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Review Article

A 7000-year record of human influence on Global River Deltas: Geomorphology, stratigraphy, the Anthropocene overprint and future

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ABSTRACT

With the inception of most of the world's deltas about 8000 years ago, deltaic floodplains started offering, about a thousand years later, arable land, water and ecosystem services for early human settlements. We identify delta geomorphic changes and proxies and geoarchaeological markers of the human presence on deltas and in their stratigraphy over the last 7000 years, and from ancient maps. We analyse the human-delta relationship in four phases: Neolithic, Metal Ages, Common Era, and Anthropocene, marking increasing human adaptation to changing delta geomorphology modulated by fluctuations in relative sea level and fluvial sediment supply. These adaptations fostered the emergence of urbanization and served as a catalyst for technological innovation and human modification of deltas. The sparse Neolithic human presence in delta stratigraphy gradually expanded to become pervasive in the contemporary Anthropocene, reflecting the twin effects of global population growth and increasingly favourable conditions for humans. We explore the links between early deltaic and non-deltaic communities and gauge the impact of humans on sediment supply from river catchments, and its consequences, notably in terms of frequent delta avulsions, expansion or vulnerability, and explore its inextricable links with climate variation. The Anthropocene is witnessing a profoundly transformed, globally distributed, human-managed delta landscape dominated by important urbanization, reduction in sediment supply, increasing intentional but also unintentional delta modifications, and vulnerability to sea-level rise compounded by

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exacerbated subsidence. Understanding the human-delta relationship over the past 7000 years contributes to fostering stronger links between geoscience and cultural heritage, to better delta management and sustainability, including an upstream river-basin scale perspective, and to better anticipation of delta futures, notably under the threat of sea-level rise.

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1. Introduction

At the nexus between land and sea, river deltas are characterized by a subaerial surface and a submarine extension both lying atop a sediment mass expressed as subsurface stratigraphy (Syvitski et al., 2022a). This sediment mass has archived, over the last 7000 years, both evidence of environmental change and the human affiliation with deltas. The terrestrial surface expression of a river delta has been traditionally viewed in terms of a dominance of river, tide or wave processes (Fig. 1) following the seminal work of Galloway (1975). Deltas are characterized, however, by great morphological as well as subsurface diversity. This delta diversity, the tremendous ecosystem services and resources deltas offer, the expanding populations they host, and increasing delta vulnerability worldwide, have given rise to a significant collection of global studies that increasingly focus on the interaction between humans and deltas. This interaction is the outcome of a long and strong relationship in the course of which deltas served as incubators for human development (Anthony et al., 2024). Gunn et al. (2019) argued that feedback between the Holocene history of the world and human development is marked by foundational transitions or 'bottlenecks' caused by variations in sea-level, climate change and major social and technological innovations. The overarching condition marking the commencement of the relationship between humans and deltas has been the relative stabilization of sea level in the Holocene (Stanley and Warne, 1994). As global sea-level rise decelerated circa 8000 years ago, the flat topography, rich ecology and water availability of developing deltas provided, starting about 1000 years later, the foundational transition for Earth's earliest city states (Day et al., 2012; Gunn et al., 2019).

The length and strength of this 7000 yr-long relationship between humans and deltas has hinged on the geographical and geological environment of each delta, and the potential resources that each delta offers to humans, along with the associated risks and hazards (Anthony et al., 2024). Many tropical and temperate deltas presently support substantial human populations. In probably all deltas, the link with humans has additionally been mediated by the waxing and waning of distant human interventions on the water and sediment supply from upstream. Anthony et al. (2024) provided a detailed panorama of the way deltas served as incubators for human development. Deltas embody the fine connection between geoscience and cultural heritage, an emerging theme that is gaining ground, especially in coastal settings (e.g., Bollati et al., 2025). The human footprint is variably recorded in delta geomorphology, stratigraphy, and sediment mass. The human-delta association can be diversely traced using archaeological, geoarchaeological, anthropological, geocultural, geomorphic, hydrological, stratigraphic, ecological, historical/archival and cartographic evidence. The input from these traditional approaches has been complemented over the past 50 years by abundant datasets from remote sensing/earth observations, and by model-based approaches that have been developed over the past two decades. Some of these sources (notably archaeological, geoarchaeological and historical archives) contribute to defining a global picture of the human-delta relationship over time, and how this relationship has influenced transitions in human development that now culminate in perilous futures for many deltas.

This review complements Anthony et al. (2024), and offers a state-of-the-art vision of the extent to which delta geomorphology, stratigraphy and sediment mass have recorded delta habitation by humans over the last 7000 years based on the extensive set of studies covering individual, or sets of deltas, globally. We explore the extent to which upstream human influences on river catchments are identifiable in a delta's sediment mass. We examine the implications of global environmental change on the human-delta relationship and delta evolutionary trajectories from a geoscience perspective, with further consideration for future research on the human footprint recorded in delta stratigraphy and sediment mass.

Deltas are individually distinct, given the complex interplay of sea level, climate, upstream topography and lithology, human activities, and accommodation that underpins how each delta evolves and diverges from global or regional patterns, or classification schemes. Stated in numerical modelling terms, each delta has unique boundary conditions. This includes a distinct history of human influence: settlements, herding, agriculture, and extractive industries and their vicissitudes in a natural environment in flux, with rapid and dramatic geomorphic changes, including land flooding or prolonged drought. While underscoring the specificities of individual deltas in their relationship with humans, we aim at identifying broad trends in the human footprint on delta geomorphology and stratigraphy. We differentiate deltas morphologically using two complementary approaches: the river-, wave-, and tide-dominant classification of Galloway (1975) based on simple planform

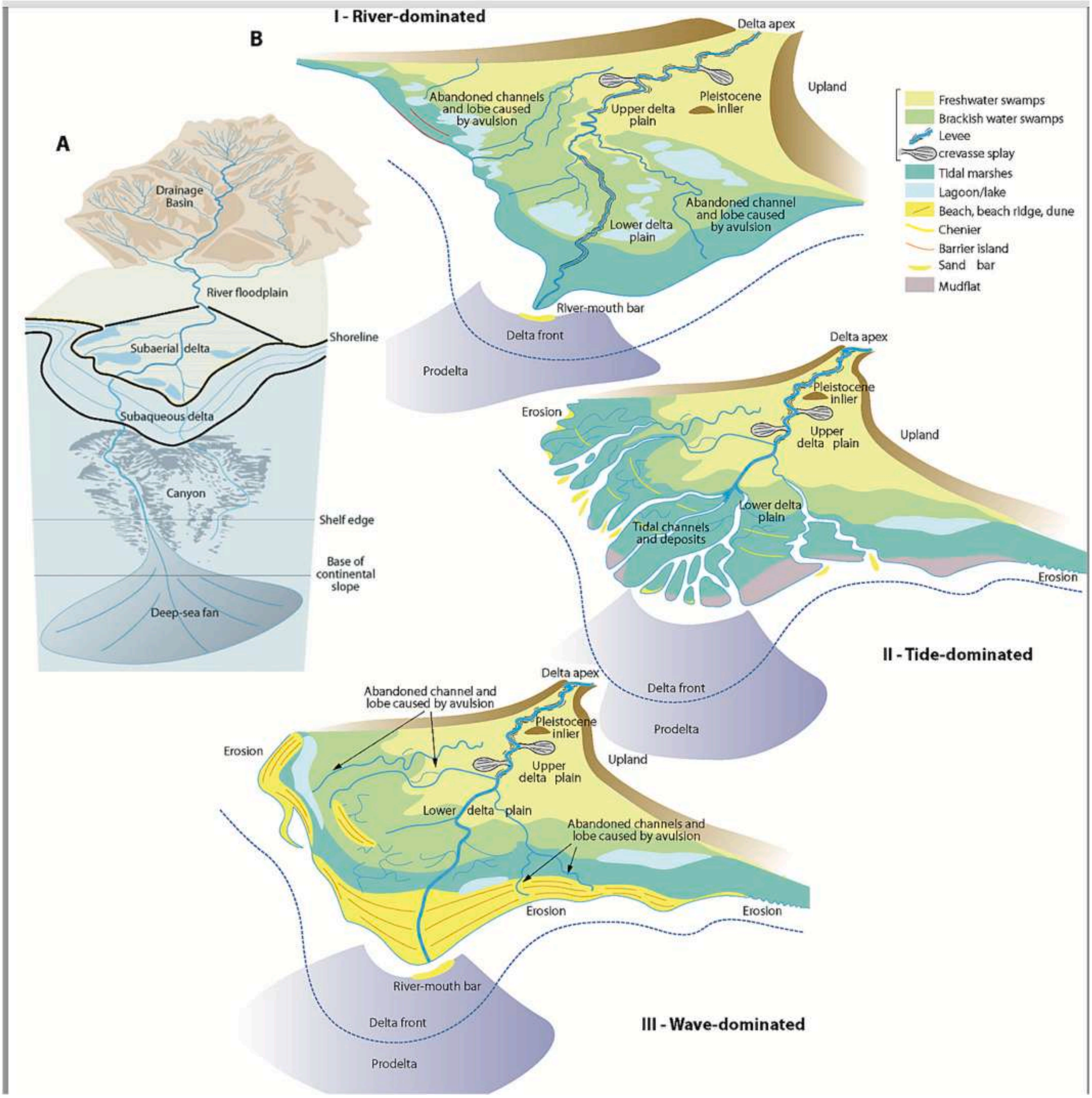

Fig. 1. Simplified sketches of a river catchment and delta types. (A) river catchment; (B) Idealized examples of river- tide- and wave-dominated deltas based on the simple tripartite Galloway (1975) classification.

characteristics and process dominance, and the size-based classification of Syvitski et al. (2022a), which defines deltas in terms of area: small (<10 km^2), medium (10–1000 km^2), and large (>1000 km^2). We keep in mind that the interactions between the terrestrial and the marine realm at the delta land-sea and freshwater-seawater interface are regulated by a complex suite of hydrodynamic processes (e.g., Wright, 1977; Zavala et al., 2024), beyond the simple tripartite framework of Galloway (1975). The size criterion proposed by Syvitski et al. (2022a) recognizes fundamental morphological and sedimentological differences between large and small deltas, and highlights increasing morphological diversity and complexity with increasing delta size.

The human-delta relationship has been shown to be ancient and most widely documented in temperate and tropical deltas in Asia (notably Mesopotamia and China), Europe, and the Mediterranean. Asian and European/Mediterranean examples offer global concepts of human influence, while underscoring continental-scale differences in terms of direct human impacts on delta development. The locations of deltas cited in this review are shown in Fig. 2. This more global coverage reflects our emphasis, in the second part of our review, on the global human-delta relationship that has unfurled over the last two centuries, and especially in the Anthropocene. Non-marine (inland) deltas are not considered in the review. Arctic deltas have been largely uninhabited. Whereas Asian deltas considered in this review are generally large, European deltas offer insight into the wide spectrum of delta sizes ranging from small, through medium, to large, especially the delta-rich setting of the Mediterraneran (Anthony et al., 2014).

Recognition of the way human activities have modified deltas, intentionally or not, and increasingly with unexpected consequences, and accelerated delta vulnerability, helps bring a range of geoscience perspectives that inform delta management and adaptation. The way natural and anthropogenic processes interact is key to the future fate of deltas worldwide, and as to whether their anticipated drowning, as sea level rises, is inevitable.

2. Framing the human-delta relationship in 7000 years of delta geomorphology and stratigraphy

Anthony et al. (2024) charted out a timeline of the human-delta relationship comprising three Holocene phases: delta inception, expansion, and upbuilding-outbuilding, succeeded by the contemporary *Anthropocene* (taken here as post-1950 CE), a term increasingly used to define a global epoch in which humans have become the dominant force determining Earth's climate and environment. Although the Anthropocene was rejected (perhaps only provisionally) as a proposed unit of geological time by the International Union of Geological Sciences (Witze, 2024), it is now a generally accepted term in scientific and social discourse. Here we propose a generalized model for interpreting the human-delta relationship in a global geomorphic-stratigraphic frame over the last 8000 years inspired by numerous studies on deltas globally, and illustrated using two stratigraphic syntheses from a large European (Po River, Italy) and a large Asian (Song Hong (Red River), Vietnam) delta (Fig. 3). The model sketches the geomorphic development phases and stratigraphy of a typical delta (Fig. 4). We analyse the human-delta relationship in four phases: Neolithic, Bronze Age and transition to the Iron Age (i.e., the Metal Ages), Common Era, and Anthropocene. We acknowledge that this general scheme embodies temporal variability with regards to delta initiation, and the geomorphic/stratigraphic development of each delta. This also holds for the Anthropocene phase characterized by different levels of delta vulnerability.

2.1. *Delta initiation and the onset of Neolithic inhabitance*

About 8200 years ago, a global deceleration of the post-glacial sea-level rise occurred (e.g., Lambeck et al., 2014; Rush et al., 2023; Hijma et al., 2025). On coasts with debouching rivers benefiting from sufficient sediment supply relative to accommodation, this enabled a progressive sedimentation turnaround, wherein infill progressively created wetlands. Based on the Po and Song Hong delta examples (Fig. 3), which can

Fig. 2. Global map showing locations of deltas cited in this review. While the human-delta relationship has been shown to be ancient and most widely documented in temperate and tropical deltas in Asia (notably Mesopotamia and China), Europe, and the Mediterranean, the map shows a more global coverage that also reflects our emphasis, in the second part of our review, on the global human-delta relationship over the last two centuries, and especially in the Anthropocene.

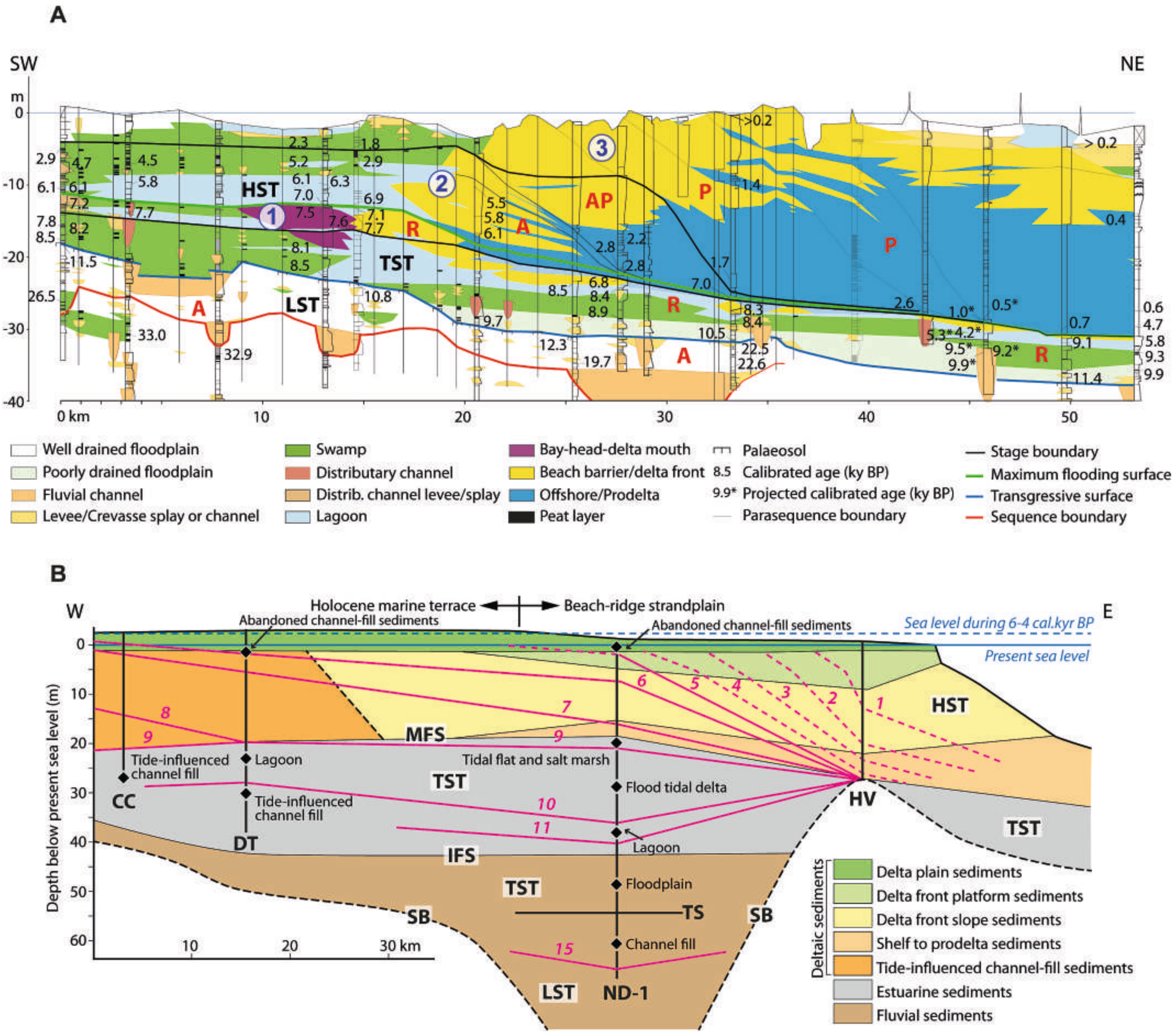

Fig. 3. Two examples of delta stratigraphy represented by the near-field Po delta (A) in Italy (adapted from from Amorosi et al., 2019) and the far-field Song Hong (Red River) delta (B) in Vietnam (adapted from Tanabe et al., 2006). Near-field and far-field contexts are defined in the text. The direction of the Po cross-section coincides roughly with the depositional-dip direction. The eastern end of the cross-section provides a transition from a dip-oriented to a strike-oriented delta lobe, as documented by the reduction of the apparent dip of the beds to horizontal. All three circled phases of development are part of the highstand systems tract (HST). LST: lowstand systems tract; TST, transgressive systems tract; MFS, Maximum flooding surface; A, aggradation; AP, aggradation to progradation; P, progradation; R, retrogradation; TS, transgressive surface; IFS, Initial flooding Surface. The numbers near the red line indicate time lines in ka. The chronostratigraphic cross-section of the Red delta depicts isochrons showing clinoforms. See also Tanabe et al. (2022), and their Fig. 15, for a comparative chronostratigraphic synthesis of far-field Tokyo Bay deltas and near-field Mediterranean deltas in the Tyrrhenian and Adriatic Seas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

probably be extrapolated to other large deltas, this phase (starting with a maximum flooding surface at ~8000–7500 yr BP), in the Neolithic, was characterized by a gradual evolution from transgressive tide-influenced estuarine infill deposits, through bayhead delta growth, to the inception of true delta development. Under still rising sea level, tidal environments started transforming into delta plains with variability in sedimentation and geomorphology. These early conditions were influenced by the slope and morphology of the pre-existing Pleistocene topography, process (wave-tide-river) dominance, sediment supply, including the ratio of fine-grained sediment to bedload, and distance from marine wave base and delta shoreline (coast and river mouth) to inland apex and confining upland relief (river valley-delta transition). Sustained sediment supply to river mouths debouching in relatively wave-sheltered bays must have been particularly favourable to delta initiation, and wetland sedimentation active in the inner delta plain to fill the accommodation created as relative sea level continued rising.

World human population as deltas started aggrading was small (9 ± 2 million) with a very low growth rate (0.03 %/yr as births minus deaths per time; Syvitski et al., 2020). Stanley and Warne (1997) identified a total of 34 earliest human settlement sites on, and adjacent to, deltas spread across all continents and bracketed in an age range from about 9450 yr BP to 5000 yr BP (uncalibrated ages), although in some of the reported references the dating method was not specified or dating was based only on ceramic cultures. Neolithic populations encroached on

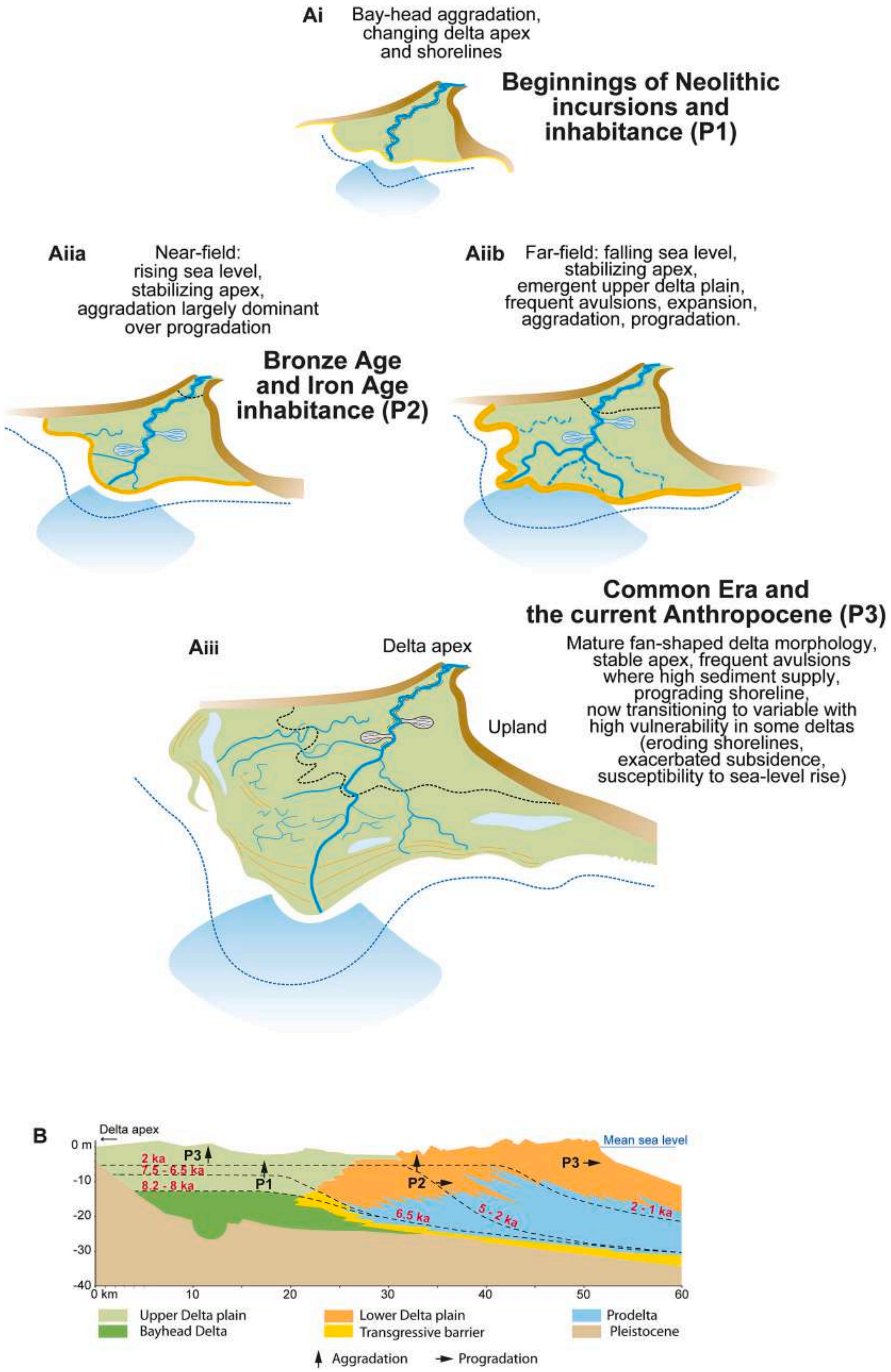

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Fig. 4. Schematic evolution of plan-view Holocene delta geomorphology and links with human inhabitance (A), and stratigraphy (B) inspired from global examples and illustrated notably by the Po and the Song Hong (Fig. 3). (A) Schematic of generalized delta geomorphic development phases (P1-P3) following the Post-Glacial deceleration of sea level about 8000 years ago. The first phase corresponds to bayhead delta aggradation under a still rising sea level, and was marked by Neolithic incursions and progressive human settlement. Geomorphic/sedimentary divergence is shown in the succeeding phase, corresponding to the Bronze and Iron Ages, as a function of the regional sea-level trend based on near-field and far-field delta location. The near-field deltas characterized by sea-level rise were largely dominated by aggradation whereas far-field deltas subjected to falling sea level were characterized by avulsions, delta plain expansion and emergent upper delta plains (delimited by dots). The Common Era saw global delta progradation under fluctuating but generally sustained sediment supply. In transitioning to the Anthropocene many deltas are becoming increasingly vulnerable as a result of deprivation of sediment supply and exacerbated subsidence caused by humans, while others still maintain dynamic morpho-sedimentary growth typical of the earlier phases of development caused by enhanced sediment supply due to human activities. (B) Schematic stratigraphy associated with the geomorphic development phases (1–3) in A.

deltas that provided wetlands for agriculture (Zong et al., 2007). Stanley and Warne (1997) connected findings on early delta inhabitance with delta geological architecture governed by post-glacial sea-level rise worldwide, and proposed three stratal units, basically corresponding, in modern sequence stratigraphy, to lowstand, transgressive and highstand systems tracts. Transitioning into the third unit involved the deceleration of global Holocene sea-level rise, leading Stanley and Warne (1997) to conclude that this marked the inception of deltas, critical to their colonization by humans. Still largely estuarine/delta-plain wetland environments in the initial phase of delta development (maximum flooding stage at the transition of the transgressive to highstand systems tract) host this inventory of the earliest record of human incursions, and probably settlements. These wetland environments were still subject to bayhead aggradation and delta-apex and coastline mobility – not yet the stereotypical delta environments conditioned by the local dynamic river-wave-tide context of Galloway (1975) that later became established in deltas as we know them today. It may be surmised that the shift to human sedentary occupation occurred as soon as delta apex and coastline positions began stabilizing, the latter with a time lag due to still rising sea level in 'near-field' deltas (Fig. 4), as defined below. This was also a period when humans were variably transitioning from a hunter-gatherer culture to pastoralism, and this could have been an important control as well.

Delta development at the global scale over the period ~7000 yr BP to ~2000 yr BP was strongly influenced by regional relative sea-level change differences between so-called 'near-field' and 'far-field' geophysical contexts related to proximity of Late Pleistocene ice caps. Incursions into developing deltas by Neolithic populations and the early relationship between Neolithic dwellers/settlers and deltas was likely conditioned by this geophysical control, notably in terms of access to resources, wetland extent, and habitable sites. In far-field deltas, the sea-level highstand was attained relatively early, between about 7000 and 6500 yr BP. This phase was associated with delta expansion, through avulsions and the formation of new delta lobes, essentially under the influence of high sediment supply. For intermediate to near-field deltas such as those bordering the North Atlantic Ocean and connected seas (Rhine in the North Sea, Po and Rhône in the northwestern Mediterranean Sea, Danube in the Black Sea), relative sea level rise remained relatively large from about 7000 to 5000 yr BP, and, subsequently slowed down, this slow-down occurring later than in the far field (e.g., Long et al., 2016), owing to glacio-isostatic subsidence (e.g., Kubo et al., 2006; Jouet et al., 2008). This is architecturally noticeable as continuous vertical aggradation in delta plain areas in the Rhine (Hijma and Cohen, 2011; Stouthamer et al., 2011) and the Po (Fig. 3A) (Amorosi et al., 2017, 2019). The post-glacial near-field position of the Rhine delta and associated sea-level history implied that progradation began by 6300 yr BP (Hijma and Cohen, 2011), the timing of maximum flooding thus lagging behind that of far-field deltas by several hundred years.

Far-field deltas bordering the Indian and Pacific Oceans underwent subtle sea-level fall (e.g. Mann et al., 2019), unlike the northwestern Mediterranean and European deltas (e.g., Tanabe et al., 2022). Delta growth involved the formation of succesive progradational lobes in response to massive sediment supply, notably from the Loess Plateau (Saito et al., 2000). Forced regression caused by this relative sea-level fall resulted in emergent Holocene marine terrace/delta plains in the upper parts of the far-field Asian deltas (e.g., Tanabe et al., 2006, 2022; Hanebuth et al., 2012; Wang et al., 2018; Chapkanski et al., 2023), marking a difference with the near-intermediate field deltas that showed significant aggradation and delayed progradation (Fig. 4Aiia). An important exception is the Ganges-Brahmaputra delta, where massive monsoon-influenced continental margin sedimentation, tectonic deformation, and subsidence have resulted in a complex history of sea-level change and delta growth (Goodbred and Kuehl, 2000; Karpytchev et al., 2018). In the far-field deltas, the emergent Holocene upper deltaic plains caused by the subtle sea-level fall could have been particularly favourable areas for human incursions and settlements by providing safer habitable sites from marine hazards. Early human occupation of deltas ran apace with, and, in many ways, mirrored developments along feeder river valleys upstream (Macklin and Lewin, 2015; Gibling, 2018), where Neolithic artefacts have been identified (e.g., Devillers et al., 2019). It is likely, therefore, that delta-adjacent sites and the emergent upper delta plains have been ones of human habitation since Neolithic times.

Climate, along with the interplay of regular flooding, delta-plain topography with alluvial ridges (super-elevated natural levees along active and fossil channels), beach ridges, and storm berm complexes, and the negative relief of floodbasins in between, significantly influenced both human settlement patterns and the preservation of archaeological evidence. Additional factors such as avulsion history (see below), dense forest cover in regions like the monsoonal deltas of Southeast Asia, and diseases, such as malaria, also played important roles in shaping the early human footprint on deltas. None of these environmental constraints precluded ancient human inhabitance of deltas. In one of the early treatises recognizing the long cultural association between humans and deltas, Büdel (1966) suggested that tropical deltas were less favourable for human settlement as a result of their inaccessibility because of seasonal flooding and malaria. Woodroffe et al. (2006) countered that the early use of Asian megadeltas may have been underestimated.

2.2. *Delta geomorphology conditions early human inhabitance*

As delta apexes became relatively stabilized, autocyclic delta-plain expansion processes associated with floods and continued incoming high sediment supply generated periodic avulsions, leading to the creation of new branches and the abandonment of former branches and lobes in far-field deltas (Fig. 4Aiib). Avulsions affected floodbasin aggradational and lobate delta-front progradational processes, altering shoreline mobility, aided by differential subsidence processes of various causes (including local tectonics, hydro-isostasy and autocompaction effects). Regular channel migration and flooding dynamics, and wetland-dryland changes also affected the delta plains. These processes no doubt conditioned rates and patterns of human inhabitance.

Notwithstanding these potential environmental hazards, developing deltas became primary sites of the global emergence of ancient societies (Fig. 5). The evolution of the earliest complex state-level societies and cities from small sedentary communities has been reported as having taken place in the Tigris-Euphrates between 8000 and 5000 yr BP under the influence of sea level, mobile shorelines, and climate change (Kennett and Kennett, 2006). The southward and eastward progradation

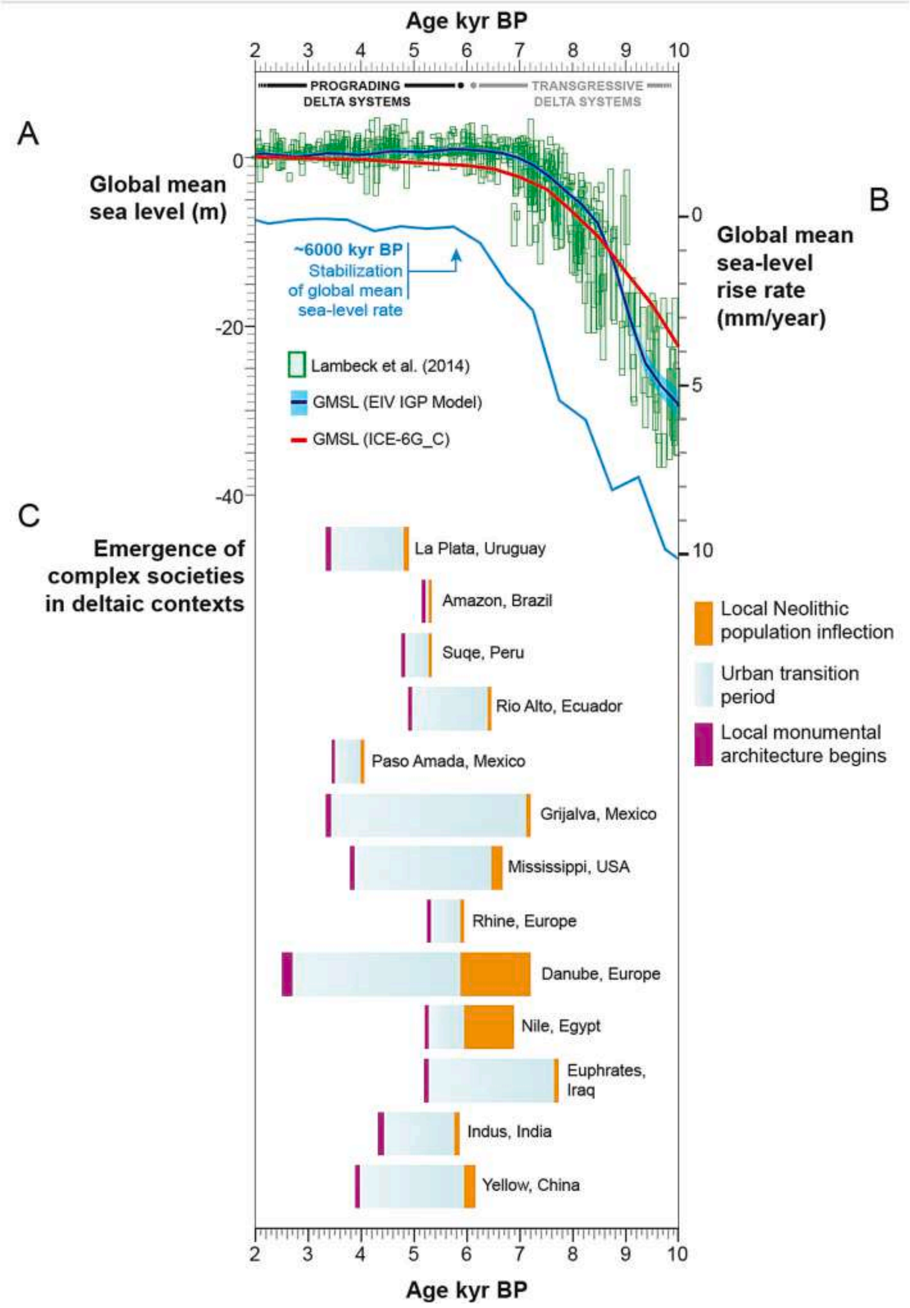

Fig. 5. Post-glacial stabilization of mean global sea level and delta inception, and the overarching role of deltas in the early global emergence of complex societies and urbanism. The emergence phases are bounded by the Neolithic population inflection approximately 1100 years after sea level stabilization. The construction of monumental architecture followed approximately 1600 years later. Local initiation times and overall means are shown for both the urban transition and construction of monumental architecture (adapted from Day et al., 2007).

of the Tigris delta left in its wake organic-rich tidal wetlands less exposed to marine hazards and that could thus be reclaimed, settled and farmed under more secure conditions (Goodman and Giosan, 2025). In the Nile delta, the sea-level trend and transition, from a largely uninhabitable marine flood-prone system exploited by herding communities beginning 7000 yr BP, to a fixed-apex, more habitable but increasingly wave-exposed system that saw the beginnings of agriculture at ~6700 yr BP (Zhao et al., 2022, 2025a, 2025b), are summarized in Fig. 6, which depicts how key phases of delta aggradation and progradation and Nile flood regimes shaped early human occupation. This time frame is similar to that of the beginnings of maize and possibly manioc cultivation in the Grijalva delta in Mexico (Pope et al., 2001). In this far-field setting where the Grijalva later built a joint delta with the Usumacinta, the formation of a massive beach-ridge plain (Nooren et al., 2017) with well-drained soils is considered as having favoured native inhabitance and cultivation (Pope et al., 2001), but the record and geographic distribution of human settlements, spanning several thousand years, still remains unresolved (Muñoz-Salinas et al., 2023). In the Yangtze, chenier ridges abandoned within the prograding delta plain provided optimal locations for Neolithic settlements (Chen et al., 2008; Wang et al., 2012).

Settlements were located in areas where avulsions, bank erosion, and flooding hazards could be avoided or adaptation possible, whereas wetland environments more subject to these hazards were more suitable for agriculture. Topographically higher and more secure non-deltaic (Pleistocene or older) inliers protruding above the surrounding delta plain (Fig. 1), and some of which subsequently became engulfed and

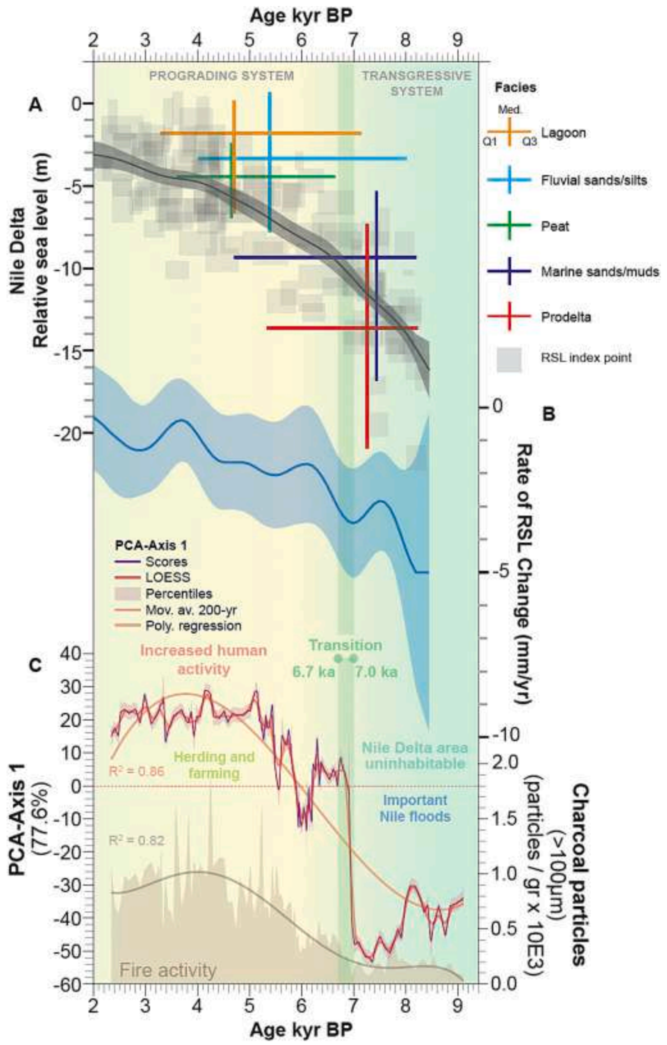

Fig. 6. Onset and evolution of Holocene Nile delta accretion and human occupation. The diagram illustrates the interplay between relative sea-level changes (a-b), sediment deposition (a) and human activities (c) in the form of herding and early farming. It highlights how key phases of delta aggradation and progradation and Nile flood regimes shaped the early human occupation of the delta area, beginning around 7000 years ago. Proxy data, including fungal spores, charcoal particles and pollen provide evidence for early pastoralism and agriculture in the West-Central Nile delta (palaeoecological data from Zhao et al., 2022).

buried by delta-plain aggradation, served as points for some Neolithic settlements. Archaeological and geoarchaeological studies in the Tigris-Euphrates suggest a clear link between avulsions and early delta-plain settlements, this process conditioning settlement location choices as early as 6000–5300 yr BP, especially as urban settlements developed over the period 5300–3600 yr BP (Morozova, 2005, 2025; Jotheri et al., 2016). A similar link between avulsions, changes in channels, and settlement persistence and relocations has been evoked for the Nile (Pennington et al., 2016, 2017; Toonen et al., 2019; Wilson and Ghazala, 2021) and the Grijalva-Ucumacinta (Muñoz-Salinas et al., 2023). We surmise that settlement patterns were also strongly influenced by the dramatic avulsions and lobe abandonments that have been so well documented in the large far-field Pacific and Indian Ocean deltas of East and Southeast Asia (Saito, 2001; Tanabe et al., 2006; Nageswara Rao et al., 2015; Kidder and Liu, 2017; Wang et al., 2018; Wu et al., 2020a; Wu et al., 2020b). Frequent avulsions in the Indus floodplain and delta, a river system associated with a desert hinterland, generally deprived settlements of water resources for drinking, agriculture, or transportation (Syvitski et al., 2012). In the Mississippi, in which several successive avulsion events and lobes have been identified (Frazier, 1967), an example of the effects of these changes on Neolithic settlements is illustrated by the growth and demise of the St. Bernard lobe (Kemp et al., 2021). This lobe started developing at ~3800 yr BP, and rapidly deteriorated following abandonment ~1800 yr BP, resulting in burial of midden sites used by indigenous people (Fig. 7). More sites were visible at the surface in 1954 than at any time since because of subsidence and edge erosion as the former sub-delta lobes were eroded away. Usage by the prehistoric people spread into new areas as the sub-deltas grew. The total number of settlements and middens is far greater than what is shown in Fig. 7 because much of the former land area has now been eroded/submerged following the abandonment of the St. Bernard lobe (Kemp et al., 2021).

In near-field European deltas such as the Rhine and the Danube, and those on the northern rim of the Mediterranean Sea, such as the Rhône and the Po, early human habitation was likely conditioned, and probably constrained, by sea-level rise and continuous aggradation, and later, avulsions. In the Danube, in addition to the exploitation of loess deposits, settlements and agriculture around 6800–6300 yr BP, during the Gumelnița–Karanovo VI Eneolithic phase, mostly thrived on the hinterland-delta plain contact, usually on the edges of river terraces but sometimes on the levees of lateral distributaries a few metres above the floodplain level to avoid temporary drowning (Carozza et al., 2012). The contemporary Danube delta floodplain lies 9 to 6 m below the present floodplain, and therefore the existence of settlements buried under sediments cannot be excluded (Țuțuianu et al., 2021). In the Rhine delta, confined in a bayhead setting and subject to sea-level rise during much of its history, farming spread to the delta plains from the higher-lying Rhine and Meuse valley floodplains and loess hillslopes upstream (7500–6500 yr BP; Linear Pottery Culture). The Neolithic transition is argued to have spread, from the delta apex region that was stabilizing at 6300 yr BP, across the full delta and coastal plain (7300–5400 yr BP; Swifterbant culture: e.g., Louwe Kooijmans, 1974, 1993, Louwe Kooijmans et al., 2005), a finding further confirmed by intense research undertaken in the delta apex in the last decade (e.g., Gron et al., 2023) at depths of 2–5 m below the Common Era delta plain. Buried Neolithic artefacts identified in several small Mediterranean deltas also attest to a dominant dynamic of aggradation (e.g., Niebieszczański et al., 2023; Chabrol et al., 2025). Berger (2021) has surmised that parts of Mediterranean delta plains that served as bridgeheads for the development of early Neolithic cultures are now buried under several metres of alluvium, as argued or documented also for the Danube (Țuțuianu et al., 2021; Carozza, 2022).

2.3. The Bronze Age: emergence of cities in deltas, and the delta-hinterland link

The benefits of a protein-rich diet from delta resources contributed to the development of complex societies following the first settlements (Zhao et al., 2025a, 2025b). Increased social ranking became instrumental in the construction of monumental architecture and the emergence of statehood (Day et al., 2012). Without entering into the diverse causes of the early emergence of statehood, we deduce that deltas, at the land-sea interface, and termini of rivers, were particularly favourable locations because of the geomorphic, hydrological, and ecological advantages they offered (Anthony et al., 2024). The challenges involved in adapting to wetland-rich delta environments and harnessing delta resources were, in turn, instrumental in determining early urbanization and technological innovations, especially regarding water control, irrigation and security in the face of hydraulic risks. Harnessing and controlling water were an important aspect of the emergence and growth of urbanization, as in the arid Tigris-Euphrates (Egberts et al., 2025; Morozova, 2025), and in pyramid-building in Ancient Egypt (Sheisha et al., 2022; Ghoneim et al., 2024; Landreau et al., 2024). Aspects of the complex relationship between early urbanism and the marshy

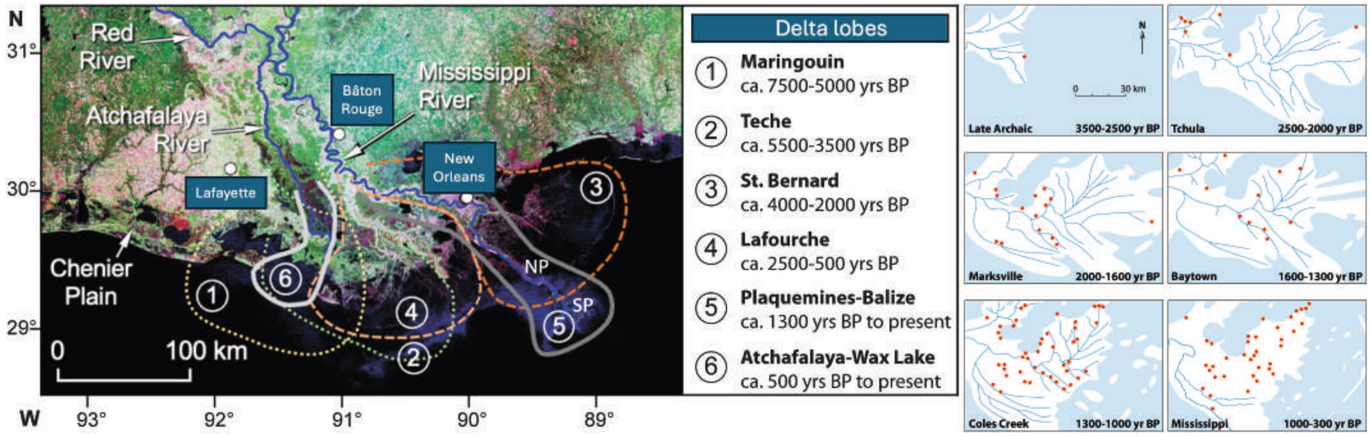

Fig. 7. Mississippi delta lobes 1–6 (adapted from Frazier, 1967: uncalibrated ages), and the current lobe of Southwest Pass (SP). Water and sediment are being significantly captured by Neptune Pass (NP), the largest new distributary to form in the Mississippi River in nearly a century (Kolker et al., 2025). On the right is the sequence of St. Bernard delta lobe (3) development beginning 3800 yr BP, and deterioration following lobe abandonment about 1800 yr BP, showing midden sites of usage by indigenous peoples during successive cultural phases prior to western contact (adapted from Braud et al., 1998, in Kemp et al., 2021). The white area shows the land area of the St. Bernard lobe in the respective time interval. The lobe area grew as new distributaries conveyed river sediment into new bays or on top of older marshes. At the same time, older distributaries lost dominance and were abandoned as crevasses breached the Mississippi natural levees elsewhere on one or the other side of the river. The settlement sites shown were assigned to different time periods based primarily on ceramics at the time of first occupation (see McIntyre, 1954, in Kemp et al., 2021). More sites were visible at the surface in 1954 than at any time since because of subsidence and edge erosion as the former sub-delta lobes were eroded away. Usage by the prehistoric people spread into new areas as the sub-deltas grew. The total number of settlements and middens is far greater than what is shown in the figure because much of the former land area has now been eroded/submerged with abandonment of the St. Bernard lobe.

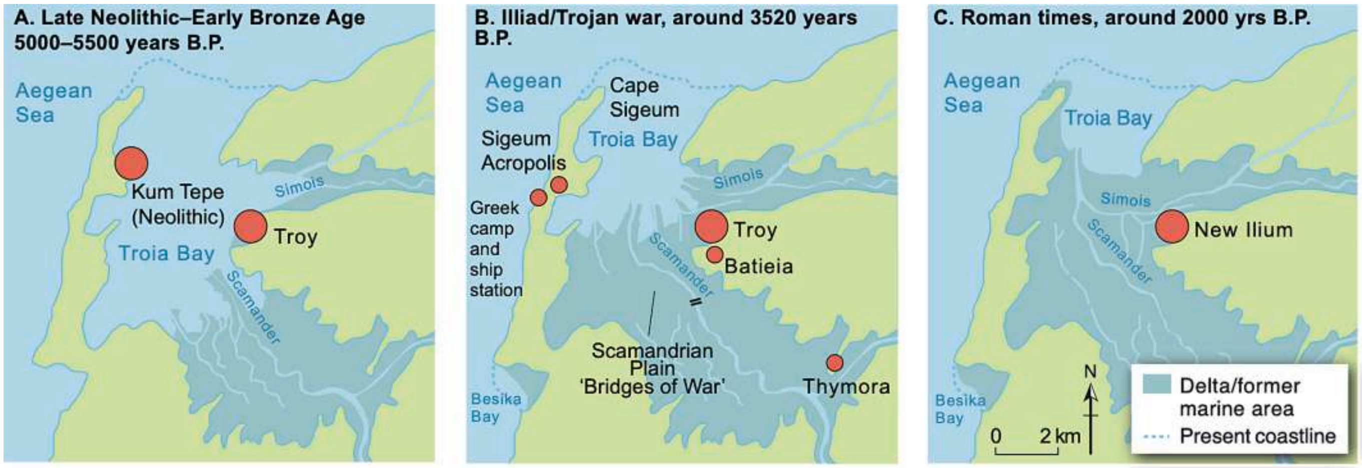

Fig. 8. Delta sedimentation and its effect on ancient human settlements and harbours, with the example of the palaeogeographic evolution of Troia Bay between the Late Neolithic–Early Bronze Age and the Roman period, and the progradation of the Scamander and Simois deltas in Asia Minor (modern Türkiye). Fluvial sediment supply and delta dynamics framed the landscape of ancient Troy. Delta progradation and the seaward-shifting shoreline played a decisive role in its accessibility, harbour potential and long-term settlement history (adapted from Kraft et al., 2003).

environment of the Tigris-Euphrates, notably revolving around the city of Lagash towards the end of the Early Dynastic Period (~4850 to 4242 BP), have been variously analyzed (Hammer, 2022, 2023; McMahon et al., 2023; Pittman et al., 2023; Goodman and Giosan, 2025; Morozova, 2025). Deltas are, however, as mentioned above, challenging environments, and only a handful of large ones seem to have been characterized by early human occupation and culture, including religion, of a level significant enough to lead to the transitional emergence of distinct cities and statehood during the Bronze Age (Anthony et al., 2024). Delta expansion through avulsions in far-field settings, and decreasing aggradation and a shift to avulsion-induced delta expansion and progradation in the latter part of this phase in near-field settings, implied more space for human development and more resources. These advantages were instrumental in the development of state-level societies during the Bronze Age (Day et al., 2007, 2012): the Tigris-Euphrates at ~5700 yr B·P. (Morozova, 2005; Marchetti et al., 2024), if not earlier (Uruk: ~6000 to 5200 yr BP; Giosan and Goodman, 2025), the Nile valley and delta at ~5300 yr BP (Dee et al., 2013; Pennington et al., 2016; Wilson and Ghazala, 2021), and the Indus valley at ~5200 yr BP (Meadow and Kenoyer, 2001; Wright, 2010). Agricultural communities supported the oldest cities in the Tigris-Euphrates and also in the Nile, where early ranked societies emerged in the 4th millennium BCE in both the delta and Lower Egypt, paving the way for the formation of the first Egyptian state at ~5000 yr BP (Bard, 2017; Köhler, 2017). Significant sites in the Nile delta include Sais (earlier than 5300 yr BP), and Kom el-Khilgan and Buto (earlier than 5250 yr BP). In Lower Egypt, important locations are Memphis (earlier than 5150 yr BP), Heliopolis, Mendes (both earlier than 5250 yr BP) and Bubastis (earlier than 5150 yr BP).

In addition to the large European/Mediterranean and Asian deltas we have seen so far, Bronze-Age activity has been identified in several small- to medium-sized deltas in the Mediterranean where enhanced sediment supply led to the rapid expansion of deltaic landscapes and appears closely linked to the regional intensification of agriculture and resource exploitation (e.g., Kraft et al., 2003, 2006; Vött et al., 2007; Marriner et al., 2012; Giaime et al., 2016; Devillers et al., 2019; Ruiz-Perez and Carmona, 2020; Degeai et al., 2020, 2024; May et al., 2022; Niebieszczański et al., 2023; Mayoral et al., 2024; Chabrol et al., 2025). Many of these deltas, located in more or less wave-sheltered embayment settings, saw the establishment of harbours (Marriner and Morhange, 2007). Although the thrust of the studies cited above is essentially archaeological, their findings nevertheless throw light on the relationship between, on the one hand, human cultural development and habitation, and the changing geomorphology of deltas due to sediment accumulation in essentially confined coastal contexts. Fig. 8 summarizes the impact of sediment supply from the Scamander and Simois rivers, in present-day Turkey, and rapid progradation of the common delta formed by these two rivers on the landscape of ancient Troy. These processes affected the accessibility, harbour potential and long-term settlement history of numerous ancient cities.

Geoarchaeological surveys have shown that Bronze Age communities developed in a pattern similar to that observed during the Neolithic, with settlement expansion occurring from hinterland areas to coastal and deltaic zones. This gradual migration is evidenced by systematic GIS surveys that identify dense artifact concentrations in depositional environments where rapid sediment accumulation both preserved and, in some cases, obscured habitation remains (Butzer, 2011). In several studies, archaeological indicators such as changes in settlement layout and the presence of industrial waste (e.g., metallurgy) support the view that human-induced environmental modifications played a critical role in shaping these landscapes (El Ouahabi et al., 2018).

In his account of the history of the Mediterranean from the beginnings to the emergence of the Classical World, Broodbank (2013) highlighted the parallel development of Bronze Age settlements on the non-deltaic coasts and islands of the eastern Mediterranean, and how trade networks and exchanges were fostered with delta communities. For instance, artefacts such as Aegean-Mycenaean ceramics discovered at inland sites like Fondo Paviani in Italy demonstrate the integration of deltaic settlements into broader economic and cultural networks (Dalla Longa et al., 2019). This exchange of goods, ideas and technologies was facilitated by the coexistence of stable inland centres and dynamic coastal hubs, each responding to the challenges posed by rapid sediment deposition and environmental change. At a wider scale, the Bronze Age witnessed significant population movements that were closely tied to environmental change. Demographic pressures in the hinterland, in part driven by the exploitation of richer agricultural lands, led to a progressive migration towards coastal regions where deltaic landscapes offered both resources and opportunities for trade (e.g., Berger, 2011). These movements were not isolated but formed part of a broader network of exchanges that connected diverse ecological zones across the Mediterranean basin (Broodbank, 2013).

2.4. *Delta sedimentation and geomorphology increasingly impacted by humans in the Bronze Age*

By 4200 yr BP, human population was ~27 M and global sea-level rise had slowed to 0.3 mm/yr (Syvitski et al., 2020) but was already falling in far-field deltas. In the Nile delta, where cultural development reached a peak with the construction of pyramids that are today a major world heritage, changes generated by allocyclic forces were interwoven with significant human interventions and variation in sediment input. In this delta, notable geomorphic changes at about 4200–4000 yr BP were driven by a combination of distant climate-generated (the 4.2 kyr event evoked later) falling sediment supply from the catchment (Stanley and Warne, 1993; Stanley et al., 2021; Peeters et al., 2024) and intensified anthropogenic impacts (Sheisha et al., 2023; Younes et al., 2024). Post-4000 yr BP towns and cities were located close to distributary channels that offered ready access to fishing, transport, and trade, and especially on natural levees above active delta-plain flooding but also with rich soils (Ginau et al., 2019).

Different parts of deltas behave differently and human occupation and activities on deltas have systematically sought to address this inherent complexity through early forms of hydraulic engineering (Mays, 2010; Tamburrino, 2010; Egberts et al., 2023). The developent of irrigation by gravity, the creation of diversion channels such as the Alexandria canal, built during the Ptolemaic period (Flaux et al., 2012), and wetland drainage for agriculture, modified sediment and water routing through the Nile delta, altered subsidence of organic-rich deltaic sediments, and led to a shift from a river-dominated delta to a more wave-influenced delta, a condition that no doubt exposed the delta margins to vulnerability from storms, while limiting progradation. This changre from river- to wave-domination is, thus, an early example of an unintentional but major consequence of human activities on delta morphology that has become rife in the Anthropocene, and a yardstick of delta vulnerability, as shown later in Section 4.3. Stanley and Warne (1993) suggested that the millennial-scale diminution of Nile water and sediment discharge combined with human channelling of the delta has been responsible for a drastic reduction in the number of distributaries from seven in early Antiquity to just two at present. Attention has been devoted to the recent discovery of one of these now defunct ancient branches along which was established the pyramid chain (Sheisha et al., 2022; Ghoneim et al., 2024).

On the alluvial ridges of the Rhine delta, agriculture in the Late Neolithic and early Bronze Age (5500–3500 yr BP) appeared to have been widespread but difficult to identify (Arnoldussen and Fokkens, 2008) owing to aggradation of younger sediments (now buried Bronze Age floodplains). Clusters of thriving farms practising trade and exchanging ceremonial goods over long distances are more regularly identified from the middle Bronze Age (3500–2800 yr BP) sites (Fontijn, 2009), with the imminent onset of a dominantly progradational floodplain regime. Network reorganization and avulsion frequency increased during this period (Stouthamer et al., 2011), associated with increased sediment supply as a result of catchment land-use change and soil erosion (Hoffmann et al., 2007). Farmers favoured older alluvial ridges along recently abandoned river courses compared to levees along young river courses (Arnoldussen, 2008). Natural levees offered elevated ground less prone to regular flooding, while silted-up residual channels served as navigable waterways connecting to active channels. The fields were exploited with the technological help of plough and wheel (Fokkens, 1986; Arnoldussen and Fokkens, 2008).

In Asia, the large deltas continued experiencing avulsions and expansion under massive sediment supply from the Loess Plateau, augmented by erosion from increasing land use (Chen et al., 2012; Kidder and Liu, 2017; Zhao et al., 2023; Yu et al., 2021; Nian et al., 2022; Yang et al., 2023). In the Yellow, human attempts to contain and constrain floods, sedimentation and avulsions have prevailed since at least 2900 yr BP, and involved the construction of dikes, dams, canals and irrigation structures that became even more entrenched engineering practices at the time of the Han Dynasty (206 BCE-220 CE), as Shu and Finlayson (1993) and Kidder and Liu (2017) have shown.

3. Humans and deltas in the Common Era

We consider that the transition from active avulsions during the Bronze Age and the Iron Age to a dominantly progradational regime induced fundamental changes in the human-delta relationship, with advantages to humans offered by delta progradation. This latter phase, comprising the Common Era (CE, including the Anthropocene), was dominated by delta-front progradation and prodelta/offshore aggradation under abundant but fluctuating sediment supply from river catchments increasingly affected by human activities. In near-field deltas, hitherto subjected to active aggradation in the Neolithic and Metal Ages when far-field deltas were already actively prograding, the CE phase was characterized by a now stabilized or even subtly falling sea level and a dominantly progradational regime like that of the far-field deltas. Avulsions became more generalized in response to pulses of abundant sediment supply, as illustrated by studies on the Rhône (Vella et al., 2005), Rhine (Stouthamer et al., 2011), and Po (Amorosi et al., 2019) river deltas. This phase conforms to the geomorphology of modern deltas as observed on maps and remote sensing sources, including the inventory in Galloway's (1975) ternary diagram. Its most recent manifestation represents the Anthropocene, with all it implies in terms of global environmental change, and the exacerbated impact, as many global deltas and their catchments became hubs of rapid population and economic growth focused around urbanization and a restructuring economy, with consequent major changes to the natural processes supporting deltas and their land use (Nicholls et al., 2020).

3.1. *Geomorphically mature and stabilizing deltas increasingly impacted by humans*

The CE marked a period of geomorphically more mature delta plains of which not just the apex regions but much larger parts became suitable for agriculture, and for more widespread surface preservation of the human presence in quasi-continuity. Global human population increased from ~27 M at 4200 yr B.P (= 2250 BCE, yr Before Common Era), at a growth rate of ~0.2 % per year, to attain ~270 M by 1 CE (Syvitski et al., 2020). The first half of the CE was characterized by a stagnation of global population (growth rate of 0.01 % over 1000 years). Progressive human adaptations to delta geomorphology during this phase were instrumental in the development of social stratifications (Pennington et al., 2020). But this phase was also marked by fluctuations in sediment supply from catchments attributed to both human activities and climate variability, and by significant delta landscape transformations by humans. In the Nile, for instance, a distinction gradually appeared in the Late Holocene between the delta apex and the lower delta plain, the former characterized by relatively infrequent avulsions, a stable river course, synergy between delta-flanking topography, river banks and a relatively narrow delta plain that formed the foundations for the urban development of Cairo, and the much wider lower delta plain characterized by distributaries and the siting of large towns such as Alexandria on fossil beach ridges. Rhine delta Iron Age (2800–2000 yr BP, 850–50 BCE) farm clusters persisted and some evolved into "oppidum" villages mentioned in Roman classic texts in the first centuries CE. Settlements preferentially built on levees appeared to have become more common, identified in the Rhône delta as early as 2500 yr BP (Arnaud-Fassetta and Landuré, 2015), the Song Hong (Red) delta at about 2000 yr BP (Funabiki et al., 2012), and the Mississippi delta at about 500 yr BP (Chamberlain et al., 2020).

As deltas thrived during the CE, the human presence became more abundant and more persistent, more entrenched in shallow delta deposits, providing scope for better detection, although, alternatively, this expanding human presence was also a cause of obliteration of some of the previous records of humans. Human expansion was largely favoured by delta planform development towards the typical broad subaerial fan-shape of modern deltas (Fig. 4Aiii). Although the dominance of progradation over aggradation at this time favoured the preservation of settlements, many others were no doubt destroyed in the course of the erosion of abandoned lobes, as in the Mississippi delta (Fig. 7). The proliferation of human settlements and exploitation of resources in deltas around the world involved increasing anthropogenic modification through urban and engineering interventions. In the latter part of this period, these actions, driven notably by population growth, cultural development, the emergence of empires across the world, and colonialism in the 19th century, became the dominant forces shaping deltaic evolution.

Deltas in Europe, the Mediterranean and China were increasingly impacted by engineering and other human modifications. The description given by Strabo (7 BCE–23 CE) of the Nile is an eloquent example: "many branches of the river [Nile] have been split off throughout the whole island and have formed many streams and islands, so that the whole Delta has become navigable — canals on canals having been cut, which are navigated with such ease that some people even use earthenware ferry-boats" (in: The Geography of Strabo Book XVII, Loeb Classical Library Ed. 1932). In China, fluvial and delta engineering is an ancient element of the sociopolitical response to massive sediment supply and the resulting avulsions, notably in the Yellow catchment, where artificial levees were built to prevent these avulsions (Kidder and Liu, 2017). In the Mediterranean, deltaic harbour locations represent examples where humans locally strongly modified the geomorphology through artificial access channels (Giaime et al., 2019a, 2019b), as in the example of Ostia on the Tiber delta near Rome (Salomon et al., 2018, 2020) and the Lez near Montpellier, France (Degeai et al., 2024). Harbour protection structures particularly favoured fine-grained sedimentation as a result of sheltering from waves (Marriner and Morhange, 2007). Along the North Sea coastal plain, Romans created tidal harbours. In the Rhine delta plain, Roman engineers deployed in the first century CE channel revetments and groynes and artificially raised levees ('*moles*', '*agger*', dykes) to protect bank infrastructure and in the course of routine military operations aimed at controlling division of channel flow in fluvial-tidal reaches (e.g., van Dinter, 2013; Verhagen et al., 2022). In the centuries prior to the Roman conquest, indigenous farmers had implemented wetland drainage and deployed hollow tree culverts to mitigate regular flooding (Pierik et al., 2018). Other transformations in delta-plain hydrology were carried out to enhance agriculture and mitigate risks, as in the Arno and Serchio deltas in Italy, where the Romans started draining wetlands from the first century CE onwards, contributing thus to the progradation of the modern delta plains of these rivers (Amorosi et al., 2013).

Early historical Medieval court and episcopal/ecclesiastical accounts (including missionary and monastic ones) throughout Europe show the accrued interest vested in fertile delta plains with their dynamic navigable water ways, especially those of the Rhône (Pichard, 1995), Po (Cencini, 1998), Danube (Bivolaru et al., 2022) and Rhine (Pierik and van Lanen, 2019), where Roman-age settlements show relative continuity, despite population and power shifts in the Dark Ages (5th to 8th century CE). Medieval interests relevant to deltas revolved around territory (i.e., resolving boundary conflicts due to shifting channels; fishing rights; land swaps) and economic use (leasing out of wilderness land; granting exploitation privilege). New villages and churches were built, especially in the Po and Rhône deltas, and especially along newly avulsed channels in the Rhine, where Roman Catholic missions were initiated at 600–700 CE by the Frankish court and the Cologne archbishopric (Norlind, 1912; Thoen et al., 2013), and in the Danube delta with the setting up of Orthodox monasteries. Agricultural activities in the delta plain intensified, and efforts towards the prevention of, and recovery from, flood damage increased, while towns emerged and population grew. Dike systems running along all active delta distributaries in the Rhine delta emerged between 1000 and 1150 CE, as bischoprics and counties rolled out systematic land reclamation campaigns to secure food production for the growing town and city populations. Early dikes were relatively low and designed more to lengthen the crop growth/harvesting seasons than to prevent regular flooding altogether. Expectations and standards regarding flood prevention were gradually raised over later centuries, as were the dikes (e.g., van Woerkom et al., 2022). In the central and lower sectors of this delta, and especially the northern and southern distal coastal plain sectors, embankments, emplodering and drainage of areas with organic topsoils and subsoils (peat) imposed land-use sustainability problems generated by human-induced land subsidence (Erkens et al., 2016; Schultz, 2024).

Both in and outside Europe, deltas during the CE were also at the heart of strategies of political conquest and domination, as attested by the Arab conquest of several major deltas (Tigris-Euphrates, Nile, Indus, and Ebro), and the use of the Danube and the Rhine by Roman armies as border rivers. The Danube served as a natural border of the Roman Empire with fortifications in the delta at Halmyris (Giaime et al., 2019a, 2019b), Salsovia (now Mahmudia), Aegyssus (now Tulcea), Dinogetia (now Gărvan) and Noviodunum - the headquarter of the Roman military fleet (Bivolaru et al., 2022). The delta became an important axis of the trade network between Asia and Europe in the 14th and 15th centuries. The Danube mouths were strategic points highly sought after by the expanding empires (i.e., Byzantine, Ottoman, Austro-Hungarian and Russian), and, thus, faced considerable human pressure and frequent changes in national power domination (Brătianu, 1999). For the Roman empire, the Rhine delta served as a border region (frontier defence line: *Limes*) and also as a bridgehead for the conquest of Britain in the first century CE. The Roman army built military roads and permanent border forts (castella) along levees of the main Rhine distributary, as well as on all mouths of the delta (van Dinter, 2013). Border forts were erected directly along the southern natural levees of the Rhine's then main branch, regardless of the elevation and height and composition of the subsoil, strategically placed opposite distributary bifurcations that provided natural access to the main river (van Dinter, 2013). Many fort locations developed into villages, and alluvial ridges south of the *Limes* were intensively used for agriculture. The swampy parts of the delta plain were heavily exploited, notably for wood, unintentionally setting the stage for avulsions. Pierik et al. (2018) identified major delta avulsive lower-delta river network reorganization over the period 300–600 CE amidst the collapse of the Roman Empire. During the Dark Ages that followed, the Rhine delta remained relatively densely populated. Important long-distance trade centres emerged, exposed to Viking raids in the 9th century CE. From 650 CE onwards, these centres were brought under new state control, leading up to the Charlemagne empire (c. 800 CE) and its political subdivision in counties and bishoprics that re-intensified the land use, with the embankment of rivers, and resulting in the triggering of anthropogenic land subsidence (see above). The elevation of the lower Rhine delta plain eventually fell below mean sea-level as a result of these anthropogenically-induced changes, harming agriculture, and increasing flooding risks. These problems were countered with continuous and growing engineering efforts (polder water management, import of wind mill technology, replaced since the 1800s by fossil-energy pumping stations; e.g., van Koningsveld et al., 2008). Similar developments affected floodbasins of the lower Po delta plain (Cencini, 1998; Simeoni and Corbau, 2009). In the Yangtze delta, Wu et al. (2025a) document geochemical changes in channel sedimentation that may reflect channel regulation projects undertaken during the Northern Song Dynasty (960–1127 CE) to counter climate-induced channel silting.

By 1670 CE, at the end of the pre-industrial period, global population reached 600 M, increasing at 0.4 % per year, although energy expenditures remained low (Syvitski et al., 2020). Between 50 and 70 % of GDP was still being used to obtain basic energy resources (human food, fodder for animals, and wood fuel). Examples of direct human influence on deltas include European Renaissance land-use changes and hydraulic engineering. The latter is well documented for the Po delta between 1500 and 1600 CE, when engineers from Venice diverted the river, generating the progradation of a "Renaissance delta" that developed into the "modern delta" (Simeoni and Corbau, 2009). Similar engineering modifications took place in the Rhône delta, starting at the end of the 18th century (Provansal et al., 2015). In the Yellow, the multi-millenial efforts aimed at offsetting the effects of floods, massive sedimentation and avulsions (Kidder and Liu, 2017) render this Asian delta an outstanding example in terms of human engineering.

By 1850 CE and the start of the global industrial interval (100 yr earlier in Europe), human population reached 1250 M (0.8 % per year growth), powered by excess energy from the combustion of fossil fuels (coal, oil) and hydroelectric plants, allowing societies to mechanize (Syvitski et al., 2020). The Industrial interval (1850–1950 CE) and the thriving of colonial empires capture the global change in human–nature interactions, leading to a generalization of human occupation and transformation of deltas in North America and South America, and later, those in sub-Saharan Africa, the sub-arctic and arctic environments. The human footprint in sub-Saharan Africa, even in areas of dense rainforest is, however, ancient. Garcin et al. (2018) detected an anthropogenic impact on fragmentation of the central African rainforest as early as 600 BCE that resulted in savanna landscapes, and in all likelihood, large sub-Saharan deltas such as the Niger, the Senegal, and the Volta, were all sites of ancient human occupation like the European, Asian, and Mediterranean deltas.

3.2. Cartographic records of the human-delta relationship

In addition to archival and historical accounts, information on the CE human relationship with deltas comes from maps prior to the advent of aerial photography and remote sensing. Historical maps offer glimpses at the human-delta relationship as far back as 2000 years ago, although most data-rich maps are recent (1600s CE through to the present). However, deciphering delta morphological changes from historical maps beyond the last 300–400 years is only possible for a small handful of deltas with classical historical records. Even relatively well-documented cases need to be considered with caution because of the inaccuracies of maps dating back to beyond three centuries (e.g., Provansal et al., 2015). Furthermore, only inferences can be drawn between marked changes in delta geomorphology such as those identified in the Rhône by Provansal et al. (2015) and discharge variations influenced by a combination of human activities, notably massive deforestation and intense erosion in European catchments prior to 1555 CE, and the Little Ice Age climate variation. In the case of the Rhône, these inferences are somewhat comforted by the existence of long-running archives (since 1500 CE) of Rhône liquid discharge (Pichard, 1995).

Traditional positioning errors associated with georeferencing of historical maps against modern topography are indeterminable for the ancient maps, and tend to be ±3 km or greater for large area charts produced in the 1700s and early 1800s CE (Syvitski et al., 2012; Provansal et al., 2015). Despite this location inaccuracy, the imagery provides useful information, such as the shape of the coastline and its overall evolution, number and relative locations of major river mouths, delta lakes and channels, towns (e.g., their locations on delta plains or around delta plains), levees, floodplains, major infrastructure (e.g., canals, roadways, coastal ports), and other examples of engineering (e.g., Pranzini, 2007; Simeoni and Corbau, 2009; Provansal et al., 2015; Constantinescu et al., 2024). In certain cases, additional data incorporation in the georefencing process (e.g., geomorphic control points from lidar imagery), georeferencing ensembles of map overlays rather than a single specimen (e.g., Salomon et al., 2024), can regionally improve the referencing accuracy to better than 100 m for well historically-covered parts of delta plains. In such cases, historical maps also become useful for the determination of delta shoreline progradation or retreat rates (e.g., Karymbalis et al., 2016).

A 1585 chart of the densely populated SW Netherlands (Fig. 9A; SOM Fig. A1) is an early data-rich example, offering a complete mapping of tidal flats and sand banks in estuaries created by medieval storm surges (e.g., Vos, 2015; de Haas et al., 2018), linking up with the Rhine-Meuse delta with its Common Era human footprint of towns and dug canals. A 1599 CE map of the Nile Delta (SOM Fig. A2) republishes the classical historical findings of Claudius Ptolemy (85–165 CE), illustrating 10 major distributary channels, ports, fortifications, cities and towns located along riverbanks, and sea monsters. European mapping of the Nile delta was updated in 1826 (Fig. 9B, SOM Fig. A3), showing for the first time all 15 distributary channels and their complex interconnections, large canals, a complex of delta lagoons, lakes and islands. The 1826 delta morphology still appears dominated by nature, in difference to the Anthropocene Nile case today. A 1764 CE chart of the Euphrates lower delta (SOM Fig. A4) shows the major distributary channels (one with bathymetry), sand banks, and a surprisingly limited human footprint: settlements were located mostly at the upstream end. Similarly, a 1777 CE Danube delta chart (Fig. 9C; SOM Fig. A5), Indus delta charts (1618 CE, SOM Fig. A6; 1816 CE, SOM Fig. A7) and the

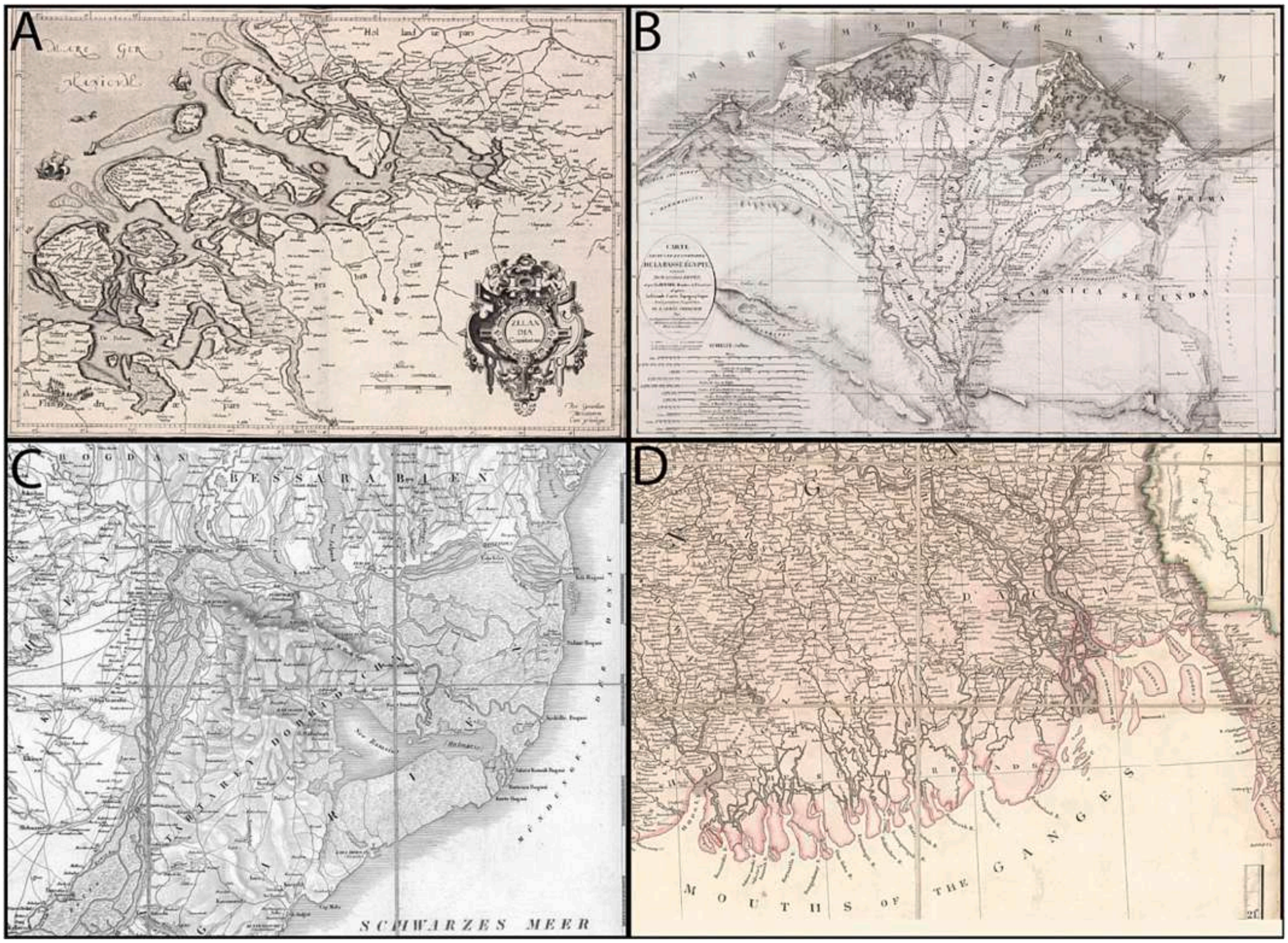

Fig. 9. Display examples of four 16th–19th century maps from the David Rumsey Map Collection (https://www.davidrumsey.com) that convey acceptable information and contribute to the question of increasing delta dominance by humans. Our Supplementary Online Material (SOM) provides readers with larger versions of these and 8 other delta maps. (A) A 1585 Rhine delta chart published by G. Mercator (1512–1594) at a scale of 1:300,000 showing distributary channels, tidal flats, canals and coastal towns. (B) An 1826 Nile delta chart published by C.L.F. Panckoucke (1788–1844) at a scale of 1:500,000 showing 15 distributary channels, lagoons and lakes, canals, towns and roads. (C) An 1829 chart of the Danube delta published by F. von Weiss (1791–1858) at a scale of 1:575,000 showing river mouth features, settlements, ports, and limited human occupation. (D) An 1816 Ganges-Brahmaputra delta chart published by A. Arrowsmith (1750–1823) at a scale of 1:1,013,760 showing topography, towns, ports, and river mouths.

Ganges-Brahmaputra-Meghna in 1816 CE (SOM Fig. A8), the world's second largest delta after the Amazon, all show still relatively natural deltas with human settlement restricted to the upper delta plain. In contrast, Indian deltas such as the Krishna and Godavari (~1816 CE, SOM Fig. A9), or the Brahmani and Mahanadi (1816 CE, SOM Fig. A10), show a complete occupation of the delta plains through to the shoreline, supported by a complex of roadways and canals.

Non-data-rich counter examples are early 19th century colonial maps, for example, that of the Mekong (1827 CE, SOM Fig. A11), which offers limited anthropogenic information with just major city locations shown. The map (1827 CE, SOM Fig. A11) retains great value, however, in showing the interconnectivity of distributary channels, including lateral drainage to the west and into the Gulf of Thailand. Today, the Mekong delta has one of the world's largest delta canal systems, on a par with the modern Nile. In investigating an identified secular decline in mud supply in the Mekong delta that thus predates the post-2010 incriminated dams and mining operations in this delta, Tamura et al. (2020) linked this secular decline in part to the delta's vast canal network created by the French early in the 20th century. Changes in the pathways of river discharge are one of the most important contributions of maps to our understanding of delta dynamics. For example, the 1816 CE Ganges-Brahmaputra-Meghna delta map (Fig. 9D; SOM Fig. A8) captures the Brahmaputra flow through the Meghna River; the 1785 CE map of China (SOM Fig. A12) captures the old Yellow River delta before an artificial avulsion moved the modern Yellow River mouth to the coastline of the Bohai Sea, leaving the old Yellow delta exposed to rapid erosion.

4. The human legacy in Pre-Anthropocene delta sediments and stratigraphy

The human presence on deltas over the last 7000 years grew progressively (ocasionally contracting under the vicissitudes of nature), embodied by the anthropogenic 'tract' (further developed in Section 5.1) over large areas, especially as delta populations and human inhabitance increased over the CE (Fig. 9). We review aspects of the pre-Anthropocene human legacy in delta sediments and stratigraphy under two perspectives: the human contribution to delta sedimentation through fluvial sediment supply from catchments, and the human presence recorded within delta sediment mass. Whereas delta landscape modifications by humans have been abundantly reported, identification of the human footprint for the Neolithic remains poorly documented in delta stratigraphy. There is better preservation of the human footprint in Bronze-Age settlements and artefacts, and in Bronze Age and later harbour sequences. Where human occupation and activities commenced in the Neolithic, there appears to have been continuity of occupation during the Bronze Age and the CE, despite a discontinuous and fragmentary record in delta stratigraphy due to geomorphic and sedimentation changes, including those generated by humans, and the challenges of coring and retrieving information on the human presence. Countless artefacts remain locked in delta sediments. However, detecting, in a delta's sediments and stratigraphy, the human influence on fluvial sediment delivery changes is an arduous task.

4.1. The unresolved question of human versus climatic influence on catchment erosion and delta sedimentation

Globally, notable changes in deltas in the 20th century reflect exploitation of available excess energy (fossil fuels), harnessing of hydropower across rivers, and mechanized systems (road construction, deforestation, mining, mechanical tilling) (Syvitski et al., 2020). If we leave aside the Industrial era and the Anthropocene, human impact on fluvial sediment supply to deltas, through deforestation, river and landscape engineering and soil erosion, is a widely claimed concept, but disentangling the hand of humans from the coeval role of climate variations is often a challenging task. There is an indirect human influence on deltas (see below), notably from upstream deforestation, and there are suggestions that delta sediment mass and geomorphic changes, especially in the CE (Figs. 3, 4Aiii,B) have a large anthropogenic legacy, if one is to judge from the presence of this legacy in upstream river deposits (e.g., Hoffmann et al., 2007; Brown et al., 2013; Gibling, 2018; James et al., 2020). Evidence for anthropogenic influence comes from sediment type, aggradation rate, charcoal, plant materials and pollen, geochemistry, artefacts, and associated palaeosols, and indirectly from induced avulsions. These sources of evidence are now routinely complemented by the analysis of satellite imagery to identify ancient anthropogenically-generated river features (Brandolini et al., 2021). River sequences are characterized by successions that may be exposed by bank erosion, including in floodplains, thus facilitating the identification of anthropogenic legacy sediments. Gibling (2018), following Brown et al. (2013), noted that legacy sediments in fluvial systems may be best documented from successions in small river valleys characterized by substantial Late Holocene aggradation and recent (re-)incision, whereas the identification of anthropogenic signatures is much more problematic for large river catchments where regional climatic effects influence sediment flux. The problem is even more complex for deciphering low-lying successions in small and large deltas, because of lag-times of signal arrivals to consider and the larger volumes of successions to evaluate. Notwithstanding this constraint, deltas have the advantage of offering a broader and more transdisciplinary scope for investigating human signatures, as they archive sedimentary inputs from entire catchments and have trapped these as sinks for the last 8000 years (Section 2), modulated by human sediment-routing changes (Section 3). Technically identifying and deciphering this human influence are another matter.

Asian rivers start showing sediment delivery changes to the coastline over the last 2000–4000 years, but even here, while being detectable, the connection with humans is not overwhelming, with rivers draining the Loess Plateau, such as the Yellow, being somewhat an exception in this regard (Chen et al., 2012). The influence of humans on sediment supply to deltas in China has been abundantly documented but this influence is often deemed as intertwined with that of climate effects (Chen et al., 2012; Kidder and Liu, 2017; Liu et al., 2020; Yu et al., 2021; Zhou et al., 2021;Nian et al., 2022; Yang et al., 2023; Zhao et al., 2023).

In Europe, deforestation and soil erosion under demographic pressure have been deemed as having favoured abundant sediment supply that led to significant growth over much of the CE, of the Rhine (Hoffmann et al., 2007; Erkens, 2009; Stouthamer et al., 2011; Pierik et al., 2018), Ebro, Po, Danube (Maselli and Trincardi, 2013; Vespremeanu-Stroe et al., 2017), Rhône (Provansal et al., 2015; Martinez et al., 2024), and Volturno (Ruberti et al., 2022) deltas. Increased delta progradation has been associated with the impact of the expansion of the Roman Empire on population growth, agriculture, and soil erosion, and that of cumulative Bronze Age, Iron Age and early CE land-use developments in general (Anthony et al., 2014). The Rhine delta plain is reckoned to have trapped 10.5 Gt (10^{12} kg) of sand and 15.6 Gt of suspension load (clay and silt) over the last 8500 years (Erkens, 2009). Timeslicing the mud and sand volumes and factoring in avulsive reworking and throughput to coastal-marine sectors enabled expressing fine sediment delivery from the Rhine catchment to its delta apex as ~2.0 Mt./yr during the Common Era (±10 %; reckoned strongly human-impacted; Hoffmann et al., 2007), whereas this load was ~1.2 Mt./yr over the period 6000 to 4000 yr BP (±10 %; reckoned minimally human-impacted; Erkens, 2009; de Haas et al., 2018). The delivery of sand over the same period appears constant (~1.2 Mt./yr; ±10 %). A detailed stratigraphic synthesis of the Rhône delta assesses its sediment volume between 11,700 yr B.P. and today at 126 billion m^3 (±10 %), but the association with climatic oscillations and anthropogenic activity, emphasized for the Roman period, the Little Ice Age (further discussed below), and the current Anthropocene (Martinez et al., 2024), remains qualitative.

During Greek and Roman Antiquity, against the backdrop of increased sediment discharge associated with catchment deforestation, the Danube experienced several major avulsions that resulted in the development of a southern distributary and the incorporation of the Greek colony of Histria, a former open-coast city, into the deltaic plain (Vespremeanu-Stroe et al., 2013), but also in the formation and rapid growth of the Chilia lobe, which is now the largest in terms of water and sediment discharge (Preoteasa et al., 2021). The dramatic landscape changes associated with the decline of the Roman occupation of Europe and the inception of the Dark Ages (Kaplan et al., 2009; Deforce et al., 2020), and the massive population decline caused by the Black Death (Kelly, 2006), between 1346 and 1353 CE, resulted in the regression of agriculture with forests regaining area, contributing to soil stabilization in river catchments. This is deemed as having affected deltas in the Mediterranean, with examples notably in Tuscany, Italy (e.g., Pranzini, 2007). Sediment decline in the Danube delta during the Dark Ages is reported to have led to the last two cases of abandoned lobes, while the Middle Ages as a whole saw the slowest expansion of the Danube delta plain in the last 2500 years (Vespremeanu-Stroe et al., 2017). In the Western Mediterranean, the growth of most deltas, probably impeded during the Dark Ages as a result of the well-reforested catchments (Anthony et al., 2014), is considered to have resumed during the Renaissance Period of socio-economic growth, with delta expansion reported as occurring from the 16th to the 18th centuries (Pranzini, 2001). These conditions may, however, have varied within the Mediterranean basin. López-Quirós et al. (2025) have identified, from subaqueous deposits of the Guadalfeo delta in southern Spain, variations in fluvial sediment supply with an Iberian Roman Humid Period (2600–1600 yr BP) characterized by diminished terrigenous input despite increased humidity, and the Dark Ages marked by elevated sedimentation linked to soil erosion.

There is a consensus on the synchronicity of population growth, deforestation and soil erosion with high river discharge in the Little Ice Age, generally identified in terms of enhanced deltaic sedimentation, especially in China (Zhou et al., 2021; Nian et al., 2022), but Mediterranean deltas also saw a significant increase in sedimentation, notably well documented in the Rhône (Provansal et al., 2015; Martinez et al., 2024) and in subaqueous delta deposits in Italy (Ruberti et al., 2022) and Spain (López-Quirós et al., 2025). In the Danube delta, rapidly prograding river-dominated lobes formed over the last 300 years (Preoteasa et al., 2021), leading to ~2.5 times higher rates of delta-plain area increase compared to the rate in the Middle Ages (Vespremeanu-Stroe et al., 2017). A similar clustering of avulsions has been observed in the

Rhône delta. In Provence, much of which is drained by the Rhône, the first parliamentary bills regarding control of deforestation date back to 1555 and 1606, but demographic growth and generalized deforestation became even more rampant in the following decades. These generated intense soil erosion in the numerous small torrential river subcatchments that deliver sediments to the Rhône delta, generating a series of avulsions and abandoned lobes (Provansal et al., 2015) that are currently being reworked by waves (Sabatier et al., 2006; Sabatier and Anthony, 2015). For the Rhine delta, the transformation from an unembanked to an embanked situation (1000–1350 CE) just preceded the gradual onset of the Little Ice Age. Sustained high sediment throughput to the lowermost tidal reaches, from 1500 CE onwards (Erkens, 2009; de Haas et al., 2018), helped in facilitating reclamation of coastal land lost as a result of storm surges (SOM Fig. A1). Nian et al. (2022) identified, over the last 500 years, the highest sedimentation rates in the history of the Yangtze delta that they attributed not only to the wetter conditions of the Little Ice Age in that region, but also to dramatic regional population growth, considered as predominant over natural forcing in determining the deltaic growth over this period. Between 1580 and 1849 CE, human-accelerated erosion of the Loess Plateau led to a super-elevated lower Yellow River channel bed that facilitated frequent breaching (up to 280 times) of the artificial river bank levees, and sediment storage, to the tune of ~312 Gt, on the river's floodplain outside these levees (Chen et al., 2018). Ninety percent of the modern delta (i.e. since 1855 CE) is due to human farming and gullying of the Loess Plateau. This massive sediment supply has also generated the historical and modern-era (since 1889) avulsions in the Yellow delta ((Xue, 1994; Saito et al., 2000; see also Fig. 2 in Ganti et al., 2014). The overarching role of human activities in fluvial sediment supply to the Pearl delta over the last 150 years has been emphasized by Ranasinghe et al. (2019).

From a review of the literature, we infer that human influence on river sediment supply started affecting small to medium deltas in a consequential way during the Metal Ages and has mainly affected large deltas since about 2500 yr BP through deforestation. This influence has been notable over the last 500 years, which incorporate the Little Ice Age, in many systems peaking in the Anthropocene. The signals reflect the major anthropogenic influence in river catchments that are independently evident from, for instance, archaeology and soil sciences (up to the time hydropower dam and reservoir constructions in catchments took off). Marks of this CE-spanning influence have included growth of lagoons due to rapid delta shoreline progradation, increase in the number of distributary channels, and the temporal clustering of avulsions on the plains between coast and delta apex.

On the other hand, climate variations influencing precipitation and water availability (thus river hydrology) constitute a much less debatable driver of river sediment supply to deltas, and climate was no doubt the major driver of delta sedimentation during the Neolithic and the Bronze Age, thus also to be reckoned of significant influence on sedimentation during the CE. Monsoon variations have been deemed as responsible for swings in the Harappan civilization (5200–3000 yr BP) from urban to rural settlements along with the abandonment of sites between 3900 and 3000 yr BP in the Indus valley (Giosan et al., 2012; Coningham and Young, 2015; Kaushal et al., 2019), the delta and the lower course being located in an area where aridity has always prevailed. The 4.2 kyr event, essentially an Indian Ocean monsoonal event, has been identified as a cause for the decline of well-established societies in a number of deltas, such as the Yangtze (Li et al., 2018) where this decline severely affected rice cultivation (Kajita et al., 2018), like the later 2.8 kyr cold event (Jia et al., 2022). The 4.2 kyr event had a profound impact on cereal agriculture in the Nile delta (Fig. 6; Kaniewski et al., 2018; Zhao et al., 2021). In the Indus valley, this event overlaps the flourishing of Harappan urbanism: 4500–3900 yr BP as for a few centuries the aridification may have diminished the intensity of floods and allowed inundation agriculture to develop across the Indus basin (Wright et al., 2008). However, the regional palaeo-climate and landscape reconstructions show that, as aridity intensified, monsoon-augmented floods became less frequent while further drying was detrimental for the Harappans (in decline since ~3900 yr BP), who relied on annual floods to sustain their economy (Giosan et al., 2012; Laskar and Bohra, 2021). In the Nile delta, Stanley et al. (2021) attributed delta stratigraphic markers to increased regional aridity and reduced Nile flow that could have periodically disrupted the regional distribution of goods and nautical activities at ~5000 yr BP, ~4200–4000 yr BP, ~3200–2800 yr BP, and ~ 2300–2200 yr BP. Peeters et al. (2024) have also shown how climatic and environmental changes have shaped the civilization of ancient Egypt between ~5000 and 2000 yr BP.

4.2. *An aggregated human-delta connection over time rather than 'man-made' deltas*

Heavily engineered, embanked, reclaimed and urbanised historic to modern deltas have been dubbed 'man-made'. Ibáñez et al. (2019) challenged this concept of 'man-made deltas,' originally proposed for Europe's Po, Ebro, Rhône, Rhine, and Danube deltas to emphasize the dominant human influence on their sedimentation patterns and geomorphology (Maselli and Trincardi, 2013), particularly through modifications to sediment supply from their river catchments. The truth or strength of the hypothesized association between human activities and deltas, probably most iconically associated in Europe with the growth and decline of the Roman Empire and in Asia by loess erosion, needs to be considered in the light of catchment and delta size and characteristics.

Altered soil erosion seldom leads to major changes in river loads, except in small rivers (defined by Syvitski et al. (2022a) as rivers with a sediment discharge not exceeding 25 m^3/yr averaged across the year), and which we can associate here with small deltas: <10 km^2). Rivers are always trying to return to equilibrium, balancing changes in sediment supply by scouring or depositing. Thus, anthropogenic changes mostly impact small rivers and streams where human influence can more readily dominate the system, and changes are more rapidly propagated through the system (Marriner et al., 2019). In the Mediterranean, for some small deltas fed by small rivers that are sensitive to system changes, it may indeed be postulated directly that orchestrated hinterland deforestation led, within a century or so, to delta progradational response (Anthony et al., 2014), as the well-documented example of the Adra delta shows (Bárcenas et al., 2024). Enhanced sedimentation probably explains the close connection between small deltas in the Mediterranean with aggradation and preservation of buried Bronze-Age artefacts. But accelerated sedimentation even in small deltas is, by no means, a clearly defined pattern. Degeai et al. (2020) noted, for instance, decreased sedimentation in the Argens delta, notwithstanding the fact that the Argens catchment has been considered as under strong human pressure since 2500 yr BP.

On most big river systems (commonly associated with large deltas: >1000 km^2), climate appears to have been the primary control on delta dynamics prior to the 20th century, including the widely proposed accelerated Little Ice Age catchment erosion that led to rapid delta growth with avulsions. Where numerous small torrential subcatchments exist close to a delta, they may become the principal contributors to river sediment supply, as in the Rhône (Provansal et al., 2014). For large deltas such as the Danube, Rhine, Rhône, Po and Ebro, overall growth more likely reflected a longer cumulative impact of development spanning the Bronze Age and Iron Age and the CE, with climate variations and increasing human activities (in the Rhine and Danube, affecting relatively erodible loess soils) jointly impacting sediment supply to the deltas. It is probable that as the global human population expanded, the effects of CE climate change became amplified, intertwined with human impacts (Ellis et al., 2013; Jenny et al., 2019). As various recent studies have noted (e.g., Munoz et al., 2018; Yu et al., 2023; Toonen et al., 2025), catchment deforestation by humans during the Late Holocene seems to have created conditions wherein hydroclimatic variability and floods were amplified, and likely occurred more frequently, due to a reduced retention capacity of these catchments.

Often, temporal resolution, research interests, and direct sources (archaeological evidence and antique historic mentions) together tend to indicate an increase in progradation for the larger delta systems during the CE. In that sense the 'association' of delta growth with humans, and notably the Roman era in and around the Mediterranean, is a strong summarizing concept. The meta-data analysis conducted by Walsh et al. (2019) on Holocene demographic fluctuations, climate and erosion in the Mediterranean, and the geoarchaeological and palaeohydrological overview of the Central-Western Mediterranean Early Neolithic human-environment interactions by Berger (2021) both highlight a complex and heterogeneous interplay, with marked local to regional variability. Elucidating and disentangling the links between upstream human and climate change effects on sediment supply and delta geomorphology will require more work.

4.3. The challenges of detecting early human presence, and of identifying its impacts on deltas

Material finds (artefacts, sites) attesting to Neolithic and Bronze Age inhabitance in delta stratigraphy are relatively sparse. In that light, our review in Section 2 is biased towards success case studies from larger deltas with long research histories, where Earth Sciences, Geomorphology and Geoarchaeology interacted with Antiquities, Egyptology, Classical Archaeology and Early History (Mediterranean deltas, Mesopotamia, Indus), and/or where 20th–21th century research has been particularly intensive (Rhine, Po, Chinese deltas), coeval with major urbanization.

The low global Neolithic population, the prevalence of hazards such as avulsions, water-level oscillations, storm surges and tsunami, as well as water-borne diseases such as malaria, typhoid, dengue and West Nile fever, could all have been obstacles to widespread delta inhabitance. Later modifications or perturbations by humans (Stanley and Warne, 1997), thick younger sediment tracts, and the reliability of radiocarbon dates (Walsh et al., 2019) are factors that limit the detection and characterization of this early presence of humans in the delta sediment mass. Putting aside the surmised role of these population and hazard issues, identifying Neolithic artefacts and sites requires relatively strategic (and lucky) coring, generally to depths >4.5 m and up to 11 m below present delta surfaces (e.g., Niebieszczański et al., 2023; Chabrol et al., 2025). Simple archaeological digs are no doubt a more important and straightforward way of unearthing artefacts.

Perhaps more importantly, sparse identification of the Neolithic presence may not be due to the fact that this presence is poorly preserved in delta stratigraphy, but rather that indices and proxies of human occupation, preferentially located on higher-lying topography (ridges, levees) rather than in the water-logged wetlands, are buried along nameless (and no doubt numerous) former avulsed branches of large deltas, long abandoned in the course of thousands of years of delta morphosedimentary development, with some covered by subsequent sedimentation and subjected to subsidence. Targeted discovery requires high-density and high-resolution coring of deltas and trained workers to detect the human presence, now also guided by increasingly high-quality remote sensing data. We note that many of the studies that do report on Neolithic delta plain occupancy did so in the wake of deltaic urbanization engineering works (notably harbour developments), often guided by existing maps (see 3.2). For the higher-lying delta apex regions, Pleistocene inliers and delta plain fringes on delta lobes long ago abandoned as a result of avulsion, the bias is less, but even in these settings, Common Era sedimentation tracts often bury and hide sediments holding evidence of older human presence.

Material finds associated with the Bronze Age have been identified in sediment cores at depths of a few metres (2.5–6 m) below the present surface in some Mediterranean deltas such as the Arno (Fig. 10) (Amorosi et al., 2013), the Anthemous (Niebieszczański et al., 2023, 2025) and the Kalamas (Chabrol et al., 2025). More evidence has come from ancient harbours located at delta mouths around the Mediterranean and in the Black Sea (e.g., Brückner et al., 2002; Marriner and Morhange, 2007; Vespremeanu-Stroe et al., 2013; Giaime et al., 2016, 2019a, 2019b). These harbours (Fig. 11A) display a typical stratigraphic signature (Fig. 11B), the 'Ancient Harbour' parasequence (Marriner and Morhange, 2006, 2007; Giaime et al., 2019a, 2019b), reflecting aggradation and progradation (transition from the Bronze Age to the CE, Fig. 4), with variation as a function of delta context, location within the delta, and changing delta geomorphology and subsidence. We note the close connection between small-sized deltas in the Mediterranean and the identification of buried Bronze-Age artefacts and the Ancient Harbour parasequence (Fig. 11). Small deltas offer scope for denser and more complete stratigraphic and geomorphic characterization.

In the eastern Mediterranean, the demise of Bronze-Age settlements has been attributed to complex conditions of changing aridity and societal response (Kaniewski et al., 2019; Hazell et al., 2022). The delta stratigraphic records from ancient harbours throughout the Mediterranean and the Black Sea (Marriner and Morhange, 2007; Giaime et al., 2019a, 2019b) suggest that aggradation and burial under abundant sediment supply and common avulsions could also have been an important component of societal collapse. Several harbours affected by delta aggradation and surface lowering by subsidence were abandoned or successively relocated nearer to the sea. Climate oscillations, including extreme events such as droughts, but also typhoons, and sea-level fluctuations have also been reported as having had a determining influence on the preservation or destruction/burial of earlier human settlements and artefacts, especially in the Yangtze delta (Zhang et al., 2005; Chen et al., 2008; Wu et al., 2014; Liu et al., 2018; Chen et al., 2023), with additional impacts on rice cultivation, a source of sustenance for delta populations.

One of the key problems of delta geoarchaeology is that sediment cores can be easily used to identify sedimentary units, but archaeological identification requires a much more widespread approach. Delta plains tend to widen and their wetlands tend to be large, which makes them challenging environments: systematic geoarchaeological investigations are time-consuming and expensive (e.g., Romano et al., 2025). In essence, an absence of evidence does not necessarily mean evidence of absence. Aspects of the complex relationship between early urbanism and the marshy environment in the Tigris-Euphrates, notably revolving around the city of Lagash have, for instance, sparked debate (Hammer, 2022, 2023; Pittman et al., 2023). Hammer (2022, 2023) used UAV photography and magnetic gradiometry data to argue that the on-site habitation of Lagash had previously been restricted to points of high elevation because of excess water, but Pittman et al. (2023) point out the absence of fundamental geoarchaeological and chronometric data to support this argument, and highlight the importance of verifiable representation in the presentation of remotely-sensed datasets on early delta urbanism. These studies, and the debate they elicit, clearly bring out the potential of delta geoarchaeological/stratigraphic studies in enhancing our understanding of ancient urbanism, but with the caveat of the necessity of having rigorous datasets in an environment where geoarchaeological investigations are faced with significant challenges.

Thus far, with the exception of the intensively cored Rhine delta, where substantial beds have been unequivocally attributed to upstream anthropogenic pressure (Stouthamer et al., 2011; Pierik et al., 2018; de Haas et al., 2018), in no other delta has a substantial deltaic stratigraphic bed, other than the commonly recognized surface 'anthropogenic' layer (e.g., Fig. 10A, see also Anthropocene section below) and occasional beds and horizons, been clearly and unequivocally attributed to distant upstream anthropogenic influence. Whereas the human influence on fluvial sediment supply has been abundantly advocated, there is a a global paucity of 3D and 4D datasets on delta sediment mass and volume, although there have been attempts on a few deltas: the Rhine (Erkens, 2009; Peeters et al., 2019), Ganges-Brahmaputra (Karpytchev et al., 2018), Yangtze (Wang et al., 2018), Rhône

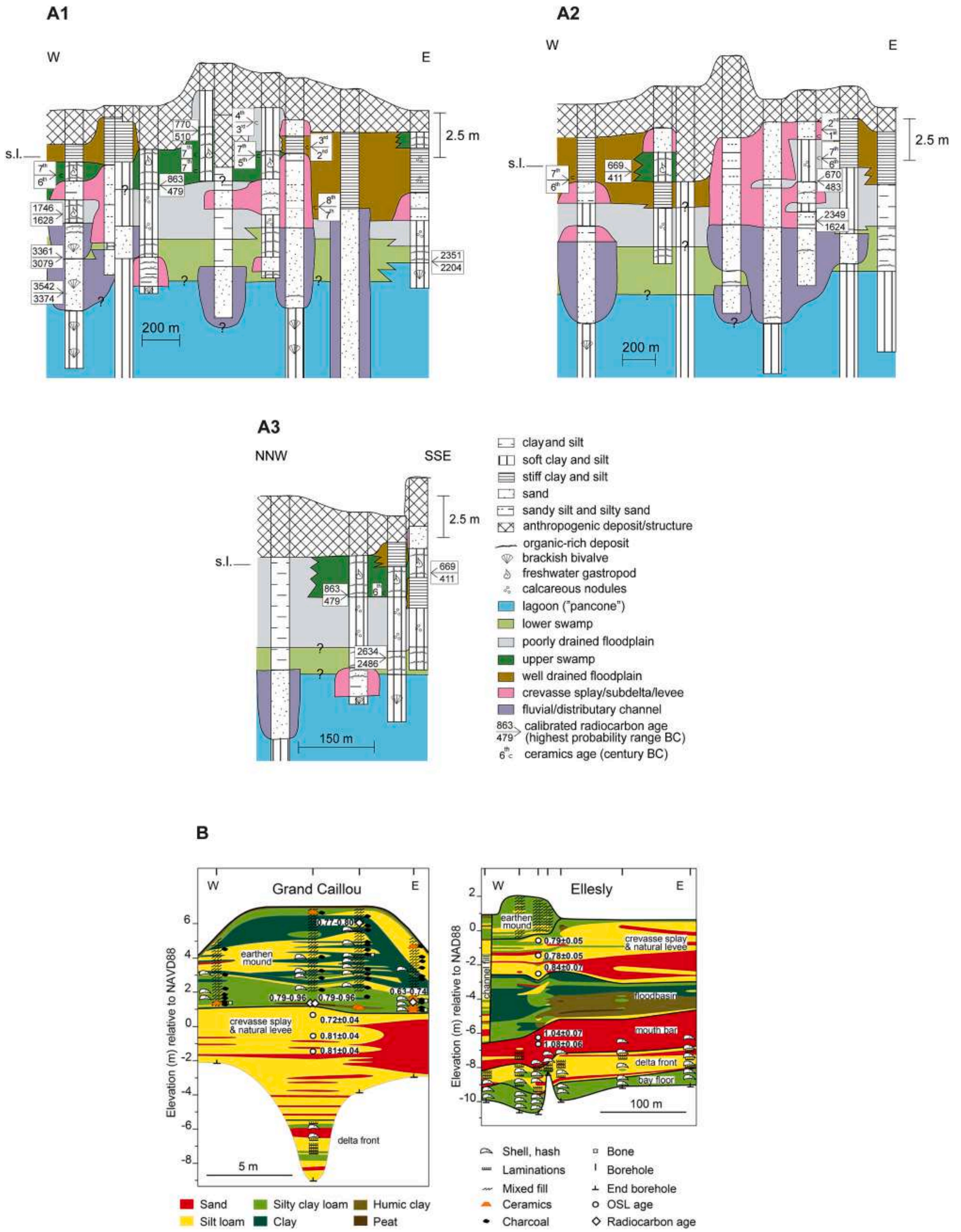

Fig. 10. Examples of delta stratigraphic sections showing the presence of ancient human artefacts buried under delta aggradation. (A) Representative sections of the middle to late Holocene facies architecture in the area of the old town of Pisa, Arno delta, Tuscany, Italy. The section is capped by the modern city of Pisa. From Amorosi et al. (2013). (B) Cross sections showing sediment texture, OSL and radiocarbon chronology in ka, natural features, human artefacts, and interpreted depositional units for the Grand Caillou and Ellesly mounds and underlying natural deposits in the Mississippi delta. From Chamberlain et al. (2020).

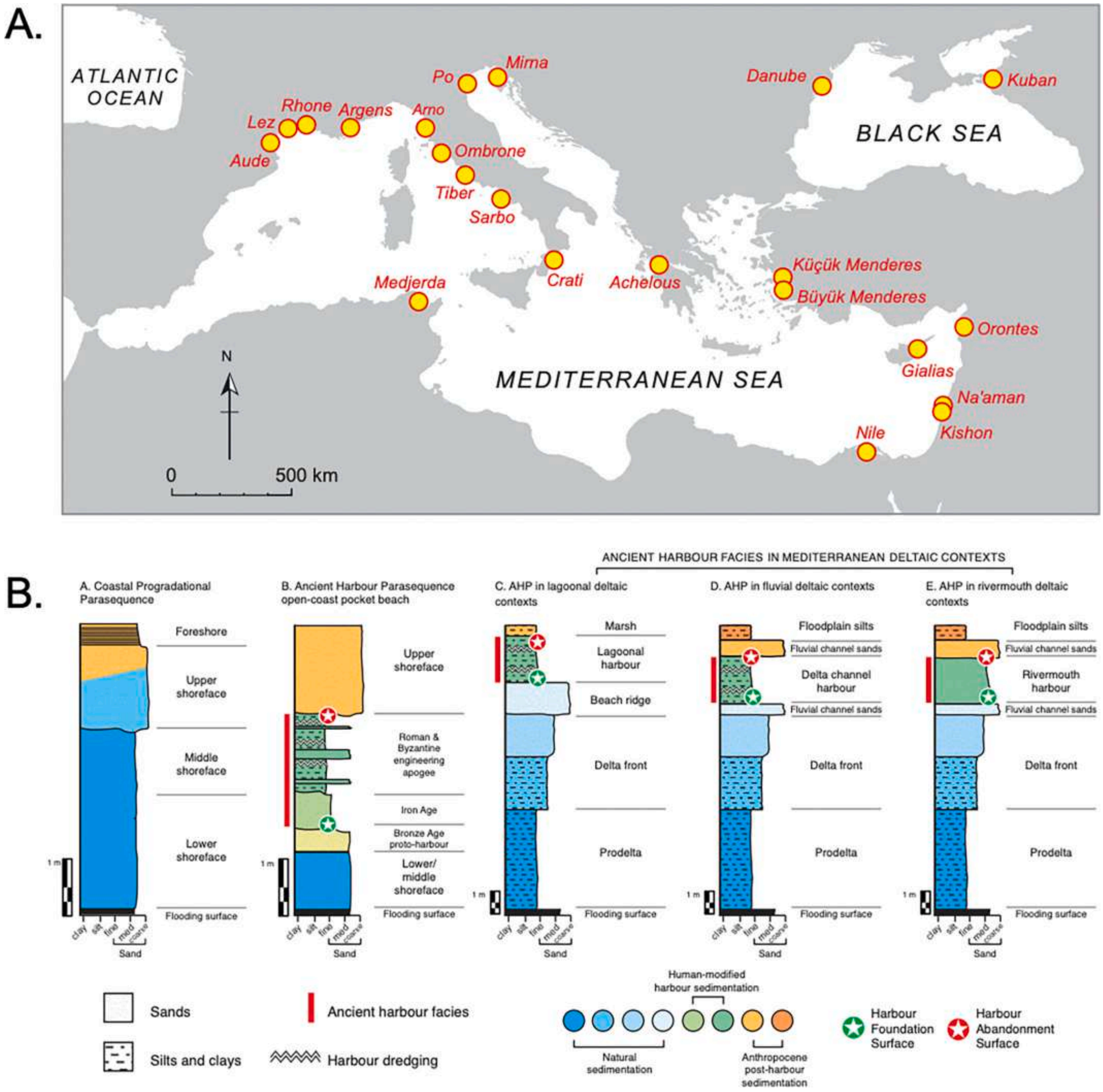

Fig. 11. Ancient harbours in the Mediterranean and Black Sea (A); delta aggradation and progradation frequently resulted in harbour decline, abandonment or successive relocations nearer to the sea (B): sedimentation and the resulting harbour facies in the coastal and delta stratigrahy - a: The Coastal Progradational parasequence; b: the Ancient Harbour parasequence (AHP) in an open-coast context; c, d, e: expressions of the AHP in various deltaic contexts. Adapted from Marriner and Morhange (2007).

(Martinez et al., 2024), Mekong (Baldan et al., 2025). Beyond this problem of data on delta architecture, there is uncertainty regarding the identification of the presence, not to mention the strength, of the human imprint in delta sediments and stratigraphy. The interpretation of delta sediment mass accumulation over time periods is systematically qualitative and invariably integrates, especially over the last 3000 years, the joint influence of climate and humans. How do we differentiate between sediments supplied from catchments under the overarching control of climate variations from sediments generated by human-induced deforestation and soil erosion? Both drivers were increasingly concomitant in the CE evolution of deltas, with the sediment subject to downstream transport, sorting, storage, weathering, and remobilization by river hydrology.

An additional problem is that some of the human legacy markers, such as charcoal and some pollen assemblages deemed anthropogenic, may, in fact not be unequivocal proof of human activity. Maybe we need to find other, still undiscovered proxies of the human influence. Pei et al. (2023) have recently looked at the problem in terms of catchment silica weathering under human influence (farming) rather than reworking of old soils. The evidence they found from major elements and clay minerals in the Pearl delta indicates an abrupt increase in chemical weathering intensity over the last 3000 years, a result, they claim, that cannot be explained by changes in provenance, climate or other natural factors, but which agrees well with stronger human activity.

At best, only a handful of studies have, in fact, defined delta sediment mass (e.g., Erkens, 2009; Nian et al., 2022; Martinez et al., 2024; Baldan et al., 2025), or sediment influx (e.g., Degeai et al., 2020) and trapping (Wang et al., 2018), in terms of periods since delta inception. This temporal benchmark provides a rough template for gauging the potentially growing influence of humans on delta sediment supply, with, notably, some consensus on the CE in both Asia and the Mediterranean, which coincides in the latter region with the Roman empire, and especially the last 500 years. This latter period incorporates rapid population growth and the Little Ice Age, but the timing of which, like climate variations in the CE, has been shown to be non-synchronous around the globe (Neukom et al., 2019).

5. The Anthropocene and delta geomorphology and stratigraphy

In the long-running 7000-year relationship, humans progressively settled over deltas, moved to increasingly bolder transformations and modifications, and now global domination, variably recorded in delta geomorphology, stratigraphy and sediment mass. The growing human-delta relationship, especially during the CE, was marked by spectacular engineering transformations. In the Yellow, for instance, where these transformations were geared to counter floods and sudden sediment fluxes and avulsion, Kidder and Liu (2017, p. 1598) highlight a 'sociopolitical system that was increasingly locked-in to a fixed path from which it became increasingly difficult to be extracted'. Santos and Dekker (2020) term as a 'locked-in' one the virtually global human-delta relationship existing over the last two centuries. However, such co-development and lock-in between flood defences and delta development has been an important element of the history of the human-delta relationship (e.g., Welch et al., 2017, and our CE review above, Section 3).

While impressive, the human footprint of the late pre-industrial and industrial/colonial interval (16th–19th centuries) has been dwarfed by changes during the 20th and 21st centuries, entering the Anthropocene, giving rise to an impressive body of studies devoted to delta systems, and their increasing vulnerability, including significant contributions on delta geomorphology, sediment mass and stratigraphy. In the 20th and 21th centuries, i.e. over the Anthropocene, data-rich documentary and instrumental records (including aerial photography and satellite imagery time series, following up on historic mapping) have been collected while deltas are being transformed. Furthermore, fairly easily accessible high-resolution sedimentary records have been produced that can provide valuable insight on recent human-driven environmental changes. At the same time, drastic reductions in fluvial sediment supply are undermining the stability of many deltas and their capacity as geomorphic systems to withstand accelerated human-induced subsidence and sea-level rise.

5.1. Delta population, the anthropogenic 'tract', and modification of delta geomorphology

Data from remote sensing, environmental analysis and modelling document the domination of human influence on deltas in the Anthropocene, in terms of population, land occupation, land-use and infrastructure growth, and the resulting effects on delta geoscience. During the Anthropocene, the global human population has grown at an averaged rate of 1.6 % per year (now ~75 M/yr). In 1975, deltas were home to about 146 M people, constituting 3.5 % of the total global population of 4000 M. In 2020, the global population had almost doubled to 7800 M, but the delta population has disproportionately increased to ~350 M (Fig. 12), representing 4.5 % of the global total, largely outpacing the global population growth (Anthony et al., 2024). In 2020, this population is concentrated in ~730,000 km^2 of deltaic lands (Syvitski et al., 2022a), yielding a density of ~480 inh/km^2, over eight times that of Earth's habitable landmass.

Global delta population is concentrated in Asia (87.3 %) (Fig. 12), even though the 15 populous Asian deltas occupy only 38.8 % of the global delta area. The Ganges-Brahmaputra delta alone hosts 40 % of the global delta human population (140 M). African deltas have undergone the most significant Anthropocene growth, with an average population

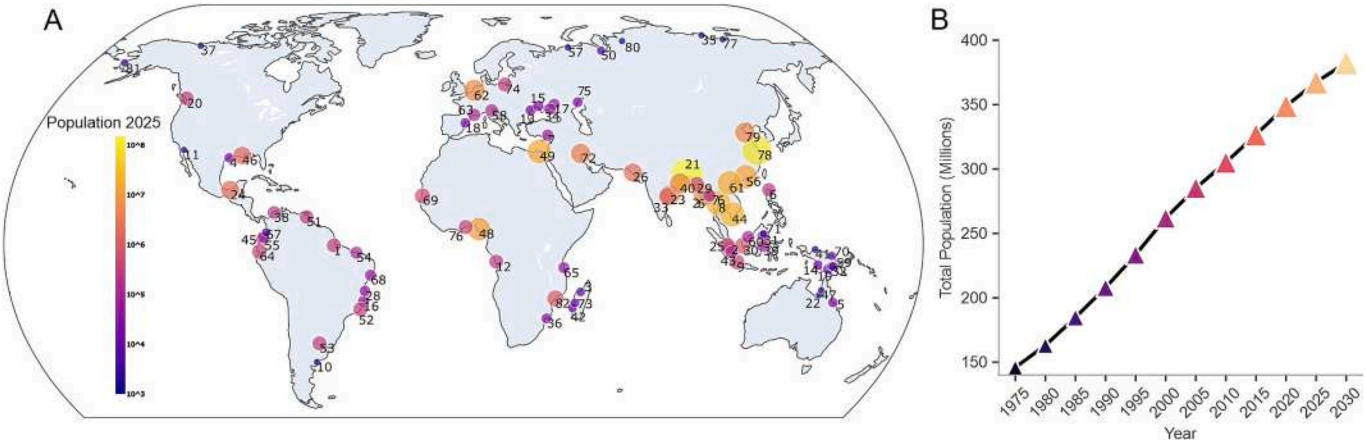

Fig. 12. Population in large deltas. (A) World map illustrating the distribution of populations living in large deltas; colour indicates the value of their relative populations in 2025, bubble sizes scaled by a cubic root transformation. (B) Total population (in millions) over time, showing historical data and projections up to 2030. Data source: GHS-POP R2023A population grid multitemporal (1975–2030) of the European Commission (Schiavina et al., 2023) available at http://data.europa.eu/89h/2ff68a52-5b5b-4a22-8f40-c41da8332cfe.

Deltas: Amazon (1), Batang Hari (2), Betsiboka (3), Brazos (4), Burdekin (5), Cagayan (6), Ceyhan Seyhan (7), Chao Praya (8), Citaro (9), Colorado-AR (10), Colorado (11), Congo (12), Danube (13), Digul (14), Dnieper (15), Doce (16), Don (17), Ebro (18), Fly (19), Fraser (20), Ganges-Brahmaputra (21), Gilbert (22), Godavari (23), Grijalva-Usumacinta (24), Indragiri (25), Indus (26), Irrawaddy (Ayeyarwaddy) (27), Jequitinhonha (28), Kaladan (29), Kapuas (30), Kayan (31), Kikori (32), Krishna (33), Kuban (34), Lena (35), Limpopo (36), MacKenzie (37), Magdalena (38), Mahakam (39), Mahanadi (40), Mamberamo (41), Mangoky (42), Masi (43), Mekong (44), Mira (45), Mississippi (46), Mitchell (47), Niger (48), Nile (49), Ob (50), Orinoco (51), Paraiba Do Sul (52), Parana (53), Parnaiba (54), Patia (55), Pearl (56), Pechora (57), Po (58), Purari (59), Rajang (60), Song Hong (Red River) (61), Rhine-Meuse (62), Rhône (63), Rio Guayas (64), Rufiji (65), Salween (66), San Juan (67), Sao Francisco (68), Senegal (69), Sepik (70), Sesayap (71), Tigris-Euphrates (Shatt Al-Arab) (72), Tsiribihina (73), Vistula (74), Volga (75), Volta (76), Yana (77), Yangtze (78), Yellow (79), Yenisey (80), Yukon (81), Zambezi (82). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

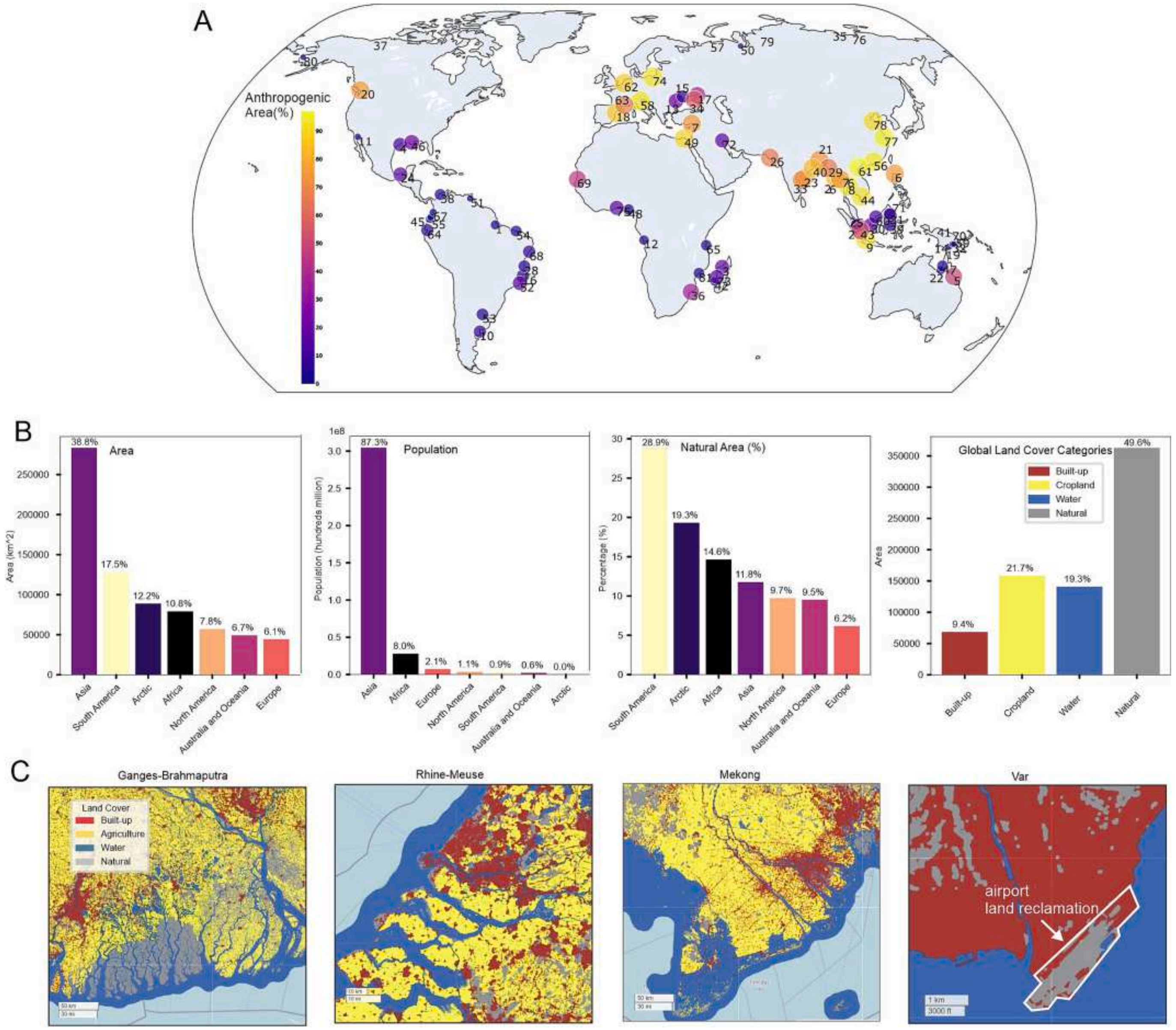

Fig. 13. Illustrations of the anthropogenic tract in deltas in the Anthropocene reflecting the increasing population growth and the pervasive development of human settelements, infrastructure and activities. (A) Total anthropogenic area; (B) Total area, population, natural area and global land cover categories for regions. (C) Examples of land cover for three large deltas (Ganges-Brahmaputra, Rhine-Meuse and Mekong, and one small delta (Var).

increase of five- to six-fold per delta. Additional major demographic increase is expected in Africa over the next few decades, especially along the West African coast, where population centres are booming in small delta systems and in the large Niger and Volta deltas (Dada et al., 2023; Angnuureng et al., 2025). Growth of deltaic populations is driven by large cities across the 86 largest deltas (delta area > 1000 km^2) that capture 84 % of the global human delta population. Some of the world's biggest cities are located in deltas. Shanghai on the large Yangtze delta now appears to be both the world's largest conurbation and city with respectively 80 M and 22.3 M inhabitants in 2018 (Geopolis, 2018), Djakarta on the large composite delta formed by the Ciliwung, Cisadane and Citarum rivers (also known as the Djakarta Delta) comes 4th in the conurbation ranking with 30 M, Dhaka on the Ganges-Brahmaputra-Meghna 9th with 22.5 M, and Bangkok on the Chao Phraya delta 13th with 18 M. Roughly 10 % of the world's population and an even higher share of its urban population are located in coastal areas under 10 m in elevation, with Asia dominating these statistics (McGranahan et al., 2023). Moreover, according to these estimates, in 2015, the deltaic area below 10 m was 2.6 times as densely populated and 1.7 times as built-up as the non-deltaic area < 10 m, while accounting for only 0.35 % of the world's land, but over 10 times the population share (279 M people) (McGranahan et al., 2023). Small deltas can sometimes host high, dominantly urban, population densities (Syvitski et al., 2022a). Arctic deltas remain so far nearly uninhabited, preserving much of their natural landscape. They stand in stark contrast to their temperate and tropical counterparts and represent a final, but relatively univiting, frontier for human habitation.

The pervasive human presence is most clearly embodied today by the anthropogenic 'tract' over large areas of deltas (Fig. 13). The tract involves extensive modification of delta geomorphology and depocentres through urban areas, industrial complexes, harbours and airports, and agriculture (with, in addition to the ancestral rice cultivation in many deltas, especially in Asia, the increasing conversion of land for palm oil cultivation), aquaculture (increasingly to the detriment of mangroves in tropical deltas), engineered distributary channels, flood control systems and coastal barriers, and the impacts of human-induced subsidence and shoreline retreat. Some small deltas such as the Var on the French Riviera (Anthony and Julian, 1999), the Francoli on the Spanish Costa Dorada (Salomon et al., 2024) and the Sumida, Arakama and Edo in Tokyo Bay (Sato et al., 2006), and various others in China and Taiwan are almost completely covered by the anthropogenic tract.

In Asia, 25.8 % of deltaic lands is occupied by settlements but 55.3 % is also devoted to agriculture, resulting in large tracts of anthropogenic landscapes. Globally, 21.7 % of deltaic area (which includes water surfaces) is covered by croplands and 9.1 % comprises human settlements. Excluding water surfaces, only ~19 % of the Asian delta plains remain undeveloped. Land reclamation and empoldering, well expressed since the Middle Ages in European deltas such as the Rhine and the Po (Section 3 above), have undergone exponential expansion during the Anthropocene in deltas globally (Sengupta et al., 2019; Zăinescu et al., 2023; van Maren et al., 2025). Although less inhabited, deltas in Europe display the Anthropocene outcome of multi-millennial-scale human modifications that have given rise to a blend of extremely diverse land uses, reflecting the Old World's cultural and developmental history. Western European deltas, such as the Vistula, Po, Rhine, and Ebro, have undergone extensive transformations, with over 80 % of their delta plains altered and empoldered, whereas Eastern European deltas, including the Danube, Volga, and Dnieper, still retain natural landscapes, with only around 20 % converted for agriculture or settlements. In South America, the still relatively preserved character of the Amazon delta at the mouths of the world's largest river catchment is progressively being called into question by increasing demographic, urban, and land development pressures in this still relatively unpopulated delta, and by problems of governance that underplay aspects of basin-wide and deltaic environmental deterioration (Anthony et al., 2021a).

The anthropogenic tract is both one of human occupation and of sediment contaminated by human activities. This tract potentially implies also that numerous vestiges and artefacts of the past human

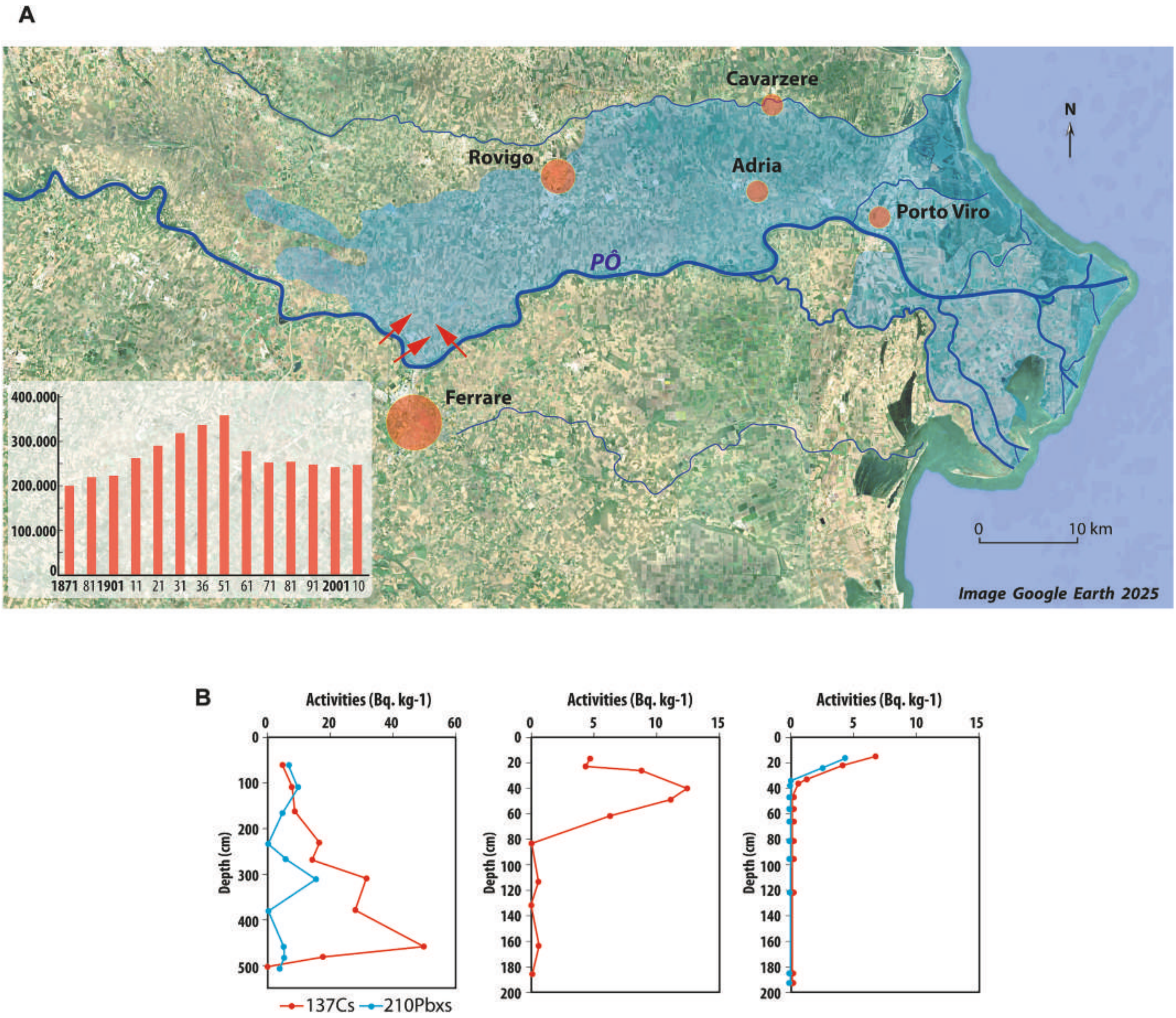

Fig. 14. Anthropocene stratigraphic markers in delta sediments. (A) Google Earth image showing (in blue) area of the lower Po valley and the delta submerged by the Polesine flood in 1951, which had a return period in excess of 200 years. Red arrows show Po dike breaches. Inset shows how the flood resulted in a dramatic and lasting decrease in population (flooded area and population from Amadio et al., 2013). Deposits left by the Polesine flood could represent an example of an Anthropocene stratigraphic marker in the lower Po catchment and delta. (B) Radionuclide profiles of ^{137}Cs (black square) and ^{210}Pbxs (open diamond) in Bq.kg^{-1} recovered from three shallow cores in the Rhône delta downstream of nuclear power plants (from Ferrand et al., 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

presence in especially shallow (< 5 m) delta deposits have now been destroyed. Helmer et al. (2023) noted how extensive Great Depression-era federal projects in the United States created the foundations of Mississippi delta archaeology but yet played a destructive role in its preservation.

5.2. Anthropocene sediments and delta stratigraphy

Anthropocene sediments form a superficial layer that is more widespread in deltas because of channel and floodplain dispersive processes than the more typically patchy but nevertheless expanding anthropogenic tract. These sediments are charged with chemical and organic inputs related to human activities both upstream and within deltas, including artificial radionuclides (e.g., Ferrand et al., 2012), large quantities of microplastics (e.g., Leslie et al., 2017; Pellegrini et al., 2023; Mendrik et al., 2025), *per-* and polyfluoroalkyl substance (PFAS) concentrations (e.g., Yang et al., 2025a), heavy metals, synthetic fibres and industrial residues, although studies are still sparse given the large number of deltas. Human-occupied deltas are prone to eutrophication and hypoxia, have elevated concentrations of lead, mercury, arsenic, cadmium and zinc due to industrial and agricultural runoff, spheroidal carbonaceous particles from fossil fuel combustion, and those with a rich agricultural basis are no doubt overloaded with nutrients. In the Mekong delta, considered as the food basket of southeast Asia, diminished fluvial supplies of sediment-bound nutrients and the consequent need to compensate with artificial fertilizers are leading to increased fertilizer levels in the sediments, while increasing the debt burden on small-scale farmers (Chapman and Darby, 2016).

Delta sediments no doubt provide numerous key marker beds to substantiate what an Anthropocene stratigraphic unit would be (Fig. 14). Potential signatures include anthropogenic debris-rich flood layers (e.g., Amadio et al., 2013), rapid infilling of delta lakes (Anthony et al., 2021b), deltaic lobe development driven by water and sediment rerouting through an artificial canal (Kolker et al., 2025), as well as geochemical components such as artificial radionuclides (e.g., Ferrand et al., 2012) and microplastics (e.g., Simon-Sànchez et al., 2022). The Polesine flood in the lower Po catchment and delta in 1951 affected an area of 1200 km^2 (Fig. 14A), led to the death of 84 people, left 180,000 homeless, and created a lasting population decline in the affected area (Amadio et al., 2013). Concentrations of ^{137}Cs, likely associated with the nuclear power plants upstream in the Rhône, show significant enrichment in the lower part of the profile, with maximum values observed in the 1960s at a depth of 0.5 m (Fig. 14B). An impressive example of an Anthropocene delta lobe is that of Neptune Pass (Fig. 7), the largest new distributary to form in the Mississippi River in nearly a century (Kolker et al., 2025). Neptune Pass developed between 2019 and 2021 when a small canal rapidly expanded by at least an order of magnitude, to now carry about 15–17 % of the flow of the Mississippi (>3000 $m^3 s^{-1}$ when the river is at moderately high flows), leading to the rapid building out of the new lobe (Kolker et al., 2025).

Land reclamations formed by landfills and/or waste are another example of the importance of Anthropocene sediments in deltas. These are mostly found in the subaqueous delta plains or in the shallowest areas of deltas, forming the uppermost layers of deltaic successions. Such anthropogenic strata are prone to geohazards, such as the 1979 submarine landslide in the densely developed Var delta near the city of Nice, on the French Riviera (Anthony and Julian, 1997), and liquefaction of deltaic deposits following the Tohoku Oki tsunami in Japan (e.g., Taira et al., 2012; Reclaimed Land Geological Research Group, 2016). Regarding the 1979 Var delta submarine landslide, the failure of both subaerial coastal and submarine slope sediments resulted in several casualties and structural and urban damage. Anthony and Julian (1997) suggested that the causes of the landslide were delta-front slope steepening, up to the angle of failure, as a result of reclamation of the upper delta-front crest and mantling of the delta-front by massive fallout of underconsolidated fine-grained sediments from this reclamation, and reclamation fill of the subaerial delta plain to enlarge the airport in Nice and provide quay facilities for the city's commercial harbour, under construction at the time, and which collapsed during the event. The anthropogenic fill led to heavy sedimentary loading and strong increases in excess pore water and gas pressures, and reduction of sediment strength. Further probable contributing factors to the landslide were scouring of the basal delta-front slopes by greater submarine groundwater discharge from a confined aquifer following heavy rains and river discharge at the time, and massive fine-grained sediment fallout on the steep delta front associated with this heavier discharge (Anthony and Julian, 1997). Identifying anthropogenic strata on deltas, their geotechnical properties, and their susceptibility to failure, are important for coastal geohazard mitigation and prevention.

5.3. Unintended consequences of diminished fluvial sediment supply on deltas

The Earth's sediment production (supply) from anthropogenic soil erosion, construction activities, mineral mining, aggregate mining, and sand and gravel mining increased by about 467 % between 1950 and 2010, while at the same time global sediment supply (all sources and transport routes) from land to the coastal ocean decreased by 23 % as a result of the impact of dams on fluvial supply (Syvitski et al., 2022b). Dams are quite an ancient form of human modification of river flow, built for irrigation, flood control, and water storage (Angelakis et al., 2024). There are millions of river barriers, including dams, worldwide (Lehner et al., 2024) that impound water and sediment, depriving deltas of sediment (Dunn et al., 2019) needed to balance subsidence and counter marine erosion. The overwhelming impacts of diminishing fluvial sediment supply on delta vulnerability via exacerbated elevation loss, as subsidence and relative sea-level rise are no longer compensated by sedimentation (e.g., Syvitski et al., 2009; Ohenhen et al., 2025), and shoreline erosion (e.g., Besset et al., 2019), have been reviewed by Anthony et al. (2024) in their analysis of global delta sustainability. Shoreline mobility, quantified from increasingly abundant remote sensing datasets, is a particularly popular yardstick for measuring this vulnerability (Besset et al., 2019) compared to exacerbated subsidence, a relatively underrated and understudied hazard (Siriwardane-de Zoysa et al., 2021; Mattei et al., 2025; Ohenhen et al., 2025), which is more difficult to determine areally, especially given the still inadequate high-resolution delta elevation data (e.g., Minderhoud et al., 2019). Ohenhen et al. (2025) analyzed spatially variable surface elevation changes across 40 deltas using interferometric synthetic aperture radar to quantify surface elevation loss. They revealed the prevalence and severity of subsidence and showed that in 37 % of these deltas, groundwater extraction is the primary anthropogenic driver of land subsidence, but various other anthropogenic factors such as reduced sediment supply, and urban expansion, contribute secondarily to additional subsidence and exacerbated elevation loss.

The diminution of fluvial sediment supply to deltas can have various unintended geomorphic consequences and effects on delta sediment mass. Many deltas are tending to shift from river-dominated to wave-dominated as sediment supply diminishes, reflected mainly in increasing downdrift asymmetry, deflection of the delta mouth(s) (Anthony, 2015), and increasingly stronger sediment bypassing at these mouths (Fig. 15), as demonstrated by numerical modelling (Zăinescu et al., 2024). Fig. 15A shows a potential net long-term trajectory of delta evolution as river influence becomes weakened by a variety of natural (changes in catchment climate and vegetation linked to the LIA, for instance, avulsion) and notably Anthropocene human-induced changes (catchment land-use and reforestation, catchment engineering, dams). For symmetric deltas on the left side of the diagram subject to divergent longshore transport, the trajectory may dominantly involve simple delta-front retreat through redistribution of sediments towards the flanks, leading eventually to delta shoreline straightening and demise of the delta protruberance. The modelling framework in Fig. 15B

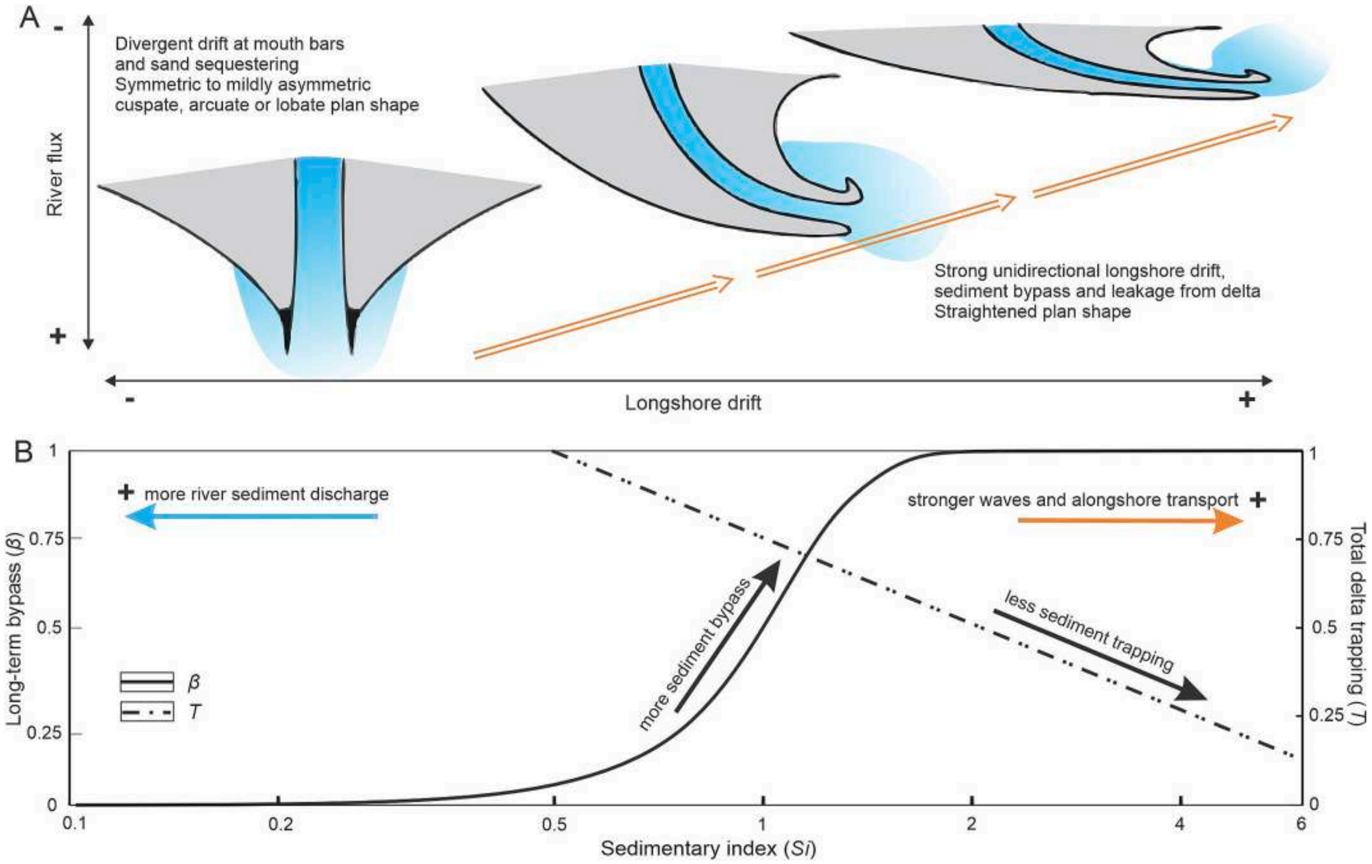

Fig. 15. Conceptual (A, from Anthony, 2015) and numerical model output based on Delft3D simulations (B, from Zăinescu et al., 2024) showing a schematic continuum of delta morphology ranging from symmetric to strongly longshore deflected, as a function of river influence relative to wave-induced longshore transport. In B, the long-term sediment bypass fraction (*β*, solid line) shows a sigmoidal increase with the Sedimentary Index (*Si*), while the total delta sediment trapping fraction (*T*, dashed line) decreases. *Si* represents the ratio of longshore sediment transport at the river mouth(LST, m^3/yr) to river sediment discharge (*Qs*, m^3/yr). Higher *Si* values indicate greater wave energy and alongshore transport relative to river sediment supply. Deltas with multiple active mouths are likely to occupy the left side of the diagram. A potential net long-term trajectory of delta evolution is proposed in A as river influence becomes weakened by a variety of natural (changes in catchment climate and vegetation linked to the LIA, for instance, avulsion) and notably Anthropocene human-induced changes (catchment land-use and reforestation, catchment engineering, dams). For symmetric deltas on the left side of the diagram subject to divergent longshore transport, the trajectory may dominantly involve simple delta-front retreat through redistribution of sediments towards the flanks, leading eventually to delta shoreline straightening and demise of the delta protruberance. The modelling framework in B potentially enables predictory exploration of delta morphsedimentary outcomes in response to human-induced upstream changes in river discharge and sediment flux.

potentially provides for predictive exploration of delta morpho-sedimentary outcomes in response to human-induced upstream changes in river discharge and sediment flux. Besset et al. (2017) have explored changes in delta ‘protrusion angle’ in the Mediterranean associated with shoreline straightening caused by reduction in sediment and water flux.

In increasingly wave-influenced large deltas with two or more distributary mouths, one feedback mechanism, as bedload supply diminishes, is the development of spits with counter-active alongshore bedload-transport cells bounding each individual lobe shoreline between the distributary mouths, a process that can block sediment sharing alongshore (e.g., Anthony, 2015; Anthony et al., 2017). In deltas with a single mouth, eroded sediments are transported alongshore towards the confines of the delta (e.g., Ferreira et al., 2025) with concomitant plan-shape shoreline straightening (Fig. 15). In tide-dominated deltas, as the sediment supply diminishes, enhanced flood asymmetry, associated with deeper, sediment-depleted channels, can lead to upstream sediment pumping and sequestration, a process that can also deprive adjacent muddy coasts of sediment supply (e.g., Anthony et al., 2015), and accelerate the salinization of delta soils (e.g., Rahman et al., 2019; Eslami et al., 2021) especially in the current context of sea-level rise. In an alongshore cascade sequence, the erosion of adjacent coasts can lead to massive sediment accumulation in shallow offshore sediment sinks, as Wei et al. (2025) have shown for the Gulf of Thailand. There is an urgent need to unravel these still poorly understood mechanistic sediment budget links, including the potential role of feedback between the offshore environment, where substantial amounts of delta sediments can be stored, and the subaerial environment where people live (Syvitski et al., 2022a).

While sediment trapping by dams in the global hydrologic north has contributed to global sediment flux declines to 49 % of pre-dam conditions, intensive land-use change, notably driven by mining in the global hydrologic south has increased erosion, with river suspended sediment concentration on average 41 ± 7 % greater than in the 1980s (Dethier et al., 2022, 2023). This north-south divergence is reconfiguring global patterns in fluvial sediment flux to the oceans, with the dominant sources of suspended sediment shifting from Asia to South America (Dethier et al., 2022). Enhanced sediment supply in the global south rejuvenates delta growth and favours avulsions, taking back some deltas to a phase of pronounced aggradation/progradation. Good examples are provided by the island of Madagascar where massive deforestation, to the tune of 44 % between 1953 and 2014, with a notable increase since 2005 (Vieilledent et al., 2018), is leading to the significant growth of deltas (Anthony, 2015; Zăinescu et al., 2023). However, large-scale ongoing and imminent dam projects will impact the stable or increasing sediment fluxes to the ocean from the global south (Dethier et al., 2022). Some Arctic deltas are also still actively prograding, as in Greenland, from sediment supply related to glacial mass loss (Bendixen et al., 2017), but steeply increasing temperatures will expand the open-water season, and increase wave energy threefold by 2100 (Overeem et al., 2022), thus exposing these deltas to marine erosion further exacerbated by permafrost melting.

6. A selection of future geoscience challenges in the human-delta relationship

Important progress in environmental analysis and modelling over the last few decades, dependent in part on massive data generated by remote sensing (from satellites and airborne LiDAR), inform our understanding of how humans have interacted with delta geomorphology and processes, and left their imprint in delta stratigraphy. Remote sensing and geophysical surveying now routinely contribute to geoarchaeological detection and unravelling of ancient human habitation in deltas by geomorphologically structuring otherwise apparently scattered vestiges and artefacts of delta plains. These efforts provide a foundation for a plethora of further investigations using increasingly more sophisticated analyses of sediments, artefacts and organic remains (e.g., Ghoneim et al., 2024). Future progress in retrieval of in-situ data, remote sensing data (Kuenzer et al., 2019) and analysis of ‘landscape heritage’ data (e.g., Brandolini et al., 2021), will be needed to further probe the human imprint on deltas as a foundation towards enhancing solutions of resilience and sustainability (Anthony et al., 2024). Evidence of ancient inhabitance of many tropical deltas, such as in sub-Saharan Africa, may also remain to be discovered, but this may become a race between time and progressive delta demise under sea-level rise induced by climate change and exacerbated subsidence, as reviewed in Section 6.4 below. Among lines of future progress are better resolution of the human-delta relationship in delta sediment mass and stratigraphy, modelling of the human impact on delta sediments and delta-coastline response (Zăinescu et al., 2024), better monitoring of subaqueous delta sedimentation, but also much higher-resolution data on delta elevation (Minderhoud et al., 2019; Seeger et al., 2023) and subsidence (Ohenhen et al., 2025), standardization of datasets and progress on resolution and caution in data analysis and interpretation (Zăinescu et al., 2023; Minderhoud et al., 2025), and the overarching condition of how we tackle the vulnerability of deltas to sea-level rise. These items, discussed in the next sub-sections, are all relevant to a consideration of delta futures. They are preceded by reflections on the time frame of human influence on deltas relative to the geological timescale.

6.1. Comparing the human versus geological time frame in rates of delta change

We note, as a preamble, and to frame the human influence vis-à-vis the geological perspective, that over geological time spans up to tens of millions of years, sedimentary bodies formed by long-lived deltas tend to sink due to compaction and isostasy (under their own weight) and because they occupy negative relief of tectonically subsiding basins (pull down). This intrinsic nature of deltas implies that it is not a matter of *whether* deltas will sink, but more a question of over what time frames. Delta-plain environments are essentially ephemeral at all but human timescales, and even there, with inter-avulsion periods of a few hundred to a few thousand years, civilizations can come and go, as we have shown, depending, for instance, on how delta distributary channels behave, and lobes formed or destroyed. This review focusses on deltas at the human timescale (Holocene-Anthropocene), in the course of which sinking also does occur, as we have shown. Leaving aside the potential, evoked below, for delta submergence due to high-end SLR scenarios in the next two centuries in the absence of climate-change mitigation (affecting Common Era and Anthropocene tracts), the deltaic tracts from the Neolithic and Metal Ages have, in many places, and in just a few millennia, already sunk geologically to depths >5 m. Deltas tracts and date-stamped surfaces will sink and get buried, but their parent delta systems will not truly disappear at the human timescale. The deep strata such as in initial transgressive beds (see Section 2), but also features from younger times formed at depth in channels (thalweg deposits, lower portions of bars within channels) and lake bottoms, and any shallower deposits) that get flooded and sediment-buried (distal wetlands annexed by new avulsions; ditto for anthropogenically-affected sunken land) hold prime preservation potential, although new river or tidal channels created in the course of transforming deltas can cut through them and rework and redistribute the sediment, and many of its essentially non-degradable anthropogenic markers (for the next thousand years into a continued Anthropocene, or in an even longer geological-time future, such as with sea-level fall during the next glacial). For the Rhine delta, separately preserved Last Interglacial strata allow for some long-term quantitative assessment (Peeters et al., 2019). These reflections are not much different from sedimentological thoughts on the preservation of ancient delta deposits: reworking of delta tops renders their preservation rare and fragmentary, reinforced where sea-level fall generates erosion of coastal prisms. Preservation of the superficial, shallowest strata produced in subaerial Holocene-Anthropocene delta-plain environments (naturally ephemerally flooding surfaces and the anthropogenic tract), may be a different matter. Such environments are more exposed to weathering and are the first to erode where storm surges hit, or river floods generate channel shifts, and this includes parts of the anthropogenic tract that are actively protected, maintained, repaired, and sustained by humans over generations. These processes are set to become more parvasive as sea level rises. Humans, as an engineering techno-morphological species, should be more capable of preserving their legacy strata below younger Anthropocene beds over large areas of delta plain surfaces than natural processes could.

In comparing human delta history to earlier and longer geological delta history, one can also bring up an all-embracing assessing question such as: ‘Have anthropogenically-induced changes, perhaps already in the Common Era, but otherwise accelerating greatly into the Anthropocene, happened markedly faster than natural changes affecting deltas before? During the Common Era, as reviewed in Section 3, regional human impacts were of similar magnitude to those attributable to climate variations. In the Anthropocene, the rate of increase of the world’s human population, alongside land-use and eco-system changes driven by a single species, is unprecedented. The rate of increase of greenhouse gasses can be regarded as at a par with that envisaged for the Permian-Triassic extinction event (251.9 Myr ago; with hopefully a less deadly Anthropocene), faster than that of the Cenozoic Paleocene-Eocene Thermal Maximum event (c. 56 Myr ago). More importantly, it is unprecedented in Pleistocene-Holocene geological history (the most relevant geological time period to compare with), and is unprecedented within human history (which is the time frame of our review). Rates of anthropogenically-induced sea-level rise in the Anthropocene are accelerating and scenario-forecast to approach those at the end of the Early Holocene (e.g., Fox-Kemper et al., 2021; Hijma et al., 2025, and many more), when deltas were initiated (Section 2). The rates are slower than those experienced by Lateglacial and Early Holocene drowning river mouths at now offshore inner shelf positions. They are comparable to rates experienced at river mouths early in the Last Interglacial (129–125 kyr ago; e.g. Georgiou et al., 2024). They are slower and less devastating than global tsunami envisaged at the Cretaceous-terminating meteor impact (66 Myr ago; e.g., Smit, 2022). Sediment fluxes mobilized by humans are no less remarkable: regionally already on the rise 1000–2000 years ago, globally markedly increasing from the 19th/20th century onwards, and eventually more than doubling the natural fluxes expected in the Holocene. The rate of river reservoir sequesqtration of sediment just within a century is considerably faster than mountain glacier retreat after the Late Glacial Maximum. These reflections all point out the exceptional anthropogenic influence currently driving deltas and determining their futures.

6.2. High-resolution delta stratigraphy, changes in delta volume, and the subaqueous domain

Deltas are no doubt rich in preserved human artefacts. Future improved tracking of the human-delta relationship in time over the 7000-year panorama requires high-resolution and high-density stratigraphic datasets and innovative analytical approaches of delta sediments that take advantage of the opportunities offered by machine-learning and artificial intelligence (e.g., Wang et al., 2024). Individual deltas being distinct entities, each with unique boundary conditions, future research perspectives should also consider the distinctness of each delta's history of human change and impacts.

In addition to accurate elevation data (provided by lidar technology but satellite imagery resolution is improving), we need to develop modelling frameworks that can use the large datasets to address the issues of changes in delta volume (Syvitski et al., 2022a), and delta morphology such as the afore-mentioned changing shape in response to mouth bypassing under increasing wave control (Zăinescu et al., 2024). As humans have come to dominate the landscapes and dynamics of deltas, notably the large populous deltas of the world, the evolution of the latter is increasingly human-driven through influence on miscellaneous delta-mass components such as virtuous organic matter production through rewilding, mangrove replanting, or reforestation, associated with carbon storage, but also oxidation through soil drainage, with the formation of acid-sulphate soils and release of acid waters, peat mining and polders, and deforestation, with potential effects on carbon release (Anthony et al., 2024). River deltas, as sinks for material from land en route to the oceans, and as areas of exceptional wetland development, play an overarching role in the global carbon cycle (Bianchi and Allison, 2009; Mcleod et al., 2009). Much of the carbon sequestration is offshore in the prodelta, as the sediments are often anoxic. In the terrestrial delta, carbon oxidation is more common. Also, coastal erosion and sediment recycling by tides and waves in the submarine environment can enable the release of sequestered carbon (Wei et al., 2025). These authors have estimated that the destabilization of muddy mangrove coasts caused by erosion processes, especially in sediment-deficient deltas, accelerates organic carbon decomposition and release. Extrapolating these findings globally for the entire coast, Wei et al. (2025) estimate a global carbon release of ~175 Tg/yr. Deltas subjected to high energy conditions and erosion might be less of a carbon bank than quieter systems. The burning of peats under tropical swamp forests such as mangroves can also generate large carbon releases (e.g., Sasmito et al., 2025).

Other impacts are caused by engineering, groundwater mining, sand and gravel mining, clay extraction, and anthropogenic infrastructure, all of which also exacerbate subsidence (Ohenhen et al., 2025) and surface deformation in growing megacities that can also be exposed to, among other hazards, earthquake deformation, the weight of monsoon floods or the effects of droughts in terms of unloading and drying. A new generation of models, such as the CASCADE (catchment sediment connectivity and delivery) (Schmitt et al., 2016) and the NATSUB3D (coupled sedimentation-compaction) (Zoccarato and Teatini, 2017; Xotta et al., 2022), are advancing process-based modelling of multi-grain-size sediment transport in rivers and entire basins as well as dynamic deltaic volume change following sedimentation-compaction processes. Building on an initial 2D transect application (Zoccarato et al., 2018), a recent application of data-driven, numerical modelling of delta growth and spatio-temporal sedimentation and compaction of the Mekong delta during the last 4000 years (Late Holocene) showcased the first application of this new generation of numerical models to a real-world delta (Baldan et al., 2025). It provides unprecedented 4D insight on sediment deposition and historical (auto)compaction, which may aid the prediction and prospecting (e.g., predicting contemporary depths of buried delta surfaces) of archaeological artefacts locked within the sinking palaeodeposits. In addition, the application of such models unlocks valuable follow-up applications, e.g., evaluation of sediment restoration and sedimentation-enhancing strategies and sediment-based nature-based solutions in deltaic landscapes prone to (auto)compaction. When properly coupled to basin/catchment models, the applications provide promising tools enabling process-based, basin-delta integrated quantifications and projections of deltaic volume change and evolution (Schmitt and Minderhoud, 2023), supporting delta management from an integrated systems perspective which considers all relevant drivers (Eslami et al., 2025).

We also need to improve our knowledge of the delta sediment mass in the subaqueous domain where large amounts of sediments, archives of environmental change (Bianchi and Allison, 2009), are commonly stored (Syvitski et al., 2022a). The expanding anthropogenic tract generally impedes delta-plain sedimentation through engineering control structures such as dikes, notably in small to medium-sized deltas, increasingly forcing the storage of incoming sediments within the subaqueous delta (e.g., Garcés et al., 2023). Shoreline erosion may have a similar subaqueous storage effect. Wei et al. (2025) show that as deltas located on the Gulf of Thailand coast (notably the Mekong) become deprived of sediment, the exacerbated erosion of adjacent coasts, especially from mangrove areas, is leading to significant accumulation of sediments in nearshore areas. We still know little about the sediments and stratigraphy of the subaqueous parts of deltas. Both the Yellow (Zhu et al., 2024) and Yangtze (Yang et al., 2025b) subaqueos deltas are now undergoing erosion due to fluvial sediment shortage.

Deltas are collectively a major Earth sediment sink. A fundamental question therefore concerns the effects of delta sediment load changes on continental margin geological (e.g., volcanic activity) and sea-level feedbacks, hence providing a link between local (river basin-delta) processes and global regulation (Anthony et al., 2024). Even with >2000 years of investigations since Herodotus first defined deltas from the Nile example, it seems like our voyage of discovery on delta geoscience has just begun (Syvitski et al., 2022a). But this discovery will now increasingly be dominated by the need to unravel the impact of humans on the past and future of the world's deltas as the Anthropocene potentially leads us headlong towards their large-scale decline and demise (Anthony et al., 2024).

6.3. Bridging the gap in understanding the human-delta relationship between the pre-Anthropocene and the Anthropocene

Authoritative compiled spatial datasets that would enable us to bridge the delta evolutionary trajectories throughout the Neolithic, Bronze and Iron Ages, the CE, and into the Anthropocene would be particularly useful. In practice, this is lacking. Research groups contributing to unravelling the human-delta relationship in the pre-Anthropocene phases tend to generate stand-alone datasets, also because when it comes to incorporating pre-satellite era data/information there is not really a shared subsuming platform. Also, although there are notable compilation products from other disciplines that are quite useful, these are rather ill-used in the delta community. There is a 'data' community for the satellite-era and present global Anthropocene. Helmer et al. (2023) highlighted, for instance, the abundant and under-utilized archaeological data generated by regulatory cultural resource surveys over the past 50 years in the Mississippi delta. Mehta et al. (2025) have called for a merger of archaeology, environmental science, and land management, in order to address dramatic losses to biocultural resources, notably in the context of sea-level rise. Another hurdle lies in the difficulty of integrating delta/coastal plain research conducted notably by coastline-focused researchers with inland delta data to generate more complete databases. Focused coastline satellite-era data and modelling approaches risk neglecting the often longer and more sustained history of humans in these inland areas, and risk over-simplifying the causation of trends observed in morphologically more-rapidly changing river-mouth and beach and barrier coastline sections. But the same problem also exists the other way round! It is only through common ground in datasets (and data quality control) that unravelling target questions in the 7000-year human-delta relationship can be fully adressed and the inherent problems ordered/separated, and analyzed through integrated modelling, and each properly explored and adressed in the future.

6.4. The future: humans and sustainable deltas in the face of sea-level rise?

An alarming situation concerns the increasing exposure of deltas to global sea-level rise under the ongoing continuous reduction of their sediment budget (Anthony et al., 2024) and exacerbated subsidence (Ohenhen et al., 2025). The relatively large amount of sediment stored in a delta's mass can, in theory, probably cope with lower-end scenarios of climate-induced sea-level rise through in-situ sediment redistribution mechanisms, including delayed backstepping of shorelines over the delta surface, and up-channel reinjection of suspension load in large tidal deltas (e.g., Anthony et al., 2015)) – on condition that the mobility of river mouths, delta plains and coastal uses engendered by the system shifts generated by these processes are acceptable to, and accommodated by, humans. These changes would imply a decline of both subaerial and subaqueous delta plain area, and, from a geoscience perspective, a turnaround to the ancestral delta initiation maximum flooding phase (Fig. 4Ai) from which many deltas have long moved out by virtue of global relative sea-level stability and sustained sediment supply. Wu et al. (2025b) analyzed temporal and spatial variations in $^{210}Pb_{ex}$ profile styles, and discrepancies between ^{210}Pb and ^{137}Cs sediment accumulation rates as proxies for the identification of the onset of erosion of the subaqueous Changjiang (Yangtze) delta front shortly after 2003 in the wake of the commissioning of the Three-Gorges dam. The profiles show erosion spreading gradually onto the deeper prodelta and distal mud. Some small deltas such as the Magra in Italy, deprived of much of their sediment through anthropogenic extractions over the last 140 years, appear to be reverting to a the ancestral estuarine state (Pratellesi et al., 2018) that characterized river mouths prior to about 8000 yr BP.

Without climate stabilization, an extreme SLR scenario (rising to and > 2 m) over the next two centuries and beyond makes progressive delta drowning likely (Anthony et al., 2024). Furthermore, subsidence in deltas has been recognized as a significant factor for some time (Syvitski et al., 2009; Nicholls et al., 2021). The high rates of subsidence observed at high accuracy and unprecedented spatial resolution by Ohenhen et al. (2025) demonstrate that contemporary subsidence surpasses absolute sea-level rise as the dominant driver of relative sea-level rise for most deltas in the 21st century. This emphasizes the need to address both human-induced subsidence as an immediate and localized but widespread challenge, and to deploy broader efforts to adapt to climate change-driven global sea-level at the same time. Maintaining sustainable deltas will, thus, require not only climate stabilization without further delay, but also a stronger action and control on human-induced subsidence, and consideration of delta morphodynamics and all the sedimentary processes, including how humans can influence them in beneficial ways in a systems perspective bridging sub-national to global scales (Schmitt and Minderhoud, 2023; Eslami et al., 2025). One potentially significant solution to the sediment shortage has been the artificial release of sediment from dams (e.g., Rhône delta: Besset et al., 2017; Yellow River delta: Wu et al., 2022) or sediment diversions in sediment-restoration efforts (e.g., Mississippi delta: Paola et al., 2011; Nittrouer et al., 2012). Artificial floods in the Yellow River since 2003 have led to successful sediment delivery to the delta, but a viable sediment management approach requires targetting vulnerable eroding areas in this large and morphologically diversified delta (Ji et al., 2025). Another perspective consists in resorting less to the widespread use of large dead storages (the portion of the reservoirs that cannot be emptied) in dam designs, and the design of smaller dead storages to alleviate sediment starvation in deltas downstream (Chua et al., 2024). On a few small catchments, dams have even been removed, reactivating delta sediment supply (e.g., Warrick et al., 2015), but this, like the creation of river channel rerouting that eventually circumvents dams, is an unlikely scenario for the medium and large deltas considered in this paper. Another solution consists in the strategic deployment of sedimentation-enhancing strategies (Dunn et al., 2023), although the effectiveness of such strategies is delta-specific and requires quantitative assessments of contributing elevation change drivers, as demonstrated for the Mekong delta (Dunn and Minderhoud, 2022). The multi-pronged problem of sediment supply to deltas as well as the internal sediment budget clearly require a comprehensive and sustainable catchment-scale source-to-delta sediment management approach (Anthony et al., 2024). Although the focus in this review is on the geoscience dimension of the human-delta relationship, the goal of having resilient deltas will require robust delta management, per se, that should be based on coordination involving society, science and politics involving, among others, the building of equitable partnerships in deltas through initiatives such as living deltas (e.g., the Living Deltas Hub, https://livingdeltas.org/).

Without this suite of radical measures, the subaqueous portions of individual deltas will probably become increasingly larger than the human-inhabited subaerial portions as large parts of the latter are drowned by relative sea-level rise. The turnaround to global erosion and drowning of deltas and the concomitant delta area loss are expected to degrade the high values of their ecosystem goods and services (Osland et al., 2022; Day et al., 2024), which is unlikely to be an option consistent with sustainable human occupation of deltas. This rather gloomy future scenario of delta erosion and drowning will not only endanger human endeavour but also geoarchaeological and cultural evidence of human presence (e.g., Helmer et al., 2023; Jones et al., 2024; Mehta et al., 2025), including the scope for a better understanding of how ancient urbanization was guided by delta environmental diversity (e.g., McMahon et al., 2023).

We anticipate that the human response to progressive delta drowning will revolve initially around continued upgraded protection in the near term, a tension discussed previously (Anthony et al., 2024). Such human intervention will almost certainly continue especially where people are concentrated - around cities and urban areas (Lincke and Hinkel, 2021; Ballesteros et al., 2025). However, protection also means that deltas will receive no new sediment inputs to counter subsidence and sea-level rise, all of which will cause progressive loss of delta elevation relative to local sea level, and the consequences of defence failure will become increasingly catastrophic. Hurricane Katrina and the flooding of New Orleans in 2005 and the examples in this paper would be illustrative examples. Hallegatte et al. (2013) discussed the prospect of fewer, but bigger flood disasters under a global protection scenario for the world's coastal cities. This raises fundamental adaptation challenges which we are only beginning to recognize. Within deltas, sea-level rise could impose untenable conditions from both environmental and economic standpoints for human occupation, leading to global-scale human retreat from deltas. This scenario would effectively terminate the 7000 year-long mutual relationship of humans with deltas as we know and live it today, and establish a future of living with drowning and drowned deltas (and new estuaries) (Anthony et al., 2024) with new difficulties for stratigraphical exploration. We could temper this rather sombre picture by hoping that in the distant future, sunken marine deltas could offer a new positive relationship with humans - in terms of new marine ecosystems, marine resource exploitation, and marine parks, for instance.

7. Conclusions

Identifying the relationship between humans and delta geoscience over the last 7000 years enhances our understanding of past geomorphic and sedimentary trajectories, as well as the varying scales of human versus natural modification across time and regions. From timid incursions into deltas, and steered by delta geomorphology and processes, human occupation and exploitation expanded and became consolidated as deltas grew seaward and widened under the influence of sediment supply. Settlements in deltas formed foundations for many of the world's oldest city states, followed by thousands of years of increasingly human-altered and managed deltas that went apace with significant urban and engineering transformations of Old-World deltas, and widespread human occupation of New-World deltas. Deltas represent thus a fine example of the concept of co-evolution of a coupled human-natural system. Deciphering this relationship sheds light on how past human activities have influenced delta sedimentation, stratigraphy and geomorphology, but also how changing delta environments determined pathways of socio-cultural development and urbanization. Probing the human-delta relationship has also enabled us to gauge the constraints and technological challenges involved in extracting data on preserved human artefacts in deltas, and in gauging spatial and temporal variability in the pace of human mediation of delta development. Exploringing this relationship holds value in terms of identifying the connections between delta geoscience and cultural diversity, and highlights how present human activities are creating a future trajectory for many of the world's deltas that is likely to be perilous. Intensive human occupation, exploitation and alteration of delta functioning, and failing river sediment supplies, are generating significant hurdles in the sustainability of many of the world's deltas. Recognition of the way human activities have modified deltas, intentionally or not, and increasingly with unexpected consequences and accelerated delta vulnerability, and anticipating these adverse effects, help bring a range of geoscience perspectives that inform delta management and adaptation, and should contribute to a better understanding of the future fate of deltas worldwide, particularly as to whether their anticipated drowning, due to sea level steadily rising, is inevitable. Saving the world's deltas will require new forms of catchment-to-delta management involving a closer relationship between society, science, and politics.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

No data was used for the research described in the article.

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