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Hydrological changes during the Roman Climatic Optimum in northern Tuscany (Central Italy) as evidenced by speleothem records and archaeological data

M. BINI,[1,2,3]* G. ZANCHETTA,[1,3] E. REGATTIERI,[4,2] I. ISOLA,[2,4] R. N. DRYSDALE,[5,6] F. FABIANI,[7] S. GENOVESI[7] and J. C. HELLSTROM[8]

[1]Dipartimento di Scienze della Terra, University of Pisa, Pisa, Italy
[2]INGV Istituto Nazionale di Geofisica e Vulcanologia, Pisa and Rome, Italy
[3]CIRSEC Centre for Climatic Change Impact, University of Pisa, Italy
[4]IGG-CNR, Pisa, Italy
[5]School of Geography, the University of Melbourne, Victoria, Australia
[6]Laboratoire EDYTEM, UMR CNRS 5204, Université Savoie Mont Blanc, France
[7]Dipartimento di Civiltà e Forme del Sapere, University of Pisa, Pisa, Italy
[8]School of Earth Sciences, The University of Melbourne, Melbourne, Australia

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ABSTRACT: 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 favourable 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 and 4rd centuries AD. Copyright © 2020 John Wiley & Sons, Ltd.

KEYWORDS: climate changes; geoarchaeology; palaeoflooding; Roman Age; 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 (Zanchetta *et al.*, 2013; Anthony *et al.*, 2014; Fyfe *et al.*, 2015, 2018; Bini *et al.*, 2015; 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; Finné *et al.*, 2011, 2017; Schneider and Adalı, 2014; Cremaschi *et al.*, 2016; Sadori *et al.*, 2016). 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 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 and Manning, 2016) especially when decadal- to centennial-scale events are investigated (Finné *et al.*, 2011; Zanchetta *et al.*, 2012a, 2012b, 2019; 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.

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; Dermody *et al.*, 2012; McCormick *et al.*, 2012; Manning, 2013; Margaritelli *et al.*, 2016). Fundamental reviews by McCormick *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 has increased in recent years, particularly in terms of chronological resolution and proxy interpretation (Regattieri *et al.*, 2014; Grauel *et al.*, 2013; Margaritelli *et al.*, 2016), but

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*Correspondence: M. Bini, as above.
E-mail: monica.bini@unipi.it

the records from continental Italy, if we exclude pollen (e.g. Di Rita *et al.*, 2018), remain scarce. By contrast, 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.

The increasing interest on climate variability during Roman Period has been fuelled by historians wishing to understand the growth and decline of the Empire (Harper, 2017) and the significant implications this has for the need to better understand the role of climate variability on society, owing to current global warming (e.g. Büntgen *et al.*, 2011). However, most studies have focused on large-scale reconstructions (e.g. Manning, 2013), while a more detailed approach at local scales comparing palaeoclimate and archaeological data to infer the impact of 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 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 centres 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 to 450 AD; McCormik *et al.*, 2012; Harper, 2017) to evaluate the local expression of the so-called 'Roman Climatic Optimum'.

Site description

Geological and geomorphological setting

The Apuan Alps massif, which rises to ca. 2000 m above sea level, forms the divide between the catchments of the Magra River to the north-west and those of the Serchio River to the north-east. 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 a^{-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 a^{-1} 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 (Drysdale *et al.*, 2004). The carbon isotope composition ($\delta^{13}C$) of dissolved inorganic carbon (DIC) is

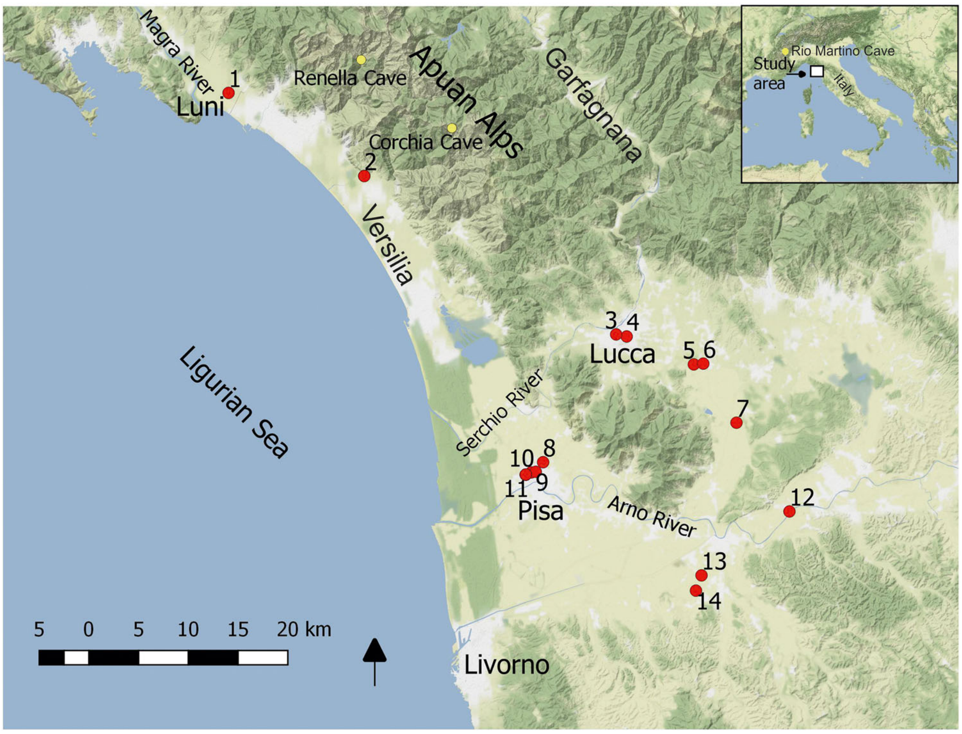

Figure 1. Location map. Red circles = archaeological sites investigated (each number corresponds to a different site listed in Table 1), yellow circles = investigated caves.

similarly constant (ca. −4‰; Baneschi *et al.*, 2011), and reflects the low contribution from biogenic CO_2 due to the thin vegetation cover, low 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 consistent 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 in 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 remain incomplete (Zanchetta *et al.*, 2016). 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 of 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). After 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 expansion in this district, which between the 3rd and 2nd centuries BC provided Rome with the logistical bases for the conquest of Sardinia and of the territories occupied by Galli and Ligurians.

The Portus Pisanus (Kaniewski *et al.*, 2018) and numerous landings along the coast served by the Aurelia coastal road (probably already joining Rome to Pisa by 241 BC) were 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 Ligurian raids prompted 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).

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

Within this framework, the Auser and 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 to 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 (Pasquinucci and Menchelli, 1999; Fabiani and Paribeni, 2012, 2016). 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 considerable changes to the economy (Frova, 1989; Gervasini and Mancusi, 2014; Gervasini, 2015). The trade in marble came to an end during the 4th 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 buildings testify to 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), as indicated by the abandonment and spoliation of many domi. This phase ended in the 3rd and 4th centuries AD, when new building programmes, mainly focused 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 buildings (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).

With 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, there was an abandonment of the northern suburbs and the progressive occupation of the latter by cemeteries, both testifying to a contraction of the urban space. Despite these factors and of a progressive crisis within 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 speleothems CC26 and RL4 have been extensively discussed in previous papers (Drysdale *et al.*, 2006; Zanchetta *et al.*, 2007). 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 that of Bajo *et al.* (2017), but is similarly accurate.

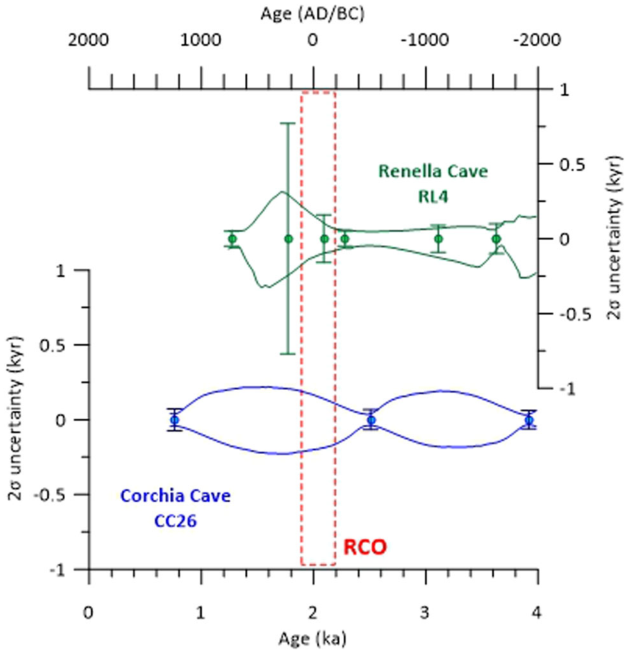

Figure 2. Age model showing 95% confidence intervals for RL4 and CC26 (Drysdale *et al.*, 2006; Zanchetta *et al.*, 2007). The red dashed lines highlight the period discussed in the text.

Figure 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 and 7 years, 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 years 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 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 the 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 was inferred from 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 to conditions of hydrogeological instability, possibly due to general climatic deterioration. Although these data must be treated with caution, they are of decisive importance in understanding not only the evolution of climatic variations but also the anthropogenic reaction to these events. The selected sites record 24 events in total, including alluvial phases, single floods and selected anthropic hydraulic interventions (Table 1). Figure 3 shows the rationale used to manage and integrate data from the palaeoclimatic and archaeological sources.

Results and discussion

Palaeohydrological interpretation of speleothem proxy records

For comparison, we show the high-resolution δ^{18}O record of RL4 (Zanchetta *et al.*, 2016) and the 'mean anomaly index' obtained from stalagmite CC26 (Regattieri *et al.*, 2014) (Fig. 4). This index was obtained by combining detrended, smoothed and normalized Mg/Ca, δ^{18}O and δ^{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 δ^{18}O record as a good indicator of effective recharge over the cave catchment, because the cave is shallower and responds rapidly to changes in hydrology. For RL4, the interpretation of δ^{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 years per data point across the considered interval) to be compared with the high-resolution isotope data of Zanchetta *et al.* (2016), and cannot be used to produce a comparable 'mean anomaly index' similar to the CC26 record.

Speleothem δ^{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; Finné *et al.*, 2017; Bini *et al.*, 2019; Regattieri *et al.*, 2018, 2019a), with lower δ^{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 quite small (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

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

No.	Site	Location	Events	Chronology	Bibliography
1	Luni	*Luni* – urban center	Single flood	380–400 AD	Durante (2001)
2	Montiscendi	*ager Lunensis*	Alluvial phase	101–120 AD.	Shepherd (1995)
			Alluvial phase	290–400 AD?	
3	Lucca, 'Miracolo di S. Frediano'	*Luca* – northern suburb	Auser river course deviation	550–575 AD	Gregorius Magnus, *Dialogues*, III, 1; Ciampoltrini (2011)
4	Lucca, Orti di San Francesco	*Luca* – eastern suburb	Alluvial phase	10–20 AD	Ciampoltrini (2007)
5	Frizzone, Casa del Lupo	*ager Lucensis*	Land reclamation intervention	1–100 AD	Ciampoltrini and Giannoni (2009)
6	Casa del Lupo	*ager Lucensis*	Alluvial phase	27 BC to 14 AD	Ciampoltrini (2004)
7	Botronchio, Orentano	*ager Lucensis*	Alluvial phase	50–100 AD	Ciampoltrini and Andreotti (1993)
			Alluvial phase/waterlogging	401–500 AD	
8	Via di Gello	*Pisae* – northern suburb	Single flood	90–110 AD	*MappaGis*, data sheets Nos. 133, 351 (http://mappagis.cs.dm.unipi.it:8081/mappa/mappa.phtml)
9	Arena Garibaldi	*Pisae* – northern suburb	Land reclamation intervention	75–100 AD	*MappaGis*, data sheet No. 169 (http://mappagis.cs.dm.unipi.it:8081/mappa/mappa.phtml)
10	Via Galluppi	*Pisae* – northern suburb	Alluvial phase	110–10 BC	Anichini *et al.* (2009)
			Alluvial phase	1–50 AD	
11	S. Rossore	*Pisae* – northern suburb	Single flood (Hellenistic shipwreck)	200–170 BC	Benvenuti *et al.* (2006); Mariotti Lippi *et al.* (2007); Camilli (2005, 2012); Camilli and Setari (2005); Camilli *et al.* (2006)
			Single flood (shipwreck M)	50–1 BC	
			Single flood (shipwrecks E, G, B, C)	1–15 AD	
			Single flood (shipwrecks H, F, N)	117–138 AD	
			Single flood (shipwreck A); alluvial phase	250–280 AD	
			Alluvial phase (shipwrecks I, Q, L)	390–410 AD	
			Single flood (shipwreck O)	401–600 AD	
12	S. Ippolito di Anniano	*ager Lucensis* (?)	Single flood?	301–500 AD	Ciampoltrini and Manfredini (2005)
13	Le Melorie	*ager Pisanus*	Alluvial phase	200–1 BC	Pasquinucci *et al.* (2008)
14	Padule di Lavaiano	*ager Pisanus*	Alluvial phase/waterlogging	201–500 AD	Pasquinucci *et al.* (1997)

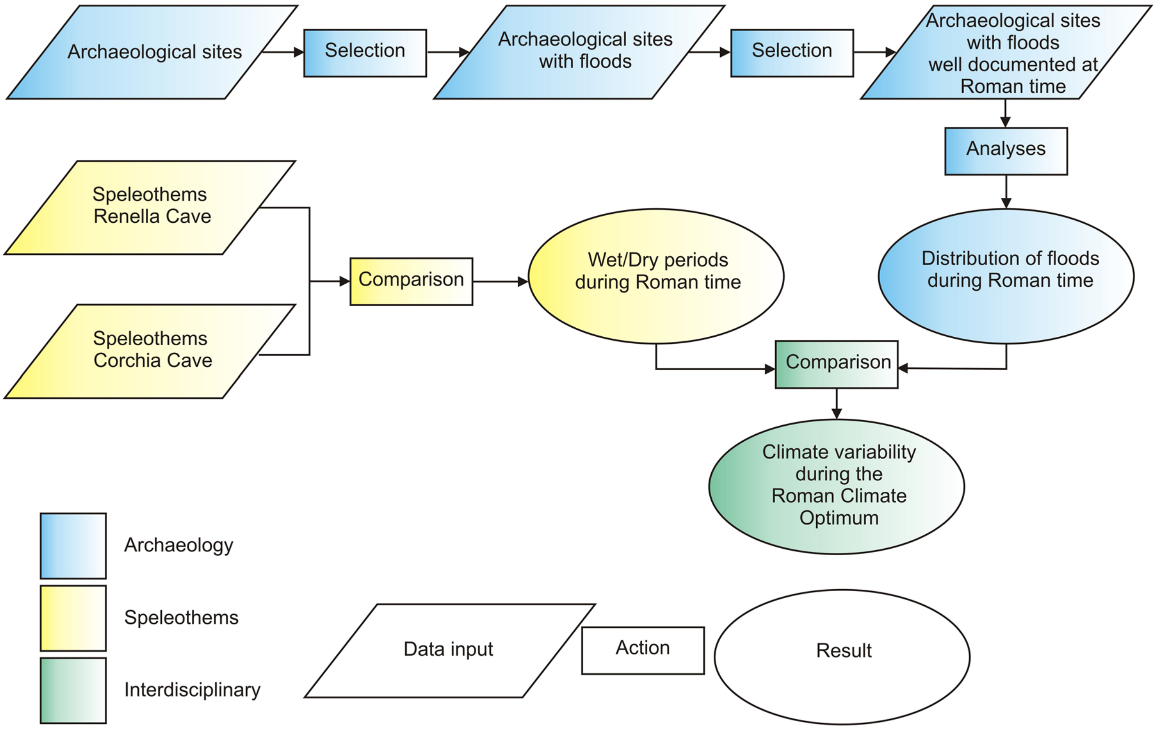

Figure 3. The methodological approach applied in this work.

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; Boretto *et al*., 2017), lacustrine carbonate (Zanchetta *et al*., 1999, 2012; Roberts *et al*., 2008; Regattieri *et al*., 2017, 2019b), 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 precipitation is higher (Piccini *et al*., 2008; Baker *et al*., 2019). However, the large and well-mixed plumbing system dampened 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 $\delta^{13}C$ record (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 $\delta^{18}O$, indicating that there is no a detectable signal of evaporation (Zanchetta *et al*., 2016).

Given these potential differences, and the inherent limitation of comparing two different age models not specifically built for investigating this period (between 3000 and 1500 years 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 centred 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 years, which can be attributed to uncertainty in age, keeping also in mind the relatively large uncertainty (ca. ±100 years) 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 years BP (within 100 BC), representing ca. 20–30 years of driest conditions (Fig. 4). This period is followed by a sharp transition to a century of wetter conditions (ca. 2000–1900 years BP, end of the 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

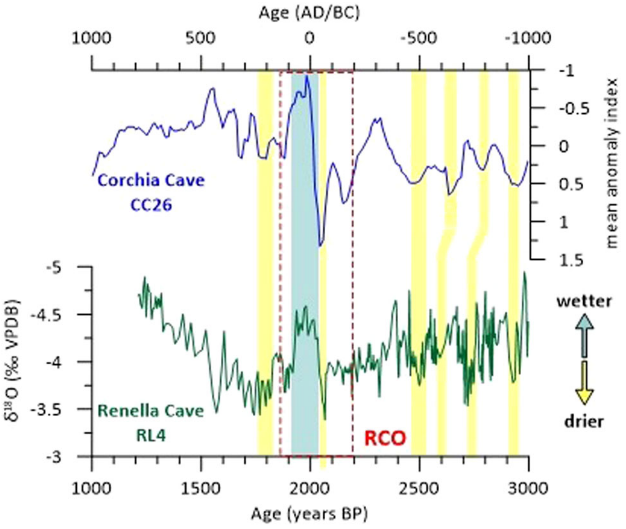

Figure 4. The $\delta^{18}O$ record of RL4 (Zanchetta *et al*., 2016) and Mean Anomaly Index for stalagmite CC26 (Regattieri *et al*., 2014). The Roman Climatic Optimum period (RCO) Harper, 2017) is highlighted. Yellow bands: drier intervals; light blue bands: period of inferred wetter conditions.

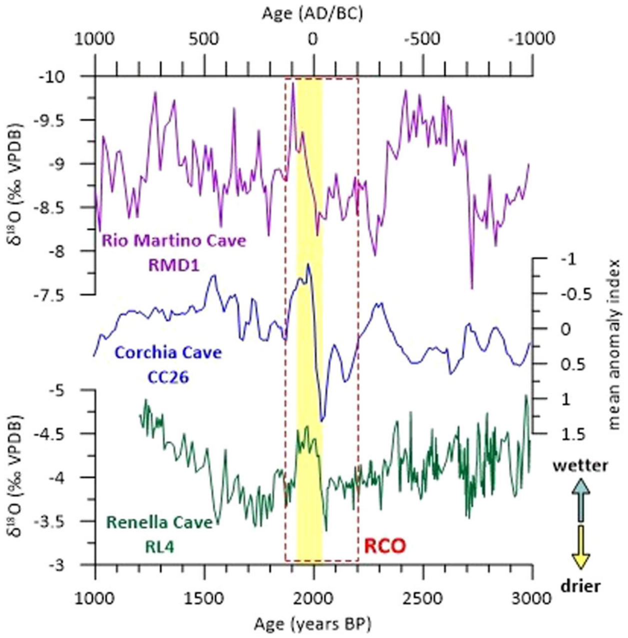

Figure 5. Comparison between RL4 and CC26 records and the Rio Martino δ^{18}O record (Regattieri *et al.*, 2019). The Roman Climatic Optimum period (RCO) (Harper, 2017) is highlighted. For the location of Rio Martino Cave, see Fig. 1.

century BC. Since then the two records have shown some significant differences. RL4 records 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 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 1st century BC). Interestingly, the dry period followed by a wetter one is consistent for this interval with a new δ^{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 (McCormick *et al.*, 2012) have 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 as prominent when considering the whole Holocene variability (Drysdale *et al.*, 2006; Zanchetta *et al.*, 2007, 2014; Regattieri *et al.*, 2014).

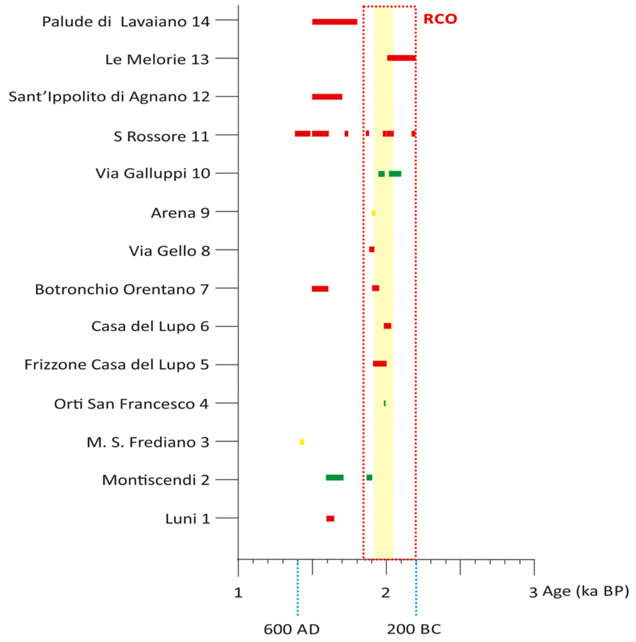

Figure 6. Recurrence of floods in the archaeological records for the studied area (see Fig. 1 and Table 1 for location). Flood events documented in archaeological excavations (red lines), alluvial phases documented in archaeological site (green lines) and hydraulic intervention (yellow lines). The period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

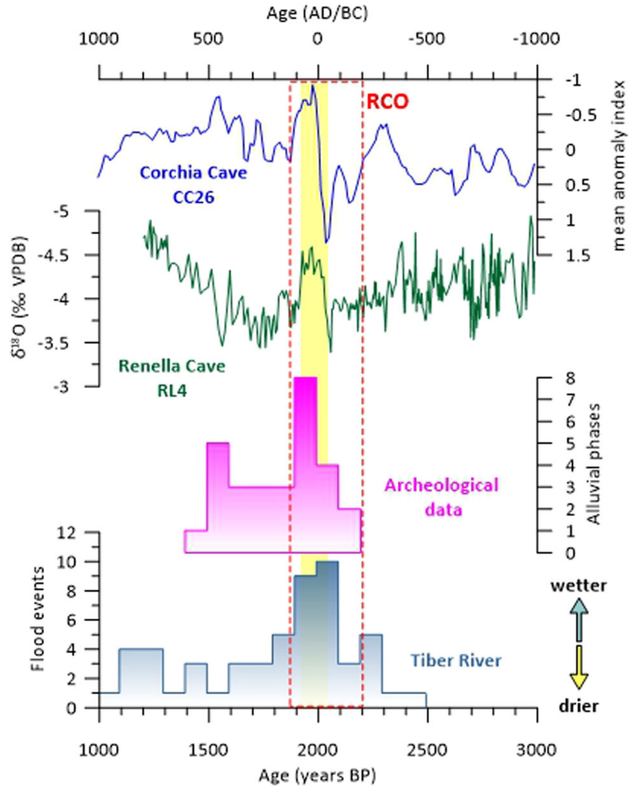

Figure 7. RL4 and CC26 records compared with floods inferred from archaeological data (source Table 1) and Tiber River flood historical records (data from Aldrete, 2007). The chronology of floods obtained from the archaeological data were spread over a century. This can produce some differences between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

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 provides several lines of evidence for 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-called 'Hellenistic shipwreck' of S. Rossore (Camilli and Setari, 1st century BC (Via Galluppi, site no. 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 no. 10; Anichini *et al.*, 2009; Le Melorie, site no. 13; Pasquinucci *et al.*, 2008). Nevertheless, there was an increase in the number 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 no. 4; Ciampoltrini, 2007), Botronchio (site no. 7; Ciampoltrini and Andreotti, 1993) and Casa del Lupo (site no. 6; Ciampoltrini, 2004); close to the last of these, the anthropogenic response to these natural events is testified by a land reclamation intervention, indicated by an amphora-shaped structure at the site of Frizzone, Casa del Lupo (no. 5; Ciampoltrini and Giannoni, 2009). At S. Rossore in Pisa, several wrecks (no. 11; ships B, C, E, G and M; Camilli and Setari, 2005; Camilli *et al.*, 2006; Camilli, 2012) have been 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 no. 8; *MappaGis*, mappagis.cs.dm.unipi.it:8081/mappa/mappa.phtml, data sheets 133 and 351) and at Via Galluppi (site no. 10; Anichini *et al.*, 2009). As already noted for Lucca, amphorae structures were put in place in the northern suburbs, along the Auser river course (site no. 9; *MappaGis*, mappagis.cs.dm.unipi.it:8081/mappa/mappa.phtml, data sheet 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 centuriation may sometimes have conflicted with the delicate hydrogeological systems of the environment where it had been introduced. It is also important to consider that although the system favoured 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 references therein: Fig. 7) interestingly mimic (within age errors) the general trend of wetter/drier conditions described by the speleothem records between about the 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 about the 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 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*, mappagis.cs.dm.unipi.it:8081/mappa/mappa.phtml, data sheet 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 no. 2; Shepherd, 1995) and in the shipwreck H, F, N at Pisa, S. Rossore (site no. 11), match with speleothem proxies, thus testifying to a period of drier climatic conditions.

Regarding the climatic conditions through the middle and late Imperial Age (200–450 AD), archaeological data from the study area highlight a new increase in alluvial events (Fig. 6). Unfortunately, the archaeological and speleothem data cannot be correlated in detail for this same period. The speleothem data are in fact inconsistent, as Renella Cave is the only one testifying to a new increase in humid climatic conditions (Fig. 4). For example, single floods are recorded at Luni (site no. 1; Durante, 2001) and in its territory (Montiscendi no. 2; Shepherd, 1995) during the 4th century AD.

The most convincing evidence for this trend are the several shipwrecks of Pisa (site no. 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 and L) and of the 5th centuries AD (ship O). The wrecks reflect long-lasting alluvial phenomena testified in the *ager Pisanus* by the progressive waterlogging phase in the south-eastern sector of the centuriated area (site no. 14; Pasquinucci *et al.*, 1997). The hydrogeological instability of the Arno River valley is indicated by a single flood recorded at S. Ippolito di Anniano, dated between the 4th and 5th centuries AD (no. 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 (no. 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 no. 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). Floods are generally recorded only when they create damage to properties and injure people. By contrast, 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 NAO phases (Villarini *et al*., 2012 and references therein). Historical reconstruction of the last 1000 years 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 depends strongly on NAO conditions during winter. 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 the 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 (Bini *et al*., 2019; Isola *et al*., 2019), which usually corresponds to winter (Piccini *et al*., 2008). Thus, reduced precipitation during the Republican Period, peaking in the 1st century BC, should be related to a decrease in the arrival of cyclones from the North Atlantic, and consequently to a decrease in secondary cyclogenesis over the Gulf of Genoa (Isola *et al*., 2019). However, a decline in winter precipitation is related not only 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 the NAO (Xoplaki *et al*., 2004; López-Moreno *et al*., 2011), whereas negative phases of the NAO give rise to a higher frequency of cyclones and precipitation (Reale and Lionello, 2013), and, as suggested by the data presented here, to floods.

Concluding remarks

Speleothem records from the Apuan Alps indicate that during the Roman Age the north-western part of Tuscany experienced a period of oscillating climatic conditions, with a particularly pronounced multidecadal dry event during the 1st 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. Our 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. These conditions could correspond to a persistent negative NAO index. Unfortunately, it is not possible to extend the correlation between speleothem records and archaeological data further 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 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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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Abbreviations. DIC, dissolved inorganic carbon; NAO, North Atlantic Oscillation; RCO, Roman Climatic Optimum.

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