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Challenging reconstruction of the plurimillennial morphodynamics of hybrid urban deltas: Trajectory from a wave-dominated delta to a human-dominated delta in the Western Mediterranean area

Ferréol Salomon [a,*], Ada Lasheras González [c], Patricia Terrado Ortuño [b], Josep-Maria Macias-Solé [c], Kristian Strutt [d], Pierre-Alexis Herrault [a], Peter R. Morgan [e], Simon Keay [d,†]

[a] Laboratoire Image Ville Environnement (UMR 7362), Centre National de la Recherche Scientifique (CNRS) and Université de Strasbourg, 3 Rue de L'Argonne, 67000 Strasbourg, France
[b] Universitat Rovira i Virgili, Av. Catalunya, 35, 43002 Tarragona, Spain
[c] ICAC - Institut Català d'Arqueologia Clàssica, Pl. Rovellat, 43003 Tarragona, Spain
[d] Department of Archaeology, School of Humanities, University of Southampton, Avenue Campus, Southampton SO17 1BF, UK
[e] School of Geography and Environmental Science, University of Southampton, Building 44, University Road, Southampton SO17 1BJ, UK

A R T I C L E I N F O

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A B S T R A C T

The reconstruction of the human impacts on the morphodynamics of river deltas in the long term is challenging. The ternary diagram of Galloway (1975) used to classify morphodynamics of deltas does not include direct human influence which is now affecting most of the deltas of the world. The study of human-dominated deltas requires specific approaches and consideration of human processes and morphologies in interaction with more commonly studied natural processes and morphologies. This study demonstrates how to combine different datasets from natural and social sciences to reconstruct long term temporal trajectories of hybrid urban deltas. The Francolí delta, associated with the UNESCO city of Tarragona, offers a perfect case study to identify the different steps of a wave-dominated delta leading to a human-dominated delta over a long-term perspective. Tarragona emerged in the 1st millennium BCE and became a significant port city in the Roman period. This study identifies the evidence of a semi-protected harbour built 2000 years ago that initiates the evolution of a hybrid urban delta towards a human-dominated delta. Until the end 19th c. CE, cyclical changes at the river mouth are observed due to natural fluvial and coastal dynamics while progradation stages are partly affected by anthropogenic structures over time. The 19th c. CE is a major turning point. Morphodynamics controlled by anthropogenic factors strongly increase while fluvial and coastal sedimentation is partly erased by dredgings. The systematic approach proposed for the Francolí delta can be standardised and applied to other hybrid urban deltas allowing better comparison between urbanised deltas.

1. Introduction

Between land and sea, river deltas are dynamic geomorphological features sensitive to climate change affecting river and coastal systems and to land cover evolutions in their upstream catchments. Generally, delta morphologies are explained by the interplay and the relative importance of three forces: rivers, waves and tides (Wright and Coleman, 1973; Galloway, 1975). Nevertheless, human activities constitute the fourth factor affecting deltas. The impacts of human activity has increased and diversified since the Neolithic revolution and the initiation of the current deltaic plain ar. 6500 years ago (Bianchi, 2016). Today, human societies strongly affect most of the deltas around the world (Nicholls et al., 2020).

Similar to river deltas, maritime port cities are also located at the land-sea interface. They are involved in changing economic networks across time (Ducruet et al., 2018) and vulnerable to a large range of hazards especially when located in deltaic areas (Tessler et al., 2015). In this paper we focus on hybrid urban deltas that are the result of

* Corresponding author.
E-mail addresses: ferreol.salomon@live-cnrs.unistra.fr (F. Salomon), alasheras@icac.cat (A.L. González), patricia.terrado@urv.cat (P.T. Ortuño), jmmacias@icac.cat (J.-M. Macias-Solé), K.D.Strutt@soton.ac.uk (K. Strutt), pierre-alexis.herrault@live-cnrs.unistra.fr (P.-A. Herrault), P.R.Morgan@soton.ac.uk (P.R. Morgan).
† Deceased.

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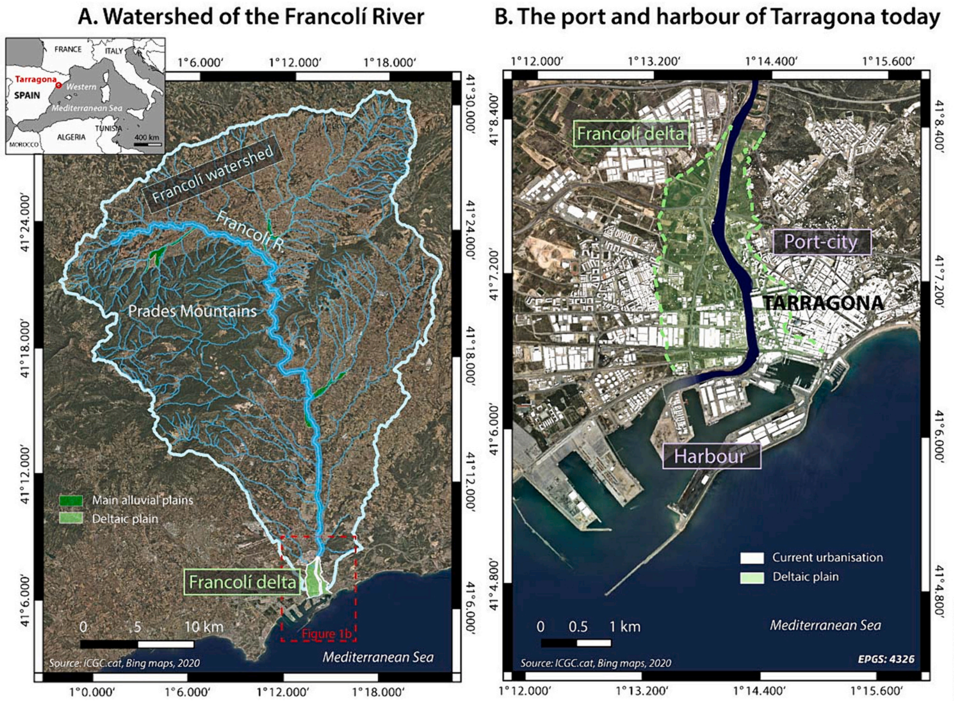

Fig. 1. Location map of the study area. (A) Watershed of the Francolí River; (B) Port and harbour of Tarragona today.

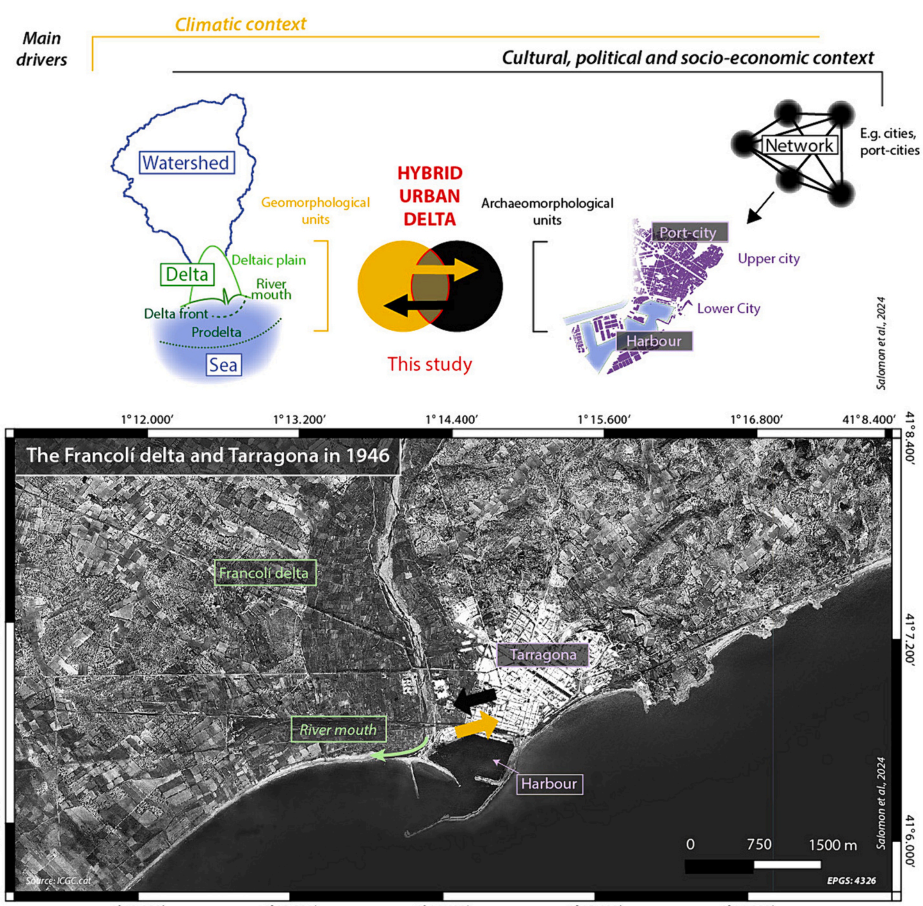

Fig. 2. Geomorphological and archaeomorphological units considered in this paper. This figure demonstrates how the concept of *hybrid urban delta* is applied to the case of the Francolí-Tarragona system.

interactive deltaic and port systems. This dual aspect makes hybrid urban deltas particularly exposed to quick climate and socio-economic changes. Their study in a long-term perspective tells us about both natural and urban systems dynamics and highlights the respective role of the natural and the human factors in their evolution. However, standardised methods and systematic approaches are still lacking to produce comparable data between different disciplines, different periods and different hybrid urban deltas.

The Francolí-Tarragona system is an ideal case study to test a methodology to reconstruct the evolution of a hybrid urban delta (Fig. 1). Tarragona and its harbour have a remarkable longevity. Founded in the 1st millennium BCE, Tarragona became an important port city along the Mediterranean coast of the Iberian Peninsula during the Roman period and is still an important harbour in Modern Spain. In addition, the deltaic plain of the Francolí is relatively small with ca. 8 km^2 and the city of Tarragona has always been a city of regional importance since the Roman period. Consequently, human and natural processes might have been alternatively dominant through time or at least were closely related. Today, small deltas are more controlled by engineering than large deltas (Besset et al., 2019), and this was also true in the past (Anthony et al., 2014; Goiran et al., 2015; Giaime et al., 2019).

In this paper, we propose methods and visualisation tools to reconstruct the evolution of the Francolí river delta and the port city of Tarragona at millennial and centennial timescales (Fig. 2) using a geoarchaeological (Goiran and Morhange, 2003; Marriner and Morhange, 2007; Salomon et al., 2016) and a geohistorical approach (Jacob-Rousseau, 2009; Valette and Carozza, 2019; Piovan, 2020) (Fig. 3). The aim is to intersect different sets of data based on different data sources in order to build a coherent reconstruction of the evolution of the Francolí urban delta. Morphological analyses are conducted on the urban fabric of the Roman and current city of Tarragona (Figs. 3 and 4). New cores drilled between Tarragona and the river mouth of the Francolí are studied and interpreted using a Palaeoenvironmental Age-Depth Model - PADM chart (Salomon et al., 2016) (Figs. 5, 6, 7 and 8). Ancient maps are compiled and georeferenced when possible to reconstruct the evolution of the hybrid urban delta between the 16th and the 19th century CE (Fig. 9). All data are visualised in interdisciplinary timelines to better reconstruct the intertwined temporal trajectories of the Francolí delta and port city of Tarragona (Figs. 10 and 11). Some processes and morphologies typical of hybrid urban delta landscape and seascape are outlined (Figs. 12, 13 and 14). Finally, conceptual models are proposed to integrate different aspects of hybrid urban deltas (Fig. 15).

Fig. 2 clarifies the elements defining a hybrid urban delta in this study. A hybrid urban delta includes geomorphological units classically associated with river deltas (deltaic plain, river mouth, delta front, prodelta) and archaeomorphological units (e.g., anthropogenic morphologies associated here with the city-port and the harbour). The aerial photography dated to 1946 clearly shows the interrelations of the city and the harbour of Tarragona with the morphologies of the Francolí delta. Fig. 2 also simplifies the two different systems affecting hybrid urban deltas. First, a river delta is part of a source-to-sink continuum and shaped by continental and marine dynamics. Second, a port city is integrated into a wider network of cities. In addition, each system is also dependent on the climatic, cultural, political and socio-economic contexts. A hybrid urban delta can only be understood by considering all of these natural and anthropic aspects.

2. Geographical, archaeological and historical context

2.1. Geomorphological and hydrological context: the watershed, the delta, the river mouth, and the bay

The Francolí River is a relatively short river of 59 km starting in the Prades Mountains at 412 m above sea level (Fig. 1). It drains a watershed of 853 km^2 with an annual mean precipitation of 525 mm. The Francolí river ends in a small delta (ca. 8 km^2) with irregular water and sedimentary inputs (Fig. 1). The annual water discharge at Tarragona is around 1.20m^3/s but the channel is generally dry in summer. By contrast, during flash flood events, large water and sediment inputs to the delta occur. It should be noted that due to its long dry periods and its flashfloods, the Francolí river is not navigable.

Research scholars from Catalonia developed detailed studies on the flood records based on historical documents (Sánchez, 1981; Llasat et al., 2005; Barriendos et al., 2014; Barriendos and Martin-Vide, 1998; Alberola et al., 2016). They record high frequency of catastrophic flood events during the last centuries (1580–1620, 1760–1800, 1840–1880). Over the last 3 millennia, dated gravel facies from alluvial plains across Spain recorded hydroclimatic crises in the first part of the 1st millennium BCE, in the 3rd-2nd centuries BCE, between the 9th and the 11th century CE and from the 14th to the 16th century CE (Thorndycraft and Benito, 2006; Wolf and Faust, 2015; Walsh et al., 2019).

Unfortunately, no detailed study focused on the evolution of the land use in the watershed of the Francolí. The closest pollen records are located at Cubelles along the coast (Riera-Mora and Esteban-Amat, 1994) and at the Estanya lake, inland, towards the north (Riera et al., 2004). These studies show that woodland clearance is observed during the Roman period together with fire signatures based on charcoal counts. This signature is more visible near Cubelles than in other pollen analyses from the northern coast of Catalonia. In the 1st millennium BCE to the 1st millennium CE, there is a change from deciduous to sclerophyllous communities, revealing drier conditions and/or human impacts. During the medieval period and the last centuries higher charcoal content suggest local and regional fire increase. During the same period, sedimentation rate is also increasing at Cubelles suggesting a correlation between more frequent fires and erosion (Riera-Mora and Esteban-Amat, 1994). From the medieval period, more grazing areas are hypothesised along the coast including damp pasture but also inland (Pyrenees: Burjachs 1990 and Montserrat, 1992) possibly related to transhumance. In parallel, pollen analyses record development of grapes (13th c. CE) and then *Olea*. Agricultural activities in the hinterland decreased in the second part of the 14th c. CE. The crisis lasted until 1650 CE. In the second part of the 17th c. CE, the hinterland is affected by increasing agricultural production and large deforestation. The 19th c. CE is characterised by the expansion of olive and wine production until the spread of the Phylloxera (1895).

Along the coast of Tarragona, the littoral drift is oriented from North to South and sediments accumulate against built structures or capes. Tidal changes are only within the range of 0.2–0.30 cm. During the last 30 years the sea level rise gauge at L'Estartit in Northern Catalonia recorded a rise of 2.5 to 3.5 mm/years (1990–2014) (Salat et al., 2019), which correlates well with modelled data for the Mediterranean (Schuckmann et al., 2018). A model for sea level change for the last 12,000 years, was proposed in Vacchi et al. (2016) for this area based on data from the Ebro and Llobregat deltas, the Cubelles coastal plain, the beachrocks from the Costa Brava, and archaeological data from Empúries. The data from Cubelles were the closest available sea level indicators to Tarragona, and reveal a relative sea level at -1.2 ± 1.2 m at ca. 4000 cal. BP.

Coastal risks include storms that affect the harbour of Tarragona, especially when coming from the south (Jiménez et al., 2012). In studying ancient texts related to the coast of Barcelona, Camuffo et al. (2000) proposed a chronology of the frequency of storms for the last six centuries. More storms seem to have occurred in the 15th century, the end of the 17th century, the first half of the 18th century, and at the end of the 18th century CE. For the last millennia, precise datasets regarding storms are available for the area to the north of the study area. This includes datasets from the Palavasian lagoon (Sabatier et al., 2012) and the Bagnas lagoon (Degeai et al., 2015) in southern France, and from the Mar Menor lagoon in south eastern Spain (Dezileau et al., 2016). A regional synthesis for the Western Mediterranean and Europe was proposed by Degeai et al. (2015). Periods of higher storm activity are observed in the 2nd millennium BCE, the 7th – 6th century BCE, the 2nd – 9th century CE especially between the 5th and the 8th century CE. The last period of storminess is identified between the 13th and 19th century CE.

Morphologically, the fluvial delta of the deltaic plain of the Francolí is larger than the progradational coastal plain. Initially a wave dominated delta, it is now largely urbanised (Gracia et al., 2011). The river is canalised in the deltaic plain before ending in the harbour basin of Tarragona.

2.2. Archaeological, historical and geographical context: the port city and the harbour

The first settlement identified archaeologically in Tarragona dates to the 6th century BCE (Adserias et al., 1993; Asensio et al., 2001). During the Second Punic War (218–201 BCE), Publius Scipio came to Tarragona and formed his headquarters at the top of the hill north of the Iberian settlement (Livy, 21, 60; Arbulo, 2014). The Roman fortress of Tarragona was located at the top of a north-south hill located between the Francolí delta and the sea. With a maximum height of 80 m a.s.l. to the north, the hill offers a low slope towards the south. Before the harbour transformations that occurred during the last two centuries, this hill ended in the sea forming a small headland towards the south-east. Citing Eratosthenes living in the 3rd century BCE / early 2nd century BCE, Strabo indicates that Tarragona had a roadstead at the end of the 3rd century BCE (*naustathmos*). By that period, a harbour for fishing boats already existed and hosted war ships of Publius Scipio (Livy, 26, 45; Polybius, 3, 76). The city grew from the 3rd century BCE onwards under Roman influence. Urban planning seems to have been organised circa 100 BCE (Macias et al., 1997). Strabo reports that the place was "not particularly blessed even with places of anchorage" (*ankryobolion*) based on a text from Artemidorus writing around 100 BCE (Strabo 3, 4, 7). At least two centuries ago, a small sandy cove existed south of Tarragona between the headland and the river mouth of the Francolí. Hypotheses suggest that the Roman harbour of Tarragona was located in this area (Terrado, 2018a).

The city became particularly important during the Augustan period when it became a Provincial Capital. Then on, important buildings were built until the 2nd century CE, especially in the Upper City but not only: The Provincial Forum, the Circus, the Amphitheatre and the Theatre (Macias and Rodà, 2015) (Fig. 4). According to Strabo (3, 4, 7) writing at the end of the 1st century BCE/beginning of the 1st century CE, Tarragona had no harbour (*alimenos*). Based on literary sources and a large amount of archaeological data, the history of the harbour of Tarragona has been recently updated by two PhD theses (Lasheras, 2018; Terrado, 2018a). They suggest that the jetty observed in maps and described by modern authors was more likely built in the 1st century CE (Fig. 4). Mainly a military harbour during the Republican period, it is also proposed that the harbour became a commercial harbour during the Imperial period (Lasheras and Terrado, 2018). *Horrea* were also built towards the river mouth during the early empire. Today, Tarragona is a UNESCO site for its well-preserved Roman remains located in and around the city.

After a decline starting at the end of the 2nd century CE and continuing during the 3rd and 4th century CE, new urban developments were observed in the port area in the Late 4th and 5th century CE (Lasheras, 2018). Houses, warehouses, and workshops were then built close to the river mouth of the Francolí along with a large necropolis and basilicas just to the north along the Francolí channel (Macias and Remolà, 2005) (Fig. 4). The Visigothic kingdom succeeded the Roman period of settlement during Late Antiquity and the Early Medieval period (Late 5th – Early 8th century CE). Tarragona was still a dynamic port city (Rodríguez et al., 2020). The Umayyad conquest of the city occurred in 713 CE. Subsequently, Tarragona's economic and strategic roles decreased in this border area between al-Andalus and the County of Barcelona, and Tarragona turned into a small town or a village (Guidi, 2016).

From the 12th century CE, documentary evidence elaborates on the evolution of Tarragona, which by then had been conquered by the Crown of Aragon. According to al-Idrīsī (1100–1165), the city had a good harbour at that time (Bramon, 2000). Afterwards, Tarragona developed around two nuclei, the Upper City, in the standing walls of the Roman city, and the Lower City around the harbour (Guidi, 2016). Harbour infrastructure also took a long time to develop. The construction of a new mole was authorised in 1484 by Ferdinand II of Aragon and the construction started in 1495 (Alemany et al., 1986) (Fig. 9, maps in Section 2). Details of the construction of the mole (for example duration and technique) are not known. However, the mole was probably affected by natural hazards since it was also repaired in 1621 (Terrado, 2018a). In 1644 the mole was bombed during the Reaper's war, and reconstruction not undertaken for some time after. The population of the area of Tarragona rose gradually during the 16th century but was strongly affected by the Reaper's war. The growth of Tarragona and its neighbouring region only started in the 17th century onwards (Moreno-Almárcegui et al., 2016). In 1773, a request to reconstruct the harbour was sent to the King Charles IV of Spain. The actual reconstruction started >20 years later. The mole called *Dique de Llevant* was built over the previous mole in the 1790s after the maps from Juan Ruiz de Apodaca (1786) (Escoda, 2002). A city wall was also built in the Lower City during this period (Virgili, 2014). In the first years of the 19th century CE, a new planned Lower City was built, replacing gardens and fishermen houses. The harbour infrastructure develop during the 19th c. until the harbour offers a fully protected harbour with large quays and an access channel through an Outer harbour. The city is also growing until the Upper and Lower city reunites in a continuous urbanisation in the second part of the 19th century CE. The growth of the harbour and the city continued until now affecting largely the Francolí delta (Figs. 1 and 2).

3. Methodology

In this paper, the methodology follows the three steps presented in Fig. 3: (1) identification of the geo- and archaeomorphologies; (2) reconstruction of the evolution of these morphologies using sedimentary cores and maps; and (3) reconstruction of the temporal trajectories of the geo- and archaeomorphologies.

Conducting geoarchaeological investigations in an old and dense urban area is particularly challenging and needs a specific approach. The best location for the geoarchaeological cores depends on a detailed reconstruction of the geo- and archaeomorphologies. Geomorphologies (e.g., strandlines, palaeochannels, palaeolagoons) are mostly hidden below thick accumulation of urban layers and visible archaeomorphologies (e.g., archaeological structures from different periods) mainly dating back to the last two centuries. Since the coastal area of the small delta of the Francolí was densely urbanised since the beginning of the 19th century, we also used old maps from the 18th century and earlier to identify palaeomorphologies. Importantly, updated syntheses of the old maps of Tarragona were recently published (Terrado, 2018a, 2018b, 2021). We georeferenced some 18th and 19th c. maps but georeferencing older maps produced too many errors and only a descriptive approach was possible. In this context, only rescue archaeology offers detailed spatial and chronological reconstruction of ancient urbanisation. Discoveries are made infrequently and rely on opportunities related to urban renewals. Fortunately, Tarragona is one of the best known Roman sites associated with an existing city (Macias et al., 2007; Lasheras et al., 2019).

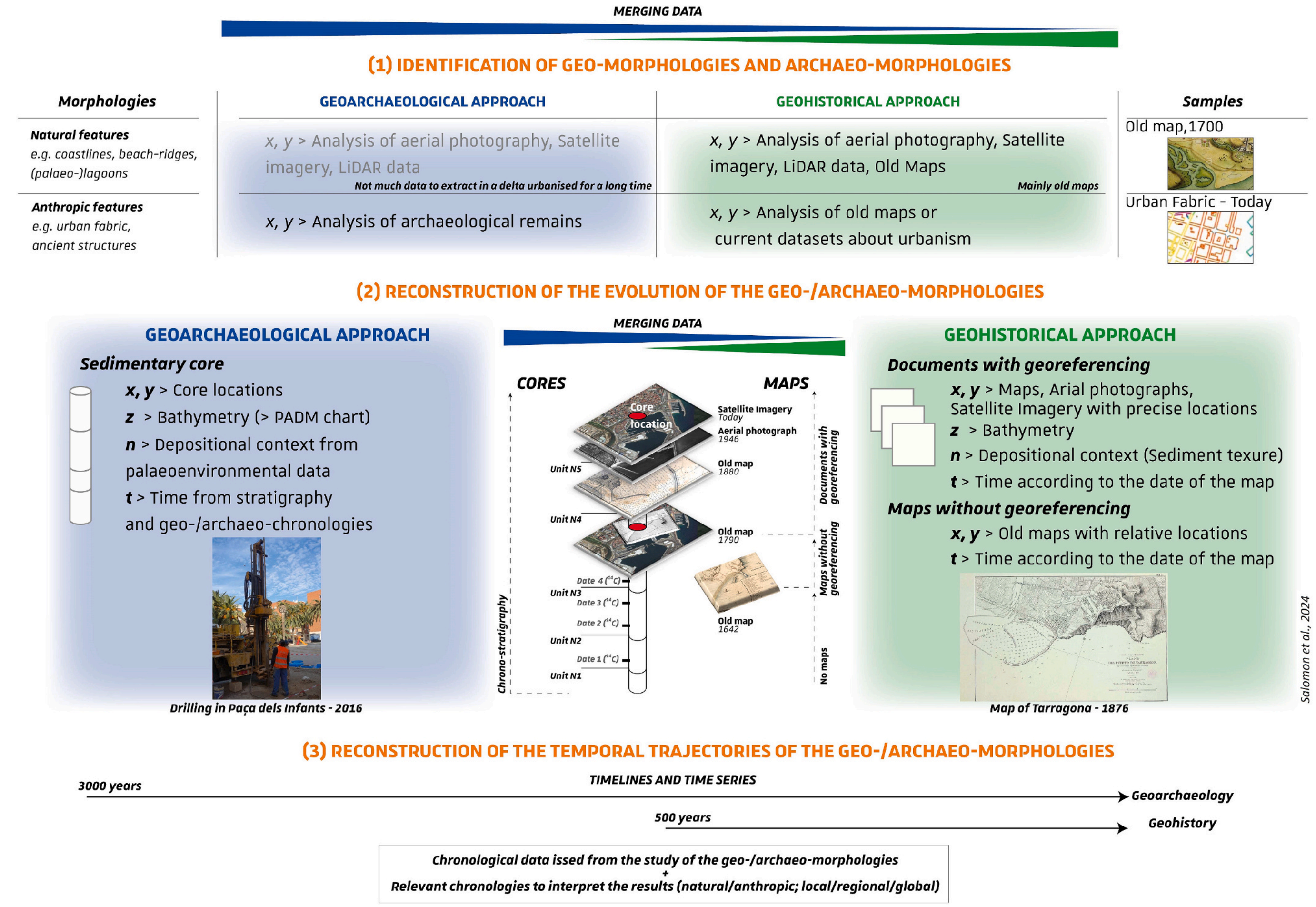

Fig. 3. Methodology followed in this paper to conduct the long-term study of a hybrid urban delta.

3.1. *Identification of the urban delta morphologies*

3.1.1. *Analysis of the urban fabric*

The analysis of the urban fabric of a deltaic city is very important for geoarchaeological studies (Salomon et al., 2018). We analyse two datasets. First, all archaeological structures excavated in Tarragona from the Roman period until Late Antiquity (including the Visigothic kingdom) were brought together (3rd century BCE to the 8th century CE). This work is based on the synthesis mapped and published in Macias et al. (2007). We added to the GIS layers new discoveries made along the coast towards the river mouth (Díaz and Roig, 2016). Second, we used the buildings of Tarragona mapped in OpenStreet map. Data were download the 11/09/2020. In order to have a comparable dataset in the two maps, we only used the layers of built structures. These analyses of the urban fabrics aim to identify any persistence of orientations over the last 2000 years in the Upper and Lower City and to test the relationship between coastlines and waterfronts.

Considering the existence of a curved wall in the spatial dataset, we split polylines into segments. We calculated the orientations using a field calculator in QGIS. Orientations are represented in different colours using a simple discretisation (every 10° from 0 to 180°). Orientations separated by 90° are represented with darker or lighter variations of the same colour. Rose diagrams present the results of the analyses. These diagrams were built using "Line direction diagram", a QGIS Python Plugin proposed by H. Tveite in 2015 (The QGIS Line Direction Histogram Plugin: https://plugins.qgis.org/plugins/LineDirectionHistogram/). We generated three rose diagrams each for the ancient and the present urban fabrics: the Upper City, the Lower City and the river or deltaic city. Due to their curved shape, the theatre and the amphitheatre were not included in the rose diagrams.

3.1.2. *Ancient maps analysis*

The database was built on several syntheses of old maps of Tarragona drawn between the 16th century and the beginning of the 19th century (Terrado, 2018a, 2018b, 2021) (Supplementary material). Most of these representations of Tarragona or maps cannot be georeferenced due to the poor quality of the geometry (especially before 1750). We used them to observe two elements: the presence or absence of the possible Roman jetty, and the presence or absence of an indentation of the coastline in place of this jetty. We used these indicators to reconstruct possible coastline mobility. Maps of the 19th century were georeferenced in order to identify changes regarding the jetty at its correct spatial location (Supplementary material).

3.2. *Long-term evolution of the Francolí-Tarragona system*

3.2.1. *Core drilling*

Between October and December 2015, two cores were drilled in the Lower City of Tarragona. The main objective was to identify deposits from the Roman period to the present and interpret them in terms of deltaic changes and harbour potential. According to archaeological structures and ancient maps from the 16th to the 19th century CE, the main Roman harbour basin was located below the Lower City (Table 1 and Fig. 4). Core TAR-1 was drilled in *Plaça dels Infants*, south of the last Roman structures identified by archaeological excavations and north of the potential Roman jetty described in ancient texts and maps (Macias and Remolà, 2005; Macias et al., 2007; Terrado, 2018a). Core TAR-2 was drilled on the *Moll de la Costa* between two old warehouses close

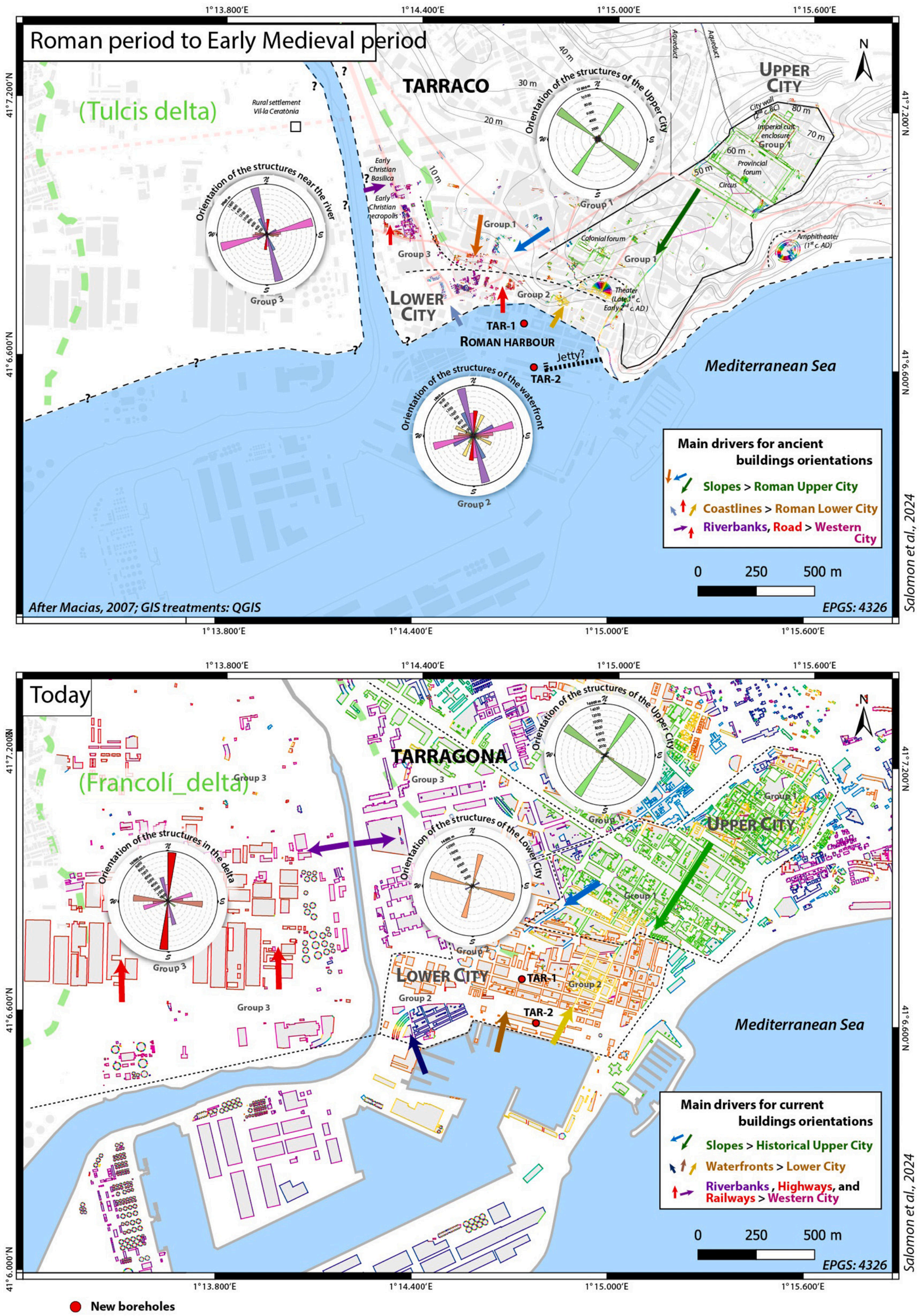

Fig. 4. Analyses of the urban fabrics during the Roman period and Late Antiquity (above) and today (below). These correspond to an analysis of the orientation of the structures of each period. Slopes, coastlines, riverbanks and roads are the main drivers of the orientation of the anthropogenic structures during Antiquity. Similar drivers are observed today together with newly built railways and highways.

to the possible Roman jetty identified on the old maps. Due to the difficulty of extracting non-cohesive sands in Core TAR-2 between 7.50 and 11 m below surface, a twin core TAR-2 BIS was drilled a few metres away from TAR-2 to extract material at these depths (Table 1). Sampling resolution remains low between 7.50 and 9.00 m b.s. but bulk samples of very well sorted sands were extracted.

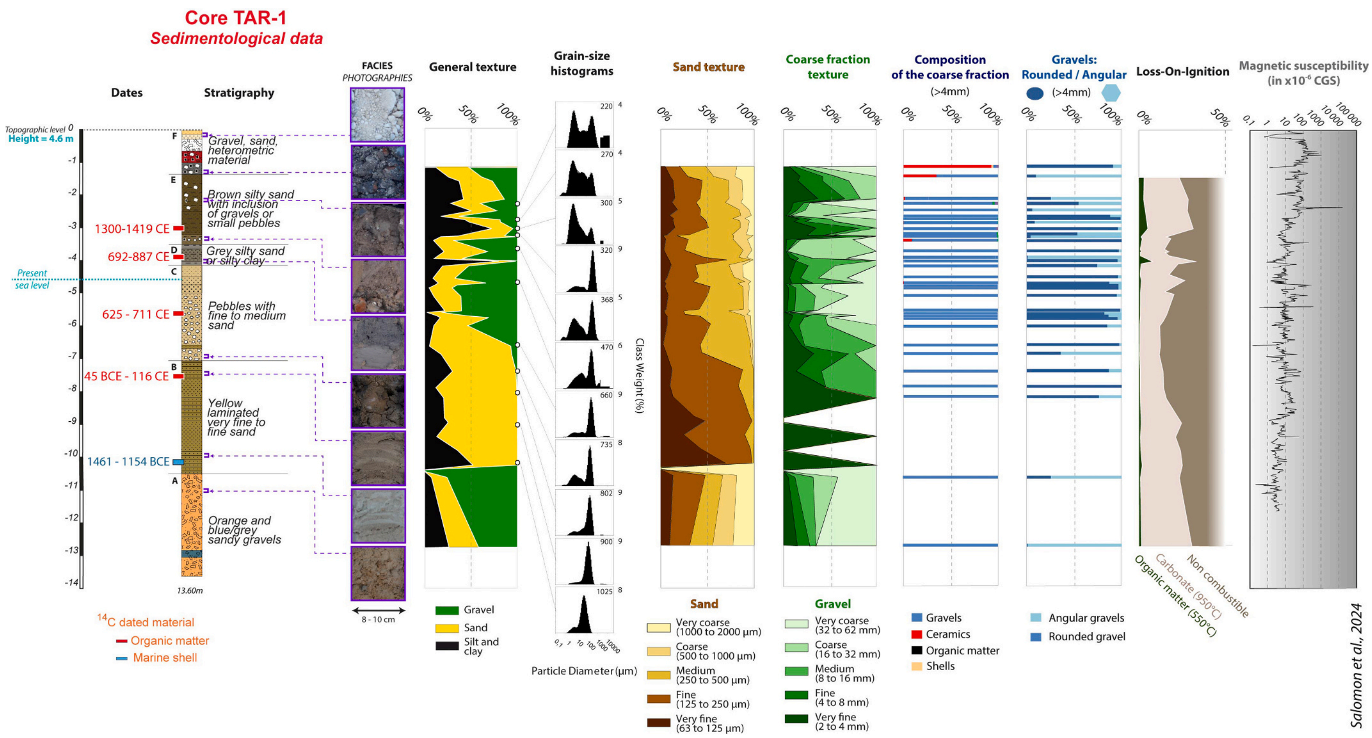

Fig. 5. Analysis of Core TAR-1 – Sedimentological data.

3.2.2. Palaeoenvironmental analyses

Palaeoenvironmental analyses were conducted at the School of Geography and Environmental Science of the University of Southampton. Magnetic susceptibility was measured on the cores before sampling. Measurements were undertaken at 10 mm intervals using a Bartington MS2E1 (Dearing, 1999). Magnetic susceptibility results were used to determine the limit of the different stratigraphical units. Wet sieving was performed to measure the relative content of coarse material (> 2 mm), sand (2 mm to 63 µm) and silt/clay (< 63 µm). More detailed results were obtained also within the sands (sieves at 63, 125, 250, 500 µm and 1 mm) and the coarse fraction (sieves at 2, 4, 8, 16, 32 and 64 mm). For the coarse fraction above 4 mm, the composition was analysed in detail and expressed in percentage (weights of gravels, ceramics, organic matter and shells). Additionally, we characterised the roundness of the gravels. In Core TAR-2, more detailed measurements of the <2 mm fraction were executed using a Malvern Mastersizer 3000 (laser grain size). Complementary information about the palaeoenvironmental context was obtained by loss-of-ignition tests. Ten grams of dry sediment under 2 mm were placed successively at 550 °C (2 h) to measure the organic content and at 950 °C (4 h) to measure the carbonate content (Heiri et al., 2001).

Malacofauna was mostly observed in Core TAR-2. Species identification was based on D'Angelo and Gargiullo (1978), Doneddu and Trainito (2010), and Cossignani and Ardovini (2011) and the online database WoRMS (World Register of Marine Species). Biocenotic environments of the different species are based on Perès and Picard (1964) and Bellan-Santini et al. (1994).

Five radiocarbon dates were performed on Core TAR-1 and eight radiocarbon dates on Core TAR-2. These dates were performed by Beta Analytic (3 dates) and in the context of the *Artemis Project* - Centre de Datation par le RadioCarbone (UMR-5138) in Lyon and Laboratoire de mesure du carbone 14 (LMC14 - UMS 2572) in Saclay (10 dates). As a priority, we selected continental material to perform the dates (e.g., charcoal, seeds). This was only possible for the upper part of Core TAR-1 and in a sample at the base of Core TAR-2. We calibrated continental material with IntCal2020 (Reimer et al., 2020). All other dates were performed on *Posidonia* sp. fibers or shells and calibrated with Marine20 (Heaton et al., 2020).

3.2.3. PADM chart

The *Palaeoenvironmental Age-Depth Model* (PADM) is an interpretative chart to better understand stratigraphies in their environmental, archaeological and historical contexts. Based on a classic age-depth model, it integrates all relevant data to better interpret the sedimentation curve (e.g., reconstructed local relative sea level curve, stratigraphical units, historical and archaeological events). It was first applied to better interpret the stratigraphies from ancient harbours (Salomon et al., 2016) but it also demonstrated high potential to interpret deltaic stratigraphic successions (Salomon et al., 2020). In Tarragona, the two cores were drilled in very dynamic fluvio-coastal contexts affected by high human impacts (e.g., harbour constructions and dredging in the Roman, medieval, and modern periods), which means that hiatus are expected in the stratigraphies. In consequence, a combination of the stratigraphical data, palaeoenvironmental analyses, and the radiocarbon dates using the PADM chart was essential to reconstruct the sedimentation curve.

3.3. Temporal trajectory of the hybrid urban delta: towards interdisciplinary timelines

The strength of the PADM chart is to show the different steps of the construction of the chronology issued from the stratigraphy. However, previous publications did not explore the potential of using the chronologies issued from the PADM chart (Salomon et al., 2016, 2020). In order to interpret the chronologies generated by the PADM charts, we selected different timelines and time series issued from different kinds of sources. We looked for four kinds of indicators: (1) urban growth, population, or economic dynamics of the port city of Tarragona or its territory; (2) main events that possibly affected the harbour and its maintenance (e.g., political changes, wars, mole construction, restoration or destruction); (3) palaeoflood records; and (4) palaeostorm records. The data from texts and old maps regarding the harbour and the

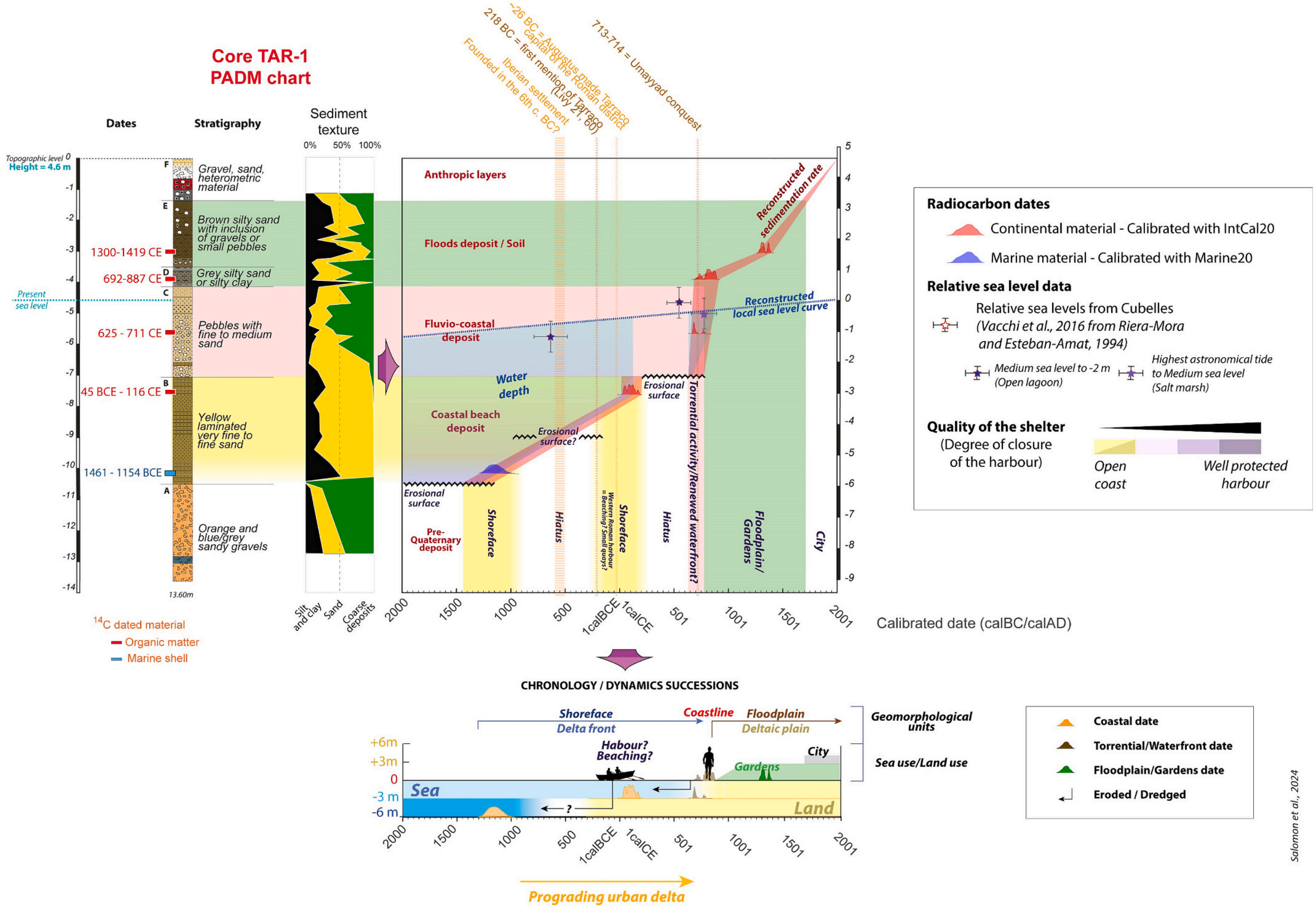

Fig. 6. Palaeoenvironmental Age-Depth Model (PADM chart) of Core TAR-1. A comprehensive chronology of the core is extracted from this chart and is integrated with the synchronised chronologies in Fig. 10.

river mouth of the Francolí are put into perspective using chronological series of the population of Camp de Tarragona, wars, palaeofloods and palaeostorms.

4. Results

4.1.1. *The Urban fabric*

From the Roman period to the Early Middle Ages, the city of Tarragona developed in two main areas: (1) between the Upper City and the Roman harbour, and (2) between the rocky promontory south-east of Tarragona and the Francolí channel (Fig. 4). Additionally, we identified three distinct areas according to the orientations: Group 1 - the hill of the Upper City; Group 2 - the deltaic plain from the rocky promontory to the Francolí river mouth (e.g., around the Roman harbour, the Lower City); Group 3 - the deltaic plain along the Francolí river. The circles of the rose diagrams correspond to accumulated lengths in metres of the line segments for each direction. The high length values are due to the sum of the distance from each individual segment issued from the split polylines (Fig. 4).

Group 1. - Most of the Late Republican *cardines* of the Upper City of Tarragona are aligned on a NNE orientation (light green at 31 ± 4° and dark green at 121 ± 4° on the rose diagram of the Upper City in Fig. 4). On the acropolis, the orientation of the *Concilium Provinciae* enclosure and the Circus, both dated to the Flavian period, are slightly different (still light green at 34 ± 4° and dark green at 124 ± 4°) (Macias et al., 2007 in the Fig. 20 of that publication). In the south-west of the hill, structures present an orientation of 58 / 148 ± 5° (blue), and then 10 / 100 ± 10° (red-brown).

Group 2. - Around the Roman harbour basin, orientation of the structures change gradually from 29 / 119 ± 3° towards the rocky promontory (yellow) to 63 / 153 ± 3° towards the river mouth (blue).

Group 3. - Along the Francolí river channel, most of the buildings are following an orientation of 73 / 163 ± 3° (purple) but also building 10 / 100 ± 10° (red-brown).

Today, the entire studied area is urbanised with a higher urban density in the old city centre (Upper City). This urban density decreases towards the deltaic plain in the east occupied by the Francolí Industrial Park *(Polígon industrial del Francolí)*. While their extent differs from the Roman and Early Medieval periods, the three groups still remain (Upper City, Lower City, deltaic plain along the Francolí).

Group 1. – The Upper City follows an orientation of 31–34 / 121–124 ± 3° (green) similar to the structures of the Roman period.

Group 2. – The Lower City presents three different sub-groups. The main group is 15 / 105 ± 3° (orange), in which is located the yellow group (25 / 115 ± 3°). The third group near the river mouth is 65 / 155 ± 3° (blue).

Group 3. – Two sub-groups characterise the orientation of the structures in the deltaic plain along the Francolí river channel. To the east, structures are 80 / 170 ± 3° (purple) and to the West, structures are (0 / 90 ± 1° (red/brown)).

While no geomorphological features were observed in the deltaic plain due to the dense and ancient urbanisation, archaeological structures delimit a small cove to the south traditionally interpreted as the Roman harbour basin (Fig. 4A, Group 2). Cores TAR-1 and TAR-2 were drilled within this cove.

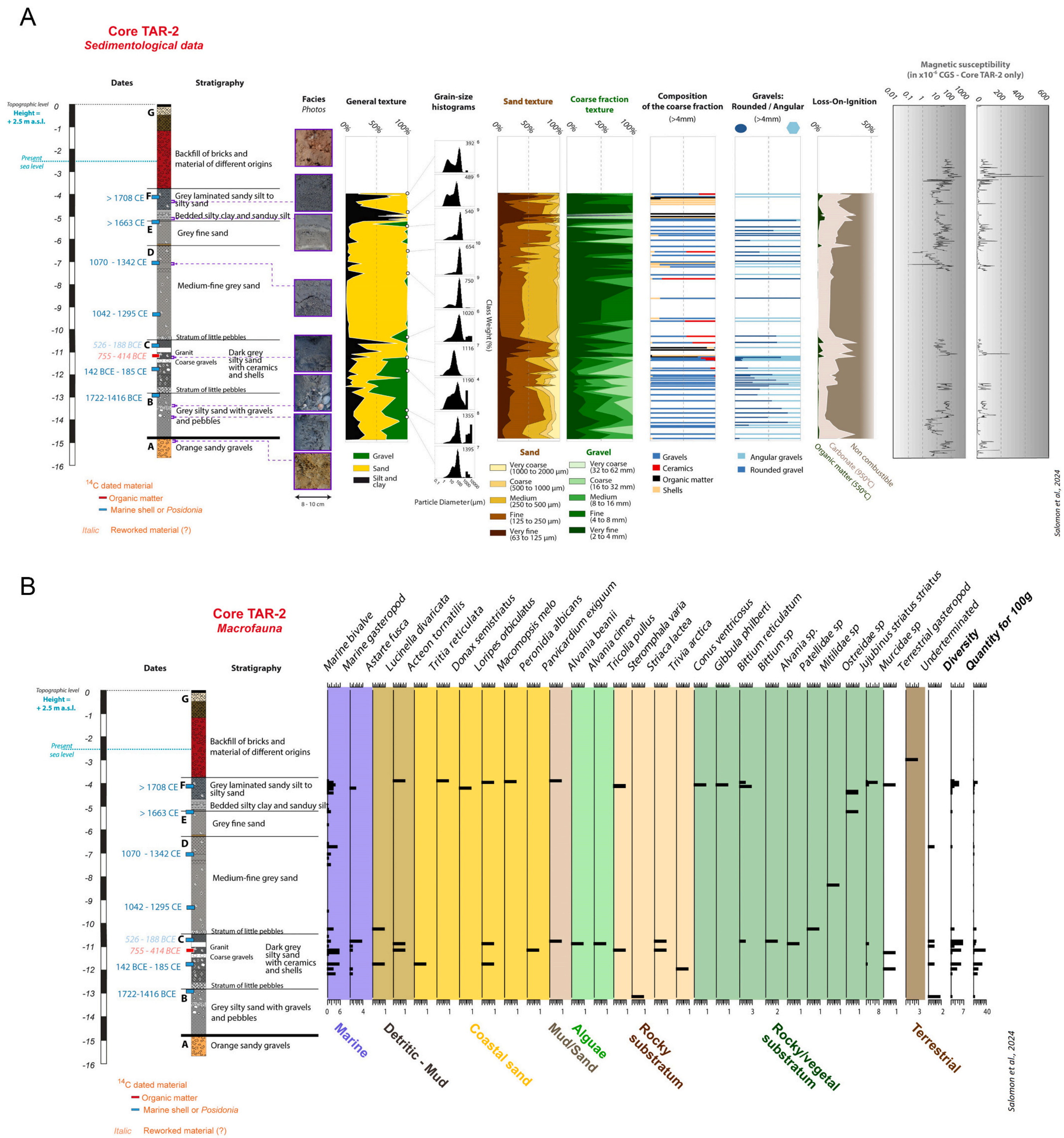

Fig. 7. A. Analysis of Core TAR-2 – Sedimentological data.
B. Analysis of Core TAR-2 – Macrofauna.

4.1.2. *Old maps*

Over the 45 documents ranging from 1563 to 1880, 12 maps show the possible Roman jetty, 14 maps show a bump along the coastline, 22 maps do not show any specific feature. Among the maps with positive results, 3 depict both the jetty and the coastline increment. The maps with both of these characteristics are only dated after the mid-18th century This can be due to the growing attention paid to the details and the better quality of the cartographic record. It suggests that the coastal indentation is closely related to the possible Roman jetty.

In Fig. 9, georeferenced maps from 1790 to 1827 demonstrate that a salient coastal indentation visible in 1803 and 1813 corresponds to the accumulation of sand along the coast that cover the possible Roman jetty observed before in 1790 and after in 1827. These changes confirm the thoughts of Remolà (2007) interpreting the view of the bay of Tarragona drawn by Anton van Wyngaerde in 1563. He suggested that the Roman jetty was covered by large amount of sediments at that time. In a map dated to 1816 (*Plano y vista de Tarragona*, F.B.C.T.C.), the Roman jetty is actually represented below the beach and below the city (Fig. 12). In the

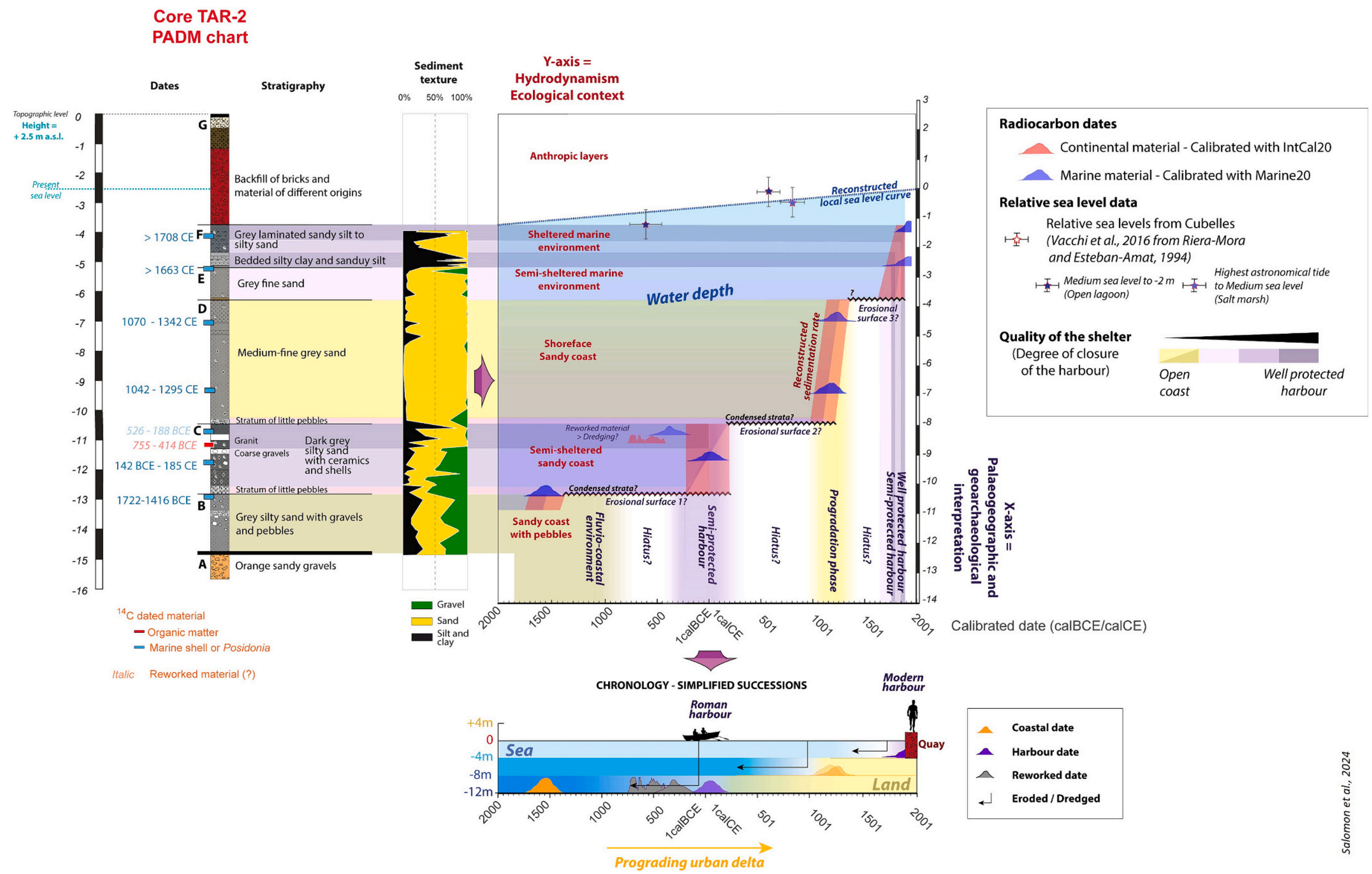

Fig. 8. Palaeoenvironmental Age-Depth Model (PADM chart) of Core TAR-2. A comprehensive chronology of the core is extracted from this chart and is integrated to the synchronised chronologies in Fig. 10.

Table 1
Sedimentary cores.

Core	X	Y	Coordinate Reference System	Z	Depth below surface (m)	Comments
TAR-1	138,628.237	5,028,815.226	WGS 84 Pseudo-Mercator	4.60 m	13.60	–
TAR-2	138,712.513	5,028,564.088	EPSG:3857	2.50 m	15.90	Missing part between 7.50 and 11 m b.s.
TAR-2 (BIS)	138,709.384	5,028,565.280		2.50 m	6 to 13.80	This core was used to complete the stratigraphy between 7.50 and 11 m b.s. in Core TAR-2

second part of the 19th century, the coastline indentation is no longer visible probably affected by the work conducted by Ciriaco Muller to remove part of the Roman jetty. Only a small indentation can be observed in the bathymetric data.

4.1.3. *Analysis of Core TAR-1 and Core TAR-2*

Core TAR-1 is located at the foot of a hill that hosted a small fortress before the mid-19th century (*Fortí Reial* – north of the current Doctor Zamenhoff street) (Fig. 4, Table 1). Fig. 5 presents chronostratigraphy of Core TAR-1 and the different sedimentological indicators measured. Macrofauna are observed in this core but shells are really fragmented and not possible to identify.

Unit A (13.60 to 10.50 m b.s. - *below surface* / 9 to 5.90 m b.s.l. - *below current sea level*). – This unit is composed of orange to blue grey sandy gravels.

Unit B (10.50 to 7.10 m b.s. / 5.90 to 2.50 m a.s.l. – *above current sea level*). – Unit B is composed of yellow laminated silts and very fine to fine sands. Scarce pebbles can be found. The proportion of very fine sand decreases towards the top of this unit while the proportion of fine sand increases. Carbonate content decreases also from the base (avg. = 23 %) to the top (avg. = 14 %) of the unit. The organic matter content remains low (avg. = 1.1 %). Scarce pebbles are observed in the upper part of Unit B. The lower part of the unit was dated with a marine shell found at 5.65 b.s.l. The shell is dated to the end of the 1st millennium BCE (1461–1154 BCE). A charcoal from the upper part of this sandy unit (3.08 m b.s.l.) was dated to the Roman period (45 BCE-116 CE) (Table 2).

Unit C (7.10 to 4.10 m b.s. / 2.50 b.s.l. to 0.50 m a.s.l. – *above current sea level*). – This unit records pebbles with fine to medium sand. Sand is dominant at the base of the unit while gravel content increases towards the top of this unit. Following this trend, coarse to very coarse sand increases together with coarse to very coarse gravels. Pebbles are dominant in the gravel fraction. By contrast to Unit B, carbonate content increases from the base (avg. 12 %) to the top of this unit (avg. = 18 %). A charcoal found at -1 m b.s.l. was dated to the Early Medieval period (610–773 CE) (Table 2).

Unit D (4.10 to 3.50 m b.s. / 0.50 to 1.10 m a.s.l.) – Unit D is located just above the current sea level. It is composed of grey silty sand and silty

Table 2
Radiocarbon dates – Materials in red are calibrated with the IntCal20 curve from Reimer et al. (2020) – Materials in blue and with an asterisk are calibrated with the Marine20 curve from Heaton et al. (2020).

Core	Sample	Depth below surface (m)	Depth below sea level	Lab. sample	Dating support	^{14}C yr B. P.	±	Age calibrated BCE-CE - 2σ
TAR-1 (+4.60 m)	TAR-1 / 311	3.11	+1.49	Lyon-14114 (SacA49756)	Charcoal	580	30	1305–1419 CE
TAR-1	TAR-1 / 390–400	3.95	+0.65	Lyon-14113 (SacA49755)	Charcoal	1220	30	687 to 888 CE
TAR-1	TAR-1 / 520–600	5.60	−1.00	Lyon-14,116 (SacA49758)	Charcoal	1355	30	610–773 CE
TAR-1	TAR-1 / 768	7.68	−3.08	Lyon-14115 (Sac49757)	Charcoal	1990	30	45 BCE-116 CE
TAR-1	TAR-1 / 1025	10.25	−5.65	Beta-485557	*Shells**	3540	30	*1461–1154 BCE**
TAR-2 (+2.50 m)	TAR-1 / 401–403	4.02	−1.52	Lyon-14117 (SacA49759)	*Posidonia**	505	30	*> 1708 CE**
TAR-2	TAR-2 / 5.16–5.18	5.17	−2.56	Lyon-14120 (SacA49762)	*Shell**	575	30	*> 1663 CE**
TAR-2 (BIS)	TAR-2(BIS) /700–710	7.05	−4.55	Lyon-14119 (SacA49761)	*Shell**	1335	30	*1070–1342 CE**
TAR-2 (BIS)	TAR-2(BIS) / 950	9.50	−7.00	Beta-4855555	*Shells**	1390	30	*1042–1295 CE**
TAR-2 (BIS)	TAR-2(BIS) / 1090–1095	10.925	−8.43	Lyon-14118 (SacA49760)	*Posidonia**	2760	30	*526–188 BCE**
TAR-2	TAR-2 / 1120	11.20	−8.70	Lyon-14122 (SacA49764)	Seeds	2455	30	755–414 BCE
TAR-2	TAR-2 / 1170–1190	11.80	−9.30	Lyon-14121 (SacA49763)	*Shell**	2455	30	*142 BCE-185 CE**
TAR-2	TAR-2 / 1300	13.00	−10.50	Beta-485556	*Shells**	3750	30	*1722–1416 BCE**

clay. The organic content rises to an average of 2.2 %. Similar to Unit C, a charcoal extracted from Unit D (0.65 m a.s.l.) date from the Early Medieval period (687 to 888 CE) (Table 2).

Unit E (3.50 to 1.30 m b.s. / 1.10 to 3.30 m a.s.l.) – Unit E presents deposits of brown silty sands with inclusion of gravels and small pebbles. First ceramics in this core are observed at the base of this layer and the proportion of ceramics in the coarse fraction (> 4 mm) increases from the base to the top of the unit. Gravels are mostly angular. The organic matter content reaches an average of 3 %, which is the highest value measured of the core. The carbonate content continues to rise compared to the three units below, and reaches an average of 21.3 %. The lower part of this unit (1.49 m a.s.l.) dates to the Late Medieval period (1305–1419 CE) (Table 2).

Unit F (1.30 m to 0 m b.s. / 3.30 to 4.60 m a.s.l.) – Finally, Unit F is composed of gravels, sands and heterometric materials. No analysis was conducted on these anthropogenic layers. Large archaeological excavations would be required to make sense of these deposits.

Core TAR-2 is located on the *Moll de la Costa* between the two long buildings along the railways (the western building is now the museum of the port) (Fig. 4, Table 1). Fig. 7.1 and .2 present the chronostratigraphy of Core TAR-1, the different sedimentological indicators measured and the macrofauna identified.

Unit A (15.90 m to 14.86 m b.s. / 13.40 to 12.36 m b.s.l.) – Orange sandy gravels with clayey silts and pebbles.

Unit B (14.86 m to 12.67 m b.s. / 12.36 to 10.17 m b.s.l.) – Grey silty sand with some shell inclusion in the upper part and small pebbles. By contrast to Core TAR-1, most of the radiocarbon dates performed in Core TAR-2 are based on marine shell material. A shell from the upper part of this layer (10.50 m b.s.l.) was dated with radiocarbon technique to the middle of the 2nd millennium BCE (1722–1416 BCE) (Table 2).

Unit C (12.67 m to 10.55 m b.s. / 10.17 to 8.05 m b.s.l.) – Dark grey silty sand with ceramics and shells. The base is marked by a stratum of small centimetric pebbles. A large piece of granite was drilled in the upper part of this unit. Ceramics are from the Roman period. Unfortunately, they could not be identified precisely considering their state of conservation (rounded or small fragments). A large diversity of marine macrofauna was identified in this layer including species living in detritic muddy environments (*Astrate fusca, Lucinella divaricata*) and coastal sands (*Axteon tornatilis, Loripes orbiculatus*), or alguae (*Alvania beanii, Alvania cimex*). Mainly from the upper part of this layer, species living in rocky substratum (*Tricolia pullus, Striaca lacteal, Trivia arctica*) to rocky – vegetal substratum (*Bittium reticulatum, Alvania* sp., *Jujubinus striatus*) were observed. In order to better date this unit, different materials were dated (marine shell, *Posidonia* sp. and seeds). The lower date performed in this unit on a marine shell (9.30 m b.s.l.) is matching the Roman period (142 BCE-185 CE) (Table 2). The two other dates above conducted on seeds at 8.70 m b.s.l. (755–414 BCE) and on *Posidonia* sp. at 8.43 m b.s.l. (526–188 BCE) are from earlier periods from the 1st millennium BCE.

Unit D (10.55 m to 6.14 m b.s. / 8.05 to 3.64 m b.s.l.) – Medium fine grey sand. The base is characterised by well sorted small pebbles. Most of the shell fragments were found in the upper part of this layer. Unfortunately, the fragment does not allow any clear identification. Two marine shells are dated in Unit D at 7.00 m and 4.55 m b.s.l. and both date to the 11th-14th century CE (Table 2).

Unit E (6.14 m to 5.10 m b.s. / 3.64 to 2.60 m b.s.l.) – Medium-fine grey sand with *Ostreidae* sp. Small rounded gravels were also observed.

Unit F (5.10 m to 3.88 m b.s. / 2.60 to 1.38 m b.s.l.) – The lower part of this unit is composed of bedded silty clay and sand, the upper part is composed of grey laminated sandy silt. Together with Unit C, Unit F contains shells reflecting large ecological range from detritic muddy environments (*Lucinella divaricata*), coastal sands (*Tritia reticulata, Donax semistriatus, Loripes orbiculatus, Macomopsis melo*), rocky substratum (*Tricolia pullus*) to rocky – vegetal substratum (*Conus ventricosus, Gibbula philberti, Bittium reticulatum, Ostreidae* sp., *Jujubinus striatus*).

Unit G (3.88 m to 0 m b.s. / 1.38 b.s.l. to 2.50 m a.s.l.) – This unit is mainly composed of bricks and coarse material of different type.

5. Discussion (1): the river delta, the harbour and the city

5.1. The river delta – dynamics of Francolí river delta affected by human activities

Units A in Cores TAR-1 and TAR-2 correspond to Early-Middle Pleistocene alluvial deposits (Vilà et al., 2016) (Figs. 6 and 8). The lower part of Unit B in Core TAR-1 and Unit B in Core TAR-2 are dated to the 2nd millennium BCE, before the development of an important settlement in Tarragona in the middle of the 1st millennium BCE. The deposit in Core TAR-2 / Unit B presents grey silty sands and inputs of small pebbles, coming either from the Francolí delta or from the hill of Tarragona. It corresponds to deposits from the lower part of the delta front trapping fluvial pebbles deposited by powerful flash floods. By contrast, Core TAR-1 / Unit B shows yellow laminated fine sands characteristic of a delta front facies. These coastal sands were probably reworked between the second part of the 2nd millennium BCE at the base and the Roman period at the top of the unit (45 BCE-116 CE). However, it is difficult to identify if these erosional surfaces are from natural or even anthropogenic origins linked to dredging activities during the Roman period. The absence of lamination could be indicative of erosional phases along the coast but the structure could have possibly disappeared during the drilling procedure. Loose sandy material is often difficult to extract from the ground. The two cores suggest that a sandy coast started to develop south of the hill of Tarragona in at least the 2nd millennium BCE. Only the upper part of TAR-2/Unit B was possible to date. This development of the delta front most probably relates to one or more progradation phases of the Francolí delta during the 2nd millennium BCE. Other coasts of the Western Mediterranean also record important progradation phases in the 2nd millennium BCE (Zazo et al., 1994; Vella et al., 2005; Somoza and Rodríguez-Santalla, 2014). Climatic factors are generally considered to trigger progradation phases during this period but archaeological and palynological data record increasing human impacts in the watersheds that could also have been affecting the sedimentation at the river mouths (Riera-Mora and Esteban-Amat, 1994; Carrión et al., 2007; Pérez-Obiol et al., 2011; Azuara et al., 2020).

The upper part of TAR-1/Unit B and TAR-2/Unit C are dated to the Roman period. The range of the radiocarbon dates extends from the 3rd century BCE to the 2nd century CE. Regarding the upper part of TAR-1/ Unit B dated to 45 BCE-116 CE, the facies is similar to deeper and older deposits from the 2nd millennium BCE in the same unit. An open sea coastal beach existed along the coast during this long period. Evidence from Core TAR-2 / Unit C confirms the existence of a Roman harbour (*see below*). Most of the sedimentary data from the 1st millennium BCE are missing. Only reworked material from this period is recorded in Core TAR-2 / Unit C possibly due to dredging activities (*see below* and in Morhange and Marriner, 2010). Several strata of small pebbles are observed in Unit B, C and D. They could represent either flash flood events or condensed strata. In this last case, they would be the result of erosional phases removing sandy particles and leaving pebbles in their place. The pebble layer in Unit B can be interpreted either way. However, the pebble layers at the base of Unit C and Unit D are most likely condensed strata. They are boundaries between different environments.

The progradational coastline of the Francolí delta reached first Core TAR-1 located landwards. It happened between the 7th and the 9th century CE. Almost 2 m of pebbles with fine to medium sands fill the shoreface (Unit C). If we consider natural factors, this deposit probably settled in one main event or during several events in a short period of time. In urban context, this could also be related to dumped material associated to human management of the land-sea interface. More cores or an excavation would be necessary to solve this issue. The area of Core TAR-2 turns into land much later in the 1880s. A backfill of bricks and material from different origins compose Unit G. According to georeferenced old maps and texts from the 19th century this was related to the construction of the *Muelle de Costa*, a new dock built between the railways and the harbour. In a hybrid urban delta perspective, this can be called an anthropogenic coastal progradation (Brandolini et al., 2020).

5.2. The river delta – successive erosional and progradational phases

Between the Roman period (Unit C) and the 1880s (Unit G), Core TAR-2 revealed two periods of sedimentation (Fig. 7). First, on top of the Roman Unit C, an almost 4 m-thick layer composed of well sorted fine to medium sand is deposited between the 11th and the 14th century CE. Second, grey fine sand (Unit E) to grey laminated sandy silts (Unit F) are deposited between the 17th century and the 1880s. CE. A condensed stratum of small pebbles is recorded at the base of Unit D (*see discussion above*). An erosional surface probably also exists at the base of Unit E where a brown layer of silty sand is observed. In the PADM charts (Figs. 6 and 8), we propose stepped sedimentation curves for TAR-1 and TAR2 with a quick succession of depositional events separated by erosional phases. The age-depth model of Core TAR-2 provides more evidence about these steps (Fig. 8). This interpretation of the cores is also based on the analyses of the old maps. Fig. 9 displays all evidence suggesting successions of depositional and erosional phases across time. Age-depth models, here from Core-TAR-2 on the left, records these successions over the last millennia. In the middle of Fig. 9, georeferenced maps from the 16th to the 18th century display moments when the coast erodes (Roman jetty visible) and when the coast progrades (Roman jetty not visible with a bump on the coastline). On the right of Fig. 9, maps from 1790 to 1827, show clearly that the coast south of Tarragona is experiencing quick succession of progradational and erosional phases. This period is also very well known in terms of historical records of hazards. Several flash floods were recorded in Tarragona at the end of the 18th century CE. These flash floods brought a large amount of sediment to the coast. These fluvial sediments were reworked by the sea, and particles contributed to fill the area around the Roman jetty. It corresponds to the progradation observed in old maps between 1790 and 1803. The capacity of this sediment trap around the Roman jetty was possibly enhanced by the construction of the modern eastern mole in the same period. Between 1813 and 1827 showed in the maps (Fig. 9), a major storm affected the harbour on the 28–29 of December 1821 (Capitania del puerto de Tarragona, 1822). It could have contributed to the erosion of the coast and revealed the Roman jetty. In this interpretation, the progradational phases are linked to floods and erosional periods are related to the storms or the littoral drift for longer periods without floods (Fig. 9). This sedimentation-erosion cycle was probably already in existence before the Roman period. However, the construction of the Roman jetty meant that the sediments were trapped in the harbour after strong floods. The strength of the erosion was probably increased to the east of the Roman jetty by wave energy converging towards the headland. This interpretation is possibly characteristic of the rocky margins of the Mediterranean river deltas. Based on old maps, succession of erosional and progradational phases were observed on the eastern margins of the Rhone delta near Fos-sur-Mer (Vella, 1999). Considering a longer timescale, a larger progradational plain on the eastern margin of the Rhone delta existed when the Roman harbour of Fos-sur-Mer was built, while now the Roman harbour structures are affected by strong erosion (Vella, 1999; Fontaine et al., 2021).

Considering this interpretative model (Fig. 9), the depositional periods in the cores should be related to periods of higher flood frequency with no coastal storm, and the erosional surface should be related to period with fewer floods and/or greater coastal storminess. The timelines of local and regional palaeofloods and coastal palaeostorms in Figs. 10 and 11 tests this hypothesis. In fact, flooding periods also correspond to periods of coastal storms in the last 5 centuries. Strong coastal erosion and strong sedimentation might occur successively within the same years or the same decennia. The temporal resolution of the maps is maybe not sufficient to observe these changes except

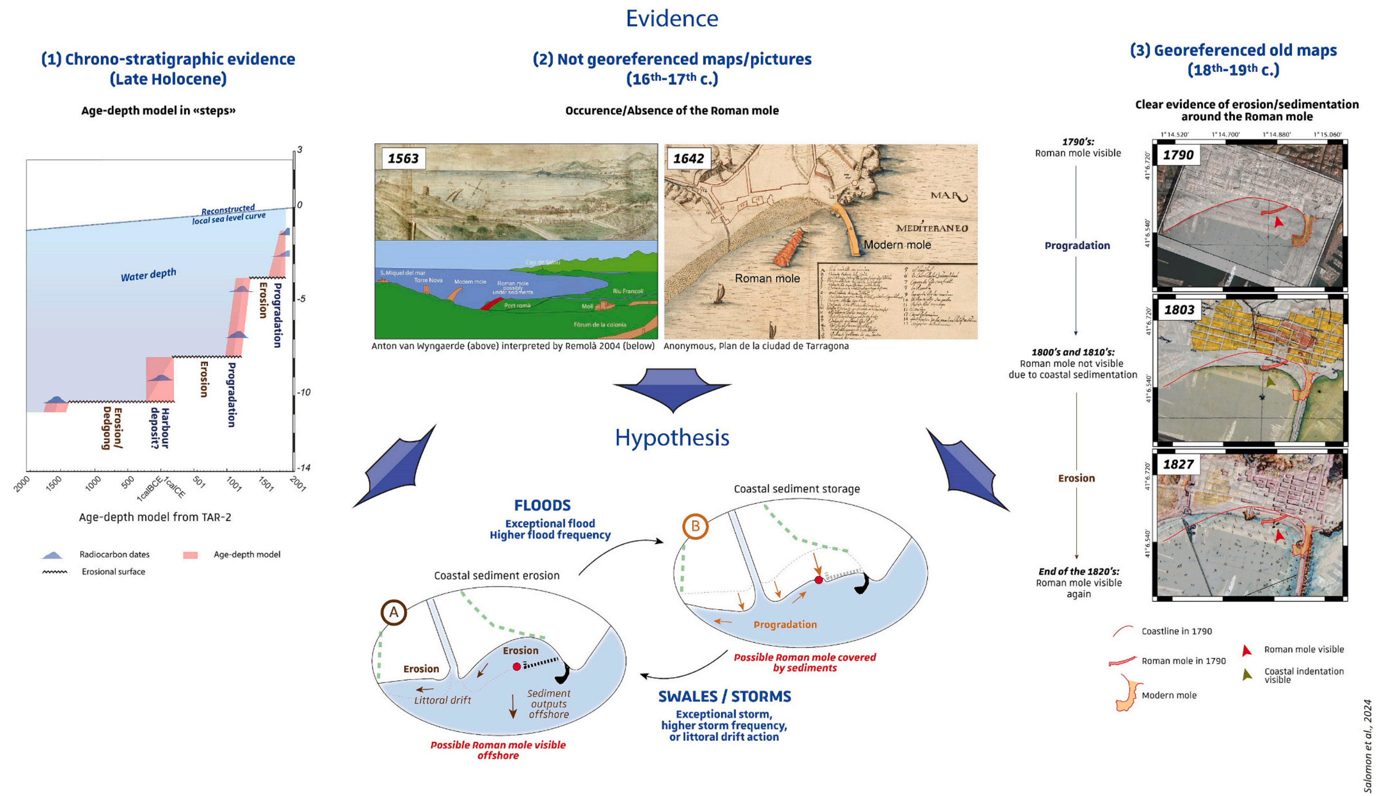

Fig. 9. Evidence supporting the hypothesis of decennial/centennial progradation-erosion cycles at the mouth of the Francolí delta.

between 1790 and 1827 (Fig. 9). During earlier periods, TAR-2 / Unit D is deposited during the 11th and the 14th century during the Medieval Optimum (Luterbacher et al., 2012) with fewer floods and storms. It is likely that this apparent progradation layer would be related to a possible increased erosion in the watershed due to land use change (Riera et al., 2004) and/or to some form of coastal engineering in favour of a better sedimentary trap during this period (e.g. quay, jetty) while the city of Tarragona is experiencing a renewal after the conquest of Tarragona by the Crown of Aragon in the 12th century CE. Layers E and F in Core TAR-2 could possibly be related to the last decades of the harbour before the construction of the *Muelle de Costa* in the 1880s.

5.3. The harbour - evolution from the Roman period to the 19th century CE

Direct evidence for the Roman harbour of Tarragona is now available through Core TAR-2 Unit C (Fig. 8). The silty sand dated to 142 BCE - 185 CE suggests the existence of a semi-protected harbour south of Tarragona during the Roman period. In addition, large amount of Roman material was identified in this layer, including ceramics and marble elements. Inverted dates in the stratigraphy can be interpreted as dredging activities (Morhange and Marriner, 2010). These materials are either related to dredging activities in the same location as Core TAR-2 or material reworked during a phase of dredging, transported in the water column of the harbour and finally deposited in the location of Core TAR-2. Core TAR-1 records the existence of a submerged beach also dated from the Imperial Roman period. It suggests that no specific engineered structure was built perpendicular to the coastline towards the east in that period. However, we do not know if these sediments were deposited at the base of a built quay (docking area) or connected to a natural sandy beach (beaching area).

Only secondary evidence tells us about a Roman jetty. The most obvious evidence is from maps but also from textual descriptions. The first evidence of the Roman jetty recorded in ancient texts dates back to the 12th century according to the writer Ponç i d'Icard (1572). Macrofauna from Core TAR-2 / Unit C suggests the proximity of a rocky substratum close by that may be the jetty.

It is difficult to know yet if the jetty described in the modern texts (Ponç i d'Icard, 1572; Hernández Sanahuja and de Torres, 1867) and the old maps could have created the hydrodynamic conditions leading to the fine deposits observed in Core TAR-2 Unit C. In addition, still very little is known regarding the configuration of the Roman harbour. It would be interesting to drill new cores to identify the extent of the fine deposits dated to the Roman period and to gather evidence of a previous Roman structure below the modern mole to the east.

The harbour layer stops abruptly and a thick layer of sands covers it. Cyclic sedimentation/erosion phases described above were then occurring (Fig. 9). Waves might have always been stronger towards the headland and in the area of the modern mole due to the convergence of the waves. Sediments were probably easily removed from the modern harbour area between the mole and the Roman arch jetty. The Roman mole jetty created a sedimentary cell limit between headland and the deltaic dynamics. If any, sediment residence was probably very short towards the headland. It was longer west of the Roman jetty, and a full Roman harbour sequence is expected to be found north and east of the Roman jetty. This should be considered for the location of future sedimentary cores.

The disappearance of the Roman harbour should not only be attributed to coastal hydroclimatic conditions. Earthquakes seem to have destroyed columns close to the harbour still visible <50 years before the observations and the text of Ponç i d'Icard (1572). This earthquake is possibly the one recorded by other ancient texts (Banda and Correig, 1984). We also know that during the Reaper's War the modern mole was damaged. Similarly, other war events could have affected the Roman structure. Finally, the constructions related to the development of the 19th century harbour did remove part of the jetty and harbour sediments. Interestingly, human impacts both accelerated the dismantlement of the Roman harbour evidence, and preserved them from further destruction depending on location. The construction of the *Molo della Costa* in the 1880s sealed part of the remains of the Roman harbour and the jetty according to the stratigraphic study and the maps georeferenced in this study.

5.4. The city – morphologic resilience of the port city of Tarragona to historical and fluvio-coastal hazards

There are two main drivers explaining the orientation of the urban fabric of Tarragona related to two prominent geomorphological units in the landscape: Tarragona's hill and the Francolí delta. The orientations of the Upper City are driven by the slopes of Tarragona's hill (Fig. 4 - Group 1) with a main organisation in NNE (light green at $32 \pm 3^{\circ}$ and dark green at $122 \pm 3^{\circ}$). This NNE orientation persists over time in the urban fabric until today. In the Upper City of Tarragona, the original orientation of the buildings is inherited from the Roman period (Fig. 4).

By contrast, the orientation of the structures located in the Lower City has changed a lot in 2000 years (Fig. 4 - Groups 2 and 3). The orientations of the Lower City is either driven by the changing coastline (Group 2) or the changing riverbanks (Group 3) in the Francolí delta. Successive constructions of roads, railways, highways, generate new orientation systems that shape the urban fabric of the Lower City from the Roman period until today (Group 3). Little is known of the Roman structures south of the theatre built in the late 1st – early 2nd century CE on the slope of the hill of which Tarragona sits (Macias et al., 2007). More is known from the south western part of port city towards the river mouth (Lasheras, 2018). However, no major structures were built in the Lower City compared to what can be found on the hill of Tarragona (e.g., Imperial forum, Colonial forum, Circus, Amphitheatre, Theatre). Instead, houses, warehouses and workshops were found in the deltaic plain close to the river mouth (Lasheras, 2018).

According to the study of the urban fabric and the remains of the archaeological material discovered over the years in the Francolí delta, some assumptions can be proposed for the fluvial and coastal dynamics of the Francolí delta during the last 2000 years. The Francolí river channel seemed to have been restricted in the eastern side of the delta. For the last 2000 years, the constructions along the right bank (e.g., Roman Vil.la Ceratonia) and the left bank (necropolis from Late Antiquity) of the Francolí river channel reveal a lateral mobility of 350 m at 1 km upstream of the river mouth location in 1800 CE. However, the absence of Roman or Visigothic structures closer to the mouth of the Francolí reveals wider action of erosion for the last 2000 years associated to both fluvial and coastal mobility.

Later during the medieval and modern periods, the Lower City was occupied mostly by gardens (Ponç i d'Icard, 1572). The brown silty sands with inclusion of gravels, small pebbles and terrestrial snails in Core TAR-1 / Unit E (Figs. 5 and 6) can be related to these gardens. Later, in the 19th century it became a square (*Plaça dels Infants*) – Unit F.

The organisation of the Lower City that had existed during the modern periods until ca. 1800 was reorganised. On the 18 of September 1802, the construction of the new port district was authorised (Fig. 9) (Ortueta Hilberath, 2011). A first phase of reorganisation was to remove the pre-existing building. Then, in the first years of the 19th century, a first block of buildings was built following the orientation of the slope of the southern part of the Tarragona's hill. This urban phase is still visible today in the urban fabric (yellow lines of Group 2 in Fig. 4). Soon after, plans were made to reorganise the main line of the urbanism in the Lower City following the orientation of the new mole called *Dique de Levante* – orange lines of Group 2 in Fig. 4 (*Plano de una nueva población en la Marina de Tarragona aprobada por el Sr. Generalísimo*. Antonio López Sopeña, 1803). This orientation was followed later in the 19th century by railways and the *Muelle di Costa* setting definitely this orientation.

The comparative study of the urban fabrics during Ancient and current periods is particularly instructive. With a similar geographical configuration over time including slopes, river and coastal interfaces, we can observe how urban development deal with these parameters and how they influence the shape of the city in terms of building and streets orientation. It can also be interpreted in terms of morphologic resilience of the urban fabric over time (Robert and Sittler, 2016). The Upper City kept its orientation and its structure over time, and so can be considered resilient (Fig. 4). Initially, during the Roman period, important buildings more prone to persist over time were constructed on the hill (e.g., temples, Imperial forum, Colonial forum, circus, amphitheatre, theatre). It seems also that the Upper City was occupied continuously from the Roman period to present, even when the city declined between the 8th and the 12th century CE (Guidi, 2016). Afterwards, the Late Medieval and the modern city of Tarragona developed again within the Roman remains and continued to preserve them. Tarragona became a UNESCO site because the Roman city is still preserved within the current Upper City, like in Rome.

The urban fabric of the Lower City is revealed to be less resilient and changes over time (Fig. 4). While activities developed around the harbour and along the river during the Roman and Visigothic periods, these areas were abandoned during the 8th and the 12th century CE (Lasheras, 2018; Terrado, 2018a). During this period of political instability, the city shrunk towards the Upper City. The model of the medieval settlements located on hills along the Mediterranean coasts during this politically unstable period can be observed here. After the 12th century CE, the Lower City and Tarragona developed very slowly. The harbour of Tarragona was in competition with better regional shelters such as in Salou and in Cambrils. The construction of a long mole around 1800 CE and the planning of a new Lower City is a major turning point in the history of Tarragona. Later in the middle of the 19th century, the Upper and the Lower City of Tarragona are eventually connected through a continuous urbanisation similar to the Roman period.

5.5. Chronological considerations and periodisation

Based on the new data produced and the chronological data reported in Figs. 10 and 11, we can only reconstruct a preliminary chronology due to scarce historical evidence especially before the 12th c. CE, uneven archaeological remains preserved through time and the strong erosion or destruction of the palaeoenvironmental archives along the coast.

The first period could at least start in the 2nd millennium BCE and finish at the end of the 1st millennium BCE. Shoreface deposits and possible progradational phases could develop under the influence of climatic factors and anthropic impacts recorded in the Iberic watersheds at these periods (Riera-Mora and Esteban-Amat, 1994; Carrión et al., 2007; Pérez-Obiol et al., 2011; Azuara et al., 2020).

During the Roman period, the hybrid coastal morphodynamics of the Francolí-Tarragona system are first attested with the construction of a semi-protected harbour. The first period includes the construction of the harbour (possibly 1st c. CE) and its maintenance. While we proved the existence of a harbour built and active during the Roman period (Core TAR-2), we do not know its precise configuration and how long this harbour was efficient and in use.

The third period is characterised by erosion, destruction of the Roman harbour structures and a lower human impact on the coast. It could start from few decades after the construction of the harbour or few centuries later (Late Antiquity/Visigothic Kingdom). This period lasts until the 15th c. with the construction of a new jetty. During this period, two phases can be identified. The first phase shows a decay associated to higher storminess from the Roman period to the end of the 1st millennium BCE (Sabatier et al., 2012) and a slow decrease of the socio-economic conditions (Fig. 10). The economy of Tarragona strengthened shortly during the Visigothic period but weakened afterwards when Tarragona become border area between al-Andalus and the County of Barcelona. The second phase starts with a revival of Tarragona in the 12th c. CE after the conquest of Tarragona by Barcelona. However, no clear information about major human infrastructure along the coast is recorded before 15th c. CE. Lower storminess affect the coast during this second phase (Sabatier et al., 2012) that could have led al-Idrīsī to

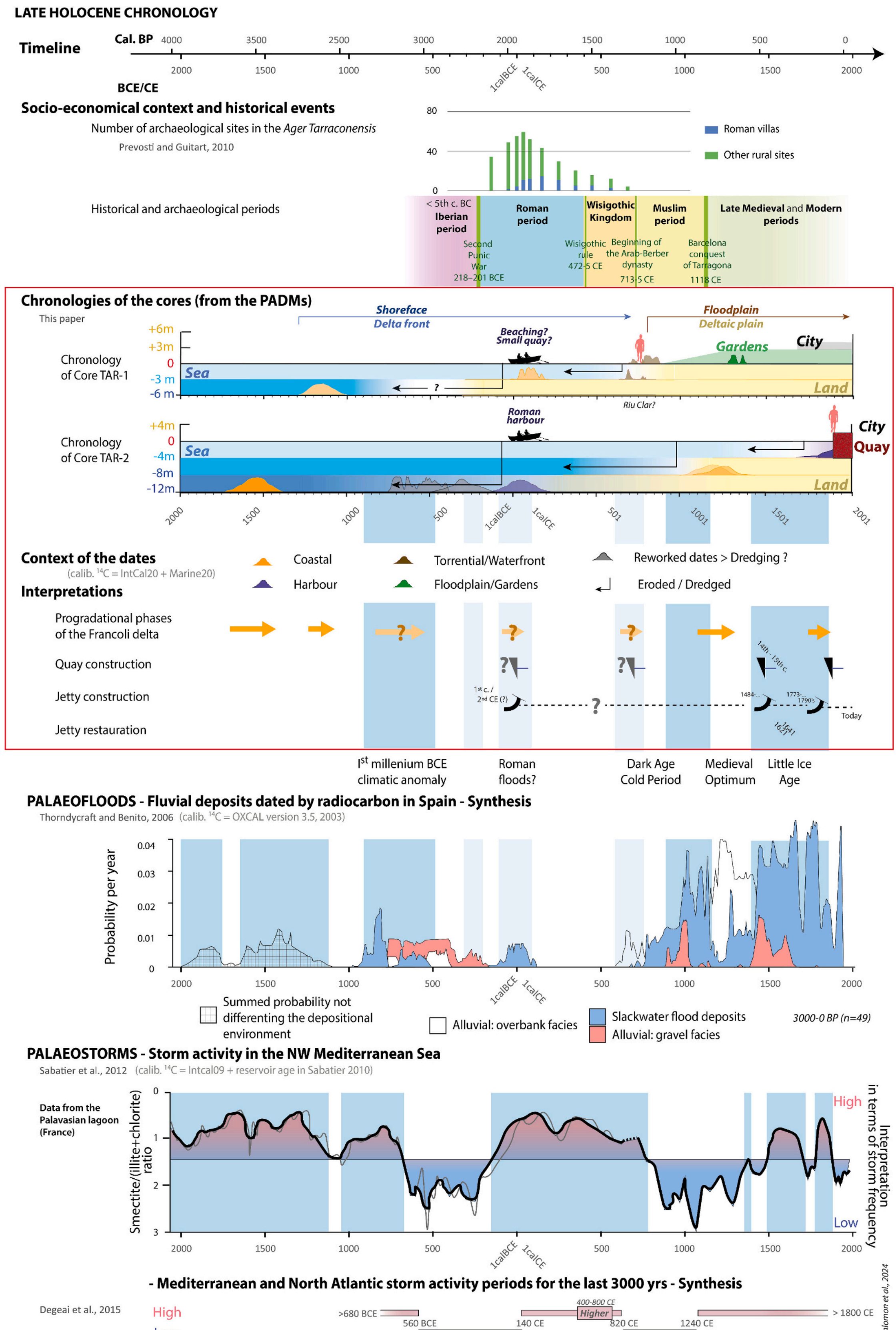

Fig. 10. Late Holocene chronology from the PADM charts of TAR-1 and 2 (Figs. 6 and 8) against historical events or periods, archaeological data, as well as palaeofloods and palaeostorms series.

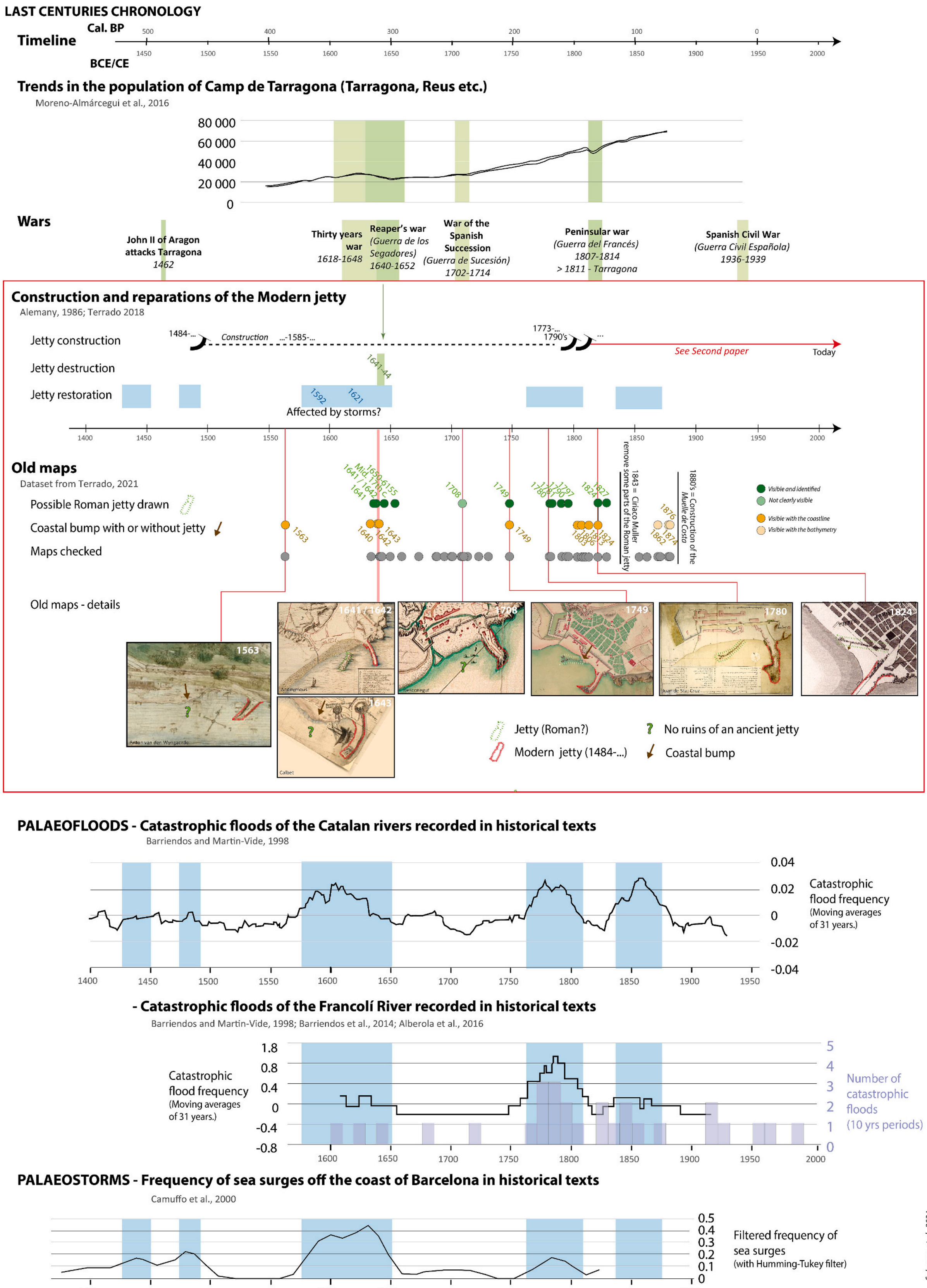

Fig. 11. Fluvial, coastal and port-related chronologies recorded in ancient maps and texts against historical data, floods and storms series.

say that the city had a good harbour in the 12th c. (Bramon, 2000). Then, storm activity increases slowly until the 15th c. (Fig. 10).

The fourth period starts in 1484 CE and lasts until 1800 CE. A new mole is built but sedimentary conditions did not fundamentally change. The mole is regularly damaged by phases of higher storminess (Camuffo et al., 2000) and wars (Fig. 11). In the 18th c. CE, regional politic, economic competition together limit the socio-economic development of Tarragona (Aresté Bargès, 1982).

The fifth phase lasts from 1800 to 1880 CE. New infrastructure is built leading to the development of semi-sheltered harbour with a finer sedimentation similar to the one observed during the Roman period. Cyclic sedimentation and erosional phases still affect the coastline and the shoreface of the delta but their control by human interventions increases. This period corresponds to the last phase of the Little Ice Age with higher storminess (Camuffo et al., 2000) and strong flash floods (Barriendos et al., 2014; Barriendos and Martin-Vide, 1998) affecting the harbour (Fig. 11). Despite this climatic context, socio-economic conditions improve during the 19th c. CE with technical developments that allows Tarragona harbour to continue to expand.

6. Discussion (2): the landscape and the seascape of a hybrid urban delta

In a long-term perspective, this study demonstrates the complexity of the interpretation of highly urbanised river deltas. Fig. 15 proposes a conceptual model to express the approach followed in this paper, considering natural and anthropic components in interaction at different levels: (1) interactive processes (Fig. 12); (2) combined morphologies (Fig. 13); and (3) hybrid landscape/seascape (Fig. 14).

6.1. Interactive human-nature processes

Sedimentary cores are ideal to study long term evolutions of hybrid urban deltas. However, identifying the processes behind the chronostratigraphies is a challenge. Stratigraphic units and erosion surfaces are the results of *direct* and *indirect* anthropogenic impacts interacting with deltaic dynamics. *Direct anthropogenic impacts* include built structures, dug or dumped material by humans, while *indirect impacts* are the effects of humans on natural erosional or depositional processes (e.g., upstream in the watershed or sedimentary dynamics close to a built structure).

Sedimentology or geomorphology alone cannot explain fluvial and coastal mobility, material deposition or erosion. By contrast, geoarchaeological studies are commonly dealing with interdisciplinary datasets from archaeology, history and geosciences. The upper part of Fig. 12 clarifies the main drivers controlling human-nature interactions in a hybrid urban delta. At the scale of the river delta, interactions are mainly understood between the lithosphere, the hydrosphere and the archaeosphere. The concept of archaeosphere, initially proposed by Capelotti (2009), was developed by and corresponds to a “unified deposit comprising all aspects of archaeological stratigraphy and artificial ground combined” (Edgeworth, 2014). Larger hydroclimatic and socioeconomic contexts control the hydrosphere (floods, droughts, or relatively calm periods) and the archaeosphere (growth or decline of the city and its harbour) contribute to transform the lithosphere in a unique hybrid urban delta.

Regarding the delta front managed with hard engineering during the last millennia in Tarragona, the lower part of Fig. 12 proposes some interactive processes affecting the coast involving dock or jetty construction with their direct and indirect impacts. TAR-1-Unit-C and TAR-2-Unit-G are typically interpreted such as built quays with a step forward, e.g., anthropogenic progradation (Fig. 12, Delta Front, A1). By contrast, sedimentation from of TAR-2-Units C and D are related to possible harbour structures contributing to trapping sediments (Fig. 12, Delta Front, B). The first case is a direct human impact with dumped material, the second case is an indirect impact of a built structure.

Generally, increased coastal sedimentation is triggered by indirect impacts due to human activities in the watershed leading to accelerated erosion. Considering pollen and ancient texts, this can be hypothesised for the Roman, late medieval and modern periods (Riera-Mora and Esteban-Amat, 1994; Riera et al., 2004). However, local anthropogenic impacts are essential to better understand the chronostratigraphies and prevent misinterpretations of accelerated sedimentation in a wider palaeoclimatic context. Enclosed ancient harbour basins in coastal areas are known to be a very good trap for sediments and increase sedimentation locally (Marriner and Morhange, 2007; Goiran et al., 2010). Similarly, in a lagoonal context from the deltaic area of the Aude river in southern France, accelerated sedimentation during the Roman period was observed and associated to a built quay from the same period (Flaux et al., 2020). In the Nile delta, current marine (Goiran, 2001) and lagoonal (Flaux, 2012) interfaces in Alexandria were directly and indirectly shaped by built structures and the sedimentation next to these structures (Heptastadion, jetties). In none of these examples is sedimentation rate driven by larger palaeoclimatic drivers.

6.2. Combined morphologies

Interactive anthropogenic and natural processes generate combined morphologies. Fig. 13 illustrates some types of combined geo- and archaeomorphologies that can be observed in hybrid urban deltas. River deltas offer a large range of natural morphologies generated by fluvial (e.g., channels, palaeochannels, levees, point bars) and coastal (e.g., coastal barriers, lagoons, beach ridges, submerged bars) dynamics. These morphologies can be modified by different kinds of human actions related to urban, rural or coastal activities. Archaeomorphologies associated with cities can also be very diverse depending on the urban culture considered. These urban cultures differ spatially but also temporally since the first urban societies developed in the Tigris-Euphrates delta around 7000 years ago (Bianchi, 2016; Pennington, 2018). Which urban fabric analyses to conduct would depend on the characteristic of the urban culture considered (Raja and Sindbæk, 2020). Archaeomorphologies also integrate natural features. For instance, urban fabric can record fluvio-coastal mobility (Salomon et al., 2018) or topographic characteristics (Mohajeri, 2012; Mohajeri et al., 2013). In this paper, Tarragona exemplifies two of these elements.

6.3. Hybrid land- and seascapes

Fig. 14 proposes a summarised map of the analyses conducted in this paper to reconstruct the main natural and anthropogenic changes during the last 2000 years. However, a better idea of a land- or seascape hybrid would be given by panoramic photographs for recent times or depicted by paintings for older periods where the different components are intertwined and not yet clearly identified.

Social and natural sciences propose different concepts to approach human-nature interactions. Some researchers express these interactions in terms of nature or human dominated environments (Messerli et al., 2000; Ernstson et al., 2010). The expression “techno coast” has also been used to characterise “shorelines stabilized with revetments and seawalls” (De Pippo et al., 2008). More specifically considering river deltas, the anthorpic component is expressed in terms of “human influenced” or “human impacted” deltas (Besset et al., 2016) or else “human dominated deltas” (Bertoni et al., 2018). In this last case, reference is made to the classic ternary diagram considering dominant tide/wave/river processes shaping deltas (Galloway, 1975; Nienhuis et al., 2015, 2020), where the human influence should also be considered. Some other researchers consider the concept of “hybrids” (Ashmore, 2015; Lespez and Dufour, 2021). It applies to river deltas considering both urban (Cheng and Le-Gates, 2018) or rural areas (Nguyen, 2020). In this paper, we use the concept of hybrid to characterise urban deltas since it is object-oriented and applies well to long term perspective with alternating human and natural dominant processes. The concept of hybrid offers the possibility

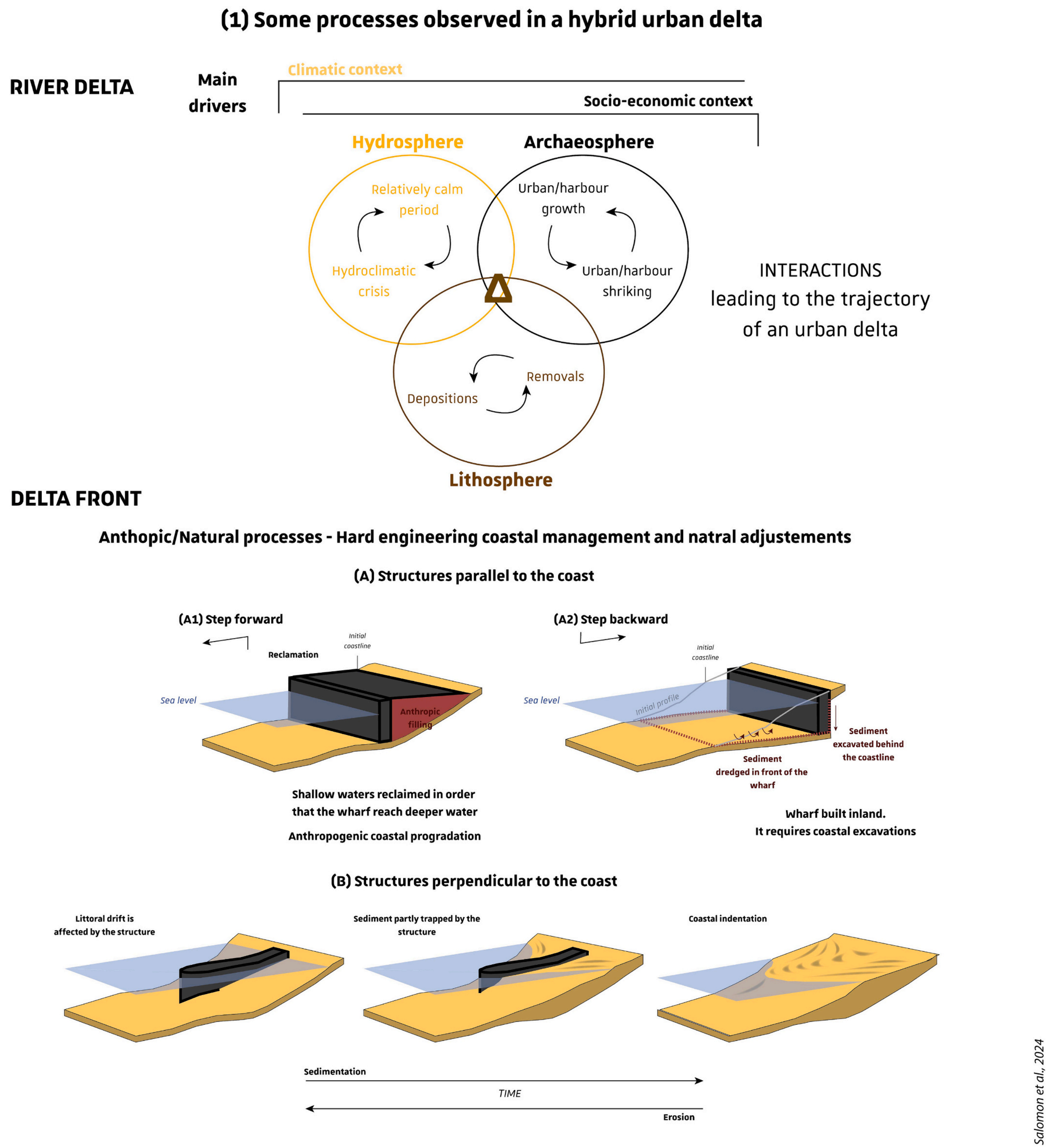

Fig. 12. Some processes observed in a hybrid urban delta.

to focus on the modalities of human-nature interactions between specific human structures (e.g., buildings, jetties, docks, polders) and geomorphological units (e.g., river channels, coastlines, deltaic plains, prodeltas). Reciprocal interactions and feedback loops should also be considered in such systems. Considering the natural dynamics affecting the Francolí delta before the late 19th c. CE (Fig. 9), the coast of Tarragona needs strong human interventions to provide a suitable harbour and a strong management. Consequently, favourable socio-economic and political contexts are essential to maintain the harbour operable. If not, the harbour would be quickly damaged, eroded or filled, increasing a possible socio-economic crisis already at stake. Strong human interventions on the delta during the Roman period and in the 15-16th c. CE were followed by periods of climate, social and political crises (e.g., storm activity, political changes, wars) (Figs. 10 and 11). In contrast, from the end of the 18th c. CE and all along the 19th c. CE, engineering work was regularly conducted in the harbour of Tarragona to maintain and expand it despite the periods of climatic crises but during a socio-economic growth (Fig. 11).

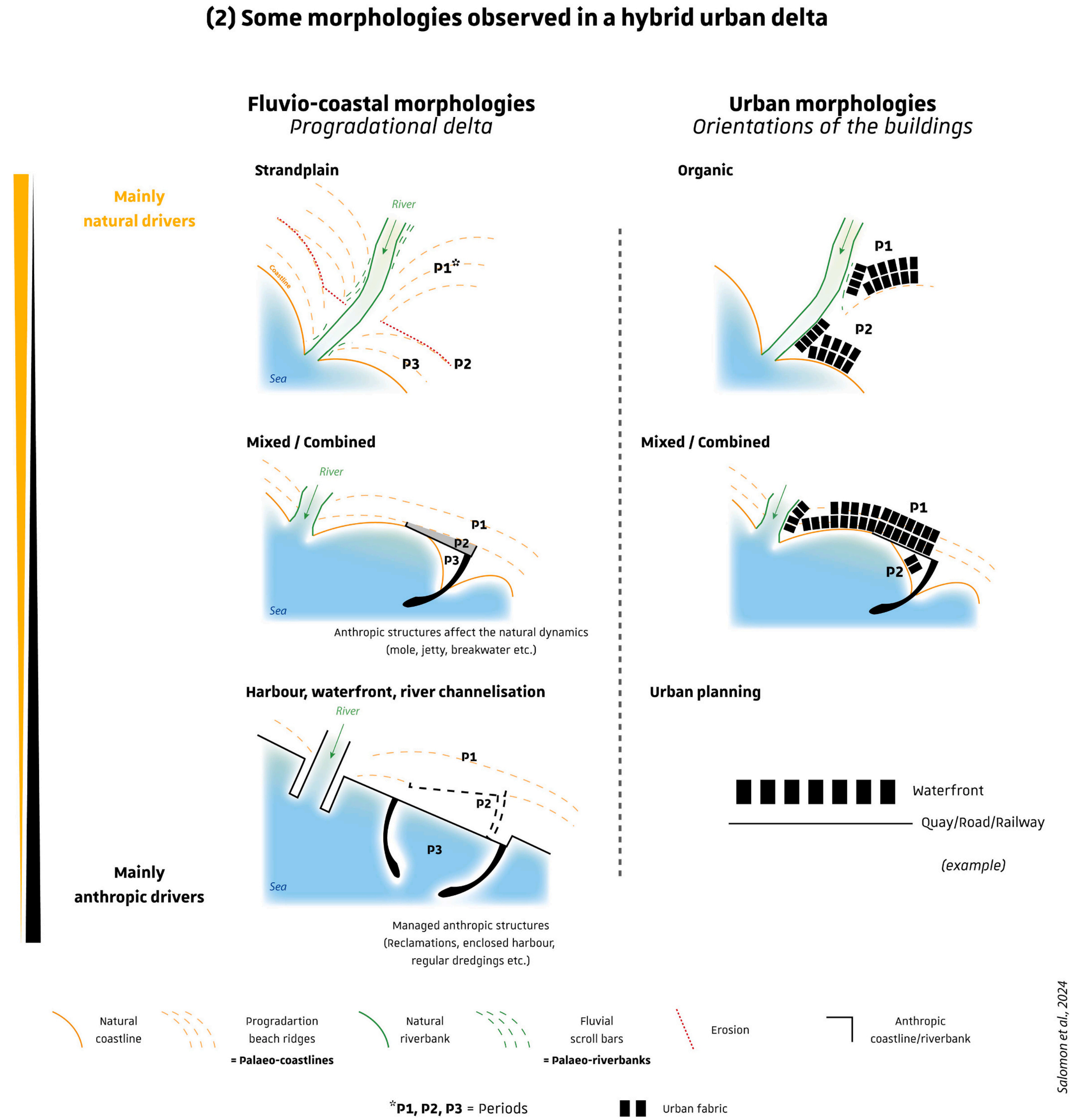

Fig. 13. Some morphologies observed in a hybrid urban delta.

Hybridity is the result of a complex human-nature intricate history. The concept of hybrid helps to insist on the interrelations between the different components of a land- and seascape object and the diversity of the processes involved whether they are of natural or anthropogenic origin (Lespez and Dufour, 2021). Hybridity however is not increasing or decreasing through time, but it can express itself through many ways depending on the processes involved. When an object is hybrid, it can be clearly perceived or would remain unnoticed until further analyses of the morphologies and the processes involved. In this study, it is expressed in looking at deltaic areas. Morphological combinations and interactive processes revealed by adapted analyses reveal dominant components, either natural (wave/tide/river dominated deltas) or anthropic (human dominated deltas).

Within hybrid urban deltas, there exist *indirect* human made deltas related to sediment fluxes issued from river catchments (Maselli and Trincardi, 2013) and *direct* human made deltas linked to urbanisation and engineered structures (Anthony, 2014; Salomon et al., 2023). The studied Francolí-Tarragona system is mostly considered as a *direct* human made but complementary analyses connecting the watershed with the delta would evidence an eventual indirect influence of human activities in the watershed and their consequence in the delta. In other words, human activities are not only affecting sediment fluxes in water

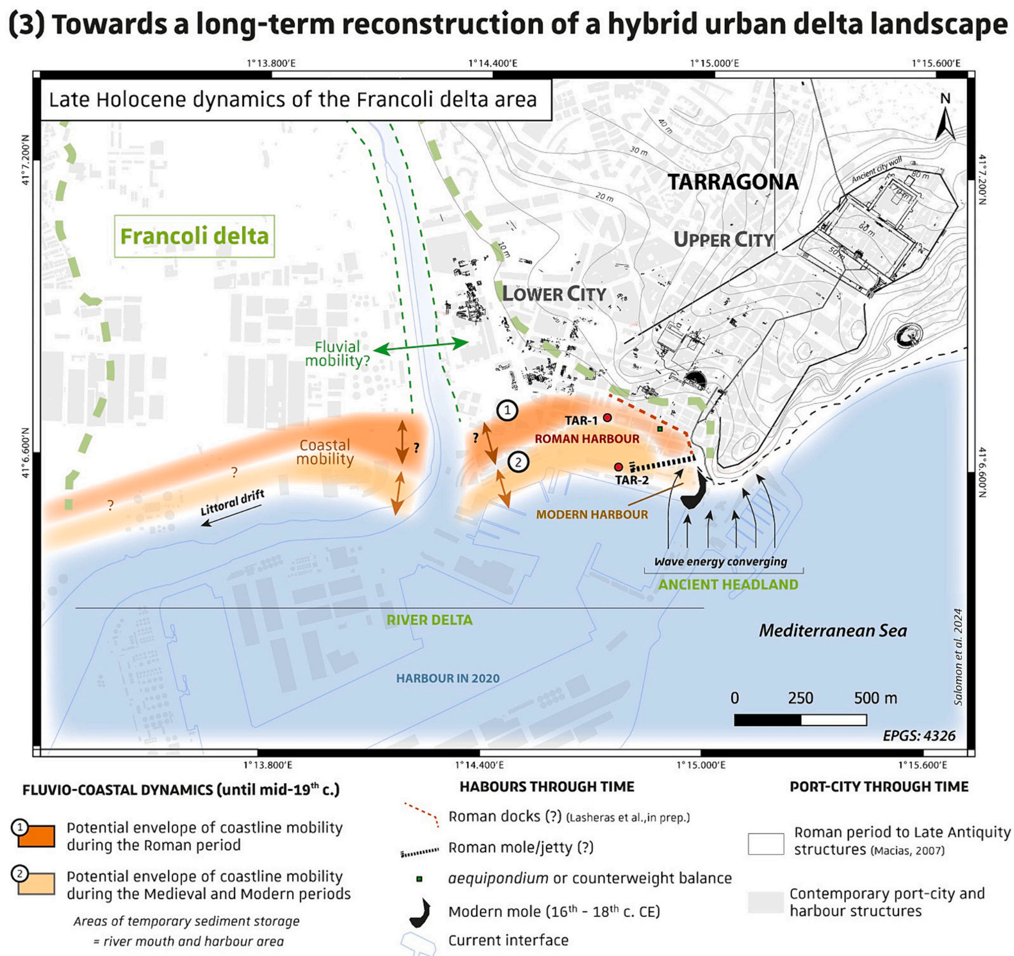

Fig. 14. Reconstruction of the main dynamics in the Francolí-Tarragona urban delta during the last 2000 years.

systems or directly modifying fluvial or marine sediments through actions such as dredging (Syvitski and Kettner, 2011; Parrinello and Kondolf, 2021), they also produce direct built deposits and constructions shaping land- and seascape morphologies driven by human forces under social, cultural, political, economic or technical control (Hooke, 2000; Ashmore, 2015). In such context, more accurate interpretative models have to be inspired by both natural sciences (e.g., source to sink or river continuum concepts, fluvial and coastal systems approaches) and social sciences (e.g., historical models, economic theories) (Salomon and Rousse, 2023).

Contingency in time is particularly important to understand temporal trajectories involving human actions (Ashmore, 2015). However, in the long term perspective adopted in this paper, it is equally important to consider archaeo- and geomorphological inheritance as much as political and socio-economical legacy setting path dependencies (Van den Berghe, 2015; Hein and Schubert, 2021). For instance, Romans made Tarragona an important political and religious city. In particular, they created an archdiocese still existing today (reestablished in 1118). Later in the 18th c., this religious authority played a major role in the choice to develop the port of Tarragona instead of Salou or Cambrils while they offered better natural opportunities to host a harbour (Aresté Bargès, 1982).

The graphical abstract of this paper replaces the trajectory of the Francolí delta within the theoretical model of Galloway (1975). In addition to the river, wave and tide processes, a fourth vertex indicates the human processes affecting river deltas and shapes a triangular-based pyramid. Hybrid urban deltas are located in all the volume of this 3D shape.

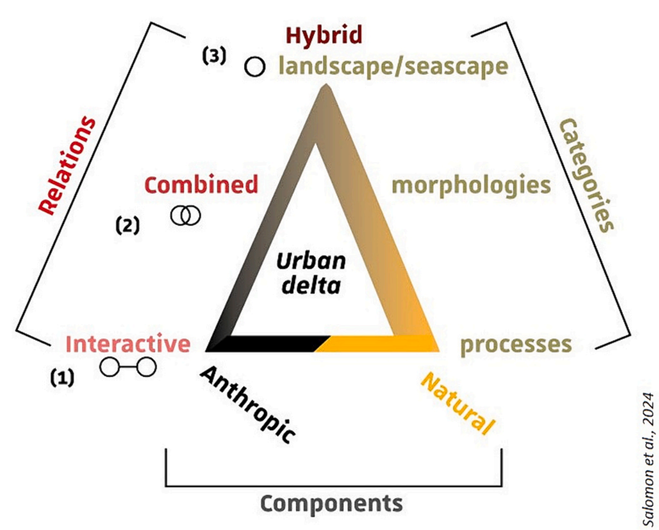

Fig. 15. Conceptual model developed in this paper to study hybrid urban deltas. The study of interactive human-nature processes (Fig. 12) shaping combined anthropic and natural morphologies (Fig. 13) contributes to reconstruct long-term evolution of a hybrid urban delta landscape/seascape (Fig. 14).

7. Conclusion

Long-term evolution of the interaction between Tarragona and the Francolí delta reveal different periods according to socio-political and palaeoclimatic contexts. Such reconstruction can only be achieved by combining a large range of data generated by diverse disciplines such as geomorphology, archaeology and history. It results in mixed approaches like geoarchaeology, geohistory but also urban geomorphology and social geomorphology allowing us to combine data.

Socio-environmental processes shaping a hybrid urban delta can be observed both on the deltaic plain (subaerial delta) in interaction with urban developments, and the delta front (subaquatic delta) in interaction with harbour infrastructure. These processes are alternately dominated by natural drivers leading to sedimentation and erosion and by anthropogenic drivers (e.g., accelerated or decelerated sedimentation/erosion, mole construction, dredging) at different degrees and following different modalities. These processes shaped both deltaic and urban morphologies, giving hybrid urban deltas specific morphologies that can hardly be synthesised within a single ternary diagram explaining deltaic morphologies (river/tide/wave dominated delta).

This study proposes to clarify the formation of a hybrid urban delta by identifying the processes and the morphologies involved in a long-term perspective and in using different tools (urban fabric analyses, PADM charts, interdisciplinary chronologies). In the Francolí-Tarragona system, the construction of jetties was the most important element to follow over time along with the associated sedimentation and erosion. The construction of the jetties can be seen as tipping points linked to climatic conditions, socio-economic contexts and technological advances (Roman and Renaissance jetties in Tarragona). They precede the major turning point of the 19th c. CE characterised by important and incremental harbour developments leading to the large harbour of Tarragona we know today. The chronologies of structures such as moles or canals can be very powerful proxies to follow along the coasts at a larger spatial scale in order to identify different rhythms of coastal anthropisation. Their impact on deltaic dynamics would give a better idea of the anthropogenic morphologies that still remain unnoticed in current river deltas.

Studies of the past confirm and claim that environmental sciences (Nicholls et al., 2020), spatial planning and urban design (Meyer, 2012; Bosselmann, 2018) are equally relevant to face future challenges in fragile deltaic areas.

CRediT authorship contribution statement

Ferréol Salomon: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing, Resources. **Ada Lasheras González:** Methodology, Resources, Writing – original draft, Writing – review & editing, Investigation. **Patricia Terrado Ortuño:** Conceptualization, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. **Josep-Maria Macias-Solé:** Conceptualization, Data curation, Methodology, Resources, Writing – original draft, Writing – review & editing. **Kristian Strutt:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Pierre-Alexis Herrault:** Methodology, Writing – review & editing. **Peter R. Morgan:** Formal analysis, Writing – review & editing. **Simon Keay:** Funding acquisition, Project administration.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2024.109178.

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