Elsevier Editorial System(tm) for Journal of Archaeological Science
Manuscript Draft

Manuscript Number: JASC13-751R1

Title: New insights into the palaeoenvironmental evolution of Magdala ancient harbour (Sea of Galilee, Israel) from ostracod assemblages, geochemistry and sedimentology

Article Type: SI: Ostracods and Archaeology

Keywords: ostracods; geochemistry; geoarchaeology; ancient harbour; Sea of Galilee; Cyprideis torosa

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Manuscript Region of Origin: ISRAEL

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New bio-sedimentary and archaeological (pottery) data document that remarkable hydrodynamic and hydrochemical changes took place during the Hellenistic period (from the 3rd-2nd century BC to the first half of the 1st century AD), in response to the construction of the oldest Magdala harbour installations and, possibly, to the following Hasmonean structures. The high V-Cr concentrations observed in the harbour sediments, and the substantial increase of ostracod species (Pseudocandona albicans) preferring slow moving waters and fine-grained substrates point to the establishment of a semi-enclosed, shallow, and organic-rich setting. Coupled ostracod-geochemical analyses also testify to an alkali ions (Na+ and K+) enrichment within whole-sediment samples, reasonably driven by increasing evaporation in response to the partial isolation of the lake margin. The increase in sodium and potassium concentrations is accompanied by the sudden appearance of Heterocypris salina, a brackish-tolerant species, and by the almost absolute dominance of noded valves of C. torosa, whose shells are enriched in Na, K and Cl. The positive covariance between Na2O+K2O values and the frequencies of noded C. torosa seems to confirm the relation between node development and changes in ionic concentration within hypohaline settings.

Highlights (for review)

- We show the value of multi-tool integrated methodology to study lacustrine harbours
- Hydrodynamic and hydrochemical changes occurred at the onset of Magdal harbour
- A semi-protected shallow, stagnant bay worked as Hellenistic harbour basin
- Sediments and ostracod fauna data document alkali enrichment in the port basin
- A good relationship is detected between past water composition and *C. torosa* nodes

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New insights into the palaeoenvironmental evolution of Magdala ancient harbour (Sea of Galilee, Israel) from ostracod assemblages, geochemistry and sedimentology

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Abstract

Despite several studies have focused on the past bio-sedimentary response of the Mediterranean coastal areas to ancient seaport activities, only few geoarchaeological and palaeoecological data are available on strictly lacustrine harbours, to date. At the archaeological site of Magdala/Taricheae (Sea of Galilee, north Israel), an interdisciplinary study, combining ostracod fauna composition and shell chemistry with sedimentology, geochemistry of sediments and archaeological data, was undertaken on the sedimentary succession buried beneath the Roman harbour structures in correspondence of two key-sections. This approach provided detailed information about past environmental changes, otherwise not visible, into a high-resolution pottery-based chronological framework at the transition from a natural (pre-harbour) to anthropogenically influenced (harbour) lacustrine depositional setting.

New bio-sedimentary and archaeological (pottery) data document that remarkable hydrodynamic and hydrochemical changes took place during the Hellenistic period (from the 3rd-2nd century BC to the first half of the 1st century AD), in response to the construction of the oldest Magdala harbour installations and, possibly, to the following Hasmonean structures. The high V-Cr concentrations observed in the harbour sediments, and the substantial increase of ostracod species (*Pseudocandona albicans*) preferring slow moving waters and fine-grained substrates point to the establishment of a semi-enclosed, shallow, and organic-rich setting. Coupled ostracod-geochemical analyses also testify to an alkali ions (Na^+ and K^+) enrichment within whole-sediment samples, reasonably driven by increasing evaporation in response to the partial isolation of the lake margin. The increase in sodium and potassium concentrations is accompanied by the sudden appearance of *Heterocypris salina*, a brackish-tolerant species, and by the almost absolute dominance of noded valves of *C. torosa*, whose shells are enriched in Na, K and Cl. The positive covariance between Na_2O+K_2O values and the frequencies of noded *C. torosa* seems to confirm the relation between node development and changes in ionic concentration within hypohaline settings.

Keywords: ostracods; geochemistry; geoarchaeology; ancient harbour; Sea of Galilee; *Cyprideis torosa*

1. Introduction

Lacustrine deposits are universally recognized as excellent high-resolution terrestrial palaeoarchives, containing non-biological and biological proxies of short-lived palaeoenvironmental/climatic changes (Cohen, 2003; Fritz, 2008; Roberts et al., 2008; Zolitschka et al., 2000). The former mainly include sedimentological and geochemical features, while the latter comprehend pollen, plant macrofossils, diatoms, crustaceans and molluscs.

Ostracods, micro-crustaceans with low-Mg calcite valves, usually represent the most abundant, well-preserved *in situ* faunal component of freshwater and saline lakes from different regions (Holmes, 2001; Holmes and Chivas, 2002). The well-known high sensitivity of ostracods to changing physico-chemical parameters of the ambient water and the bottom sediments (i.e. solute chemistry, salinity, nutrient availability, dissolved oxygen, temperature, hydrodynamic conditions and mean grain size), along with the abundance of shells within small-sized samples, make them an important tool in high-resolution palaeolimnological studies, aimed to reconstruct past hydrochemical and hydrological changes (Börner et al., 2013; Carbonel et al., 1988; Frenzel and Boomer, 2005; Horne et al., 2012; Marco-Barba et al., 2012, 2013b; Palacios-Fest et al., 2005; Véron et al., 2013).

Combining ostracod fauna species composition, shell morphology (carapace size and noding development) and chemistry, high-frequency palaeoenvironmental changes induced by natural factors (climate, groundwater interactions, catchment geology, tectonic activity), anthropogenic factors (hydrological modifications, urban waste discharge and shoreline artificialization) or both can be detected within the lake sedimentary record.

Recently, several geoarchaeological works have documented the primary role of ostracods as sentinels of human-induced environmental changes on lacustrine and alluvial depositional systems characterized by a long history of human occupation (Anadón and Gabas, 2009; Bates et al., 2008; Escobar, 2010; Mischke et al., 2013; Palacios-Fest et al., 1994; Rosenfeld et al., 2004; White et al., 2013). In these studies, the analysis of the ostracod fauna, combined with additional geological, geomorphological and archaeological data, has extensively been used to better understand the evolution of human-environment interactions, focusing on pre-human occupation conditions and human-induced water chemistry changes.

In contrast, few integrated geoarchaeological and palaeoecological data are available from the stratigraphic record of ancient lagoon/lacustrine or fluviatile harbours recently discovered in the Mediterranean area (Benvenuti et al., 2006; Flaux et al., 2012; Morhange et al., 2000; Stefaniuk et al., 2003; Tronchère et al., 2012; Vecchi et al., 2000; Vött, 2007). In these contexts, the importance of ostracods as bioindicators is further enhanced by the absence of foraminifera, whereas both benthic groups are abundant in most marginal marine environments and widely used to reconstruct the evolution of Mediterranean seaports (Bellotti et al., 2011; Bernasconi and Stanley, 2011; Bini et al., 2012; Di Bella et al., 2011; Goiran et al., 2013; Goodman et al., 2009; Marriner and Morhange, 2007; Marriner et al., 2008, 2012; Morhange et al., 2003; Mazzini et al., 2011; Reinhardt et al., 2006).

In the northern part of Israel, along the W coastline of the Sea of Galilee, also known as Lake Tiberias or Lake Kinneret, recent excavations at the ancient city of Magdala/Taricheae (Fig. 1), directed by Stefano De Luca (Magdala Project; http://www.magdalaproject.org/WP/), have unearthed the remains of stonework-landing places active from the Late Hellenistic to the Islamic period (167 BC-800 AD; De Luca, 2010; Lena, 2012).

On the basis of a geoarchaeological approach (Marriner and Morhange, 2006), Sarti et al. (2013) recognized two main depositional units buried beneath the Roman harbour structures, corresponding to the pre-harbour foundation phase and the earliest harbour phase, respectively. The latter was dated by radiocarbon ages to the Hellenistic period.

Herein, refined ostracod fauna analysis combined with geochemical analysis of sediments are used to obtain new insights on the evolution of Magdala harbour and to detect changes in environmental conditions during the first phase of harbour use. Specific aim of this study is to assess to what extent the synergy among sedimentological, palaeontological and geochemical data, framed into a high-resolution pottery-based chronological framework, can yield valuable information about past environmental parameters at the transition from a natural to an anthropogenic-dominated lacustrine setting.

2. Background

2.1. Geological and geomorphological setting

The Sea of Galilee, in northern Israel, is a relatively freshwater-oligohaline lake (Nishri et al., 1999) located at an average elevation of 210 m below the mean sea level, with a total area of ~ 166 km^2 (21 km maximum length x 12 km maximum width) and a maximum depth of ~ 43 m (Israel Oceanographic and Limnological Research http://www.ocean.org.il/eng/kineret/lakekineret.asp; Kolodny et al., 1999). The lake occupies the northern subsiding pull-apart basin of the Jordan-Dead Sea Rift Valley, a long and narrow tectonic depression stretching for about 300 km along the N-S Dead Sea Transform-DST (Abbo et al., 2003; Marco et al., 2003; Fig. 1A). The activity of this left-lateral fault is responsible for the intense seismic history of the area, documented by geological, archaeoseismic data (Belitzky and Ben-Avraham, 2004; Ellenblum et al., 1998; Marco et al., 2000, 2003, 2005; Wechsler et al., 2009) and historical sources (Karcz, 2004; Nur and Burgess, 2008; Russell, 1985).

The lake is mainly fed by the Upper Jordan River, which flows from N to S, and by a series of wadis draining the Golan Heights to the E and the Lower Galilee highlands to the NW (Fig. 1B). The catchment area consists predominantly of Neogene-Quaternary volcanic rocks, mainly basalts, and Eocene carbonates (limestone, chalk and chert), bordering the lake along the west and north sides. Miocene continental sedimentary deposits (sandstone, mudstone and conglomerate) crop out along the east side and with patchy exposures along the west side (Fig. 1B; Geological Survey of Israel http://www.gsi.gov.il; Singer et al., 1972). In the southern part, Quaternary sedimentary deposits formed within freshwater to brackish lacustrine and fluvial environments extensively occur (Heimann and Braun, 2000).

Small springs situated onshore, along the coastline, and offshore, at the lake bottom, subordinately supply the basin with saline hot waters fed by Pliocene residual brines (Farber et al., 2007; Klein-BenDavid et al., 2005; Kolodny et al., 1999). The mixing between saline and fresh waters determines the higher salinity (total dissolved solids-TDS value of ~ 700±100 mg/l) and alkaline composition of the basin, relative to the feeder streams (Farber et al., 2007; Nishri et al., 1999; Rimmer and Gal, 2003; Stiller et al., 2009).

The lacustrine sedimentation is mainly characterized by the massive production of autochthonous $CaCO_3$ (calcite carbonate phase), which represents more than 50% of the sediment composition (Nishri et al., 1999). Allochthonous deposits are delivered into the lake by strong river floods, diluting the authigenic calcite content.

To date, no deep-lacustrine cores have been recovered, preventing the detailed reconstruction of the late Quaternary evolution of this sedimentary basin. Nevertheless, the widespread occurrence of palaeo-beach deposits and archaeological sites at various stratigraphic levels along the lake coastline reveals water-level fluctuations over the course of the past millennia (Hazan et al., 2004, 2005; Robinson et al., 2006). Even though incomplete, the resulting Holocene lake-level curve shows high-frequency episodes of relative rises and declines of tens of metres that are simultaneous with the more prominent changes independently recorded in the Dead Sea (Hazan et al., 2004, 2005).

These in-phase Sea of Galilee-Dead Sea water-level oscillations show a good chronological correlation with the high-frequency climate changes occurred in the eastern Mediterranean area under the predominant control of the Mediterranean rain system (Hazan et al., 2005; Robinson et al., 2006). In particular, the late Holocene palaeolimnological and pollen records from the Sea of Galilee and the Dead Sea consistently indicate a phase of relatively high precipitation rates covering the Hellenistic and Roman periods (ca. 2300-1800 cal yr BP), when the region was heavily populated (Dubowski et al., 2003; Leroy et al., 2010; Quintana Krupinski et al., 2013). Close to the end of the Byzantine times (ca. 1400 cal yr BP) a regional, drier climatic phase occurred (Dubowski et al., 2003; Leroy et al., 2010; Orland et al., 2009; Quintana Krupinski et al., 2013).

At present, seasonal water-level fluctuations recorded at the Sea of Galilee reflect the distinctive alternations between rainy winters and dry summers, typical of the Levantine region (Hambright et al., 2004; Rindsberger et al., 1983). However, the unique topography of the lake (~ 210 m bsl) induces higher temperatures (average annual temperature above 18 °C) and lower annual rainfall (400 mm) with respect to its immediate surroundings (~700 mm), determining a hot semi-arid climate over the Sea of Galilee area (http://www.israelweather.co.il/english/kineret.asp). Consistent with these climatic features, the vegetation shows a mix of trees, shrubs and grasses of the Mediterranean and Irano–Turanian biomes (Zohary, 1973). In particular, around the lake *Tamarix* sp. trees occur at higher altitudes while thickets of *Phragmites australis* and *Cyperus* spp. grasslands and marshland are found approaching the water (Tibor et al., 2012).

The Magdala archaeological site is located ~ 250 m west of the present-day lake shore (Fig. 2A), recorded around 212-213 m bsl during the 2011 field campaign. About 50 m from the site, a 2-3 m-thick escarpment bank, marked by an eucalyptus tree-line (Fig. 2A), abruptly interrupts the slightly lakeward inclined coastal plain. The eucalyptus trees were planted during the British Mandate (1920-1948 AD) to reclaim the swampy coastal areas facing the lake, suggesting a higher water-level than the present one. On the western side, the archaeological site is bounded by the Lower Galilee hills composed predominantly of limestones and basalts and deeply incised by the Amud, Tzalmon, Arbel and El Amis wadis that have been recently affected by artificial channelization (Fig. 1B). Through the Wadi Arbel the main daily wind, the westerly Mediterranean Sea Breeze, penetrates strongly and passes over the lake, playing a crucial role in the generation of lake gyres, transient currents and thermocline displacements (Pan et al., 2002). Indeed, the wind curl induced by the passage of the Mediterranean Sea Breeze produces the counter-clockwise surface current that characterizes the central part of the lake (Fig. 1B; Pan et al., 2002). With respect to the direction of this current, the Magdala site is placed in a more protected area compared to the eastern lake coast.

2.2. Archaeological and historical context

According to Plinius (Nat. Hist. 5:71) the lake owes its name to the prominent city-port of Taricheae, whose importance and prosperity was mainly linked to the quality of the fish processing industry and trade, as reflected by both its toponym and the account of Strabo: “ε□ν δὲ ται□ς καλουμέναις Ταριχέαις η□ λίμνη μὲν ταριχέιας ι□κθύων α□στείας παρέχει” (Geogr. XVI:2,45). The city – known in the Semitic sources also by the name of Migdal/Magdala (Leibner, 2009) – was probably founded, along with the articulated port facilities, during the Late Hellenistic time by the Hasmoneans (cf. 1Macc 5:14-20) as the capital of a Toparchy (administrative district), on the site of an earlier settlement located on the crossroads of important routes directed to the main cities of the region (i.e. Tyre and Akko). During this early stage of city development (3rd-1st century BC) the urban layout (De Luca, 2009, 2010, 2011a), identified through the archaeological excavation, was planned according to a network of orthogonally paved crossing roads and an articulate underground water supply and sewage system, connected to a water tower (A1) built upon a spring (Fig. 2B). A domestic area, identified in the W portion of the site, several public buildings (e.g. the "stoa-shape fountain" D1) and two impressive harbour structures also occurred (Fig. 2B). These consist in a *quadriporticus* (Q) and in a tower-port (TP), both facing the lake (Fig. 2B). The latter, due to its architectural features (casemattes) and its strategical location, was probably built for military purposes, as also suggested by some parallels (De Luca, 2010). Indeed, the city was than involved in the Roman military campaigns against the Parthians (Bell. Iud. I:8.9.180; cf. letter of Cassius

Longinus to Cicero of 43 BC: Ad Fam 24:11) and in the First Jewish Revolt of 66-70 AD (Bell. Iud. 3:497. 499), when it was conquered by Vespasianus and Titus, as also reported by Svetonius (De Vita Caesarum, Titus 4:3).

During the 1st century AD the city, which was assigned by Nero to Herod Agrippa II in 53 AD, underwent many transformations maintaining its remarkable economic role in the region, even after the foundation of Tiberias, built by Herod Antipas (18-20 AD) as the new capital of Galilee. While maintaining its earliest Hellenistic layout, the dwelling quarter was reorganized around the W-E (De Luca, 2008, 2009, 2010; Lena, 2013) and S-N street networks. New productive areas (Zapata and Sanz, 2013) and new public buildings, comprising a synagogue (Avshalom et al., 2013), were established. A wide thermal bath – with *praefurnium*, *caldarium-tepidarium* supplied with *hypocaustum*, pools and *latrinae* (De Luca, 2011b; De Luca and Lena, 2014b) – occupied area C, in the northernmost sector, and area E, where it was partially set on the Hasmonean tower-port (Fig. 2B). Moreover, the harbour facilities were totally renovated with the construction of new quays (De Luca, 2010, 2011b, 2013; De Luca and Lena, 2014a; Lena, 2012).

The archaeological indicators for the Middle and Late Roman periods attest a continuum of settlement until the half of the 4th century AD. Probably as a result of the earthquake of 363 AD, to which some structural collapses are ascribed (De Luca and Lena, 2014a), Magdala had ceased to exist as an urban settlement. Only in the S sector a fortified monastery, linked to the cult of Mary Magdalene (Mt 15: 39, 27:61; Mk 8:10, 15:47, 16:1-9; Lk 8:2; Jh 20:1-18) was built to serve the travelers along the pilgrimage routes to the Christian holy places (De Luca, 2012).

2.2. Geoarchaeological background of the Magdala harbour

On the basis of an integrated geoarchaeological approach undertaken on three sections (F18, F25 and F27 in Fig. 2B), three thin depositional units were recently distinguished within the late Holocene succession buried beneath the archaeological site (Lena, 2012; Sarti et al., 2013). These units, together with the stonework-landing structures, reveal an articulate sedimentary history characterized by three main evolutionary phases: pre-harbour, harbour and post-harbour (Fig. 3).

The pre-harbour foundation phase is recorded by lacustrine beach sands almost barren in archaeological remains. These deposits are abruptly overlain by a thin succession of dark silty sands rich in osteological fragments and potsherds, and characterized by a sharp increase in heavy metals content connected to human activity (average values in pre-harbour samples: 18 mg/kg Cu, 30 mg/kg Zn, 3 mg/kg Pb; average value in harbour samples: 46 mg/kg Cu, 80 mg/kg Zn, 56 mg/kg Pb; from Sarti et al., 2013). This unit documents the development of a populated semi-protected bay, interpreted as the stratigraphic record of the first phase of use of the Magdala harbour basin during the Hellenistic period (Lena, 2012; Sarti et al., 2013). The establishment of an harbour basin implies a sudden, strong anthropogenic control on coastal sedimentation and the development of an anthropogenically forced sheltered basin (*sensu* Marriner and Morhange, 2007), likely connected to the lakeward construction of harbour structures, such as jetties and quays, active up to the Early-Middle Roman period and no more visible. Sandy and gravelly beach deposits record the following harbour abandonment phase dated to the Middle-Late Roman period transition (Sarti et al., 2013).

Concerning the archaeological phases (Fig. 4), the Hellenistic harbour system (archaeological phase I/2) included the tower-port (TP) and the *quadriporticus* (Q) (Fig. 2B). The TP, which shows a rectangular plan, is ascribed to the Hasmonean period, by judging the stratigraphic context and the masonry's walls with dressed margins and projecting central bosses. Enclosed in the external wall in the SE corner (E32) a mooring stone was discovered (MS2; Fig. 2B). To the N the TP faced a basin, which was delimited also on its W and N sides (De Luca, 2010, 2013; De Luca and Lena, 2014a; Lena, 2012).

Along the E side of Q (Fig. 2B) – which extends over an area of about 33 m per side and faces the great paved street V2 to the W – a mooring stone (MS1) is still preserved *in situ*. The walls of Q are thicker along the E and S sides as they were both in contact with the lake's surface (De Luca, 2013).

During the following Early Roman phase (Phase II in Fig. 4), a thermal bath was based on TP, whilst against the E façade an artificial *platea* was built (PL). A mooring stone (MS3), similar to MS2, was found fallen on the E side of PL, suggesting that it was equipped with moorings (De Luca, 2013; Fig. 2B). Also the Hellenistic basin N of TP was artificially filled in. The PL was paved with reused stone elements and was limited to the S, E and N by massive walls plastered by hydraulic mortar. The wall (UMS 317) that was built along the original E façade of Q, obliterating MS1, shows that it had the same waterproof treatment. This new dock (UMS 317) conserves *in situ* four mooring stones (MS4-7; Fig. 2B). A slipway – which extends from the dock foundation toward the Lake forming the bottom of the basin – is still preserved along with the original stone staircase in the S sector (De Luca, 2010). The docks/ports structures were still in use during the Roman conquest of 67 AD.

Starting from the second half of the 3rd century AD, at the transition to the Late Roman period (270-350 AD), the port's structures were abandoned and the basin was quickly filled with beach sands and gravels in response to a bad maintenance, possibly connected to the gradual loss of importance of the city in favour of Tiberias and/or a natural phenomenon (Phase IV in Fig. 4). In this respect, the subsequent level of ruins can be ascribed to the earthquake of 363 AD – evidences of which were uncovered elsewhere in the site. During the following Byzantine/Islamic phases new and more simple landing places were built (Phases V and VI in Fig. 4).

3. Methodological approach

An interdisciplinary, multi-tool approach, combining sedimentology, geomorphology, geochemistry of sediments, ostracod fauna composition, ostracod shell chemistry and archaeological data, was carried out on the depositional succession buried beneath the Roman slipway at key-sections F18 and F25 (Fig. 2B).

This methodology was adopted to obtain a more detailed picture of the bio-sedimentary response to the earliest phases of Magdala harbour activity recently defined by Sarti et al. (2013), focusing on the environment-ostracod fauna relationships at the transition from a natural to an anthropogenic-dominated lacustrine setting.

3.1. Stratigraphic and geochemical analyses of sediments

The sedimentological analysis of F18 and F25 and the collection of samples for laboratory analyses were performed during the 2011 field surveys. The former was based on visual detailed description of vertical changes in sediment texture and colour, sedimentary structures and accessory materials, mainly including mollusc shells and fragments, and vegetal debris. The occurrence of archaeological remains (see sub-section 3.3.) was also considered. The thickness of the lithofacies/stratigraphic units discussed in this paper, the sandy beach/pre-harbour unit and the semi-protected bay/harbour unit (Fig. 5), as well as the elevation of the trenches, were benchmarked to the present mean sea level using a total station Leica TCR 305 via the Infrared EDM system with a standard prism GPH1-GPR1 and linked to an absolute altitude with accuracy of 10 mm ± 2 ppm (De Luca, 2010; Sarti et al., 2013).

With respect to the previous works (Lena, 2012; Sarti et al., 2013) sedimentary features of the pre-harbour and harbour units were more strictly combined with whole-rock geochemical compositional data (XRF), in order to provide palaeoenvironmental constraints about the sediment-water interactions. XRF analyses were performed on 25 samples (11 samples from F18 and 14 from F25) collected along the 1.50 m-thick successions (Fig. 5). XRF analyses were carried out on powder pellets at the Bologna University laboratories using Philips PW1480 spectrometry with Rh tube. Major elements were determined by a full matrix correction procedure (Franzini et al., 1975).

The calculation methods of Franzini et al. (1972), Leoni et al. (1982) and Leoni and Saitta (1976) were used to assess trace metal concentrations.

3.2. Palaeontological analysis

Palaeontological analyses essentially focused on the ostracod fauna, representing the most abundant and well-preserved biological group constantly recorded along the entire thickness of F18 and F25 successions (Sarti et al., 2013). In this paper, a more detailed picture of ostracod species distribution is reported on the basis of quantitative analyses, which involved rare taxa (<1%) and un-noded *versus* noded forms of *Cyprideis torosa* (corresponding to *C. torosa* forma *littoralis* and *C. torosa* forma *torosa*, respectively), separately counted despite the ecophenotypical origin of the nodes (Athersuch et al., 1989; Frenzel and Boomer, 2005; Keyser, 2005; van Harten, 2000). Indeed, upsection variations in rare taxa abundances and in un-noded *versus* noded *C. torosa* mutual frequencies can be sensitive proxy of high-frequency palaeoenvironmental changes, especially in hypohaline settings (Frenzel and Boomer, 2005; Lord et al., 2012; Slack et al., 2000).

Whenever possible for each sample, prepared following the standard procedure (see Sarti et al., 2013), at least 150-200 well-preserved valves (adult valves-A and late-instar juveniles A-1 and A-2) were identified to the species level and counted in the size fraction >125 µm. The 63-125 µm size fraction was qualitatively observed to verify the presence in the same sediment sample of both juveniles and adults, and thus assess the *in situ* accumulation of the ostracod assemblage (Holmes, 1992; Lord et al., 2012). Finally, the percent relative abundance of each taxon was determined. The identification of species was based on key literature data (Athersuch et al., 1989; Henderson, 1990; Meisch, 2000) and specific publications focusing on the Israel ostracod fauna (Martens et al., 2002; Mischke et al., 2010, 2012; Rosenfeld et al., 2004). Given the impossibility to examine specific diagnostic features (marginal ripplets on the inner lamella; Meisch, 2000) under the binocular microscope, following Mischke et al. (2010) all non-tuberculated *Ilyocypris* specimens were considered together (*Ilyocypris* spp.). The palaeoenvironmental interpretation of the ostracod fauna relied upon species autoecological data available from literature (Athersuch et al., 1989; Henderson, 1990; Meisch, 2000) and the spatial distribution patterns of ostracods from the present-day Sea of Galilee (Lake Kinneret) and other Israel freshwater bodies (Mischke et al., 2010, 2012, 2013).

To obtain additional data about past lacustrine environmental conditions at Magdala, mainly regarding water solute composition, six well-preserved, clean A-1 specimens of un-noded and noded *C. torosa* were selected from 4 samples representative of F18 and F25 stratigraphic units and processed for combined SEM-EDS analyses (JSM-5400 scanning microscope-IXRF Systems Iridium EDS system). *Cyprideis torosa* was chosen because of its abundance throughout the sections. The scarcity, within the selected samples, of well-preserved and adequately clean adult specimens (adult valves-A) implied the use of A-1 valves. X-ray maps with areal intensity spectra were performed on the almost flat central zones of the external carapace. Additional spot spectra were also carried out *ad hoc*. The valves were cleaned in deionised water, using a fine (0000) paint brush, under a binocular microscope (Method A in Holmes, 1992; Keatings et al., 2006; Marco-Barba et al., 2013a) and carbon coated to increase their conductivity and to allow EDS analysis.

3.3. Archaeological analysis and chronological examination

Sedimentological and palaeontological data were also complemented by the archaeological findings mainly recovered within the harbour unit. These data consist of pottery fragments and osteological remains (animal bones), accompanied by sporadic fragments of glass vessels, bronze nails, coins and charcoal.

The archaeological assemblages can furnish key information about the relative chronology of the harbour phases and changes in the buildings use (Lena, 2012). The pottery was described and catalogued following the criteria used by Loffreda (2008a, b, c) for the nearby archaeological site of Capernaum (Fig. 1B). These criteria mainly include the shape identification and the description of fabric, inclusions (size and type), colour (Munsell colour chart), surface treatment and firing (as illustrated in Supplementary Table 1). Chronological interpretation of the pottery assemblages was inferred by comparison with the typologies studied from other sites of the region (for references see Supplementary Table 1).

The high resolution (century-scale) pottery-based chronology, associated with the coin findings (research in progress by Prof. Bruno Callegher), strongly supports and refines the temporal framework derived from absolute radiocarbon dates published in Sarti et al. (2013), to which the reader is referred for more detailed information. In this paper, all ages are reported as calibrated yr BC/AD (2-sigma highest probability range).

4. Results

In the following sections, the bio-sedimentary and archaeological record of the Magdala coastal succession, buried beneath the Roman harbour slipway along the waterfront side of the *quadriporticus* (Fig. 2B), is fully explained to shed new light on the palaeoenvironmental features and dynamics of the study site.

4.1. Ostracod fauna, lithofacies and archaeological data

A mixture of well-preserved adult and juvenile ostracods, mainly found as single valves, characterizes the entire sedimentary succession at both trenches. Variable amounts of reworked ostracods, mainly poorly-preserved, black-coloured valves of *C. torosa*, and foraminifers, including benthic and planktonic taxa, are also encountered. Approximately 5500 ostracod valves, representing eight species and one group (*Ilyocypris* spp.), were identified within the studied samples (Appendix A).

In the context of the lithofacies/stratigraphic units presented in Sarti et al. (2013), the detailed description of ostracod fauna characteristics is combined with unpublished archaeological data mainly concerning the pottery assemblages, essential for a high-resolution chronological framework of the studied succession (Fig. 6 and Supplementary Table 1). The results are reported below.

4.1.1. Pre-harbour beach sands

Description

This sandy unit, located at the bottom of the exposed sections, is characterized by the occurrence of several mollusc shells, mainly *Melanopsis*, and centimetric-thick pebble layers rich in bioclasts.

An abundant oligotypic ostracod fauna occurs throughout the succession, with the exception of 6 samples showing a sparse ostracod assemblage almost entirely composed of juvenile specimens (Fig. 5). All samples are strongly dominated by the euryhaline species *Cyprideis torosa*, whose relative abundance percentages range between 95% and 100%. This almost monospecific assemblage shows a stable proportion (~ 1:1 or 1:2) of un-noded and noded valves of *C. torosa*. Unique exception is the uppermost F18 sample, collected few centimeters below the boundary with the overlying lithofacies and characterized by an abrupt increase of noded *C. torosa* percentage (Fig. 5).

The remaining faunal elements are represented by just two hypohaline taxa, *Pseudocandona albicans* and *Ilyocypris* gr. (Meisch, 2000), which sporadically occur with very low percentages (0-3%; Fig. 5). At both trenches, a slightly increase upsection of *P. albicans* percentages (up to 2-3%) is recorded and accompanied by an abrupt colour change of sands, from yellow to dark-grey, and the sudden occurrence of sparse osteological remains and pottery, among which few body sherds of presumably Early Hellenistic shapes (Fig. 5).

Interpretation

The dominance of the polythermophilic, euryhaline, opportunistic *C. torosa*, able to resist wave scouring (Meisch, 2000), and the co-occurrence of un-noded and noded forms (Frenzel and Boomer, 2005; Pint et al., 2012) point to a shallow, hypohaline (up to oligohaline) setting with high-energy, coarse-grained bottom corresponding to the lake-shore area. A similar oligotypic ostracod fauna was found at ~ 5 m of water depth in the present-day Sea of Galilee (Mischke et al., 2010) and the specific preference of *C. torosa* for Na^+ and Cl^- -dominated waters (Mischke et al., 2012) is consistent with the natural chemical composition of the basin (sub-section 2.1.).

The upward slightly increasing trend of *P. albicans* and the abrupt transition to dark-grey sands likely reflect the establishment of slightly more organic-rich, stagnant conditions (Henderson, 1990), possibly connected to the earliest historical stages of human frequentation at Magdala, and dated fairly before the beginning of the 2nd century BC. During this period, human settlements were probably installed further westward along the slopes of Mt. Arbel (De Luca, 2010; Sarti et al., 2013).

4.1.2. Harbour bay silty sands

Description

This unit, marked at the base by a cm-thick pebble layer, consists of dark, fine-very fine sands with high clay-silt content and numerous mollusc shells, seeds, charcoal and other vegetal debris, and osteological remains (sheep, cattles, microvertebrates, fish teeth and plates). The ostracod fauna is abundant and shows a higher interspecific diversity compared to the pre-harbour beach sands. A total of four ostracod taxa (*P. albicans*; *Ilyocypris* spp.; *Ilyocypris hartmanni* and *Heterocypris salina*) commonly accompanies the dominant species *C. torosa*, which accounts for the 85-95% of the entire assemblage (Fig. 5). Among the secondary taxa, *P. albicans* is the most represented, ranging between 2% and 7%. *Ilyocypris* gr. varies between 1% and 8%, while *H. salina* displays very low values (0.3-1.2%, respectively; Fig. 5). Other three species, *Heterocypris incongruens*, *Humphcypris subterranea* and *Psychrodromus* sp., are only sporadically found as few valves. Another diagnostic feature of the ostracod assemblage is the dominance of noded forms of *C. torosa* relative to the un-noded ones. The former can reach up to 88% of the entire assemblage and never falls below 75% (Fig. 5).

Within this unit a rich assemblage of human artifacts, including potsherds, fragments of glass vessels and bronze nails belonging to the ship's carpentry, was also found (De Luca, 2010; Lena, 2012). Concerning the pottery, several fragments of locally made amphorae of the type Anf2 (Fig. 6:8), Anf3 (Fig. 6:2.5-7), Anf4 (Fig. 6:4), Anf7, Anf10 and Anf13 (Fig. 6:3.9) and some imported amphorae (Fig. 6:13) occur. Among the cooking ware a few samples of the Late Hellenistic type of Pent4 and rims, resembling the type Pent5 (Fig. 6:19-20), are encountered along with fragments of *orlo bifido* pan, well attested through the Mediterranean area from the 2nd century BC to the 1st century AD and beyond (Fig. 6:16). The type of casserole with everted rim Teg12 (Fig. 6: 14-15) shows differences in fabric, surface treatment and rim inclination with respect to the well-known type of Kefar Hananiah ware ascribed to the Early Roman period. Moreover, several fragments of Galilean Coarse Ware-GCW *pithoi* are recorded. Regarding the glass fragments, forms dating from the 3rd century BC to the 1st century AD (Fig. 6: 23-24) are found. For a detailed description of the archaeological findings, the reader is referred to the Supplementary Table 1.

Interpretation

The in-depth analysis of the ostracod fauna furnishes new palaeoenvironmental information about the depositional setting of this unit, interpreted by Sarti et al. (2013) as a semi-protected bay formed in response to the earliest Late Hellenistic phases of the Magdala harbour management.

Throughout the unit the remarkable abundance of *P. albicans*, a species preferring shallow, slow moving waters (Meisch, 2000), is indicative of relatively stagnant conditions, in accordance with the dark sediments colour and the high amount of well-preserved seeds and other vegetal remains. The abundance of osteological fragments (mainly meal remains) and human artifacts attests the harbour basin being use also as a waste dump by the oldest citizens of Magdala, according to the thesis formulated by Marriner and Morhange (2007) for seaport contexts. According to the available radiocarbon dates, as a whole the archaeological assemblage, characterized by a clear predominance of the oldest forms, refers to a chronology between the 2nd century BC and the first half of the 1st century AD, when the Roman slipway was built (Fig. 5).

The occurrence of brackish-tolerant species commonly found in shallow waters with slightly saline character as *H. salina* and *P. albicans* itself (Meisch, 2000), along with the absence of taxa restricted to extremely low salinity-still waters indicate remarkable solute concentrations. Moreover, the dominance of noded *C. torosa* suggests a stressed environment possibly affected by unstable ionic composition. Indeed, recent studies have stated that noding development under low salinity/oligohaline conditions should be considered such as a morphological response driven by osmoregulation difficulties (Frenzel and Boomer, 2005; Keyser, 2005). Although the actual mechanism responsible for noding during molting stages is still largely unknown, water chemistry (ionic composition) changes have been recently indicated as an important factor in driving noding development within inland waters (Frenzel et al., 2012; Mischke et al., 2010; Pint et al., 2012).

------------------------------ link to the Supplementary Table 1 around here ------------------------------

4.2. SEM-EDS analysis of C. torosa shells

Particular attention was paid to the morphological and geochemical features of *C. torosa* shells (molt stage A-1), selected from the pre-harbour and harbour units of the studied trenches (sub-section 3.2.) and observed under the scanning electron microscope (SEM). Irrespective of the stratigraphic units from which they were collected, the un-noded and noded valves show specific ornamentation features. The carapace of un-noded *C. torosa* is characterized by fine to large pits, the latter being less numerous (Fig. 7). In contrast, a heavy ornamentation with larger depressions (*fossae*) separated by walls (*muri*) occurs on the external surface of the noded valves, forming a dense and pronounced pattern of reticulation (Fig. 7). Three well-developed nodes are clearly identified on all the observed valves, forming the typical "basic triangle" in the carapace central zone (Athersuch et al., 1989); other nodes or proto-nodes of variable size and shape are rarely observed close to the dorsal and ventral edges. The nodal structures, characterized by stretching signs along the margins, are commonly rounded, but less frequently they show a more elongate shape (Fig. 7).

Although EDS technique can furnish only presence/absence information about major and trace elements, a different chemical composition of *C. torosa* shells was detected for the reticulated noded specimens relative to the punctuated un-noded ones, suggesting different water chemistry conditions during valves calcification. At each molting stage the new carapace is precipitated from ions in solution at thermal-chemical equilibrium with the surrounding waters (Chivas et al., 1983; Holmes, 1996; Ito and Forester, 2009; Mischke and Holmes, 2008; Smith and Horne, 2002).

All the EDS intensity spectra show the two main peaks of calcium (Ca-K_{α} and Ca-K_{β}) and the main peaks of carbon (C-K_{α}) and oxygen (O-K_{α}), accompanied by minor peaks of magnesium (Mg-K_{α}) and strontium (Sr-L_{α}). These data reflect the low-Mg calcite composition of the ostracod shells, where strontium occurs as vicariant element of calcium (Fig. 7). Less pronounced peaks that can be attributed to Fe and S are also evaluated. A *suite* of additional trace elements is detected by pronounced EDS intensity peaks within the reticulated noded valves. In this regard, a significant amount of sodium, potassium, chloride, and terrigenous elements (Si, Al, and Rb) is recorded (Fig. 7). About the potential influence of contaminants, mainly adhering aluminosilicates within shell depressions, spot spectra performed on the clean walls of the carapace reticulation support the presence of terrigenous elements within the carbonate structure of noded *C. torosa*.

4.3. XRF analysis of sediments

X-ray fluorescence (XRF) analysis of sediment samples was performed as a complement to the stratigraphic and palaeontological data previously described. To this purpose, the geochemical properties of the pre-harbour hosting deposits were plotted against their harbour counterparts, and we selected two scatterplot diagrams (Fig. 8A-B) as the most representative of changing environmental conditions at the basin floor through time.

In the Na_2O-K_2O diagram (Fig. 8A), a major distinction can be observed between the pre-harbour deposits, which show relatively low Na and K contents compared to the overlying harbour deposits. The same stratigraphic trend, which suggests onwards increasing solute concentrations at the transition from a natural beach environment (pre-harbour sediments) to a relatively restricted human-forced bay (harbour sediments), is documented from both trenches, F18 and F25. Moreover, the intermediate values of Na and K recorded in correspondence of the lower and upper boundaries of the harbour unit (Fig. 8A) reveal a strict relationship between the Na-K concentrations and the evolutionary pathway of the Hellenistic harbour basin.

Finally, changing oxygenation conditions at the lake floor were evaluated through the determination of trace metal enrichments in sediments (Fig. 8B). It is widely accepted that high V and Cr concentrations can reflect reducing environments (Calvert and Pedersen, 1993; Schaller et al., 1997). The concentration of V in the water column of relatively anoxic basins is commonly lower than in oxic water because of precipitation and uptake into sediments. The clear-cut separation, in terms of Cr and V distribution, between pre-harbour and harbour deposits, with sharp increase of these two metals in the latter (Fig. 8B), can be taken as evidence of decreased bottom water oxygen during harbour construction and development. In this diagram, high Cr and V contents may also reflect fine-grained lithologies (i.e., high metal values in two pre-harbour samples in Fig. 8B), thus emphasizing relatively low-energy conditions, where slow moving waters may occur.

5. Discussion

On the basis of multiple lines of evidence (sedimentology, geochemistry, ostracod fauna and archaeological data), a detailed picture of palaeoenvironmental conditions is reconstructed at the transition from a nature-dominated to a human-dominated depositional context in the Magdala coastal area.

Beneath the Roman harbour structures, ~ 250 m west of the modern coastline, the vertical stacking pattern of lithofacies, ostracod assemblages and geochemical features framed into a high-resolution pottery-based chronology (Fig. 9) reveal the occurrence of remarkable hydrodynamic and hydrochemical changes within the Magdala coastal succession. Around 211 m bsl, an eastward-dipping centimetre-thick layer, containing numerous mollusc shells, pebbles and small-sized, sharp-edged stones of ambiguous (anthropogenic?) origin, marks the boundary between the lake beach deposits, formed under natural conditions, and the overlying harbour succession (Fig. 9; Sarti et al., 2013). This layer, characterized by the same biological content and geochemical features of the harbour unit (Fig. 9), may represent the base of a rudimentary harbour system that should comprise, at distal locations, an accumulation of stones, stacked to facilitate ships landing and repair in the Magdala area. At trench F18, one radiocarbon date chronologically constrains its formation to the Hellenistic period around 205-50 cal yr BC (Figs. 5, 9). Integrated radiocarbon ages (ca. 170 cal yr BC-20 cal yr AD) and potsherds furnish a consistent age for the overlying harbour fine-grained unit, formed during a chronological interval ranging between the 2nd century BC and the first half of the 1st century AD (Fig. 5; sub-section 4.1.2.). This chronological framework and the complex lateral-vertical relationships between the harbour unit and the Hasmonean harbour structures (Lena, 2012) document the continued existence and exploitation of an “artificial” shallow basin during the entire Late Hellenistic period, at least. Consistent with this interpretation, across the archaeological site a dm-thick dark silty interval containing several Hellenistic potsherds was recovered in a stratigraphic position correlative to the harbour unit at F18 and F25 (Lena, 2012). These archaeological evidences, referable to a period comprised between the 3rd century BC and the beginning of the 1st century AD, show a remarkable presence of the earliest forms, among which Hellenistic amphorae derived from Persian type (Fig. 6:1), red slip Hellenistic *lagynoi* (Fig. 6:12), casseroles with inclined everted rim with pointed internal apex (Fig. 6:14-15), juglets sometimes with traces of slip (Fig. 6:10-11), very fine saucers/cups (Fig. 6:17-18), radial oil lamps (Fig. 6:22) and several fragments of GCW *pithoi*.

The local waning wave energy and the resulting development of a semi-protected bay environment, serving as harbour basin (Sarti et al., 2013), do not represent the only environmental changes connectable to the construction of Hellenistic harbour installations at Magdala.

As revealed by integrated ostracod fauna and geochemical data, the changes in water circulation patterns, in turn, altered the floor conditions and the water chemistry of the basin. The concomitant substantial increase in the sediments of both V-Cr concentrations and ostracod species preferring slow moving waters and fine-grained substrates (*P. albicans*) points to the establishment of a shallow, stagnant organic-rich basin with relatively low-oxygen levels at the bottom, in contrast with the oxic pre-harbour nearshore depositional setting (Fig. 9). The oxygen-depleted organic-rich floor conditions, tolerated by the dominant opportunistic species *C. torosa* (Meisch, 2000) and also documented by the widespread occurrence of well-preserved vegetal and osteological remains, testify to the reduced water exchange of the embayed environment with the forward lake system (semi-enclosed confined setting). This abrupt human-forced shift towards a higher degree of protection resembles the typical depositional evolution of the Mediterranean ancient harbours, where the reduced water exchange with the open sea translates in an increase in organic matter and a decrease of salinity (Marriner and Morhange, 2006, 2007).

Nevertheless, in lacustrine hypohaline settings the “artificial” confinement of selected coastal portions may turn into more complex water body changes that involve the total dissolved ion content (salinity) and the ionic composition, following the evolutionary pathways principally driven by local climate conditions. The XRF analysis highlights an enrichment in Na and K within the Magdala harbour sediments with respect to the underlying pre-harbour beach sands (Fig. 8). In the context of the Sea of Galilee basin, characterized by dominant autochthonous carbonate sedimentation and semi-arid climate, the local enrichment of alkali free-ions already present in the water (Nishri et al., 1999) may reflect modifications of the precipitation/evaporation ratios. Since palaeoclimatic records document relatively high precipitation rates during the Hellenistic-Roman periods (sub-section 2.1.), an increase in surface water's evaporation is feasible and connectable to the partial isolation of a marginal sector of the basin. At the same time, changing proportions between freshwater (Jordan River and inflowing streams) and solute water inflows (onshore saline springs; sub-section 2.1.) to the Magdala area, likely connected to the development of the harbour basin, cannot be excluded *a priori*. However, since the harbour structures are aimed to protect a portion of the coast, they would decrease, rather than increase, the inflows of lacustrine waters within the basin.

Besides the relatively high degree of protection, other factors linked to the Hellenistic harbour structures might have contributed to the alkaline enrichment of the Magdala basin, including ordinary port operations as ships traffic and cargo handling-storage. In particular the trade of salt, possibly also from the Dead Sea, essential for the fish processing industry and documented by archaeological data and historical sources (Clamer, 1997, 1999; Hirshfeld, 2006), may have partially contributed to Na, K and Cl enrichment in the harbour area.

Significant changes in the chemistry of the sediment-water system are also recorded by the ostracod fauna composition at the boundary with the harbour unit (Fig. 5). The sudden appearance of *H. salina*, a species tolerant to elevated conductivity levels and variable solute composition (Meisch, 2000; Mischke et al., 2012), points to a general increase of cations and anions concentration within the basin. In this regard, the almost absolute dominance of noded valves of *C.*

torosa, whose shells are enriched in Na, K and Cl with respect to the un-noded ones (Fig. 7; sub-section 4.2.), suggests major availability of these elements, as free-ions, to be uptaken for shell calcification. Moreover, a good relationship is detected by comparing Na+K sediment values with noded *C. torosa* frequencies (Fig. 10), suggesting a positive relationship between noding development and increasing alkali accumulation in the Magdala basin.

Indeed, the hydrochemical features of the host water rather than salinity in itself seem to play a key-role in noding development, especially within oligohaline settings and inland waters (Frenzel and Boomer, 2005; Frenzel et al., 2012; Keyser, 2005; Pint et al., 2012; van Harten, 2000). Since Keyser (2005), noding is interpreted as an osmotic-controlled phenomenon that develops in response to high-stressed multifactorial environments, characterized by low salinity (usually less than 7 psu) and changing water ionic composition. In this respect, several hypotheses have been formulated, including low Ca^{2+} availability (Frenzel et al., 2012) and/or increasing barium and magnesium concentrations (Bodergat, 1983). Moreover, Mischke et al. (2010) suggested an affinity between low K concentrations in the host waters and the occurrence of noded shells of *C. torosa* collected from several present-day water bodies in Israel. This hypothesis is apparently in contrast with the concomitant remarkable increase of Na+K values and noded *C. torosa* frequencies recorded within the Magdala harbour basin (Figs. 9, 10). Therefore, all these studies clearly reveal that the complex mechanism favouring the development of nodosities during *C. torosa* molting is still largely unknown. In the next future, experiments are needed to shed new light on the relationships between different water chemical compositions and morphology of *C. torosa* shells under oligohaline conditions (Frenzel et al., 2012; Pint et al., 2012).

Finally, although all available data point to a strong anthropogenic impact on Magdala coast in concomitance with the oldest (Late Hellenistic) harbour installations, there is evidence that human activity in the study area began in earlier times, with the formation of the lacustrine beach grey sands containing scattered potsherds. The ostracod fauna, especially the one encountered within the uppermost sample of the grey sandy succession (Fig. 5), is consistent with the establishment of stressed, less oxic conditions likely reflecting a transitional proto-harbour zone developed during the earliest phases of Hellenistic harbour construction. However, it is clear that additional stratigraphic, palaeontological and geochemical data from other trenches and cores across the archaeological site are necessary to confirm this hypothesis.

6. Conclusions

The multi-proxy (sedimentological, ostracod and geochemical) study of the bio-sedimentary record buried beneath the Roman harbour slipway at the ancient city of Magdala (Sea of Galilee, Israel) gives new insights into the palaeoenvironmental evolution of the archaeological site. The dynamics of the complex relationship between lacustrine sedimentation and human activity are framed into a high-resolution temporal framework, mainly based on pottery assemblages tied to radiocarbon ages. This approach also furnishes new data about the degree of protection and degradation of the Hellenistic harbour basin, highlighting the key-role exerted by the ostracod fauna (assemblage composition and chemical features of *C. torosa* valves) to decipher subtle environmental changes in the lacustrine anthropogenic-forced context.

The major outcomes of this work are as follows:

1. The pre-Roman succession beneath the archaeological site exhibits a vertical stacking pattern of lithofacies, ostracod assemblages and geochemical features indicative of remarkable hydrodynamic and hydrochemical changes occurred around the 2nd century BC, at the onset of the harbour system. These environmental changes strongly support the hypothesis (Lena, 2012; Sarti et al., 2013) of waterfront construction of man-made structures partially protecting the coastal area in front of the ancient city of Magdala;

2. Concomitant changes in V-Cr sediment concentration and ostracod fauna composition point to the sudden development of a semi-protected shallow bay with high-organic and relatively low-oxygen levels along the Magdala coast. This embayment worked as a harbour basin during almost the entire Hellenistic period, as testified by scattered archaeological evidences;

3. The alkali enrichment recorded in the Hellenistic harbour basin by both sediments and the ostracod fauna documents local changes in the lake water character that well match a protected marginal lacustrine area in a hot, semi-arid climate region;

4. In the Magdala depositional record a close relationship is detected between Na+K sediment concentrations and relative frequencies of noded *C. torosa*, whose valves are themselves enriched in alkali, thus confirming the important role exerted by the oligohaline water chemistry in nodosities formation;

5. Our data confirm that hypohaline ostracods are excellent bioindicators of the surrounding physico-chemical conditions, even at the transition from a nature- to a human-influenced depositional context.

Acknowledgements

The authors thank the ENVIMED MISTRALS GEOISRAEL program and IUF, the LABEX OT MED and the Magdala Project team for their support to this study. This is a contribution to MISTRALS/PALEOMEX and to the Labex OT-Med (ANR-11-LABEX-0061) funded by the Investissements d'Avenir, French Government program of the French National Research Agency (ANR) through the A*Midex project (ANR-11-IDEX-0001-02). We are strongly indebted to Dr. Steffen Mischke and an anonymous reviewer for their invaluable suggestions and comments to the paper. We are also grateful to A. Rimmer and A. Sandler for the bibliographical help, Giorgio Gasparotto for the technical help with the EDS-SEM analysis and Federico Fanti for the useful

discussion about vertebrate remains.

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Figure captions

Figure 1: A) Tectonic sketch map of the Near East region (from Leroy, 2010). The Sea of Galilee area is highlighted by the black square. DST: Dead Sea Transform Fault; B) Geological sketch map of the area surrounding the Sea of Galilee (slightly modified from Singer et al., 1972) with position of the Magdala site along the western lakeshore. The dotted lake area corresponds to the marginal zone with water depth < 10 m. The arrows show the counter-clockwise circular current (from Pan et al., 2002) affecting the central part of the lake (see sub-section 2.1.). Black square: position of other ancient cities mentioned in the text.

Figure 2: A) Aerial image of the archaeological site of Magdala (property of the Magdala Project Excavation); B) General Plan of the Magdala Project Excavations (2007-2012; courtesy of Stefano De Luca-copyright and A. Ricci). The location of trenches F18, F25 and F27 and the main archaeological remains are shown. Different colours represent distinct archaeological phases: Late Hellenistic (green); Roman (yellow); Byzantine (light blue); Islamic (purple). See also Figure 4 for architectural details.

Figure 3: Stratigraphic relationships between the lacustrine deposits and the harbour structures identified in the subsurface of the Magdala site, in front of the *quadriporticus* (see Fig. 2B for trenches location). The three depositional units, corresponding to the main evolutive phases of Magdala ancient harbour, are also reported (slightly modified from Sarti et al., 2013). C: clay and silt; S: sand and G: gravel. HFS-harbour foundation surface and HAS-harbour abandonment surface *sensu* Marriner and Morhange (2006, 2007) are traced. Radiocarbon ages are reported here as calibrated yr BC/AD (slightly modified from Sarti et al., 2013).

Figure 4: Archaeological/historical phases of the Magdala site (colours as in Fig. 2B). The link between archaeological remains and geoarchaeological phases is also proposed.

Figure 5: Stratigraphy of the two studied trenches (F18 and F25) and vertical distribution of the main representative ostracod taxa. Samples containing rare ostracod valves (less than 50 A+A-1+A-2 valves) are also highlighted. Radiocarbon ages are reported as the highest probability range in calibrated yr BC/AD. See Figure 3 for the key to particle size and the uppermost portions (harbour abandonment unit) of F18 and F25 trenches.

Figure 6: Specimen of the pottery and glass assemblages from the Magdala Project Excavation of the Harbor (HFS and AHF). Courtesy of S. De Luca and A. Lena, the Magdala Project, from Lena (2012). Draws: F. Pollastri and S. De Luca; Layout and Table: S. De Luca. See text and Supplementary Table 1 for more details.

Figure 7: Representative SEM images of un-noded (right valve) and noded (left valve) *Cyprideis torosa* and relative EDS intensity spectra. The valves were extracted from the pre-harbour beach sands at F18 trench. The EDS spectra show the major (C; O; Ca) and minor (Na; Mg; Sr; Cl; K) peaks discussed in the text. The white scale bars correspond to 200 micron.

Figure 8: Scatterplots of Na_2O *vs* K_2O content and V *vs* Cr from F18 and F25 sediment samples. Sample groups are differentiated according to their stratigraphic position at each trench. Open symbols (diamonds): pre-harbour samples; filled symbols (circles): harbour samples.

Figure 9: Vertical profiles of selected geochemical elements discussed in the text, relative proportions (percentages) of un-noded *C. torosa* (light grey) *vs* noded *C. torosa* (dark grey) and distribution trend of *P. albicans* along the studied trenches. Asterisks indicate samples containing rare ostracod valves (< 50). Palaeoenvironmental interpretation is also shown.

Figure 10: Scatterplot of Na_2O+K_2O *vs* noded *C. torosa* abundances. Samples from the studied trenches (F18 and F25) are grouped according to their stratigraphic position. Open symbols (diamonds): pre-harbour samples; filled symbols (circles): harbour samples.

Appendix A

Taxonomic Reference List. This list includes genus and species of the ostracods cited in the paper.

Cyprideis torosa – *Candona torosa* Jones, 1850; p. 27, pl. 3 figs. 6a-e.

Heterocypris salina – *Cypris salina* Brady, 1868; pl. 26 figs. 8-13.

Ilyocypris – *Ilyocypris* Brady and Norman, 1889; p. 106.

Pseudocandona albicans (Brady, 1864) – *Candona albicans* Brady, 1864; p. 61, pl. 4 figs. 6-10.

Inline Supplementary Material

Supplementary Table 1: Pottery Catalog. Description of the pottery assemblage illustrated in Figure 6 by S. De Luca and A. Lena, updated from Lena (2012). The reference list is also provided.

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New insights into the palaeoenvironmental evolution of Magdala ancient harbour (Sea of Galilee, Israel) from ostracod assemblages, geochemistry and sedimentology

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Abstract

Despite several studies have focused on the past bio-sedimentary response of the Mediterranean coastal areas to ancient seaport activities, only few geoarchaeological and palaeoecological data are available on strictly lacustrine harbours, to date. At the archaeological site of Magdala/Taricheae (Sea of Galilee, north Israel), an interdisciplinary study, combining ostracod fauna composition and shell chemistry with sedimentology, geochemistry of sediments and archaeological data, was undertaken on the sedimentary succession buried beneath the Roman harbour structures in correspondence of two key-sections. This approach provided detailed information about past environmental changes, otherwise not visible, into a high-resolution pottery-based chronological framework at the transition from a natural (pre-harbour) to anthropogenically influenced (harbour) lacustrine depositional setting.

New bio-sedimentary and archaeological (pottery) data document that remarkable hydrodynamic and hydrochemical changes took place during the Hellenistic period (from the 3rd-2nd century BC to the first half of the 1st century AD), in response to the construction of the oldest Magdala harbour installations and, possibly, to the following Hasmonean structures. The high V-Cr concentrations observed in the harbour sediments, and the substantial increase of ostracod species (*Pseudocandona albicans*) preferring slow moving waters and fine-grained substrates point to the establishment of a semi-enclosed, shallow, and organic-rich setting. Coupled ostracod-geochemical analyses also testify to an alkali ions (Na^+ and K^+) enrichment within whole-sediment samples, reasonably driven by increasing evaporation in response to the partial isolation of the lake margin. The increase in sodium and potassium concentrations is accompanied by the sudden appearance of *Heterocypris salina*, a brackish-tolerant species, and by the almost absolute dominance of noded valves of *C. torosa*, whose shells are enriched in Na, K and Cl. The positive covariance between Na_2O+K_2O values and the frequencies of noded *C. torosa* seems to confirm the relation between node development and changes in ionic concentration within hypohaline settings.

Keywords: ostracods; geochemistry; geoarchaeology; ancient harbour; Sea of Galilee; *Cyprideis torosa*

1. Introduction

Lacustrine deposits are universally recognized as excellent high-resolution terrestrial palaeoarchives, containing non-biological and biological proxies of short-lived palaeoenvironmental/climatic changes (Cohen, 2003; Fritz, 2008; Roberts et al., 2008; Zolitschka et al., 2000). The former mainly include sedimentological and geochemical features, while the latter comprehend pollen, plant macrofossils, diatoms, crustaceans and molluscs.

Ostracods, micro-crustaceans with low-Mg calcite valves, usually represent the most abundant, well-preserved *in situ* faunal component of freshwater and saline lakes from different regions (Holmes, 2001; Holmes and Chivas, 2002). The well-known high sensitivity of ostracods to changing physico-chemical parameters of the ambient water and the bottom sediments (i.e. solute chemistry, salinity, nutrient availability, dissolved oxygen, temperature, hydrodynamic conditions and mean grain size), along with the abundance of shells within small-sized samples, make them an important tool in high-resolution palaeolimnological studies, aimed to reconstruct past hydrochemical and hydrological changes (Börner et al., 2013; Carbonel et al., 1988; Frenzel and Boomer, 2005; Horne et al., 2012; Marco-Barba et al., 2012, 2013b; Palacios-Fest et al., 2005; Véron et al., 2013).

Combining ostracod fauna species composition, shell morphology (carapace size and noding development) and chemistry, high-frequency palaeoenvironmental changes induced by natural factors (climate, groundwater interactions, catchment geology, tectonic activity), anthropogenic factors (hydrological modifications, urban waste discharge and shoreline artificialization) or both can be detected within the lake sedimentary record.

Recently, several geoarchaeological works have documented the primary role of ostracods as sentinels of human-induced environmental changes on lacustrine and alluvial depositional systems characterized by a long history of human occupation (Anadón and Gabas, 2009; Bates et al., 2008; Escobar, 2010; Mischke et al., 2013; Palacios-Fest et al., 1994; Rosenfeld et al., 2004; White et al., 2013). In these studies, the analysis of the ostracod fauna, combined with additional geological, geomorphological and archaeological data, has extensively been used to better understand the evolution of human-environment interactions, focusing on pre-human occupation conditions and human-induced water chemistry changes.

In contrast, few integrated geoarchaeological and palaeoecological data are available from the stratigraphic record of ancient lagoon/lacustrine or fluviatile harbours recently discovered in the Mediterranean area (Benvenuti et al., 2006; Flaux et al., 2012; Morhange et al., 2000; Stefaniuk et al., 2003; Tronchère et al., 2012; Vecchi et al., 2000; Vött, 2007). In these contexts, the importance of ostracods as bioindicators is further enhanced by the absence of foraminifera, whereas both benthic groups are abundant in most marginal marine environments and widely used to reconstruct the evolution of Mediterranean seaports (Bellotti et al., 2011; Bernasconi and Stanley, 2011; Bini et al., 2012; Di Bella et al., 2011; Goiran et al., 2013; Goodman et al., 2009; Marriner and Morhange, 2007; Marriner et al., 2008, 2012; Morhange et al., 2003; Mazzini et al., 2011; Reinhardt et al., 2006).

In the northern part of Israel, along the W coastline of the Sea of Galilee, also known as Lake Tiberias or Lake Kinneret, recent excavations at the ancient city of Magdala/Taricheae (Fig. 1), directed by Stefano De Luca (Magdala Project; http://www.magdalaproject.org/WP/), have unearthed the remains of stonework-landing places active from the Late Hellenistic to the Islamic period (167 BC-800 AD; De Luca, 2010; Lena, 2012).

On the basis of a geoarchaeological approach (Marriner and Morhange, 2006), Sarti et al. (2013) recognized two main depositional units buried beneath the Roman harbour structures, corresponding to the pre-harbour foundation phase and the earliest harbour phase, respectively. The latter was dated by radiocarbon ages to the Hellenistic period.

Herein, refined ostracod fauna analysis combined with geochemical analysis of sediments are used to obtain new insights on the evolution of Magdala harbour and to detect changes in environmental conditions during the first phase of harbour use. Specific aim of this study is to assess to what extent the synergy among sedimentological, palaeontological and geochemical data, framed into a high-resolution pottery-based chronological framework, can yield valuable information about past environmental parameters at the transition from a natural to an anthropogenic-dominated lacustrine setting.

2. Background

2.1. Geological and geomorphological setting

The Sea of Galilee, in northern Israel, is a relatively freshwater-oligohaline lake (Nishri et al., 1999) located at an average elevation of 210 m below the mean sea level, with a total area of ~ 166 km^2 (21 km maximum length x 12 km maximum width) and a maximum depth of ~ 43 m (Israel Oceanographic and Limnological Research http://www.ocean.org.il/eng/kineret/lakekineret.asp; Kolodny et al., 1999). The lake occupies the northern subsiding pull-apart basin of the Jordan-Dead Sea Rift Valley, a long and narrow tectonic depression stretching for about 300 km along the N-S Dead Sea Transform-DST (Abbo et al., 2003; Marco et al., 2003; Fig. 1A). The activity of this left-lateral fault is responsible for the intense seismic history of the area, documented by geological, archaeoseismic data (Belitzky and Ben-Avraham, 2004; Ellenblum et al., 1998; Marco et al., 2000, 2003, 2005; Wechsler et al., 2009) and historical sources (Karcz, 2004; Nur and Burgess, 2008; Russell, 1985).

The lake is mainly fed by the Upper Jordan River, which flows from N to S, and by a series of wadis draining the Golan Heights to the E and the Lower Galilee highlands to the NW (Fig. 1B). The catchment area consists predominantly of Neogene-Quaternary volcanic rocks, mainly basalts, and Eocene carbonates (limestone, chalk and chert), bordering the lake along the west and north sides. Miocene continental sedimentary deposits (sandstone, mudstone and conglomerate) crop out along the east side and with patchy exposures along the west side (Fig. 1B; Geological Survey of Israel http://www.gsi.gov.il; Singer et al., 1972). In the southern part, Quaternary sedimentary deposits formed within freshwater to brackish lacustrine and fluvial environments extensively occur (Heimann and Braun, 2000).

Small springs situated onshore, along the coastline, and offshore, at the lake bottom, subordinately supply the basin with saline hot waters fed by Pliocene residual brines (Farber et al., 2007; Klein-BenDavid et al., 2005; Kolodny et al., 1999). The mixing between saline and fresh waters determines the higher salinity (total dissolved solids-TDS value of ~ 700±100 mg/l) and alkaline composition of the basin, relative to the feeder streams (Farber et al., 2007; Nishri et al., 1999; Rimmer and Gal, 2003; Stiller et al., 2009).

The lacustrine sedimentation is mainly characterized by the massive production of autochthonous $CaCO_3$ (calcite carbonate phase), which represents more than 50% of the sediment composition (Nishri et al., 1999). Allochthonous deposits are delivered into the lake by strong river floods, diluting the authigenic calcite content.

To date, no deep-lacustrine cores have been recovered, preventing the detailed reconstruction of the late Quaternary evolution of this sedimentary basin. Nevertheless, the widespread occurrence of palaeo-beach deposits and archaeological sites at various stratigraphic levels along the lake coastline reveals water-level fluctuations over the course of the past millennia (Hazan et al., 2004, 2005; Robinson et al., 2006). Even though incomplete, the resulting Holocene lake-level curve shows high-frequency episodes of relative rises and declines of tens of metres that are simultaneous with the more prominent changes independently recorded in the Dead Sea (Hazan et al., 2004, 2005).

These in-phase Sea of Galilee-Dead Sea water-level oscillations show a good chronological correlation with the high-frequency climate changes occurred in the eastern Mediterranean area under the predominant control of the Mediterranean rain system (Hazan et al., 2005; Robinson et al., 2006). In particular, the late Holocene palaeolimnological and pollen records from the Sea of Galilee and the Dead Sea consistently indicate a phase of relatively high precipitation rates covering the Hellenistic and Roman periods (ca. 2300-1800 cal yr BP), when the region was heavily populated (Dubowski et al., 2003; Leroy et al., 2010; Quintana Krupinski et al., 2013). Close to the end of the Byzantine times (ca. 1400 cal yr BP) a regional, drier climatic phase occurred (Dubowski et al., 2003; Leroy et al., 2010; Orland et al., 2009; Quintana Krupinski et al., 2013).

At present, seasonal water-level fluctuations recorded at the Sea of Galilee reflect the distinctive alternations between rainy winters and dry summers, typical of the Levantine region (Hambright et al., 2004; Rindsberger et al., 1983). However, the unique topography of the lake (~ 210 m bsl) induces higher temperatures (average annual temperature above 18 °C) and lower annual rainfall (400 mm) with respect to its immediate surroundings (~700 mm), determining a hot semi-arid climate over the Sea of Galilee area (http://www.israelweather.co.il/english/kineret.asp). Consistent with these climatic features, the vegetation shows a mix of trees, shrubs and grasses of the Mediterranean and Irano–Turanian biomes (Zohary, 1973). In particular, around the lake *Tamarix* sp. trees occur at higher altitudes while thickets of *Phragmites australis* and *Cyperus* spp. grasslands and marshland are found approaching the water (Tibor et al., 2012).

The Magdala archaeological site is located ~ 250 m west of the present-day lake shore (Fig. 2A), recorded around 212-213 m bsl during the 2011 field campaign. About 50 m from the site, a 2-3 m-thick escarpment bank, marked by an eucalyptus tree-line (Fig. 2A), abruptly interrupts the slightly lakeward inclined coastal plain. The eucalyptus trees were planted during the British Mandate (1920-1948 AD) to reclaim the swampy coastal areas facing the lake, suggesting a higher water-level than the present one. On the western side, the archaeological site is bounded by the Lower Galilee hills composed predominantly of limestones and basalts and deeply incised by the Amud, Tzalmon, Arbel and El Amis wadis that have been recently affected by artificial channelization (Fig. 1B). Through the Wadi Arbel the main daily wind, the westerly Mediterranean Sea Breeze, penetrates strongly and passes over the lake, playing a crucial role in the generation of lake gyres, transient currents and thermocline displacements (Pan et al., 2002). Indeed, the wind curl induced by the passage of the Mediterranean Sea Breeze produces the counter-clockwise surface current that characterizes the central part of the lake (Fig. 1B; Pan et al., 2002). With respect to the direction of this current, the Magdala site is placed in a more protected area compared to the eastern lake coast.

2.2. Archaeological and historical context

According to Plinius (Nat. Hist. 5:71) the lake owes its name to the prominent city-port of Taricheae, whose importance and prosperity was mainly linked to the quality of the fish processing industry and trade, as reflected by both its toponym and the account of Strabo: “ε□ν δὲ ται□ς καλουμέναις Ταριχέαις η□ λίμνη μὲν ταριχέιας ι□κθύων α□στείας παρέχει” (Geogr. XVI:2,45). The city – known in the Semitic sources also by the name of Migdal/Magdala (Leibner, 2009) – was probably founded, along with the articulated port facilities, during the Late Hellenistic time by the Hasmoneans (cf. 1Macc 5:14-20) as the capital of a Toparchy (administrative district), on the site of an earlier settlement located on the crossroads of important routes directed to the main cities of the region (i.e. Tyre and Akko). During this early stage of city development (3^{rd}-1^{st} century BC) the urban layout (De Luca, 2009, 2010, 2011a), identified through the archaeological excavation, was planned according to a network of orthogonally paved crossing roads and an articulate underground water supply and sewage system, connected to a water tower (A1) built upon a spring (Fig. 2B). A domestic area, identified in the W portion of the site, several public buildings (e.g. the "stoa-shape fountain" D1) and two impressive harbour structures also occurred (Fig. 2B). These consist in a *quadriporticus* (Q) and in a tower-port (TP), both facing the lake (Fig. 2B). The latter, due to its architectural features (casemattes) and its strategical location, was probably built for military purposes, as also suggested by some parallels (De Luca, 2010). Indeed, the city was than involved in the Roman military campaigns against the Parthians (Bell. Iud. I:8.9.180; cf. letter of Cassius

Longinus to Cicero of 43 BC: Ad Fam 24:11) and in the First Jewish Revolt of 66-70 AD (Bell. Iud. 3:497. 499), when it was conquered by Vespasianus and Titus, as also reported by Svetonius (De Vita Caesarum, Titus 4:3).

During the 1st century AD the city, which was assigned by Nero to Herod Agrippa II in 53 AD, underwent many transformations maintaining its remarkable economic role in the region, even after the foundation of Tiberias, built by Herod Antipas (18-20 AD) as the new capital of Galilee. While maintaining its earliest Hellenistic layout, the dwelling quarter was reorganized around the W-E (De Luca, 2008, 2009, 2010; Lena, 2013) and S-N street networks. New productive areas (Zapata and Sanz, 2013) and new public buildings, comprising a synagogue (Avshalom et al., 2013), were established. A wide thermal bath – with *praefurnium*, *caldarium-tepidarium* supplied with *hypocaustum*, pools and *latrinae* (De Luca, 2011b; De Luca and Lena, 2014b) – occupied area C, in the northernmost sector, and area E, where it was partially set on the Hasmonean tower-port (Fig. 2B). Moreover, the harbour facilities were totally renovated with the construction of new quays (De Luca, 2010, 2011b, 2013; De Luca and Lena, 2014a; Lena, 2012).

The archaeological indicators for the Middle and Late Roman periods attest a continuum of settlement until the half of the 4th century AD. Probably as a result of the earthquake of 363 AD, to which some structural collapses are ascribed (De Luca and Lena, 2014a), Magdala had ceased to exist as an urban settlement. Only in the S sector a fortified monastery, linked to the cult of Mary Magdalene (Mt 15: 39, 27:61; Mk 8:10, 15:47, 16:1-9; Lk 8:2; Jh 20:1-18) was built to serve the travelers along the pilgrimage routes to the Christian holy places (De Luca, 2012).

2.2. Geoarchaeological background of the Magdala harbour

On the basis of an integrated geoarchaeological approach undertaken on three sections (F18, F25 and F27 in Fig. 2B), three thin depositional units were recently distinguished within the late Holocene succession buried beneath the archaeological site (Lena, 2012; Sarti et al., 2013). These units, together with the stonework-landing structures, reveal an articulate sedimentary history characterized by three main evolutionary phases: pre-harbour, harbour and post-harbour (Fig. 3).

The pre-harbour foundation phase is recorded by lacustrine beach sands almost barren in archaeological remains. These deposits are abruptly overlain by a thin succession of dark silty sands rich in osteological fragments and potsherds, and characterized by a sharp increase in heavy metals content connected to human activity (average values in pre-harbour samples: 18 mg/kg Cu, 30 mg/kg Zn, 3 mg/kg Pb; average value in harbour samples: 46 mg/kg Cu, 80 mg/kg Zn, 56 mg/kg Pb; from Sarti et al., 2013). This unit documents the development of a populated semi-protected bay, interpreted as the stratigraphic record of the first phase of use of the Magdala harbour basin during the Hellenistic period (Lena, 2012; Sarti et al., 2013). The establishment of an harbour basin implies a sudden, strong anthropogenic control on coastal sedimentation and the development of an anthropogenically forced sheltered basin (*sensu* Marriner and Morhange, 2007), likely connected to the lakeward construction of harbour structures, such as jetties and quays, active up to the Early-Middle Roman period and no more visible. Sandy and gravelly beach deposits record the following harbour abandonment phase dated to the Middle-Late Roman period transition (Sarti et al., 2013).

Concerning the archaeological phases (Fig. 4), the Hellenistic harbour system (archaeological phase I/2) included the tower-port (TP) and the *quadriporticus* (Q) (Fig. 2B). The TP, which shows a rectangular plan, is ascribed to the Hasmonean period, by judging the stratigraphic context and the masonry's walls with dressed margins and projecting central bosses. Enclosed in the external wall in the SE corner (E32) a mooring stone was discovered (MS2; Fig. 2B). To the N the TP faced a basin, which was delimited also on its W and N sides (De Luca, 2010, 2013; De Luca and Lena, 2014a; Lena, 2012).

Along the E side of Q (Fig. 2B) – which extends over an area of about 33 m per side and faces the great paved street V2 to the W – a mooring stone (MS1) is still preserved *in situ*. The walls of Q are thicker along the E and S sides as they were both in contact with the lake's surface (De Luca, 2013).

During the following Early Roman phase (Phase II in Fig. 4), a thermal bath was based on TP, whilst against the E façade an artificial *platea* was built (PL). A mooring stone (MS3), similar to MS2, was found fallen on the E side of PL, suggesting that it was equipped with moorings (De Luca, 2013; Fig. 2B). Also the Hellenistic basin N of TP was artificially filled in. The PL was paved with reused stone elements and was limited to the S, E and N by massive walls plastered by hydraulic mortar. The wall (UMS 317) that was built along the original E façade of Q, obliterating MS1, shows that it had the same waterproof treatment. This new dock (UMS 317) conserves *in situ* four mooring stones (MS4-7; Fig. 2B). A slipway – which extends from the dock foundation toward the Lake forming the bottom of the basin – is still preserved along with the original stone staircase in the S sector (De Luca, 2010). The docks/ports structures were still in use during the Roman conquest of 67 AD.

Starting from the second half of the 3rd century AD, at the transition to the Late Roman period (270-350 AD), the port's structures were abandoned and the basin was quickly filled with beach sands and gravels in response to a bad maintenance, possibly connected to the gradual loss of importance of the city in favour of Tiberias and/or a natural phenomenon (Phase IV in Fig. 4). In this respect, the subsequent level of ruins can be ascribed to the earthquake of 363 AD – evidences of which were uncovered elsewhere in the site. During the following Byzantine/Islamic phases new and more simple landing places were built (Phases V and VI in Fig. 4).

3. Methodological approach

An interdisciplinary, multi-tool approach, combining sedimentology, geomorphology, geochemistry of sediments, ostracod fauna composition, ostracod shell chemistry and archaeological data, was carried out on the depositional succession buried beneath the Roman slipway at key-sections F18 and F25 (Fig. 2B).

This methodology was adopted to obtain a more detailed picture of the bio-sedimentary response to the earliest phases of Magdala harbour activity recently defined by Sarti et al. (2013), focusing on the environment-ostracod fauna relationships at the transition from a natural to an anthropogenic-dominated lacustrine setting.

3.1. Stratigraphic and geochemical analyses of sediments

The sedimentological analysis of F18 and F25 and the collection of samples for laboratory analyses were performed during the 2011 field surveys. The former was based on visual detailed description of vertical changes in sediment texture and colour, sedimentary structures and accessory materials, mainly including mollusc shells and fragments, and vegetal debris. The occurrence of archaeological remains (see sub-section 3.3.) was also considered. The thickness of the lithofacies/stratigraphic units discussed in this paper, the sandy beach/pre-harbour unit and the semi-protected bay/harbour unit (Fig. 5), as well as the elevation of the trenches, were benchmarked to the present mean sea level using a total station Leica TCR 305 via the Infrared EDM system with a standard prism GPH1-GPR1 and linked to an absolute altitude with accuracy of 10 mm ± 2 ppm (De Luca, 2010; Sarti et al., 2013).

With respect to the previous works (Lena, 2012; Sarti et al., 2013) sedimentary features of the pre-harbour and harbour units were more strictly combined with whole-rock geochemical compositional data (XRF), in order to provide palaeoenvironmental constraints about the sediment-water interactions. XRF analyses were performed on 25 samples (11 samples from F18 and 14 from F25) collected along the 1.50 m-thick successions (Fig. 5). XRF analyses were carried out on powder pellets at the Bologna University laboratories using Philips PW1480 spectrometry with Rh tube. Major elements were determined by a full matrix correction procedure (Franzini et al., 1975).

The calculation methods of Franzini et al. (1972), Leoni et al. (1982) and Leoni and Saitta (1976) were used to assess trace metal concentrations.

3.2. Palaeontological analysis

Palaeontological analyses essentially focused on the ostracod fauna, representing the most abundant and well-preserved biological group constantly recorded along the entire thickness of F18 and F25 successions (Sarti et al., 2013). In this paper, a more detailed picture of ostracod species distribution is reported on the basis of quantitative analyses, which involved rare taxa (<1%) and un-noded *versus* noded forms of *Cyprideis torosa* (corresponding to *C. torosa* forma *littoralis* and *C. torosa* forma *torosa*, respectively), separately counted despite the ecophenotypical origin of the nodes (Athersuch et al., 1989; Frenzel and Boomer, 2005; Keyser, 2005; van Harten, 2000). Indeed, upsection variations in rare taxa abundances and in un-noded *versus* noded *C. torosa* mutual frequencies can be sensitive proxy of high-frequency palaeoenvironmental changes, especially in hypohaline settings (Frenzel and Boomer, 2005; Lord et al., 2012; Slack et al., 2000).

Whenever possible for each sample, prepared following the standard procedure (see Sarti et al., 2013), at least 150-200 well-preserved valves (adult valves-A and late-instar juveniles A-1 and A-2) were identified to the species level and counted in the size fraction >125 µm. The 63-125 µm size fraction was qualitatively observed to verify the presence in the same sediment sample of both juveniles and adults, and thus assess the *in situ* accumulation of the ostracod assemblage (Holmes, 1992; Lord et al., 2012). Finally, the percent relative abundance of each taxon was determined. The identification of species was based on key literature data (Athersuch et al., 1989; Henderson, 1990; Meisch, 2000) and specific publications focusing on the Israel ostracod fauna (Martens et al., 2002; Mischke et al., 2010, 2012; Rosenfeld et al., 2004). Given the impossibility to examine specific diagnostic features (marginal ripplets on the inner lamella; Meisch, 2000) under the binocular microscope, following Mischke et al. (2010) all non-tuberculated *Ilyocypris* specimens were considered together (*Ilyocypris* spp.). The palaeoenvironmental interpretation of the ostracod fauna relied upon species autoecological data available from literature (Athersuch et al., 1989; Henderson, 1990; Meisch, 2000) and the spatial distribution patterns of ostracods from the present-day Sea of Galilee (Lake Kinneret) and other Israel freshwater bodies (Mischke et al., 2010, 2012, 2013).

To obtain additional data about past lacustrine environmental conditions at Magdala, mainly regarding water solute composition, six well-preserved, clean A-1 specimens of un-noded and noded *C. torosa* were selected from 4 samples representative of F18 and F25 stratigraphic units and processed for combined SEM-EDS analyses (JSM-5400 scanning microscope-IXRF Systems Iridium EDS system). *Cyprideis torosa* was chosen because of its abundance throughout the sections. The scarcity, within the selected samples, of well-preserved and adequately clean adult specimens (adult valves-A) implied the use of A-1 valves. X-ray maps with areal intensity spectra were performed on the almost flat central zones of the external carapace. Additional spot spectra were also carried out *ad hoc*. The valves were cleaned in deionised water, using a fine (0000) paint brush, under a binocular microscope (Method A in Holmes, 1992; Keatings et al., 2006; Marco-Barba et al., 2013a) and carbon coated to increase their conductivity and to allow EDS analysis.

3.3. Archaeological analysis and chronological examination

Sedimentological and palaeontological data were also complemented by the archaeological findings mainly recovered within the harbour unit. These data consist of pottery fragments and osteological remains (animal bones), accompanied by sporadic fragments of glass vessels, bronze nails, coins and charcoal.

The archaeological assemblages can furnish key information about the relative chronology of the harbour phases and changes in the buildings use (Lena, 2012). The pottery was described and catalogued following the criteria used by Loffreda (2008a, b, c) for the nearby archaeological site of Capernaum (Fig. 1B). These criteria mainly include the shape identification and the description of fabric, inclusions (size and type), colour (Munsell colour chart), surface treatment and firing (as illustrated in Supplementary Table 1). Chronological interpretation of the pottery assemblages was inferred by comparison with the typologies studied from other sites of the region (for references see Supplementary Table 1).

The high resolution (century-scale) pottery-based chronology, associated with the coin findings (research in progress by Prof. Bruno Callegher), strongly supports and refines the temporal framework derived from absolute radiocarbon dates published in Sarti et al. (2013), to which the reader is referred for more detailed information. In this paper, all ages are reported as calibrated yr BC/AD (2-sigma highest probability range).

4. Results

In the following sections, the bio-sedimentary and archaeological record of the Magdala coastal succession, buried beneath the Roman harbour slipway along the waterfront side of the *quadriporticus* (Fig. 2B), is fully explained to shed new light on the palaeoenvironmental features and dynamics of the study site.

4.1. Ostracod fauna, lithofacies and archaeological data

A mixture of well-preserved adult and juvenile ostracods, mainly found as single valves, characterizes the entire sedimentary succession at both trenches. Variable amounts of reworked ostracods, mainly poorly-preserved, black-coloured valves of *C. torosa*, and foraminifers, including benthic and planktonic taxa, are also encountered. Approximately 5500 ostracod valves, representing eight species and one group (*Ilyocypris* spp.), were identified within the studied samples (Appendix A).

In the context of the lithofacies/stratigraphic units presented in Sarti et al. (2013), the detailed description of ostracod fauna characteristics is combined with unpublished archaeological data mainly concerning the pottery assemblages, essential for a high-resolution chronological framework of the studied succession (Fig. 6 and Supplementary Table 1). The results are reported below.

4.1.1. Pre-harbour beach sands

Description

This sandy unit, located at the bottom of the exposed sections, is characterized by the occurrence of several mollusc shells, mainly *Melanopsis*, and centimetric-thick pebble layers rich in bioclasts.

An abundant oligotypic ostracod fauna occurs throughout the succession, with the exception of 6 samples showing a sparse ostracod assemblage almost entirely composed of juvenile specimens (Fig. 5). All samples are strongly dominated by the euryhaline species *Cyprideis torosa*, whose relative abundance percentages range between 95% and 100%. This almost monospecific assemblage shows a stable proportion (~ 1:1 or 1:2) of un-noded and noded valves of *C. torosa*. Unique exception is the uppermost F18 sample, collected few centimeters below the boundary with the overlying lithofacies and characterized by an abrupt increase of noded *C. torosa* percentage (Fig. 5).

The remaining faunal elements are represented by just two hypohaline taxa, *Pseudocandona albicans* and *Ilyocypris* gr. (Meisch, 2000), which sporadically occur with very low percentages (0-3%; Fig. 5). At both trenches, a slightly increase upsection of *P. albicans* percentages (up to 2-3%) is recorded and accompanied by an abrupt colour change of sands, from yellow to dark-grey, and the sudden occurrence of sparse osteological remains and pottery, among which few body sherds of presumably Early Hellenistic shapes (Fig. 5).

Interpretation

The dominance of the polythermophilic, euryhaline, opportunistic *C. torosa*, able to resist wave scouring (Meisch, 2000), and the co-occurrence of un-noded and noded forms (Frenzel and Boomer, 2005; Pint et al., 2012) point to a shallow, hypohaline (up to oligohaline) setting with high-energy, coarse-grained bottom corresponding to the lake-shore area. A similar oligotypic ostracod fauna was found at ~ 5 m of water depth in the present-day Sea of Galilee (Mischke et al., 2010) and the specific preference of *C. torosa* for Na^+ and Cl^- -dominated waters (Mischke et al., 2012) is consistent with the natural chemical composition of the basin (sub-section 2.1.).

The upward slightly increasing trend of *P. albicans* and the abrupt transition to dark-grey sands likely reflect the establishment of slightly more organic-rich, stagnant conditions (Henderson, 1990), possibly connected to the earliest historical stages of human frequentation at Magdala, and dated fairly before the beginning of the 2^{nd} century BC. During this period, human settlements were probably installed further westward along the slopes of Mt. Arbel (De Luca, 2010; Sarti et al., 2013).

4.1.2. Harbour bay silty sands

Description

This unit, marked at the base by a cm-thick pebble layer, consists of dark, fine-very fine sands with high clay-silt content and numerous mollusc shells, seeds, charcoal and other vegetal debris, and osteological remains (sheep, cattles, microvertebrates, fish teeth and plates). The ostracod fauna is abundant and shows a higher interspecific diversity compared to the pre-harbour beach sands. A total of four ostracod taxa (*P. albicans*; *Ilyocypris* spp.; *Ilyocypris hartmanni* and *Heterocypris salina*) commonly accompanies the dominant species *C. torosa*, which accounts for the 85-95% of the entire assemblage (Fig. 5). Among the secondary taxa, *P. albicans* is the most represented, ranging between 2% and 7%. *Ilyocypris* gr. varies between 1% and 8%, while *H. salina* displays very low values (0.3-1.2%, respectively; Fig. 5). Other three species, *Heterocypris incongruens*, *Humphcypris subterranea* and *Psychrodromus* sp., are only sporadically found as few valves. Another diagnostic feature of the ostracod assemblage is the dominance of noded forms of *C. torosa* relative to the un-noded ones. The former can reach up to 88% of the entire assemblage and never falls below 75% (Fig. 5).

Within this unit a rich assemblage of human artifacts, including potsherds, fragments of glass vessels and bronze nails belonging to the ship's carpentry, was also found (De Luca, 2010; Lena, 2012). Concerning the pottery, several fragments of locally made amphorae of the type Anf2 (Fig. 6:8), Anf3 (Fig. 6:2.5-7), Anf4 (Fig. 6:4), Anf7, Anf10 and Anf13 (Fig. 6:3.9) and some imported amphorae (Fig. 6:13) occur. Among the cooking ware a few samples of the Late Hellenistic type of Pent4 and rims, resembling the type Pent5 (Fig. 6:19-20), are encountered along with fragments of *orlo bifido* pan, well attested through the Mediterranean area from the 2nd century BC to the 1st century AD and beyond (Fig. 6:16). The type of casserole with everted rim Teg12 (Fig. 6: 14-15) shows differences in fabric, surface treatment and rim inclination with respect to the well-known type of Kefar Hananiah ware ascribed to the Early Roman period. Moreover, several fragments of Galilean Coarse Ware-GCW *pithoi* are recorded. Regarding the glass fragments, forms dating from the 3rd century BC to the 1st century AD (Fig. 6: 23-24) are found. For a detailed description of the archaeological findings, the reader is referred to the Supplementary Table 1.

Interpretation

The in-depth analysis of the ostracod fauna furnishes new palaeoenvironmental information about the depositional setting of this unit, interpreted by Sarti et al. (2013) as a semi-protected bay formed in response to the earliest Late Hellenistic phases of the Magdala harbour management.

Throughout the unit the remarkable abundance of *P. albicans*, a species preferring shallow, slow moving waters (Meisch, 2000), is indicative of relatively stagnant conditions, in accordance with the dark sediments colour and the high amount of well-preserved seeds and other vegetal remains. The abundance of osteological fragments (mainly meal remains) and human artifacts attests the harbour basin being use also as a waste dump by the oldest citizens of Magdala, according to the thesis formulated by Marriner and Morhange (2007) for seaport contexts. According to the available radiocarbon dates, as a whole the archaeological assemblage, characterized by a clear predominance of the oldest forms, refers to a chronology between the 2nd century BC and the first half of the 1st century AD, when the Roman slipway was built (Fig. 5).

The occurrence of brackish-tolerant species commonly found in shallow waters with slightly saline character as *H. salina* and *P. albicans* itself (Meisch, 2000), along with the absence of taxa restricted to extremely low salinity-still waters indicate remarkable solute concentrations. Moreover, the dominance of noded *C. torosa* suggests a stressed environment possibly affected by unstable ionic composition. Indeed, recent studies have stated that noding development under low salinity/oligohaline conditions should be considered such as a morphological response driven by osmoregulation difficulties (Frenzel and Boomer, 2005; Keyser, 2005). Although the actual mechanism responsible for noding during molting stages is still largely unknown, water chemistry (ionic composition) changes have been recently indicated as an important factor in driving noding development within inland waters (Frenzel et al., 2012; Mischke et al., 2010; Pint et al., 2012).

------------------------------ link to the Supplementary Table 1 around here ------------------------------

4.2. SEM-EDS analysis of C. torosa shells

Particular attention was paid to the morphological and geochemical features of *C. torosa* shells (molt stage A-1), selected from the pre-harbour and harbour units of the studied trenches (sub-section 3.2.) and observed under the scanning electron microscope (SEM). Irrespective of the stratigraphic units from which they were collected, the un-noded and noded valves show specific ornamentation features. The carapace of un-noded *C. torosa* is characterized by fine to large pits, the latter being less numerous (Fig. 7). In contrast, a heavy ornamentation with larger depressions (*fossae*) separated by walls (*muri*) occurs on the external surface of the noded valves, forming a dense and pronounced pattern of reticulation (Fig. 7). Three well-developed nodes are clearly identified on all the observed valves, forming the typical "basic triangle" in the carapace central zone (Athersuch et al., 1989); other nodes or proto-nodes of variable size and shape are rarely observed close to the dorsal and ventral edges. The nodal structures, characterized by stretching signs along the margins, are commonly rounded, but less frequently they show a more elongate shape (Fig. 7).

Although EDS technique can furnish only presence/absence information about major and trace elements, a different chemical composition of *C. torosa* shells was detected for the reticulated noded specimens relative to the punctuated un-noded ones, suggesting different water chemistry conditions during valves calcification. At each molting stage the new carapace is precipitated from ions in solution at thermal-chemical equilibrium with the surrounding waters (Chivas et al., 1983; Holmes, 1996; Ito and Forester, 2009; Mischke and Holmes, 2008; Smith and Horne, 2002).

All the EDS intensity spectra show the two main peaks of calcium (Ca-K_{α} and Ca-K_{β}) and the main peaks of carbon (C-K_{α}) and oxygen (O-K_{α}), accompanied by minor peaks of magnesium (Mg-K_{α}) and strontium (Sr-L_{α}). These data reflect the low-Mg calcite composition of the ostracod shells, where strontium occurs as vicariant element of calcium (Fig. 7). Less pronounced peaks that can be attributed to Fe and S are also evaluated. A *suite* of additional trace elements is detected by pronounced EDS intensity peaks within the reticulated noded valves. In this regard, a significant amount of sodium, potassium, chloride, and terrigenous elements (Si, Al, and Rb) is recorded (Fig. 7). About the potential influence of contaminants, mainly adhering aluminosilicates within shell depressions, spot spectra performed on the clean walls of the carapace reticulation support the presence of terrigenous elements within the carbonate structure of noded *C. torosa*.

4.3. XRF analysis of sediments

X-ray fluorescence (XRF) analysis of sediment samples was performed as a complement to the stratigraphic and palaeontological data previously described. To this purpose, the geochemical properties of the pre-harbour hosting deposits were plotted against their harbour counterparts, and we selected two scatterplot diagrams (Fig. 8A-B) as the most representative of changing environmental conditions at the basin floor through time.

In the Na_2O-K_2O diagram (Fig. 8A), a major distinction can be observed between the pre-harbour deposits, which show relatively low Na and K contents compared to the overlying harbour deposits. The same stratigraphic trend, which suggests onwards increasing solute concentrations at the transition from a natural beach environment (pre-harbour sediments) to a relatively restricted human-forced bay (harbour sediments), is documented from both trenches, F18 and F25. Moreover, the intermediate values of Na and K recorded in correspondence of the lower and upper boundaries of the harbour unit (Fig. 8A) reveal a strict relationship between the Na-K concentrations and the evolutionary pathway of the Hellenistic harbour basin.

Finally, changing oxygenation conditions at the lake floor were evaluated through the determination of trace metal enrichments in sediments (Fig. 8B). It is widely accepted that high V and Cr concentrations can reflect reducing environments (Calvert and Pedersen, 1993; Schaller et al., 1997). The concentration of V in the water column of relatively anoxic basins is commonly lower than in oxic water because of precipitation and uptake into sediments. The clear-cut separation, in terms of Cr and V distribution, between pre-harbour and harbour deposits, with sharp increase of these two metals in the latter (Fig. 8B), can be taken as evidence of decreased bottom water oxygen during harbour construction and development. In this diagram, high Cr and V contents may also reflect fine-grained lithologies (i.e., high metal values in two pre-harbour samples in Fig. 8B), thus emphasizing relatively low-energy conditions, where slow moving waters may occur.

5. Discussion

On the basis of multiple lines of evidence (sedimentology, geochemistry, ostracod fauna and archaeological data), a detailed picture of palaeoenvironmental conditions is reconstructed at the transition from a nature-dominated to a human-dominated depositional context in the Magdala coastal area.

Beneath the Roman harbour structures, ~ 250 m west of the modern coastline, the vertical stacking pattern of lithofacies, ostracod assemblages and geochemical features framed into a high-resolution pottery-based chronology (Fig. 9) reveal the occurrence of remarkable hydrodynamic and hydrochemical changes within the Magdala coastal succession. Around 211 m bsl, an eastward-dipping centimetre-thick layer, containing numerous mollusc shells, pebbles and small-sized, sharp-edged stones of ambiguous (anthropogenic?) origin, marks the boundary between the lake beach deposits, formed under natural conditions, and the overlying harbour succession (Fig. 9; Sarti et al., 2013). This layer, characterized by the same biological content and geochemical features of the harbour unit (Fig. 9), may represent the base of a rudimentary harbour system that should comprise, at distal locations, an accumulation of stones, stacked to facilitate ships landing and repair in the Magdala area. At trench F18, one radiocarbon date chronologically constrains its formation to the Hellenistic period around 205-50 cal yr BC (Figs. 5, 9). Integrated radiocarbon ages (ca. 170 cal yr BC-20 cal yr AD) and potsherds furnish a consistent age for the overlying harbour fine-grained unit, formed during a chronological interval ranging between the 2nd century BC and the first half of the 1st century AD (Fig. 5; sub-section 4.1.2.). This chronological framework and the complex lateral-vertical relationships between the harbour unit and the Hasmonean harbour structures (Lena, 2012) document the continued existence and exploitation of an “artificial” shallow basin during the entire Late Hellenistic period, at least. Consistent with this interpretation, across the archaeological site a dm-thick dark silty interval containing several Hellenistic potsherds was recovered in a stratigraphic position correlative to the harbour unit at F18 and F25 (Lena, 2012). These archaeological evidences, referable to a period comprised between the 3rd century BC and the beginning of the 1st century AD, show a remarkable presence of the earliest forms, among which Hellenistic amphorae derived from Persian type (Fig. 6:1), red slip Hellenistic *lagynoi* (Fig. 6:12), casseroles with inclined everted rim with pointed internal apex (Fig. 6:14-15), juglets sometimes with traces of slip (Fig. 6:10-11), very fine saucers/cups (Fig. 6:17-18), radial oil lamps (Fig. 6:22) and several fragments of GCW *pithoi*.

The local waning wave energy and the resulting development of a semi-protected bay environment, serving as harbour basin (Sarti et al., 2013), do not represent the only environmental changes connectable to the construction of Hellenistic harbour installations at Magdala.

As revealed by integrated ostracod fauna and geochemical data, the changes in water circulation patterns, in turn, altered the floor conditions and the water chemistry of the basin. The concomitant substantial increase in the sediments of both V-Cr concentrations and ostracod species preferring slow moving waters and fine-grained substrates (*P. albicans*) points to the establishment of a shallow, stagnant organic-rich basin with relatively low-oxygen levels at the bottom, in contrast with the oxic pre-harbour nearshore depositional setting (Fig. 9). The oxygen-depleted organic-rich floor conditions, tolerated by the dominant opportunistic species *C. torosa* (Meisch, 2000) and also documented by the widespread occurrence of well-preserved vegetal and osteological remains, testify to the reduced water exchange of the embayed environment with the forward lake system (semi-enclosed confined setting). This abrupt human-forced shift towards a higher degree of protection resembles the typical depositional evolution of the Mediterranean ancient harbours, where the reduced water exchange with the open sea translates in an increase in organic matter and a decrease of salinity (Marriner and Morhange, 2006, 2007).

Nevertheless, in lacustrine hypohaline settings the “artificial” confinement of selected coastal portions may turn into more complex water body changes that involve the total dissolved ion content (salinity) and the ionic composition, following the evolutionary pathways principally driven by local climate conditions. The XRF analysis highlights an enrichment in Na and K within the Magdala harbour sediments with respect to the underlying pre-harbour beach sands (Fig. 8). In the context of the Sea of Galilee basin, characterized by dominant autochthonous carbonate sedimentation and semi-arid climate, the local enrichment of alkali free-ions already present in the water (Nishri et al., 1999) may reflect modifications of the precipitation/evaporation ratios. Since palaeoclimatic records document relatively high precipitation rates during the Hellenistic-Roman periods (sub-section 2.1.), an increase in surface water's evaporation is feasible and connectable to the partial isolation of a marginal sector of the basin. At the same time, changing proportions between freshwater (Jordan River and inflowing streams) and solute water inflows (onshore saline springs; sub-section 2.1.) to the Magdala area, likely connected to the development of the harbour basin, cannot be excluded *a priori*. However, since the harbour structures are aimed to protect a portion of the coast, they would decrease, rather than increase, the inflows of lacustrine waters within the basin.

Besides the relatively high degree of protection, other factors linked to the Hellenistic harbour structures might have contributed to the alkaline enrichment of the Magdala basin, including ordinary port operations as ships traffic and cargo handling-storage. In particular the trade of salt, possibly also from the Dead Sea, essential for the fish processing industry and documented by archaeological data and historical sources (Clamer, 1997, 1999; Hirshfeld, 2006), may have partially contributed to Na, K and Cl enrichment in the harbour area.

Significant changes in the chemistry of the sediment-water system are also recorded by the ostracod fauna composition at the boundary with the harbour unit (Fig. 5). The sudden appearance of *H. salina*, a species tolerant to elevated conductivity levels and variable solute composition (Meisch, 2000; Mischke et al., 2012), points to a general increase of cations and anions concentration within the basin. In this regard, the almost absolute dominance of noded valves of *C.*

torosa, whose shells are enriched in Na, K and Cl with respect to the un-noded ones (Fig. 7; sub-section 4.2.), suggests major availability of these elements, as free-ions, to be uptaken for shell calcification. Moreover, a good relationship is detected by comparing Na+K sediment values with noded *C. torosa* frequencies (Fig. 10), suggesting a positive relationship between noding development and increasing alkali accumulation in the Magdala basin.

Indeed, the hydrochemical features of the host water rather than salinity in itself seem to play a key-role in noding development, especially within oligohaline settings and inland waters (Frenzel and Boomer, 2005; Frenzel et al., 2012; Keyser, 2005; Pint et al., 2012; van Harten, 2000). Since Keyser (2005), noding is interpreted as an osmotic-controlled phenomenon that develops in response to high-stressed multifactorial environments, characterized by low salinity (usually less than 7 psu) and changing water ionic composition. In this respect, several hypotheses have been formulated, including low Ca^{2+} availability (Frenzel et al., 2012) and/or increasing barium and magnesium concentrations (Bodergat, 1983). Moreover, Mischke et al. (2010) suggested an affinity between low K concentrations in the host waters and the occurrence of noded shells of *C. torosa* collected from several present-day water bodies in Israel. This hypothesis is apparently in contrast with the concomitant remarkable increase of Na+K values and noded *C. torosa* frequencies recorded within the Magdala harbour basin (Figs. 9, 10). Therefore, all these studies clearly reveal that the complex mechanism favouring the development of nodosities during *C. torosa* molting is still largely unknown. In the next future, experiments are needed to shed new light on the relationships between different water chemical compositions and morphology of *C. torosa* shells under oligohaline conditions (Frenzel et al., 2012; Pint et al., 2012).

Finally, although all available data point to a strong anthropogenic impact on Magdala coast in concomitance with the oldest (Late Hellenistic) harbour installations, there is evidence that human activity in the study area began in earlier times, with the formation of the lacustrine beach grey sands containing scattered potsherds. The ostracod fauna, especially the one encountered within the uppermost sample of the grey sandy succession (Fig. 5), is consistent with the establishment of stressed, less oxic conditions likely reflecting a transitional proto-harbour zone developed during the earliest phases of Hellenistic harbour construction. However, it is clear that additional stratigraphic, palaeontological and geochemical data from other trenches and cores across the archaeological site are necessary to confirm this hypothesis.

6. Conclusions

The multi-proxy (sedimentological, ostracod and geochemical) study of the bio-sedimentary record buried beneath the Roman harbour slipway at the ancient city of Magdala (Sea of Galilee, Israel) gives new insights into the palaeoenvironmental evolution of the archaeological site. The dynamics of the complex relationship between lacustrine sedimentation and human activity are framed into a high-resolution temporal framework, mainly based on pottery assemblages tied to radiocarbon ages. This approach also furnishes new data about the degree of protection and degradation of the Hellenistic harbour basin, highlighting the key-role exerted by the ostracod fauna (assemblage composition and chemical features of *C. torosa* valves) to decipher subtle environmental changes in the lacustrine anthropogenic-forced context.

The major outcomes of this work are as follows:

1. The pre-Roman succession beneath the archaeological site exhibits a vertical stacking pattern of lithofacies, ostracod assemblages and geochemical features indicative of remarkable hydrodynamic and hydrochemical changes occurred around the 2nd century BC, at the onset of the harbour system. These environmental changes strongly support the hypothesis (Lena, 2012; Sarti et al., 2013) of waterfront construction of man-made structures partially protecting the coastal area in front of the ancient city of Magdala;

2. Concomitant changes in V-Cr sediment concentration and ostracod fauna composition point to the sudden development of a semi-protected shallow bay with high-organic and relatively low-oxygen levels along the Magdala coast. This embayment worked as a harbour basin during almost the entire Hellenistic period, as testified by scattered archaeological evidences;

3. The alkali enrichment recorded in the Hellenistic harbour basin by both sediments and the ostracod fauna documents local changes in the lake water character that well match a protected marginal lacustrine area in a hot, semi-arid climate region;

4. In the Magdala depositional record a close relationship is detected between Na+K sediment concentrations and relative frequencies of noded *C. torosa*, whose valves are themselves enriched in alkali, thus confirming the important role exerted by the oligohaline water chemistry in nodosities formation;

5. Our data confirm that hypohaline ostracods are excellent bioindicators of the surrounding physico-chemical conditions, even at the transition from a nature- to a human-influenced depositional context.

Acknowledgements

The authors thank the ENVIMED MISTRALS GEOISRAEL program and IUF, the LABEX OT MED and the Magdala Project team for their support to this study. This is a contribution to MISTRALS/PALEOMEX and to the Labex OT-Med (ANR-11-LABEX-0061) funded by the Investissements d'Avenir, French Government program of the French National Research Agency (ANR) through the A*Midex project (ANR-11-IDEX-0001-02). We are strongly indebted to Dr. Steffen Mischke and an anonymous reviewer for their invaluable suggestions and comments to the paper. We are also grateful to A. Rimmer and A. Sandler for the bibliographical help, Giorgio Gasparotto for the technical help with the EDS-SEM analysis and Federico Fanti for the useful

discussion about vertebrate remains.

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Figure captions

Figure 1: A) Tectonic sketch map of the Near East region (from Leroy, 2010). The Sea of Galilee area is highlighted by the black square. DST: Dead Sea Transform Fault; B) Geological sketch map of the area surrounding the Sea of Galilee (slightly modified from Singer et al., 1972) with position of the Magdala site along the western lakeshore. The dotted lake area corresponds to the marginal zone with water depth < 10 m. The arrows show the counter-clockwise circular current (from Pan et al., 2002) affecting the central part of the lake (see sub-section 2.1.). Black square: position of other ancient cities mentioned in the text.

Figure 2: A) Aerial image of the archaeological site of Magdala (property of the Magdala Project Excavation); B) General Plan of the Magdala Project Excavations (2007-2012; courtesy of Stefano De Luca-copyright and A. Ricci). The location of trenches F18, F25 and F27 and the main archaeological remains are shown. Different colours represent distinct archaeological phases: Late Hellenistic (green); Roman (yellow); Byzantine (light blue); Islamic (purple). See also Figure 4 for architectural details.

Figure 3: Stratigraphic relationships between the lacustrine deposits and the harbour structures identified in the subsurface of the Magdala site, in front of the *quadriporticus* (see Fig. 2B for trenches location). The three depositional units, corresponding to the main evolutive phases of Magdala ancient harbour, are also reported (slightly modified from Sarti et al., 2013). C: clay and silt; S: sand and G: gravel. HFS-harbour foundation surface and HAS-harbour abandonment surface *sensu* Marriner and Morhange (2006, 2007) are traced. Radiocarbon ages are reported here as calibrated yr BC/AD (slightly modified from Sarti et al., 2013).

Figure 4: Archaeological/historical phases of the Magdala site (colours as in Fig. 2B). The link between archaeological remains and geoarchaeological phases is also proposed.

Figure 5: Stratigraphy of the two studied trenches (F18 and F25) and vertical distribution of the main representative ostracod taxa. Samples containing rare ostracod valves (less than 50 A+A-1+A-2 valves) are also highlighted. Radiocarbon ages are reported as the highest probability range in calibrated yr BC/AD. See Figure 3 for the key to particle size and the uppermost portions (harbour abandonment unit) of F18 and F25 trenches.

Figure 6: Specimen of the pottery and glass assemblages from the Magdala Project Excavation of the Harbor (HFS and AHF). Courtesy of S. De Luca and A. Lena, the Magdala Project, from Lena (2012). Draws: F. Pollastri and S. De Luca; Layout and Table: S. De Luca. See text and Supplementary Table 1 for more details.

Figure 7: Representative SEM images of un-noded (right valve) and noded (left valve) *Cyprideis torosa* and relative EDS intensity spectra. The valves were extracted from the pre-harbour beach sands at F18 trench. The EDS spectra show the major (C; O; Ca) and minor (Na; Mg; Sr; Cl; K) peaks discussed in the text. The white scale bars correspond to 200 micron.

Figure 8: Scatterplots of Na_2O *vs* K_2O content and V *vs* Cr from F18 and F25 sediment samples. Sample groups are differentiated according to their stratigraphic position at each trench. Open symbols (diamonds): pre-harbour samples; filled symbols (circles): harbour samples.

Figure 9: Vertical profiles of selected geochemical elements discussed in the text, relative proportions (percentages) of un-noded *C. torosa* (light grey) *vs* noded *C. torosa* (dark grey) and distribution trend of *P. albicans* along the studied trenches. Asterisks indicate samples containing rare ostracod valves (< 50). Palaeoenvironmental interpretation is also shown.

Figure 10: Scatterplot of Na_2O+K_2O *vs* noded *C. torosa* abundances. Samples from the studied trenches (F18 and F25) are grouped according to their stratigraphic position. Open symbols (diamonds): pre-harbour samples; filled symbols (circles): harbour samples.

Appendix A

Taxonomic Reference List. This list includes genus and species of the ostracods cited in the paper.

Cyprideis torosa – *Candona torosa* Jones, 1850; p. 27, pl. 3 figs. 6a-e.

Heterocypris salina – *Cypris salina* Brady, 1868; pl. 26 figs. 8-13.

Ilyocypris – *Ilyocypris* Brady and Norman, 1889; p. 106.

Pseudocandona albicans (Brady, 1864) – *Candona albicans* Brady, 1864; p. 61, pl. 4 figs. 6-10.

Inline Supplementary Material

Supplementary Table 1: Pottery Catalog. Description of the pottery assemblage illustrated in Figure 6 by S. De Luca and A. Lena, updated from Lena (2012). The reference list is also provided.

Figure 1A-B

Click here to download high resolution image

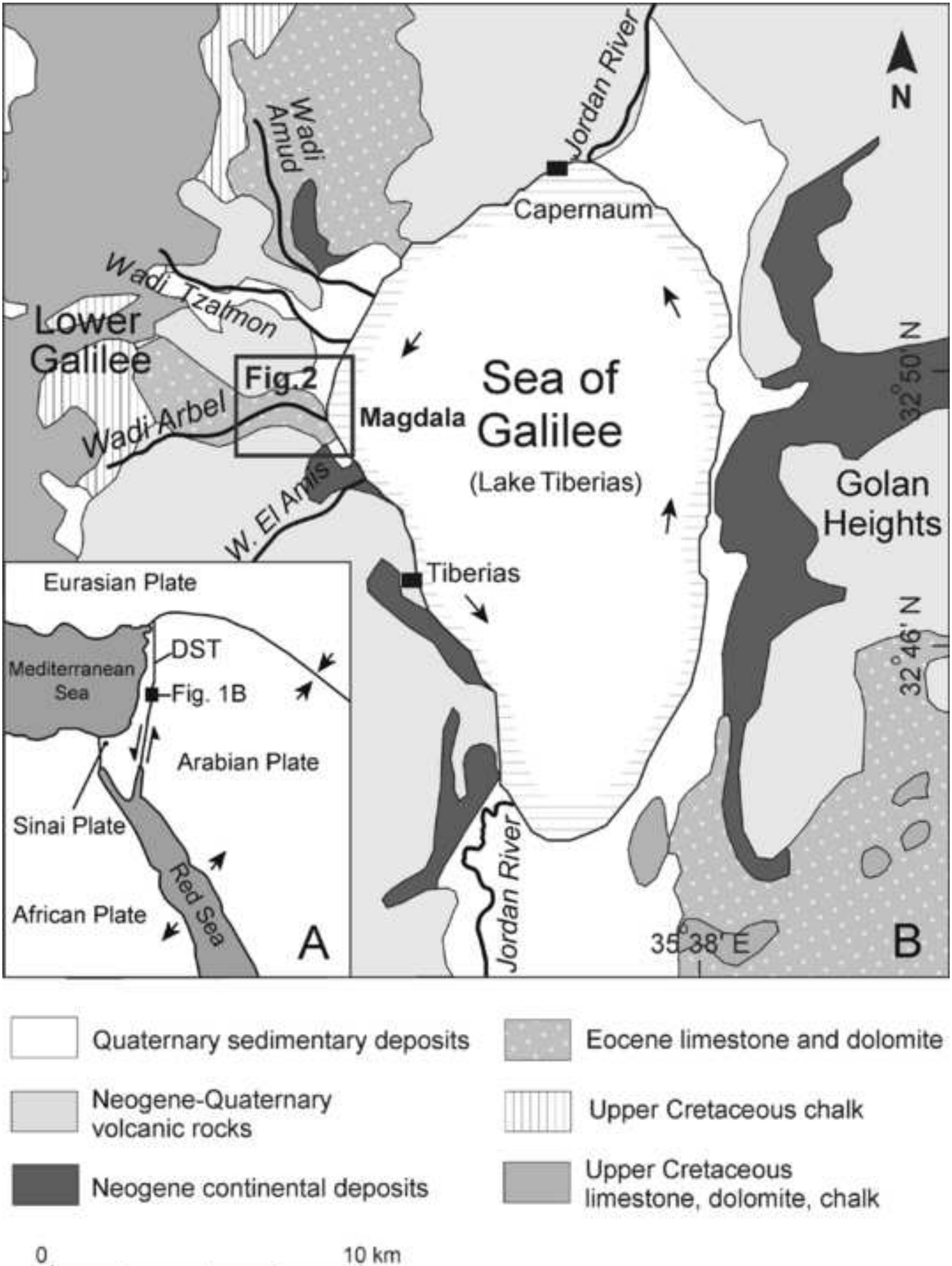

Figure 2A-B

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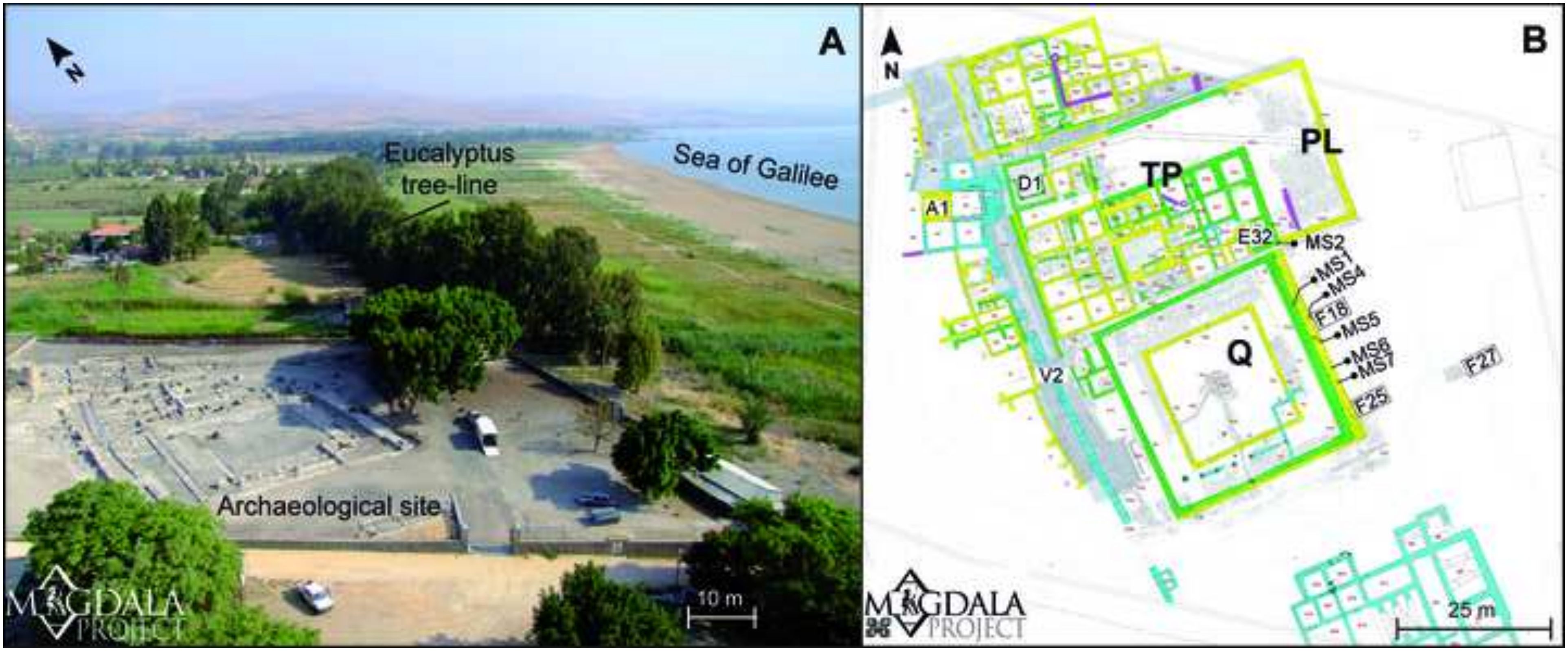

Figure 3
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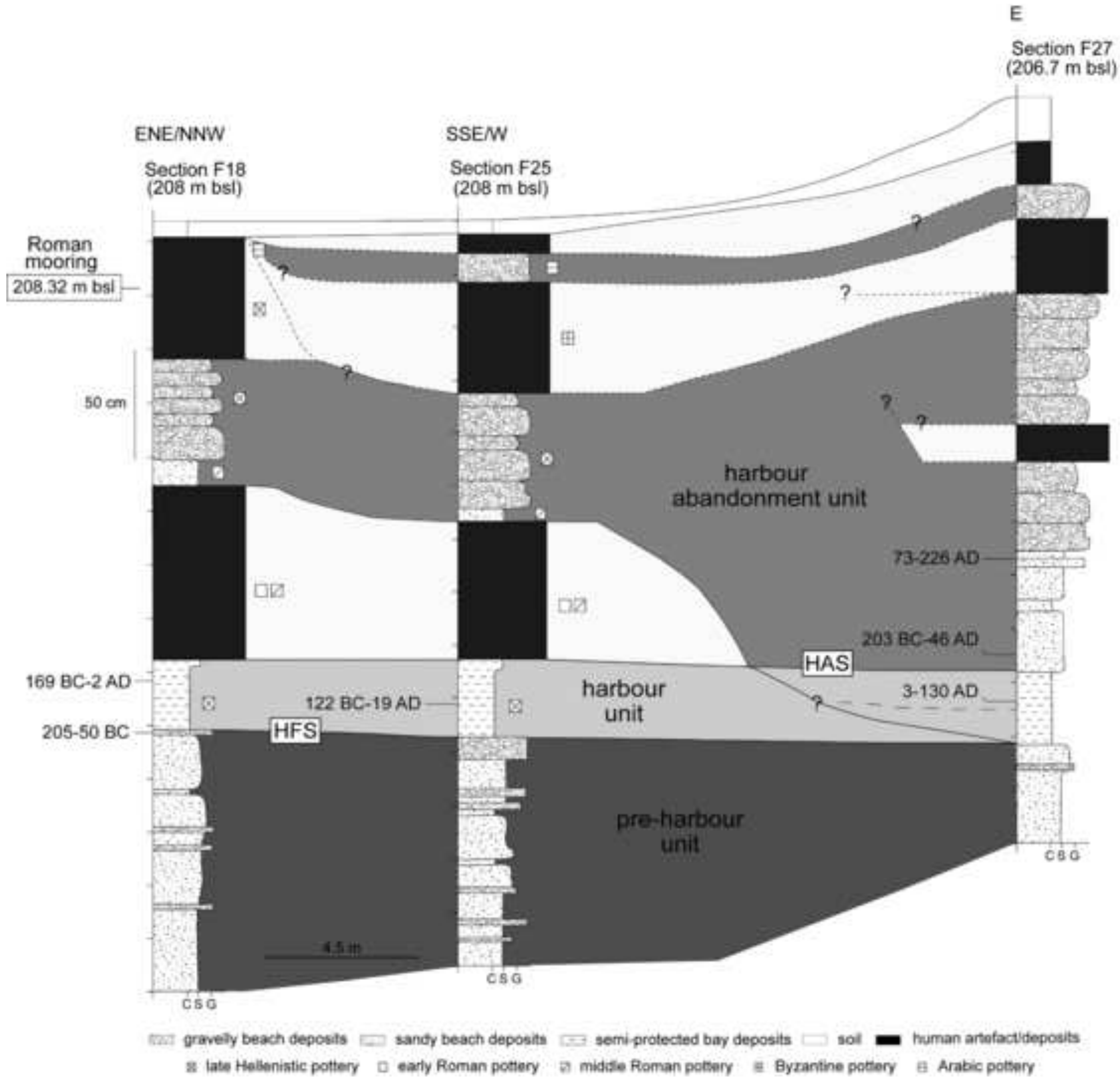

Figure 4

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<table>
<tr><th rowspan="2">PHASE</th><th rowspan="2">PERIOD</th><th colspan="2">ARCHAEOLOGICAL REMAINS</th><th rowspan="2">GEOARCHAEOLOGY</th></tr>
<tr><th>CITY</th><th>HARBOUR</th></tr>
<tr><td>Phase I/1</td><td>Old Hellenistic
(332-167 BC)</td><td>Scarce remains</td><td>(Scattered pottery)</td><td>Pre-harbour</td></tr>
<tr><td>Phase I/2</td><td>Late Hellenistic
(167-63 BC)</td><td>Road and water network
Water tower A1
Dwelling areas
Public buildings
(balaneia, fountain D1)</td><td>Hasmonean tower-port (TP)
with mooring stone MS2
Quadriporticus (Q)
with mooring stone MS1</td><td rowspan="3">Harbour</td></tr>
<tr><td>Phase II</td><td>Early Roman
(63 BC-70 AD)</td><td rowspan="2">Road and water network
Water tower A1
Dwelling areas
Workshops
Public buildings
(thermae, synagogue,
latrinae, market)</td><td rowspan="2">Platea (PL)
Roman dock
USM 317- 1118
mooring stones MS 4-7
along the E and S side
of the Quadriporticus (Q)
Pebblework slipway
Staircase</td></tr>
<tr><td>Phase III</td><td>Middle Roman
(70-270 AD)</td></tr>
<tr><td>Phase IV</td><td>Late Roman
(270-350 AD)</td><td>Dwelling areas
Workshops
Public Buildings
(thermae and latrinae)</td><td>(Basin siltation)</td><td>Harbour abandonment</td></tr>
<tr><td>Phase V</td><td>Byzantine
(350-650 AD)</td><td rowspan="2">Public buildings
(aqueduct, monastery
and church)
Workshop
Water network renovation</td><td rowspan="3">Landing places</td><td rowspan="3">(New port facilities)</td></tr>
<tr><td>Phase VI/1</td><td>Early Islamic
(650-1000AD)</td></tr>
<tr><td>Phase VI/2</td><td>Middle Islamic
(1000-1400AD)</td><td>Sporadic occupation
Church and monastery (?)</td></tr>
</table>

Figure 5

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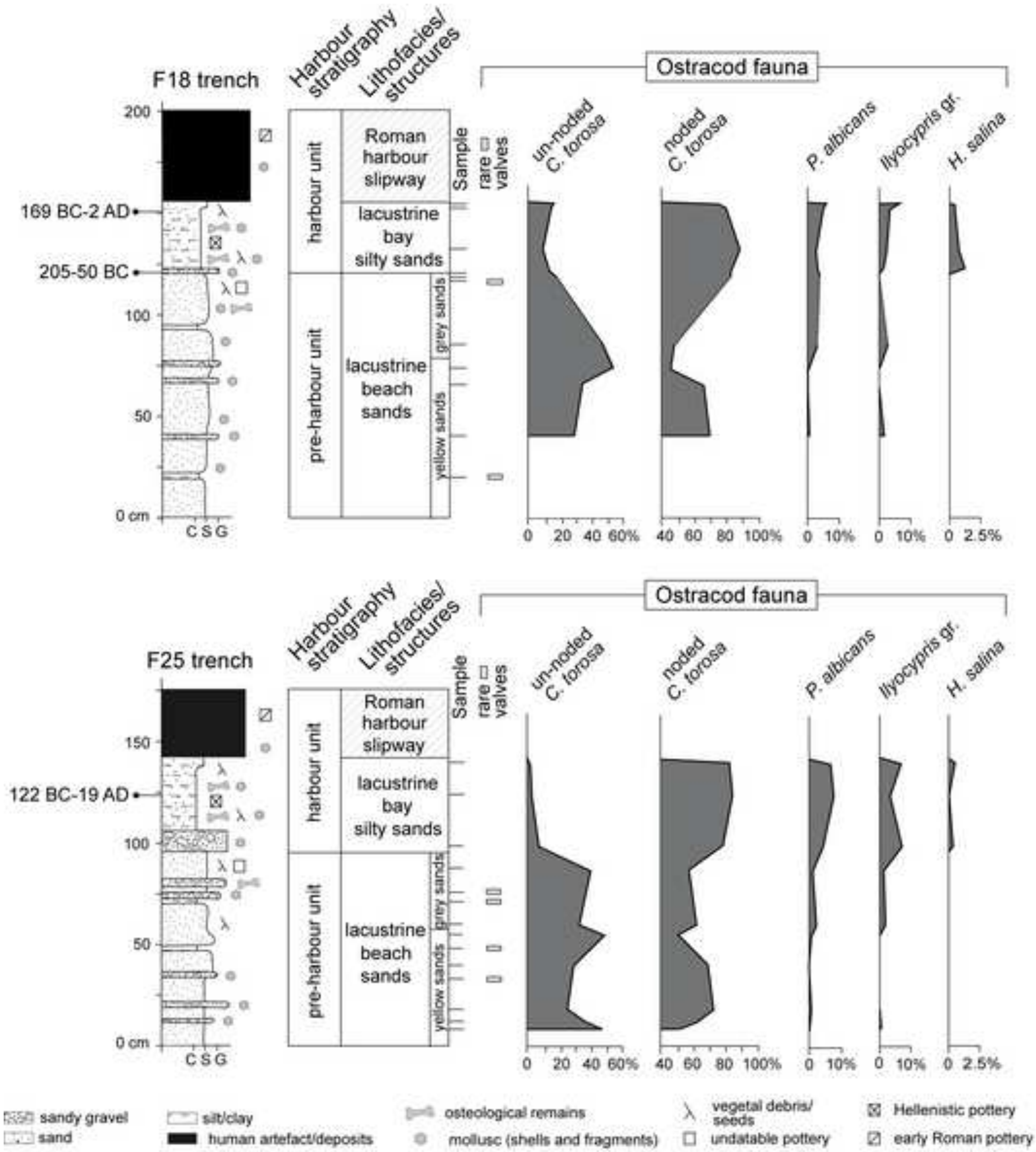

Figure 6

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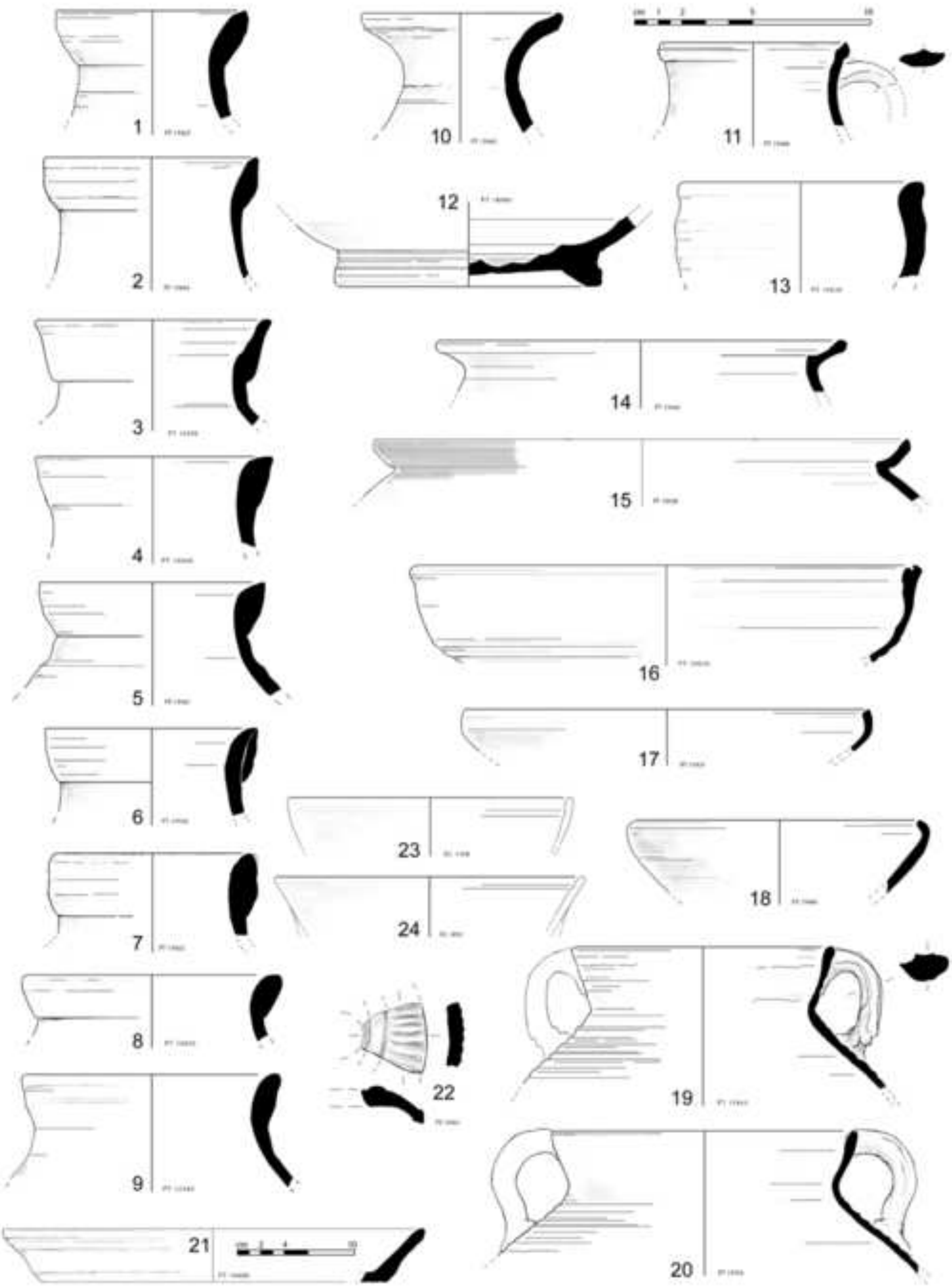

Figure 7
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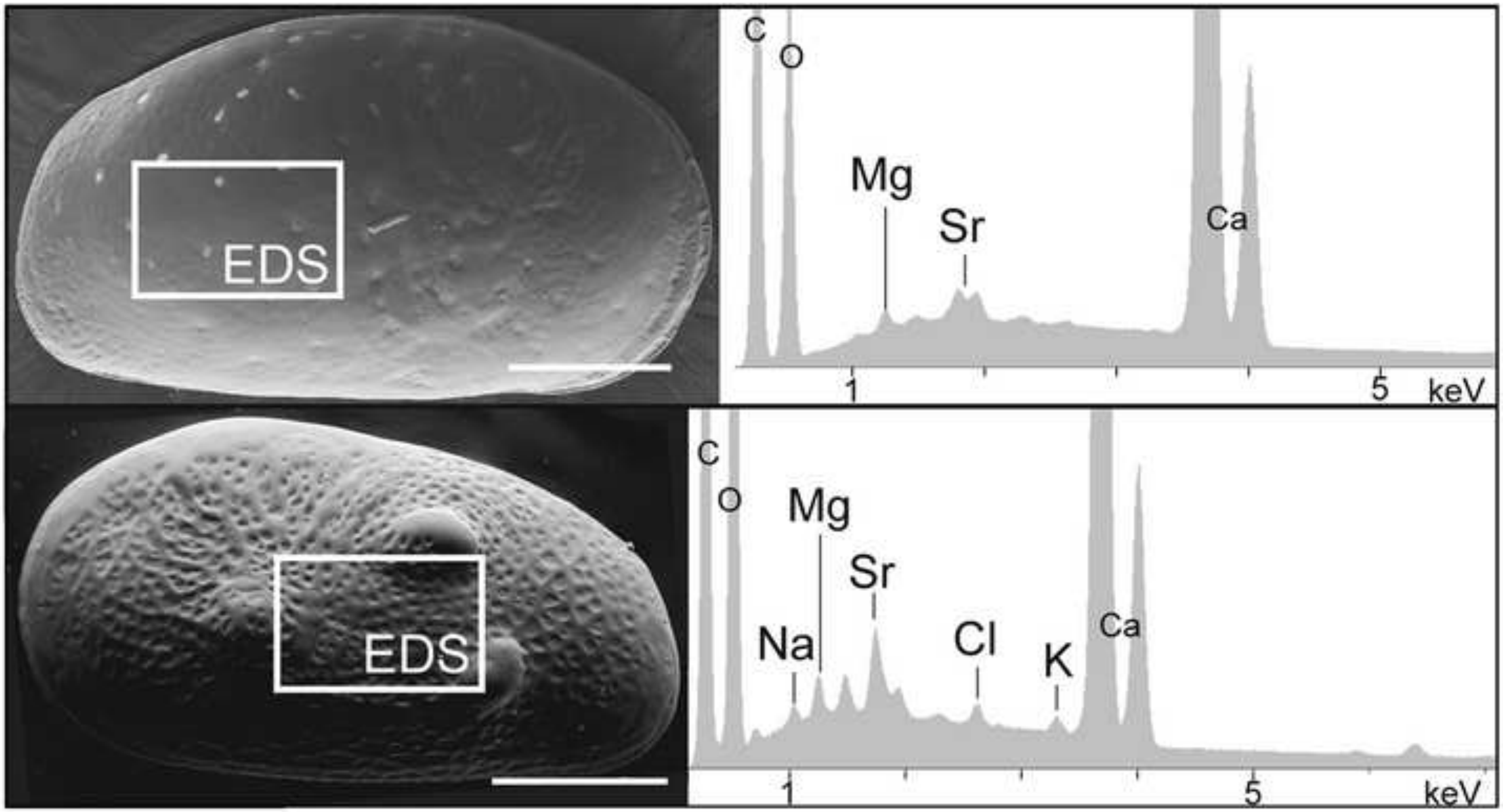

Figure 8A-B
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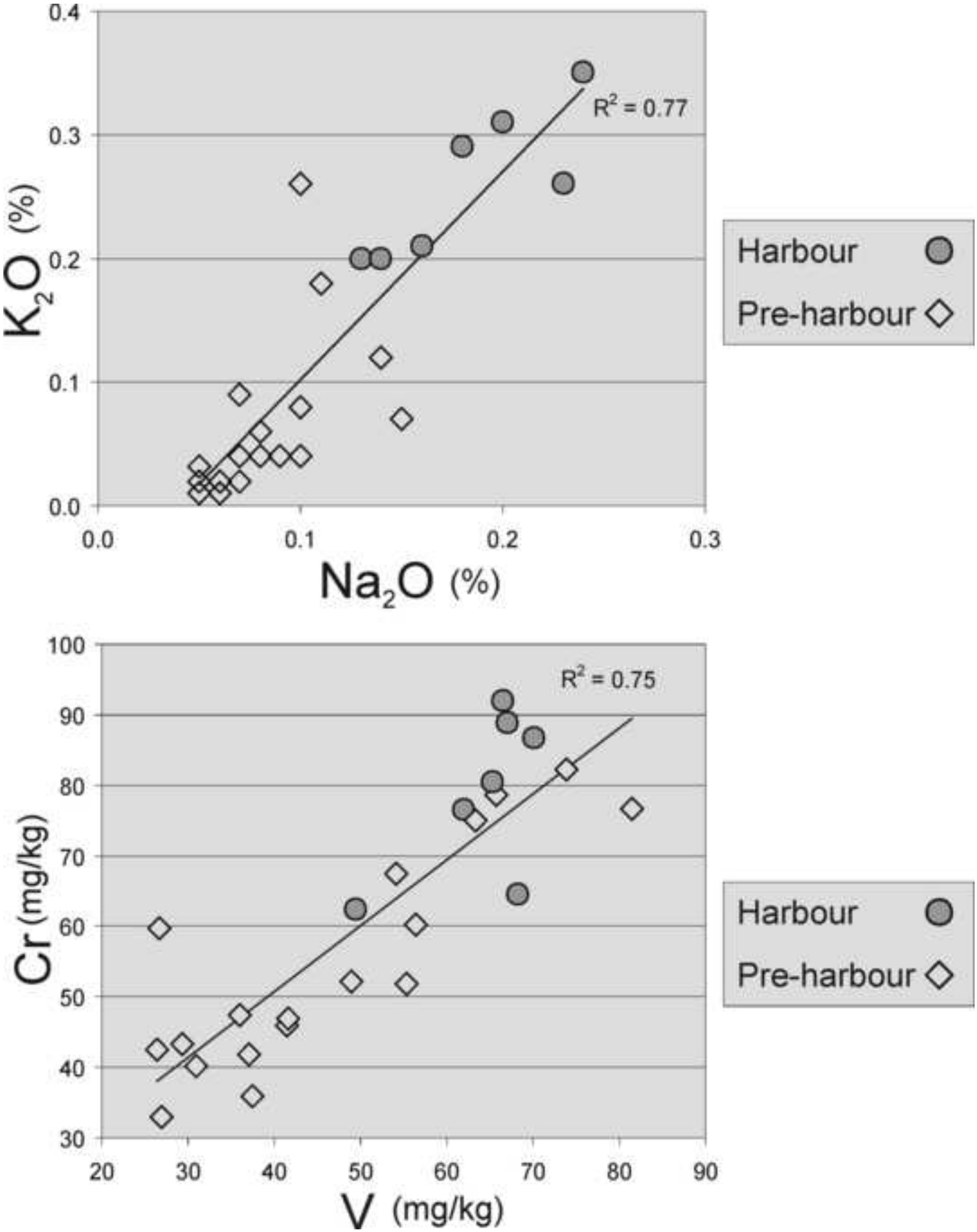

Figure 9

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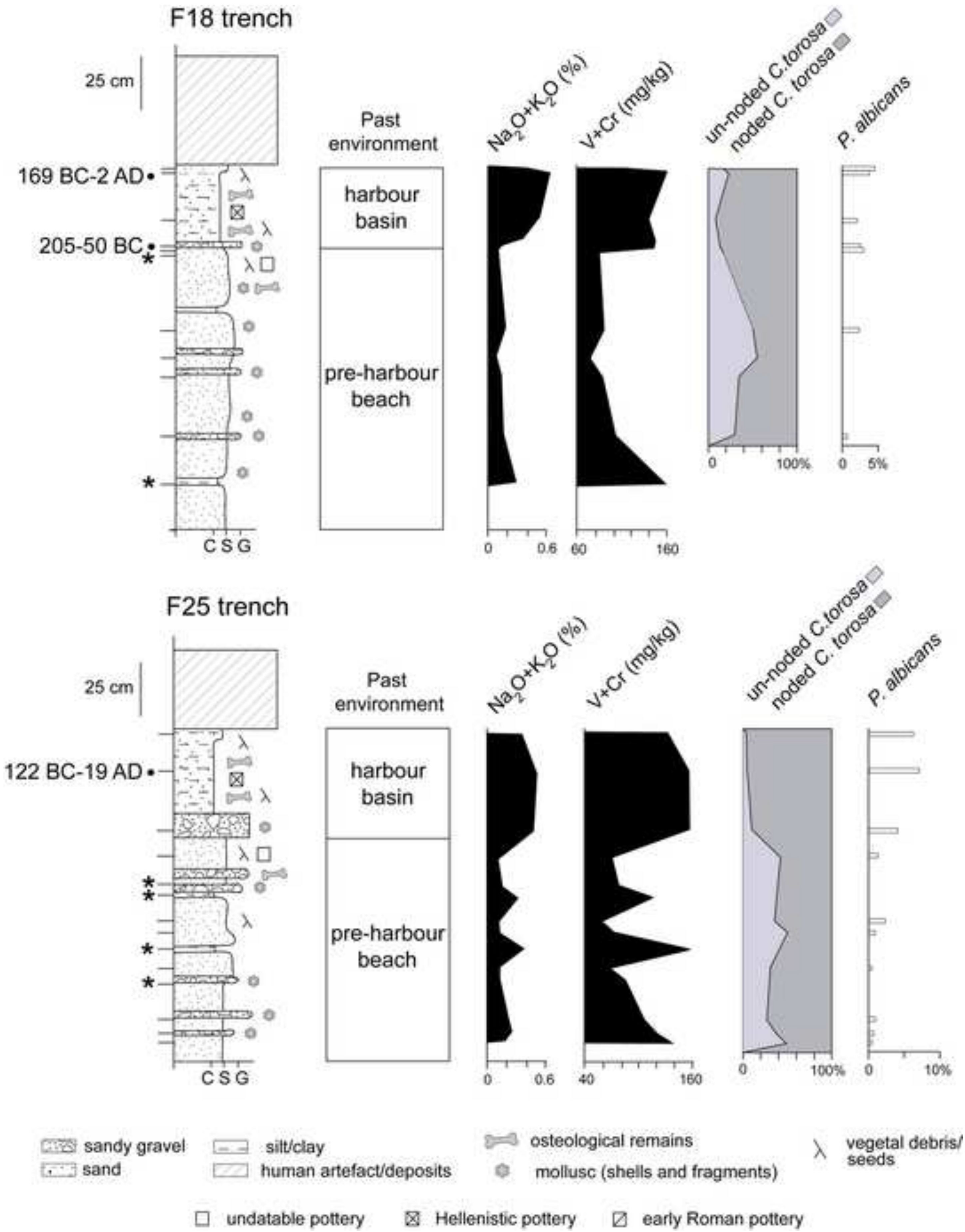

Figure 10
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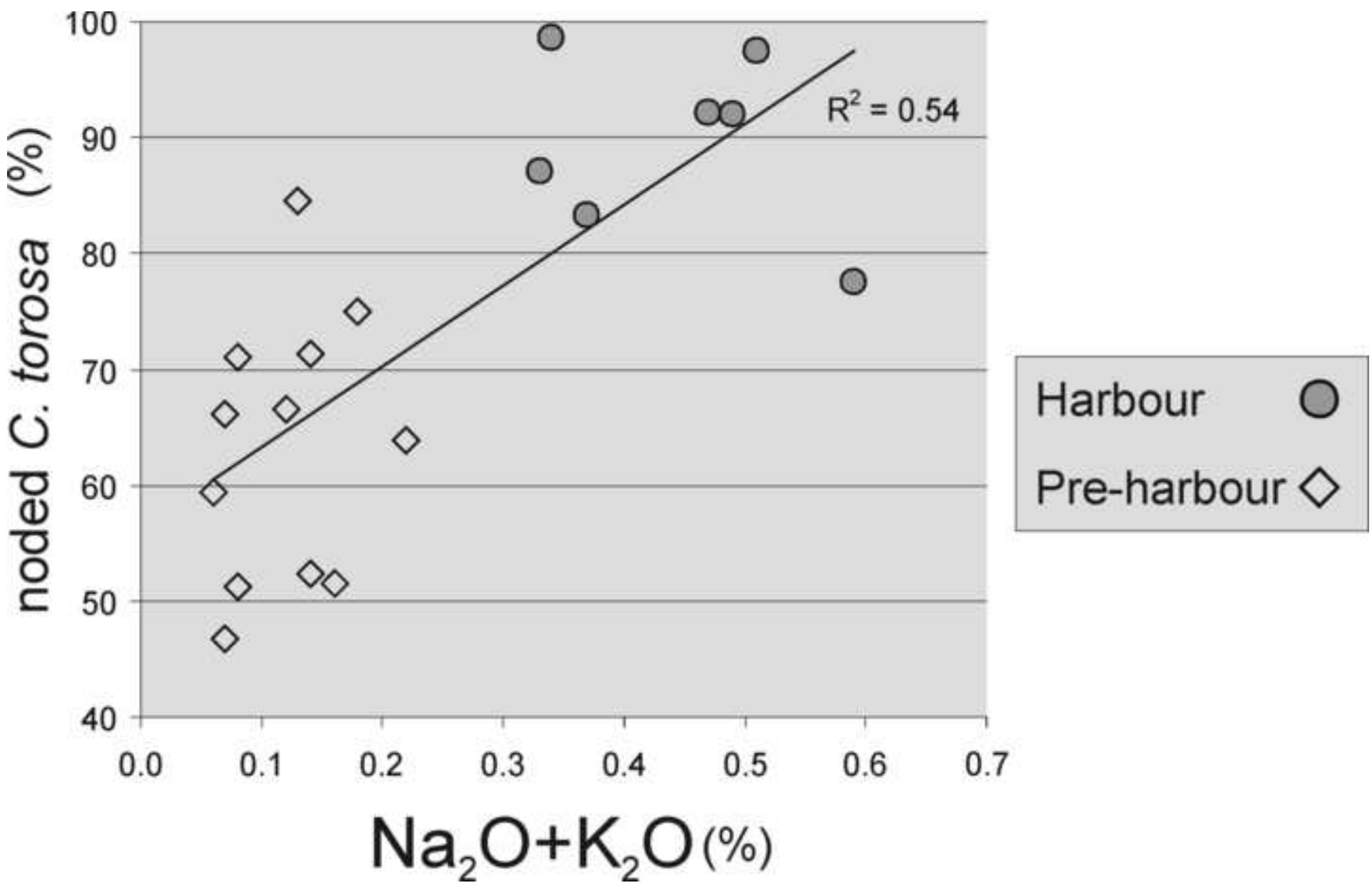

Inline Supplementary Table 1

Supplementary Table 1

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Figure 6 Number	Catalog Number	Family Shape	Fabric	Inclusions		Colour			Surface Treatment	Firing	References
				Size	Type	External	Interior	Core			
1	PT 17427	Amphora	Medium	Medium	Calcareous	5YR 6 6	5YR 6 6	5YR 4 4		Mid	Loffreda 2008b: 66 (Anf2); Roll–Tal 1999: Fig. 5.15,6; Młynarczyk 2011: 244 n. 32; Lena 2012: Tav. 1,3.
2	PT 17444	Amphora	Medium	Fine to Medium	Calcareous, Siliceous, Black	7.5YR 6 1	7.5YR 8 3	7.5YR 5 5		Hard (strong)	Loffreda 2008b: 66,13 (Anf3); Roll–Tal 1999: Fig. 5.15,6; Guz-Zilberstein 1995: Fig. 2.36,10; Lena 2012: Tav. 3,1.
3	PT 11970	Amphora	Fine	Fine	Calcareous, Black	5YR 6 6	5YR 6 6	5YR 4 1		Hard	Loffreda 2008a: 126-127 (Anf13); Lena 2012: Tav. 2,6.
4	PT 14040	Amphora	Very fine	Fine	Calcareous	5YR 5 6	5YR 5 6	5YR 4 1		Hard	Loffreda 2008a: 120-121 (Anf4); Bar-Nathan 2002: JSJ 4a2; Lena 2012: Tav. 6,2.
5	PT 17441	Amphora	Fine	Fine to Medium	Calcareous, Black	5YR 6 6	7.5YR 6 3	5YR 6 4	Slip (Internal)	Hard	Loffreda 2008a: 119-120 (Anf3); Getzov et al. 2006: Fig. 5.13,1; Roll–Tal 1999: Fig. 5.15,10; Regev 2010: 124-125, Fig. 3; Lena 2012: Tav. 3,2.
6	PT 17426	Amphora	Medium	Fine	Calcareous, Black	7.5YR 3 1	7.5YR 3 1	7.5YR 3 2		Medium	Loffreda 2008a: 119-120 (Anf3); Lena 2012: Tav. 1,1.
7	PT 17422	Amphora	Medium	Fine to Medium	Calcareous, Black	2.5YR 6 8	2.5YR 6 8	2.5YR 6 8		Hard	Loffreda 2008a: 119-120 (Anf3); Roll–Tal 1999: Fig. 5.15,6-10; Guz-Zilberstein 1995: Fig. 6.36,12; Lena 2012: Tav. 1,2.
8	PT 14025	Amphora	Fine	Very fine	Calcareous, Black	10YR 8 3	10YR 8 3	10YR 8 3		Hard	Loffreda 2008a: 119 (Anf2); Getzov et al. 2006: 148, Fig. 5.13,1; Guz-Zilberstein 1995: 311; Regev 2010: Fig. 3,14; Balouka 2013: 63, Pl. 3,5; Lena 2012: Tav. 6,1.
9	PT 12340	Amphora	Fine	Fine to Medium	Calcareous, Black	7.5YR 6 4	7.5YR 6 4	7.5YR 5 1		Hard	Loffreda 2008b: 66 (Anf13); Regev 2010: Fig. 3,12; Lena 2012: Tav. 2,2.
10	PT 17442	Jug	Very fine	Fine	Black, Ferrous	2.5YR 7 2	2.5YR 7 2	7.5YR 5 4		Hard	Guz-Zilberstein 1995: 309, Fig. 6.31,9-10; Lena 2012: Tav. 3,13.
11	PT 17448	Jug	Very fine	Very fine	Calcareous, Micaceous	2.5YR 7 2	2.5YR 7 2	7.5YR 5 4	Traces of slip	Hard	Hartal 2002: Fig. 22,10-12; Lena 2012: Tav. 3,14.
12	PT 18985	ESA Lagynos	Depurate			10R 4 6	7.5YR 7 4	7.5YR 7 6	Slip Ware	Hard	Hayes et al. 1985: 42-43 (Form 101), Tav. IX,2; Crowfoot et al. 1957: 340, Fig. 82.1; Herbert 1997: 230, FW 289, Pl. 25; Berlin–Pilacinski 2004: Fig. 6,115; Lena 2012: Tav. 3,22.
13	PT 14039	Amphora	Very fine	Fine to Medium	Calcareous, Siliceous, Ferrous	5YR 6 6	5YR 6 6	5YR 5 1		Hard	Berlin 2006: 109, n.10; Bar-Nathan 2002: Pl. 6,39; Avissar 2005: 96, Fig. X.6,6; Lena 2012: Tav. 6,3.
14	PT 17424	Casserole	Very fine	Fine	Calcareous, Black	2.5YR 4 6	2.5YR 4 6	2.5YR 4 2		Hard	Guz-Zilberstein 1995: Type CP5; Lena 2012: Tav. 1,9.
15	PT 19108	Casserole	Very fine	Fine to Medium	Calcareous, Black	2.5YR 5 6	2.5YR 5 6	2.5YR 4 3	Traces of painting	Hard	Młynarczyk 2011: 246 n. 78; Lena 2012: Tav. 8,19.
16	PT 14034	“Orlo bifido” Pan	Very fine	Very fine	Calcareous Black	2.5YR 5 6	2.5YR 5 6	2.5YR 5 6		Hard	Warner-Slane 1986: Fig. 15,90; Lena 2012: Tav. 6,12.
17	PT 17431	Cup	Very fine	Very fine	Calcareous	5YR 5 6	5YR 5 6	5YR 5 6		Hard	Bar-Nathan 2002: Pl. 14,208 (Type J-BL3A3); Roll–Tal 1999: Fig. 5.12,12-15; Balouka 2013: Pl. 1,13; Lena 2012: Tav. 3,24.
18	PT 17446	Cup	Very fine	Very fine	Calcareous	7.5YR 5 1	7.5YR 5 1	7.5YR 5 1		Hard	Bar-Nathan 2002: Pl. 14,207; Balouka 2013: Pl. 1,31; Lena 2012: Tav. 3,23.
19	PT 17463	Cooking Pot	Fine	Medium	Calcareous	2.5YR 5 6	2.5YR 5 6	10R 4 4	Traces of slip	Metallic	Loffreda 2008a: 181 (Pent5); Guz-Zilberstein 1995: Fig. 6.17,3; Lena 2012: Tav. 4,27.
20	PT 17455	Cooking Pot	Fine	Fine to Medium	Calcareous	2.5YR 5 6	2.5YR 5 6	2.5YR 5 6		Metallic	Loffreda 2008a: 181 (Pent5); Młynarczyk 2011: 245 n. 61; Lena 2012: Tav. 4,28.
21	PT 14888	Baking dish	Medium		Clcareous, Micaceous, Siliceous	7.5YR 3 1	7.5YR 6 4	7.5YR 6 4		Hard	Herbert 1997: Tav. 34 (“backing dish”); Getzov et al. 2006: Tav. 5.10,6: Lena 2012: Tav. 14,24.
22	PT 17451	Oil lamp	Fine	Fine to Medium	Calcareous	2.5YR 4 6	5YR 7 6	5YR 7 6	Slip	Hard	Guz-Zilberstein 1995: Fig. 5.16 (see caption Fig. 5.17); Loffreda 1996: Fig. 49,1-16 (Group 74); Herbert–Berlin 2003: Fig. 8,7; Lena 2012: Tav. 1,5.

Figure 6 Number	Catalog Number	Shape	Technique	Colour	Decoration	References
23	GL 1168	Bowl	Cast	Transparent / clear greenish	Internal horizontal grooves	Davidson-Weinberg 1970: Profile 17-18; Dussart 1988: AII 11.7; Lena 2012: Tav. 36,1.
24	GL 802	Bowl	Cast	Yellowish / brownish	Internal horizontal grooves / ribbed	Davidson-Weinberg 1970: 21, Profile 34; Dussart 1988: AIII 3; Davidson-Weinberg 1973: Fig. 3,26; Lena 2012: Tav. 36,2.

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