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Late Quaternary sea-level changes and early human societies in the central and eastern Mediterranean Basin: an interdisciplinary review

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Abstract

This article reviews key data and debates focused on relative sea-level changes since the Last Interglacial (approximately the last ~132,000 years) in the Mediterranean Basin, and their implications for past human populations. Geological and geomorphological landscape studies are critical to archaeology. Coastal regions provide a wide range of resources to the populations that inhabit them and coastal landscapes and resources are increasingly the focus of scholarly discussions from the earliest exploitation of littoral resources and early hominin cognition, to the inundation of the earliest permanently settled fishing villages and eventually, formative centres of urbanisation. In the Mediterranean, these would become hubs of maritime transportation that gave rise to the roots of modern seaborne trade. As such, this article represents an original review of both the geo-scientific and archaeological data that specifically relate to sea-level changes and resulting impacts on both physical and cultural landscapes from the Palaeolithic until the emergence of the Classical periods. Our review highlights that the interdisciplinary links between coastal archaeology, geomorphology and sea-level changes are important to explain environmental impacts on coastal human societies and human migration. We review geological indicators of sea level and outline how archaeological features are commonly used as proxies for measuring past sea levels, both gradual changes and catastrophic events. We argue that coastal archaeologists should, as a part of their analyses, incorporate important sea-level concepts, such as indicative meaning. The interpretation of the indicative meaning of Roman fishtanks, for example, plays a critical role in reconstructions of late Holocene Mediterranean sea levels. We identify avenues for future work, which include the consideration of glacial isostatic adjustment (GIA) in addition to coastal tectonics to explain vertical movements of coastlines, more studies on Palaeolithic island colonisation, broadening of Palaeolithic studies to include materials from the entire coastal landscape and not just coastal resources, a focus on rescue of archeological sites under threat by coastal change, and expansion of underwater archaeological studies in combination with submarine geomorphology. This article presents a collaborative synthesis of data, some of which have been collected and analysed by the authors, as the MEDFLOOD (MEDiterranean sea-level change and

projection for future FLOODing) community, and highlights key sites, data, concepts and ongoing debates.

Keywords: Sea-level change, Pleistocene, Holocene, Mediterranean Archaeology

Table of Contents

1. Introduction

The study of past sea-level changes in the Mediterranean Sea has been a focus of coastal scientists for almost two centuries. While interest in vertical land and sea movements is recorded at least as early as the Roman Period (e.g., Strabo, 1st century AD), the first modern sea-level studies may be attributed to Lyell (1833) and Négris (1903a,1903b; 1904). Gignoux (1913), Issel (1914) and Blanc (1920), were the first to define the 'Tyrrhenian' (the last interglacial) as a chronostratigraphic subunit along the Tyrrhenian coasts of Italy, especially in Sardinia, Tuscany and Lazio. Coastal and sea-level studies flourished especially post World War II, with the early studies of Bonifay and Mars (1959) and Stearns and Thurber (1965) in the western Mediterranean. In the late 1970s, and through the 1980s and 1990s, the investigations of Mediterranean Sea levels grew to become a stand-alone scientific discipline championed by geologists, biologists, geophysicists and geochemists. Scientists increasingly acknowledged the connection between past sea-level changes and human migrations along the coasts. Changes in coastal conditions impacted upon landscapes, waterways, ecological zones and people as the coastlines migrated as a result of sedimentation, erosion and sea-level change.

In parallel, archaeologists throughout the 20th century documented coastal sites, which demonstrated intensive maritime activity around the Mediterranean basin, though much of the focus remained on the relatively recent periods since the adoption of metal and written language, while less attention was given to earlier periods and the archaeological significance of coastal changes over longer periods of time. In many respects, the eastern Mediterranean, where Africa and Eurasia meet, is an ideal study area, and important for the integrated studies of landscape evolution and archaeology; it has contributed significantly to our understanding of human dispersals and migrations, as well as terrestrial and maritime trade routes.

The overarching aim of this article is to define the state of the art of Mediterranean sea-level studies, a century after its inception, and to consider the impacts of past sea-level and coastal changes on human-environment interaction. We identify and highlight the major on-going discussions and gaps in knowledge which we expect to at least partially define the next decade of integrated sea-level research into past coastal environments and archaeology (Figure 1). In doing so, we aim to bring together the research of the geomorphological and archaeological communities and promote interdisciplinary work specifically related to sea-level change.

This article stems from the efforts of the MEDiterranean sea-level change and projection for future FLOODing (MEDFLOOD) community, and is focused primarily on the central and eastern Mediterranean basin. This review is not designed to be geographically all-inclusive and there are some references to specific data or sites from further afield, for example the western Mediterreanean, where they are representative, especially significant, or where the resolution of data (in the principle study area) is too low to discuss important concepts in a meaningful way. We base discussions on our own expertise and use examples from selected regions from the early Prehistoric, Protohistoric (or 'Later Prehistoric' Bronze and Iron Age periods) and early Classical periods. Through these lenses, we review the existing evidence in the geomorphological and archaeological records that document or contextualise early human-environment interactions.

The review is sub-divided chronologically from the Last Interglacial to the Holocene using Marine Isotopic Stages (MIS, Imbrie et al., 1984). Defining the chronological boundaries from $\delta^{18}O$ benthic stacks as applied to coastal and terrestrial records is not straightforward; therefore at the beginning of each subsection we provide an overview of the timing for each MIS. We base the age attribution of each MIS mainly on the Lisiecky and Stern (2016) $\delta^{18}O$ stack, making reference, where available, to specific data. For a more detailed discussion on the duration of past interglacials and their boundaries see Berger et al. (2015).

In each section, we first describe the sea-level changes that occurred, followed by sub-sections on human coastal occupation, contemporary with, and influenced by, relative sea-level change. We begin with a review of geological sea-level indicators. Towards the end of the article we include a section on the use of archaeological sea-level indicators, of interest to both archaeologists and geoscientists.

All the elevations in the text are referred to mean sea level, with a ‘+’ prefix if they are above it or a ‘-‘ prefix if they are below modern sea level. Throughout the text we maintain the disctinction between relative sea level (RSL) whenever we refer to local coastal sea level, uncorrected for tectonic, isostatic and other post-depositional processes. We use eustatic sea level (ESL) when we refer to global mean sea level or ice-equivalent sea-level changes. For a more detailed description of RSL and ESL, we refer the reader to Milne et al. (2009) and Rovere et al. (2016b).

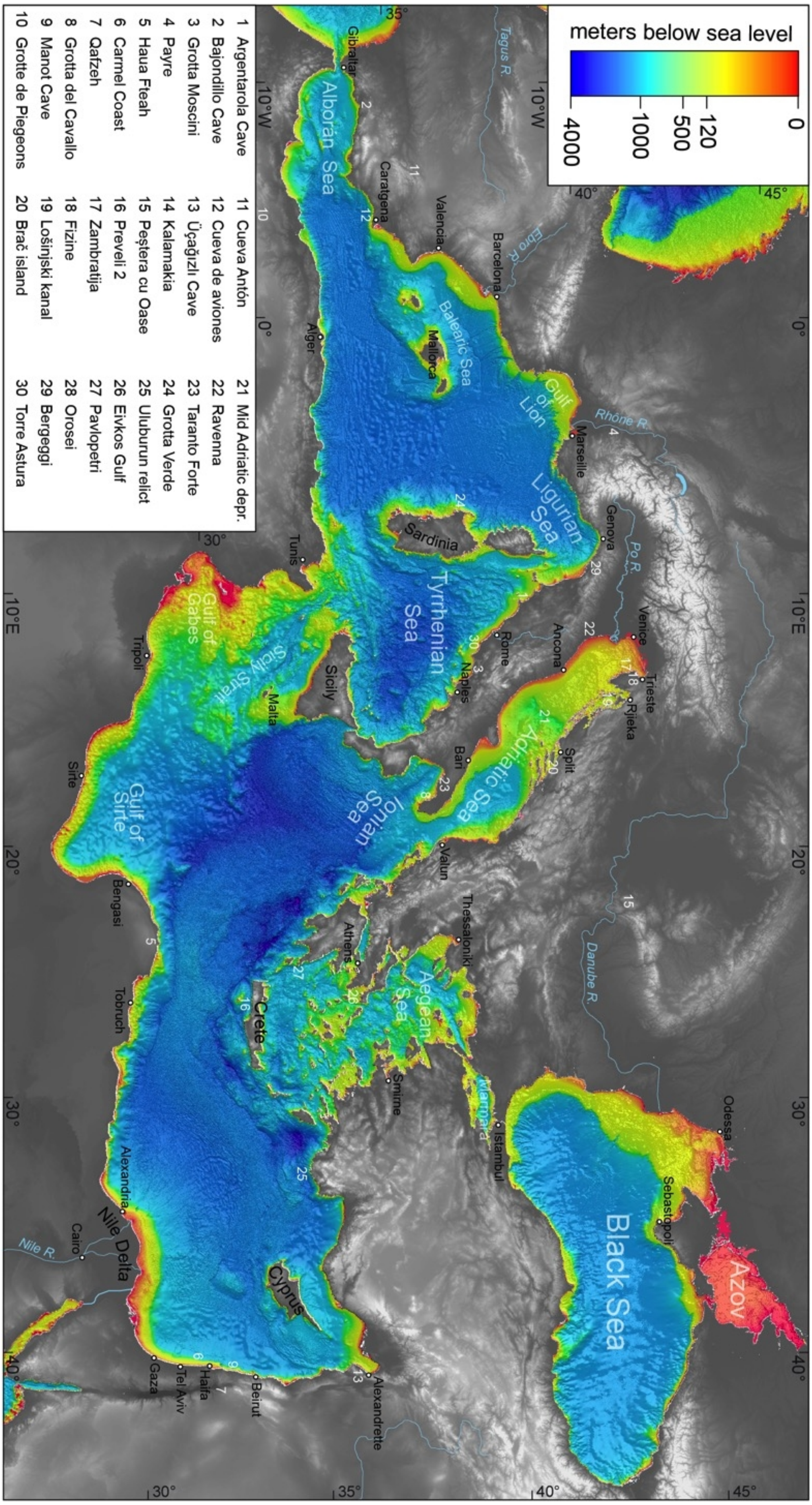
meters below sea level
0
120
500
1000
4000
1 Argentarola Cave
2 Bajondillo Cave
3 Grotta Moscini
4 Payre
5 Haua Fteah
6 Carmel Coast
7 Qafzeh
8 Grotta del Cavallo
9 Manot Cave
10 Grotte de Piegeons
11 Cueva Antón
12 Cueva de aviones
13 Üçağizli Cave
14 Kalamakia
15 Peştera cu Oase
16 Preveli 2
17 Zambratija
18 Fizine
19 Lošinjski kanal
20 Brač island
21 Mid Adriatic depr.
22 Ravenna
23 Taranto Forte
24 Grotta Verde
25 Uluburun relict
26 Eivkos Gulf
27 Pavlopetri
28 Orosei
29 Bergeggi
30 Torre Astura
Alborán Sea
Balearic Sea
Gulf of Lion
Ligurian Sea
Tyrrhenian Sea
Sardinia
Sicily
Sicily Strait
Gulf of Gabes
Adriatic Sea
Ionian Sea
Gulf of Sirte
Aegean Sea
Crete
Cyprus
Marmara
Black Sea
Azov
Nile Delta
Gibraltar
Caratgena
Valencia
Barcelona
Mallorca
Marseille
Genova
Venice
Trieste
Rijeka
Split
Ancona
Rome
Naples
Bari
Valun
Thessaloniki
Athens
Smirne
Istambul
Odessa
Sebastopoli
Alexandrette
Beirut
Haifa
Tel Aviv
Gaza
Cairo
Alexandria
Tobruch
Bengasi
Sirte
Tripoli
Malta
Tunis
Alger
Tagus R.
Ebro R.
Rhône R.
Po R.
Danube R.
Nile R.
10°W
0°
10°E
20°
30°
40°
35°
45°

Figure 1. A topographic map of the Mediterranean Sea region with bathymetric data derived from the European Marine Observation and Data Network (http://www.emodnet.eu/). Topographic data derived from Shuttle RADAR Topographic Mission (SRTM, srtm.csi.cgiar.org). Key sites as mentioned in text. (credit: A. Fontana)

2. Indicators of past sea-level changes

RSL variations have left imprints on the modern coastlines and continental shelves worldwide. Past human cultures have also built infrastructure in close connection with RSL throughout the Mediterreanean dating to at least the Neolithic, and with increasing intensity through Classical and later periods. A landscape feature, a fossil, or a sedimentary deposit whereby its elevation can be linked to a former sea level is considered a RSL indicator. Note that the term 'relative' implies that an indicator measures both the local sea surface change and the sum of all vertical land movements (e.g. due to tectonics, and/or different forms of isostasy) that affected the indicator since its formation (for a summary of these, see Rovere et al., 2016b and references therein). Once a RSL indicator is identified and measured in the field, it is necessary to establish its indicative meaning (Van de Plassche, 2013; Shennan et al., 2015). The indicative meaning defines the elevation where the RSL indicator was formed or was built with respect to the palaeo sea level and includes a measure of uncertainty. The main RSL indicators that have been used to reconstruct past sea-level changes in the Mediterranean are listed in Table 1. In the following subsections we describe these, and eventually we detail the on-going discussions on the interpretation of their indicative meaning. For a more in depth description of each marker and examples of their use to reconstruct paleo RSL, the reader is referred to the works cited in Table 1. In the following paragraphs we describe natural, non anthropogenic RSL indicators. Anthropogenic (archeological) RSL indicators are described in a later section as they are only relevant to the Holocene.

Table 1. Indicators and proxies used to reconstruct past Mediterranean sea levels

Type of RSL marker	Chronology	Typology	Elements improving RSL estimate	References and examples
Tidal notches	Late Quaternary	Geomorphological	Fixed biological indicators	Antonioli et al., 2015; Rovere et al., 2016° Goodman-Tchernov and Katz 2016
Abrasion notch and sea caves	Late Quaternary	Geomorphological	Fixed biological indicators (may be difficult to find due to erosion).	Rovere et al., 2016a; Ferranti et al., 2006
Shore / Abrasion platforms	Late Quaternary	Geomorphological	Biological indicators	Rovere et al., 2016a; Ferranti et al., 2006
Marine terraces	Late Quaternary	Geomorphological/ sedimentary	Fixed biological indicators or sedimentary features	Rovere et al., 2016a; Ferranti et al., 2006; Lambeck et al., 2004b
Speleothems	Late Quaternary	Geomorphological/ sedimentary	Fixed biological indicators	Antonioli et al., 2004; Dutton et al., 2009
Beach deposits	Late Quaternary	Sedimentary	Biofacies, orientation and integrity of shells, sedimentary structures.	Rovere et al., 2016a; Galili et al., 2007, 2015; Goodman et al. 2008, 2009
Beachrocks	Late Quaternary	Sedimentary	Sedimentary structures, types of cement	Vousdoukas et al., 2007; Mauz et al., 2015b
Salt-marsh deposits	Holocene	Sedimentary	Faunal assemblages (foraminifera, ostracods, molluscs) and plant remains	Vacchi et al., 2016b; Lambeck et al., 2004° Nixon et al, 2009
Lagoonal deposits	Holocene	Sedimentary	Faunal assemblages (foraminifera, ostracods, molluscs)	Vacchi et al., 2016; Lambeck et al., 2004a
River deltas	Holocene	Sedimentary	Sedimentary structures	Stanley 1995; Anthony et al. 2014
Fossil fixed bioconstructions	Holocene	Sedimentary	Midlittoral species	Laborel and Laborel-Deguen, 1994; Rovere et al., 2015
Harbour structure (quay, pier, breakwater)	Late Holocene	Archaeological	Fixed biological indicators	Auriemma and Solinas, 2009; Morhange and Marriner, 2015

Fishtanks	Late Holocene	Archaeological	Preservation of all structural parts, presence of fixed biological indicators	Lambeck et al., 2004b; Mourtzas et al., 2012a
Coastal quarries	Late Holocene	Archaeological	Preservation of the lowest quarry level	Lambeck et al., 2004b Auriemma and Solinas, 2009; Galili and Sharvit 1998
Slipways	Late Holocene	Archaeological	Fixed biological indicators	Lambeck et al., 2010; Anzidei et al., 2014; Morhange and Marriner, 2015
Coastal Water Wells	Holocene	Archaeological	Definition of the ancient water table	Galili and Nir, 1993; Sivan et al., 2004; Rovere et al., 2011

2.1 Depositional, bio-constructional and erosional RSL indicators

Natural, non-anthropogenic RSL indicators can be divided roughly into three categories: depositional (e.g. estuarine or deltaic brackish sediments, salt-marshes, coastal lagoons, beachrocks, etc.), biological (e.g encrustations by marine organisms, such as vermetids, algae, etc.) and erosional (e.g. abrasion platforms and marine notches). These sea-level indicators require stabilization of sea level, for at least a short period, for their formation and preservation (Table 1).

2.1.1 Depositional sea-level indicators

Some of the most useful and precise depositional indicators are salt-marsh foraminifera and testate amoebae (Scott and Medioli, 1978; Gehrels, 1994; Edwards and Horton, 2000; Barnett et al., 2017). Salt marshes are abundant in northeastern Italy, Croatia and Greece, for example, and host a limited number of cosmopolitan foraminiferal taxa. Some have very restricted depth and salinity constraints, which allow for decimetre-scale sea-level reconstructions (e.g., Serandrei Barbero et al., 2006; Shaw et al., 2016). Similarly, vertical distributions of ostracods and malacofauna of Mediterranean coastal lagoons and estuarine or deltaic brackish areas, has proved to be useful for sea-level reconstructions (e.g., Mazzini et al., 1999; Marco Barba et al., Vacchi et al., 2016a). Typically, studies incorporating these methods apply coring campaigns along shore-perpendicular transects to identify the salt-marsh, lagoonal or other brackish facies and determine their age by radiocarbon dating.

Another widely used depositional Holocene sea-level indicator are beach deposits and beachrocks. A beachrock is a form of calcarenite that is present within the littoral zone and often is characterised by significant amounts of marine-associated inclusions such as shell or broken coral remains, and depending on its age and composition can be crumbly and pliable. Beachrocks represent the hard fossilised section of a former sandy/gravel coast, of both clastic and biogenic origin, rapidly cemented by the precipitation of carbonate cements (e.g., Mauz et al., 2015b).

Beachrock formation is traditionally associated with an interface between stable seawater and fresh groundwater, but may also form in the absence of groundwater (Kelletat, 2006) by river floods, storms, or tsunamis (Vött et al., 2010; May et al., 2012). Regardless of its genesis, beachrock forms within a limited distance of the coastline and is therefore regarded as a proxy for sea level (Mauz et al., 2015b). The presence of soda bottles and modern trash incorporated into some beachrock today reinforce arguments that diagenesis can be rapid. In best cases, beachrock can provide one-metre vertical accuracy (Hopley, 1986). Cementation occurs either in the intertidal or in the swash/backwash and spray zone under complex physicochemical and biological conditions, under low wave energy conditions and possibly in the presence of meteoric water. Intertidal sediments may be difficult to determine on the basis of the cement alone (Hopley, 1986). However, analysis of sedimentary structures and cement microstratigraphy of Mediterranean beachrocks can result in very detailed RSL reconstructions (e.g., Desruelles et al., 2009; Vacchi et al., 2012; Mauz et al., 2015a; Ozturk et al., 2016)

The Mediterranean shelf contains multiple depressions that flooded during high stands but which are isolated from the sea during lowstands, and therefore can preserve records of marine flooding during the Quaternary. Examples of such places include the Sea of Marmara (Taviani et al., 2014b), the Maltese shelf (Micallef et al., 2012) or the Evoikos Gulf (Drinia et al., 2014). The flooded karst depressions along the eastern Adriatic Coast, such as at the Lošinjski Canal Bay, contain records of multiple marine incursions, which are controlled by the relative mean sea-level position and the elevation of a sill (Figure 2). Sediment cores from such basins hold valuable information on sedimentary architecture, chronology, geochemical and biological proxies related to Quaternary sea-level changes.

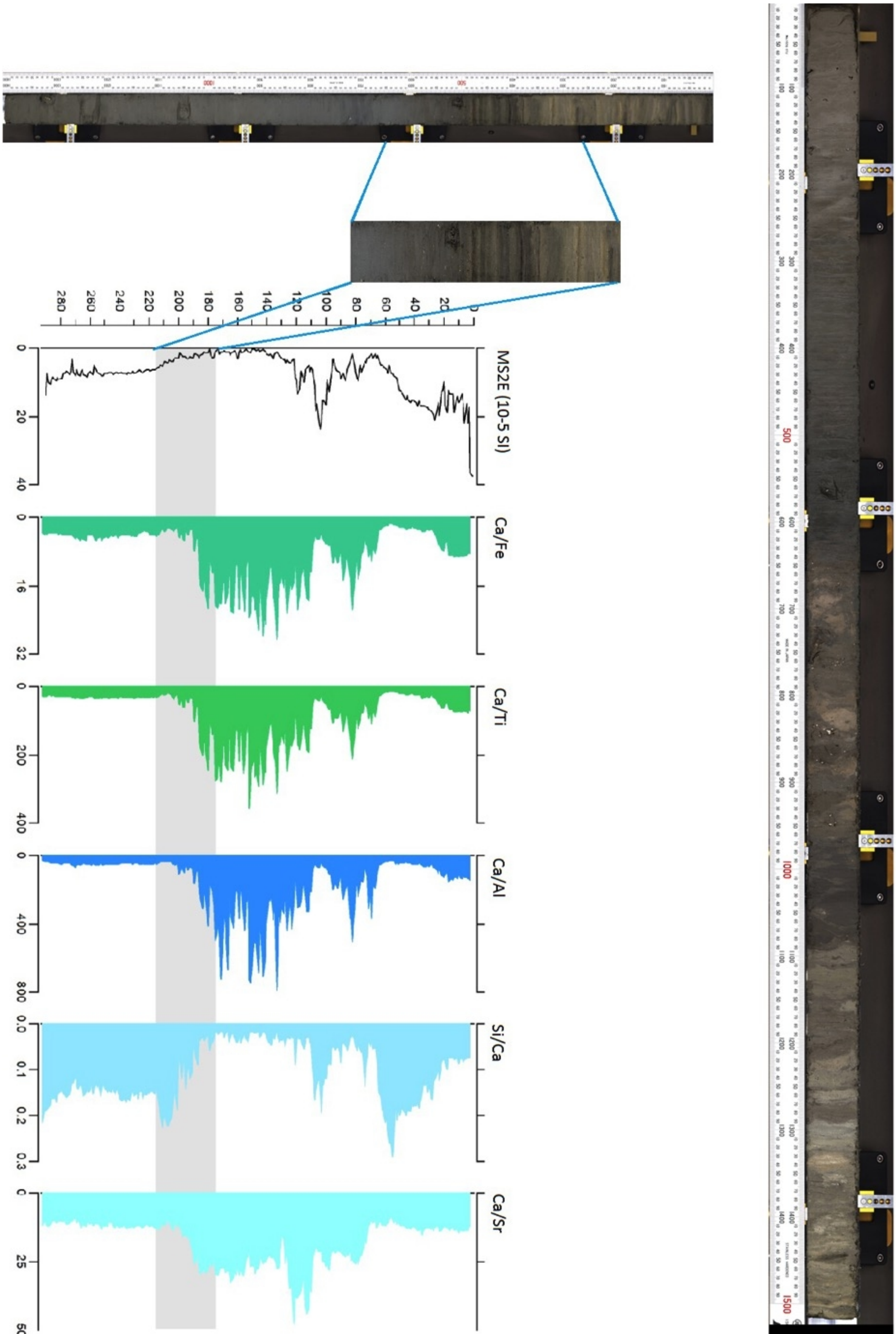
MS2E (10-5 SI)
Ca/Fe
Ca/Ti
Ca/Al
Si/Ca
Ca/Sr
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0

Figure 2. A split core form the karst depression in the Lošinjski Kanal Bay (-72 m), isolated from the Northern Adriatic Sea by a sill at -50 m. The core displays multiple marine flooding (gray homogeneous sediment, low Ca/Sr ratio, top and bottom parts of the Core) and a lake sediment sequence (laminated sediments-high Ca/Sr ratio). (Photo: S. Miko)

2.1.2 Biological sea-level indicators

Some examples of biological RSL indicators include the bioconstructions created by coral reefs or vermetids. Some shallow water coral reefs can yield sea-level reconstructions that are accurate to within ±1 m (Lighty et al., 1988). Other bioconstructions, such as large reefs formed by vermitids, for example *Dendropoma petraeum*, are formed within a vertical range of ±0.10 m and are excellent sea-level indicators (Laborel, 1986; Antonioli et al., 1999; Sivan et al., 2010). Fossil remains fixed to former sea cliffs, such as *L. lithophaga*, *Cerastoderma glaucum*, limpets and barnacles, particularly in conjunction with other sea-level indicators, have also been used as past sea-level indicators (van de Plassche, 2013; Rovere et al., 2015 and references therein). Biological indicators can also be erosive in nature, when the former sea level can be reconstructed from bioeroded surfaces (see next section). The most common features produced by bioerosion are borings left on rocky carbonate coasts by molluscs (such as *L. lithophaga*) or by sponges (such as Clionadae).

2.1.3 Erosional sea-level indicators

Marine notches and abrasion platforms are commonly used as erosional sea-level indicators in the Mediterranean. Tidal notches have been classically divided into: i) tidal notches, formed in sheltered rocky areas in the intertidal zone; ii) infra-littoral notches, formed in the sub-tidal zone under exposed conditions and high surf; iii) surf notches, formed under exposed conditions in the supra-littoral zone (Pirazzoli, 1986). Abrasion platforms (shore platforms) are the product of marine erosion in exposed rocky coasts under periods of stable sea level (Trenhaile, 1987; Kennedy, 2015).

Tidal notches can be very precise sea-level indicators, as their width is related to the tidal range of the locality where they form and the deeper point of the notch is closely correlated to mean sea level (Antonioli et al., 2015 and references therein). The rate of notch formation is faster in seaward, less sheltered, sites, as well as in softer or more porous matrixes (e.g. Goodman-Tchernov and Katz 2016). Measurements of tidal notches at 73 sites in the Central Mediterranean Sea suggested that several processes contribute, at varying rates, to the formation of tidal notches (Furlani et al., 2014a). These processes include bioerosion, weathering, hyperkarst and mechanical erosion: the relative dominance of each process can produce a slightly different notch morphology. One of the main factors favouring the development of a tidal notch is the existence of submarine fresh-water springs which enhance rock dissolution (Furlani et al., 2014b). We note the current, on-going debate regarding whether or not tidal notches are disappearing due to the recent increasing rates of sea-level rise. While this view is supported by studies in Greece (Evelpidou et al., 2012; Pirazzoli and Evelpidou, 2013; Evelpidou and Pirazzoli, 2015), other studies elsewhere in the Mediterranean reject this hypothesis (Boulton and Stewart, 2013; Antonioli et al., 2015, 2016, Goodman-Tchernov and Katz 2016).

Figure 3. Measurement of a fossil tidal notch (Orosei Gulf, Sardinia Italy) using a metered rod. The measured height of the notch is 8.7 m. (Photo: F. Antonioli).

3. MIS 5

3.1 Sea level

ESL in the last 2 million years reached positions as low as 130 m below the present mean sea level during glacial periods, and highstands up to ~ +6 m and possibly +13-15 m during interglacial periods (Rohling et al., 1998; Dutton et al., 2015; Lisiecki and Raymo, 2005; Grant et al., 2014; Raymo and Mitrovica, 2012; Spratt and Lisiecki, 2016; see also Figure 4 herein). MIS 5 includes several sub-stages that were characterised by both higher and lower-than-modern sea levels: MIS 5.5, MIS 5.3 and MIS 5.1. These three substages are described separately in the following sections, detailing examples of sea-level indicators found in the Mediterranean Sea.

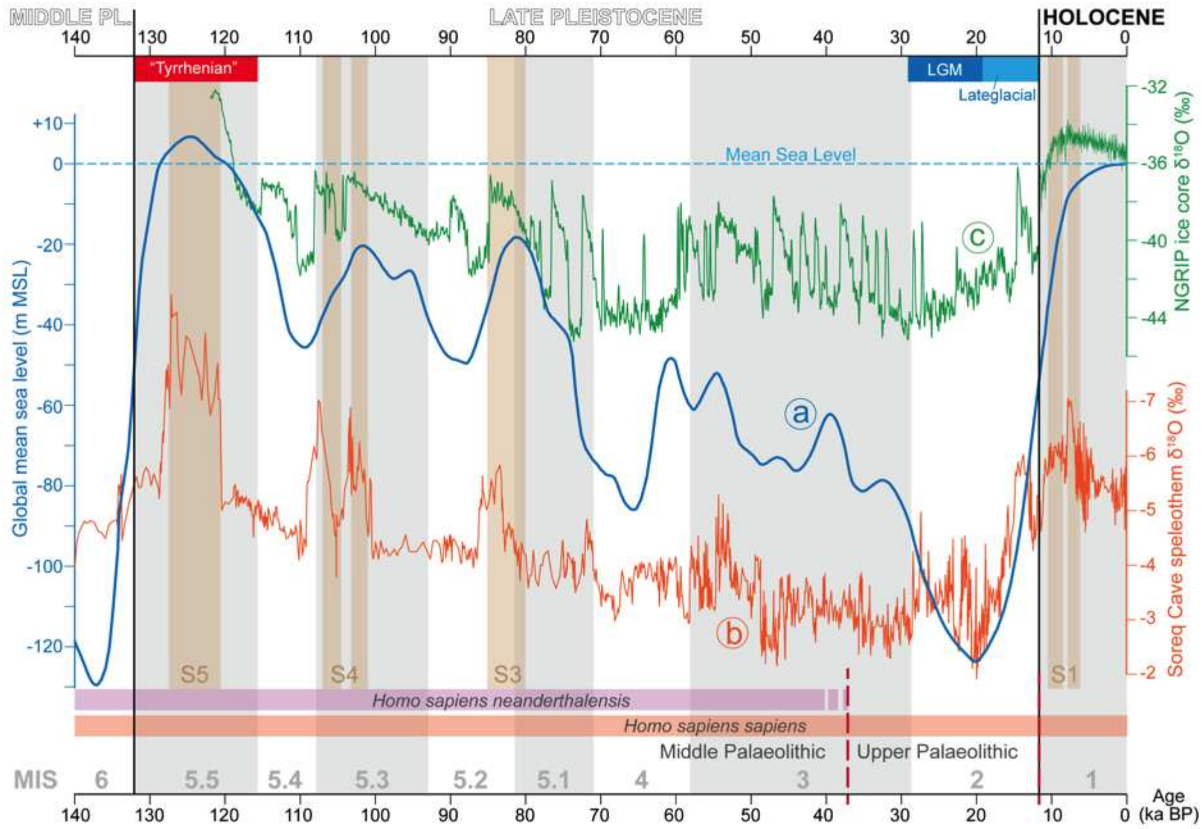

Figure 4. Comparison between the reconstruction of the past global mean sea level and palaeoclimatic, palaeoenvironmental and archaeological data for the Mediterranean Sea since 140 ka. a) Global mean sea-level curve with uncertainty indicated in light blue (Waelbroeck et al., 2002). As a palaeoclimatic proxy for the SE Mediterranean region the δ^{18}O composition of the Soreq Cave speleothem (b) is plotted, while for the palaeoclimate of the Northern Hemisphere, the δ^{18}O composition of NGRIP ice core (c) is represented (NGRIP members, 2004; Kindler et al., 2014). Grey and white rectangles indicate the MIS according with the LS16 δ^{18}O stacked benthic composition (d) (Lisiecky and Stern, 2016). Brown dashed shading indicates the period of sapropel deposition (Rohling et al., 2015).

3.1.1 MIS 5.5

In a global sense, the Last Interglacial (MIS 5.5) in the δ^{18}O benthic record begins, chronologically at 127.5 ka, approximately in sync with the ESL highstand. The end of the interglacial shows a significant regional variability (Lisiecky and Stern, 2016). Atlantic benthic δ^{18}O increases in fact gradually from 122 to 111 ka, whereas Pacific benthic δ^{18}O increases rapidly from 119 to 116 ka (Lisiecky and Stern, 2016). Dutton et al. (2015) and Kopp et al. (2009) set the beginning of the interglacial to ~129 ka, while Hibbert et al. (2016) report that, globally, corals above present sea level attributed to MIS 5.5 date from 139 to 111 ka.

Sea-level deposits associated with MIS 5.5 in the Mediterranean Sea have been referred to as ‘Tyrrhenian’, despite the fact that, in the formal terminology, the Tyrrhenian Stage encompasses a time period longer than MIS 5.5 (260 to 11 ka), while MIS 5.5 corresponds to the Eutyrrhenian subunit (e.g. Gignoux, 1913; Asioli et al., 2005). Global estimates based on the analysis of RSL indicators corrected for GIA and tectonics constrain the maximum MIS 5.5 ESL between +5.5 to +9 metres (Dutton and Lambeck, 2012; Kopp et al., 2009).

A large database focussed on MIS 5.5 RSL indicators in Italy was published by Ferranti et al. (2006) and was later used by Pedoja et al. (2011, 2014) in the framework of a global synthesis (Figure 5a). From the spread of elevations of MIS5.5 RSL indicators in the Mediterranean, it is evident that some areas are tectonically highly active, producing rapid rates of subsidence and uplift, with shorelines now found at elevations between -105 and +210 m since MIS 5.5 (Anzidei et al., 2014). In other areas, the elevation of MIS 5.5 RSL indicators is constrained between +2 to +3 m (e.g. Mallorca, Balearic Islands; Vesica et al., 2000) and +7 to +8 m (e.g. western Italy; Antonioli et al., 2006a) or up to +7m at the end of MI5.5 in the east Mediterranean (Sivan et al., 2016). These areas are generally considered as tectonically ‘stable’, despite slight variations in the elevation of the MIS 5.5 RSL indicators.

Commonly used MIS 5.5 sea-level indicators in the Mediterranean include marine terraces, tidal notches (e.g. in the well dated MIS 5.5 notches of the Galilee coast, Israel; Sisma-Ventura et al., 2017), beachrocks, coastal conglomerates and sediments containing diagnostic fauna (e.g. Hearty, 1986; Galili et al., 2015, Sivan et al., 2016). In the Mediterranean, the key fossil indicator for MIS 5.5 found in palaeo beach deposits is the gastropod currently named as *Persististrombus latus* (Taviani, 2014a), but generally described in the literature with its former name, *Strombus bubonius* (e.g., Gignoux, 1913; Sivan et al., 1999; 2016; Zazo et al., 2003, 2013, Figure 5b). This gastropod is the most conspicuous specimen of the “Senegalese fauna” (Figure 5b-g), which indicates a relatively warm coastal and littoral environment. *Strombus*-bearing terraces are mainly attributed to MIS 5.5, although they also occur in terraces assigned to MIS7 in the western Mediterranean (Zazo et al., 2013).

Another important element found in fossil MIS 5.5 deposits is *Cladocora caespitosa* (Fig 5c), a stony coral of the subclass Hexacorallia. This coral can still be found living in the Mediterranean today (Peirano et al., 1998) and has been used to infer MIS 5.5 temperatures (Peirano et al., 2004). In Mediterranean deposits, this is one of the few fossils that can be dated by U-series (e.g. Jedoui et al., 2003; Muhs et al., 2015).

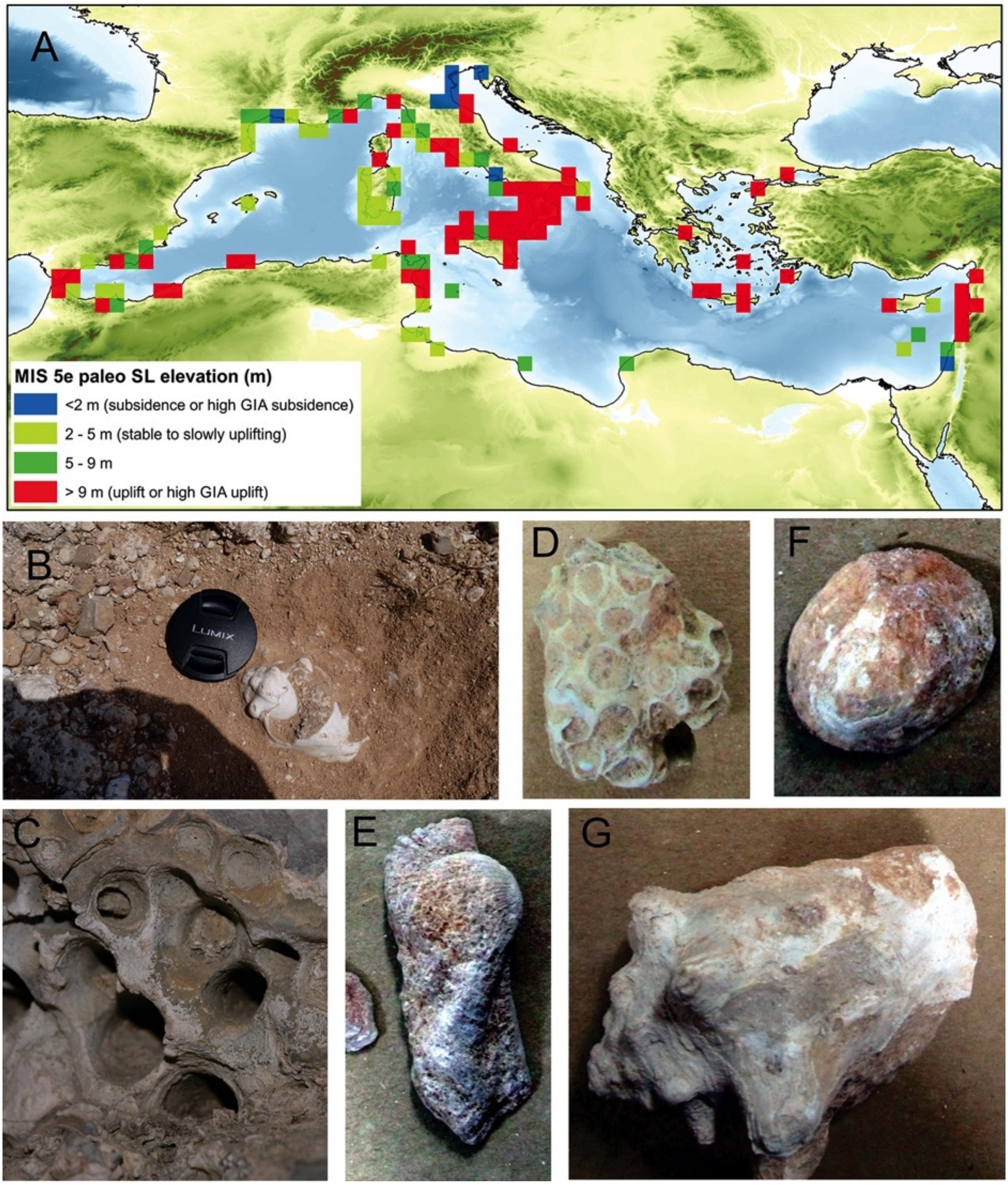

Figure 5. A) Average elevation per area of the MIS 5.5 shoreline (data from Ferranti et al., 2006; Pedoja et al., 2014); B) MIS 5.5 deposit containing *Strombus latus* (ex bubonius); C) *Lithophaga lithophaga* in the marine cave of Bergeggi (Italy, Liguria, Western Mediterranean). Each borehole has a diameter of ~2–3 cm; D-G) typical senegalese fauna, from deposits in Mallorca (Spain, Catalunya, Western Mediterranean, collection J. Cuerda Barceló): D) *Cladocora caespitosa*, one of the few corals in the Mediterranean that can be used to obtain reliable U-series ages (the fossil length is ~5cm); E) *Arca noae* (the fossil length is ~7cm); F) *Patella lusitanica* (the fossil length is ~4cm); G) *Persistrombus latus* (ex *Strombus bubonius*) (the fossil length is ~10cm). (Photos: A. Rovere).

Despite studies on MIS 5.5 RSL indicators dating back at least to the beginning of the last century (Gignoux, 1913; Issel; 1914; Blanc, 1920), several geological research questions remain unanswered. These are briefly outlined below.

It is uncertain if the Mediterranean RSL indicators point to the stability of ESL during MIS 5.5 or to a sea level characterised by significant variations and pulses of meltwater. The ongoing debate over the sea-level behaviour during MIS 5.5 is global in scope (as summarised in Long et al., 2015). Whether eustatic sea level during MIS 5.5 was stable around a certain value (typically +5.5 to +9 m, Dutton and Lambeck, 2012), fluctuating with peaks (Rohling et al., 2008b; Kopp et al., 2009), or around +2 to +3 m for most of the interglacial with drastic rising peaks towards the end (Hearty et al., 2007; O'Leary et al. 2013) is still under debate. While some of the classic MIS 5.5 sites in the Mediterranean preserve the evidence of two sea-level highstands during this period (e.g., deposits of Cala Mosca, Sardinia, Italy, see Ulzega and Hearty, 1986 for a detailed description), other sites preserve only a single RSL highstand (e.g., Capo San Vito Sicily, Italy; see Antonioli et al., 2006b). More detailed studies, elevation measurements and GIA models are needed particularly for those Mediterranean MIS 5.5 indicators that point to a stepped MIS 5.5 relative sea-level history (e.g. Sivan et al., 2016).

Another important issue is that, while low tidal ranges and relatively low wave energy favor the development of precise RSL indicators (i.e. with relatively small indicative meaning), there is, in the Mediterranean, a scarcity of deposits bearing corals for which relative chronologies within MIS 5.5 can be obtained through U-series dating and that fulfil the criteria of reliable U-series ages (Brocas et al., 2016).

A large portion of Mediterranean MIS 5.5 sea-level evidence is represented by erosional RSL indicators, in particular fossil tidal notches (Ferranti et al., 2006) (Figure 3). While one of the main advantages of tidal notches is that they can be tightly related to palaeo mean sea level (see section 2.1.3), their main disadvantage is that, being erosional in nature, they cannot be dated directly. This difficulty is overcome when it is possible to correlate the tidal notch with deposits for which the MIS 5.5 age can be either inferred (e.g. deposits containing *Persististrombus* fossils) as in the case of the Galilee notch in Israel where MIS5.5 sediments infill the notch (Sisma-Ventura et al., 2017) or calculated with analytical tools (e.g. U-series ages on deposits containing the coral *Cladocora caespitosa*). At present, there is no known methodology to directly date fossil tidal notches and other erosional RSL indicators, although advancements in the application of cosmogenic dating (e.g. ^{36}Cl cosmogenic dating, Mitchell et al., 2001) to limestone surfaces might open, in the future, new possibilities to give more precise age constraints to these important landforms.

Another important application of MIS 5.5 RSL indicators in the Mediterranean is their use to assess neotectonic uplift rates. The general procedure used is the subtraction of a global eustatic sea-level estimate (usually 6 – 9 m) from the elevation of the RSL indicator. The result is then divided by the age of the indicator (e.g. Antonioli et al., 2006b). This process does not take into account the effect of the solid earth response to melting ice (Lambeck and Purcell, 2005; Creveling et al., 2015), a process that in the Mediterranean has been occasionally considered qualitatively (Antonioli et al., 2006a; Mauz et al., 2012), but has been quantified only in some MIS 5.5 studies (e.g. Rovere et al., 2016a; Sivan et al., 2016). Predictions of GIA for MIS 5.5 can have, however, large variations and efforts are still ongoing to obtain reliable

GIA predictions for this period (e.g. see Lambeck and Purcell, 2005). Such modelling studies will need to consider varying mantle viscosities and varying ice-sheet configurations to obtain reliable uncertainties on the predicted GIA contribution to the departure from eustasy in MIS 5.5 Mediterranean records. The extrapolation of tectonic rates since MIS 5.5 to calculate modern vertical movements of coastal areas (e.g. Antonioli et al., 2017) should be considered within this context.

When the elevation of a MIS 5.5 RSL indicator is not corrected for GIA (for a discussion on MIS 5.5 GIA corrections, see Creveling et al., 2015), both the comparison with global eustatic sea levels and the calculation of tectonics from the elevation of MIS 5.5 RSL indicators should be treated with a degree of caution.

3.1.3 MIS 5.1 – MIS 5.3

Temporally, the peak of MIS 5.3 and MIS 5.1 in the δO^{18} benthic record correlates with Northern Hemisphere summer insolation maxima at, respectively, ca. 93-108 ka and ca. 80–85 ka (Lisiecky and Raymo, 2005; Lisiecky and Spratt, 2016). The dating of RSL indicators for these two periods is less constrained than for MIS 5.5, as there are very few reliable U-series ages for RSL indicators attributed to this period (see Creveling et al., 2017).

Regarding sea levels, and in terms of oxygen isotope records, Waelbroek et al. (2002) place global ESL during MIS 5.1 at -21 m. A recent global compilation of field data (with related GIA calculations) placed ESL during MIS 5.1 in a range between -22 and +1 m, and MIS 5.3 sea level between -24 to +2 m, using the best dated field records available globally (Creveling et al., 2017).

The lack of available GIA corrections for the Mediterranean Sea in this period makes it difficult to compare regional MIS 5.1 measurements with global data. Gzam et al. (2016) associated alignments of submerged fossil dunes in the Gulf of Gabes, Tunisia, where palaeoshorelines formed during the MIS 5.1 are found at about -8 m (with MIS 5.3 at -19 m and MIS 5.5 at +3 m). Rovere et al. (2011, Table 1) reported on submerged RSL indicators across the Italian peninsula, and discussed their possible attribution to MIS 5.1 and 5.3 or older periods (e.g. MIS 7). On the Island of Krk (Croatia) two stalagmites, collected from -14.5 m and -18.8 m, have been interpreted to infer two RSL peaks at ~84 ka and ~77 ka based on the absence of tectonic deformation (Surić et al., 2009). Further evidence comes from Mallorca, where a phreatic speleothem sampled in a partially submerged cave was dated to MIS 5.1 (Dorale et al. 2010), support RSL reconstruction at ca. +1 m. Also on Mallorca, other deposits containing fossils of *Cladocora caespitosa* were recently dated to MIS 5.5 at an elevation between +1 and 2 m RSL, having previously been attributed to MIS 5.1 (Muhs et al., 2015).

3.2 Human populations during MIS 5

Coastal regions provide a wide range of resources to the populations that inhabit them, and this was particularly important to hunter-gatherers and mobile groups of foragers during prehistory (Erlandson, 2001; Bailey and Milner, 2002). The exploitation of coastal landscapes and resources has been the subject of major discussion in recent years. Debates include the identification of the earliest systematic exploitation of littoral resources and its significance for hominin cognition (e.g. Marean, 2014), the role of coastal regions in facilitating dispersals of *Homo sapiens* populations out of Africa (Stringer, 2000; Mellars et al., 2013), and the ability of coastal regions to act as refuges during environmental downturns (e.g. Finlayson, 2008; Jennings et al., 2011; Garcea 2012; Shtienberg et al., 2016). Understanding the spatial relationship between populations and coastlines in the Mediterranean during MIS 5 is therefore crucial to understand interactions of early human populations with the landscape, and also human migrations and extinctions.

The MIS 5 archaeological record in the Mediterranean, and in particular MIS 5.5, is the most promising period for examining the role of coastal resources during the Middle Palaeolithic (a period defined by lithic technology which broadly corresponds to 300ka – 40 ka). The fact that, in most areas, MIS 5.5 RSL proxies are found above present sea level means that coastlines from this period should be largely accessible for research today, except in areas of subsidence. In tectonically active sites, it is possible that MIS5.3 and 5.1 coastal records may too be preserved above present sea level, unlike the period from MIS 4 to the early Holocene (Bailey and Flemming, 2008). The archaeological record of occupation in the period 129 – 71 ka around the Mediterranean is relatively rich and is characterised by Middle Palaeolithic/Middle Stone Age (MP/MSA) industries, manufactured by two populations of Homo species: *H. neanderthalensis* (or *H. sapiens neanderthanlensis*) in Europe and *H. sapiens* (or *H. sapiens sapiens /* Anatomically Modern Humans, [AMH]) in North Africa. Archaeological deposits of Middle Paleolothic coastal dwellers embedded in beach deposits, however, are relatively rare.

The MP/MSA archaeological record in the Levant contains the first evidence for *H. sapiens* dispersals into Eurasia during MIS 5.5-3, with their remains preserved in terrestrial contexts at Skhul and Qafzeh caves dated to 100–130 ka (#7 in Figure 1, Grün and Stringer, 1991; Grün et al 2005). Both Neanderthals and *H. sapiens* populations utilised MP/MSA technology in the Levant during this period (Shea, 2003). The extent to which these populations exploited the coastal regions and the resources they contained is becoming clearer with targeted research into the origins of marine exploitation. Outside of the Mediterranean, evidence for exploitation of marine resources (molluscs, mammals etc.) by *H. sapiens* is known from MIS 6 contexts in southern Africa, with populations there developing a full 'coastal adaptation' by ~110,000 ka (Marean, 2014). Possible occupation of coastal environments during MIS 5.5, presumably by *H. sapiens*, are also suggested from the Red Sea region (Walter et al., 2000; Bailey et al., 2015).

Exploitation of marine molluscs and fauna preserved in cave sites can be observed in the archaeological record around the Mediterranean. Such evidence exists from ~150 ka at Bajondillo Cave, southern Spain (Cortés-Sánchez et al., 2011) and evidence for freshwater fish processing by Neanderthals in Payre, France 250–125 ka (Hardy and Moncel, 2011). Neanderthal subsistence strategies included exploitation of marine molluscs during early MIS 5 at sites such as Vanguard Cave, Gibraltar (Stringer et al., 2008) and Grotta dei Moscini, Italy (Stiner, 1993). Similar levels of sporadic marine mollusc exploitation are shown in North Africa by *H. sapiens* at the Haua Fteah, Libya (Klein and Scott, 1986; Barker et al., 2010, 2012), although caves in the Maghreb do not contain much evidence for the collection of molluscs for subsistence purposes until after MIS 5 (Marean, 2014).

Tracing the importance and use of marine resources in open air sites remains difficult. In the Levant, activity in coastal environments during early MIS 5 is shown in the form of MP stone industries in several MIS 5.5 beach deposits on the Israeli coast (Galili et al., 2007; Ronen et al., 2008), where assemblages containing molluscs, animal bones and Middle Palaeolithic flint implements were recovered from such deposits on the Carmel coast at Nahal Bir Ibdawiya and Nahal Me’arot

(Figure 6; #6 in Figure 1). Whilst the molluscs in these beach deposits may be naturally occurring, the deposition of stone tools and animal bones highlights an occupation and use of the wider coastal landscape. It appears that whilst marine resources were exploited by both *H. sapiens* and Neanderthal populations, these economies likely used marine molluscs as part of a range of resources available during this period of relative environmental stability and high sea levels around the Mediterranean.

There is also evidence that interactions with coastlines during MIS 5 were not necessarily limited to consumption of resources. Shell tools were manufactured by Neanderthals during MIS 5.1 in Mediterranean cave sites such as Grotta del Cavallo (#8 in Figure 1, Romagnoli et al., 2015). That technology persisted until ~50 ka (Douka and Spinapolice, 2012). Perforated shell beads from early MIS 5 cave contexts associated with *H. sapiens* dated to 100–135 ka (MIS 5.5-5.3) are known from Skhul (e.g. Vanhaeren et al., 2006) as well as Qafzeh where, dated to ~90–100 ka (MIS 5.3), they were stained with pigment (Bar-Yosef Mayer et al., 2009). Both cave sites were ca. 35 km from the coastline, indicating specific transport of personal ornaments away from the coast (Bar-Yosef Mayer et al., 2009). Similar beads have also been found in cave sites in the Maghreb around 82 ka, again linked to *H. sapiens* populations (Bouzouggar et al., 200, 7D'Errico et al., 2009). There are no known symbolic uses of marine shells by Neanderthals until MIS 4 (see below). In North Africa these ornaments seem to disappear from the archaeological record after 70 ka, remaining absent until around 50–40 ka, indicating that they may have been part of specific symbolic adaptations, the disappearance of which may have marked a cultural discontinuity (D'Errico et al., 2009).

Only a few marine fish bones have been recovered in coastal Middle Palaeolithic sites of the Levant, while at inland sites of that period there is evidence for fresh water fishing (Van Neer et al., 2005). However recent studies by Zohar (2017) show that exploitation of marine resources during the Middle Palaeolithic did occur; marine material has been identified in Kebara cave, Mount Carmel, some five kilometres inland.

The Palaeolithic colonisation and occupation of Mediterranean islands remains a matter of debate. Lower and Middle Palaeolithic finds from Preveli 2 on Crete have been assigned to at least MIS 5.3 and 5.1 based on geomorphological context (Strasser, 2011). That interpretation is contested, however, as it would indicate sea crossings during these periods. Mousterian Palaeolithic artefacts are also known from the Ionian islands (e.g. Ferentinos et al., 2012), closer to the mainland, but their age is not assessed by securely dated finds (Phoca-Cosmetatou and Rabett, 2014b). Palaeolithic island colonisation is therefore a research theme where further interdisciplinary study is needed.

To further our understanding of the relationships between populations and coastlines during MIS 5, we must continue to trace marine mammal and mollusc exploitation through the recovery of shells and faunal remains from deep cave stratigraphies that dominate the Mediterranean archaeological record. It is also important to consider the occupation of wider littoral environments and the opportunities they produce including, but not limited to, marine mollusc exploitation (Bailey et al., 2008). This will require further survey of coastal deposits and areas linked to the MIS5.5 high sea stands and palaeoshoreline features (Bailey and Flemming, 2008; Bailey et al., 2015) to locate evidence of activity within the coastal zone, as at Nahal Bir Ibdawiya and Nahal Me’arot (Galili et al., 2007), as well as areas where deposits created by the later high stands are preserved above present day sea level. In broadening the focus to the whole of the coastal biome, not simply to one strand of coastal resources, and by combining material from surface and landscape contexts, we can begin to reconcile how Middle Palaeolithic populations interacted with their coastlines. In that way we can assess how these populations responded to the impacts of coastal change.

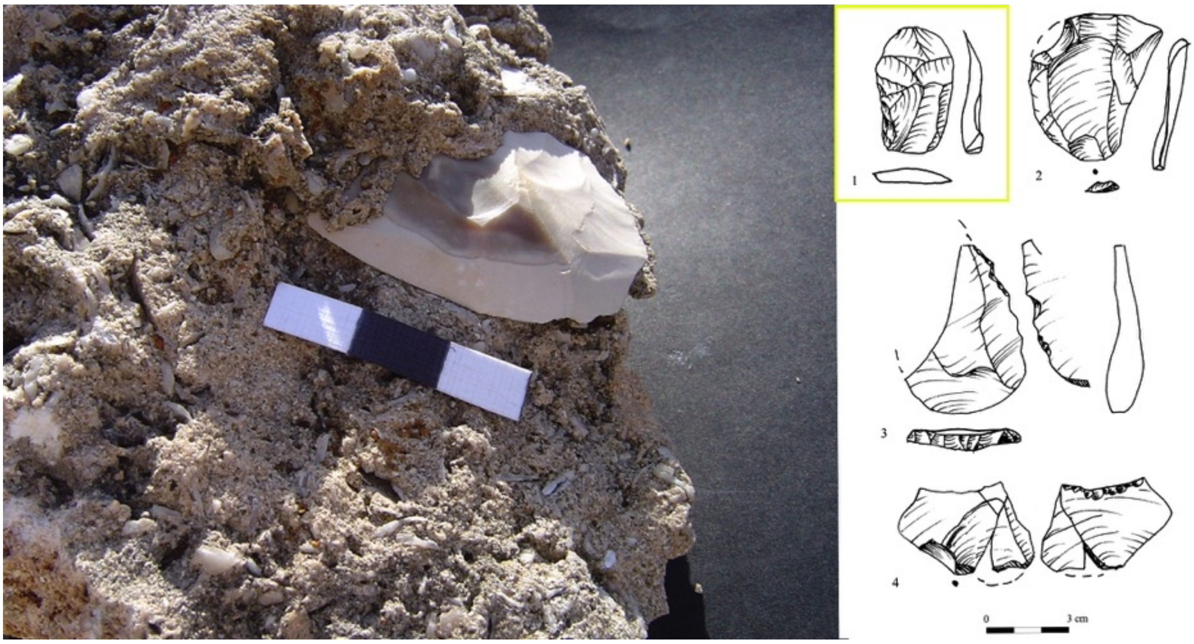

Figure 6. Middle Palaeolithic stone tools from the coastal Levant (Carmel Coast, Israel, #6 in Figure 1) contemporary with the highstand at MIS 5.5 (after Galili et al., 2007).

4. MIS 4, MIS 3 and MIS 2

4.1 Sea level

Throughout most of the last glacial-interglacial cycle, ESL was tens of metres lower than its present position (Waelbroeck et al., 2002, Grant et al., 2014). The extended periods when sea level was low (MIS 4 and MIS 3) and reached its maximum lowstand (MIS 2) (see Figure 4a) were crucially important in shaping the present Mediterranean basin, as large portions of the seabed were exposed and coastlines were further seaward than at present. The cold peak in the MIS 4 $\delta^{18}O$ benthic records occurs between 67 ka and 63 ka (Spratt and Lisiecky, 2016), while MIS 3 can be generally constrained between 60 ka and 29 ka (Clark et al., 2009; Hughes et al., 2013). MIS 2 follows MIS 3 and ends chronologically with the beginning of the Holocene, 11.7 ka.

Several factors make investigations of coastal and marine processes (and sea level) during these periods difficult: i) the areas where suitable coastal geomorphic features or coastal sediments formed are currently submerged, often at depths of few tens of meters below present sea level, and their accessibility is therefore difficult; ii) the preservation of geomorphic features and sedimentary records is limited; iii) the dating of most deposits has been considered to be prone to methodological problems; iv) in places there is a lack of high resolution bathymetry and subsurface survey at the scale required to assess seabed conditions. This final point highlights the need for more submarine surveys and exploration.

In many areas, the ESL rise after the Last Glacial Maximum (LGM) eroded and reworked older stratigraphic and morphologic evidence, especially through the development of ravinement surfaces. Moreover, long periods of subaerial exposure altered and/or eroded pre-existing deposits and fluvial and aeolian processes, as well as weathering, soil-forming activity and karstification affected large sectors of the Mediterranean coastal areas. Recent work by Shtienberg et al. (2016, 2017) demonstrate how the study of the seabed, through marine seismic interpretation, paired with terrestrial geotechnical analysis, can be used to investigate the shelves that are now (partially) submerged, but which were previously uninterrupted landscapes, exploited by humans as a result of sea-level fall.

Because of the incomplete sea-level record in the Mediterranean Sea, data from other regions (e.g. the Red Sea, Tahiti) or a 'global eustatic' curve are commonly used for the period 116-20 ka (e.g. Imbrie et al., 1984; Bard et al., 1996; Waelbroeck et al., 2002; Rohling et al., 2008a). Moreover, a detailed history of ice-volume changes in the Mediterranean has been proposed only as far back as 35 ka (Lambeck et al., 2014), while geophysical models describing the sea-level evolution before 20 ka are not usually available for the Mediterranean Sea (Lambeck et al., 2011).

Isotopic analyses of speleothems in coastal caves in karstic areas can produce records of submergence and emergence. Along the eastern Adriatic, where the rocky coast consists of limestone (Pikelj and Juračić, 2013; Furlani et al., 2014b), more than 140 submarine caves with speleothems are known to exist, some of which have been studied for sea-level reconstructions (Surić et al., 2005, 2009, 2010). The deepest speleothems along the Croatian coast reach depths of -71 m near the island of Brač in southern Dalmatia (Garašić, 2006). In some other caves, speleothems formed during MIS 3 show evidence of subaerial formation and confirm that sea level was at an elevation lower than -40 m (Surić et al., 2005). Despite the potential of the eastern Adriatic, reliable constraints of RSL during MIS 4 and 3 remain lacking. Nevertheless, this and other karstic coasts of the Mediterranean are key areas for future research into Quaternary coastal evolution, early human populations, migration routes and coastal settlement and resource exploitation. Submerged caves have also been identified as a major opportunity for future archaeological prospection and submerged karstic regions throughout the Mediterranean are likely to yield well preserved organic material (Benjamin et al. 2011; Campbell 2017).

In ESL curves, a relative short-lived highstand occurred c. 52 ka at about ~-60 m (Shackleton et al., 2000). Three other sea-level fluctuations are shown for MIS 3, with amplitudes of 20–30 m and their peaks centered at about 55 ka, 45 ka and 38 ka respectively. At the transition to MIS 2, ESL fell at a relatively sharp rate to nearly -80 m, subsequently culminating in a lowstand between 29 ka and 21 ka, when ESL is usually estimated to be between -120 m and -140 m (Lambeck et al., 2014).

In the Po Plain, south of the present Po Delta, between -75 m and -25 m, cores containing deposits dated to MIS 4 and MIS 3 indicate alluvial environments in this long period (Amorosi et al., 2004). In the central Adriatic, geophysical surveys have found clear sedimentary traces of forced regressions occurring during the sea-level fall following MIS 5.5 (Ridente et al., 2009; Maselli et al., 2010; Pellegrini et al., 2017).

The formation and growth of the Alpine ice sheet during the LGM only minimally affected the eustatic curve because of its limited volume as compared to polar ice sheets (e.g. Lambeck et al., 2004a). Notwithstanding their limited effect on ESL, the glacial advances in the Alps and partly in the Dinarides and Pyrenees, strongly affected the general environmental conditions of the northern side of Mediterranean basin. In particular, the Po river dramatically enlarged its catchment basin during the marine lowstand (De Marchi, 1922; Maselli et al., 2010). Moreover, the fluvial systems of the southern Alps received enhanced sedimentary input supplied by glacial activity, allowing the widespread aggradation and progradation of alluvial fans and megafans, that prograded for tens of kilometres over the exposed shelf in the Adriatic (Fontana et al., 2014) and in the Gulf of Lion (Jouet et al., 2006).

The lowstand deposits produced by the Po River mainly consist of a sequence of prodeltaic deposits that prograded for 40 km in the foredeep basin and reached a maximum thickness of about 350 m in the Middle Adriatic Depression and of 70 m on the shelf (Trincardi et al., 2004; Pellegrini et al., 2017). Topset beds of the LGM delta can be recognised through geophysical soundings from a depth of -100 m and below, and this elevation is a constraint for the LGM sea-level position (Ridente et al., 2008; Trincardi et al., 2011a, 2011b; Amorosi et al., 2016; Pellegrini et al., 2017). In the Tyrrhenian Sea, submerged depositional terraces are documented at variable depths between -50 m and -200 m. Between -90 m and -150 m they are interpreted as the evidence of the LGM shoreline (Chiocci et al., 1997; Milli et al., 2016). Direct evidence of the LGM lowstand is known from offshore near Termini Imerese in northern Sicily, where a piston core collected a sample dated to 21.8 ka at a depth of -127 m (Caruso et al., 2011). Another location with LGM shoreline deposits has been found near the Asinara Island, in northern Sardinia, through grab sampling at a depth of -129 m; this yielded an age of 19.2 ka (Palombo et al., in press).

4.2 Human populations from MIS 4 to MIS 2

The period from the onset of MIS 4 to the MIS 2 was characterised globally by major and sometimes relatively rapid oscillations in temperature and ESL, changes that are documented around the Mediterranean (e.g. Almogi-Labin et al., 2009; Moreno et al., 2002, 2005; Shtienberg, et al., 2016, 2017).

The onset of MIS 4 brought hyperaridity in the Sahara, leaving potential refuges along the North African Mediterranean coast, such as Cyrenaica and the Maghreb (Garcea, 2012), and the advance of the ice sheets in northern Europe forced the contraction of human populations into southern European refuges (Van Andel et al., 2003). Many of these refuges were in coastal regions such as southern Iberia, Gibraltar (Jennings et al., 2011) and the Levant (Belmaker and Hovers, 2011; Bailey et al., 2008; Finlayson, 2008; Stewart and Stringer, 2012). Understanding the relationship between populations and coastlines is therefore a key to understanding the ways in which populations adapted to these shifting environments and the cultural changes we see in the archaeological record during this period.

This period of climatic instability documents significant biological and cultural changes around the Mediterranean basin. *H. sapiens* populations carrying late Middle Palaeolithic to early Upper Palaeolithic technology dispersed out of Africa into the Levant. By 54.7 ± 5.5 ka they had reached Manot Cave, Israel (Hershkovitz et al., 2015), spreading across Europe as early as ~45-43 ka (Benazzi et al., 2011) and, further afield (e.g. into Australia as early as *c.*55 ka; Hiscock 2008). It is possible that these *H. sapiens* populations interbred with Neanderthals in the Levant between 65-47 ka (Sankararaman et al., 2012). Neanderthal populations had almost disappeared by 41-39 ka (Higham et al., 2014). However, a population of Neanderthals in Iberia/Gibraltar persisted to at least 28 ka (Finlayson et al., 2006). In North Africa, the spread of Upper Palaeolithic (UP) / Later Stone Age (LSA) technology was not accompanied by the spread of a new species as the region was already occupied by *H. sapiens* populations and our understanding of the mechanisms of this spread remains poorly understood. Genetic evidence may suggest a migration of *H. sapiens* populations from southwest Asia between 40–45 ka, utilising the southern Mediterranean coast to move into North Africa from the Levant (Olivieri et al., 2006). The current available data for the region, however, remain insufficient to confirm this hypothesis. It is, however, clear that UP/LSA industries are present after 43 ka in Cyrenaica at the Haua Fteah, Libya (Douka et al., 2014), and 30–29 ka onwards in the Maghreb at the Grotte de Pigeons, Taforalt, Morocco (Barton et al., 2007).

These population movements and cultural changes took place when sea level was far below that of the present day in areas with low-lying shelves. In areas where narrow continental shelves existed, sea-level change would have had little impact on travel times to the coastline and coastal resources were still exploited as they had been during MIS 5 (Colonese et al., 2011). In Gibraltar, at Gorham's and Vanguard caves, Neanderthals exploited marine mammals and molluscs during MIS 3. The quantity of marine shells and other marine indicators in these caves is limited, but there is no evidence that it was any greater in the Upper Palaeolithic levels, indicating a consistent level of exploitation through the Late Pleistocene (Brown et al., 2011; Stringer et al., 2008). Exploitation of marine molluscs at the Haua Fteah, Libya is low during the late MSA/Early LSA levels (Klein and Scott, 1986), but this may be due to a more ephemeral occupation at the site during these periods.

Shell beads were manufactured in large numbers in the Upper Palaeolithic layers at Üçağızlı Cave II in southern Turkey (#13 in Figure 1) between 40–23 ka (Stiner et al., 2013) and became a feature of Upper Palaeolithic contexts across Europe (Bar-Yosef 2002). Evidence for Neanderthal shell tool manufacture in MP contexts, focussed on *Callista chione* and *Glycymeris sp.* shells, continued until around ~50 ka (Douka and Spinapolice, 2012). Examples of retouched shell tools, produced by Neanderthals before 40 ka were found in Kalamakia Cave, Greece (#14 in Figure 1; Darlas, 2007; Douka and Spinapolice, 2012).

Isotopic analysis suggests that *H. sapiens* from across Europe exploited marine and freshwater resources between 40–24 ka, with freshwater fishing at Pe⊠teracu Oase (#15 in Figure 1), Romania, potentially accounting for high nitrogen values in the Oase 1 individual (Richards and Trinkaus 2009). Whilst there is some evidence for pelagic fish exploitation on a global scale (ie. from 42 ka in Jerimalai, East Timor;

O'Connor et al., 2011), there is little direct evidence that marine fishing was carried out in the Mediterranean until the late Palaeolithic and Late Glacial (Stiner and Munro 2011) (see section 5.2). Whilst in Haua Fteah, northern Libya (#5 in Figure 1), important coastal records for this period were preserved above modern sea level due to their geographic setting, the now submerged landscapes and coastlines accessible during MIS 4 and the LGM are one of the main areas where future research must focus.

Underwater archaeological prospection for Palaeolithic sites and artefacts may be more difficult than that of later periods given the nature of the record left by hunter-gatherer populations, prior to sedentism. The archaeological signature is mostly void of recognisable architectural remains and the sites themselves ephemeral in nature. However, recent discoveries by archaeologists working in the Atlantic at La Mondrée off the coast of Normandy illustrate that artefacts from these periods can be preserved (Cliquet et al., 2011), and that the records of human movement and occupation in coastal areas during this period were not necessarily destroyed by late glacial and Holocene sea-level rise (Flemming et al., 2012; Stanford et al., 2015). In deeper water the probability of recovering significant submerged traces of prehistoric activity is limited by the fact that those environments were above sea level and habitable for shorter durations. Thus, there is higher probability of tracing submerged remains of later human occupations in shallower waters, than those from earlier periods in deeper waters. This should not be confused, however, with any notion that such deeper, older sites would be less significant archaeologically. In fact, future interdisciplinary research undertaken by archaeologists and marine scientists may further demonstrate the value of submerged Pleistocene sites.

As well as presenting a taphonomic challenge to archaeologists wishing to trace past coastal occupation, lower sea levels during MIS 4 and MIS 3 would have exposed landscapes that may have been crucial to the movement and occupation of areas of the Mediterranean. Although seafaring probably did not develop until after the LGM (Broodbank, 2006), lower sea levels would have connected many present-day islands, and reduced the distance between others, making them accessible via short crossings (Phoca-Cosmetatou and Rabett, 2014a). Large areas of exposed land also provided new opportunities for populations to migrate, for example in the northern Adriatic, where a large plain was exposed during periods of low sea level (Correggiari et al., 1996; Spry-Marqués 2012).

New investigations of the landscape submerged since the LGM, alongside further research in areas where sea-level change had little impact on the position of the coastline, are therefore needed in order to better understand human-coastal interactions around the Mediterranean rim, and their implications for global histories. In particular, rescue surveys and research operations should be considered as a priority by heritage managers in places where coastal and underwater erosion and development activities may adversely impact submerged prehistoric remains. The European Marine Board has published a position paper (Flemming et al. 2014) which highlights the strategic need to better understand and manage submerged landscape archaeology, from the Palaeolithic through later periods and has identified the concern of preservation and modern threats to underwater archaeology.

5. Significant palaeoenvironmental phases of the Upper Pleistocene

In this short section, we digress to provide a short overview of the main environmental events or phases which occurred in the Upper Pleistocene, discussing their main characteristics and chronology. It is important that archeaologists are aware of the major environmental changes that occurred during the Late Pleistocene, even if they are not directly linked to changes in sea level. The period between MIS 5 and MIS 2 has been characterised by the occurrence of some climatic and environmental variations with a relatively short duration (i.e. from decades to few millennia). Parts of these fluctuations are clearly recorded in the Mediterranean and, even if some of them are not directly related to coastal change, they affected the evolution of the basin and its environmental and oceanographic settings. Thus, part of these short-lived variations could have impacted on past human populations. Some of the palaeoenvironmental fluctuations generated marker layers in the stratigraphy or left their signature in other proxy records, allowing the cross correlations between different archives and regions, with potential applications in coastal and maritime archaeology.

In the eastern Mediterranean, the depositional sequences of deep waters are characterised by the quasi-cyclical occurrence of dark layers, rich in organic carbon, called 'sapropels' (Negri et al., 2012; Rohling et al., 2015; Grant et al., 2016 and reference therein). They correspond to hypoxic or anoxic episodes that are recorded east of the Sicily Strait (Figure 1) and during which oxygen starvation occurred in deep basins and caused the collapse of the deep ecosystems, but affected the entire water column (e.g. Cramp and O'Sullivan, 2001). The most recent sapropel has a Holocene age (Figure 7), while another 4 sapropels are documented during the Late Pleistocene (Figure 4). In different parts of the Mediterranean they can display some noticible differences in their age limits and duration (De Lang et al., 2008; Grant et al., 2016). The causes that led to the sapropel formations are still a question of debate, but their deposition was influenced by astronomical forces and generally correspond to periods of enhanced monsoon rainfall (e.g. Rossignol-Strick et al., 1982; Grant et al., 2016). In the late Quaternary, the sapropels generally caused notable sedimentation during periods of major fresh-water input, probably in connection with enhanced discharge of the Nile River linked with monsoon activity (e.g. Rohling et al., 2015).

During MIS 4 and especially MIS 3, several rapid climatic variations occurred. Among these fluctuations, the so-called Heinrich Events (HEs) are of particular importance, because they represent global climatic episodes that are widely recognised in many archives of the Upper Pleistocene (e.g. Hemming, 2004; Lisiecky and Stern, 2016). The HEs correspond to periods of important collapse of the ice shelves of the northern hemisphere, which caused the release of massive cold fresh-water inputs in the North Atlantic and induced a sensitive drop in the sea surface temperature (Hemming, 2004; Naughton et al., 2009). HEs have been noticeably recorded in the Alboran Sea (Cacho et al., 1999), while their footprint is not clearly evident in the central and eastern Mediterranean (though for further discussion see Wulf et al., 2004). In the eastern and central sectors of the Mediterranean Basin a peculiar role is played by HE4, which occurred ca. 39 ka. It overlaps with the Laschamp geomagnetic excursion (Tric et al., 1992) and is contemporaneous with the eruption that generated the Campanian Ignimbrite ca. 39.3 ka (De Vivo et al., 2001). This volcanic event, which originated in the Campi Flegrei area in southern Italy, represents one of the largest late-Quaternary eruptions in Europe and the related tephra has been recognised in many marine cores and continental sequences (Fedele et al., 2008). Another well-recorded volcanic episode produced by the same volcanic area is represented by Neapolitan Yellow Tuff (ca. 14.5 ka), but also some tephra layers related to the explosive activity of the Hellenic

Arc are important in the eastern Mediterranean, such as the Cape Riva tephra from Santorini Island (ca. 22 ka, Wulf et al., 2002).

Apart from the catastrophic events themselves, layers of non-visible ash (cryptotephra) are relatively diffuse in the marine cores and their occurrence provides a correlation between marine and terrestrial archives at a Mediterranean and European scale (e.g. Lowe et al. 2007; Bourne et al., 2010; Davis et al., 2012). Moreover, tephra layers are a major tool in the chronostratigraphy of MIS 3 and previous periods, because they can be independently dated through isotopic geochemistry (e.g. $^{40}Ar/^{39}Ar$; K/Ar). This is of particularly value for the deposits older than 40 ka, which can be difficult to date because they are at the boundary or radiocarbon dating, compounded with the marine reservoir effect of the biogenic fossils (i.e. shells, foraminifers), which is generally unknown for this period. Tephra stratigraphy may also have applications to coastal and maritime archaeology, especially for correlating in time human occupation sites across the Mediterranean and beyond.

6. LGM through the early Holocene

While we respect a need for consistency in general, for the Holocene (starting at ca. 11,700 BP) we intentionally change the dating conventions, from thousand years ago (ka) to calibrated years before present (BP), which facilitates the discussion of the links between archaeology and coastal geomorphology in the Holocene.

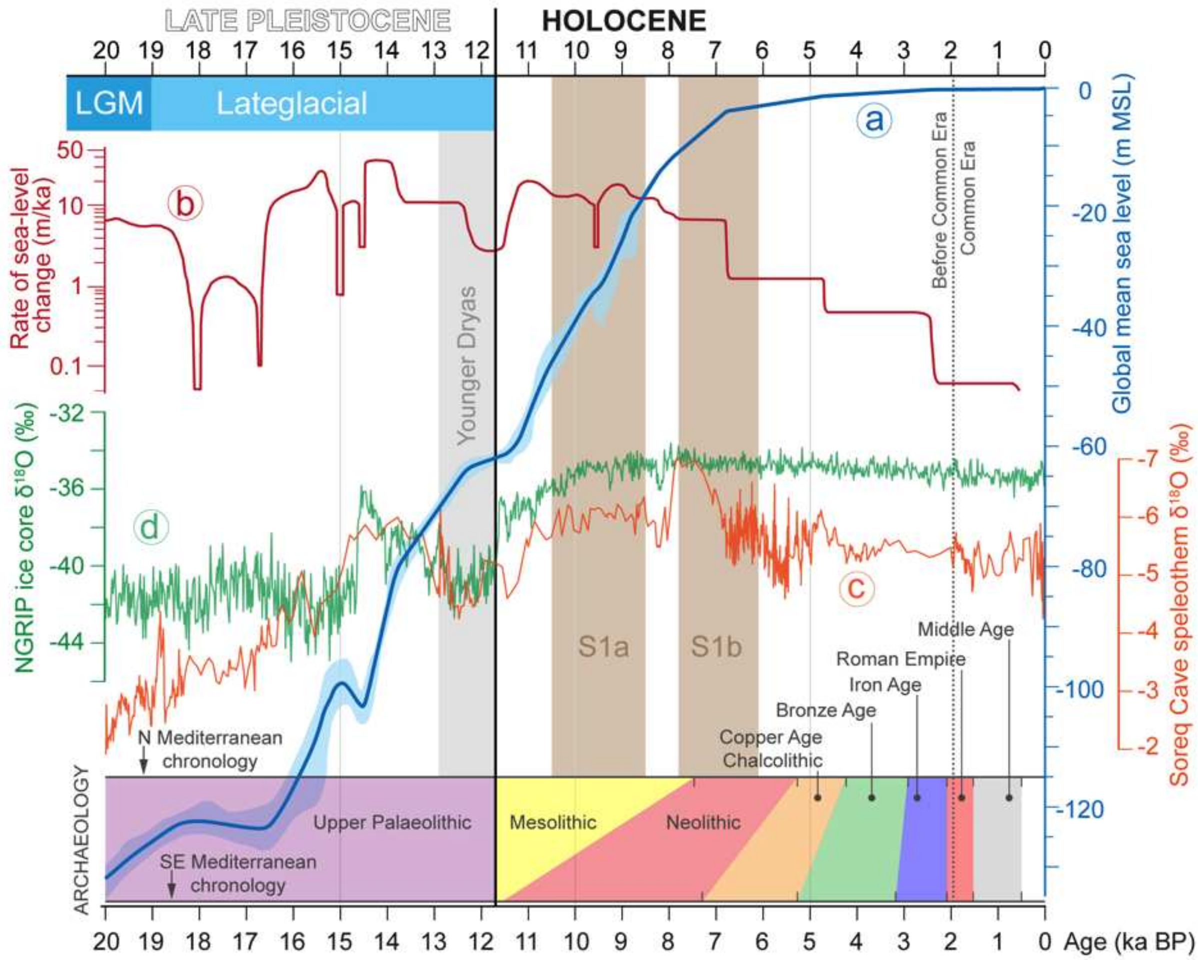

Figure 7. Comparison between the reconstructed curve of global mean sea level and palaeoclimate, palaeoenvironmental and archaeological data for the Mediterranean Sea in the last 20 ka. a) Global mean sea level curve with indication of the uncertainty shown in pale light blue (Lambeck et al., 2014); b) rate of sea-level change (Lambeck et al., 2014); c) δ18O composition of the Soreq Cave speleothem; d) δ18O composition of NGRIP ice core (NGRIP members, 2004). Brown shading indicates the period of deposition of sapropel1 (Rohling et al., 2015). The durations of the main archaeological phases are reported in the lower portion of the plot, according to the general chronology of south-eastern and northern Mediterranean (cf. Broodbank, 2013).

5.1 Sea level

Since the end of the Last Glacial Maximum (LGM), significant volumes of meltwater have been released into the global oceans as a consequence of ice sheets melting, resulting in a global sea-level rise of about 120 m (Fairbanks, 1989; Edwards, 2006; Clark et al., 2009). Sea level rose during the period between 19 ka – 7000 BP by a mean rate of 10 mm/yr. Although the rise is measured generally to have been consistent and sustained, at least two major punctuated episodes of ice melting are known. The first significant addition of meltwater may have started about 19 ka when ocean levels rose 10–15 m in less than 500 years (Clark et al., 2004). An even more significant phase of accelerated sea-level rise, known as Meltwater Pulse (MWP) 1A. The exact timing of this event and the magnitude of the pulse have been subject to debate. Weaver et al. (2003) reported that MWP-1A occurred between 14.6-13.5 ka when global sea level may have increased by as much as 16 to 24 metres. Other studies have suggested sea-level rise during MWP 1A of 20 metres during the period between 14.3-13.8 ka, sourced from both the Laurentide and Antarctic ice sheets (Bard et al., 1996, Clark et al., 2002; Rohling et al., 2004; Siddall et al., 2010). Deschamps et al. (2012) dated MWP-1A to 14.65-14.31 ka with sea levels rising 14-18 m, coincident with the Bølling warming in the Northern Hemisphere. They suggested that the rate of eustatic sea-level rise exceeded 40 mm/yr during MWP-1A (Deschamps et al., 2012). That rate of change would be noticeable by humans living in coastal areas during a single generation, particularly in low-lying areas and especially where coastal resources were a significant source of dietary protein, fuel and other aspects of economy.

The last deglaciation was abruptly interrupted by the Younger Dryas event, which began approximately 12.8 ka. In this short interval the rate of sea-level rise slowed, as documented in Tahiti (Bard et al., 1996, 2010), the Huon Peninsula, New Guinea (Edwards et al., 1993; Cutler et al., 2003), Vanuatu (Cabioch et al., 2003), and Barbados (Peltier and Fairbanks, 2006), consistent with the overall cooling in the Northern Hemisphere.

In the Northern Adriatic, the slowdown led to the formation of the well developed deltaic complex of the Po River. This sedimentary body is partly preserved at a depth around -40 m between 40–60 km offshore of the city of Ravenna (Correggiari et al., 1996; Cattaneo and Trincardi, 1999). Slightly north of this area, lagoon-barrier systems were formed under transgressive conditions during the early Holocene. RSL indicators dating to the interval 11,000 – 10,000 BP are found between -38 m and -35 m (Moscon et al., 2015). Some lagoonal deposits dating to 10,000 – 9500 BP are found near the coastline of the present Po River mouth (Amorosi et al., 2008), and in other sites, at -30 m (Correggiari et al., 1996; Trincardi et al., 2011b). The transgression of the Adriatic reached the area of Trieste by approxiately 9000 BP (Antonioli et al., 2009; Trincardi et al., 2011b).

The early Holocene sea-level rise was probably punctuated by smaller meltwater peaks due to the episodic deglaciation of the Laurentide Ice Sheet (Carlson et al., 2008). For example, a multi-millennial interval of enhanced rates of sea-level rise between 11,000 – 8800 BP included a probable peak rate of rise of 13-15 mm/yr (67% confidence) at around 9500 BP (Stanford et al., 2011). The 8.2 ka cold event may have been preceded by a sea-level jump of one or two metres (Törnqvist and Hijma, 2012) that also affected the Mediterranean Sea. Some have argued that this flood led to the sudden loss of farming land and the abrupt migration of some Neolithic groups (Turney and Brown, 2007).

5.2 Human populations during the early Holocene

The transition from the LGM to early Holocene saw major changes to both coastal landscape evolution and human populations. The Neolithic transition, or ‘Neolithisation’ process, can be described as a cultural shift beginning with the emergence of agriculture and animal husbandry; it is one of the pivotal developments in human evolution, comparable in scale with language, tool use and bipedalism (Zeder, 2006). This is particularly relevant to the Mediterranean Basin, which is thought to have played a significant role in its spread, coinciding with a period of rapid sea-level change and the Neolithisaion process, which begins approximately at the transition between the terminal Pleistocene and the beginning of the Holocene in the Levant.

The scope and span of the area in question and the inevitable research bias resulting from the much greater studied northern coastlines of the Basin makes a survey of this period feel naturally incomplete. Nevertheless, sufficient historical interest and data have been generated to enable some overview synopses across the region’s coastal zones, though mainly through European material. The Neolithic emerges from the Epipalaeolithic (as it is referred to in the Levant) and the Mesolithic (as it is known in European archaeology).

Summarising the coastal Mediterranean populations of the European Mesolithic, Pluciennik (2008) points out that the Mesolithic begins and ends in a somewhat arbitrary way; it is a transitional period that generally describes the last hunter-gatherer groups, or the pre-farming/agricultural communities of the early Holocene approximately 13,000 – 9000 BP in the Mediterranean region (and progressively later in an east-west direction as well as a north-south direction from its origin in the middle east). This period saw dramatic change in both the cultural and environmental records, with much debate centred around cause-and-effect of this human-environment interaction and, possibly what is described as environmental determinism (see Wright, 1993). Avoiding the intricacies of such debates here, it will suffice to say that during a time when postglacial sea-level rise was relentlessly redrawing the coastlines of the Mediterranean map, so too were dramatic changes taking place amongst the cultural practices of the people who occupied the region.

Sea-level rise changed the physical landscape, inundated coastal sites, displaced fishing and shellfishing grounds and created isolated environments in the form of new islands, bays and straits, which would have been culturally occupied throughout these processes of evolution and occasionally punctuated events of both eustatic and tectonic origin. Questions surrounding the apparently low population of the late Mesolithic, which has left little archaeological signature across entire regions of the coastal Mediterranean landscape (e.g. Forenbaher and Miracle, 2005) may be answered, in part by underwater archaeology (Fitzpatrick et al., 2015: 3), though this has only begun to scratch the surface of potential in the Mediterranean (cf. Galili et al., 1993, Galili and Rosen, 2011; Bailey and Flemming, 2008; Ammerman et al., 2011; Benjamin et al., 2011; Flemming et al 2014).

The classic debates by archaeologists in the 20th century centred on the Mesolithic-Neolithic transition and often focused around the questions of demic diffusion (e.g. Ammerman and Cavalli-Sforza, 1971), or modified versions of demic diffusion (e.g. Van Andel and Runnels, 1995), which described the migration of people in the form of a ‘wave of advance’ model hypothesis (for clarification see Ammerman, 1989). This was opposed to the transmission of cultural practices, including indigenous adoption of new ‘technology’ and substance by existing populations. Theories generally posit that incoming populations replaced or advanced from the southeast and east, or via a ‘leapfrog’ process by maritime pioneers, an idea popularised by Zilhão (1997, 2001). Much focus has been placed on domesticated flora and fauna, however other indicators have also played a key role in establishing cultural typology, particularly pottery. Budja (2009) provides a historical overview on this topic and compares results with genetic data as this technique was becoming popularised in the last decade. Population expansion is often at the centre of these debates, with many discussions related to a decline in late Mesolithic population (e.g. Van Andel and Runnels, 1995; Forenbaher and Miracle, 2005). The archaeological discussion has sometimes centred on whether late Mesolithic populations were reduced significantly in numbers prior to the arrival of Neolithic people or the Neolithic cultural ‘package’ (or marker components of the package), or whether the archaeological signatures for those cultures pre-dating the Neolithic have largely not survived. Some have argued that the notion of a single migration is in itself incorrect and that repeated dispersals, each replacing the previous, would have been a more likely scenario (eg. Zevelebil and Zevelebil, 1988).

It is now generally accepted that the extended process, which saw the human inhabitants of the Mediterranean basin during the early Holocene shift from a subsistence model of hunter-gatherer to herder-farmer, can be considered a complex and dynamic process which took some three millennia to complete its course along Mediterranean coasts (Zeder, 2008, Figure 2) and which has even been characterised as a ‘mixed migrationist/diffusionists model’ (Richards, 2003). Recent focus has shifted away from early models of a steady ‘wave of advance’ popularised by Ammerman and Cavalli-Sforza (1971), which predicted an annual rate of the westward spread of the Neolithic package, mainly domesticated plants and animals. Studies of demography (e.g. Bocquet-Appel, 2011), burial practices (e.g. Hershkovitz and Galili, 1990) as well as those focused on early herding (e.g. Mlekuz, 2003), have continued to make a significant contribution to the key debates. Such discussions also have been impacted by recent studies in ancient DNA (e.g. Richards, 2003; Haak et al., 2010; Skoglund et al., 2012).

Early maritime voyages have also been suggested to have played a key role in pre-Neolithic life in the eastern Mediterranean (Simmons, 2007). Other island colonisation debates remain unresolved. Antonioli et al. (2014) suggested that the earliest presence of *H. sapiens* on Sicily coincided with the land-bridge connection during the LGM. Palombo et al. (2016), on the other hand, found that the oldest *H. Sapiens* from Sardinia is dated to 8500 BP. Colonisation of uninhabited islands aside, it can be difficult to establish the extent of impact the rising sea-levels had on past societies when much of the archaeological record has been lost, or remains under water, undiscovered. For example, Van Andel and Runnels (1995) reject that a large coastal Mesolithic population could have existed, in their example, along the Black Sea coast. They regard the “complete wipe-out” of coastal Mesolithic cultures as “implausible” (Van Andel and Runnels, 1995, 481). While well known specialists are eager to point out the likelihood of Mesolithic marine resource exploitation leading to increased coastal and riverine populations, including potentially sedentary communities (e.g. Zvelebil and Zvelebil, 1988; Richards, 2003), they have often stopped short of considering the true impact of Mediterranean sea-level rise which may have preserved material of this nature, as it has done in the Baltic Sea (e.g. Fischer, 1995). Indeed, materials have been preserved of Bronze Age (e.g. Henderson et al., 2011), Copper Age (i.e. Chalcolithic/Eneolithic; Benjamin et al., 2011), and early Neolithic period (Galili and Nir 1993).

The Zambratija Bay site, in northern Croatia, (#17 in Figure 1), which remains to be explored in detail, represents a submerged settlement in the northern Adriatic (Benjamin et al., 2011, Fig 16.4). It is still unclear as to why the site was abandoned, though early indications do not exclude sea-level rise as a direct cause. The site represents an important opportunity in this respect, and further, detailed study will be required to resolve the abandonement question (Benjamin and Bonsall, 2009; Benjamin, 2010).

The Grotta Verde in Sardinia (Italy, #24 in Figure 1) has yielded submerged archaeological material in the form of cardial ceramics at -10m depth and human remains at -8 m (Antonioli et al., 1996) in what appears to be a submerged grave, dated to approximately 7300 BP (Figure 8).

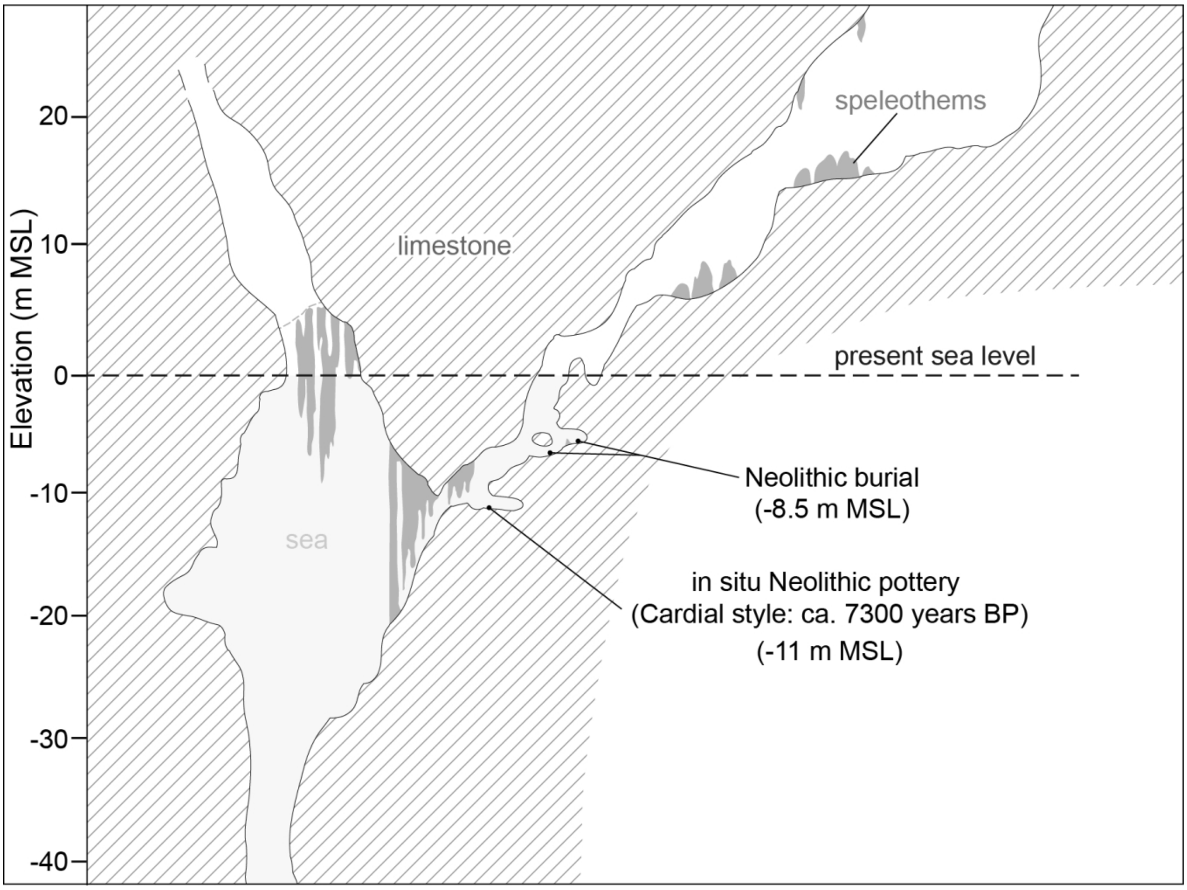

Figure 8. The Grotta Verde (Green Cave), Sardinia, Italy. Submerged Neolithic material was located associated with associated human remains in what appears to have been a ritualised burial in the cave prior to innundation (after Antonioli et al., 1996; Palombo et al., 2016).

The oldest submerged Neolithic site known in the Mediterranean, Atlit Yam in Israel, dates to 9000 BP and is contemporaneous with much of the Mesolithic hunter-gather societies occupying central, western and northern Europe at that time (Galili et al., 1993; Galili and Rosen 2011). The Pre Pottery Neolithic C (PPNC) site is located in an area 200 to 400 m offshore, at -8 to -12 m in the North Bay of Atlit (Galili and Nir, 1993) and radiocarbon determinations range from 9250–7970 BP. Excavations have revealed human burials, rectilinear structures and rich assemblages of implements made on flint, stone, bone and wood, as well as faunal and floral remains (Galili and Rosen, 2011). The village economy was based on hunting, herding, fishing and agriculture.

A further six settlement sites from the later Pottery Neolithic belonging to the Wadi Rabah culture were also discovered on the Israeli Carmel coast. These sites, dated to the 8th millennium BP, are located close to the present coastline at a depth of 0 to –5 m (Galili and Weinstein-Evron, 1985; Galili and Nir, 1993; Galili and Rosen, 2011). The Kfar Samir well indicates that during the Pottery Neolithic, some 7000–8000 years ago, sea level on the Carmel coast was at -9 to -10 m (Figure 9). The archaeological studies of the Carmel Coast indicate that sea level rose from -35 m to -7 m between 9000–6500 BP, at an average rate of 11 to 13 mm/yr. This demonstrates how the coastal Neolithic population was responding to the rising sea level as the older settlements were abandoned and new sites were established landward.

The early Neolithic village at Atlit Yam (Galili et al.,1993; Galili and Rosen, 2011), and the Neolithic and Chalcolithic material from Grotta Verde and Zambratija further demonstrate the potential of submerged archaeology to contribute significantly to prehistory and sea-level studies as foreseen by Masters and Flemming (1983) in their benchmark interdisciplinary volume *Quaternary Coastlines and Marine Archaeology*. Increased research into coastal and submarine geomorphology and archaeologicy will continue to increase knowledge of the significant environmental and cultural transitions which took place throughout the early and middle Holocene.

Figure 9. Archaeologist (E. Galili) records a Pottery Neolithic water well at the Kfar Samir site (dated to ca. 7000 BP), now submerged at a depth of -5 m. Such archaeological sites are useful indicators of sea-level change and provide limiting dates for transgression. (Photo: J. Benjamin)

7. Middle and late Holocene

7.1 Sea level

Evidence for middle and late Holocene sea-level changes in the Mediterranean are based on geomorphological evidence (such as tidal notches and beachrocks), fixed biological indicators (such as coralline algae, boring molluscs, oyster beds and the fixed vermetidae *Dendropoma petraeum*) and archaeological indicators. The most precise sea-level indicators are specific types of fixed biological indicators (Laborel

1996; Laborel and Laborel-Deguen, 1994; Morhange et al., 2001; Sivan et al., 2010; Rovere et al. 2015).

Holocene sea-level curves have been constructed in Italy (e.g., Lambeck et al 2004a, 2011), Croatia and Slovenia (e.g., Antonioli et al., 2007; Faivre et al., 2013), southern France and Corsica (e.g., Laborel and Laborel-Deguen, 1994; Vacchi et al., 2016a); Turkey (Anzidei et al., 2011a), Greece (e.g., Pirazzoli, 2005; Vött, 2007; Pavlopoulos et al., 2011; Vacchi et al., 2014; Mourtzas et al., 2016; Kolaiti and Mourtzas, 2016; Mourtzas and Kolaiti, 2016) Tunisia and Libya (Anzidei et al., 2011b), the Aeolian Islands (Anzidei et al., 2014a; 2016), Israel (Sivan et al., 2001; 2004, Toker et al., 2012; Anzidei et al., 2011b; Galili et al. 1988, 2005) and Lebanon (Morhange et al., 2006; Sivan et al., 2010).

Data collected from tectonically stable regions, some charachterised by negligible isostatic effects (Sivan et al., 2001; 2004; Toker et al., 2012) for the last 4000 years, indicate that sea level was close to present levels by 4000–3600 BP (Galili et al., 2005; Galili and Sharvit 1998; Porat et al., 2008). Depending on the location in the Mediterranean, RSL fluctuated either below or slightly above the present since that time (Sivan et al., 2004; Toker et al., 2012; Vacchi et al., 2016). As an example, RSL along the coastlines of Israel rose from -7 m to the present level at a rate of 2.5 to 3.5 mm/yr between 6800–4000 BP. At the same location, RSL was approximately between -2.5 m and -5 m during the Chalcolithic period (6000–5700 BP). By the Middle Bronze Age (~4000 BP) the sea had reached its present level and the coastline reached its current form. Since then, RSL has been relatively stable with possible fluctuations of no more than 0.5 m vertically (Galili et al., 2005, Sivan et al., 2001, 2004; Anzidei et al., 2011a). A recent notch study by Goodman-Tchernov and

Katz (2015) does however question this stability and theorises that a more punctuated rise may have occurred during the Holocene.

Although the Mediterranean basin lies beyond the direct influence of ice sheets, ice-sheet loading had a pronounced effect on the shape of Mediterranean sea-level curves. This is seen in the output of GIA models, which produce lower sea levels when ice loading is increased (e.g. Lambeck and Purcell, 2005; Stocchi and Spada, 2009). In the eastern and southern regions of the Mediterranean, the ice-loading effect is least significant and along coasts where tectonics can be discarded (e.g. Lybia) the regional sea level approximates the global eustatic value (Milne and Mitrovica, 2008). In most of the Mediterranean, water loading (hydro-isostasy) is an important contributor to middle and late Holocene relative sea-level change, but because the glacio-isostatic signal is of the opposite sign, middle Holocene sea-level highstands are not found across most of the Mediterranean basin (Lambeck and Purcell, 2005; Stocchi and Spada, 2007). An exception is the coast of the Gulf of Gabes (Tunisia), where it has been proposed that relative sea level between 6000–5000 BP was close to +1.5 m (Mauz et al., 2015a, 2015b; Vacchi et al., 2016b; Morhange and Pirazzoli, 2006). This highstand is correctly predicted by the GIA model of Lambeck and Purcell (2005), but their predicted highstand in the northern Adriatic, supposedly due to the Alpine glacial load, is not supported by sea-level field data (e.g. Antonioli et al., 2007; 2009).

7.2 Human populations: protohistory and urbanisation

The end of prehistory and the beginnings of urbanisation in the eastern Mediterranean have yielded an extensive record of archaeological sites and material. For a recent and comprehensive overview, Broodbank (2013) has devoted multiple chapters of the *Making of the Middle Sea* to these periods of intense development, innovation and technological and cultural changes. Broodbank's recent work is also significant to this discussion because it is a mainstream archaeological text that focuses heavily on maritime peoples, their way of life and relationship with the sea, past and present. It also draws upon evidence from the submerged sites discussed in sections above and serves to highlight that submarine geoarchaeology has become indispensably linked to the terrestrial record. This current section, therefore avoids an impossible attempt at a comprehensive review of all Mediterranean coastal archaeology. Here we focus on human-sea-level interaction, and highlight representative sites from across our geographical and temporal remit.

The Protohistoric coastal structures of the Mediterranean Basin and their archaeological signatures, have suffered from the development of later societies: many sites were destroyed, incorporated or generally transformed the pre-existing archaeological evidence. In particular, widespread diffusion and large stone construction (especially during the Classical periods) have resulted in the loss of the protohistoric features, through human reuse and recycling of materials. Thus, information on sea levels in the Bronze and Iron Age based on coastal settlements' remains is not as well documented as in later periods and is often related to a few selected sites, as in the case of the harbour of Marseille (Morhange et al., 2001), the Northern Cyclades, the central and eastern Crete (Mourtzas and Kolaiti, 2016; Mourtzas et al., 2016), or along the coast of modern day Israel (Sivan et al., 2001). The rare finding of a protohistoric vessel that would have entered a harbour might offer an extraordinary window on maritime life and seafarers ways (e.g. Uluburun in Turkey, #25 in Figure 1; Bass et al., 1986), however shipwrecks of the open seas do not provide good indication of past sea levels. Conversely, relicts of beached or abandoned vessels (particularly vernacular vessels used for every day short-range activity), which can be confidently determined to have been left at or near sea level at the time, may contribute information related to sea level and environment.

Once the Holocene sea-level rise had slowed down, various areas throughout the eastern Mediterranean continued to undergo significant regional and micro landscape changes owing to adjustment in land level caused by tectonic activity. The Bronze Age site at Pavlopetri (Greece, #27 in Figure 1), was first investigated in the 1960s for its archaeological implications and for its contribution to sea-level studies in the Peloponnese (Flemming, 1978) and later revisited and systematically mapped by Henderson et al. (2011). The changes in landscape around similar coastlines would certainly not have gone unnoticed by local populations and oral traditions are likely to persist in the region’s modern collective memory.

During the Middle and Late Bronze Ages (ca. 3600 – 3100 BP) of northwestern Adriatic, society flourished along the rims of the lagoons of Venice, Carole and Grado-Marano. Villages developed on slightly elevated fluvial ridges entering in the lagoon, and also on salt marshes. Several archaeological structures constrain sea level to -3.0 ± 0.6 m around 4000 BP and -2.0 ± 0.6 m at 3000 BP (Fontana et al., 2017). This symbiotic relationship between lagoon and dwelling sites existed in the area also in the Iron Age, as clearly depicted in the 1st century BC by the geographer Strabo in his description of the cities of the Venetian people, that “stand in the midst of water like islands, others are only partially surrounded. Such as lie above the marshes in the interior are situated on rivers navigable for a surprising distance” (Strabo, Geografia, V, 1, 5). Thus, it seems that the settlement system of the Bronze Age represents the early evidence of an Adriatic culture strongly related to the brackish environments. This was later developed in the same area during the Iron

Age and the Roman period with the harbour cities of Aquileia, Concordia Sagittaria, Altinum, Adria, Spina and Ravenna (#22 in Figure 1), and later, during the early Middle Age, by Venice and its Republic.

While submergence occurred in some parts of the world due to tectonics or loading of the underlying deltaic sediments, other coastal cities from the same periods are now positioned several kilometres inland as a result of river sedimentation. Sites such as Troy (Kraft et al., 2003), Miletus (Brückner et al., 2006), Liman tepe (Goodman-Tchernov et al., 2009b), and Acco (Morhange et al., 2016) provide such examples. There, the slowing of sea-level rise allowed the build-up of alluvial sediment that ultimately closed these anchorages and proto-harbors, leaving the settlements some distance from the sea. Liman Tepe, located in the Bay of Izmir, Turkey, for example, has indications for a large bay that closed just before the construction of an archaic harbour on the new shoreline. Today, the presence of those features and settlements are useful markers for reconstructing the process of coastal progradation and its relation to sea-level change.

Sites lost to the sea due to subsidence and tectonic activity are not unique to prehistory and as noted by Broodbank (2013) ‘the end of the beginning’ or the emergence of classical periods, saw entire cities submerged. The now well known ‘sunken cities’ of Egypt (Robinson and Goddio, 2015; see also Stanley and Bernasconi, 2007) are also in contrast to the earlier site at Pavlopetri (Late Bronze Age), because they appear to have been submerged during a period of their flourishment, and not after their abandonment. The cognitive impacts on lost habitat would have differed from that of earlier periods, particularly pre-Neolithic settled societies; the scale of these proto-urban and fully urban submerged sites would have resulted in a much greater cumulative impact than during the Neolithic or earlier periods, due to population size and overall settlement scale. Imprints on the collective histories, both oral and written, relating to sea levels, land loss, and their practical and spiritual impacts require increased consideration by the archaeological community for both fully sedentary and mobile societies.

8. Archaeological RSL indicators

Archaeological indicators of RSL are most precise when they can be associated with the biological remains of organisms living in close connection with tidal ranges. A classic example of such remains used by geoscientists and archaeologists alike, is that of barnacles (*balanidae*) which once clung to the inside harbour walls and other fixed structures (e.g. in Marseille, France, Morhange et al., 2001). Classical and historic archaeological features can be useful palaeo-sea-level indicators, however those from earlier prehistory tend to be less precise and less common, particularly those from hunter gatherer contexts (e.g. shell middens, cave deposits). But sea level and geomorphic impacts upon these earlier societies (and the human responses they resulted in) are no less important – and can inform on debates such as dispersals, migrations, and even the development of capabilities such as sea faring.

Figure 10. Archaeological features partially submerged at Caesarea, Israel. While harbor features are useful sea-level markers, it is important to understand the original function and position of the features. (Photo: B. Goodman-Tchernov).

8.1 Early, middle and late Holocene archeological sea-level indicators

Archaeological evidence for early and middle Holocene sea-level rise is found throughout Europe (e.g. Benjamin et al., 2011), but excellent examples are found in the Mediterranean Sea, especially the Neolithic sites of the Carmel Coast of Israel. Though the submerged Neolithic (described above) is relatively sparse compared with later periods, it is very informative for sea-level studies. Its settlements and burial sites provide evidence of ancient populations, and in some instances, how people coped with environmental changes and their response and resilience to coastline shifts and sea-level rise (Galili and Rosen 2011).

In the later Holocene, direct evidence of submerged terrestrial land surfaces and many types of archaeological features associated with the coastal and marine environment can be used as highly accurate sea-level indicators (e.g. Morhange and Marriner, 2015). Keys to the successful application of any archaeological element to reconstructing past sea levels are: (i) careful measuring of the site elevation relative to the present sea level; (ii) the definition of the site function, and (iii) determining its association with the sea level in the past (e.g. Blackman, 1973; Flemming, 1969; Galili et al., 1988, 2005, 2015; Galili and Sharvit, 1998, Sivan et al., 2001, 2004; Toker et al., 2012, Antonioli et al., 2006a; Goodman et al., 2008; Lambeck et al., 2004b; Vacchi et al., 2016b).

Coastal structures may be found today in situations that prevent them from functioning for one or several reasons: i) RSL change resulting from vertical land movements (e.g. Galili and Sharvit, 1998; Stiros et al., 2010; Anzidei et al., 2014, 2016;) generated by local or regional tectonics, as well as isostatic adjustments, or sea-level rise or fall; ii) settling of structures into unconsolidated sediments; iii) erosion and collapse of structures; iv) progradation of the coastline (e.g., Morhange et al., 2013). While archaeological features can directly benefit sea-level reconstructions, supporting (multi-proxy) datasets can significantly improve interpretations of past sea level (Vacchi et al., 2016b).

Later Holocene archaeological features used as sea-level markers can be divided into two broad categories (Flemming, 1978; Blackman, 1973; Galili and Sharvit, 1998; Sivan et al., 2001, Lambeck et al., 2010; Morhange and Marriner, 2015):

i) Features that need to be at or partially below sea level in order to function properly. These include pools that are fed by seawater driven by gravity, slipways, harbour installations, salt production installations, etc. These structures typically mark the uppermost or lowermost sea level at the time of construction (Figure 11).

ii) Features that are located normally only on dry land, including dwellings, quarries, roads, water-wells, freshwater pools, etc. These structures usually provide the uppermost sea level at the time of construction (Pirazzoli, 1976, 1986, Galili and Sharvit, 1998).

Figure 11. The submerged site at Fizine, Slovenia (northern Adriatic Sea, #18 in Figure 1) is interpreted to be a Classical *vivarium* or fishtank. Stones from the shallower sections of this site have been removed for re-use during historical periods. (Photo: J. Benjamin)

An alternative classification, as described by Mourtzas et al. (2016) and Mourtzas and Kolaiti (2013), describes archaeological sea-level indicators in further detail. They are modified here as:

i) Ancient coastal settlements and buildings that were constructed above sea level along the coast, but lack accurate position in relation to the past shoreline. Their present position provides only limiting data to past sea level and should be used with caution.

ii) Maritime constructions that were partially built below sea level (e.g. harbours, piers, quays etc.). Such structures may be dated, with variable confidence, where recorded in ancient literature. These are generally more reliable than the previous category.

iii) Ancient maritime constructions whose function was strictly related to past sea levels, where age is confidently determined. Fish tanks and ancient ship sheds where spatial proximity to the contemporary shore can be determined, may provide reliable data.

iv) Coastal water tables and their changes in response to sea-level change. Usually coastal aquifers are in hydraulic connection with the adjacent sea. Therefore, sea-level rise may result in the flooding of water installation supplies of archaeological sites built on land near the shore (Mourtzas, 2010; Pagliarulo et al., 2013).

v) Indications of relative sea level-change based on historical sources such as ancient texts, drawings, etc.

Harbour installations such as breakwaters, jetties, docks and quays were originally built, at least partly, under water and thus are good limiting markers for sea levels. It is generally agreed that walking and working surfaces in harbours were planned to be above sea level. However, determining sea level using these features has some limitations: i) it is not always possible to determine whether the uppermost surface found today represents the original surface used in the past because some courses of stones may have been removed either by natural or cultural agents (Blackman 1973: 124); ii) it is possible that some small harbour and coastal installations were not designed to function year-round and in all sea conditions; iii) some constructions seemed to be built deliberately under water and there is historical evidence for such activities (Galili and Sharvit 1998: 158; Marsden as cited in Blackman 1973: 138) iv) compaction and liquefaction of unconsolidated sediments may cause settling and subsidence of harbour installations.

At Caesarea, south of Haifa in Israel, there are ample indications for relative sea-level and tectonic stability in the past 2000 years (Sivan et al., 2001, 2004, Goodman-Tchernov and Katz 2015). One of the best indicators is the presence throughout the site within Roman and later coastal features of notch features in both pools and harbour features. However, while the portions of the large Roman harbour of Caesarea that were built directly on nearshore bedrock remain at the correct level relative to sea level, the offshore portions of it are today submerged between -1 and -5 m (Figure 10). This is most likely due to the combined effects of tsunami damage and liquefaction (Reinhardt et al., 2006; Goodman-Tchernov et al., 2009a; Dey and Goodman-Tchernov, 2010, Goodman-Tchernov and Austin 2015). Such variables, in an otherwise tectonically stable environment, serve as a reminder that local dynamic processes do have a profound impact on sea-level records which can influence the archaeological interpretation of key processes and events.

8.2 The debate on Roman fishtanks

Several studies have reconstructed past sea levels from rock-cut coastal fish tanks (Figure 12) in Italy (Dreghorn, 1981; Auriemma and Solinas, 2009; Evelpidou et al., 2012), Greece (Kolaiti and Mourtzas, 2016), Israel (Galili and Sharvit, 1998; Toker et al., 2012), Croatia (Florido et al., 2011) and Cyprus (Galili et al*.,* 2015). Lambeck et al. (2004b) compiled an exhaustive analysis of the central Tyrrhenian Sea fish tanks placing sea level in the Roman period at -1.3 m RSL. This level corresponds to that reported by Mourtzas (2012a, b) along the coasts of central and eastern Crete (~1.25 m) and by Schmiedt et al. (1972) for some sites in Italy. The archaeological interpretation in Lambeck et al. (2004b) was based on field surveys and analysis of ancient Latin publications. An important fish tank feature is represented by the channel systems equipped with sluice gates (*cataracta*) that controlled the water exchange between the tanks and the open sea, preventing the fish from escaping. Water exchange took place through multiple channels, sometimes carved in bedrock. A breakwater is often built around the fish tank to protect the inner basin from sea waves. The latter are often delimited by foot walks (*crepido*), generally occurring at two or three levels that were not recognised or interpreted in earlier studies. These levels, together with the sluice gates, are key in interpretations of the position of former sea level in relation to the fish tanks.

Lambeck et al. (2004b) demonstrated that the top of the sluice gate corresponds to the elevation of the lowest level foot-walk (*crepido*) (Figure12). According to the Latin treatise *De Re Rustica XIII, (Columella, early 1st century AD)* the *crepido* should lie above the highest tidal level, as also reported in the description by Pliny the Elder (23-79 A.D., in Naturalis Historia) in a constructional part that looks at the water **(***marginum eam partem, quae aquas spectat).*

Using sites with complete preservation of channels, sluice gates and foot-walks, Lambeck et al. (2004b) estimated that the palaeo high tide in Roman time was about 0.2 m below the lowest *crepido*. Further, Lambeck et al. (2004b), and subsequently Auriemma and Solinas (2009) and Mourtzas (2012a, 2012b), suggested that the flow of water inside the fish tanks was tidally controlled and that the palaeo mean sea level was placed at the middle of the sluice gate, while mean low tide was denoted by the channel thresholds, often corresponding to the base of the mobile *cataracta*. Past RSL was then constrained by these structural features of the fishtanks (Figure 12). Such interpretation was also applied at a number of sites throughout the Mediterranean (e.g. Antonioli et al., 2007; Anzidei et al., 2011a; Anzidei et al., 2014b).

Evelpidou et al. (2012) also performed a detailed survey of some Tyrrhenian Sea fish tanks, previously observed by Schmiedt et al. (1972) and Lambeck et al. (2004b) and proposed that RSL in Roman period ranged between ~-0.6 and ~-0.3 m. Evelpidou et al. (2012) disagreed with the interpretation of an original supratidal position of the lowest *crepido* proposed by Lambeck et al. (2004b). Further, they stated that the height of the *cataracta* proposed by Lambeck et al. (2004b) would not be sufficient for the fish tanks to function properly. They suggested that the upper part of the *cataracta* corresponds to the upper *crepido* instead of the lower one. Evelpidou et al. (2012) assumed that the top of the upper *crepido* was high enough to prevent the fish tank from flooding by sea surges, which could lead to a loss of fish. Pirazzoli and Evelpidou (2013) stated that the heights of the channel threshold and the base of the *cataracta* can vary and they argued, therefore, that this structural feature was weak to precisely reconstruct the palaeo RSL.

In absence of a definitive interpretation of the sea level related to the fishtanks of the Mediterranean, Vacchi et al. (2016b) adopted the conservative solution to consider both the archaeological interpretations summarised above in the calculation of the palaeo sea level. As these structures are highly relevant for the reconstruction of sea level in the Common Era, it is necessary to implement field strategies beyond the archaeological interpretation of these indicators, and couple them with other independent sea-level proxies (e.g. sea level reconstruction from nearby or contextual fixed biological indicators). As an example, in the Tiber Delta, in *Portus*, the harbour of ancient Rome, Goiran et al. (2009, 2010) placed RSL during Roman time at −0.8 ± 0.2 m using fixed biological indicators. This is the only study that obtained dates on sessile fauna found *in situ* on a maritime archaeological structure in the area, and places the Roman-era sea level in between the two previously described interpretations.

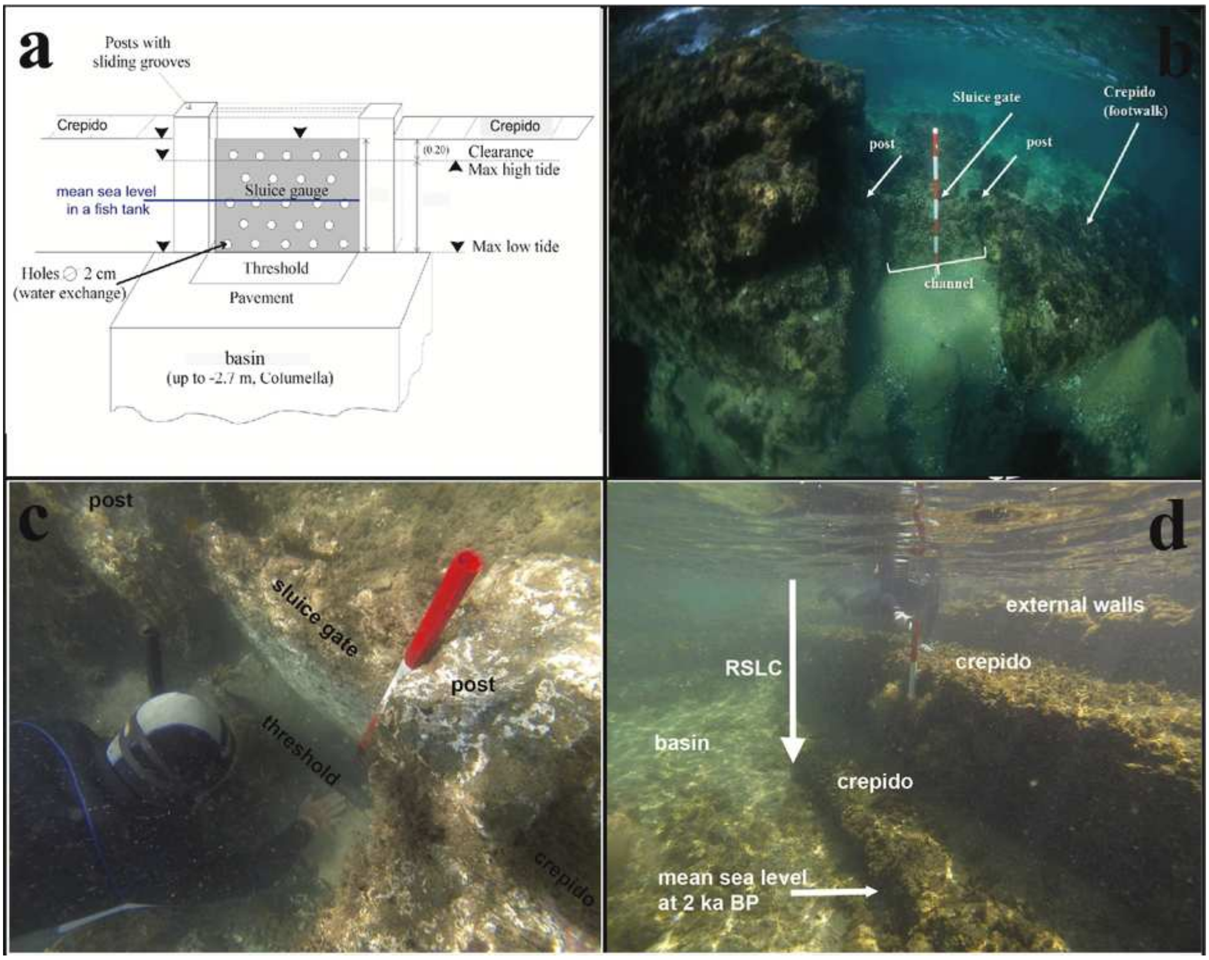

Figure 12. The typical features of a fish tank, used as an archaeological sea-level marker. a) Sketch of the channel and the sluice gate with sliding posts, threshold and lowest level of crepido. The complete gate consist of: (i) a horizontal stone surface that defines the threshold with a groove to receive the gate; (ii) two vertical posts with grooves to guide the movement of the gate; (iii) an upper stone slab (missing in this specific case) with horizontal slot to extract the gate; (iv) the gate itself with small holes for water exchange. b) Underwater photo of the in situ sluice gate, channel and crepido at the fish tank La Banca, at Torre Astura (Italy). (Adapted from Lambeck et al. 2004; photos: F. Antonioli & M. Anzidei)

9. Concluding remarks

This article has summarised the current knowledge and discussed some of the key gaps and debates in sea-level studies from geomorphological and archaeological perspectives, spanning ca. 132,000 years of human-environment interaction around the Mediterranean Sea. Focus has been mainly on the eastern and central Mediterranean, though some data have been introduced from other parts of the Mediterranean Sea to support overall themes of sea-level change and its impact on past human societies and the integration of archaeological and geomorphological data to study past coastal and sea-level changes, particularly where data remains sparse or fragmented.

In the past decade, issues related to modern climate change and future sea-level rise have motivated some archaeological studies to focus on the direct consequences of past climate change (e.g. Van de Noort, 2011, 2013) and the 'Attacking Ocean' (Fagan 2013). Weninger et al. (2006, 2014) describe the rapid climate change which would have occurred immediately following the collapse of the Laurentide ice sheet and Hudson Bay outflow for its impact on contemporary populations. While it is possible that gradual inundation rates would have been slow enough to be invisible during a single generation, it is likely that oral histories would have conveyed this process culturally though time. It is all but certain that these climate events would have had a direct and profound impact on those past cultures who were unlucky enough to have chosen to live on low-lying coastal margins. Evidence of oral traditions may be difficult to obtain, however the archaeological signature of coastal defense or population retreat, may be a boon to the next generation of those studying past societies and sea-level change of the Mediterranean.

The Mediterranean, the micro-tidal cradle of western civilisation with low rates of isostasy, has a long-standing and important role to play in determining the global sea-level history in the late Holocene. Mediterranean data have featured prominently in late Holocene sea-level sections of various IPCC assessment reports. It is critical to establish the rate of late Holocene global sea-level rise, because it forms the background against which modern accelerations of sea level rise are evaluated (Gehrels 2010a, b; Gehrels et al., 2011). Local rates of Holocene relative sea-level rise are important for estimating future sea levels as they reflect the rate of long-term background sea-level rise to which predictions, such as those by the IPCC, can be added to generate local predictions of relative sea-level rise that are of interest to coastal management. Moreover, local rates allow us to evaluate in detail the tectonic displacement rates that closely relate to the same just aforementioned questions. Whilst many Mediterranean sea-level studies address local tectonics, the regional vertical land movements produced by GIA processes are also important; the modelling of these, not only for Holocene but also for Last Interglacial sea levels, remains a challenge that should be addressed in future work.

Relative sea-level changes in the Mediterranean Sea are complex and variable, primarily due to tectonics and volcanism, although, as mentioned, glacio-isostatic adjustment also plays a crucial role. Sea-level rise is predicted to increase up to five fold in the next century compared to the past 100 years. This will take place against a background of rapid vertical land motion in many coastal areas that have produced, and continue to produce, changes in the relative positions of land and sea, as demonstrated by geological and archaeological methods outlined in this review. Humans will continue to adapt to coastal change so it is of utmost societal importance that the past history of relative sea level is taken into account on local and regional scales for effective and strategic coastal management.

A fully integrated study of the entire Mediterranean Basin, including a comprehensive analysis of the greater region’s sea-level history and its impacts on past societies, should include more data from the western Mediterranean and, especially, include increased attention to the shorelines of North Africa, where studies are scarce. This goal will require increased European-African cooperation by the communities of geoscientists and archaeologists. As with many other aspects of physical environmental and archaeological sciences, there is a huge, largely untapped, opportunity for study along the Mediterranean coast of North Africa; the data gaps encountered by this review have highlighted this discrepancy between Mediterranean Eurasia and Mediterranean Africa, and their need to be filled. Filling these gaps will require a concerted multi-disciplinary effort by both archaeologists and geo-scientists. Such an approach will require the will, support and international cooperation of scientists, governments, funding agencies and industry partners from across the region. We hope this contribution will have highlighted the necessity for interdisciplinary research and trans-border collaboration and has gone some way to propel future regional studies related to Mediterranean sea levels, environment and culture.

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