HYDROLOGICAL CHANGES DURING THE ROMAN CLIMATIC OPTIMUM IN NORTHERN TUSCANY (CENTRAL ITALY) AS EVIDENCED BY SPELEOTHEM RECORDS AND ARCHAEOLOGICAL DATA

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Running Head: Hydrological changes during Roman Climatic Optimum in Central Italy

Abstract

The study of the climate in the Mediterranean basin during different historical periods has taken on a particular importance, particularly regarding its role, together with other factors, in the evolution of human settlement patterns. Although the Roman age is traditionally considered a period with a favorable climate, recent studies have revealed considerable complexity in terms of regional climate variations. In this paper, we compare the hydrological change from speleothem proxy records with flood reconstructions from archaeological sites for Northern Tuscany (central Italy). We identify a period of oscillating climatic conditions culminating in a multidecadal dry event during the 1st century

BC, followed by a century of increased precipitation at the beginning of the Roman Empire and subsequently a return to drier conditions in the 2nd century AD. The period of rainfall increase documented by the speleothems agrees with both the archaeological flood record as well as historical flood data available for the Tiber River, ca. 300 km to the south. These data also suggest a return to wetter conditions following the 3nd-4rd centuries AD.

Keywords: Climate changes, geoarchaeology, Roman Age, palaeoflooding, Tuscany

Introduction

Since the Neolithic Age, the Mediterranean has been the cradle of ancient civilizations and its landscape has been deeply modified by the interaction between natural factors and human activities (Anthony et al., 2014; Zanchetta et al., 2013; Fyfe et al., 2015, 2016; Bini et al., 2018). Increasing evidence shows that, alongside historical, social and economic factors, climate may have played an important role in affecting the Mediterranean populations (Kaniewski et al., 2010, 2012; Schneider and Adalı, 2014; Sadori et al., 2016; Cremaschi et al., 2016; Finné et al., 2011, 2017). The role of climate in the environment and in social development is rarely simple or direct (Harper, 2017), and needs to be identified side-by-side with other sources of evidence in order to establish firm chronologies for climatic changes and archaeological data (Mensing et al., 2015). However, it is often difficult to compare archaeological and palaeoclimatic data because they are obtained from different archives –often spatially separated– and their chronologies cannot always be directly reconciled. In particular, an unavoidable limitation characterizing many age models obtained for different palaeoclimatic records makes the comparison between archives complex (Knapp et al., 2016) especially when decadal- to centennial-scale events are investigated (Finné et al., 2011; Zanchetta et al., 2012, 2018; Bini et al., 2019). However, careful selection of the best-resolved archives can produce large geographical gaps in palaeoclimatic reconstructions, reducing our ability to identify regional climatic patterns (Bini et al., 2019; Finné et al., 2019). In addition, highly resolved palaeoclimate archives supported by precise and accurate chronologies allowing comparisons of this type are rare and/or cover only limited periods of time.

The Roman Age has been traditionally considered a period of generally "benign" climate (the so-called Roman Warm Period, e.g. Lamb, 1995, or Roman Climatic Optimum (RCO), 200 BC – AD 150 e.g. Harper, 2017). However, recent and detailed investigations have shown that this period is probably climatically complex and regionally articulated (e.g. Büntgen et al., 2011, McCormik et al., 2012, Manning, 2013;; Dermoty et al., 2012; Margaritelli et al., 2015). Fundamental reviews by McCormik et al. (2012) and Manning (2013) highlight the paucity of palaeoclimatic data from continental Italy, which represents an important gap that needs to be fulfilled, particularly in the light of the richness of the region's human history.

Nevertheless, the number of higher resolution studies in Italy have increased in recent years, particularly in terms of chronological resolution and proxy interpretation (Frisia et al., 2005; Regattieri et al., 2014; Grauel et al., 2013; Margaritelli et al., 2015), but the records from continental Italy, if we exclude pollen (e.g. Di Rita et al., 2018), are still scarce. On the other hand, pollen suffers the unavoidable problem of human impact on vegetation (Di Pasquale et al., 2014; Fyfe et al., 2015, 2018), which makes many pollen-based climatic reconstructions questionable during periods of highly dense human settlements.

On the other hand the increasing of interest on climate variability during Roman Period has been fueled by historians to understand the growth and decline of the Empire (Harper, 2017) and the significant implications this has for the necessity to better understand the role of the climate variability on society, owing to current global warming (e.g. Büntgen et al., 2011). However, most of the studies are focused on large-scale reconstructions (e.g. Manning, 2013), whilst a more detailed approach at local scales comparing palaeoclimate and archaeological data to infer impact of the climate on human settlements and landscape has rarely been attempted. Therefore, our specific approach here is to correlate local hydroclimatic conditions defined by proxy records extracted from proximal natural archives to complement archaeological data in order to gain deeper insights into past climate and its impact at the local scale. Specifically, we discuss two speleothem records collected in two different cave systems in the Apuan Alps of Central Italy (Fig. 1), a region made famous for its marble exploitation since ancient times (Bruschi et al., 2004), and its links with the surrounding area, which was densely settled in the Roman Age and connected to the urban centers of Luni, Lucca and Pisa. Both records have been previously studied and discussed (Drysdale et al., 2006; Zanchetta et al., 2007, 2014, 2016) and have highlighted millennial-to-centennial scale palaeoenvironmental changes during the Holocene. In this paper, we reconstruct hydrological variability in the period between the Late Republican Period to the Late Antiquity (ca. 200 BC – 450 AD; Cormik et al., 2012; Harper, 2017) in order to evaluate the local expression of the so-called "Roman Climatic Optimum".

Site description

Geological and Geomorphological setting

The Apuan Alps massif, which rises ca. 2000 m above sea level, is the divide between the catchments of the Magra River on the NW and those of the Serchio River in the NE. Wide alluvial fans and a littoral alluvial plain separate the massif from the Tyrrhenian sea on the SW border. From a geological point of view, the massif (Fig. 1) comprises intensively karstified Mesozoic marbles and metadolostones (Piccini et al., 2008). The massif is located in front of the Gulf of Genoa, which is one of the most important centres of cyclogenesis in the Mediterranean (Trigo et al., 2002), with the Apuan massif acting as an orographic barrier for air masses, of mostly North Atlantic origin, moving eastwards (Reale and Lionello, 2013). This produces abundant precipitation, which locally reaches 3000 mm yr^{-1} (Piccini et al., 2008). Winter precipitation is strongly controlled by North Atlantic Oscillation (NAO; López-Moreno et al., 2011).

The two caves –Antro del Corchia and Buca della Renella– and their speleothem records have been described in detail elsewhere (Drysdale et al., 2004; Piccini et al., 2008; Baneschi et al., 2011) and only general information is reported here. The two caves are very different. Corchia is the higher, larger and deeper cave of the two (ca. 54 km long and 1200 m deep).
The speleothem examined in this study (stalagmite CC26, Zanchetta et al., 2007) was collected in the "Galleria delle Stallatiti", situated ca. 400 m below the surface at ca. 840 m a.s.l. The chamber has a near-constant mean annual temperature of 7.5 °C and receives a recharge of 2500/3000 mm/yr over an elevation range of ca. 1200-1400 m (Drysdale et al., 2004; Piccini et al., 2008). Drip-waters in the chamber have a near-constant oxygen isotopic composition ($\delta^{18}O$: ca. −7.4‰, Piccini et al., 2008; Baneschi et al., 2011), which is consistent with predicted values of rainfall at the estimated recharge elevation (Mussi et al., 1998; Drysdale et al., 2004). The carbon isotope composition ($\delta^{13}C$) of dissolved inorganic carbon (DIC) is similarly constant (ca. -4‰ Baneschi et al., 2011), and reflects the low contribution from biogenic CO_2 due to the thin vegetation cover, cool mean annual temperatures and long interaction with the marble bedrock, as well as changes in the proportion of both closed vs open-system conditions and carbonic-acid vs sulphuric-acid dissolution (Bajo et al., 2017). Cave hydrochemistry (pH, ion concentrations, isotopic composition) shows very constant values, suggesting well-mixed waters and a stable and deep plumbing system (Baneschi et al., 2011).

Renella Cave has its entrance at ca. 275 m a.s.l., measures ca. 200 m length and has developed over a few tens of metres (Zhornyak et al., 2011). Cave temperature is ca. 12 °C (Zanchetta et al., 2016). Cave monitoring is in progress and detailed data on long-term variability of drip waters are still incomplete (Zanchetta et al., 2016 and unpublished). The record discussed in this paper is from the RL4 flowstone, which was collected in the upper chamber of the cave (Drysdale et al., 2006; Zhornyak et al., 2011; Zanchetta et al., 2016). For RL4, Drysdale et al. (2006) presented a multiproxy record (stable isotope, trace elements and fluorescence properties) at low resolution (1 mm). The resolution of the stable isotope record was subsequently improved to 200 µm (Zanchetta et al., 2016, age model recalculated in the SISAL record Atsawawaranunt et al., 2018).

Historical and Archaeological framework

During the pre-Roman age, the area was variously settled by Etruscan and Ligurian populations (Paribeni, 1990; Bruni, 1998). Since the 3rd century BC, owing to its high strategic value, the region was the target of the expansionist programme of Rome. The emerging Roman power sought to create the functional structures necessary for its expansion overseas towards the west and to guarantee access of the Apennine passages to the Po Valley. The pro-Roman policy of the Etruscan city of Pisa favoured Roman penetration in this district, which between the 3rd and 2nd centuries BC provided Rome with the logistic bases for the conquest of Sardinia and of the territories occupied by Galli and Ligurians.

The Portus Pisanus (Kaniewski et al., 2018) and the numerous landings along the coast, served by the Aurelia coastal road (probably already joining Rome to Pisa since 241 BC), are the strategic points of strength of the territory. At the end of the same century the Aurelia road extended to Portus Lunae at the mouth of the Magra river (Fabiani, 2006). The continuous threat of the Ligurian raids pushed Pisa to grant the internal part of its territory for the foundation of the Latin colony of Lucca in 180 BC. After the defeat of the Ligurians, who had occupied the northernmost part of its territory, Pisa was forced to accept the foundation of the Roman colony of Luni in 177 BC (Fig.1).

Since their foundation, the territories of Lucca and Luni had been deeply reorganized according to the centuriatio system, while new interventions were carried out in the triumviral and Augustan Ages (second half of 1st century BC - beginning of 1st century AD). In this period, the countryside of Pisa, which had become a colony, was also centuriated (Ciampoltrini, 1981; Ciampoltrini, 2004; Pasquinucci, 1995). The data offered by the archaeological excavations and field surveys allow the reconstruction of the settlement network, consisting of small-to-large farms, luxury villas (Ciampoltrini, 1994), manufactures and scattered necropoles.

In this framework, the Auser and the Arno rivers flowing through Pisa played a strategic mediation role between the trading sea and the vast hinterland, while agricultural and manufacturing activities, including those related to the production of pottery and bricks, testify the strengths of the local economy (Menchelli, 2018).

Olive and wine cultivations were developed in the territories of the three cities, according to the nature of the soils (Fabiani, Paribeni, 2012; Fabiani, Paribeni 2016; Pasquinucci, Menchelli, 1999). Intensive exploitation of marble developed in the Apuan massif from the Augustan Age. Apuan marble was exported from Luni harbour to Rome across the Western Mediterranean basin (Paribeni and Segenni, 2015). At Luni and its hinterland, the Middle and the late Imperial Ages (3rd-5th centuries AD) were characterized by deep changes in the economy (Frova, 1989; Gervasini, 2015; Gervasini and Mancusi, 2014). The marble trade came to an end within the IV century AD, while the few data currently available on the countryside suggest a strong decrease in wine production and pottery and brick manufacturing. At the end of the 4th century an earthquake, detected by archaeological sources, destroyed the town; in the aftermath, the early structures of the insula episcopalis, the enrichment of a few domi and the lack of interest for the destroyed public building testify the birth of a new town, very different from that of the early Imperial Age.

During the 2nd century AD the urban centre of Lucca went through a crisis (Abela, 1999), testified by the abandonment and spoliation of many domi. This phase ended in the 3rd and 4th centuries AD, when new building programmes, mainly focussed on churches, were promoted. The inner city witnessed a decrease in the number of buildings, with more empty spaces and settled areas located next to the main building (the bishop's seat, the Lombard Duke's palace, etc.). A similar trend was recorded in the surrounding countryside, with the end of many settlements and other structures (such as roads and bridges), strongly connected to a general and increasing deterioration of the hydrogeological conditions (Ciampoltrini, 2004).

Because of the strong development of the towns in the Middle Ages, the transformations of the urban centre of Pisa in the Middle and Late Imperial Ages are not easy to understand (Menchelli, 2003; Pasquinucci, 2003). However, we observe an abandonment of the Northern suburbs and the progressive occupation of the latter by cemeteries, both testifying a contraction of the urban space. In spite of these factors and of a progressive crisis of the neighbouring settlements, trade along the Auser and the Arno rivers continued on a large scale throughout this period, at least until the 7th-8th centuries AD.

Methods

Details of the U/Th dating and chronology of CC26 and RL4 speleothems have been extensively discussed in previous papers (see Zanchetta et al., 2007 and Drysdale et al., 2006). The CC26 age model has been substantially confirmed by Bajo et al. (2017) based on a larger set of U/Th ages. However, the low-resolution (1 mm) stable isotope record obtained by Bajo et al. (2017), even if in general agreement with the isotope records reported by Zanchetta et al. (2007), lacks sufficient resolution to be useful for our purpose owing to the low growth rate of the speleothem. Moreover, the low-resolution time series, which has been obtained on a different section of the speleothem, cannot be tuned unambiguously for this interval at fine-scale with the high-resolution (200 μm) record of Zanchetta et al. (2007) ensuring an improving chronology. However, it is reasonable to assume that the chronology of Zanchetta et al. (2007) is less precise than Bajo et al., (2017), but similarly accurate.

Figure 2 shows 95% confidence intervals for the age-model of the RL4 and CC26 speleothem records. Average temporal resolution for the interval considered for the Corchia and Renella records is 13 yr and 7 yr respectively. The original U/Th ages are referred to the year of measurement, but for a better comparison with archaeological and radiocarbon data, both age models are converted to yr BP (i.e. before 1950), which are equivalent to the calendar year BP in radiocarbon chronology. The chronological interval discussed in this paper is the interval where the age model of both speleothems has lower associated interpolation errors.

The proxy records discussed (stable isotopes and trace elements) are mostly used as palaeohydrological indicators of the cave recharge and then are compared to flood evidence derived from archaeological data. Regarding the archaeological data, the stratigraphy of several archaeological sites was reviewed to identify evidence of historical floods. To identify published archaeological data for the Roman Period, we selected an area comprising Lucca, Pisa, Luni and Versilia plains, the Lower Valdarno and Garfagnana (Fig. 1). About 20 sites containing in their stratigraphy evidence of floods during the Roman Period were selected for further evaluation. However, sites with insufficient stratigraphic and chronological information were discarded. A total of 14 archaeological sites were finally selected for this study (Table 1). The chronology of the alluvial phases was based on published archaeological evidence (for details of the chronology for each site see the references in Table 1), which usually relates to pottery chronological successions (Manacorda 2008). The chronology has been defined by dating the lower and upper archaeological layers comprising the alluvial phase or directly on the material collected (presumably partially reworked) in the alluvial sediments. For one of the selected sites (– n. 3 Lucca – “Miracolo di San Frediano” –, Table 1) the occurrence of alluvial events has been inferred on the basis of ancient written sources.

A different order of problem is the identification of flooding in archaeological excavations. This could be challenging, owing to often-ambiguous evidence and to the different sensitivity of different archaeologists to record this evidence. It is not always possible to separate single flood events from longer phases of alluvial aggradation. Moreover, it is often difficult to define with accuracy the chronology of flood events/phases captured in archaeological stratigraphy. It is important to consider the analyses of indirect data (e.g. land reclamation interventions, centuriation recovery, raising of the walking plans, regulation of the hydraulic network), which may testify conditions of hydrogeological instability, possibly due to general climatic deterioration. Even if these data must be treated with caution, they have a decisive importance in understanding not only the evolution of climatic variations but also the anthropogenic reaction to these events. The selected sites record a total of 24 events, which includes alluvial phases, single floods, and selected anthropic hydraulic interventions (Table 1). Figure 3 shows the rationale used to manage and integrate data from palaeoclimatic and archaeological sources.

Results and discussion

Palaeohydrological interpretation of speleothem proxy records

For comparison, we show the high-resolution $\delta^{18}O$ record of RL4 (Zanchetta et al., 2016) and the "mean anomaly index" obtained from CC26 stalagmite (Regattieri et al., 2014) (Fig. 4). This index was obtained by combining de-trended, smoothed and normalized Mg/Ca, $\delta^{18}O$, and $\delta^{13}C$ time series, assuming that all three respond sensitively to hydrological variations and in particular to changes in cave recharge (Regattieri et al., 2014). This statistical treatment better highlights significant hydrological changes, and is considered a more robust palaeohydrological indicator compared to a single proxy (Regattieri et al., 2014; Isola et al., 2019) for the deep and complex cave system of Corchia. For Renella, we consider the $\delta^{18}O$ record as a good indicator of effective recharge over the cave catchment, since the cave is shallower and rapidly responds to changes in hydrology. For RL4, the interpretation of $\delta^{18}O$ records (e.g. hydrological indicators) is supported by low-resolution variations in the Mg/Ca molar ratio and in the fluorescence properties of trapped organic matter (Drysdale et al., 2006). Unfortunately, the resolution of trace element and florescence series in the original paper of Drysdale et al. (2006) is too low (ca. 50 yr per data point across the considered interval) to be compared with high-resolution isotope data of Zanchetta et al. (2016), and cannot be used to produce a comparable "mean anomaly index" similar to CC26 record.

Speleothem $\delta^{18}O$ in the Central Mediterranean is usually related to the amount of precipitation (e.g. Bar-Matthews et al., 1999; Bard et al., 2002; Drysdale et al., 2004; Regattieri et al., 2019a, 2018; Finné et al., 2017; Bini et al., 2019), with lower $\delta^{18}O$ values of speleothem calcite interpreted as increasing precipitation, and *vice versa*. In this interpretation, changes in cave temperature have a minor role (Drysdale et al., 2004; Zanchetta et al., 2007, 2014), particularly during the Holocene, when changes in temperature were rather limited (Marcott et al., 2013; Martrat et al., 2014). This interpretation is strictly correct if no dramatic changes occur in the isotopic composition of the source of the vapour (i.e. surficial sea water), a case which cannot be assumed, for instance, during glacial to interglacial transitions (e.g. Marino et al., 2015), or during phases of increased freshwater runoff within the basin (Bar-Matthews et al., 2000; Rohling et al., 2015). For the Mediterranean region, the oxygen isotope composition of other continental carbonates has been interpreted in a similar way (i.e. lower $\delta^{18}O$ values of carbonate indicate wetter conditions, and *vice versa*). This is the case for pedogenic carbonate (Zanchetta et al., 2000, 2017; Borretto et al., 2017), lacustrine carbonate (Roberts et al., 2008; Zanchetta et al., 1999, 2012; Regattieri et al., 2019b, 2017), and land snail shells (Colonese et al., 2007, 2010, 2014; Yanes et al., 2011; Prendergast et al., 2016). However, different effects, notably evaporation, can play different roles in defining the final isotopic composition of carbonates in different environments.

An additional point to be considered is the timing of calcite precipitation. The two caves have different plumbing systems and at Renella the speleothem $\delta^{18}O$ signal could be skewed towards the time of calcite precipitation vs time of water recharge. It is generally reasonable to assume that most of the recharge for both caves occurs during autumn and winter, when precipitations are higher (Piccini et al., 1998; Baker et al., 2019). However, the large and well-mixed plumbing system dampened the inter-annual variability much less at the shallow Renella than at Corchia, which was able to better record long-term and smoothed trends.

Land use changes and deforestation during historical periods may also affect the soil/epikarst system of the two caves via, for example, increasing soil evaporation and changes in soil-water residence time, as well as CO_2 productivity in the soils (e.g. Fairchild and Baker, 2012). These can impact the speleothem $\delta^{18}O$ and $\delta^{13}C$ (e.g. Bar-Matthews et al., 2003). The use of a multiproxy approach for CC26 buffers these influences. At Renella, the very recent impact of quarry activity on the cave catchment would have exerted a large impact on infiltration waters. However, this is not observed in the monitoring data for the $\delta^{18}O$, indicating that there is no a detectable signal of evaporation (Zanchetta et al., 2016).

Considering these potential differences, and the inherent limitation of comparing two different age models not specifically built for investigating this period of time (between 3000 to 1500 yr BP), the two records show some interesting patterns (Fig. 4). In the first part of the record (between ca. 3 and 2.3 ka, ca. 1000 BC to 350 BC) there is evidence for three short (multi-decadal) drying events centered at ca. 2.9 (ca. 950 BC), 2.7 (750 BC) and 2.5 ka BP (ca. 550 BC). Between the two records these events are offset by ca. 50 yrs, which can be attributed to uncertainty in age, keeping also in mind the relatively large uncertainty (ca. ±100 yr) of the two age models in this section. However, the most striking similarity is the drying trend observed since 2.3 ka, which peaks in both records at ca. 2050 yr BP (within 100 BC), representing ca. 20-30 yrs of driest conditions (Fig. 4). This period is followed by a sharp transition to a century of wetter conditions (ca. 2000-1900 yrs BP, end of 1st century BC and 1st century AD), ending abruptly and leading to a new period of drier conditions, even if not stronger than the events of the 1st century BC. Since then the two records have shown some significant differences. RL4 shows the end of the drier conditions at ca. 500 AD, followed by a long-term trend towards wetter conditions. The end of the drier conditions for the CC26 record definitively stops at ca. 300 AD, and wetter conditions are apparent with a peak at ca. 650 AD. The extremely slow growth for CC26 in this period and the difficulties of precise dating for both records hamper the possibility to synchronize the two records in the late period.

Integration of proxy record with archaeological and historical data

The hydrological variability expressed by the speleothem proxies in the historical framework shows that the definitive affirmation of Roman power over Northern Tuscany, and the foundation and development of the main cities occurred within a period of generally drier conditions, which were more pronounced towards the end of the period (first half of the first century BC). Interestingly, the dry period followed by wetter one is consistent for this interval with a new $\delta^{18}O$ palaeohydrological record from speleothems from Rio Martino Cave in the Mediterranean Alps, (Fig. 5; Regattieri et al., 2019a). However, this record for other periods shows some significant differences.

At the beginning of the Common Era a prominent wet period lasting about a century was recorded by the speleothem proxies, followed by a new drier period in the 2nd century AD. Some authors (McCormik et al., 2012) reported that favourable and exceptionally stable conditions prevailed across the Roman Empire from ca. 100 BC to ca. 200 AD and, according to some scholars, this probably fostered the Empire's unparalleled rise (e.g. Harper, 2017). These inferences are not supported by the detail shown in our records, which instead suggest a detectable change from dry to wet conditions occurring around 50 BC. It is important to stress that the climatic trends deduced from the Apuan speleothems are not so prominent considering the whole Holocene variability (Drysdale et al., 2006; Zanchetta et al., 2007, 2014; Regattieri et al., 2014).

In the period corresponding to the drying trend that culminated in the 1st century BC, the alluvial plains of Luni and Lucca were organized according to centuriation. This first general organization of the landscape with centuriation during the Roman Late Republican Age was followed by a second centuriation agreed during the Triumviral and Augustan Ages. This second centuriation then seems to have occurred during a period of increasing rainfall. Systematic investigations in the Lucca alluvial plain indicate an evident phase of flooding between the two centuriations, with deposition of alluvial sands (Ciampoltrini, 2004). A progressive demise of the Roman management on the alluvial plain caused by long-lasting socio-political turbulence of the Late Republican Period has been suggested (Ciampoltrini, 2014), but a comparison with the data derived from speleothems makes it reasonable to also assume a connection with climatic deterioration.

This compelling archaeological evidence can be further improved on a wider scale. Revision of the 14 selected archaeological sites of Luni, Lucca, Pisa, and the coastal plain allows to identify several lines of evidence during the second half of the 1st century BC to the 1st century AD (Fig. 6; Table 1), which can be interpreted as floods and/or phases of increased alluvial sedimentation, even if such floods are also documented in different historical periods. For example, evidence of alluvial events is testified during the drier period by the so colled "Hellenistic shipwreck" of S. Rossore (Camilli and Setari, 1st century BC (Via Galluppi, site n. 10; Anichini et al., 2009; Le Melorie 2005) and by long-lasting alluvial phenomena that occurred between the 2nd and the very end of the 1st century BC (Via Galluppi, site n. 10; Anichini, Constantini, Bertelli 2009; Le Melorie, site n. 13; Pasquinucci et al., 2008). Nevertheless, we can state an increase of alluvial events between the second half of the 1st century BC and the end of the 2nd century AD. At Lucca and in its territory there is evidence of alluvial phases at the Orti di San Francesco (site n. 4; Ciampoltrini 2007), Botronchio (site n. 7; Ciampoltrini and Andreotti 1993) and Casa del Lupo (site n. 6; Ciampoltrini, 2004); close to the latter, the anthropogenic response to these natural events is testified by a land reclamation intervention, made possible by an amphora-shaped structure at the site of Frizzone, Casa del Lupo (n. 5; Ciampoltrini and Giannoni 2009). At S. Rossore in Pisa, several wrecks (n. 11; ships B, C, E, G, M; 2005; Camilli and Setari 2005; Camilli et al., 2006; Camilli 2012) were recorded for this wet period. These single events reflect rainfall-related phenomena, connected to the whole hydrographic basin of the Auser River and possibly of the Arno River.

Alluvial phases were detected in the town's territory at Via di Gello (site n. 8; *MappaGis*, http://mappagis.cs.dm.unipi.it:8081/mappa/mappa.phtml, data sheets 133, 351) and at Via Galluppi (site n. 10; Anichini et al., 2009). As already noticed for Lucca, amphorae structures were put in place in the northern suburbs, along the Auser river course (site n. 9; *MappaGis*, http://mappagis.cs.dm.unipi.it:8081/mappa/mappa.phtml, data sheet n. 169) to face any alluvial events.

Floods are related to specific meteorological events not necessarily correlated to the wider year-round climatic conditions normally captured by speleothem proxies; indeed, flooding is not a measure of the overall rainfall regime, but an extreme event. However, archaeological data are consistent with the speleothem data in suggesting an increase in rainfall from the late 1st century BC to the 1st century AD, despite possible chronological offsets between the two records (Figs. 5 and 6). However, it is worth pointing out that flooding in the Roman Empire may have been exacerbated by anthropogenic activities, such as the devastation inflicted on mountain and lowland forests (Aldrete, 2007; Harris, 2013), or even centuriation itself. It cannot be excluded that centuration may sometimes have entered into conflict with the delicate hydrogeological systems of the environment where it had been introduced. It is also important to consider that although the system favored an optimal water flow, it required continuous management: non-constant or neglected maintenance would have led to flow inefficiency, especially in conjunction with climatic changes or flooding events.

The records of flood recurrence in the Tiber River in the city of Rome (e.g. Aldrete, 2007 and reference therein: Fig. 7) interestingly mimic (within age errors) the general trend of wetter/drier conditions described by the speleothem records between ca. 1st century BC and the 2nd century AD and our archaeological data (Fig. 7). The Tiber data indicate a particular increase in flood frequency between ca. 1st century BC and 1st century AD. The creation in 15 AD of the post of *curator riparum et alvei Tiberis* (Dio Cass., LVII, 14; Svet., Aug., 37; C.I.L. XIV, 4704a-c), entrusted with the cleaning of the Tiber banks and riverbed, reflects the need to find an effective and long-lasting solution to the recurring danger of flood events (Guaglianone, 2017). The consolidation works of the Auser river banks, conducted in Pisa during the Augustan Age by means of amphorae structures (*MappaGis*, http://mappagis.cs.dm.unipi.it:8081/mappa/mappa.phtml, data sheet n. 169), can be identified by public interventions, similar to those of the Tiber river. Significantly, the scarce evidence of alluvial events dating back to the 2nd century AD, namely an alluvial phase in the ager Lunensis (site n. 2; Sheperd 1995) and in the shipwreck H, F, N at Pisa, S. Rossore (site n. 11) – match with speleothem proxies, thus testifying a period of drier climatic conditions.

As concerns the climatic conditions through the middle and late Imperial Age (200-450 AD), archaeological data from the study area highlight a new upswing of alluvial events (Fig. 6). Unfortunately, the archaeological and speleothem data cannot be correlated in detail in this same period. The speleothem data are in fact inconsistent, since Renella Cave is the only one testifying a new increase in humid climatic conditions (Fig. 4). For example, single floods are recorded at Luni (site n. 1; Durante 2001) and in its territory (Montiscendi n. 2; Sheperd 1995) during the 4th century AD.

The most convincing evidence of this trend are the several shipwrecks of Pisa (site n. 11; Camilli 2005, 2012; Camilli and Setari 2005; Camilli et al. 2006), dating back to the end of the 3rd century AD (shipwreck A), between the end of the 4th and the beginning of the 5th (ships I, Q, L) and of the 5th centuries AD (ship O). The wrecks reflect long-lasting alluvial phenomema testified in the *ager Pisanus* by the progressive waterlogging phase in the south-eastern sector of the centuriated area (site n. 14; Pasquinucci et al. 1997). The hydrogeological instability of the Arno River valley is testified by a single flood recorded at S. Ippolito di Anniano, dated between the 4th and 5th centuries AD (n. 12; Ciampoltrini and Manfredini 2005).

The long-lasting period of hydrogeological instability is recorded in the *ager Lucensis* of the 5th century AD at the site of Botronchio (n. 7; Ciampoltrini and Andreotti, 1993), while the dangers caused by the *Auser* river over time probably forced the community to divert the river course during the 6th century AD, as suggested by the so-called "S. Frediano's miracle" (site n. 3). According to Gregorius Magnus (*Dialogues*, III, 1), the bishop of Lucca, Frediano is likely to have moved the dangerous river away from the city.

Possible synoptical-scale climate condition

The validity of the Tiber flood record based on historical chronicles as a climatic indicator is debatable (see for instance Aldrete, 2007 for a detailed discussion). It is a fact that floods are generally recorded only when they create damage to properties and injure people. On the other hand, floods would seem to reflect the occurrence of extreme events, which can be related to specific synoptic climate conditions. For instance, in some European regions flood frequency has been related to North Atlantic Oscillation phases (NAO, Villarini et al., 2012 and reference therein). The historical reconstruction of the last 1000 yr of the damaging hydrological events in Peninsular Italy suggests that large floods are strictly related to NAO status, with floods increasing during periods of negative NAO (Diodato et al., 2019). According to Zanchettin et al. (2008), the river discharge peak of the Po River strongly depends on NAO conditions during wintertime. Thus, our revision of archaeological and speleothem data reinforce the climatic valence of the flood record from the Tiber River, at least for the period considered, namely the end of 1st century BC and 1st century AD (Fig. 7).

Application of these data to the whole Mediterranean is not possible, and it is beyond the scope of this paper to discuss the extra-regional climate in detail. However, the conditions recorded in the Apuan speleothems are mostly related to the season of cave recharge (Isola et al., 2019; Bini et al., 2019), which usually corresponds to winter (Piccini et al., 1998). Thus, reduced precipitation during the Republican period, peaking in the first century BC, should be related to a decrease in the arrival of cyclones from the North Atlantic, and consequently to a decrease in the secondary cyclogenesis over the Gulf of Genoa (Isola et al., 2019). However, a decline in winter precipitation is not only related to reduced cyclogenesis, but also to a reduction in the amount of precipitation generated by each single cyclone (e.g. Zappa et al., 2015). Today, this situation is mostly related to a positive phase of NAO (Xoplaxi et al., 2004; Lopez-Moreno et al., 2011), whereas negative phases of NAO give rise to a major frequency of cyclones and precipitation (Reale and Lionello, 2013), and, as suggested by the data presented here, in floods.

Concluding remarks

Speleothem records from the Apuan Alps indicate that during the Roman Age the northwestern part of Tuscany experienced a period of oscillating climatic conditions, with a particularly pronounced multidecadal dry event during the first century BC. About a century of increased precipitation is documented at the end of the 1st century BC/beginning of the Common Era, followed by a return to drier conditions during the 2nd century AD. The survey of archaeological data indicates the occurrence of flooding in northern Tuscany, which coincides, within chronological uncertainties, with the wetter period inferred from speleothem data. Interestingly, the Apuan speleothem records resemble the historical record of floods in the Tiber River, suggesting a regional link between the rainfall increase recorded by the speleothem and the occurrence of floods. This condition could correspond to a persistent negative NAO index. Unfortunately, it is not possible to extend further the correlation between speleothem records and archaeological data due to the increasing chronological disagreement between the Corchia and Renella records. However, after a drier period, a tendency towards wetter conditions can be generically inferred towards the late Antiquity, as also suggested by the archaeological data. To better define the conditions in the area after the 2nd century AD, it is necessary to extend the proxy record *ad hoc* by using newly recovered and better dated speleothems.

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Figure 1: Location map. Red circles=archaeological sites investigated (each number corresponds to a different site listed in Table 1), yellow circles= investigated caves.

Figure 2: Age model showing 95% confidence intervals for RL4 and CC26 (Drysdale et al., 2006; Zanchetta et al., 2007). The red dashed lines highlight the period discussed in the text.

Figure 3: The methodological approach applied in this work.

Figure 4: The δ^{18}O record of RL4 (Zanchetta et al., 2016) and Mean Anomaly Index for stalagmite CC26 (Regattieri et al., 2014). The Roman Climatic Optimum period – RCO - (Harper, 2017) is highlighted. Yellow bands: the drier intervals; light blue bands: the period of inferred wetter conditions.

Figure 5: Comparison between RL4 and CC26 records and Rio Martino δ^{18}O record (Regattieri et al., 2019). The Roman Climatic Optimum period – RCO - (Harper, 2017) is highlighted. For the location of Rio Martino Cave, see Fig 1.

Figure 6: Recurrence of floods in the archaeological records for the studied area (see Table 1 and Figure 1 for the location). Flood events documented in archaeological excavations (red lines), alluvial phases documented in archaeological site (green lines) and hydraulic intervention (yellow lines). The period of higher precipitation inferred from speleothem records is highlighted (yellow). Blue dotted line indicate the investigated archaeological period (600 AD – 200 BC) ; the red dotted lines indicate the Roman Climatic Optimum – RCO - (Harper, 2017).

Figure 7: RL4 and CC26 records compared with floods inferred from archaeological (source Table 1) and Tiber flood from historical records (data from Andrate, 2007). Chronology of flood obtained from archaeological data were spread over century. This can produce some differences between the number of flood between Table 1 and this figure. This has no impact on the spike during the 1st century AD.

Table 1. Archaeological sites or historical data mentioned in the text.

References

Abela E., 1999. Lucca, in Archeologia urbana in Toscana. La città altomedievale, Mantova, pp. 23-41.

Aldrete G.S., 2007. Flood of the Tiber in Ancient Roma, Baltimore.

Anichini F., Bertelli E., Costantini A., 2009. Via Galluppi 2009: Intervento di scavo stratigrafico preventivo indagini geoarcheologiche nel sito pluristratificato dell'Acquarella (Camaiore –LU), *Notiziario della Soprintendenza per i Beni Archeologici della Toscana*, **3**, pp. 54-60.

Anthony E.J., Marriner N., Morhange C. 2014. Human influence and the changing geomorphology ofediterranean deltas and coasts over the last 6000 years: From progradation to destructionphase? *Earth-Science Reviews*, **139**, 336-361.

Atsawawaranunt, K., Comas-Bru, L., Amirnezhad Mozhdehi, S., Deininger, M., Harrison, S. P., Baker, A., Boyd, M., Kaushal, N., Ahmad, S. M., Ait Brahim, Y., Arienzo, M., Bajo, P., Braun, K., Burstyn, Y., Chawchai, S., Duan, W., Hatvani, I. G., Hu, J., Kern, Z., Labuhn, I., Lachniet, M., Lechleitner, F. A., Lorrey, A., Pérez-Mejías, C., Pickering, R., Scroxton, N. and SISAL Working Group Members, 2018. The SISAL database: a global resource to document oxygen and carbon isotope records from speleothems, *Earth Syst. Sci. Data*, **10**, 1687–1713.

Baker A., Hartmann A., Duan W., Hankin S., Comas-Bru L., Cuthbert M.O., Treble P.C., Banner J., Genty D., Baldini L.M., Bartolomé M., Moreno A., Pérez-Mejías C., Wener M., 2019. Global analysis reveals climatic controls on the oxygen isotope composition of cave drip water. *Nature Communications* **10**, 2984, https://doi.org/10.1038/s41467-019-11027-

Bajo P., Borsato A., Drysdale R.N., Frisia S., Zanchetta G., Hellstrom J.C., Woodhead J., 2017. Stalagmite carbon isotopes and dead carbon proportion (DCP) in a near-closed-system situation: An interplay between sulphuric and carbonic acid dissolution. *Geochimica et Cosmochimica Acta*, **210**, 208-227.

Baneschi, I., Piccini, L., Regattieri, E., Isola, I., Guidi, M., Lotti, L., Mantelli, F., Menichetti, M., Drysdale, R.N., Zanchetta, G., 2011. Hypogean microclimatology and hydrogology of the 800-900 m asl level in the Monte Corchia cave (Tuscany, Italy): Preliminary considerations and implications for paleoclimatological studies [Mikroklima in hidrologija na nadmorski višini 800-900 m v jamskem sistemu monte corchia: Prve ugotovitve in pomen za paleoklimatološke raziskave]. *Acta Carsologica*, **40** (1), 175-187.

Bard, E.,Delaygue, G.,Rostek, F.,Antonioli, F.,Silenzi, S.,Schrag, D., 2002. Hydrological conditions in the western Mediterranean basin during the deposition of Sapropel 6 (ca. 175 kyr). *Earth Planetary Science Letters* **202**, 481–494.

Bar-Matthews, M., Ayalon, A., Kaufman, A.,Wasserburg, G.J., 1999. The Eastern Mediterranean paleoclimate as a reflection of regional events: Soreq cave, Israel. *Earth Planetary Science Letters* **166**, 85–95.

Bar-Matthews, M.,Ayalon, A.,Kaufmann, A., 2000. Timing and hydrological conditions of sapropel events in the eastern Mediterranean, as evident from speleothems, Soreq cave, Israel. *Chem. Geol.* **169**, 145–156.

Bar-Matthews, M., Ayalon, A., Gilmor, M., Matthews, A. Hawkeshworth, C.J., 2003. Sea– land oxygen isotopic relationships from planktonic foraminifera and speleothems in the Eastern Mediterranean region and their implication for paleorainfall during interglacial intervals. *Geochim. Cosmochim. Acta* **67** (17), 3181–3199.

Bini, M., Fabiani, F., Pappalardo, M., Schuldenrein, J., 2018. Urban geoarchaeology in the Mediterranean Basin, Introduction. *Geoarchaeology*, **33** (1), 1-13.

Bini M., Rossi V., Amorosi A., Pappalardo M., Sarti G., Noti V., Capitani M., Fabiani F., Gualandi M.L., 2015. Palaeoenvironments and palaeotopography of a multilayered city during the Etruscan and Roman periods: Early interaction of fluvial processes and urban growth at Pisa (Tuscany, Italy). *Journal of Archaeological Science*, **59**, 197-210.

Bini M., Zanchetta G., Perşoiu A., Cartier, R., Català A., Cacho I., Dean J.R., Di Rita F., Drysdale R.N., Finnè M., Isola I., Jalali B., Lirer F., Magri D., Masi A., Marks L., Mercuri A.M., Peyron O., Sadori L., Sicre, M.A., Welc F., Zielhofer, Brisset E., 2019. The 4.2 ka BP Event in the Mediterranean Region: an overview. *Climate of the past*, **15**, 555–577.

Boretto, G., Zanchetta, G., Ciulli, L., Bini, M., Fallick, A.E., Lezzerini, M., Colonese, A.C., Zembo, I., Trombino, L., Regattieri, E., Sarti, G., 2017. The loess deposits of Buca dei Corvi section (central Italy): revisited. *Catena* **151**, 225–237.

Bruni S. 1998. Pisa etrusca. Anatomia di una città scomparsa, Milano.

Bruschi G., Criscuolo A., Paribeni E., Zanchetta G., 2004. ^{14}C-dating from an old quarry waste dump of Carrara Marble (Italy): evidences of the pre-Roman exploitation. *Journal of Cultural Heritage,* **5**, 3-6.

Büntgen, U., Tegel, W., Nicolussi,K.McCormick, M. Frank, D. Trouet V.6 Kaplan, Jed O. Herzig, F., Heussner, K.-U., Wanner, H., Luterbacher, J., Esper J., 2011. 2500 Years of European Climate Variability and Human Susceptibility. *Science* **331**, 578-582.

Camilli A., 2005. Il contesto delle navi antiche di Pisa. Un breve punto della situazione. *Fasti Online* Documents 31.

Camilli A., 2012. Ambiente, rinvenimenti e sequenza. Un breve riassunto aggiornato dello scavo delle navi. In: Remotti E. (Eds), Il bagaglio di un marinaio. Roma, pp. 13-18.

Camilli A., Setari E. (Eds), 2005. Le navi antiche di Pisa. Guida archeologica. Milano.

Camilli A., De Laurenzi A., Setari E. (Eds.), 2006. Pisa. Un viaggio nel mare dell'antichità. Catalogo della mostra (Roma 2006). Milano.

Ciampoltrini G., 1981. Note sulla colonizzazione augustea nell'Etruria settentrionale. *Studi Classici e Orientali* **31**, 41-55.

Ciampoltrini G., 1994. Gli ozi dei Venulei. Considerazioni sulle "Terme" di Massaciuccoli. Prospettiva 73-74, 119-130.

Ciampoltrini G., 2004. Gli agri divisi di Lucca. Ricerche sull'insediamento negli agri centuriati di Lucca fra Tarda Repubblica e Tarda Antichità. Siena.

Ciampoltrini G., 2011. La città di San Frediano. Lucca fra VI e VII secolo: un itinerario archeologico. Bientina.

Ciampoltrini G., 2014. La terra dell'Auser. II. Le ricerche archeologiche in località Frizzone e il Territorio di Capannori in Età Romana. *I segni dell'Auser* 10. Lucca.

Ciampoltrini G., Andreotti A., 1993. Vie rurali di età romana nell'*ager Lucensis*: contributi dall'alveo del Bientina. In: Quilici L., Quilici Gigli S. (Eds), Strade romane. Percorsi e infrastrutture, 2, pp. 183-192.

Ciampoltrini G., Giannoni A. (Eds), 2009. La terra dell'*Auser*. I. Lo scavo di Via Martiri Lunatesi e i paesaggi d'età romana nel territorio di Capannori. Bientina.

Ciampoltrini G., Manfredini R., 2005. Sant'Ippolito di Anniano a Santa Maria a Monte. Preistoria e storia di una pieve sull'Arno. Pontedera.

Colonese, A.C., Zanchetta, G., Fallick, A.E.,Martini, F., Manganelli, G., Lo Vetro, D., 2007. Stableisotope composition of Late Glacial land snail shells from Grotta del Romito (Southern Italy): palaeoclimatic implications. *Palaeogeography. Palaeoclimatology. Palaeoecology*. **254,** 550–560.

Colonese, A.C., Zanchetta, G., Fallick, A.E., Martini, F., Manganelli, G., Drysdale, R.N., 2010. Stable isotope composition of Helix ligata (Müller, 1774) from Late Pleistocene-Holocene archaeological record from Grotta della Serratura (Southern Italy): palaeoclimatic implications. *Global Planetary Change.* **71**, 249–257.

Colonese A. C., Zanchetta G., Fallick A. E., Manganelli G., Lo Cascio P., Hausmann N., Baneschi I., Regattieri, E., 2014. Oxygen and carbon isotopic composition of modern terrestrial gastropod shells from Lipari Island, Aeolian Archipelago (Sicily). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **394**, 119-127.

McCormick, M.; Buentgen, U.; Cane, M.A.; Cook, E.R.; Harper, K.; Huybers, P.; Litt, T.; Manning, S.W.; Mayewski, P.A.; More, A.F.M., Nicolussi K., Tegel W. 2012. Climate change during and after the Roman Empire: Reconstructing the past from scientific and historical evidence. *Journal of Interdisciplinary History*,**43** (2), 169-220..

Cremaschi M., Mercuri M.A, Torri P., Florenzano A., Pizzi C., Marchesini M., Zerboni A., 2016. Climate change versus land management in the Po Plain (Northern Italy) during the Bronze Age: New insights from the VP/VG sequence of the Terramara Santa Rosa di Poviglio. *Quaternary Science Reviews* **136**, 153-172.

Dermody B.J., Boer H.J., Bierkens M.F.P., Weber S.L., Wassen M.J., Dekker S.C. 2012. A seesow in Mediterranean precipitation during the Roman Period linked to millennial-scale changes in the North Atlantic. *Climate of the Past*, **8,** 637-651.

Diodato N., Ljungqvist F.C., Bellocchi G. 2019. A millennium-long reconstruction of damaging hydrological events across Italy. *Scientific Report*, 9:9963 https://doi.org/10.1038/s41598-019-46207-7.

Di Pasquale G., Buonincontri M.P., Allevato E., Saracino A. 2014. Human-derived landscape changes on the northern Etruria coast (western Italy) between Roman times and the late Middle Ages. *The Holocene* **24** (11) 1491– 1502.

Di Rita, F., Lirer, F., Bonomo, S., Cascella, A., Ferraro, L., Florindo, F., Insinga, D. D., Lurcock, P. C., Margaritelli, G., Petrosino, P., Rettori, R., Vallefuoco, M., and Magri, D.: Late Holocene forest dynamics in the Gulf of Gaeta (central Mediterranean) in relation to NAO variability and human impact, *Quaternary Science Reviews*, **179**, 137–152, 2018.

Drysdale, R., Zanchetta, G., Hellstrom, J., Maas, R., Fallick, A.E., Pickett, M., Cartwright, I., Piccini, L., 2006. Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone. *Geology* **34**, 101–104.

Drysdale R., Zanchetta G., J. Hellstrom, Fallick A.E., Zhao J., Isola I., Bruschi G. 2004. The palaeoclimatic significance of a Middle to late Pleistocene stalagmite from the Alpi Apuane karst, central-western Italy. *Earth Planetary Science Letters*, **227**, 215-229.

Durante A. M. (Ed.), 2001. *Città antica di Luni. Lavori in corso*. La Spezia.

Fabiani F., 2006. "… stratam antiquam que est per paludes et boscos …". Viabilità romana tra Pisa e Luni. Pisa.

Fabiani F., Paribeni E. (Eds.), 2012. Il frantoio romano dell'Acquarella. Pisa.

Fabiani F., Paribeni E. (Eds.), 2016. Archeologia a Massa, Scavi all'ombra del Mercurio. Roma.

Fabiani F., Ghizzani Marcìa F., Gualandi M.L., 2013. Dai metodi alla storia: Pisa in età romana e tardoantica. In: Mappa. Metodologie applicate alla predittività del potenziale archeologico, 2. Roma, pp. 161-184.

Finné, M., Holmgren, K., Sundqvist, H.S., Weiberg, E., Lindblom, M., 2011. Climate in the Eastern Mediterranean, and adjacent regions, during the past 6000 years - a review. *Journal of Archaeological Science*, **38**, 3153–3173.

Finné, M., Woodbridge, J., Labuhn, I., Roberts C.N., 2019. Holocene hydro-climatic variability in the Mediterranean: A synthetic multi-proxy reconstruction. The Holocene, **29**, 847–863.

Finné M, Holmgren K, Shen C-C, Hu H-M, Boyd M, Stocker S (2017) Late Bronze Age climate change and the destruction of the Mycenaean Palace of Nestor at Pylos. *PLoS ONE* **12**(12): e0189447.

Fyfe, R.M., Woodbridge, J., Roberts, N., 2015. From forest to farmland: pollen-inferred land cover changes across Europe using the pseudobiomization approach. *Global Change Biology* **20**, 1197–1212.

Fyfe, R. M., Woodbridge, J., and Roberts, C. N. 2018. Trajectories of change in Mediterranean Holocene vegetation through classification of pollen data, Veg. Hist. *Archaeobot.*, **27**, 351–364.

Frova A. (Ed), 1989. Luni. Guida archeologica, Sarzana 1989.

Gervasini L.,2015. Luni e il marmo. In Paribeni E., SegenniS. (Eds), Notae lapicidinarum dalle cave di Carrara. Milano 2015, pp. 35-41.
Gervasini L., Mancusi M., 2014. Da splendida civitas a civitas episcopalis, in E. Scaravella, B. Sisti (Eds), Ecce lignum crucis. Alle origini della fede, La Spezia 2014, pp. 61-63.

Grauel A-L., Goudeau M.-L. S., de Lange G.J., Bernasconi S.M., 2013. Climate of the past 2500 years in the Gulf of Taranto, central Mediterranean Sea: A high-resolution climate reconstruction based on $\delta^{18}O$ and $\delta^{13}C$ of *Globigerinoides ruber* (white). *The Holocene* **23** (10) 1440–1446.

Guaglianone A., 2017. Roma contro il Tevere: le devastazioni delle esondazioni nell'antichità e i tentativi di sottrarre l'Urbe alla furia del fiume. *Forma Urbis*, **10**, 5-12.

Harper K. 2017. The Fate of Rome. Climate, disease and the end of an empire. Princeton University.

Harris W.V. 2013. Defining and Detecting Mediterranean Deforestation, 800 BCE to 700 CE. Harris W.V.(ed): The Ancient Mediterranean Environment between Science and History. *Columbia Studies in the Classical Tradition*, **39**, 73-194.

Isola I., Zanchetta G., Drysdale R.N., Regattieri E., Bini M., Bajo P., Hellstrom J.C., Baneschi I., Lionello P., Woodhead J., Greig A. 2019. The 4.2 ka event in the central Mediterranean: new data from a Corchia speleothem (Apuan Alps, central Italy). *Climate of the Past*, **15**, 135-151.

Kaniewski, D., Paulissen, E., Van Campo, E., et al., 2010. Late second-early fist millennium BC abrupt climatic changes in coastal Syria and their possible significance for the history of the Eastern Mediterranean. *Quaternary Research* **74**, 207–215.

Kaniewski, D., Van Campo, E., Weiss, H., 2012. Drought is a recurring challenge in the Middle East. *PNAS* **109**, 3862–3867.

Kaniewski, D., Marriner, N., Morhange, C., Vacchi, M., Sarti, G., Rossi, V., Bini, M., Pasquinucci, A. C., Otto, T., Luce, F.,Van Campo, E., 2018. Holocene evolution of Portus Pisanus, the lost harbour of Pisa. *Scientific Reports* **8**, 1, 1, 11625.

Knapp AB, Manning SW. Crisis in Context: The End of the Late Bronze Age in the Eastern Mediterranean. *Am. J Archaeol*. 2016; 120: 99. https://doi.org/10.3764/aja.120.1.0099.

Jalali B., Sicre M.-A., Bassetti M.-A., Kallel N., 2016. Holocene climate variability in the North-Wetern Mediterranean Sea (Gulf of Lions). *Climate of the Past*, **12**, 91-101.

Lamb H.H., 1995. Climate History and the Modern World. Second Edition, Routledge, London, 433 pp.

López-Moreno J.I, Vicente-Serrano S.M., Morán-Tejeda E., Lorenzo-Lacruz J., Kenawya A., Beniston M. 2011. Effects of the North Atlantic Oscillation (NAO) on combined temperature and precipitation winter modes in the Mediterranean mountains: Observed relationships and projections for the 21st century. *Global and Planetary Change* **77**, 62–76.

Manacorda D. 2008, *Lezioni di archeologia*, Laterza Ed., Roma-Bari

Manning S.W. 2013. The Roman world and climate: context, relevance of climate change, and some issues. Harris W.V.(ed): The Ancient Mediterranean Environment between Science and History. *Columbia Studies in the Classical Tradition*, **39**, 103-107.

Marcott S.A., Shakun J.D., Clark P.U., Mi, A.C., 2013.A Reconstruction of Regional and Global Temperature for the Past 11,300 Years. *Science*, **39**, 1198-201.

Margaritelli, G., Vallefuoco, M., Di Rita, F., Capotondi, L., Bellucci, L. G., Insinga, D. D., Petrosino, P., Bonomo, S., Cacho, I., Cascella, A., Ferraro, L., Florindo, F., Lubritto, C., Lubritto C., Lurcock, P. C., Magri, D., Pelosi, N., Rettori, R., and Lirer, F. 2016, Marine response to climate changes during the last five millennia in the central Mediterranean Sea, *Global Planetary Change* **142**, 53–72, 2016.

Marino G., Rohling E. J., Rodrìguez-Sanz L., Grant K. M., Heslop D., Roberts A. P., Stanford J. D., Yu J. 2015. Bipolar seesaw control on last interglacial sea level. *Nature*, **522**, 197-201.

Martrat, B., Jimenez-Amat, P., Zahn, R., and Grimalt, J.O., 2014, Similarities and dissimilarities between the last two deglaciations and interglaciations in the North Atlantic region. *Quaternary Science Reviews*, 99, p. 122–134.

McCormick M., Büntgen U., Cane M.A., Cook E.R., Harper K., Huybers P., Litt T., Manning S.W., Mayewski P.A. , More A.F.M., Nicolussi K., Tegel W. 2012. Climate Change during and after the

Roman Empire: Reconstructing the Past from Scientific and Historical Evidence. *Journal of Interdisciplinary History*, **43**(2), 169–220.

Menchelli S., 2003. Pisa nelle rotte commerciali mediterranee dal III secolo a. C. all'età tardoantica. In: Tangheroni M. (Ed.), Pisa e il Mediterraneo. Uomini, merci, idee dagli Etruschi ai Medici. Milano, pp. 99-104.

Menchelli S., 2018. Pisa e la ceramica in età romana e tardoantica: le produzioni locali e le importazioni. In: Baldassarri M. (Ed.), Pisa, città della ceramica. Mille anni di economia e d'arte, dalle importazioni mediterranee alle creazioni contemporanee. Pisa, pp. 59-68.

Mensing S.A., Tunno I., Sagnotti L., Florindo F., Noble P., Archer C., Zimmerman S., Paony-Carrasco F.J., Cifani G., Passigli S., Piovesan G., 2015. 2700 years of Mediterranean environmental change in central Italy: a synthesis of sedimentary and cultural records to interpret past impacts of climate on society. *Quaternary Science Reviews,* **116**, 72-94.

Paribeni E. (Ed.), 1990. *Etruscorum antequam Ligurum*. La Versilia tra VII e III sec. a. C., Catalogo della Mostra (Pietrasanta 1989). Pontedera.

Pasquinucci M., 1995. Colonia Iulia Opsequens Pisana: qualche riflessione sulla città ed il suo territorio. Anna della Scuola Superiore di Pisa XXV, 1-2, 311-317.

Pasquinucci M., 2003. Pisa e i suoi porti in età etrusca e romana. In: Tangheroni M. (Ed.), Pisa e il Mediterraneo. Uomini, merci, idee dagli Etruschi ai Medici. Milano, pp. 93–97.

Pasquinucci M., Menchelli S., 1999. The landscape and the economy of the territories of Pisae and Volaterrae (coastal North Etruria). *Journal of Roman Archaeology* **12**, 122-141.

Pasquinucci M., Mecucci S., Morelli P., 1997. Territorio e popolamento tra i fiumi Arno, Cascina ed Era: ricerche archeologico-topografiche ed archivistiche. In: I Congresso di Archeologia Medievale (Pisa). Firenze, pp. 239- 247.

Piccini L., Zanchetta G., Drysdale R.N., Hellstrom J., Isola I., Fallick A.E., Leone G., Doveri M., Mussi M., Mantelli F., Molli G., Lotti L., Roncioni A., Regattieri E., Meccheri M., Vaselli L., 2008. The environmental features of the Monte Corchia cave system (Apuan Alps, central Italy) and their effects on speleothems growths. *International Journal of Speleology,* **37**(3), 153-173.

Prendergast, A.L., Stevens, R.E., O'Connell, T.C., Hill, E.A., Hunt, C.O., Barker, G.W., 2016. A Late Pleistocene refugium in Mediterranean North Africa? Palaeoenvironmental reconstruction from stable isotope analyses of land snail shells (Haua Fteah, Libya). *Quaternary Science Reviews* **139**, 94–109.

Reale M., Lionello P., 2013. Synoptic climatology of winter intense precipitation events along the Mediterranean coasts. *Natural Hazards Earth System Science,* **13**, 1707-1722.

Regattieri E., Zanchetta G., Isola I., Zanella E., Drysdale R.N., Hellstrom J.C., Zerboni A., Dallai L., Tema E., Lanci L., Costa E., Magrì F. 2019. Holocene Critical Zone dynamics in an Alpine catchment inferred from a speleothem multiproxy record: disentangling climate and human influences. *Scientific Reports,* **9**, 17829.

Regattieri E., Zanchetta G., Drysdale R.N., Isola I., Hellstrom J.C., Dallai L. 2014. Lateglacial to Holocene trace element record (Ba, Mg, Sr) from Corchia Cave (Apuan Alps, central Italy): paleoenvironmental implications. *Journal of Quaternary Science* **29**, 381–392.

Regattieri E., Isola I., Zanchetta, G., Tognarelli, A., Hellstrom, J.C., Drysdale R.N., Boschi, C., Milevski, I., Temovski, M. 2019a. Middle-Holocene climate variability from a stalagmite from Alilica Cave (Southern Balkans). *Alpine and Mediterranean Quaternary*, **32** (1),

Regattieri, E., Zanchetta, G., Isola, I., Bajo, P., Perchiazzi, N., Drysdale R.N., Boschi, C, Hellstrom J., Franke A., Wagner, B., 2018. A MIS 9/MIS 8 speleothem record of hydrological variability from Macedonia (FYROM). *Global and Planetary Change* **162**, 39-52.

Regattieri, E., Giaccio, B., Mannella, G., Zanchetta, G., Nomade, S., Tognarelli, A., Perchiazzi, N., Vogel, H., Boschi, C., Drysdale, R.N., Wagner, B., Gemelli, M., Tzedakis, P.C. 2019b. Frequency and dynamics of millennial-scale variability during Marine Isotope Stage 19: Insights from the Sulmona Basin (central Italy). *Quaternary Science Reviews*, **214**, 28-43.

Regattieri E., Giaccio B., Zanchetta G., Nomade S., Francke A., Vogel H., Drysdale R.N., Perchiazzi N., Wagner B., Gemelli M., Mazzini I., Boschi C. 2017. A Last Interglacial record of environmental changes from the Sulmona basin (Central Italy), *Palaeogeography Palaeoclimatology Palaeoecology* **472**, 51-66.

Roberts N., Jones M.D., Benkaddur A., Eastwood W.J., Filippi M.L., Frogley M.R., Lamb H.F., Leng M.J., Reed J.M., Stein M., Stevens L., Valero- Garcè B., Zanchetta G**.,** 2008, Stable isotope records of Late Quaternary climate and hydrology from Mediterranean lakes: the ISOMED synthesis. *Quaternary Science Review*, **27**, 2426-2441.

Rohling, E.J., Marino, G., Grant, K., 2015. Mediterranean climate and oceanography, and the periodic development of anoxic events (sapropels). *Earth-Science Reviwes* **143**, 62-97.

Sadori L., Giraudi C., Masi A., Magny M., Ortu E., Zanchetta G., Izdebski A. 2016. Climate, environment and society in southern Italy during the last 2000 years. A review of the environmental, historical and archaeological evidence. *Quaternary Science Reviews* **136,** 173-188.

Schneider, A.W., Adalı, S.F., 2014. “No harvest was reaped”: demographic and climatic factors in the decline of the Neo-Assyrian Empire. *Climatic Change* **127**, 435–446

Sicre M.-A., Jalali B., Martrat B., Schmidt S., Bassetti M.-A., Kallel N., 2016. Sea Surface temperature variability in the North Western Mediterranean Sea (Gulf of Lion) durin the Common Era. *Earth and Planetary Science Letters*, **456**, 124-133.

Shepherd E.J. 1995, *Montiscendi (Pietrasanta)*, in *Museo Archeologico Versiliese Bruno Antonucci, Pietrasanta*, Viareggio, pp. 132-140.

Trigo, I.F., Bigg, G.R., Davies, T.D., 2002. Climatology of cyclogenesis mechanisms in the Mediterranean. *Am. Meteorol. Soc*. **130**, 549–569.

Xoplaki, E., Gonzalez-Rouco, J.F., Luterbacher J., Wanner H., 2004. Wet season Mediterranean precipitation variability: influence of large-scale dynamics and trends. *Climate Dynamics*, **23**, 63-78.

Yanes, Y., Romanek, C.S., Molina, F., Cámara, J., Delgado, A., 2011. Holocene paleoenvironment (7200–4000 cal BP) of the Los Castillejos archaeological site (SE Spain) inferred from the stable isotopes of land snail shells. *Quaternary International*, **244**, 67–75.

Villarini G., Smith Ja.A., Serinaldi F., Ntlekosb A.A, Schwarz U. 2012. Analyses of extreme flooding in Austria over the period 1951–2006. *International Journal of Climatology* **32,** 1178–1192.

Zanchetta G., Bonadonna F.P., Leone G., 1999. A 37-meter record of paleoclimatological events from stable isotope data on molluscs in Valle di Castiglione, near Rome, Italy. *Quaternary Research*, **52**, 293-299.

Zanchetta G., Di Vito A., Fallick A.E., Sulpizio R., 2000. Stable isotopes of pedogenic carbonate from Somma-Vesuvius area, Southern Italy, over the last 18 ka: palaeoclimatic implications. *Journal of Quaternary Science*, **15** (8) 813-824.

Zanchetta G., Bini M., Giaccio B., Manganelli G., Benocci A., Regattieri E., Colonese A.C., Boschi C., Biagioni C. 2017. Middle Pleistocene (MIS 14) environmental conditions in the central Mediterranean derived from terrestrial molluscs and carbonate stable isotopes from Sulmona Basin (Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology* **485**, 236–246.

Zanchetta G., Giraudi C., Sulpizio R., Magny M., Drysdale R.N., Sadori L., 2012. Constraining the onset of the Holocene "Neoglacial" over the central Italy using tephra layers. *Quaternary Research*, **78**, 236-247.

Zanchetta G., Bini M., Cremaschi M., Magny M., Sadori L. 2013. The transition from natural to anthropogenic-dominated environmental change in Italy and the surrounding regions since the Neolithic: an introduction. *Quaternary International*, **303**, 1-9.

Zanchetta G., Bini M., Di Vito M.A., Sulpizio R., Sadori L. 2019. Tephrostratigraphy of paleoclimatic archives in central Mediterranean during the Bronze Age. *Quaternary International*, **499**, 186-194.

Zanchetta G., Drysdale R.N., Hellstrom J.C., Fallick A.E., Isola I., Gagan, M., Pareschi M.T. 2007. Enhanced rainfall in the western Mediterranean during deposition of Sapropel S1: stalagmite evidence from Corchia Cave (Central Italy). *Quaternary Science Reviews*, **26**, 279-286.

Zanchetta G., Bar-Matthews M., Drysdale R.N., Lionello P., Ayalon A., Hellstrom J.C., Isola, I., Regattieri E. 2014. Coeval dry events in the central and eastern Mediterranean basin at 5.2 and 5.6 ka recorded in Corchia (Italy) and Soreq Cave (Israel) speleothems. *Global and Planetary Change*, **122**, 130-139.

Zanchetta G., Regattieri E., Isola I., Drysdale R.N, Bini M., Baneschi I., Hellstrom J.C.. 2016. The so-called "4.2 event" in the central Mediterranean and its climatic teleconnections. *Alpine and Mediterranean Quaternary*, **29** (1), 5 – 17.

Zanchetta G., van Welden A., Baneschi I., Drysdale R.N., Sadori L., Roberts N., Giardini M., Beck C., Pascucci V. 2012. Multiproxy record for the last 4500 years from Lake Shkodra (Albania/Montenegro). *Journal of Quaternary Science*, **27**, 780-789.

Zanchettin D., Traverso P., Tomasino M. 2008. Po River discharges: a preliminary analysis of a 200-year time series. *Climatic Change* **89**, 411–433.

Zappa G., Hawcroft M.K., Shaffrey L., Black E., Brayshaw D.J., 2015. Extratropical cyclones and projected decline of winter Mediterranean precipitation in the CMIP5 models. *Climate Dynamics*, **45**, 1727-1738.

Zhornyak L.V., Zanchetta G., Drysdale R.N., Hellstrom J.C., Isola I., Regattieri E., Piccini L., Baneschi I., 2011. Stratigraphic evidence for a "pluvial phase" between ca. 8200-7100 ka from Renella Cave (Central Italy). *Quaternary Science Review*, **30**, 409-417.