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Roman Ports in the Mediterranean: Geomorphology, Environment and Resilience

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Statement:

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Abstract
Classical ports in the Mediterranean Sea existed not only in a social, economic and technical contexts but also in a geomorphological context. This geomorphological context, which includes both the harbour landform and the catchment (if any) is a function of the geomorphology of coasts and catchments (including neotectonics) and marine factors (bathymetry, low amplitude tides, surges, tsunamis etc.). A simple geomorphological analysis of the major Roman 50 ports of the Mediterranean shows that they are dominated by river mouth (42%) and lagoonal/deltaic settings (16%) but also included rocky bays/promontories and totally artificial basins (14%). All types of Roman ports had siltation problems, as nearly all ports do, but this is even more pronounced for river-mouth ports all of which suffered, partly due to low tidal amplitudes and supressed estuarine energy regimes. Many adaptations can be illustrated including construction materials, mole design, dredging, and not infrequently, changing port location. The resilience of river-mouth ports was closely connected to river catchment dynamics of erosion and sediment transport as well as socio-political factors. The generally short, and relatively steep gradients, of most rivers entering the Mediterranean (with obvious exceptions) limited the storage space for fine sediment, and resulted in high rates of estuarine and deltaic plain sedimentation. A recent analysis of pan-Mediterranean erosion by Walsh *et al.* (2019) has shown that although erosion/sedimentation rates varied catchment to catchment, there was a general increase over the early Roman Period followed by a decline, and then an increase again in the Medieval Period, although some regions, e.g. S France are out of phase with this pattern. Optically-stimulated luminescence (OSL) dating of sediments in the Tiber catchment shows a pulse of sediment deposition in the late Roman-early Post Roman period and again later in the Renaissance (c. 1500-1700 AD) caused by a combination of intensive cultivation and climate, including the Little Ice Age. This paper concludes that the history of Roman ports cannot be de-coupled from their sediment-catchments, either coastal cells and/or fluvial catchments, as both placed heavy burdens on the sustainability of ports but to different degrees. Along with technological change and the geopolitics of trade these geomorphic factors played a role in the spatially differential resilience of Mediterranean ports during and after the Roman period.

Introduction

The Classical Mediterranean civilisations, that included the network of Greek colonies and the Roman Empire relied on their ports for survival and the economic and political control of their regions. Grain for example had to be moved for most of its journey by sea, and given that 'Africa fed Rome' (Rickman 1980, p. 264) marine shipment and transhipment were essential components of the Roman economic, social and political system, and connectivity around the Mediterranean (Horden and Purcell 2000; Robinson and Wilson 2011; Broodbank

2013; Keay 2013; Walsh 2013; this volume). But ports in the Mediterranean environment were, and remain, particularly sensitive to a range of environmental factors as clearly illustrated by Giaime *et al.* (2019). The semi-arid Mediterranean climate, vegetation and mountainous terrain can produce high sediment loads in rivers many of which discharge through estuaries and deltas in which Classical ports were originally located. The neotectonic activity of the region can also produce port-specific subsidence/uplift and the low tidal range (under 1m) and limited sea-fetches are important factors in controlling coastal and deltaic sedimentation. Because of the wide range of geomorphological settings of these ports from deltas (e.g. Portas, Alexandria, Ostia, Istria, ..), through deltaic-plain estuaries (Pisa, Ostia..) to rocky coasts (Carthage, Leptiminus…) these factors will have effected ports differentially, leading to pressures on both local and Empire-wide economic and thus cultural history (Figure 1). This paper reports an analysis of Roman port location and siltation history before focussing in more detail on three specific regions and the changing geomorphological regime of these port systems. It is based upon a wide range of resources, both archaeological and geomorphological as well as specific studies undertaken by the authors in Italy and Greece.

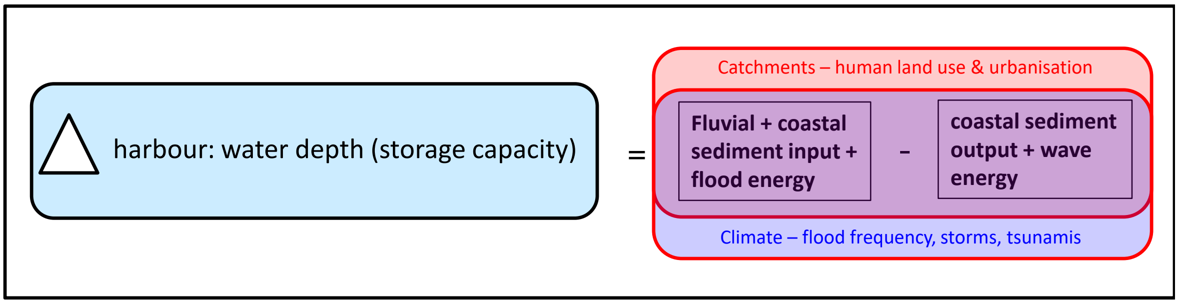

Fig. 1. The port harbour siltation problem as defined in this paper.

Port-harbour types: Geomorphology

The geomorphology of Mediterranean coastlines has significantly constrained the form and development of ports from pre-Roman times to the present day. Although port location is generally governed by socio-economic factors such as settlement pattern and transport routes, harbour form is determined largely by coastal geomorphology. From an engineering perspective there are few perfect harbours (*cf.* perfect natural harbours/all season harbours) and this is particularly the case in the Mediterranean due to coastline being dominated by either rocky-limestone capes and small bays, relatively small deltas (with major exceptions) or lagoonal areas at river mouths. The key requirement of shelter often conflicts with both harbour size and water depth. There are several databases of Roman ports ranging from containing just those under investigation, such as the PortusLimen database (https://portuslimen.eu/sites/) to the 'Ancient Ports and Harbours Catalogue' which contains over 4000 ports, harbours and landing places (de Graauw 2017).

For the analysis reported here only the top 50 were used as these were regionally important, contained specific port infrastructure and had data concerning their site and changing conditions over time. A simple four-fold division of port type is used here, which whilst not encompassing all landings for boats, does cover the majority of geomorphic harbour-forms (*cf.* Marriner *et al.* 2015; Giaime *et al.* 2019). The fluvial/river mouth category (FB) includes ports in estuaries which over time become increasingly deltaic. Many ports, such as Oiniadai and the western Anatolian ports, were located in drowned river valleys but become deltaic as sediment progrades in lobes out of the submerged valley to surround islands. The rate of progradation depends upon both sediment supply and tectonic factors. The larger Mediterranean deltas, started forming often within estuaries c. 8000 – 6000 yrs BP when the rate of sediment supply exceeded the rate of sea level rise (Anthony *et al*. 2014; Pennington *et al.* 2017) and although they commonly stabilised in the mid-Holocene many saw the development of new lobes in the Roman Period and later in the Little Ice Age (Maselli and Trincardie 2013). The second class, lagoonal harbours (LH), includes harbours on these larger deltas (such as the Nile) but not at a river mouth, and are most typically sandy bays formed of beach barriers across shallow lagoons. The third category, rocky bays and promontories (RB), are often related to islands and tombolos (e.g. the two ports at Alexandria and Piraeus). The last category (AH) is where there was no natural harbour and so a basin or jetty had to be created. The advantages and disadvantages of each from a geomorphological, engineering and economic perspective are listed in Table 1 (see end of paper). This simple classification which is solely geomorphological, which although similar to that recently published by Giaime *et al.* (2019), does not include human modification or activity (e.g. dredging) except for the artificial harbour category.

As can be seen from Figure 2 the most common geomorphological port-type is the fluvial or river mouth location (21). Followed by lagoonal settings which are largely beach barriers (8) and rocky bays and promontories or islands (14). The last is a broader and more varied category than the fluvial and lagoonal harbours and so is probably numerically over-represented. There is a clear geomorphological pattern to the distribution of port types, with the rivers with large catchments or high discharges in mountainous areas on the northern and central to western Mediterranean. The Levant and North Africa is more varied with only one major delta (Nile), lower relief and a semi-arid climate, which posed a challenge for transporting goods to the rest of the Empire. This resulted in a high number of artificial ports with no topographic harbour (7) but instead either long jetties or constructed basins such as

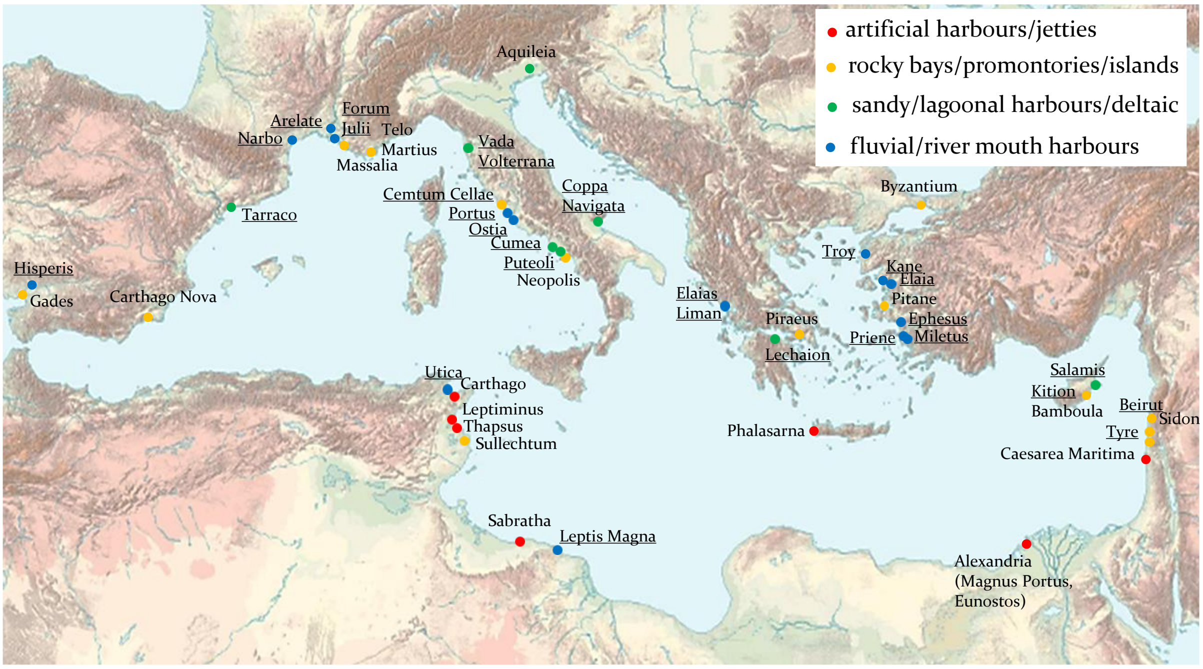

Fig. 2. Map of the Mediterranean with all the ports used in this study. Those underlined are known to have suffered siltation problems in or just after the Roman period. Inset pie diagram is port typology as % of total.

Carthago (Carthage). These sites are a testiment to Roman engineering achievement but also the relative lack of suitable natural harbours in areas of high agricultural or mining activity (Stone 2014). A good example is the port of Leptiminus in modern Tunisia, where the ancient city had no natural harbour but instead a sandstone wave-cut platform extending outwards from the beach. Leptiminus's development in the 2nd-3rd centuries CE as an agricultural centre with associated centralised pottery/amphora production (Brown and Mattingly 2001: Brown *et al.* 2011) was accompanied by the construction of a 370m long jetty made of ashlar blocks with a total area of 12,700m^2 and a wharfage length of 720m (Stone 2016).

Of these 50 ports at least 30 experienced major siltation problems in antiquity, with the majority of these (21) being river-mouth and deltaic ports. This is not surprising as the Mediterranean coast is characterised by relatively short, often highly seasonal, rivers, with high sediment loads and coasts with low tidal amplitudes (generally 0.1-0.15m but greater towards the Atlantic) and often relatively low fetch distances, although tidal effects around islands and in narrows do occur but not in estuaries (McElderry 1963). The result is a tendency to siltation with a lack of tidal flushing. In some cases this meant that the original site was abandoned or replaced by a new port (e.g. Pisa) and in a few cases the port location remains unknown especially in the Black Sea (de Graauw 2016).

Bays and lagoonal harbours are vulnerable to siltation due to long-shore drift and coastal barrier growth. Classical examples of this are Histria on the Danube (Vespremeanu-Stroe *et al.* 2013) and the Roman ports along the coast of SW Anatolia (see later section). Almost all the Mediterranean is neotectonically active and in several cases the down-throw, or upthrow, of a fault system has adversely effected classical cities and ports, the most famous example being the columns of the Temple of Serapis in Naples with its evidence of marine molluscan column-boring that featured in Lyell's *Principals of Geology* (1830-33) and which have an iconic place in the history of geology (Fortey 2005). Others include Puteoli and Alexandria which have sunk (Carayaon *et al.* this volume), and Phalasarna which has been uplifted. However, probably the largest neotectonic effect is less obvious – as it acts through the rejuvination of catchments and changes to sediment supply (Brown *et al.* 2016). Neotectonic activity is high and variable across the Mediterranean and the most effected areas are Central-Southern Italy, Greece, the Aegean and western Turkey where block-faulting can cause different tectonic histories for adjacent coastal cells (Carafa *et al.* 2015).

Case Study I: Lechaion Harbour, Peloponnese, Greece – a Complex History

Two concurrent excavation projects, the Lechaion Harbour Project (Danish Institute in Athens) and the Lechaion Harbour Settlement Land Project (American School of Classical Studies at Athens, 2019) are working on unravelling the history of this port site which has a complex history involving neotectonics, coastal drift, tsunami sedimentation and possibly fluvial input. Situated on the southeast coast of the Gulf of Corinth, the harbour of Lechaion was, at one point, one of the most important harbours in western Greece (Rothaus 1995; Stiros 1996), serving often as a military port during antiquity and as an important economic port during the Roman Period.

The Harbour occupies a stretch of beach (Outer Harbour) and a marsh (Inner Harbour) which formed at the mouth of a torrent channel (Mourtzas *et al.* 2013; Figure 3). The outer

Harbour is protected by three stone-built moles with an approximate length of 40-50 m (Mourtzas *et al.* 2013). The Inner Harbour consists of a series of artificially excavated basins along a channel which connects the coast to a natural lagoon. Furthermore, as the coastal morphology and Lechaion, as a location, appears in textual references as early as the late 6th century BCE, and is mentioned in war records by the early 4th century BCE (Stiros *et al.* 1996). The harbour installation is first mentioned in 44 BCE by Strabo (8.6.22), although its use most certainly began in the 6th century BCE or earlier. From 353 CE to 358 CE, the harbour was the subject of a reconstruction campaign, according to the inscription on the base of a monument to the Roman governor of the Peloponnese (Papachatzis 1974). Prior to excavation, the construction and use of the site were dated via AMS ^{14}C dates from bio-encrustations at the entrance to the Inner Harbour (600 to 50 BCE) and on the Roman 'monument' within the 'Lagoon' (330–46 BCE). The last historical reference to the port of Lechaion is in the 2nd century CE by Pausanias (2.2.3). The last evident use of the area is the construction of the Basilica of Saint Leonidas, which was built in the early 6th century CE, and suffered severe damage shortly thereafter (Apostopooulos *et al.* 2015).

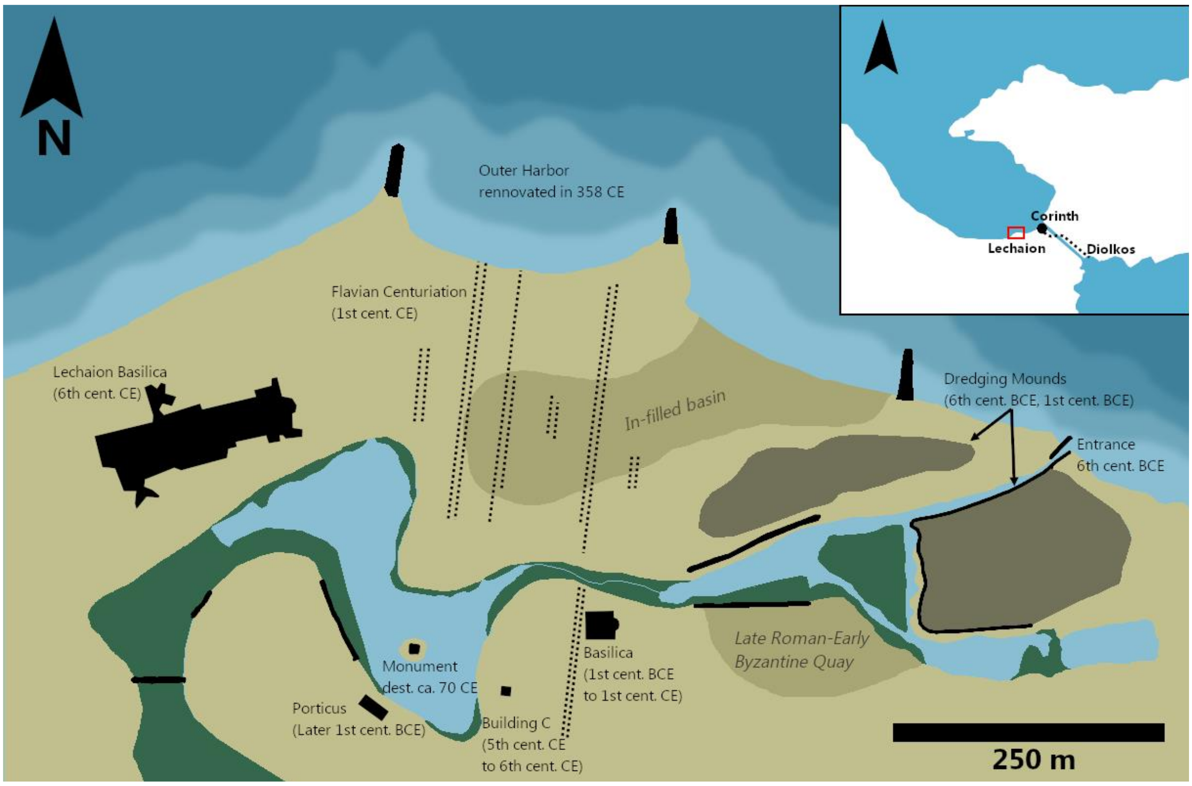

Fig. 3. Diagram of the harbour system at Lechaion with approximate dates for known architetural features. Adapted from Mourtzas et al. (2014), Apostomopoulos et al. (2015), Danish Institute in Athens (2018) and the Lechaion Harbor Settlement Project (2019).

The Gulf of Lechaion, the southeastern portion of the Corinthian Gulf, is a tectonically active rift structure, with the Perachora peninsula on the northern margin uplifting over 3 m between the fifth century BCE and the fourth century CE (Pirazzolli *et al.* 1994). Between the 4th and 6th centuries the coast at Lechaion submerged by 2 m, rising 1.10 m after 1600 CE. The intermittent uplifting of the harbour seems to have exacerbated the issue of silting, which was already a significant risk due to the low energy of the stream channel, which deposited sediments from inland without flushing them out to sea (Morhange *et al.* 2012). The Inner Harbour may have been dredged and reinforced as early as the 4th century BCE (Stiros *et al.* 1996; Wiseman 1978). The entrance to the inner harbour, just beyond the eastern mole, is flanked by two large mounds, which contain coarse sands and gravels. Importantly, the dredging mounds contain coarser sands and gravels than would normally be expected for dredged sediments, suggesting that in-filling in the Inner Harbour was not governed by fine-sediment siltation. There is significant debate concerning how coastal gravels and sands were deposited on the site, with researchers supporting either tsunamis (Vött et al. 2018) or more gradual coastal processes (Kolaiti *et al.* 2017).

While the historical record for tsunamis is sparse (Papadopoulos 2003), multi-proxy investigation via vibracore, ground-penetrationg radar (GPR), electrical resistivity tomography (ERT), and geochemical analysis appear to indicate the occurrence of two or three high-energy impacts, resulting in the deposition of thick units of sand and coarse gravel accompanied by an increase in the ratio of Ca to Fe (Hadler *et al.* 2013). From this evidence, researchers have suggested three possible tsunamis between the 8th century CE to the 6th century CE (Hadler *et al*. 2011, 2013; Koster *et al.* 2011), each associated with evidence for large earthquakes in the vicinity of Lechaion and Corinth (Vött *et al.* 2018). GPR and ERT uncovered extensive scour marks below the surface in the west end of the inner Harbour (Koster *et al.* 2013). ERT in the vicinity of the St. Leonidas Basilica showed depressions created by the liquefaction of sands during earthquakes (Apostopoulos *et al.* 2015), further demonstrating the impact of seismic events on the area.

The Basilica of Leonidas, built circa 520 CE, appears to have been damaged shortly after its construction and portions of it buried under coarse sands and gravels. Kolaiti and colleagues suggest that this burial could not have been from a tsunami, as a 7th-century CE coin was found in a fill within a building of the cathedral (Kolaiti *et al.* 2017), however, this single find tells us little about the nature of the fill or the use history of the building (Vött 2018). Excavation by Lechaion Harbour Settlement Land Project (LHSLP) from 2016 to 2018 have uncovered a Roman civic basilica from the Augustine and Neronian/Flavian periods, founded on and partially buried by coarse sands and gravels. This basilica seems contemporary to the centuriation found on the site, indicating the urban plan of the greater harbour town. Centuriation, supposedly Flavian in date (Romano 2006), overlies the in-filled coastal basin - identified as 'Basin 4' by the (Danish Institute Lechaion Harbour Project 2019), demonstrating that this basin was out of use by the 1st century CE. The newly discovered basilica, partially buried by sands and gravels in a state of collapse, may have been buried by the same event responsible for the coarse deposits at the 6th century CE basilica. This is typical of the complex interplay of natural forces and urban morphology that characterises the history of Lechaion.

River-mouth Port Vulnerability

In this study all river ports - deltaic, river mouth and inland - are grouped together as they are genetically related and indeed many ports change from being at the mouth of small deltas to being inland as deltaic progradation occurs. This includes the 'fluvial harbours', 'river-mouth harbours' of Giaime *et al* (2019). River-mouth siltation results from a number of factors including long flushing times, hypersalinity, barrier blocking and high delivery rates of suspended sediment (Figure 1). Both inputs from the adjacent coasts into river mouths, a factor common in the Mediterranean due to the low discharge of estuaries, and changing basin sediment supply will have marked responses within any estuary or river mouth. So it is not surprising that Roman engineers frequently constructed basins away from natural channels connected by canals to the estuarine river (e.g. Portus and Ephesus). The supply from up-drift eroding coasts is probably underestimated and it is noticeable that the majority of the coastal cells in Spain, France, Italy and Greece are eroding systems today as recognised by United Nations Environment Program map (UNEP 2013; Satta 2017). This is also greatest where many rivers discharge into the same bay as in the case of the harbour of Baelo – the ancient port of Cádiz – which had high sediment input from the west (Bernal-Casasols this volume). An archaeologically visible response to port siltation is dredging. The sites at Piazza Municipio in Naples has revealed scour marks in the tufa (volcanic rock) bed of the harbour caused by dredging (Morhange and Marriner 2005; Giaime *et al.* 2019) and similar evidence has been found at Tyre (Marriner and Morhange 2006). In the ancient harbour of Marseilles three Roman dredging boat dated to the 1st-2ndmillennium CE have been excavated from the harbour floor (Marriner *et al.* 2016). Another response to siltation is modifications in mole design although it is difficult to isolate different factors, such as local variation, in novel designs. The combination of siltation and hiatuses caused by dredging produces harbour sedimentary para-sequences (Marriner *et al.* 2010) and these are integrated in Salomon's Palaeoenvironmental Age-depth Model (PADM) which is fundamentally the application of Quaternary sequence stratigraphy to sediment cores from port harbours (Salomon *et al.* 2016).

Changing Catchment Inputs to Ports

The Mediterranean has been a classic location for studies of changing catchment erosion and sedimentation for over 50 years, with classic studies by from Spain to Jordan (Brown and Walsh 2016; Walsh *et al.* 2019). Several summaries have shown differences between the western and eastern Mediterranean caused by the declining influence of the Atlantic weather systems going eastwards (Roberts et al. 2012; Zielhofer *et al.* 2017) and W-E variation which is seen in palaeo-records and reproduced in modelling (Brayshaw et al. 2013). A recent evaluation of erosion at a pan-Mediterranean scale (Walsh *et al.* 2019) used both lake and fluvial data from 13 areas in the northern Mediterranean. The lakes (n=31) showed considerable variation with only five (predominantly in the western Mediterranean) showing a clear increase in sedimentation during the Roman period and immediately after. The preliminary analysis of fluvial OSL dates (n=140) provides a clearer pattern with an increase in all dates during the period and particularly in Greece, Italy and Spain (Figure 4). This is supported by regional studies in Iberia (Schulte 2003; Thorndycraft 2006), S France, Middle Rhone (Notebaert *et al.* 2014), the Rieti basin in Central Italy (Mensing *et al*. 2015), Greece (Fuchs 2007) and Salagassos, S Anatolia (Bakker *et al*. 2012) and summarised in Walsh *et al.* (2019).

Case Study II: Erosion, sedimentation and the SW Anatolian Ports

The Classical ports of Ilium (Troy), Kane, Elaia, Ephesus, Priene, and Miletus all have a similar geomorphological settings – along incised drowned river valleys (rias formed by early Holocene sea level rise) within grabens draining approximately W-E along the strike of the Western Anatolian massif (Russell 1954; Yilmaz 1997; Chorowicz et al. 1999, Figure 5). This region lies at the junction of the Anatolian and Aegean sub-plates and has the most active neotectonic extensional regime in the entire Mediterranean with high seismicity, lithospheric stress, and high horizontal velocities with both active strike slip and normal faulting common (Carafa *et al.* 2015). One result has been the dominance of subsidence along this coast (Anzidei *et al.* 2014) which also stimulates deposition by increasing sediment accommodation space which is protected from coastal erosion. The siltation of these estuarine-deltaic systems has been remarkably well revealed by generations of archaeological work, but also recent targeted geoarchaeological research particularly by Helmut Brückner and German/Austrian-Turkish archaeological projects. In all these cases the original or earliest harbours predated the Roman period and at the time were at, or near, the mouth of meandering rivers or on the coast.

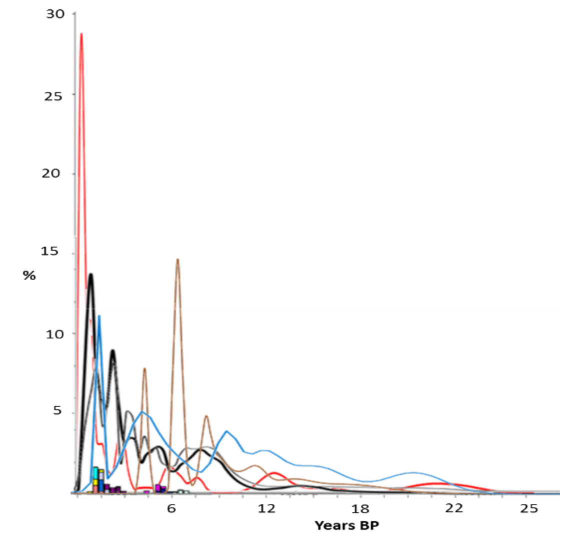

Fig. 4. Frequency analysis of alluvial OSL dates available for the Mediterranean basin by area. For further comment see Walsh et al. (2017).

In a classic paper Kraft *et al.* (2003) showed that for the most northerly port along this coast, Troy, the Classical narrative of Homer's Troy could be married with the geological evidence in the Trojan Plain. Over the Holocene the deltaic plan of the Scamanda River (*aka*. Karamenderes) extended 16.5 km with the river displaying an anastomosing and anabranching (distributary) system. By the Roman period the delta front was 3.2km from the present coastline. The port in both the late Bronze Age and Roman period are not well known but it appears that at least two canals were cut from the river systems to the western coast, possibly involving a silt removal basin (Zangger *et al.* 1996) but it is unknown when these systems went out of use.

Moving south to the Gulf of Elaia there are three ancient ports either side of the Kalikos delta (Kane, Pitane and Elaia) which served the city of Pergamon and its hinterland. The exact location of the coastal harbour(s) of Pitane is unknown but probably lie under the modern town of Candarli and is thought to be related to a tombolo (PortusLimen Website) between two small bays. Kane is also a rocky bay and much of its remains, including a breakwater have only just been located underwater (Brückner et al. 2013; Feuser and Brückner this volume). Elaia was a port by the 3rd century BCE when an enclosing basin was built along with other infrastructure but declined in the late Roman period and was finally abandoned in the Byzantine period (Seeliger *et al.* 2013; Pirson 2014). A core from the ancient harbour (Ela-70) Shows sediment accumulation from before the harbour construction to the present day saltmarshes (Shumilovskikh *et al.* 2016). A noticeable feature is the increase in sedimentation rate around 2000 BP, when water depth would have been under 4m, attributed by the authors to land use intensification. This was probably caused by reducing proximity to the eastern lobe of the Kalikos delta which would have increased sediment influx locally and which would have been transported eastwards into the harbour.

Further to the south is one of the most studied is ancient ports at Ephesus. From research spanning over 100 years but particularly due to the modern work of Brückner (2005), Stock *et al.* (2013) and Brückner *et al.* (2017) the geomorphic history of the port is known in great detail. The location of six successive harbours illustrates the rate of the Kücük Menderes delta plain progradation, with the Roman harbour now being 5km from the coastline. Using a core from the Roman harbour Delile *et al.* (2015) have revealed the siltation of the harbour and a major fluvial event at approximately 0 BCE/CE. This led to anoxia in the harbour and a reduction in sediment supply possibly related to an avulsion of the Kücük river, and which it appears is related to the demise of the port. The delta-plain had by this time built out to the point where it had surrounded several former coastal islands effectively creating a series of bays fed by distributary channels (Brückner *et al.* 2017).

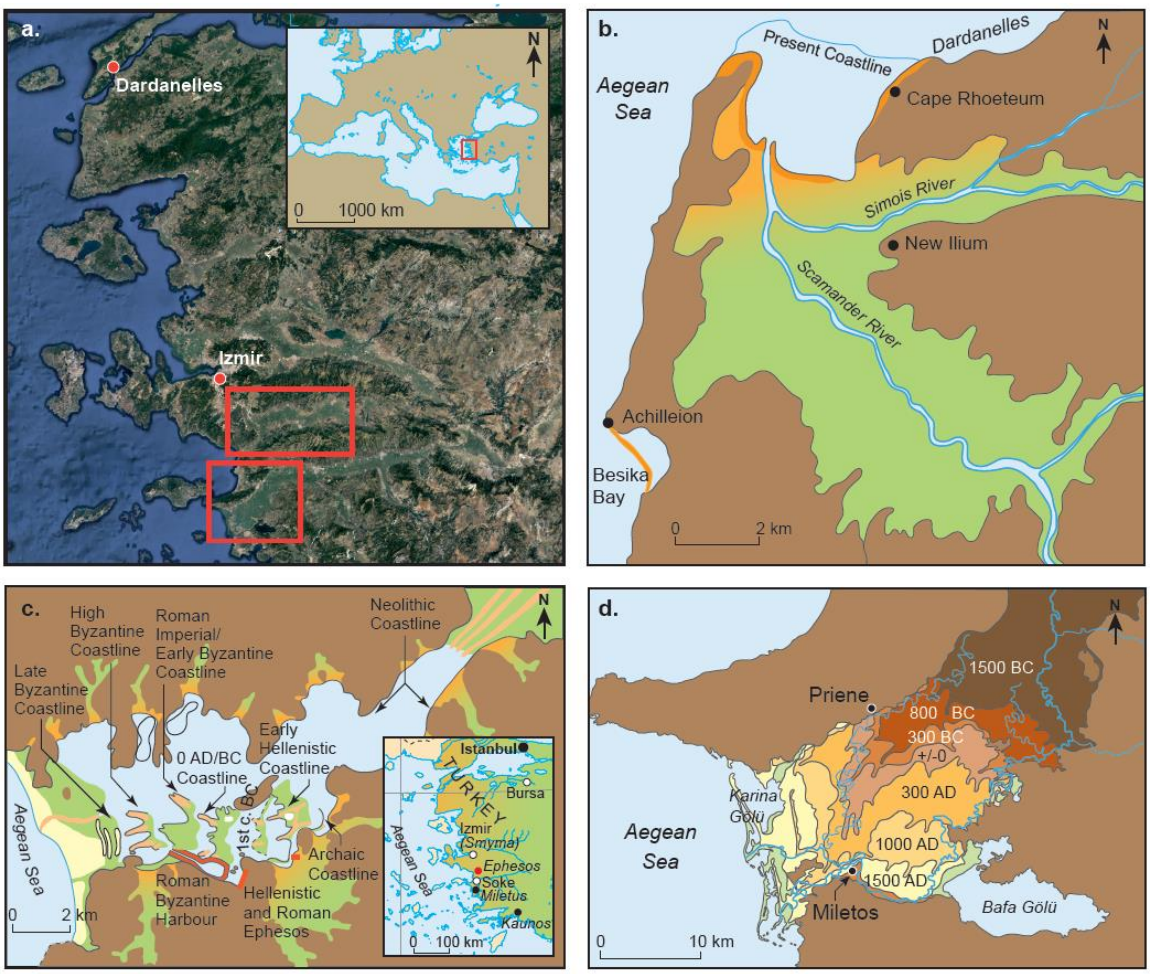

Fig. 5. The Anatolian river valley ports discussed in this paper with sedimentological maps: (b) Troy adapted from Kraft et al. (2003), (c) Ephesos and the Kücuk Menderes valley adapted from Brückner et al. (2017), (d) Miletus and Priene and the Bücuk Menderes Delta plain adapted from Brückner et al. (2017).

The two most southerly ports considered here, Priene and Miletus both lie in the Büyük Menderes (Maeander river) delta plain which discharges into the Latmian Gulf. Again the delta-plain in this graben-valley prograded over 80km in the Holocene with assymetric delta grown first along the northern shore reaching the Hellenistic port of Priene by the 8th century BCE. By the Roman period the southern branch of the delta was still approximately 10km from the coast today (Brückner *et al.* 2017). A factor here is rising relative sea levels in *c.* 3000-2000 BCE probably resulting from neotectonic subsidence. Strong siltation problems at Miletus during the Roam period are attributed to intensification of land use, clearing of forests and livestock farming (Brückner *et al.* 2005). Unfortunately this area has no lakes and so there is very little pollen data to independently assess vegetation change. However, there are sites in southern Anatolia and an analysis of these by Woodbridge *et al.* (2019) shows major reduction in trees and increase in herbs during the last 2000 years attributed to population growth.

The tectonic structures and relative sea level rise created the accommodation space for delta sedimentation but its rate was largely driven by the rate of sediment input from these catchments. Until recently there was little or no geomorphic data on rates of soil erosion to relate to these Holocene sediment stores, however recent work using radioisotopes (especially ^{137}Cs and ^{10}Be) have now provided some estimates. The most comprehensive data is for the Küyük and Büyük Menderes catchments and sub-catchments in the Bozdağ and Aydin mountain ranges. This data includes catchment wide erosion estimates by Buscher (2017) and Heineke *et al.* (2017). The rates for the mountain crests all fall between 0.03-0.09 mm yr^{-1} on both mountain ranges. The rates on the southern flanks of the Bozdağ Range are up to 0.35 mm yr^{-1} and on the north flanks of the Aydin range they are in the range 0.15-0.43 mm yr^{-1}. This reflects the variation in lithologies from erodible faulted and fractures mica schists, to more resistant gneisses in the Aydin range (Heineke et al. 2017). There has been little archaeological survey in these areas but they are all medium-sized catchments (1-157 km^2) and are within 80 km of the classical cities of Ephesus, Priene and Miletus. Using the rates for 22 sub-catchments draining into the Küyük Menderes valley we estimate a mean rate of 0.28±0.03 mm yr^{-1}. These rates compare to catchment wide erosion rates of 0.08-0.46 mm yr-1 for the Bozdag Range and Gediz Detachment made by Buscher et al. (2013). When multiplied by the total catchment area (3500 km^2) this gives an annual background flux of *c.* 100,000 m^3 per year or approximately 200,000 tons of sediment. These are long-period estimates that can be regarded as balancing the continuing uplift of the Büyük Menderes graben sides with exhumation (erosion) and with only the western end being in quasi-equilibrium (Heineke *et al*. 2019).

For present and short-term rates we can use ^{137}Cs rates that have been measured for reservoir life-estimates from two studies in the region, both catchments under cultivation but with lower relief than the Küyük Menderes massif (Haciyakupoglu 2005; Murat and Ichedef 2015). These give a mean rates of 300-540 t km^{-2} yr^{-1} which is equivalent to approximately 500-1000 tons km^{-2} yr^{-1} which would yield 2-3.5 M t yr^{-1} input to the river valley. The range of these estimates probably covers much of the variation during the Holocene from natural rates under forested conditions in the early to middle Holocene to accelerated rates in the late Holocene, and any variation due to changing precipitation and rainfall erosivity. A very approximate comparison with the volume of the Küyük Menderes valley of around 8 M m^3 suggests that these figures are at least in the right order of magnitude, with around 100,000 m^3 infill per year at a constant rate. It also suggests that the variation in sedimentation rates seen at Ephesos from 0.4 mm yr^{-1} to over 4 mm yr^{-1} does reflect changing sediment input from changes in land use as suggested by Stock *et al.* (2014).

A combination of naturally high sediment input from relatively steep erodible semi-arid catchments and neotectonic activity meant that these locations were, over the longue durée, never going to be sustainable. In fact the siltation problem of ports along this coast was observed in the Roman period as revealed in comments by Thucydides (5th century BCE), Herodotus (4th C BCE) Strabo (1 C BCE-1st century CE), Pausanias (2nd century CE)(Brückner 2003; Brückner *et al.* 2017) and Pliny the Elder (Bostock 1855). The archaeological record reveals some of the mitigations that were taken (e.g. successive harbour and canal construction), although it is unclear if any of these observers linked the rate of sedimentation to conditions in the respective catchments. In addition as progradation continued a natural tendency for avulsion increased as floodplain width increased producing bifurcations into an evolving distributary form. This tendency to more channels also reduced individual channel width and depth. This evolution is of course best exemplified by the Kücuk Menderes which gave its name to 'meandering' as a word and geomorphological term commonly accredited to Herodotus and Strabo (Russell 1954; Brown 1997). In fact as noted by Brückner *et al.* (2017) it, and the other valleys discussed here all show bifurcation both near the head of the delta-plain (the deltaic bifurcation node), then about one third down-valley (probably associated with levelling off of the rate of relative sea level rise *c.f.* Pennington *et al.* 2017) and then again when the topographic valley is about two thirds full which is at about the location of most valleys between the Hellenistic and Roman Periods. This could be related to an increase in bedrock slope, a change in sediment supply, or a combination of both. The result is that the classic meandering pattern existed in systems dominated by anastomosing and anabranching channels. From this research we can also see that it was probably in the 19th- early 20th century CE that these systems reached a quasi-equilibrium when they had infilled the whole of the topographic valley above sea-level and started building lobes out into the gulf between promontories, most notably in the case of the Büyük Menderes and the Scamander delta (Troy) with the least lobate being the Kücuk Menderes. At this point the deltas become more sensitive to coastal erosion and continued rising sea levels which has resulted in erosion recognised as a contemporary problem by The United Nations Environment Program map (UNEP 2013; Satta 2017).

Case Study III: Italy and the Tiber: catchment to delta.

As the centre of the Empire for over 350 years Rome has a special place in this subject area. Much has been written about the harbours of Rome (Campbell 2012; Keay 2013; Salomon *et al.* 2018) but here we make an attempt to link the harbour history to sediment delivery from the catchment. Located on only the 5th largest (but 3rd longest) river in Italy, Rome always had a requirement, and over time a dependency on its port(s), as there developed a densely populated hinterland, an unsurprising corollary of being the Empire's capital. Yet the Tiber is far from ideal – being relatively small, with a strongly seasonal discharge and a delta interfingering with a relatively wide coastal lagoonal system resulting in part from pre-Holocene deltaic deposits (Bellotti *et al.* 2007). The Tiber catchment is formed by the lower and upper Tiber basins. Both basins are tectonic in origin with the Upper basin (Tiber graben) being an extensional system that started forming in the lower Pleistocene with intermontane normal fault bounded basins filled with fluvial and lacustrine deposits (Melelli *et al.* 2012). Also the whole Tiber drainage network has undergone uplift since the lower Quaternary (Marra *et al.* 2017). The catchment also includes many relatively erodible lithologies including soft volcanics (pyroclastics-tufa), turbidites, marls, carbonates and Quaternary clastic deposits (Funicello and Giordano 2008). Early Rome was created by the aggregation of villages and the development of trade with the Greek world in the 8th century BCE. The location was advantageous as Rome is about far up the Tiber as it was possible to get river boats all the year round due to a valley constriction by volcanic rocks (Pozzolana complex) just to the south of the junction with the Aniene river (Zeni *et al.* 2011). The early port was therefore river wharfage with goods having to be transferred from maritime craft to river skiffs (*naves caudicariae*) at sea which was hazardous and inefficient, and this lead in time to the development of a 'port system' comprising Rome itself, Ostia, Portus, Centumcellae and Puteoli. Both Ostia and Portus were located on the Tiber delta plain.

Ostia which was a small settlement at the mouth of the Tiber became a military camp (*castrum*) and functioned as a port from Rome from as early as the 4th century BCE (*c.* 330 BCE from sedimentary coring by Salomon et al. 2016). Since the harbour, only recently located by Goiran *et al.* (2014), was located just downstream of a large tidal meander loop it was particularly vulnerable to both siltation and channel change. Coring in the harbour basin has revealed that the harbour started in the 4th-2nd centuries BCE over 6m deep due to construction, then silted, and by the beginning of the 1st century CE depth had reduced to less than 0.5 m (Goiran *et al.* 2014). The sediment record includes several high-energy events (floods) between 164 BCE and 63 CE (Salomon *et al*. 2016). The port was already abandoned during the early development of Portus. The flood-related instability of the Tiber at Ostia is also shown by the avulsion in CE 1557 which cut-off the large meander (Fiume Morto, Goiran *et al.* 2014) and this along with the perennial problem of sandbanks at the mouth of the river reduced port resilience. Much recent work has been undertaken at Portus under the PortusLimen Project (Keay this volume) and here only aspects pertinent to sedimentation and fluvial history will be discussed. The most complete cores from the harbour at Portus which have a basal date just after the end of the 1st century CE reflect sediment input from the Fiumicino branch of the Tiber through the Canale Traverso and also marine influence through the outer harbour. The sequence reveals flood inputs *c.* 138-379 CE but the port continued to function until at least the 9th century AD. Combining these records and also records from the nearly Ostia lagoon (Vittori *et al.* 2015) we have periods of high floods and silt delivery in the early Roman Period (*c.* 160 BCE- 63 AD) and also the later Imperial Period (140-380 CE) and again later in the 16th century. Major floods occurred in 1530 CE, 1557 CE (which caused the avulsion at Ostia) and 1598 CE all of which are well described in contemporary documents (Huijzenveld 2017).

The flood history in parts of the Tiber basin and the region have been investigated over several years (Brown and Ellis 1996; Brown 1997; Walsh *et al.* 2019) and it was one of the first areas to have OSL dating of Holocene fluvial sequences from 3 catchments in the region (Treia, Marta and Fiori). In this study the records of these adjacent basins could be compared with independent proxies of variation in lake levels and also the population of Rome. Of most relevance here is the record from the Treia basin which is a right bank tributary of the Tiber that enters the main channel 40 km north of Rome into the Upper Tiber Basin. This can be combined with the remarkable Tiber flood record (Camuffo and Enzi 1994; Bersani and Bencivenga 2001; Aldrete 2007) and the lake levels of Lake Bolsena (Figure 6). What is fairly clear is a peak in floods in the early Roman period, a slight reduction and then again in the late Roman period. There is then a larger increase in both floods and sedimentation in the Medieval to Renaissance period. This increase in Roman and Medieval-historic alluviation is in agreement with several other data sets including the sedimentation rate in the Stagno di Maccarese which was a lagoon in the Roman period and shows an upturn and high rate of sedimentation after *c.* 300 CE (Giraudi 2011). Another data set is the infra-red stimulated luminescence (IRSL) dating of the coastal dune system near Ostia favoured for villas of the wealthy Romans - where Rendell *et al.* (2007) have shown a x5 increase in progradation since the Roman period.

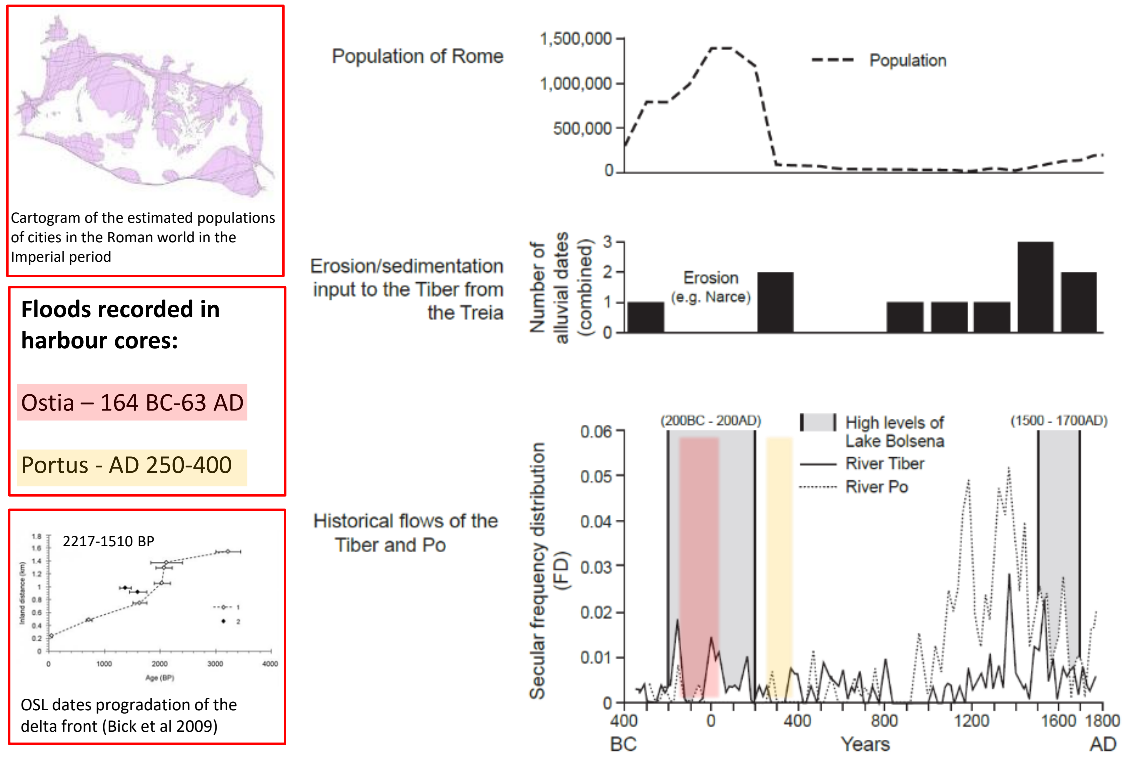

Fig. 6. Flood and alluviation data from the Tiber area. (a) population of Rome, adapted from Hanson (2016), Hanson and Ortman (2017), (b) erosion and sedimentation in the Treia sub-catchment, Rhodes and Ellis unpub.: (c) the Tiber flood history and Lake Bolsena level record adapted from Camuffo and Enzi (1994) and Bersani and Benivenga 2001.

Some of these authors, and others working on alluviation in the region, have attributed the changing sediment rates to climatic fluctuations as recorded in other proxies such as the Alpine glacial record (e.g. Giraud 2011, 2014) or the strength of westerly cyclonic systems across Italy (Judson 1963; Vita-Finzi 1976; Huijzenveld 2017) but other have regarded land use change as critical (Van Andel et al. 1986; Brown 1997; Feiken 2014; Walsh et al. 2019). The relevance of vegetation and land use change is well attested to by the clear imprint of Roman woodland clearance and increases in arable agriculture from pollen diagrams in the region including Lago di Monterosi (Hutchinson 1970), Lago di Baccano (Bonatti 1963) and Lake Martignano (Kelly and Huntley 1991). The importance of land use in the Central Apennines for sediment delivery has also been shown both empirically and through modelling (Borelli *et al.* 2014). It has also been proposed that an anomalous peak in sedimentation in Rome around 2600 BP which caused the formation of the Tiber Island was caused by fault displacement (Marra *et al.* 2018) and this could have had effects downstream. However, both climatic and land use factors are probably involved in both peaks in sedimentation in the Tiber catchment with the early period being coincident with both high lake levels in lake Bolsena and high levels of agriculture and horticulture required to provision what had become the largest city in the Mediterranean. In the later period the record is probably a response to the Little Ice Age. There is certainly non-stationarity of the flood series over the last 500 years which Calenda *et al.* (2005) attribute to climate change. This upstream record fits well with the record from the ports – the flood and siltation problems that resulted in the demise of Ostia, and creation of Portus and then the flooding that eventually lead to the abandonment and burial of much of Portus. It is also likely that Portus remained sustainable for so long due to a combination of its design, dredging and a relative reduction in river flooding and silt input.

Conclusions

An analysis of the geomorphology of 50 key Roman ports highlights that around half were located within or at the mouths of deltaic plains and were sensitive to changing fluvial and catchment conditions. Interestingly many of those that were coastal on rocky bays and tomobolos actually survived into modern times as ports even if buried by modern urban development (e.g. Tarracco-Taragona, Narbo, Piraus). These and other part-constructed ports, such as Lechaion, faced multiple stresses from coastal sedimentation or erosion, and uplift or subsidence which resulted in continuous dredging and in many cases harbour redesign. All of the deltaic plain – fluvial ports, faced problems of siltation which had also been faced in Hellenistic times. The Anatolian Roman ports were particularly vulnerable due to a combination of high geological erodibility (including neotectonic factors), land use change and subsidence. Potential exists in this area to apply a sediment budget approach to the infilling of these graben sediment traps. Many Roman ports suffered from siltation problems towards from the 2nd-4th centuries CE to the point in some cases of complete burial (e.g. Pisa) or abandonment (e.g. Ostia). It is likely that this was largely driven by upstream land use change and intensification associated with population growth. However, some such as Portus, continued through periods of high sediment flux assisted by the use of an improved design and dredging, whereas other such as Pisa and Ostia become inoperable. The sustainability of Roman ports, was an issue in the Roman period and may have stimulated innovations and led to variable resilience in ports. So geomorphology – particularly related to initial location and catchment history are important factors in the individual histories of Roman ports and port systems. Interestingly out of the 5 largest maritime port in the Mediterranean today (Algeciras, Valencia, Barcelona, Gioia, Genoa) all except Gioia (began in CE 1995) were Roman ports located on bays and set off from small rivers mouths, but not one is located on a deltaic plain.

Acknowledgements

The authors must acknowledge a number of collaborators who have assisted with both the case studies and text. These include Ed Rhodes, Clare Ellis, Ferreol Salomon, Greame Barker, Tim Potter (deceased) and particularly Simon Keay who encouraged this work throughout. Work utilised here was funded under a variety of grants including from the British Academy and the British School in Rome.

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Table 1

Type	Description	Hazards	Examples
Artificial Harbours (AH)	Either jetties, breakwaters or moles where there is no bay at all or basins excavated into bedrock (cothons) connected to the sea by canal	Jetties etc suffer from RSL changes, and erosion, basins can silt up due to a lack of flushing (sediment traps)	Leptiminus (jetty) Carthago (basin) Phalasarna (cothon) Caesarea Maritima (enclosed basin) Alexandria (enclosed basin) Byzantium (breakwaters, moles etc.)
Rocky Bays (RB)	Small bays (coves) in hard-rock (limestone) steep coasts often with small streams entering and rocky islands (or reefs) off bays that can be connected to the mainland forming a harbour (cf. artificial tombolo)	If have fluvial input siltation can be a problem, occasionally changes in coastal sediment supply which can create tombolos with two bays, neotectonic changes	Gades (island type) Carthago Nova (natural bay) Massalia (rocky cove) Cemtum Cellae (cove at mouth of ephemeral river) Neapolis (natural bay augmented) Pieus (island connected to mainland) Byzantium (rocky bays) Pitane (island becomes tombolo) Kition Bamboula (natural embayment) Beirut (island-reef) Sidon (rocky bay with a reef) Tyre (2 rocky bays) Sullectum (rocky bay and island), Pollentia (Mallorca)
Lagoonal Harbours (LB)	Harbours within or at the mouth of shallow lagoons in deltas r large coastal plains, mouths protected by barriers & generally a fluvial input (but not always)	Closure of the mouth by barrier growth, lagoonal sedimentation, delta growth into the lagoon, eutrophication	Vada Volterrana (coastal plain) Cumae (lagoon behind barrier) Puteoli (probable lagoon – canal) Coppa Navigata (lagoon) Galias (lagoonal bay), Lechaion
Fluvial Harbours (FB)	At river mouths or upstream in larger rivers or in floodplains connected to rivers by canal	Channel changes, including avulsions, siltation (from the river and sea), coastal progradation, barrier growth, debris accumulations, neotectonics	Hispalis (river port R. Quadalquivir) Tarraco (river mouth of R. Sulcis) Narbo (river mouth R Aude) Arelate (river port R Rhone) Forun Julii (river mouth R Reyran) Portus (river mouth R Tiber) Ostia (river mouth R Tiber) Aquiliea (river port R Natisone) Elaias Limen(river mouth R Acheron) Troy (river port R Scamander) Kane (river port R Cayster) Elaia (river mouth R Caïcus) Ephesus (river mouth-canal R Kaystros) Miletus (river mouth R Meander) Priene (river port R Meander) Leptis Magna (wadi mouth Libda Wadi) Utica (river mouth R Medjerda) Saintes-Maries (France), Oiniadai (Greece), Herakleion (Nile Delta), Seleucia Piera (Turkey)