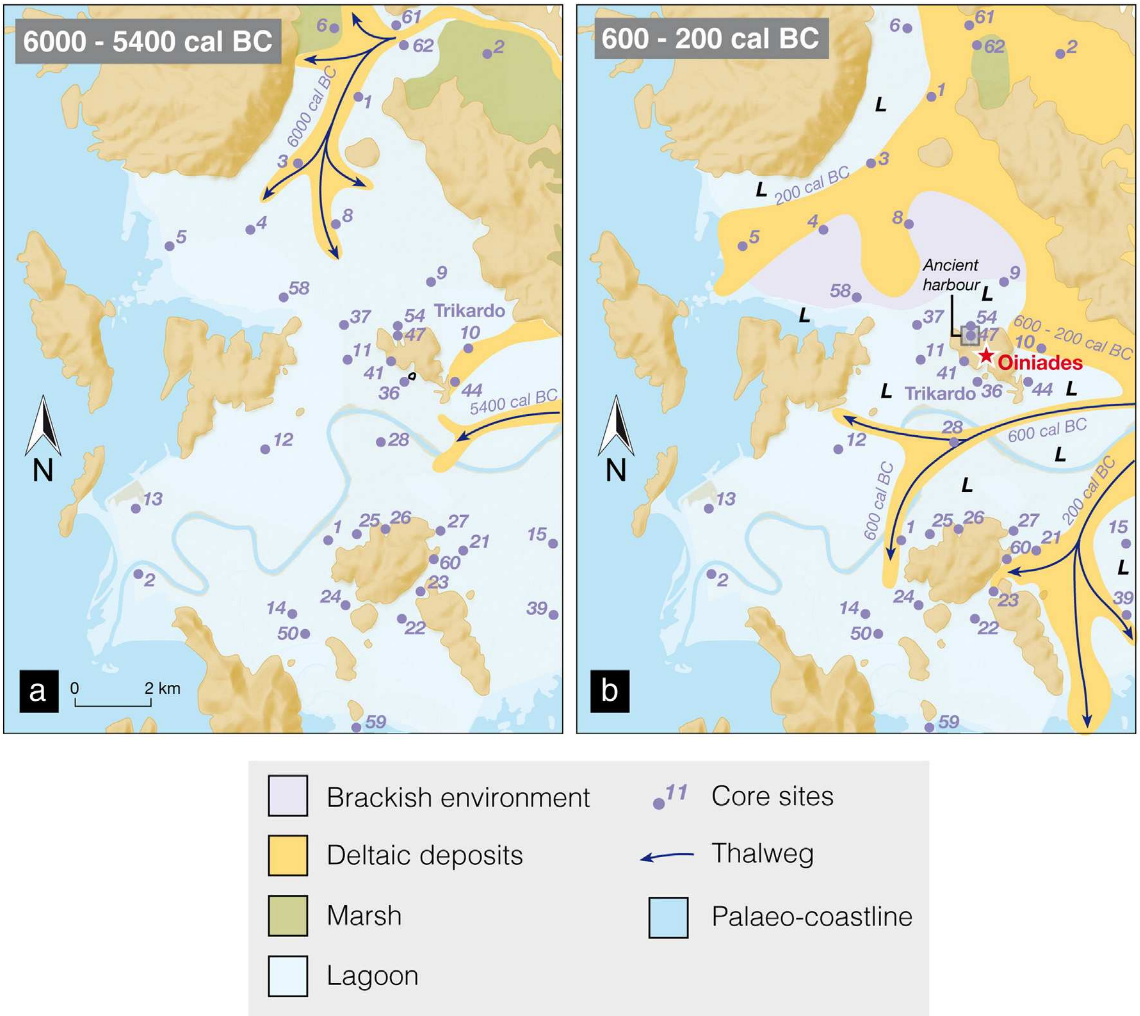

Fig. 9. 6000 years of Acheloos delta formation (Greece) and landlocking of the classical city of Oiniades. Prior to the progradation of the delta, the area was characterised by a series of palaeo-islands (adapted from Vött et al., 2007).

Tiber delta dates to the fourth century BC, when human activity is also clearly recorded by pollen data. Bicket et al. (2009) have shown that the timing of settlement along the Laurentine shore (around the 1st century BC) is set against the backcloth of pronounced Tiber delta progradation. Roman villas, constructed within a series of dune ridges, dominated the delta coastline south of the Tiber river mouth. At present, these archaeological remains lie around 900 m from the current shoreline as a result of high sediment supply and relative sea-level stability. Recent luminescence dates from these dune ridge systems, coupled with the archaeology, demonstrate that there has been a fivefold increase in aggradation rates since the end of the Roman occupation compared to the early Holocene (Rendell et al., 2007).

A quiescent phase of reduced sediment supply related to abandonment of catchment slopes and reforestation following the fall of the Roman Empire in Europe has been postulated for both the Arno and the Ombrone deltas (Pranzini, 1989, 2001). In Tuscany, the sensitivity of deltas to human impact is further demonstrated by the erosion that occurred in the 14th and 15th centuries, very likely due to decimation of over half of the population in this Italian region caused by the Black Death epidemy (Pranzini, 2001). In Mediterranean Spain, a marked imprint of human influence appears to have occurred later in connection with the Islamic period and the Reconquista, during which the catchments of Spanish rivers were significantly modified by deforestation and timber exploitation (e.g. Carmona and Ruiz, 2011). Vita-Finzi (1975) considered that many small deltas on the southern Spanish coast did not form until the 15–16th centuries, as sediment supply accelerated following hillslope deforestation. The larger Ebro delta started evolving from an estuary into a delta about 2000 years ago, under the Roman period and especially during the Islamic occupation, and underwent strong progradation from 1500 to 1650 (Guillén and Palanques, 1997; Palanques and Guillén, 1998).

In the rest of the Western Mediterranean, the growth of most deltas, probably impeded during the Dark Ages as a result of the well-reforested catchments, is deemed to have resumed during the Renaissance Period of socio-economic growth, much of the expansion occurring from the 16th to the 18th centuries (Pranzini, 2001). The effects of such Renaissance land-use changes and hydraulic engineering have, for instance, been well documented for the Po delta. Between 1500 AD and 1600 AD, Venetian technicians diverted the Po, inducing a “Renaissance delta” that was cut off from the hydraulic network, and the formation of the “modern delta”, the progradation of which was significant up to the middle of the 20th century due to the abundant sediment supply (Simeoni and Corbau, 2009). These latter changes correspond to the wet period of the Little Ice Age, during which demographic pressures on catchments and high river discharges favoured abundant sediment supply that led to enhanced delta growth.

8. The impacts of anthropogenic changes in river catchments on coasts and deltas since ca. 1800 AD

The impacts of changes in Mediterranean river catchment characteristics induced by human activities over the last two centuries have been

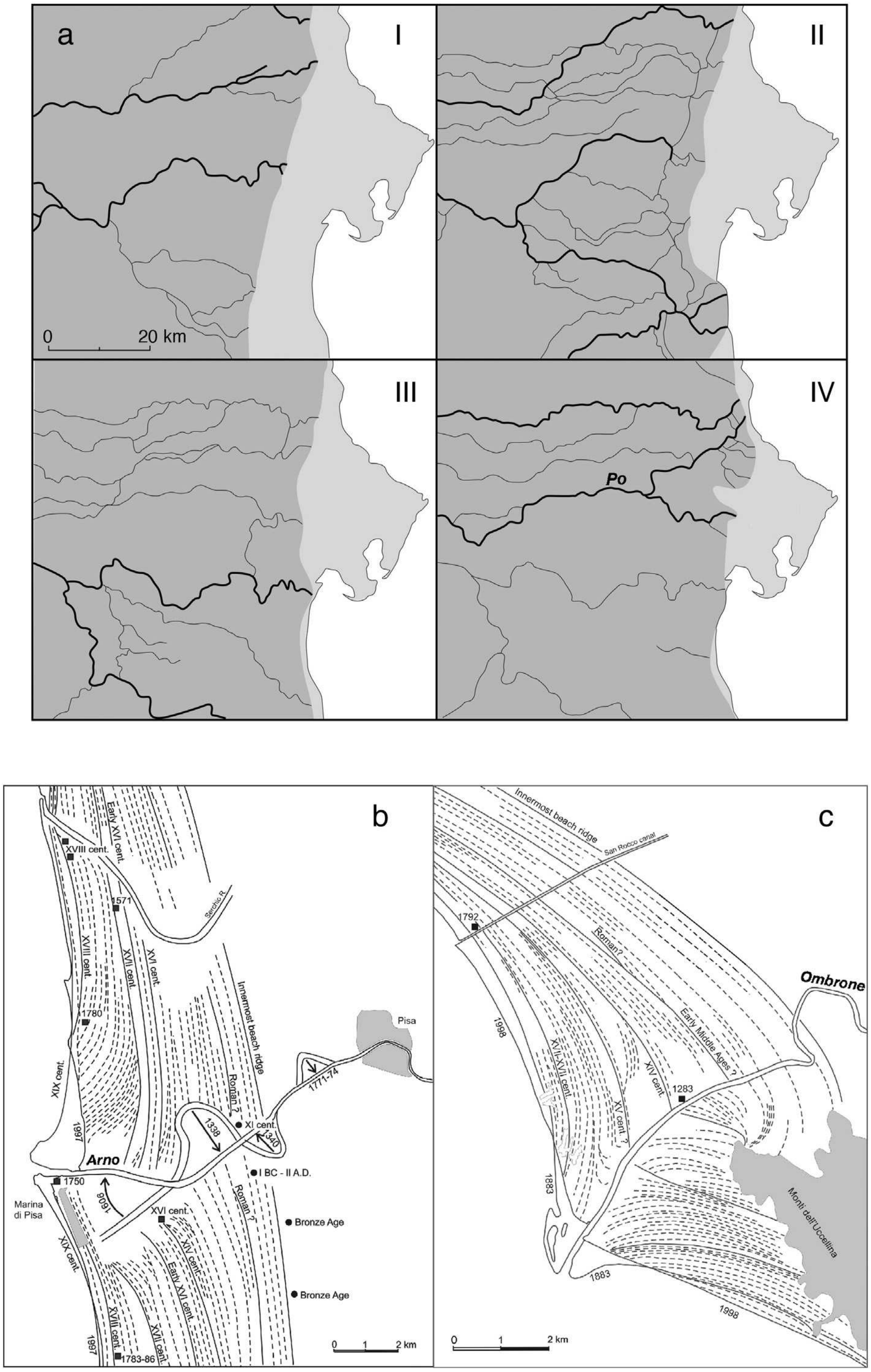

Fig. 10. Growth phases of the Po, Arno and Ombrone River deltas in Italy. (a) The Po delta: (i) at the end of the Bronze Age; (ii) during Roman times; (iii) at the end of the Medieval period; (iv) at the beginning of the 17th century. From Simeoni and Corbau, 2009; (b), (c) waxing and waning phases of the Arno and Ombrone deltas related to human influence on the river catchments that source these deltas in sediment.
From Pranzini (2001, 2007).

well documented in numerous case studies as well as in basin-scale syntheses (e.g., Poulos and Collins, 2002; Hooke, 2006; Milliman and Farnsworth, 2011). A reduction in the frequency of extreme river discharges at the end of the LIA (Hohensinner et al., 2008) and agricultural decline in mountain catchments attended by reforestation have been reported to have led to a decrease in sediment supply (Bravard, 2002; Wohl, 2006; Hoffmann et al., 2010; Hinderer, 2012). Engineering works aimed at flood control and navigation, such as torrent management, channel embanking, and in-channel gravel and sand extractions have also affected riverine sediment supply to the coast. The geomorphic effects of embankments constructed on the Po and Arno Rivers and on the growth of the deltas at the mouths of these rivers were recognised by Cuvier (1818) nearly two centuries ago. However, hydropower dams appear to stand out as the overarching cause of fluvial sediment deficit through the interception and storage of much of the total sediment flux in reservoirs (e.g. Surian and Rinaldi, 2003). The construction of hundreds of dams in river catchments draining into the Mediterranean Sea (Fig. 12) has resulted in significant reductions in

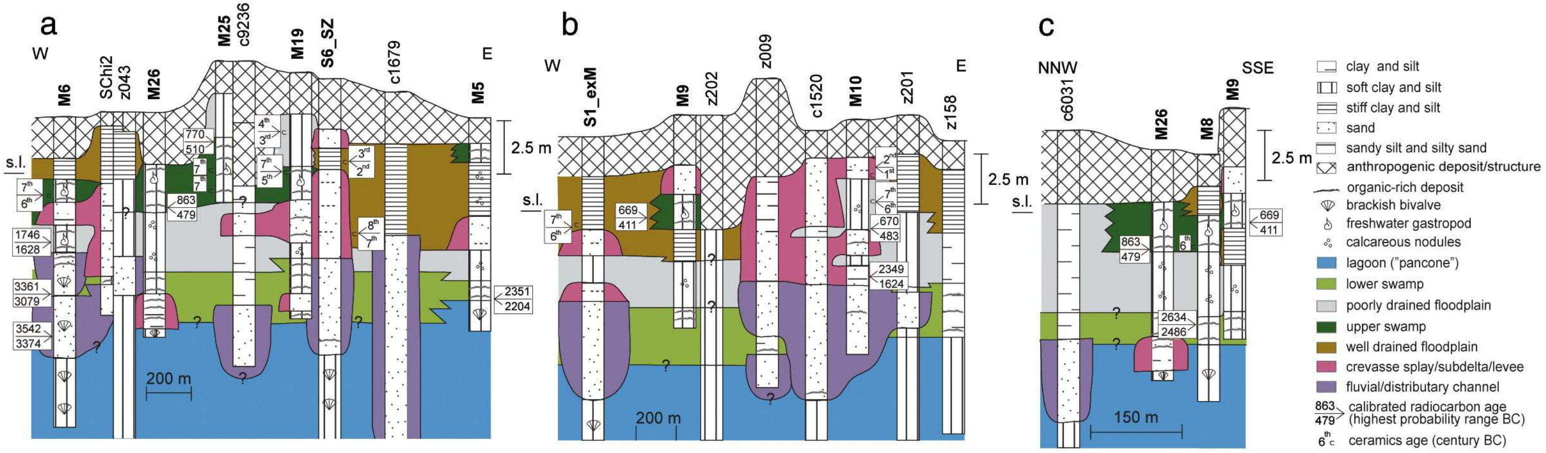

Fig. 11. Representative stratigraphic sections of the middle to late Holocene facies architecture in the area of the old town of Pisa, Tuscany, Italy, near the Arno River (see Fig. 9b). Radiocarbon data are reported as calibrated BC. The sections show anthropogenic influence embedded in the coastal–plain stratigraphy, culminating in the modern city of Pisa.
From Amorosi et al. (2013b).

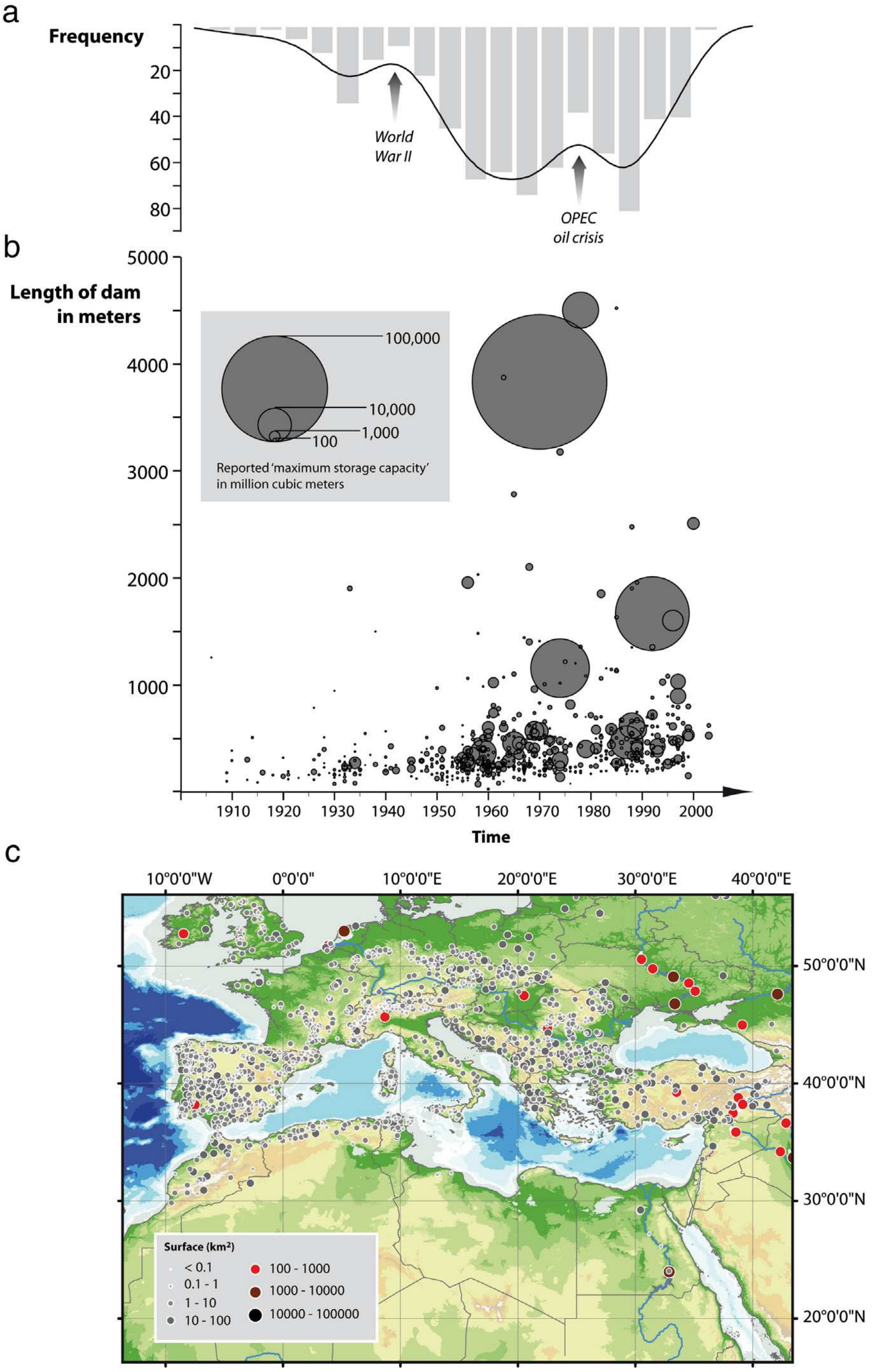

Fig. 12. Mediterranean dams and reservoirs. (a) Upper plot: histogram representing the construction date of dams in the Mediterranean and Europe (5-year bins) from 1900 to present. Solid line denotes the kernel density. Bottom plot: Length and storage capacity of European and Mediterranean dams. (b) Surface area of reservoirs rimming the Mediterranean and Europe (in square kilometres).
All data adapted from the Global Reservoir and Dam Database (Lehner et al., 2011).

the sediment loads of many rivers, attaining 98% in the iconic case of the Nile (Table 2). At the same time, land-use changes in Mediterranean catchments, especially the abandonment of farmland in the mountainous hinterlands, have led to reforestation. Reductions in fluvial sediment loads have had severe effects on many Mediterranean deltas and their adjacent coasts.

The most dramatic changes have affected the Nile delta. Unlike many deltas in the Mediterranean characterised by mosquito-infested wetlands with low population densities (e.g. Rhône delta), the Nile delta has consistently been very heavily populated, a heritage of an ancient civilisation based on agriculture, with present population densities of up to 1600 inhabitants per square kilometre, and the delta includes important industrial and commercial cities, and numerous centres for summer tourism and recreation (El Banna and Frihy, 2009). The Nile delta has attracted significant research attention as fears of subsidence and projected sea-level rise potentially threaten one of Egypt's most valuable economic resources and the future livelihood of more than 50 million people (Becker and Sultan, 2009; Hereher, 2010; Aly et al., 2012; Marriner et al., 2012d; Stanley and Corwin, 2013). The Intergovernmental Panel on Climate Change has assigned the Nile depocentre to its 'extreme' category of vulnerability hotspots (Nicholls et al., 2007), one of just three deltas to fall into this group. Analyses of

Table 2
Pre- and post-dam changes in annual water discharge (Q) and sediment discharge (Q_s) in Mediterranean rivers. Modified after Milliman and Farnsworth (2011).

River	Basin area (km^2)	Country	Pre-dam Q (km^3/yr)	Post-dam Q (km^3/yr)	Pre-dam Q_s (Mt/yr)	Post-dam Q_s (Mt/yr)	% Q_s loss
Rhône	96,000	France	54		59	6.2	89
Ebro	87,000	Spain	50	17	18	1.5	92
Po	74,000	Italy	46		15	10	33
Tiber	17,000	Italy	7.4		1.3	0.3	77
Pescara	3300	Italy	1.7	0.9	2.2	1.2	45
Ombrone	3200	Italy	0.8		1.3	1.9	81
Tronto	1200	Italy	0.3		1.2	0.6	50
Drini	19,600	Albania	12		16	2.1	87
Vijose	6700	Albania	6.4		29	8.3	71
Semani	5300	Albania	5.6		30	16	47
Asi	23,000	Turkey	2.7		19	0.36	98
Ceyhan	21,000	Turkey	7		5.5	4.8	13
Moulouya	54,500	Morocco	1.3	0.2	13	1	92
Cheliff	44,000	Algeria	1.3		8	4	50
Totals (w/o Nile)	262,700				227	58	75
Nile	2,900,000	Egypt	80	≪30	120	2	98
Totals (w/Nile)	3,162,700				347	60	83

historical maps show that, during the 1800s, the Rosetta and Damietta delta promontories, corresponding to the two modern branches of the delta, prograded by 3 to 4 km, in response to the large sediment supply to the coast that went through these branches (Frihy and Lawrence, 2004). The construction of two dams on the upper river in Aswan and barrages on both the upper and lower Nile river at the beginning of the 20th century led to a cut-off of almost all water discharge from the river and delivery of sediments to the coast, resulting in a switch of the accretion regime to one of erosion (Frihy and Khafagy, 1991). Between 1825 and 1902, the estimated suspended sediment load upstream of the Low Aswan Dam was 200 × 10^6 t a year, whereas from 1902 to 1963 the average load was reduced by approximately 20% to 160 × 10^6 t yr^{-1}. From 1963 to 2000, the average suspended load upstream of the dam experienced a further decline reaching 126 × 10^6 t yr^{-1} (El Banna and Frihy, 2009).

Other factors have also contributed to the extensive erosion of the delta coastline during recent times. These include an abrupt decrease in the annual discharge of the Nile River during the 20th century due to low rainfall within its catchment area in the Ethiopian Plateau and central Africa that has led to reduced sediment delivery to the river, and sea-level rise (Fig. 13). Local deltaic subsidence is another contributory factor, and can exceed 5 mm yr^{-1} in some areas (Becker and Sultan, 2009). Subsidence is particularly pronounced in the youngest deltaic sediments, which undergo the most important phase of volume

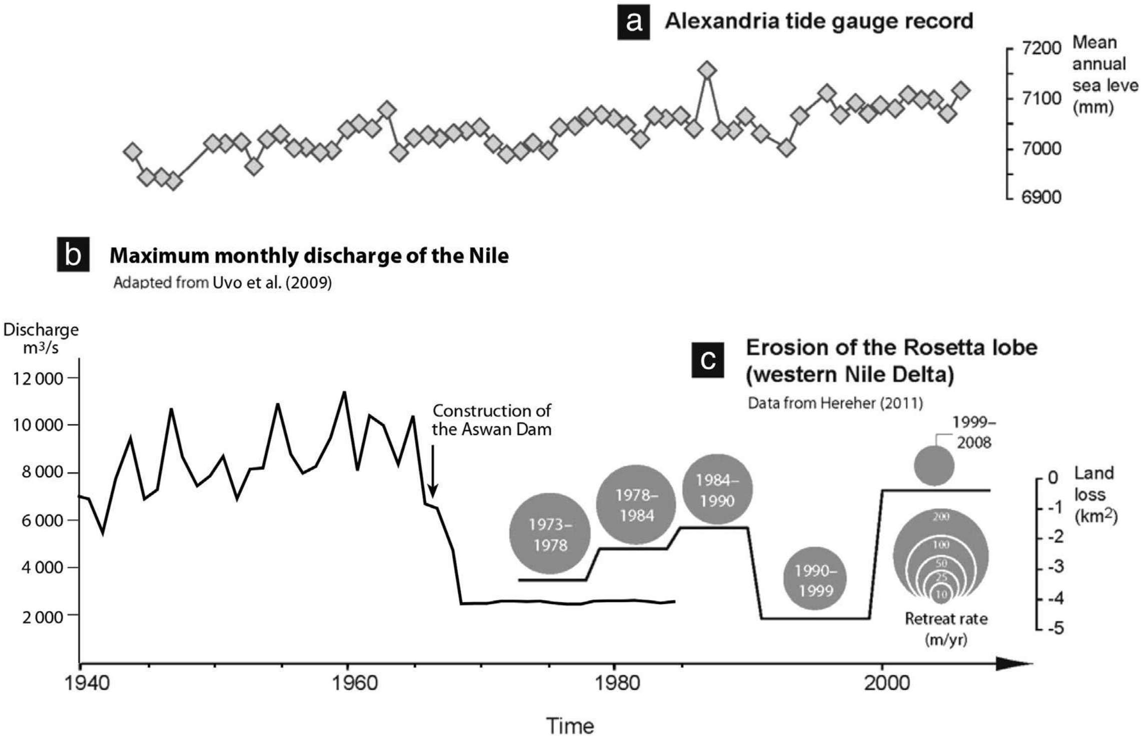

Fig. 13. Exacerbation of erosion of the Rosetta branch of the Nile delta by sediment trapping by the Aswan Dam. (a) RSL data from the tide guage record at Alexandria, depicting a gradual rise since the 1940s. (b) Maximum monthly discharge of the Nile in m^3/s (adapted from Uvo et al., 2009). Note the sharp drop in discharge after the construction of the Aswan Dam and its implications for sediment supply to the Nile Delta area. (c) Erosion of the Rosetta lobe, depicted in both land loss area (km^2, black line) and retreat rate (m/yr, grey circles).
Adapted from data in Hereher (2011).

loss immediately after deposition, meaning that the present Damietta and Rossetta lobes are particularly vulnerable to degradation under the present sediment-starved regime (Frihy et al., 2003; Stanley and Corwin, 2013). Both lobes have undergone significant erosion during the past 50 years (Hereher, 2011).

For many of the Mediterranean's deltas, sharp reductions in sediment supply, subsidence and artificial lowering of the piezometric zone have also engendered problems related to saltwater intrusion and soil salinisation (Werner et al., 2013). This has impacted upon the exploitation of economic resources, both industrial and agricultural, and the ecology of deltaic wetlands. The Nile delta hosts around 70% of Egypt's industrial activity and is home to more than half of Egypt's population both of which place heavy demands on the delta. High population densities have notably created pressures on the delta's freshwater resources; excessive pumping has led to saline water intrusion from the sea boundary with a concomitant increase in soil salinity (Ebraheem et al., 1997). Up to 60% of agricultural lands in the lower delta are now considered as being affected by soil salinisation.

In the Ebro catchment, the total load downstream of dams, now estimated at around 0.45×10^6 t yr^{-1}, represents only 3% of what was transported at the beginning of the 20th century to the delta plain (Vericat and Batall, 2006). Sediment yield is three to four times lower below the dams due to trapping within the reservoirs, which according to these authors, concerns 100% of the bedload. This decrease in sediment discharge has, thus, especially affected the sand fraction, directly impacting the stability of the deltaic shoreline, which, after several centuries of progradation, evolved into an erosional regime in the second half of the 20th century (Palanques et al., 1990). According to Simeoni and Corbau (2009), reductions in sediment supply by the Po River to the coast during the 20th century, caused by dams, riverbed excavations, land reclamations, and methane extractions from the superficial ground water table, have strongly affected the delta, leading, in particular, to chronic coastal erosion. Since the mid-19th century, both the Arno and Ombrone deltas have also experienced severe erosion, beginning at the river mouth and gradually expanding to the lateral beaches and barriers (Pranzini, 2001). Approximately 800 m of coast were eroded at the apex of the Ombrone delta and 1200 m on the unprotected northern side of the Arno delta, whereas the recently documented maximum erosion rates are 11 and 20 m a year, respectively. This erosion is attributed to mountain reforestation, river damming, river-bed quarrying and wetland reclamation (Pranzini, 2001).

A detailed sediment balance for the lower Rhône river over the last 130 years has been constructed by Provansal et al. (2014) who showed net storage ($+13.08$ to $+17.1$ Mm^3 of sediment) in the channel margins related to engineering works and afforestation prior to dams, and a net loss (-4.64 to -11.2 Mm^3 of sediment) for this lower fluvial reach resulting from trapping upstream by dams. These authors also showed that sediment accumulation at the mouth of the Rhône occurred to the tune of $+3.4$ Mm^3/y prior to 1970, and $+1.2$ Mm^3/y since then, i.e., a more than 50% drop.

Liquete et al. (2005) have noted, however that sediment load reduction effects have, to date, had, little effect on many of the deltas of the small, steep rivers and torrents of the coast of Andalusia. In other areas, deltas have actually accreted as a result of land-use changes, fine examples being the Meric (Ekercin, 2007) and the Ceyhan (Alphan, 2005), in southeastern Turkey, whereas the neighbouring Seyhan delta has undergone significant retreat in the last thirty years following upstream river damming (Kuleli, 2010). The effects of changes in river sediment yield on delta morphology resulting from human activities have also been documented for the Shkumbini, Semani and Vjosë deltas of Albania, which have surprisingly high sediment yields relative to catchment size (Ciavola et al., 1999). Probably the most radical transformation of a delta in the Mediterranean is that operated on the small Var delta (c. 10 km^2) on the French Riviera coast in the course of the 20th century (Fig. 14). These changes included the construction of several run-of-the-river barrages in the lower course of the Var River to control flooding and enhance water supply (Julian and Anthony, 1996), and total reclamation and engineered extension of the Var delta plain through infill of its seaward margins in order to expand the accommodation and runway facilities of the international airport of Nice. These engineering operations have led to a gain in artificially created area of 3.5 km^2, and an armouring of the artificial shoreline thus created (Anthony, 1994; Anthony and Julian, 1999). An important accident resulting from these drastic changes was a submarine landslide in 1979 that led to several casualties and severe structural damage, including the collapse of a harbour pier under construction adjacent to a Messinian canyon (Fig. 14b) near the mouth of the delta (Anthony and Julian, 1997). The natural supply of gravel to the adjacent embayed beaches, especially that of Nice, has also been completely cut off, leaving present beach sediment budgets with zero natural inputs. The resulting chronic beach erosion since the 1960s needs to be contained by frequent beach nourishment (Anthony et al., 2011), the total volume of which, over the last thirty years, far exceeds the entire volume of the initial gravel barrier.

9. Delta morphodynamic changes over time and the human impact

Flucutations in sediment supply mediated by human activities and climate changes (see Section 11) and engineering of river channels have also largely conditioned the morphology of Mediterranean deltas, against a background of fetch-limited waves, narrow tidal range and variability in storminess. Delta morphologies have apparently varied in time, although reported case studies are sparse. The earliest morphodynamic changes occurred in the bay-head ria deltas that became increasingly exposed to waves following infill of embayment accommodation space by progradation, as well as in the Nile (Figs. 8, 9). The growth of these ria-type deltas may be envisaged in a three-phase model: (1) marine transgression creating fluvial embayments between around 8000 to 6000 years ago; (2) rapid deltaic progradation probably expressed by a digitated delta morphology in a protected environment (e.g., the Menderes delta in Turkey (Brückner et al., 2002) and the Caimenderes delta around Troy (Kraft et al., 2006)); and (3) shoreline regularisation at the ria mouth, which translates the stadial transition from fluvial-dominated processes in sheltered bay-head settings to increasing exposure to waves.

Several of the larger deltas such as the Nile, the Po and the Rhône have been characterised by the development of successive lobes in adjustment to human-mediated sediment supply fluctuations, delta channel engineering and ensuing balances between progradation and aggradation. The millennial-scale decline in Nile flow and human channeling of the delta that led to a gradual reduction in the number of fluvial branches from seven, in early Antiquity, to just two at present (Stanley and Warne, 1993) has favoured enhanced wave reworking of the delta. The Po delta began life as a strongly wave-influenced delta between 4000 and 2000 years ago, evolved to a digitated river-dominated delta during the 1500s under the influence of strong progradation related to increasing destabilisation of the catchment hillslopes in the late Middle Ages, and has recently re-entered the original strongly wave-influenced category due to reduction in river sediment input (Pranzini, 2013). The phases of lobe abandonment and new lobe development associated with this dynamic delta have been recently synthesised by Simeoni and Corbau (2009). These changes echo those that have been described from the analysis of ancient maps of the Rhône, involving shifts from digitated, through lobate plan shapes—typical of a balance in favour of strong river influence relative to waves—to more cuspate shapes expressing stronger wave control of delta morphodynamics (Provansal et al., in press).

At present, many Mediterranean deltas are relatively symmetrical, in morphometric terms, and subject to bi-directional drift (Fig. 15), such as the Ebro (Jimenez et al., 1997), the Ombrone, Arno, Tiber and Volturno (Aminti and Pranzini, 1990; Pranzini, 2001), the Shkumbini in Albania (Ciavola et al., 1999), and the main Pila lobe of the Po (Simeoni and

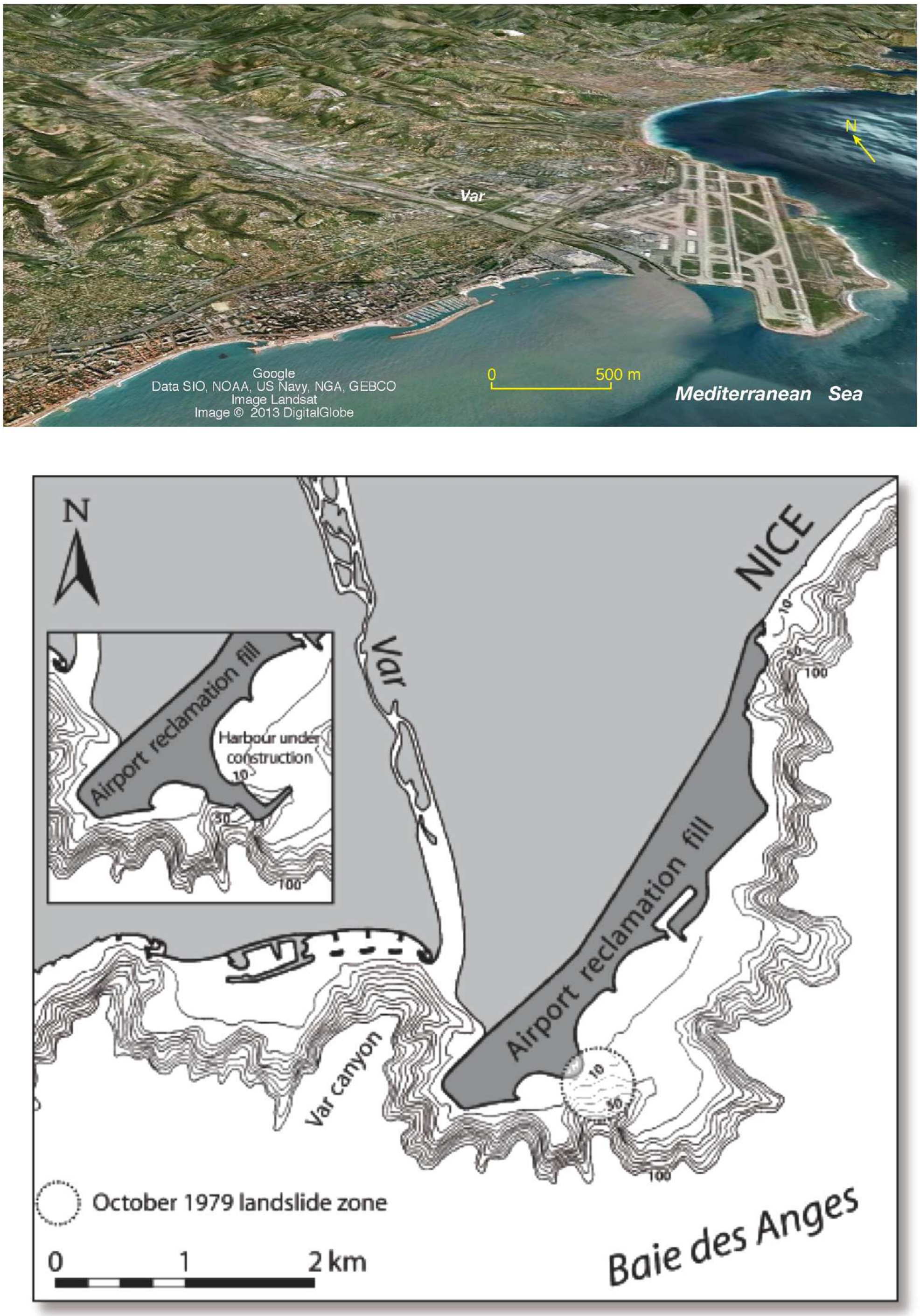

Fig. 14. The Var River delta on the French Riviera, southeastern France. (a) Google Earth image of the delta, a fine example of radical human transformation of a delta, ranging from the effects, on sediment supply, of the construction of several barrages in the lower course of the river a few kilometres upstream of the delta, to reclamation and extension of the delta plain. (b) Infill and complete armouring of the shoreline for the construction of the international airport of Nice. Up to 3.5 km^2 of additional space was gained by reclamation of part of the steep, muddy delta front through construction of groynes, embankments and infill structures. Part of this reclamation fill, including a harbour breakwater, collapsed on October 16 1979, following a submarine landslide, causing numerous casualties.

Corbau, 2009). This drift divergence leads to redistribution of fluvial deposits on both flanks of these deltas, fulfilling their role as sediment purveyors to adjacent coasts. Pranzini (2001) showed this common trend towards delta symmetry to be a product of self-organised delta growth despite an initial dominant regional drift direction. Within the context of abundant sediment supply that has seen the growth of these deltas, this development may reflect: (1) a commonly single parent channel, (2) the relatively fetch-limited wave conditions and large directional apportionment of the wave energy, potentially limiting wave removal of fluvial sediment, but with one dominant wave window, (3) high winter river discharges that also coincide with the most energetic waves, potentially favouring the rapid growth of cuspate-type deltas facing the energetic wave window and subject to divergent drift from the mouth.

The pulsed pattern of delta development involving the waxing and waning of delta size between the Roman period and the Little Ice Age has now become much less reversible in the modern era following widespread drastic reductions in fluvial sediment inputs. The recent

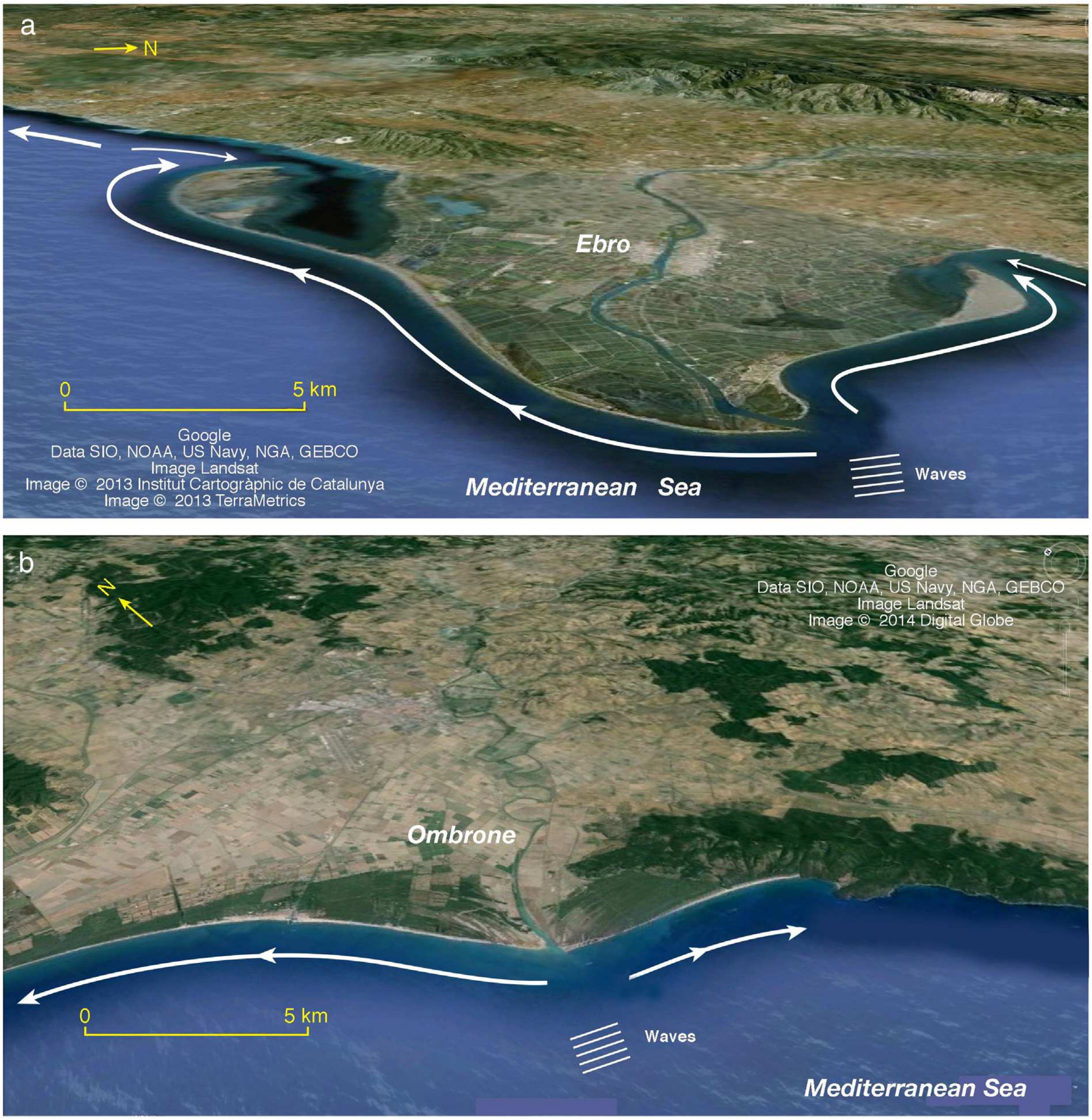

Fig. 15. The Ebro and Ombrone river deltas. These morphometrically relatively symmetrical deltas are characterised by divergent drift from the mouth following a pattern of progradation wherein delta growth has occurred to face the dominant wave direction.

massive reductions in river sediment supply to Mediterranean deltas are presently affecting the morphodynamic framework of many of these deltas, inducing river-mouth erosion and a shift in particular to an increasingly wave-influenced regime, as has been documented for the Nile (El Banna and Frihy, 2009), the Rhône (Sabatier et al., 2006), the Ombrone (Pranzini, 2007), the Po (Pranzini, 2013), and the Ebro (Ibáñez et al., 2014). In some cases, notably where small deltas have developed along the semi-arid shores of the Mediterranean, wave reworking has led to rapid delta demise. For instance, prior to dam construction, the sediment supply of the Moulouya (53,500 km^2), though relatively small (about 12×10^6 t yr^{-1}) as a result of the weak liquid discharge in the semi-arid setting of western Morocco, was significant enough to have led to the progradation of a small asymmetric delta of about 30 km^2 skewed east of the mouth of the river by longshore drift (Snoussi et al., 2002). Since the construction of a major dam on the river, the fluvial sediment input has been reduced by 93%, leading to the straightening of the shoreline, delta destruction and narrowing of the mouth (Snoussi et al., 2002). Drastic changes affecting the small Adra delta (c. 30 km^2) in southeastern Spain have also been reported by Jabaloy-Sánchez et al. (2010). Between 1872 and 1972, damming of the natural river channel very close to its mouth and the construction of two successive artificial channels to divert the river flow resulted in erosion of the original delta and the formation of a new, asymmetrical delta at the mouth of the artificial channels. Between 1972 and 2010, the damming of the trunk river in the central sector of the catchment led to a drastic reduction in sediment flow to the coast, thus triggering general erosion and coastline retreat.

One possible outcome of delta erosion is that it may be assuring a degree of temporary stability to barrier coasts downdrift, the updrift deltaic reworking feeding these downdrift barriers (Stanley and Warne, 1998). In exact contrast to this process of ‘cannibalism’, marked variations in erosion and accretion resulting from the sharp gradients in sediment transport induced by decreasing deltaic sediment budgets may be leading to increased sediment sequestering in the vicinity of the deltas, in a process of self-organised delta preservation. This is likely to be the case in the larger-discharge deltas. These aspects, which have important implications for the survival of the Mediterranean's clastic coasts and deltas, are briefly examined in Section 12.

10. Large-scale anthropogenic destabilisation of non-deltaic coasts

Since rivers draining into the Mediterranean have been subjected to marked fluctuations in sediment yield related to anthropogenic activity in the catchments, especially since the Graeco-Roman period, and to climate change, these fluctuations have, in turn, impacted on the stability of adjacent barrier coasts. The changes in fluvial sediment supply that generated pulses of delta-plain growth and stagnation in the Mediterranean have been shown, for instance, to have affected the geomorphic development of adjoining coastal barriers (e.g., Dubar and Anthony, 1995).

Many of these barrier systems are now exposed to erosion and subjected to pervasive engineering works. Although direct human interventions on Mediterranean shores can be traced back to the cases of harbour development in Antiquity discussed earlier, and more spectacularly to the tombolos constructed in Tyre and Alexandria by Alexander the Great's engineers during the Hellenistic period (Marriner et al., 2008b), massive and pervasive coastal engineering interventions with far-reaching consequences are products of urban, port and tourism development over the last few decades. In the course of the 20th century, the coastal impacts of riverine sediment reductions associated with the Agricultural and Industrial Revolutions have been aggravated by direct anthropogenic pressures on the shores of the Mediterranean, at the same time as this basin has become the world's leading tourism and leisure destination. Accommodating this leading position has involved both direct shoreline appropriation by the economic sector, notably based on tourism, and engineering efforts aimed at stabilising shores that are now increasingly prone to erosion or rendered artificial. Long and enduring anthropogenic pressures on the depositional coasts of the Mediterranean have had a destabilising effect on beach–dune systems. Fine examples of coastal geomorphic changes induced by these developments have been described from the Tangiers (Sedrati and Anthony, 2007) and Tetouan coasts (El Mrini et al., 2012) of Morocco, the coast of Tunisia (Halouani et al., 2013), the northeastern coast of the Nile delta (El Banna and Frihy, 2009), Haifa Bay in Israel (Zviely et al., 2009), the Tuscany coast in Italy (Anfuso et al., 2011), the Catalonia coast in Spain (Jiménez et al., 2012) and the French Riviera and Gulf of Lyons coasts in France (Anthony, 1994; Anthony and Sabatier, 2012, 2013; Brunel et al., 2014). Coastal sediment budget determinations referencing these impacts are, however, rare. Exceptions include the secular-scale budgets computed from bathymetric surveys for the Rhône delta by Sabatier et al. (2006) and for the western gulf of Lyons coast and shoreface by Brunel et al. (2014). The latter study highlighted, in particular, a shoreface sediment budget reduction of over 30 million m^3 concerning 200 km of coast over the last 25 years, generated essentially by deficient sediment supply from rivers.

On all these clastic coasts, the most pervasive development effect has been a drastic reduction of beach width due to the growth of urban fronts, and destruction of aeolian dunes, resulting in perturbations of beach–dune sediment exchanges. Beach erosion has often been aggravated because of the incapacity of dammed rivers to supply fresh sediment. The plethora of seawalls aimed at protecting urban fronts, and groynes and breakwaters constructed to contain erosion, has commonly resulted in worsening the situation, generating further downdrift erosion, with the unfortunate recourse to further engineering structures. Shoreline changes have also strongly affected seagrass colonies that play a role in dissipating wave energy on Mediterranean shores (e.g., Simeone and De Falco, 2012). This is the case of both *Posidonia oceanica* and *Zostera noltei*, largely destroyed by beach protection structures, beach nourishment operations, 'marina'-type developments, and pollution.

11. Discussion: disentangling the human influence from that of climate change

The antiquity of the long relationship between Humans and Mediterranean coasts is most clearly illustrated by the development of numerous ancient harbours throughout the Mediterranean from the Bronze Age onwards, reflecting palaeo-engineering accompaniments of varying degrees to situations of shelter from waves favourable to the development of trade. Expressions of this long relationship are further expressed by patterns of river delta growth and decay reported in a large corpus of studies. This relationship may be synthesised schematically in terms of a rising continuum with embedded variability from ancient to present times, characterised by phases of significant deltaic progradation punctuated by stagnation or delta retreat (Fig. 16).

Beyond this general statement, the anthropogenic impact on river sediment supply and delta morphogenesis is likely to have been variable—both in space and time—throughout the Mediterranean, depending on lithology, human pressures on landscapes, and climate variability (Stewart and Morhange, 2009; Dusar et al., 2011). Climate changes and human societies have impacted upon basin hydrology and land cover, thus influencing the sediment production from source to sink areas that has effectively been, in turn, a key agent in mediating human occupation of the Mediterranean's clastic coasts. Climate changes have modulated not only river flow and sediment delivery, but also the frequency and intensity of coastal storms and storm reworking of coastal deposits (e.g. Dezileau et al., 2011). However, disentangling the influence of climate variability on sediment supply to base level and delta growth and decay from that of Humans over the last 6000 years is far from being straightforward, whatever the type of environmental proxy used (Fig. 17). In the Nile River, for instance, significant millennial-scale decreases in sediment supply are underpinned by an orbitally-driven southern displacement of moisture-bearing monsoon rains (Fig. 18). These not only acted as pacemakers for widespread deltaic changes (e.g. Bernhardt et al., 2012), but also influenced the nature and distribution of human activities along the Nile's fluvial corridor, culminating in the emergence of Egypt's Pharaonic civilisation around 5000 years ago (Brooks, 2006; Kuper and Kröpelin, 2006). The delta area was particularly attractive due to its low topography (despite the risk of flooding), high productivity and rich biodiversity. It rapidly became a focal point for Egyptian civilisation (Butzer, 1976). In the case of the Tuscan deltas, links between changes in delta area over time and human activities have been identified mainly from one or a combination of the following approaches: (1) archaeological data, (2) distant correlations between, on the one hand, radiometric ages of deltaic beach–ridge strandplains and their patterns, and historical documentation of land-use changes in the catchments, on the other hand, and (3) from morphostratigraphic and palynological data. Nevertheless, whatever their respective merits as palaeoenvironmental records, land-use, river and delta morphometric and sediment archives have significant limitations because they may entail large chronological uncertainty that is a source of difficulty in assessing rates of landscape change (Dusar et al., 2011). Furthermore, as these authors also noted, because of the rich cultural heritage of the Mediterranean, most palaeo-environmental research has been conducted on or near archeological sites, where direct human impact may blur the indirect impact on sediment dynamics arising from land-use changes.

The problem is also inherent to the spatial and temporal variability of climate and climate change in the Mediterranean. Mediterranean rivers are sourced by catchments that have been particularly sensitive to climatic events over the last 5000 years, within a context of increasing anthropogenic landscape perturbation. There is, however, significant uncertainty regarding spatio-temporal fluctuations in climatic signals throughout the Mediterranean basin. These signals are considered as

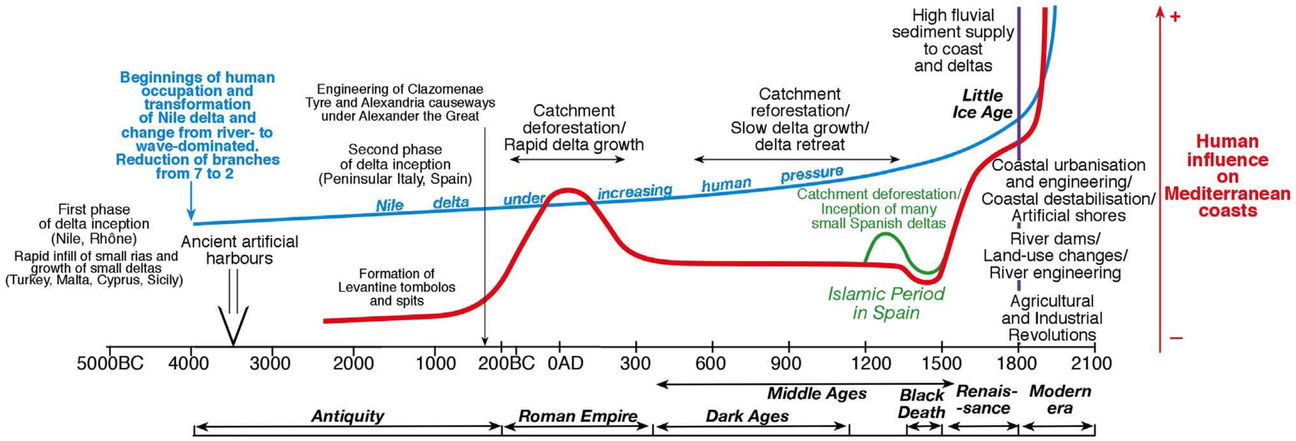

Fig. 16. A schematic synthesis of human-induced impacts on the coasts of the Mediterranean, including ancient harbour development and palaeo-engineering, and phases of river delta growth and decay over the last 6000 years. Red line shows the general human impact pattern, the blue line the Nile delta pattern, and the green line local changes in Islamic Spain.

having had potentially variable effects in an extremely variable Mediterranean context of fluvial hydrology and sediment supply to base level (e.g., Grove and Rackman, 2001; Stewart and Morhange, 2009; Fletcher and Zielhofer, 2013; Magny et al., 2013). Although human-driven increases in river flow and sediment discharge have been reported to have occurred in Roman times in the Rhône catchment, for instance, resulting in enhanced deltaic progradation, these increases have also been interpreted as echoing a distant climatic influence in the upstream reaches (Bruneton et al., 2001; Arnaud-Fassetta, 2002).

The example of the Rhône underlines the difficulty of separating climatic forcing on sediment supply fluctuations (e.g. Fletcher and Zielhofer, 2013) from the effects of anthropogenic pressures (e.g. Faust et al., 2004; Butzer, 2005; Lespez, 2007; Casana, 2008; Dusar et al., 2011; Brisset et al., 2013). Together with the spatial variability of patterns of delta growth under the influence of Humans, it also warns against a simplistic view of Mediterranean deltas as human constructs. Human-driven changes in sediment supply are, for instance, almost completely ignored by Fletcher and Zielhofer (2013) in their synthesis of late Holocene rapid climate changes in the Mediterranean. The breakdown of Mediterranean catchment landscapes has been viewed recently in terms of a two-phased process, wherein rapid climate-driven fluctuations have triggered weaknesses that have made these landscapes vulnerable to human activities (e.g. Casana, 2008; Brisset et al., 2013). This probably adequately synthesises the joint action of these two sets of drivers of environmental change in the Mediterranean.

This complex nexus between human activities and rapid climate change is perhaps more clearly exemplified by the better-constrained climatic, hydrological and historical archives relating to the Little Ice Age. The significant progradation of the Rhône delta, for instance, as of many other deltas in the Western Mediterranean between the end of the 16th and middle of the 19th centuries, owes much to the hydrological regime generated by the cold and wet climatic conditions that accompanied the LIA and its numerous internal oscillations (Sections 6 and 7). In the case of the Rhône River, for instance (undoubtedly one

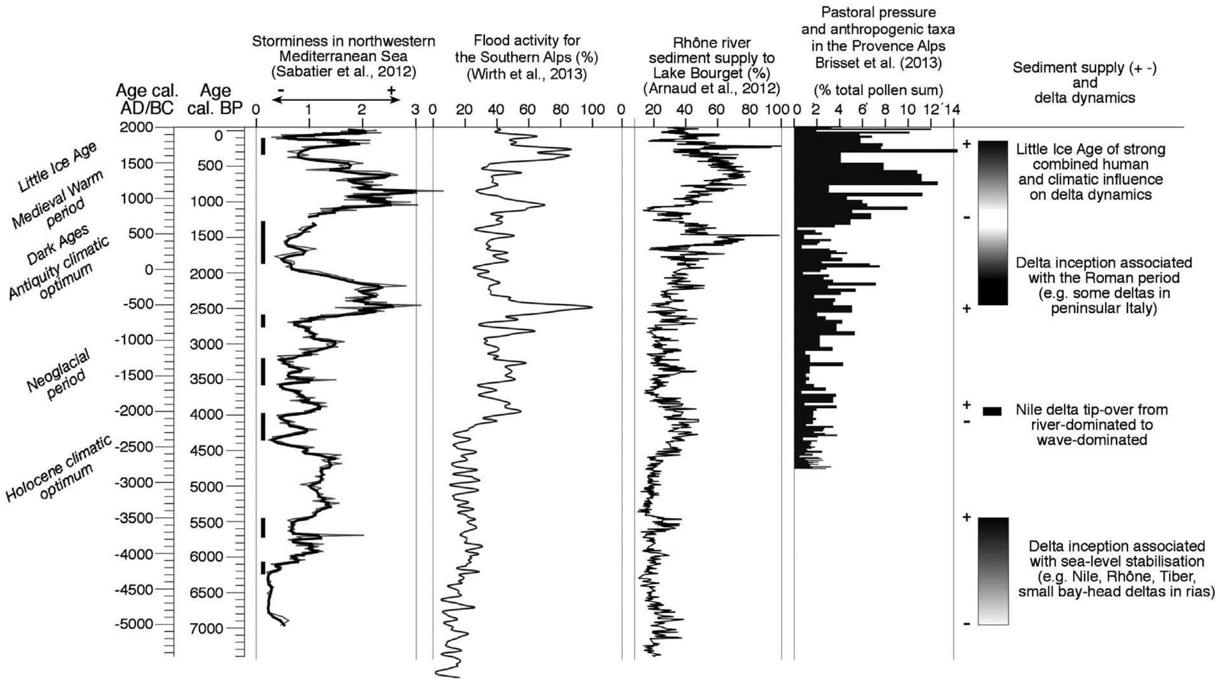

Fig. 17. A selection of circum-Western Mediterranean environmental proxies based on work by Sabatier et al. (2012), Wirth et al. (2013), Arnaud et al. (2012) and Brisset et al. (2013), and fluvial sediment supply, delta growth and decay patterns. Vertical bars in the storminess column show major barrier overwash phases identified by Sabatier et al. (2012) in the Gulf of Lions.

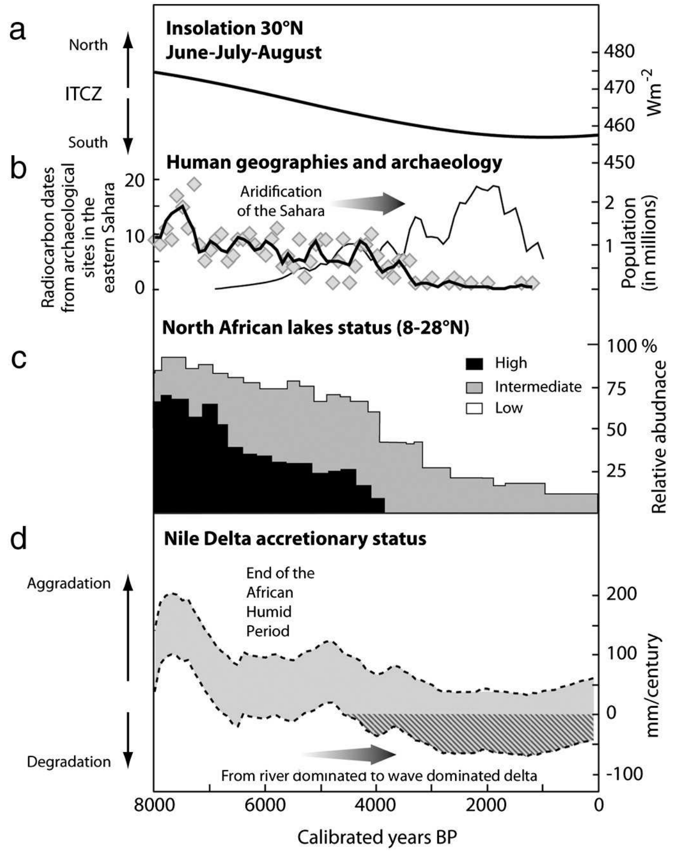

Fig. 18. A comparison of regional environmental proxies, human population, and the sedimentary and geomorphic status of the Nile Ddelta during the Holocene (adapted from Marriner et al., 2013). (a) Holocene insolation at 30° N for June–July–August (Laskar et al., 2004). (b) On the right axis: radiocarbon dates from early and mid-Holocene occupation sites in the Eastern Sahara (Kuper and Kröpelin, 2006). The solid black line denotes a three-point moving average. On the left axis: estimates for the population of the Nile valley in Egypt (Butzer, 1976). These are represented by the thin black line. (c) North African lake levels (Gasse and Roberts, 2004). (d) Nile delta accretionary status. The record shows that the Nile delta has a particularly long history of vulnerability to extreme events (e.g., floods and storms) and sea-level rise, although the present sediment-starved system, since the construction of the Aswan High Dam, does not have a direct Holocene analogue. It highlights the importance of the world's deltas as sensitive archives to investigate Holocene geosystem response to climate change, risks and hazards, and societal interaction.

of the rivers of the world with the oldest series of hydrological archives—the Histrhône data base (http://histrhone.cerege.fr—generated by the historical work of Pichard and Roucaute (2014)), the confrontation of discharge data with ancient maps corroborated by geomorphic interpretation highlights two main phases of Rhône delta progradation that coincided with strong river floods, respectively at the end of the 16th century and start of the 18th century (Provansal et al., in press). Between these periods, a reduction in river energy was accompanied by a clear command of marine processes on the delta shoreline, marked especially by the formation of large spits from the reworking of abandoned lobes. However, hydrological forcing was only efficient when coupled with abundant sediment fluxes generated by agricultural stripping of the Rhône catchment generated by strong population growth after the crisis of the 14–15th centuries. These changes are corroborated by multi-proxy analyses of cores from the Rhône prodelta which show four different intervals over the LIA, each of which has been correlated with phases of channel avulsion induced by climate events and/or by human activities (Fanget et al., 2012).

In the same vein, although dams are pointed out as the primary cause of modern fluvial sediment retention, with the consequent negative impact on coastal sediment budgets in the Mediterranean, there are very few studies that have actually attempted to disentangle decreases in sediment flux caused by natural and land-use changes from those generated by dams. An exception is that of the well-documented Rhône river budget. Following a fine-tuned analysis of the morphological and sediment budget changes that have affected the lower Rhône over the last 130 years, Provansal et al. (2014) concluded that hydroelectric dams constructed on the river over the last thirty years have had little or no impact, the river having already been transformed by navigation and flood control works before upstream dam installations could impact the downstream reach and the coast. The sources of sediment, torrential in origin, had already been exhausted before the dams were constructed.

12. Conclusions and perspectives: the future of the Mediterranean's coasts and deltas

The nature of the Mediterranean's clastic coasts and the growth of deltas reflects the cumulative interplay of several natural factors and the increasingly overarching influence of human activities over the last 6000 years (Fig. 16). These factors include inherited coastal geology and coastal morphology, determinant in terms of accommodation space for coastal sediment accumulation, sea-level oscillations, which have mediated the available accommodation space, a potentially complex and variable relationship between climate change, landscape degradation and fluvial sediment supply, and the oceanographic regime that acts on sediment dispersal in coastal areas. The human influence has acted directly and indirectly on fluvial sediment supply and via engineered interventions on rivers and the coast. This influence will grow as sediment supplies will need to balance accomommodation space created by sea-level rise, as has been demonstrated for both Mediterranean overwashed barriers and large pocket beaches, for instance (Brunel and Sabatier, 2009). The vulnerability of coasts and deltas resulting from various human activities and in the face of sea-level rise associated with climate change has been abundantly addressed in the recent literature (e.g., Ericson et al., 2006; Syvitski et al., 2009; Ibáñez et al., 2014; Masselink and Gehrels, 2014). By reducing river liquid discharge and sediment supply, human activities invariably also enhance the potential influence of waves in destroying coasts and deltas. They also set a template of environmental vulnerability within which future rapid climate changes will operate (Fletcher and Zielhofer, 2013).

As far as Mediterranean deltas are specifically concerned, two potential directions of morphological change following the weakening of river influence may be invoked. Deltas facing the dominant waves, common in the Mediterranean for reasons evoked in the preceding section, may retreat while keeping their plan shape, although over time positive feedback effects may lead to a dominant drift direction. This type of situation is typical of the eroding Rosetta lobe of the Nile (Hereher, 2011) and of the Ombrone (Pranzini, 2001). The other direction may be represented by increasingly skewed or asymmetric and finally deflected or straigtened deltas as net river strength decreases over the long term whereas the wave climate is likely to become more energetic in response to climate change and greater storminess. The example of the Moulouya illustrates this situation.

Ibáñez et al. (2014) argued that Mediterranean river deltas may be capable of coping with sea-level rise (SLR) through three self-reinforcing mechanisms as the SLR rates increase, and claimed that these mechanisms would tend to enhance the efficiency of the deltaic sedimentary trap. These are: (a) an increase in the frequency of delta lobe switching with accelerated SLR leading to the formation of new lobes in shallow areas; (b) an increase in the frequency and magnitude of flood events in the delta plain as a consequence of increased crevassing through the natural river levees, leading to enhanced sediment deposition; and (c) an increase in the frequency and magnitude of overwash events in the delta fringes, enhancing the ability of sandy beaches to adapt to SLR. Ibáñez et al. (2014) also suggested that vertical aggradation (what they refered to as "rising grounds") more so than "rising dikes", or a combination of both, may be needed in many cases, such rising grounds being achieved through sediment management, such as in the Ebro delta, where the natural fluvial sediment supply has been drastically reduced by human activities. These considerations require, however, that the ongoing rise in sea level rise, and the sinking of deltas be more or less matched by fluvial sediment supply or by managed sediment husbandry. Although many Mediterranean deltas are largely products of human transformations of river catchments, the switch towards significant reductions in fluvial sediment supply reaching the coast today (Milliman and Farnsworth, 2011) may mean that this balance is not likely to be achieved, thus probably heralding the sinking and destruction of Mediterranean deltas.

The move towards any form of future sustainability of the Mediterranean's coasts and deltas will require a better understanding of fluvial source-to-coastal sink sediment transfers and coastal sediment budgets at various spatial and temporal scales (e.g. Provansal et al., 2014), coastal morphodynamic processes, and the determination of shoreline change rates. These efforts will also require balancing strategies of economic development that concern not only the prosperity of high-revenue urban shores notably open to tourism, but also low-revenue shores that are more likely to be of ecological value (e.g., Armaroli et al., 2012). The Mediterranean region is considered as a major hotspot with respect to the expected effects of global warming (Giorgi, 2006). These objectives will therefore need to be achieved within a framework that clearly identifies the stakes of the future, including the impacts of climate change and sea-level rise, especially along the deltaic coasts, and concerted management strategies, especially those relating to river sediment inputs, urbanisation and coastal infrastructure development.

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