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Late-Holocene catastrophic floods in the terminal Arno River (Pisa, Central Italy) from the story of a Roman riverine harbour

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Abstract: The results of the stratigraphic and sedimentological analysis carried out at an exceptional archaeological site situated in the coastal plain of the Arno and Serchio Rivers (western Tuscany, Italy) are reported. The site, discovered near central Pisa, records a 1000-yr history of a riverine harbour built by the Etruscans and used by the Romans. This harbour was adjacent to the Arno River, located within an abandoned channel then still connected to the sea, thus allowing efficient stock transfer to and from Roman Pisa. The archaeological importance of this site is primarily due to the discovery of at least 16 well-preserved Roman ships and many other remains mostly deriving from their cargoes. The sedimentological relevance of this record is related to the recurrent, catastrophic, destruction of the harbour documented by the features of the sediment encasing the ships and by the ships' distribution and age. Such repeated destruction was related to catastrophic flood flows generated by levee crevassing of the Arno River during high-magnitude floods that occurred between the second century BC and the fifth century AD. The Pisa harbour tells a story of river channel instability. The repeated flooding of the harbour indicates that the Roman Arno River attempted to abruptly change its course, exploiting a pre-existing river channel. The concomitance of climatic and eustatic causes is expounded upon to explain the sedimentary dynamic of a coastal floodplain during historical times.

Key words: Late Holocene, Arno River floodplain, Roman harbour, catastrophic floods, river channel instability, Italy.

Introduction

Late Holocene floodplains represent terrestrial sedimentary archives suitable for searching evidence of recent environmental changes. The geomorphic and depositional dynamic of Late Quaternary floodplains results from a complex interplay of eustatic, tectonic, climatic and, in recent times, anthropogenic factors controlling river profile stability, water and sediment discharges to fluvial systems (Blum *et al.*, 1994; Blum and Tornqvist, 2000; Straffin and Blum, 2002; Gregory and Benito, 2003; Thorndycraft *et al.*, 2003).

Among various physical processes operating in floodplain environments, river channel instability (avulsion) may be of particular interest in understanding the geomorphic and sedimentary dynamic of these settings.

Fluvial channel instability occurs when a critical threshold is exceeded, making flood events able to breach the channel levees (Jones and Schumm, 1999). Avulsion can be the response of a river system to local channel clogging or obstruction resulting from a wide range of local causes. Factors operating on longer periods and controlling the overall system's slope and geometry, also trigger avulsions such as base-level change (Bristow *et al.*, 1999; Jones and Schumm, 1999; Stouthamer and Berendsen, 2000), tectonic movements (Peakall *et al.*, 2000) hydrological (high-magnitude or catastrophic floods) or sedimentary events (rising sediment influx, mass failures) (Jones and Schumm, 1999).

The case discussed in this paper documents an exceptional example of how natural and anthropogenic processes interacted, over a timespan of about 1000 years, promoting or preventing channel instability in the terminal reach of the Arno River (central Italy). The data have been provided by the

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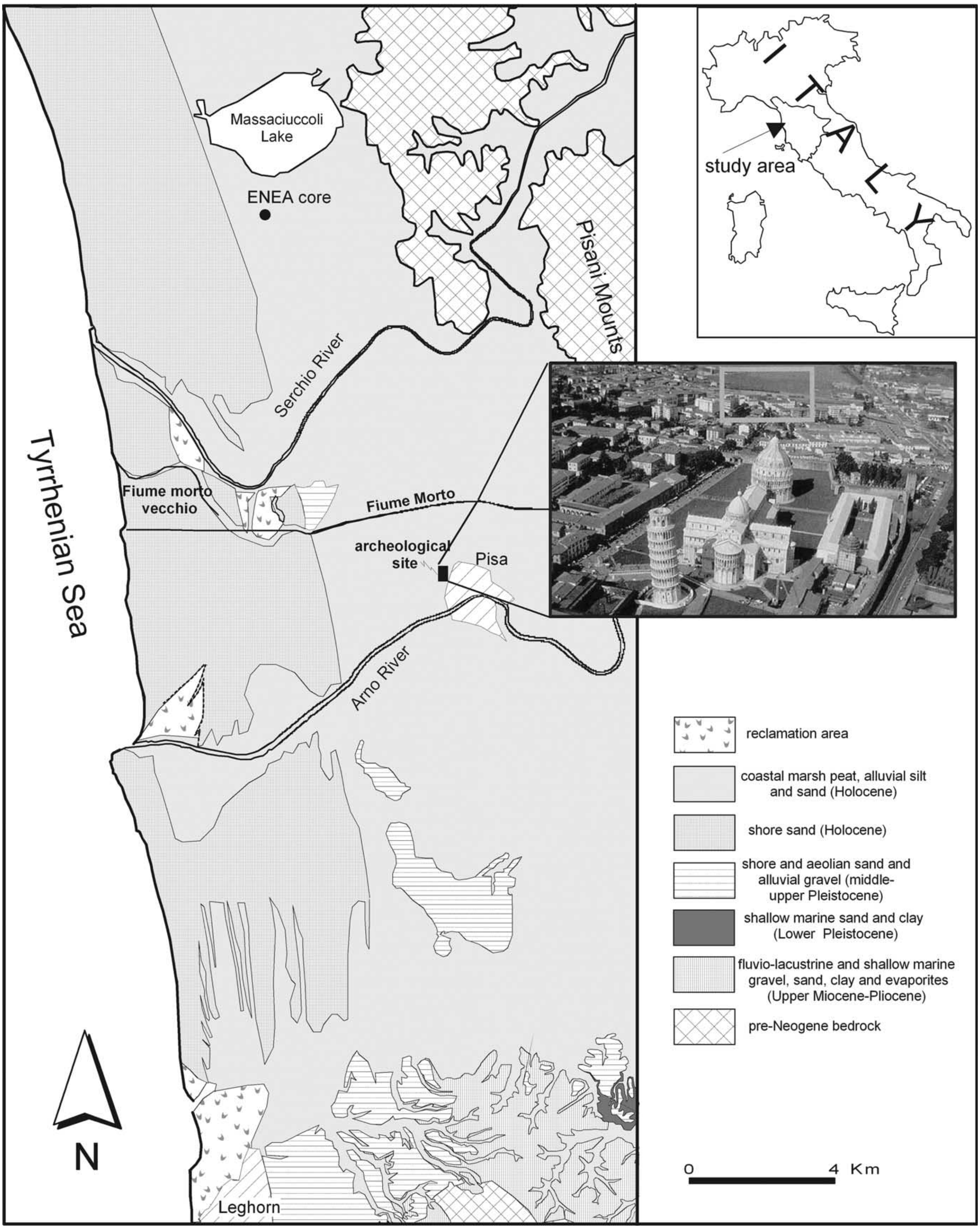

Figure 1 Schematic geological map of the Arno and Serchio rivers coastal plain. The oblique aerial photograph shows the approximate location (boxed area) of the archaeological site in respect to the famous Piazza dei Miracoli

discovery of the remains of a Roman urban harbour in December 1998 at Pisa (Figure 1). The archaeological importance of this discovery is mainly due to the presence of 16 extraordinarily well-preserved vessels, eight of which have been almost excavated; and second, to the quantity and variety of the items that were part of their cargo and the crew's equipment (Bruni, 2000, 2002, 2003). However, from a sedimentological perspective these items represent unusual tracers of high-magnitude flood events that affected the Arno River plain. The focus of this paper concerns the interplay of

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high-magnitude hydro-climatic events, century-scale sea-level fluctuations and possible human management of a floodplain on the dynamics of geomorphic and sedimentary processes.

Geological setting

The study site is located in western Tuscany (Central Italy) on the coastal plain of the Arno and Serchio rivers (Figure 1), an area dominated by meandering river migration, fine-grained overbank deposition and human settlement since prehistoric times. The floodplain is characterized by a dense network of secondary drainage, in large part made of artificial ditches but also of abandoned river channels. Among the most prominent, the *Fiume Morto* (dead river) and the *Fiume morto vecchio* (old dead river) are former river channels, still occupied by water, suggesting what the coastal plain must have been like about 2000 years ago (see below).

At present the area is part of the coastal Arno River basin (Viareggio Basin, Martini *et al.*, 2001), filled by 2000 m thick Neogene and Quaternary, fluvial and shallow marine gravel, sand, clay and evaporites of Messinian age (Lazzarotto *et al.*, 1990). The basin is contained within a widespread system of tectonic depressions developed since the late Miocene on the western side of the Northern Apennines and, in coastal Tuscany, strongly influenced by the extensional opening and widening of the northern Tyrrhenian Sea (Martini and Sagri, 1993; Martini *et al.*, 2001).

The Quaternary fill of the coastal Arno River plain is known from a few exposures on the southern end of the basin, and from cores (Della Rocca *et al.*, 1987; Baldacci *et al.,* 1994; Mazzanti, 2002; Aguzzi *et al.*, 2005). In particular the Upper Pleistocene and Holocene fill of the basin consists of more than 100 m of fluvial and coastal terrigenous sediments accumulated during and following the last glacial period (Aguzzi *et al.*, 2005).

The archaeological site: location and geology

The site is located in the Pisa urban area (Figure 1), about 1 km north of the Arno River and 9 km from the Tyrrhenian coast. The site was discovered during construction works in 1998, in a N–S trending, roughly rectangular, excavation about 5 m deep below the local topographic surface (about 2–3 m a.s.l.). The archaeological material (Figure 2A, B) is mostly encased in sands and consists of eight complete ships, partial remains of eight more ships and their freight, including thousands of amphorae and other well-preserved items, with abundant animal and vegetal remains in subfossil conditions (Bruni, 2000). The location of the ships (labelled from A to H) and related material are described, making reference to five areas (1–5) of archaeological excavation (Figure 3). Preserved portions of possible harbour infrastructure were also discovered at the site, consisting of an *in situ* wooden palisade (Figure 2C), two stone piers and fragments of a wooden pier.

A radiocarbon chronology is available for some materials of the southern side of the site (Belluomini *et al.*, 2002), such as the palisade that could be part of an early, Etruscan, harbour and wood bracketed between the eighth and second centuries BC. Dating performed on the ships and on wood in the sediment encasing the Roman material, together with an archaeological chronology, point to an overall timespan ranging from the fifth century BC to the fifth century AD (Bruni, 2000), including therefore the entire Roman Age (Tables 1 and 2, see also Figure 8).

Two main stratigraphic units are exposed in the excavation (Figure 3): (1) pre-Roman-harbour fine sands and muds on which the palisade was erected; and (2) sands and subordinate muds containing the ships and correlated Roman material.

Shallow cores (Figures 3 and 4) extracted from the surrounding area indicate that about 5 m of post-Roman/modern floodplain mud and anthropogenic debris rest over 2–5 m of fluvial sand. The latter are characterized by an upper portion, about 2–3 m thick, encasing the archaeological material (Roman sand), resting on a lower portion lacking any remains (pre-Roman sand). On the whole these sands erosively overlie brackish muds, which in turn rest over floodplain deposits. The latter are referred to the last glacial sea–level lowstand (late Pleistocene) whereas the former are referred to the subsequent postglacial transgression (early–middle Holocene). A calibrated age of about 6430–6045 yr BP from *Cerastoderma* cf. *glaucum* shells sampled in the uppermost brackish mud of core 4 (Figure 4) supports this conclusion. A similar succession was cored in the nearby coastal region of Versilia (ENEA core, Figure 1), about 11 km NW of the site and 5 km from the sea, and calibrated through extensive radiocarbon dating (Antonioli *et al.*, 2000; Lambeck *et al.*, 2004a). Brackish mud dated at about 10 146 ± 90 BP and found at a depth of 34 m marks the beginning of the postglacial transgression of the Versilia Plain.

The sharp, erosive, contact between the sands and the underlying brackish muds suggests that fluvial incision occurred in the coastal plain during the late Holocene, a time considered to mark the postglacial highstand of sea level.

The stratigraphic position of the sandy body bearing archaeological remains and its resulting lens geometry resulted in the exceptional preservation of wood and other delicate perishable items. Encased between mud-rich deposits, the sandy body represents a confined, isolated, small-scale saturated aquifer, characterized by the absence of groundwater flow, thus preventing the oxidation of organic matter.

Facies analysis

Several archaeological trenches enabled detailed stratigraphic and sedimentologic analyses on the deposits exposed in the site. Four main lithofacies assemblages were distinguished: (a) pre-Roman-harbour fine sand and mud, (b) NW-accreting coarse-medium sand, (c) W-accreting coarse-medium sand and (d) fine sand and mud draping both assemblages (b) and (c).

The pre-Roman-harbour fine sand and mud

These deposits (Figure 2C) have been observed exclusively in the southern portion of the main site (see Bruni, 2003, for further documentation), for a total thickness of about 0.7 m, consisting of silty-sandy and muddy horizontal beds. These deposits represent the substratum of human activity since the Iron Age (Etruscan period), as documented by the palisade driven in their top and by other lines of evidence collected in neighbouring areas (see below).

The silty sand is greyish, both massive and thinly plane-laminated. Muddy beds are green-reddish, mostly massive. Organic-rich beds formed by vegetal debris occur locally. No macrofossil remains have been found in these deposits whereas pollen analysis carried out in muddy beds provided some interesting results (Begliomini *et al.*, 2003; Mariotti-Lippi *et al.*, 2006). The stratigraphically lowest muddy levels sampled

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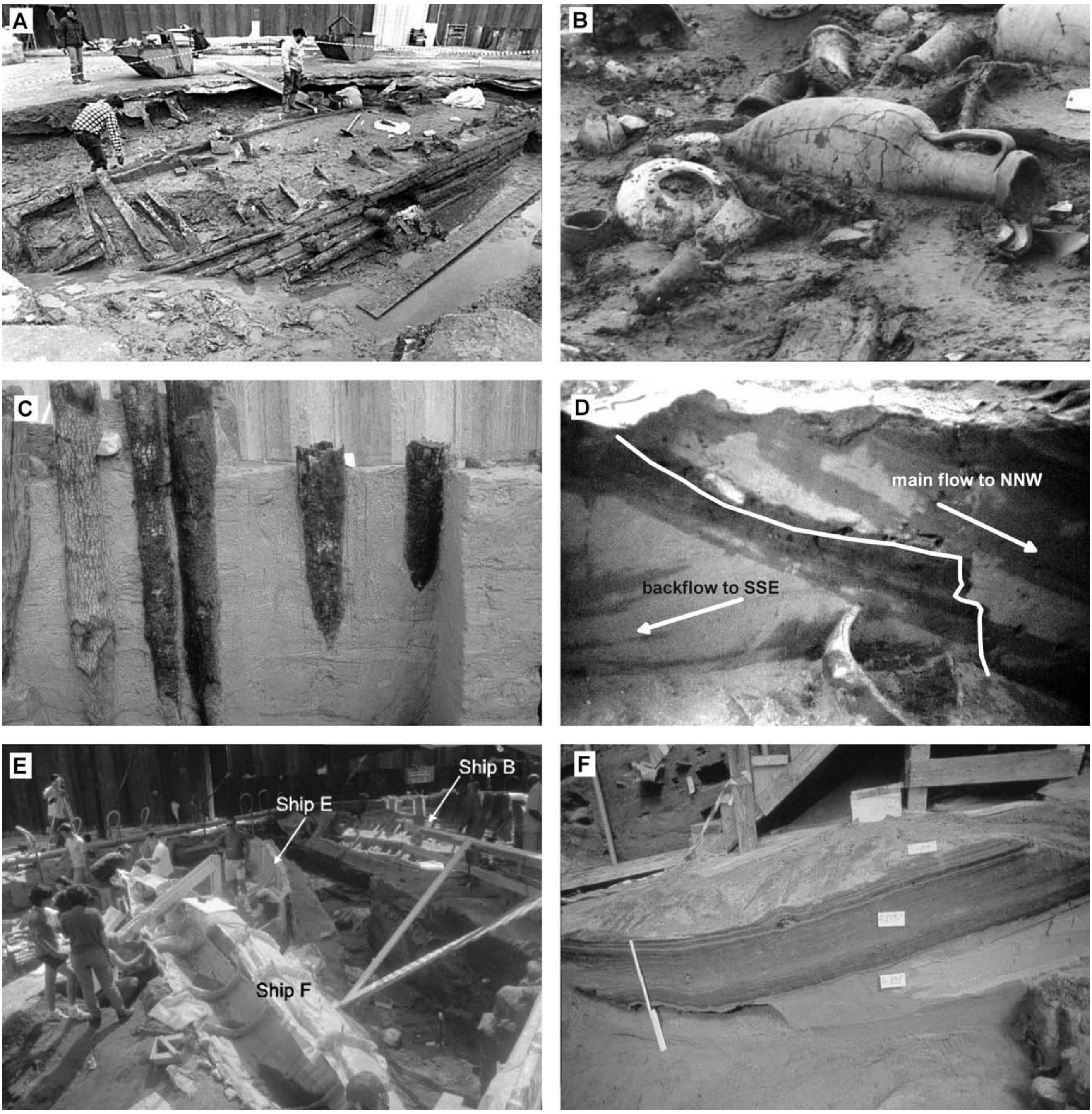

Figure 2 Archaeological and sedimentary features of the Pisa-S.Rossore site: (A) ship D (person for scale); (B) amphorae from the ship's cargos; (C) tree logs of the Etruscan palisade within the lithofacies (a) deposits; (D) cross-bedded sands dipping to NW (lithofacies (b)), note the amphora 'clast' in the sand and the upcurrent (ie, SE-dipping) laminae related to backset stratification (Figure 5A for details); (E) area 2–3: imbricated ships B, E and F from NW-flowing flood flows, persons for scale; (F) vegetal debris-rich inclined silty-sandy beds (lithofacies (d)) on the top of unit 1 in area 4 (the rod is 30 cm long)

are characterized by an arboreal cover mainly constituted by *Abies* and *Fagus*. *Fagus* pollen particularly reaches very high percentages (25–27%), which have not been recorded in other samples in the site suggesting the development of a cold-moist forest close to the site. In Tuscany, the occurrence of *Fagus* at low altitudes during the early sub–Atlantic has been hypothesized based on relic *Fagus* populations and archaeobotanical remains (Negri, 1927; Castelletti, 1980). In the upper levels, *Abies* and *Fagus* pollen abundance decreases, whereas a deciduous broadleaved forest seems to expand as a consequence of warmer climate. Throughout the succession, the pollen grains of hygrophilous plants, particularly *Alnus* cf. *glutinosa* and aquatic plants either appear or increase, although their percentages are always low. Halophytes are sporadic ($\leq 1\%$), indicating a condition fully compatible with the present pollen concentration of these taxa in the inland areas of Tuscany.

Interpretation

Lithology, texture and bedding of these rhythmically stratified deposits point to depositional conditions alternating between fluidal flows, loaded with silt and fine sand, and settling of mud and organic material in more tranquil conditions. Lack of marine or brackish fossils suggests a fully terrestrial depositional setting that is also confirmed by pollen analysis. These data support the picture of a local environment initially characterized by a cold-moist forest, expanse of fresh water in the area and a negligible marine influence. On the basis of

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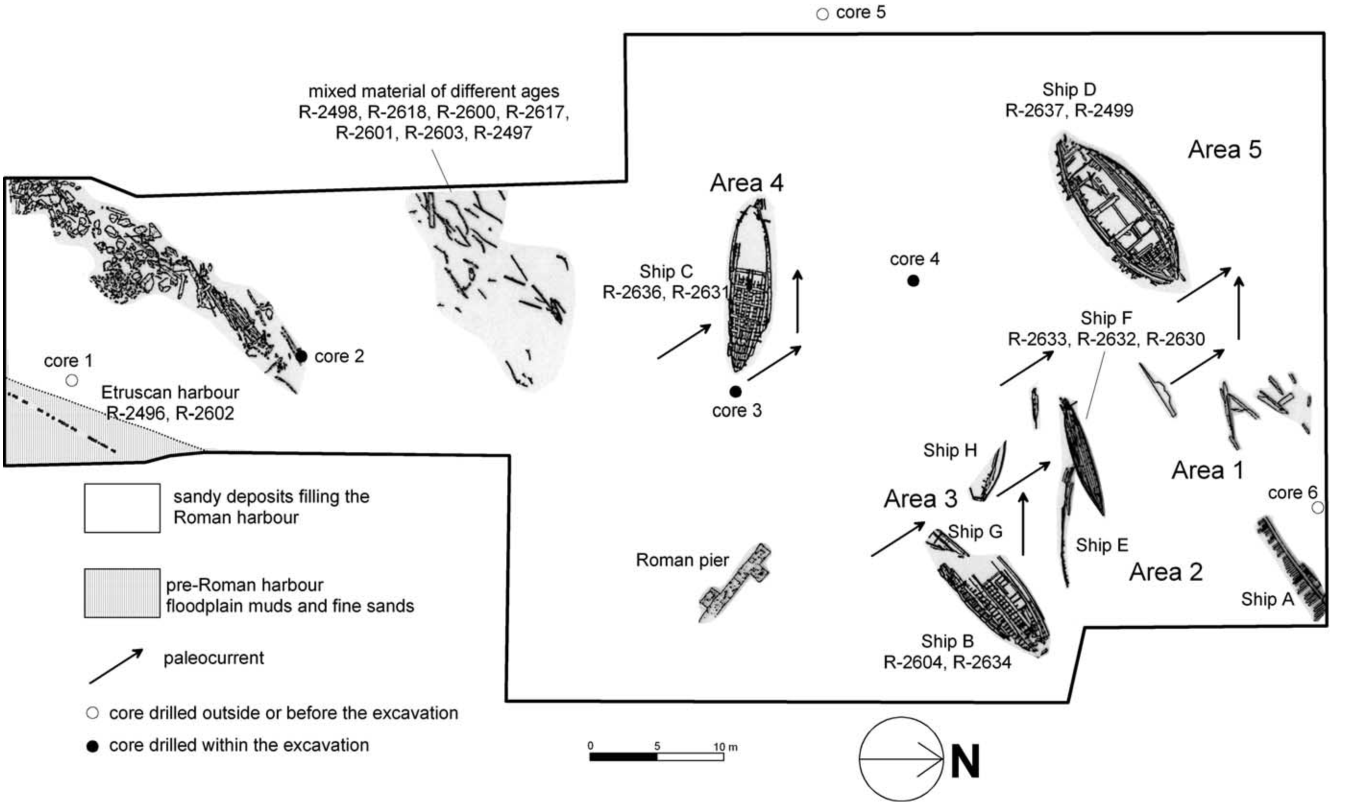

Figure 3 The archaeological site (plane): distribution of the ships and other materials and measured palaeocurrents (drawn to scale of ships after Bruni, 2000). Codes refer to the dated materials (see Table 1). Trenches were excavated in areas 1–5 around the ships

the lithological and bedding features, these deposits, in fact, are interpreted as the product of fluvial overbank settling, inducing the vertical accretion of a floodplain during a cold-moist/temperate climate transition. Sand-silt laden flows derived from a nearby active channel during major floods and fine-grained deposition occurred during the subsequent waning stages and/or following lesser floods.

NW-accreting coarse–medium sand

Sediment encasing most of the archaeological material consists of coarse–medium sand in decimetre to metre-scale planar cross-beds with intervening thin muddy and silty-sandy beds (Figure 2D, 5A). These beds dip mostly to the NW, that is in a direction subparallel to the nearby Tyrrhenian coast. Sandy cross-beds include centimetre to decimetre thick lenses of

Table 1 C14 datings of archaeologic and palaeontologic materials from the Pisa site

Laboratory code	Dating material	Conventional C14 age	Calibrated C14 age	Sedimentary unit
Beta-171194[a]	*Cerastoderma* shell	5800 ± 80 BP	4430 ÷ 4045 BC	Brackish mud–core 4
R–2602[b]	Palisade	2688 ± 107 BP	1000 ÷ 400 BC	Lithofacies (a)
R–2498[b]	Ship fragment	2658 ± 31 BP	900 ÷ 790 BC	See Figure 4
R–2618[b]	Pier fragment	2596 ± 53 BP	860 ÷ 520 BC	See Figure 4
R–2600[b]	Pier fragment	2558 ± 53 BP	830 ÷ 510 BC	See Figure 4
R–2496[b]	Palisade	2499 ± 38 BP	800 ÷ 480 BC	Lithofacies (a)
R-2636[b]	Ship C	2476 ± 47 BP	780 ÷ 400 BC	Lithofacies (b)–Unit 1
R-2633[b]	Ship F	2341 ± 116 BP	800 ÷ 250 BC	Lithofacies (b)–Unit 2
R-2632[b]	Ship F	2329 ± 121 BP	800 ÷ 210 BC	Lithofacies (b)–Unit 2
R-2631[b]	Ship C	2280 ± 113 BP	800 ÷ 360 BC	Lithofacies (b)–Unit 1
R-2630[b]	Ship F	2357 ± 54 BP	800 ÷ 350 BC	Lithofacies (b)–Unit 2
R–2617[b]	Pier fragment	2264 ± 42 BP	330 ÷ 200 BC	See Figure 4
R–2601[b]	Ship fragment	2233 ± 41 BP	400 ÷ 190 BC	See Figure 4
R-2604[b]	Ship B	2211 ± 63 BP	390 ÷ 50 BC	Lithofacies (b)–Unit 1
R-2629[b]	Ship F	2179 ± 55 BP	390 ÷ 90 BC	Lithofacies (b)–Unit 2
R–2603[b]	Ship fragment	2159 ± 69 BP	390 ÷ 140 BC	See Figure 4
R-2634[b]	Ship B	2239 ± 78 BP	410 ÷ 50 BC	Lithofacies (b)–Unit 1
R–2497[b]	Pier fragment	2120 ± 39 BP	240 ÷ 40 BC	See Figure 4
Beta-171195[a]	Clastic wood	2000 ± 40 BP	80 BC ÷ AD 80	Lithofacies (b)–Unit 2
Beta-171196[a]	Clastic wood	1980 ± 50 BP	80 BC ÷ AD 120	Lithofacies (b)–Unit 3
R-2635[b]	Ship D	1805 ± 52 BP	AD 80 ÷ 350	Lithofacies (b)–Unit 4
R-2499[b]	Ship D	1605 ± 34 BP	AD 380 ÷ 550	Lithofacies (b)–Unit 4

[a] Dates from Belluomini *et al.* (2002).
[b] Dates from this study.

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Table 2 Archaeological dating of materials and ships from Bruni (2002)

Ship	Archaeological age	Dating material
A	Second century AD	Cargo material (mostly amphorae)
B	AD 7	Asse Augusteo (bronze coin)
C	First century BC–first century AD	Cargo material (mostly amphorae)
D	Fifth century AD	Ship building technique
E	AD 40	Cargo material (mostly amphorae)
F	AD 130	Asse Adriano (bronze coin)
G	First–second century AD	Cargo material (mostly amphorae)
H	First–second century AD	Cargo material (mostly amphorae)

pebbly sand with associated mud clasts, characterized by a SE-dipping lamination (Figure 2D). Subfossil organic remains in these deposits are always reworked and are represented by vertebrate bones (including *Homo*, wild and domestic animals, Bruni, 2000), mollusc shells related to both marine and brackish environments, and vegetal remains ranging from large tree trunks to leaves and seeds. The ships and the thousands of finds represent unusual outsized 'clasts' dispersed within the sand. The keels of some ships are oriented roughly parallel to the bed strike and dip toward the NW (Figure 2E). On the whole, NW-dipping bedsets are bounded by high-relief erosional surfaces.

Interpretation

These deposits are interpreted as frontal accretion of sandy macroforms from NW-directed flood flows. The dimension and orientation of the sandy cross-beds make a marine origin of such macroforms highly improbable. Storms and tidal inflows, in fact, can not be invoked because of the distance of the site from the contemporary coastline (about 3 km, see below) and to the microtidal regime characterizing the northern Tyrrhenian coast during the Quaternary, respectively. The fossil content indicates a mechanical reworking of terrestrial and shallow marine organisms in large part related to the cargo of specific ships (see Bruni, 2000, for details). In particular the shell remains, in large part represented by *Glycimeris*, point to a mollusc association typical of the lower shoreface, an environment significantly far from the site in the Roman time (see below). Provenance of the marine shells can be related to the ships' cargoes, as indicated by many shells found within some ships, or alternatively in the case of abraded shells, to reworking from Pliocene and lower Pleistocene marine deposits cropping out in the terminal Arno River basin.

These flood flows, fully compatible with a fluvial source close to the site (see below), were loaded with sand as well as the ships and their cargo, which were transported from a nearby mooring area. Thin inclined muddy and sandy-silty beds record waning stages among major flood surges. Occasional lenses of SE-dipping pebbles and sands impart a bipolar

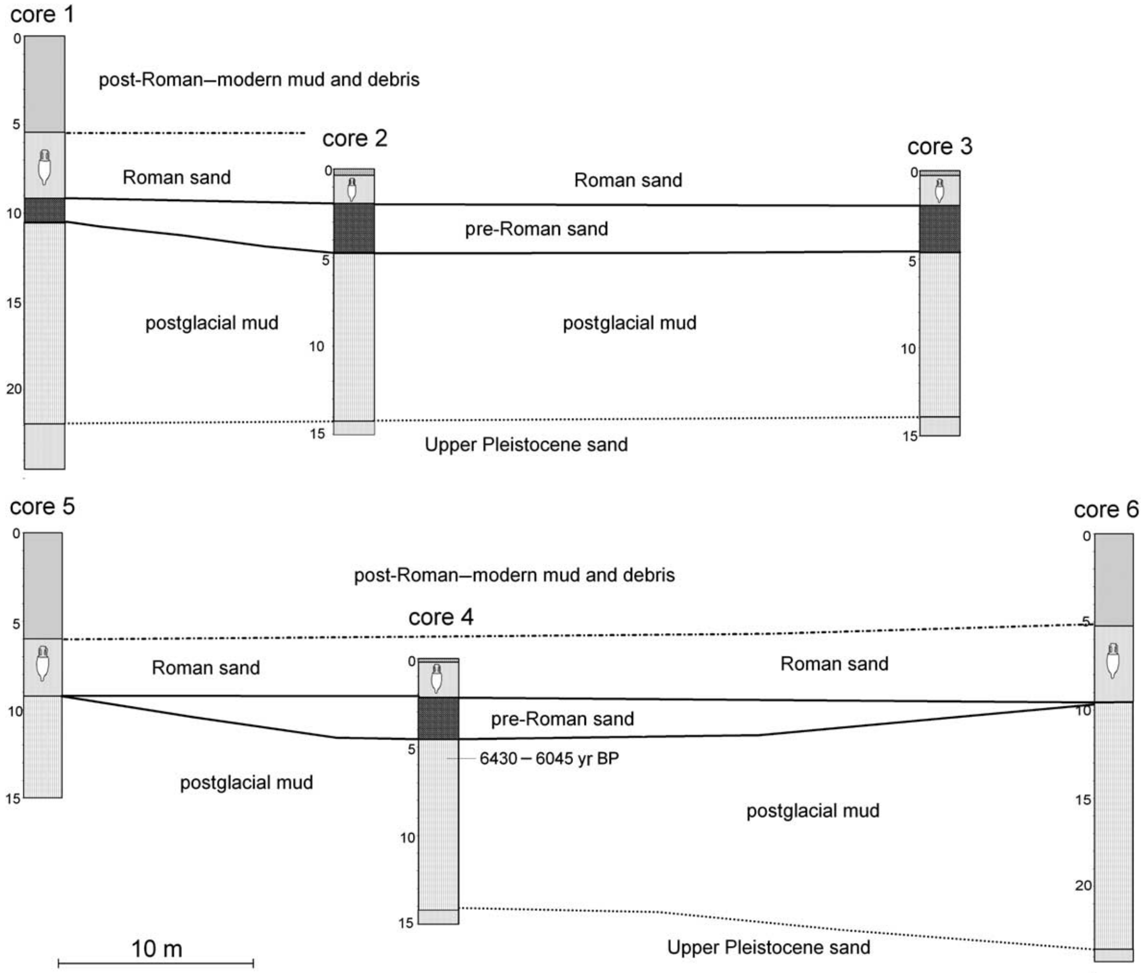

Figure 4 Correlation among the cores available in the site and in the surrounding areas (see Figure 3 for the core locations). The top of cores is referred to the local topographic surface, vertical scale in metres

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current pattern to these deposits. The microtidal setting of the coastal area facing the site, joined with the dimension and orientation of cross-bedding, makes reverse flows of tidal origin an improbable cause for these structures. They are interpreted as a backset stratification related to backflows on the lee side of the macroforms. This stratification is quite a common depositional feature in subaqueous slopes such as delta fronts and steep shorefaces being referred to the occurrence of hydraulic jump that generates flow separation and turbulent vortexes (Massari, 1996). The latter cause bottom erosion and backfilling of scours with 'upflow'-accreting cross-beds. In the present case backflows may have been caused by obstacles on the bottom, such as ships, amphorae or large tree trunks, which locally disturbed the main flow, generating vortexes. Scours in the bed were then filled with coarse pebbly-sandy backset units. The stratal architecture of this facies, ie, cross-bedsets bounded by high-relief erosional surfaces, indicates cut and filling stages during a major flood phase.

W-accreting coarse–medium sand and pebble

Coarse–medium sands with sparse pebbles, characterized by less abundant archaeological material and organic remains and erosionally stacked on the NNW accreting macroforms, occasionally occur in areas 3, 4 and 5. These deposits are characterized by a complex cross-bedding indicating palaeocurrent dominantly to the W. Inclined bedsets are up to 1 m high and in strike sections they appear trough-cross-bedded with coarse-grained sands and pebbles displaying a lateral interfingering: inclined sandy beds abruptly pass on to pebbly beds. Similarly to the NW-accreting sands, thin muddy beds are interbedded within the coarse-grained material.

Interpretation

These deposits denote frontal accretion of sandy macroforms from flows directed to the W. Erosional contacts with NW-accreting macroforms indicate scouring of older deposits and subsequent fill by the westward accretion of sands and pebbles. The abrupt transition of sand and pebble in sections orthogonal to palaeoflow are quite similar to those reported from ancient and recent deposits of bedload-dominated multichannel rivers (Siegenthaler and Huggenberger, 1993). In deposits of braided rivers this lateral graded bedding is interpreted to result from flows loaded with different grain-size populations merging in a pool, and this could be a suitable interpretation for the case at hand. Again the multitude of objects in the flooded harbour area disturbed the main flood-flow controlling the development of small channels and pools then filled by converging flows carrying selectively sandy or pebbly bedloads.

Fine sand and mud drapes

Fine-grained deposits drape both NW- and W-accreting macroforms (Figure 2F). These are made of fine sands, silts and muds in planar-inclined centimetre to decimetre thick beds, forming bedsets up to 1 m thick. Beds can be both massive, because of bioturbation by roots and possibly terrestrial and freshwater invertebrates, or thinly laminated. In particular, silty beds rich in vegetal debris, mostly composed of leaves of deciduous trees, are common and characterized by thin lamination. Pollen analysis has been performed on these deposits (Begliomini *et al.*, 2003; Mariotti-Lippi *et al.*, 2006). Despite an overall scarce arboreal cover, *Abies* and *Fagus* pollen grains feature low percentages whereas the *Quercus* deciduous group is widely present together with other elements of the deciduous broadleaved forest (*Corylus*, *Carpinus betulus*, *Ostrya*/*Carpinus orientalis*, *Tilia*, *Acer*, *Ulmus*, *Fraxinus*, etc.). The Mediterranean sclerophyllous evergreen elements, including *Quercus ilex*, *Pistacia* and *Myrtus*, are few or sporadically present. Hygrophilous plants, particularly *Alnus* cf. *glutinosa*, and aquatic herbs are abundant.

Interpretation

These deposits are interpreted as the draping of the coarse-grained deposits, described above, which accumulated from low-volume flows punctuating major flood stages. Suspension settling of mud and vegetal debris and possibly traction plus fall-out of silty sand determined the deposition of these beds. Climate was temperate during these depositional events, as demonstrated by pollen analysis. The significant abundance of hygrophilous plants indicate a freshwater environment, as indirectly confirmed by the absence of or very low, pollen percentages of the halophytes thus, again, of a negligible marine influence.

A stratigraphic model

Available exposures of the ship-bearing deposits led to a physical correlation among several sections (Figure 5B) measured in different areas. This correlation outlines the stacking pattern of lithofacies assemblages (b), (c) and (d) within four main unconformity-bounded stratigraphic units (1 to 4, Figure 5B), which rest on the lithofacies assemblage (a) and older postglacial deposits (Figure 5C). Units 1–4 are characterized by high-relief bounding erosional surfaces and their overall geometry is lobate, with lobe-feeding channels cross-cutting the older lobes. Each unit bears single or clusters of ships and shows a complex internal stratigraphy made up of several unconformity-bounded subunits (Figure 5B).

Besides this internal complexity, each unit features a recurrent stacking pattern of facies consisting of a sandy portion made of assemblages (b) and subordinately (c) and overlain by muds of assemblage (d). Most of the units are characterized by a dominant occurrence of NW-accreting macroforms (lithofacies (b)) with the exception of unit 1. The deposits of unit 1 in fact document a series of catastrophic flood flows directed to the NW, responsible for the sinking of ships B, C and F, followed by flood flows directed to the W as indicated by lithofacies (c) deposits. This stacking pattern was interpreted to record major phases of catastrophic flood events followed by periods of minor floods that affected the Roman harbour of Pisa and floodplains of the Arno and Serchio rivers.

Chronological calibration

The calibration of the four units is made possible by the integration of available chronological data, based on C14 analysis and on archaeological considerations (Bruni, 2000, 2002; Belluomini *et al.*, 2002; Tables 1 and 2; see also Figure 8).

Besides the chronologic calibration of units 1–4, the available data do not solve the precise chronostratigraphic positioning of the floodplain deposits of lithofacies (a) at least younger than 6430–6045 yr BP (Table 1; see Figure 8). Nevertheless, alternative hypotheses can be advanced on the basis of palaeoclimatic considerations. Pollen analysis (Begliomini *et al.*, 2003; Mariotti-Lippi *et al.*, 2006) points to cold-moist climatic conditions in the early vertical aggradation of this plain. The radiocarbon chronology of the palisade erected on these deposits indicates an age ranging from 1000 to 400 BC. In the Holocene climatostratigraphic sequence (Ravazzi, 2003), this span of time is included within the early sub-Atlantic stage (900–300 BC) that is widely recognized as a

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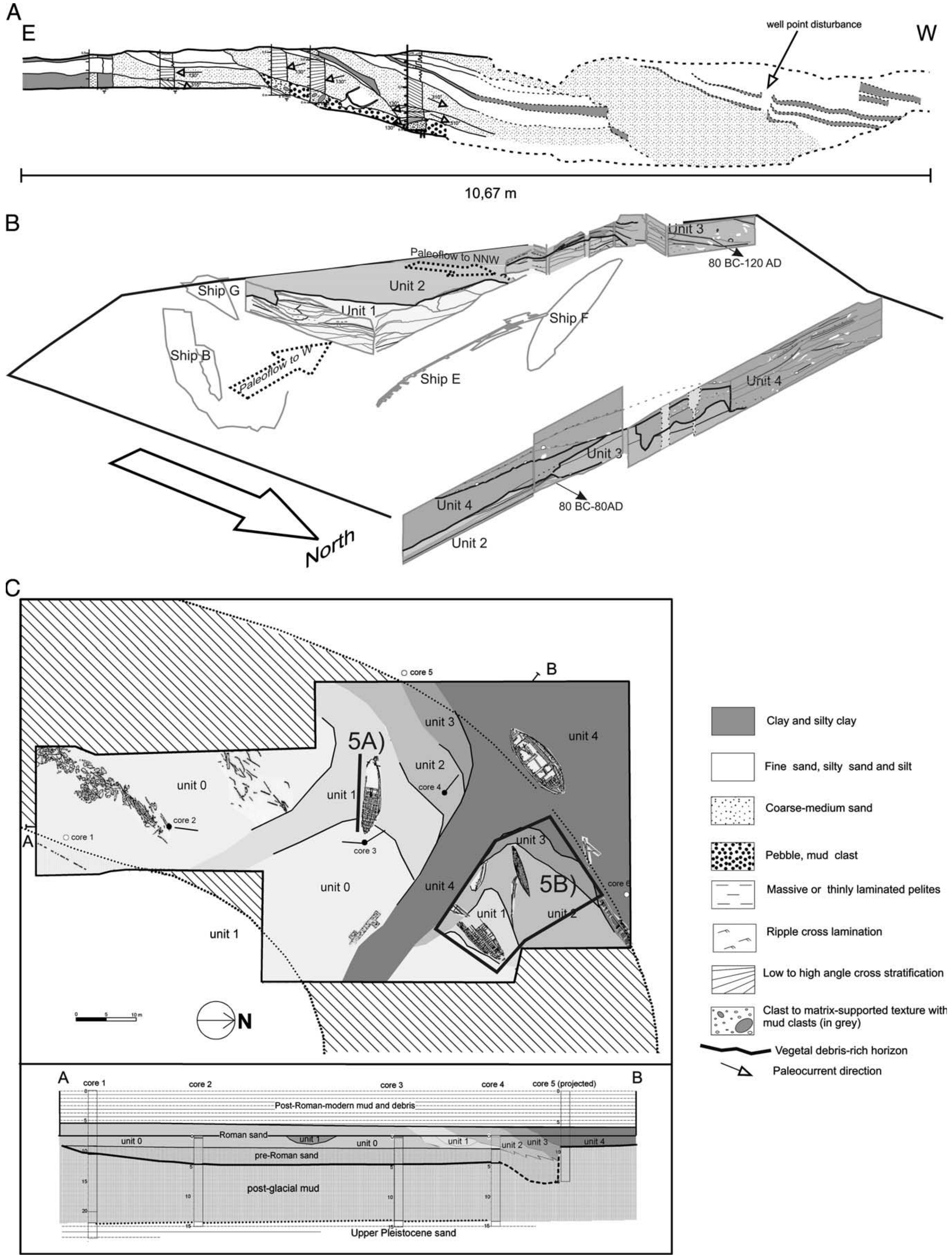

Figure 5 (A) Logged section on lithofacies (b) in area 4 (see also Figure 2D); (B) graphical correlation of logged sections in areas 1–2–3; (C) schematic map and cross section of the site from exposures and core data. Unit 0, not discussed in the text for lack of field data, represents a complex unit possibly including pre-unit 1 (ie, earliest Roman) sandy lobes as well as the fills of channels feeding lobes of units 1–4. Location for Figure 5A and B is shown

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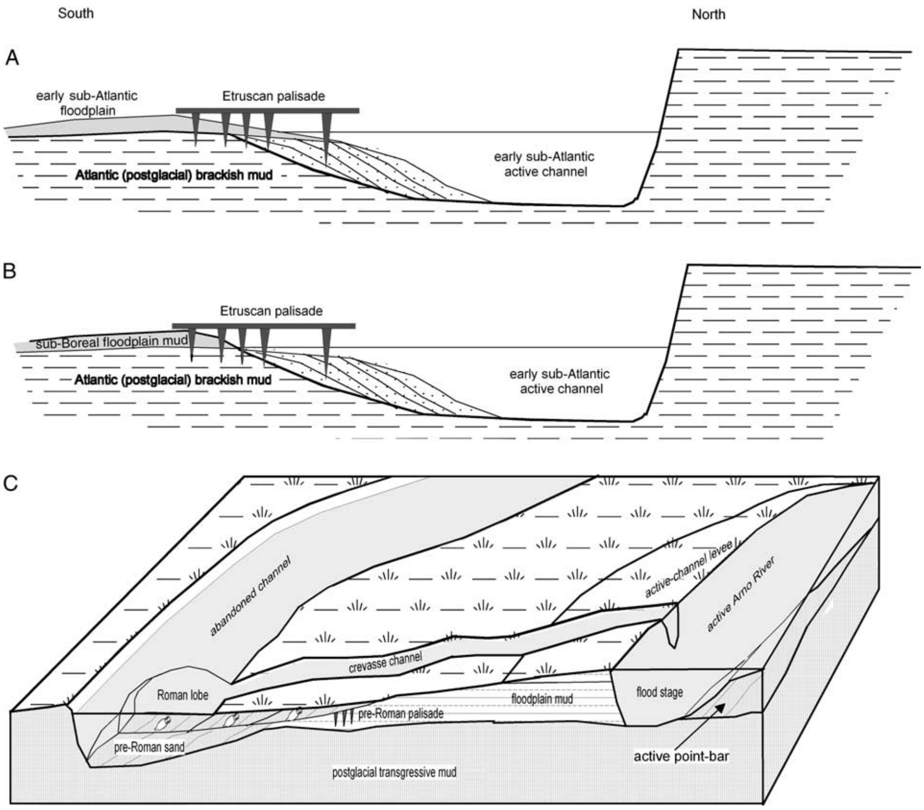

Figure 6 (A) and (B) hypotheses, discussed in the text, on the relation between pre Roman harbour floodplain muds (lithofacies (a)) and the pre-Roman sand at the base of the channel fill; (C) depositional model for the overbank flood flows affecting the harbour area in Roman times. Not to scale

period dominated by cold-moist conditions (Lamb, 1996). The preceding climatic stage, the sub-Boreal (3500–900 BC), following on to the early–mid Holocene climatic *optimum*, ie, the Atlantic stage, was characterized by a highly variable and unstable climatic regime with a prominent climatic deterioration at about 2200 BC (Lamb, 1996). On the grounds of these considerations, the following hypotheses can be formulated (Figure 6A and B).

(1) The floodplain, represented by lithofacies (a), is almost coeval with the palisade and was actively aggrading during the cold-moist early sub-Atlantic stage (Figure 6A). The pre-Roman channel fill detected in the site indicates that an active channel was adjacent to the floodplain. In other terms the Etruscans founded an early fluvial harbour on the southern bank of an active river channel through which they reached the sea.
(2) Lithofacies (a) documents the development of a floodplain during cold-moist conditions that occurred within the sub-Boreal stage (Figure 6B). In this case the channel detected in the site was incised both in lithofacies (a) and in the underlying postglacial, brackish, deposits. Cores in the southeast corner of the site are planned to test the two hypotheses.

Palaeoenvironment at the site

Shallow cores drilled in the archaeological site have been selected to establish the local setting of the fluvial harbour. Correlation among the available cores and the observed stratigraphic architecture of the ship-bearing deposits confirm that the latter fill a concave depression incised within the postglacial transgressive deposits (Figure 5C). Such a depression may have represented a pre-Roman river channel as indicated by the lower part of the sandy fill devoid of any archaeological remains, thus outlining an older channel fill. The northwestward time-transgressive distribution of the ships and related archaeological material and the data from the shallow cores support the hypothesis that such a palaeochannel was characterized by a deeper segment close to its northern bank. Therefore the palaeochannel could have been an abandoned meandering river course. The utilization of the palaeochannel by the Romans as a fluvial harbour was made possible by the existence of such a residual, deeper segment close to the northern bank, not yet filled with sediments. Nevertheless, periodic high-magnitude floods from an adjacent river course forced a progressive shift of the harbour area because of the migration of the NW-accreting macroforms, leading to the ultimate siltation of the channel.

The Roman harbour in the Arno and Serchio rivers alluvial plain

A morphological analysis of the coastal Arno River plain, based on aerial photograph and satellite image analysis (Della Rocca *et al*., 1987; Pieri and Pranzini, 1989; Figure 7A), has been used to reconstruct the environment surrounding the Roman fluvial harbour. Abandoned channels, in fact, are clear lines of evidence of the late-Holocene river avulsion (Figure 7A). Among the several palaeochannels, the most relevant for this study is the one referred to as the Roman paleoSerchio, which flowed towards Roman Pisa bordering the western slope of Pisani Mounts. Remote sensing reveals a complex late-Holocene-evolution of the Arno River wave-dominated delta and of the related accretionary shoreline (Pranzini, 2001). The ancient human presence in the plain is morphologically documented by the plan-view pattern of extensive Roman field subdivision (*centuriazione*).

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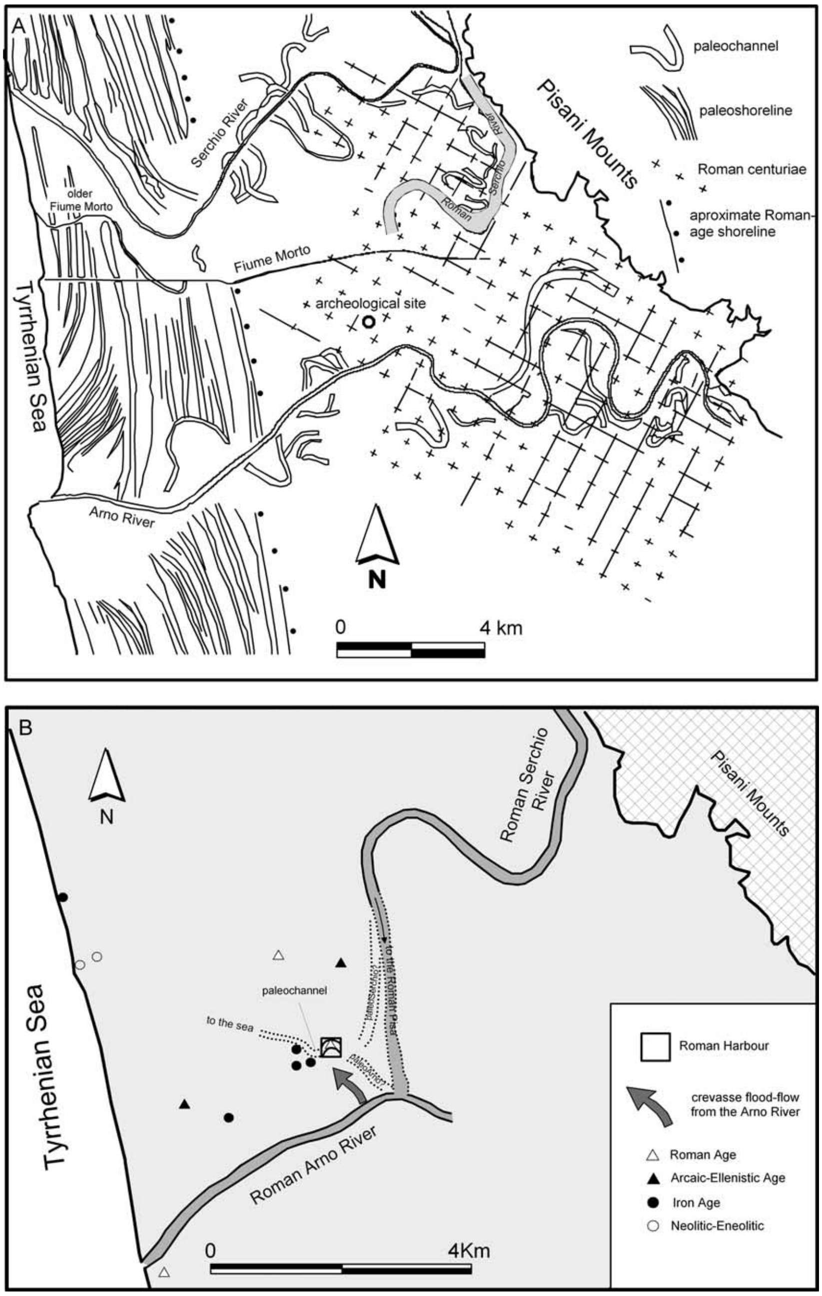

Figure 7 (A) Main morphological features of the Arno and Serchio rivers coastal plain (from Della Rocca *et al.*, 1987); (B) palaeogeographic reconstruction of the Arno and Serchio rivers coastal plain at about 2000 years ago with reference to the Pisa fluvial harbour

The palaeogeographic reconstruction of the plain of the Roman Arno-Serchio rivers (Figure 7B), based also on the occurrence of scattered archaeological sites dating back to the Neolithic, suggests that the Pisa harbour was located 3–4 km from the contemporary shoreline, in a floodplain area possibly characterized by two main, active, fluvial courses: the palaeoSerchio flowing S and the palaeoArno flowing to the WSW. Iron Age material (sixth century BC), found at a shallow depth (about 2 m below the surface) a few tens of metres WSW and SSE of the site, allows us to reconstruct the morphology of the plain surrounding the harbour in the early first millennium BC. The floodplain, inhabited during the Iron Age, was adjacent to a fluvial channel where first the Etruscans, and then the Romans, created a fluvial harbour. This channel, abandoned in Roman times but still connected to the sea, represented, therefore, a convenient way to the sea where the cargoes of large commercial vessels were collected and transported to the town by a fleet of relatively small river boats. On the basis of its presumed orientation, such a palaeochannel could either have been an abandoned meander of the palaeoSerchio or a previous course of the Arno River.

Discussion

The exceptional find of well-preserved Roman ships and associated cargo in the Pisa site not only represents a source of archaeological and historical information, but provides important data for the understanding of the late-Holocene geomorphic and sedimentary dynamics of the Arno coastal plain. In particular, three aspects concerning river channel instability and catastrophic overbank deposition in the harbour area will be discussed in this section.

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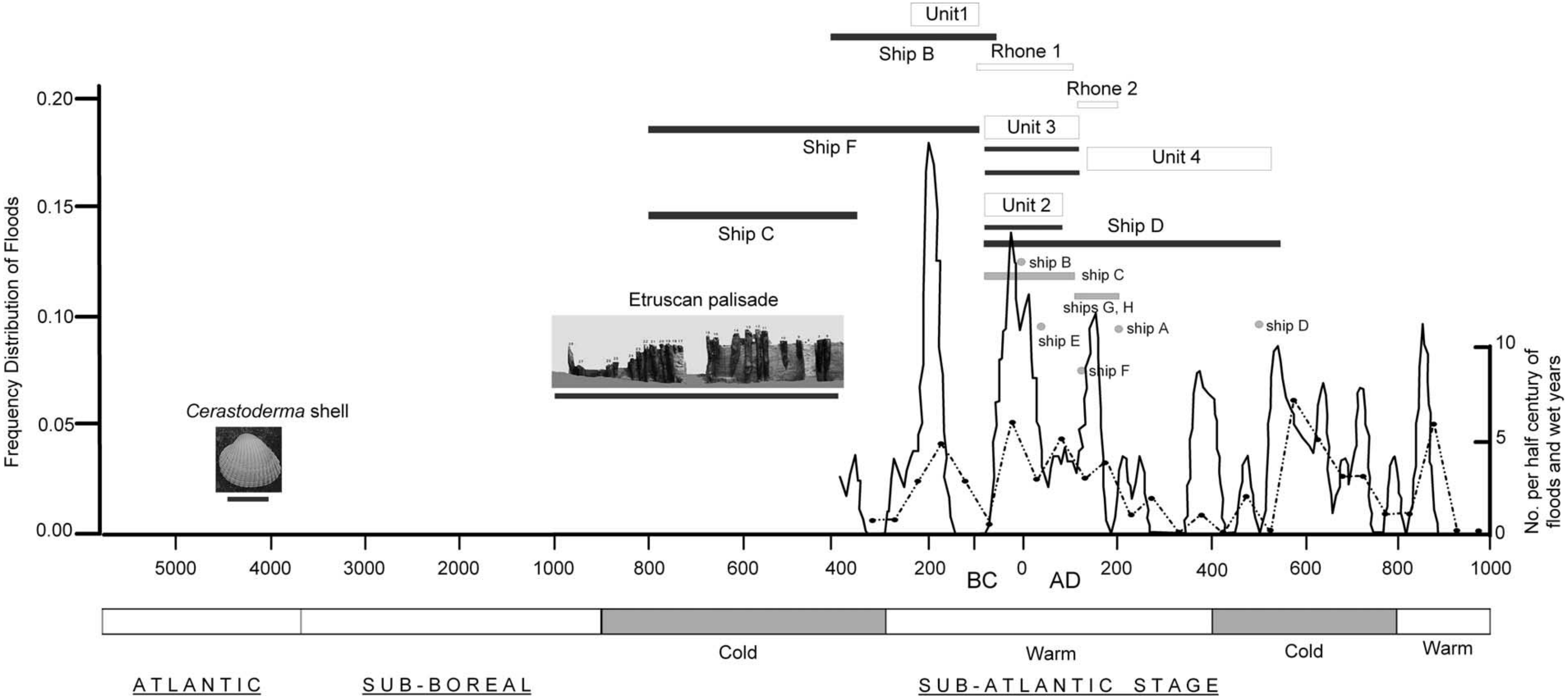

Figure 8 Diagram showing the chronology of the Pisa-S.Rossore site based on calibrated C14 ages (see Table 1): maximum chronologic range, indicated by black bars, is averaged from different samples. Grey dots and bars refer to the archaeological dating of the ships (see Table 2). This chronology is compared with proxy records of Tiber River flood frequency (Camuffo and Enzi, 1995; right axis for scale), and climate in Italy during the Roman age (Lamb, 1996; right axis for scale). Rhone 1 and 2 refer to the chronological ranges of flood-dominated regimes in the Rhone delta (Arnaud-Fassetta, 2002). The possible age range of units 1–4 (white bars) derives from integration of all these data

Catastrophic floods in the Roman Harbour

The ship-bearing sediments buried in the shallow subsoil of Pisa-S.Rossore indicate a portion of a fluvial harbour whose possible mooring structures were progressively shifted from S to N. The harbour was built in an abandoned channel and, because of the close presence of major active rivers, was affected by recurring catastrophic overbank floods. The particularly destructive ones, recurring (centennial intervals) over longer than a millennium, were generated by the Arno River. High-magnitude floods breached the Arno River levees (Figure 7B) and flooded the nearby harbour area, sweeping away the ships and progressively filling the available space in the abandoned channel through NW-accretion of the sandy lobes. Cores at the site (Figures 4 and 5C) show that these lobes not only filled the pre-existing channel but also spread onto the northern bank, hollowed out directly in the postglacial transgressive deposits. Subordinate flood flows from the east outline the occurrence of small channels that could testify to subordinate overbank flows from a N–S directed river, possibly the palaeoSerchio.

Such a catastrophic sedimentation in the Arno River floodplain contrasts with the depositional regime inferred from the pre-Roman harbour fine-grained deposits of lithofacies (a). The latter, in fact, point to overbank deposition characterized by lesser volume flood flows, possibly generating small aggrading crevasse splays and vertical accretion of fines on the southern bank of the palaeochannel. The palisade driven in these deposits by the Etruscans suggests that the early infrastructures of the fluvial harbour were in part founded on the floodplain and levee of a possibly still active river channel. Also the post-Roman deposits observed in cores 1, 5 and 6 (Figures 4 and 5) document vertical aggradation of the alluvial plain through deposition of fine-grained sediment. The depositional regime of the floodplain during Roman times, thus, appears controlled by high-magnitude hydroclimatic events (see below) that forced instability of the Arno River. In this hypothesis, recurring channel crevassing of the Arno River caused scouring of the floodplain and concentration of flood flows within avulsive channels, which fed the sediment lobes of units 1–4 (Figure 6B). The latter prograded within an abandoned channel, therefore re-occupation of pre-existing drainage on the floodplain strongly controlled the overbank deposition.

Sediment lobes point to periods during which floods were high enough to breach the Arno river levees and to force channel avulsion. In other terms, interflood periods, recorded in each unit by the thin muddy blanketing (lithofacies (d)) and documented by the younger archaeological material from southern to northern locations, point to re-utilization of the harbour. This aspect favours the hypothesis of a management or acceptance of the hydraulic risk affecting an area used for a long span of time as a fluvial harbour.

Hydro-climatic control on the fluvial dynamic

The comparison between proxy data on climate fluctuations in Roman times (Figure 8) demonstrates that the sedimentary record in the harbour at Pisa is consistent with the historical records of floods and wet years in Italy (Lamb, 1996) and with the frequency of exceptional floods of the Tiber River (Camuffo and Enzi, 1995). The available data in fact indicate frequent floods around the second century BC, a low flood frequency around the first century BC and a high flood frequency around the birth of Christ decreasing toward the third to fourth centuries AD.

The millennium coinciding with the Roman age witnessed worldwide warm climate following and preceding colder times (the ninth to third centuries BC and the early Middle Ages). The deposits in the harbour of Pisa are important physical evidence suggesting that the frequent floods of the Tiber River where almost coeval with catastrophic floods of the terminal Arno River. This evidence may indicate that such a warm Roman period was characterized in central Italy by a rainfall regime determining hydrological conditions, which oscillated from flood-prone to flood-quiescent status on centennial scale. It appears, therefore, that the channel instability of the Roman Arno River was triggered by repeated high-magnitude flood events.

Such a hydroclimatic regime recorded by the four sedimentary units in the Pisa harbour is in agreement with the ‘flood-dominated regime’ of the Rhone delta between the first century BC and the second century AD (Arnaud-Fassetta, 2002). Over this timespan the Rhone delta plain experienced frequent avulsions of its distributary channels, related to increase in palaeodischarges generated in a catchment of about 97 800 km^2, hence reflecting hydroclimatic variations of wide significance (Arnaud-Fassetta, 2002). The chronological calibration highlights two periods of more frequent avulsion, the first century BC-end of the first century AD and the second century AD, separated by a short quiescent interval. This alternation of flood-dominated and flood-quiescent periods fits the inferred chronology of flood events responsible for the deposition of units 2 and 3 in the Pisa site quite well.

River channel instability and sea-level rise

Despite the invoked multiple factors promoting river channel instability (Jones and Schumm, 1999), base-level change may play an important role. Base-level changes, first of all, determine channel slope changes, hence the possibility that fluvial discharge is locally hindered, forcing crevassing of levees. When referring to relative sea-level change, it is important to stress that changes in river gradient can be highly variable in response to falling and rising sea levels (Schumm, 1993). Avulsion in coastal areas can be facilitated during sea-level fall when the gradient of the shelf is lower than the subaerial gradient of fluvial or coastal plains (Jones and Schumm, 1999). This will then reduce the gradient of the river profile, extended through sea-level fall, facilitating avulsion. Rivers may change their course at times of rising or high sea level. The response of river systems to sea-level rise outlines the role of coastal floodplains as traps for alluvial sediments during transgression (Wright and Marriot, 1993; Shanley and McCabe, 1994). This means that rising sea level, in addition to decreasing the fluvial gradient, creates accommodation space in the floodplain that is filled with alluvial deposits during transgressions. Such a filling necessarily occurs through frequent overbank deposition, hence levee crevassing and channel avulsion. In terms of sea-level change the case presented can be referred to channel instability favoured by the condition of rising sea levels.

In the region comprising the coastal plain of the Arno and Serchio rivers, following the last glacial maximum, the Tyrrhenian Sea rose quite rapidly in the early–mid Holocene with rates of the order of 7 mm/yr from about 10 ky to 6 ky (Antonioli *et al.*, 2000; Lambeck *et al.*, 2004a). During the last 6000 years the rate of sea-level rise dropped to less than 1 mm/yr with a slight increase in rate around 2 ky ago when the eustatic sea level in the western Mediterranean has been estimated to be from 0.5 (Pirazzoli, 1976) to about 0.13 m (Lambeck *et al.*, 2004b) lower than it is at present.

At the site, Roman material is entombed at a maximum depth of about 6 m below the present-day sea level, suggesting

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some subsidence in this portion of the floodplain. Etruscan sites around the harbour dating back to the sixth century BC and buried about 2 m below the surface (Figure 7B), allow an assessment of local average subsidence rate of about 0.8 mm/yr in the last 2600 years. This evidence indicates, first of all, that the Versilia Plain is apparently more stable (Lambeck *et al.*, 2004a), with the exception of very fast local compaction of peaty sediments (Antonioli *et al.*, 2000), than the moderate subsidence in the harbour area possibly caused, not excluding a tectonic control, by modern groundwater exploitation.

A second, more important, conclusion concerns the possible evidence of a small-amplitude (metre-scale) sea-level fluctuation that occurred between 6400 and 2000 BP. In the site area, in fact, the river channel documents incision of the transgressive brackish mud. The absence in the available cores of a gradual facies transition from these deposits and the sandy channel-fill does not fit the gradual regression expected in the transition from the postglacial transgression to the highstand of sea level. The channel, thus, seems to have formed in response to base-level lowering reasonably forced by small-amplitude sea-level fall because of the vicinity to the coast. The channel was filled following the slight increase in the rate of sea-level rise recorded during Roman times. Geomorphic and sedimentary effects of this sea-level rise on the floodplain were: (1) abandonment of the pre-Roman channel forced by rise of base level and (2) filling of the abandoned channel, re-utilized as a harbour, with overbank deposits supplied by a nearby, unstable, active channel. This hypothesis could explain the possible avulsive behaviour of the Roman Arno River not only as the effect of catastrophic floods but also as the response to a small-amplitude rise in sea level. Large volume discharges and high base level in the channel, in fact, may account for the repeated attempts of the Arno River to change its course.

Further data are needed to test the hypothesis of a short-term sea-level fluctuation during the late Holocene and to clarify if this possible event was of local rather than wider significance.

Conclusions

At least 16 ships and related cargoes testify to periodical destruction, over *c.* 1000 years, of a Roman riverine harbour buried in the shallow subsoil of Pisa. The dynamics of such recurring destructions are strictly related to high-magnitude geomorphic and sedimentary processes operating in river systems. The archaeological and sedimentary lines of evidence allow reconstruction of four major phases of catastrophic sand deposition from high-magnitude overbank flood flows of the Arno River. These floods swept away the ships and deposited them and their cargoes within large-scale NW-accreting macroforms. Each flood stage was followed by quiescent periods during which the macroforms were draped with fine-grained deposits. These deposits filled an abandoned river channel during the Roman age (300 BC – AD 500), documenting a persisting channel instability of the Arno River. The ships and their cargo document the entire Roman age, suggesting that the harbour was re-utilized after each flood stage. Based on this evidence, an efficient management of the local hydraulic risk may be hypothesized. The available data support the hypothesis that the Arno River channel instability was driven by the concurrent effect of sea-level rise and high-magnitude flood events acting, respectively, as preparatory and triggering factors.

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