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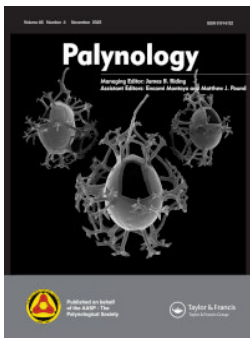
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# High-resolution Bronze Age palaeoenvironmental change in the Eastern Mediterranean: exploring the links between climate and societies

Calian J. Hazell , Matthew J. Pound  and Emma P. Hocking 

Department of Geography & Environmental Sciences, Northumbria University, Newcastle upon Tyne, UK

## ABSTRACT

Bronze Age archaeological records from the eastern Mediterranean identify two periods of widespread so-called societal 'collapse' between ca. 4.50–ca. 4.20 cal ka BP and ca. 3.50–ca. 2.80 cal ka BP, respectively, which have been linked to a number of proposed causes, including climate change. However, the role of climate change in the 'collapse' of eastern Mediterranean Bronze Age societies has been questioned due to the resolution of climate proxy records. In this paper we present a regional synthesis of the highest resolution palaeoclimate records and compare these to archaeological evidence. By recalibrating radiocarbon dates onto a consistent timescale and using pollen, oxygen and carbon isotopes from both marine and terrestrial deposits, we reconstruct aridity at a 50-year resolution. Our results challenge a simple 'climate destroyed society' hypothesis. Instead, we find a more complex record of changing aridity and societal response and provide a nuanced perspective on climate versus non-climate causes of Bronze Age societal 'collapse' events. Our results have implications for the generation of palaeoclimate records aimed at exploring links between climate and societal change, emphasising the need for high resolution records proximal to archaeological sites.

## KEYWORDS



Pollen; stable isotopes; Mediterranean; archaeology; synthesis; societal collapse


## 1. Introduction

The Mediterranean basin is the largest area on Earth to experience a climate of summer drought and winter rain of cyclonic origin (Roberts et al. 2004). Throughout the Holocene, the Mediterranean region has been highly sensitive to climate variability, with pronounced and often geographically variable environmental responses to global climatic events (Lionello 2012), and a complex atmospheric circulatory system (Roberts et al. 2004; Robinson et al. 2008). It is the epicentre where three global climate forcing mechanisms meet, with the African-Arabian/Asian monsoon exerting greater control in the summer (Russell, Talbot, et al. 2003; Alpert et al. 2006; Baioumy et al. 2010; Triantaphyllou et al. 2014), the Siberian High dominating springtime climates (Rohling et al. 2002; Geraga et al. 2010; Roberts et al. 2012), and the North Atlantic Oscillation (NAO) affecting winter conditions (Kaniewski et al. 2015; Katrantsiotis et al. 2019). Evidence suggests a cyclic nature in the extremes of these climatic regimes, typically oscillating every ~1500 years with the NAO (Mayewski et al. 1997; Bianchi and Mccave 1999; Bond et al. 2001) and 2300–2500 years with the Siberian High (Denton and Karlén 1973; Van Campo and Gasse 1993; Bianchi and Mccave 1999; Rohling et al. 2002). The coincidence of these cyclic events can result in widespread, abrupt, and rapid centennial-scale shifts in

Mediterranean climates (Mayewski et al. 2004; Finné et al. 2019; Rohling et al. 2019).

Palaeoclimate and archaeological research frequently converges in interests during the Mediterranean Bronze Age, most broadly dated from ca. 5.66–2.75 ka BP (Litt et al. 2009), when two widespread cold and arid centennial-scale abrupt climate change events are recorded. The first is termed the 4.2K Event, and is reported between 4.50 and 3.90 ka BP (Roberts et al. 2011), the shorter range of 4.50–4.20 ka BP (Kaniewski et al. 2008; Mercuri et al. 2011; Guiot and Kaniewski 2015; Finné et al. 2019), and more specifically at ca. 4.30 ka BP (Guiot and Kaniewski 2015), ca. 4.20 ka BP (Mercuri et al. 2011), and ca. 4.00 ka BP (Mauri et al. 2015). The second is termed the 3.2K Event and occurred in two distinct phases, the first comprising a cold and arid interval from 3.50 to 3.30 ka BP (Kaniewski et al. 2008; Kaniewski et al. 2010; Finné et al. 2019) and the second a cold and wet interval between 3.10 and 2.90 ka BP (Mayewski et al. 2004; Incarbona et al. 2008; Rohling et al. 2019) that typically featured a three-pulse arid-wet-arid event between 3.35 and 2.80 ka BP (Roberts et al. 2011; Drake 2012; Kaniewski et al. 2013; Mercuri and Sadori 2013; Mauri et al. 2015; Kaniewski et al. 2019). It is widely theorised that these climate change events contributed to two intervals of large-scale so-called societal 'collapse' throughout the Mediterranean (Carpenter 1966; Neumann and Parpola 1987; Weiss et al. 1993; Weiss

**CONTACT** Calian J. Hazell  [c.j.hazell@northumbria.ac.uk](mailto:c.j.hazell@northumbria.ac.uk)  Department of Geography & Environmental Sciences, Northumbria University, Ellison Building, Newcastle upon Tyne, NE1 8ST UK

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in assessing the potential role of climate change in so-called societal ‘collapse’ events, surrounds the resolution of palaeoclimate records (Finné et al. 2011; Holmgren et al. 2016; Knapp and Manning 2016; Homsher and Cradic 2017). With the exceptions identified in this paper, many Bronze Age palaeoclimate records suffer from poor chronological control and low-resolution analyses of single proxy records. From an archaeological perspective, (bi-)annual chronologies are ideal for identifying societal shifts, with sub- and multi-decadal records considered adequate and low resolution respectively (Knapp and Manning 2016). Most palaeoclimate records provide multi-centennial resolution, and sub-decadal palaeoclimate records are uncommon, typically restricted to speleothem/varved lake deposits (Wick et al. 2003; Ruan et al. 2016) (Supplementary 1). This makes direct correlation between climatic and societal shifts difficult from both chronological and geographical perspectives (Finné et al. 2011; Butzer and Endfield 2012; Knapp and Manning 2016; Homsher and Cradic 2017). It is possible to use written documentary evidence to accurately date specific climatic events where radiocarbon dating results are of a low resolution (Bronk Ramsey et al. 2010), however where no such written documentary evidence is available, another approach is to take a regional perspective and explore the geographical distribution of climate change (Berger et al. 2016). There is also uncertainty regarding the ability to accurately correlate climatic events between different studies that implement different radiocarbon calibration schemes (Finné et al. 2019). This uncertainty can be addressed by recalibrating radiocarbon datasets using a single calibration scheme, a method that has not been utilised by previous climatic syntheses (Finné et al. 2019). Whilst recent syntheses of Mediterranean climate change records have advanced understanding, these have been focussed at coarser spatial (Bini et al. 2019) or temporal (Drysdale et al. 2006) resolution, and have identified rather than addressed chronological issues.

A further issue is one of anthropogenic obfuscation and what constitutes a definitive anthropogenic signal in pollen datasets. For instance, *Olea* has been considered both

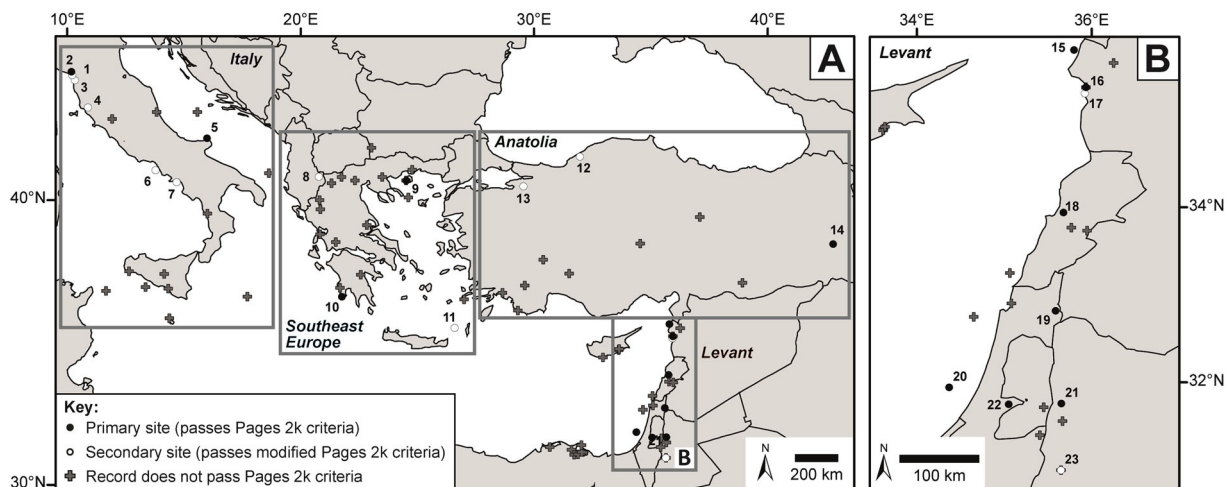
indicative of wild xerophilous/sclerophyllous forest/shrub habitats (Prentice et al. 1996; Tarasov et al. 1998; Wick et al. 2003; Neumann, Schözel, et al. 2007; Colombaroli et al. 2008; Allen et al. 2009; Collins et al. 2012; Fall 2012; Kaniewski et al. 2013; Sadori et al. 2013; Gambin et al. 2016), and also indicative of agriculture (Bordon et al. 2009; Litt et al. 2012; Langgut et al. 2016; Margaritelli et al. 2016; Miebach et al. 2016; Sorrel and Mathis 2016).

This paper therefore aims to thoroughly evaluate potential correlation between periods of climatic (aridity) change and intervals of known societal ‘collapse’ between ca. 4.50 and 2.80 cal ka BP throughout central and eastern Mediterranean regions: Italy, southeast Europe, Anatolia, and the coastal Levant encompassing Syria, Lebanon, Israel and Jordan. A regional synthesis is produced using only standardised palaeoclimate records of the highest temporal resolution, and pollen datasets are subject to multivariate statistical ordination in an effort to associate different assemblage components with anthropological or natural affinities that could otherwise be overlooked. Previously published palaeoenvironmental records are tested against the established data selection criteria of the Pages 2K consortium (PAGES 2k Consortium T 2014), and proxy records with 50 year resolution chronologies have been recalibrated to the same calibration curve. This dataset is then used to evaluate the role of abrupt climate change events during the EBAC and LBAC in the eastern Mediterranean.

## 2. Materials and methods

### 2.1. Synthesis of palaeoclimate records

From a search of peer-reviewed literature presenting palaeoclimate proxy datasets from the eastern Mediterranean, 92 studies were found covering the Bronze Age from 4.50 to 2.80 ka BP (Figure 2; Table 1; Supplementary 1). A recent synthesis of Mediterranean climate change through the Holocene focused on hydro-climate proxies and therefore excluded pollen-based reconstructions that can be affected



**Figure 2.** Location of sites providing palaeoclimate and archaeological records in the (a) eastern Mediterranean and (b) Levant. Full details of Pages 2k criteria used to define ‘primary’ and ‘secondary’ sites are provided in the methods section. Site location numbers refer to Table 1, which provides more detailed information about each palaeoclimate record.

Table 1. Details and references of sites that passed the dating and sample resolution.

Site ID	Site	Region	Latitude (°N)	Longitude (°E)	Original publication	Record type	Original ID	Dating method	Proxies		
Primary	2	Renella Cave, Apuane Alps	Italy	44.1	10.18	Zanchetta et al. (2016)	Speleothen	RL4	U/Th (years before 1950)	$\delta^{18}\text{O}$ , $\delta^{13}\text{C}$	
	5	Adriatic Sea	Italy	42	16	Piva et al. (2008)	Marine sediment core	AMC99-1	Radiocarbon	$\delta^{18}\text{O}$	
	9	Skala Marion Cave, Thasos	Southeast Europe	40.64	24.51	Psmiadis et al. (2018)	Speleothen	A. MAR_L	U/Th (years before 1950)	$\delta^{18}\text{O}$ , $\delta^{13}\text{C}$	
	10	Mavri Trypa, Peloponnesus	Southeast Europe	36.74	21.76	Finné et al. (2017)	Speleothen	S1(mt)	U/Th (years before 1950)	$\delta^{18}\text{O}$ , $\delta^{13}\text{C}$	
	14a	Lake Van, Taurus Mountains, Turkey	Anatolia	38.53	42.8	Wick et al. (2003)	Lacustrine sediment core	Van 90-10	Varve years before 1990	Pollen, $\delta^{18}\text{O}$	
	14b	Lake Van, Taurus Mountains, Turkey	Anatolia	38.53	42.8	Şimşek and Çağatay (2018)	Lacustrine sediment core	V08G04	Varve years before 2008	$\delta^{18}\text{O}$ , $\delta^{13}\text{C}$	
	15	Ebla, Idlib Governorate, Syria	Levant	35.8	35.8	Fiorentino et al. (2008)	Terrestrial organic matter (outcrop)	LTL (i), VERA (1) (ii)	Radiocarbon	$\delta^{13}\text{C}$	
	16	Tell Tweini, Jableh, Syria	Levant	35.37	35.94	Kaniewski et al. (2011)	Terrestrial organic matter (wall profile)	-	Radiocarbon	$\delta^{13}\text{C}$	
	18	Jeita Cave, Beirut, Lebanon	Levant	33.94	35.64	Verheyden et al. (2008)	Speleothen	JeG-stm-1	U/Th (years before 2006)	$\delta^{18}\text{O}$ , $\delta^{13}\text{C}$	
	19	Lake Kinneret, Israel	Levant	32.82	35.59	Schiebel and Litt (2018)	Lacustrine sediment core	K10(comp)	Radiocarbon	Pollen	
	20	Ashdod Coast, Israel	Levant	31.94	34.37	Schilman et al. (2001)	Marine sediment core	GA-112	Radiocarbon	$\delta^{18}\text{O}$ , $\delta^{13}\text{C}$	
	21	Ein Gedi Shore, Dead Sea, Israel	Levant	31.76	35.65	Litt et al. (2012)	Lacustrine sediment core	KIA5/1/9	Radiocarbon	Pollen	
	22	Soreq Cave, Judean Mountains, Israel	Levant	31.75	35.05	Schilman et al. (2002); Bar-Matthews and Ayalon (2011)	Speleothen	Compliation; 2-N	U/Th (years before 1950)	$\delta^{18}\text{O}$ , $\delta^{13}\text{C}$	
	Secondary	1	Corchia Cave, Apuan Alps	Italy	43.98	10.22	Regattieri et al. (2014)	Speleothen	CC26	U/Th (years before 1950)	$\delta^{18}\text{O}$ , $\delta^{13}\text{C}$
		3	Lago di Massaciuccoli, Tuscany	Italy	43.98	10.33	Colombaroli et al. (2007)	Lacustrine sediment core	LML, LMM	Radiocarbon	Pollen
4		Lake Accessa, Tuscany	Italy	43.98	10.88	Peyron et al. (2011); Magny et al. (2007)	Lacustrine sediment core	AC3/4, VERA (2)	Radiocarbon	Pollen	
6		Gulf of Gaeta, Tyrrhenian Sea	Italy	43.98	13.78	Margaritelli et al. (2016)	Marine sediment core	SW104-C5	Radiocarbon <sup>108</sup>	$\delta^{18}\text{O}$	
7		Salerno Gulf, Tyrrhenian Sea	Italy	43.98	14.7	Lirer et al. (2013, 2014)	Marine sediment core	C90, C836	Radiocarbon	$\delta^{18}\text{O}$	
8		Lake Maliq, Albania	Southeast Europe	43.98	20.78	Bordon et al. (2009)	Lacustrine sediment core	MALIQS1	Radiocarbon	Pollen	
11		Aegean Sea, Greece	Southeast Europe	43.98	26.58	Rohling et al. (2002)	Marine sediment core	LC21	Radiocarbon	$\delta^{18}\text{O}$	
12		Sofular Cave, Zonguldak, Turkey	Anatolia	43.98	31.95	Gökürk et al. (2011)	Speleothen	So-1	U/Th (years before 1950)	$\delta^{13}\text{C}$	
13		Lake Izmik, Bursa Province, Turkey	Anatolia	43.98	29.54	Miebach et al. (2016)	Lacustrine sediment core	LC1	Radiocarbon	Pollen	
17		Tell Sukas, near Jableh, Syria	Levant	43.98	35.92	Sorrel and Mathis (2016)	Marine sediment core	TSII	Radiocarbon	Pollen	
23		Mount Sedom, Israel	Levant	43.98	35.65	Frumkin (2009)	Terrestrial organic matter (tree branch)	SN5	Radiocarbon	$\delta^{13}\text{C}$	

by temperature changes (Finné et al. 2019). In this paper pollen records were included for both their climatic (e.g. Bini et al. 2019) and anthropogenic inferences. A second recent climatic synthesis aimed to gather a wide regional coverage using 62 records, and so included records with a relatively low resolution and age controls (Bini et al. 2019). This paper takes an opposite novel approach, aiming to assess the chronological and proxy resolution of each study using the internationally agreed PAGES 2k criteria (PAGES 2k Consortium T 2013, 2014). In this way, all sites utilising pollen or isotope data that featured a continuous age model allowing for interpolation of proxy data were identified. For sites with two or more publications on a single proxy type, preference was given to the most recent record for quantitative analyses. Twelve records passed the original PAGES 2k guidelines ('primary sites') and a further eleven records satisfied less stringent criteria ('secondary sites') (Table 1). The testing criteria used were; record duration (minimum 500/300 years for primary/secondary sites), chronological accuracy (dating constraints near the start and the end of the record with a minimum average dating resolution of 500/800 years for primary/secondary sites), proxy resolution (minimum average proxy resolution of 200/350 years for primary/secondary sites), and data availability (raw primary data available in a peer-reviewed publication). At passing sites, palaeoclimate proxy data were extracted at 50 year intervals from the original publications. As there are a number of passing sites that feature proxy resolutions that are greater than 50 years (Supplementary 1), this was achieved by normalising pollen datasets followed by the application of Principal Component Analysis (PCA) (see Section 2.3), or standardising isotope datasets to normal values (see Section 2.2), and then interpolating the results to allow for proxy data extraction at a 50 year resolution. This is similar to the data synchronisation method featured in a recent climatic synthesis, where isotope records were transformed into regional z-scores and then extracted at a 200 year resolution (Finné et al. 2019). As noted by the authors, this method of greater data manipulation resulted in a failure to capture shorter intervals of dry/cold climates, for instance the 4.2K and 3.2K Events (Finné et al. 2019). In this paper therefore, a simpler transformation to normal values was utilised for isotope datasets, along with PCA for pollen assemblages, allowing for the implementation of higher resolution intervals for proxy extraction. These methods of data standardisation and interpolation are justified in this case, as it is not absolute values of proxies that are of importance to the environmental reconstructions of the study, but the relative positivity or negativity of standardised trends over time. Isotope data were extracted between 4.50 and 2.80 cal ka BP, whereas full pollen records were used to enable understanding of longer term vegetation changes.

Fifteen of the original publications utilised radiocarbon dating methods, while seven used uranium-thorium dating, and two used varve counting. Varved records were also required to contain  $^{14}\text{C}$  or U/Th point dates that passed the PAGES 2K dating resolution, and all dates were standardised to years before 1950 (Table 1). For the radiocarbon studies,

the original authors calibrated radiocarbon ages using different calibration curves and applied different marine reservoir corrections (where applicable), a factor that has been previously identified as introducing uncertainty and yet also not previously addressed in a recent climatic syntheses (Finné et al. 2019). In this paper all original published dates were recalibrated in Calib 7.0.4, using the updated IntCal13 calibration curve for terrestrial ages and Marine13 curve for marine ages (Reimer et al. 2013) with the standard global marine reservoir correction ( $\Delta R$ ) value of 400 years (Stuiver and Braziunas 1993).

## 2.2. Palaeoclimate proxy records

Seven lacustrine sediment cores, six marine sediment cores, seven speleothems, and three terrestrial organic matter archives (a sediment outcrop, an archaeological trench section and a fossilised tree branch cross section) provided palaeoclimate data of sufficient resolution (Figure 2; Table 1). This resulted in a total of eight pollen assemblages, thirteen oxygen isotope profiles, and thirteen carbon isotope profiles (Figure 3; Table 1).

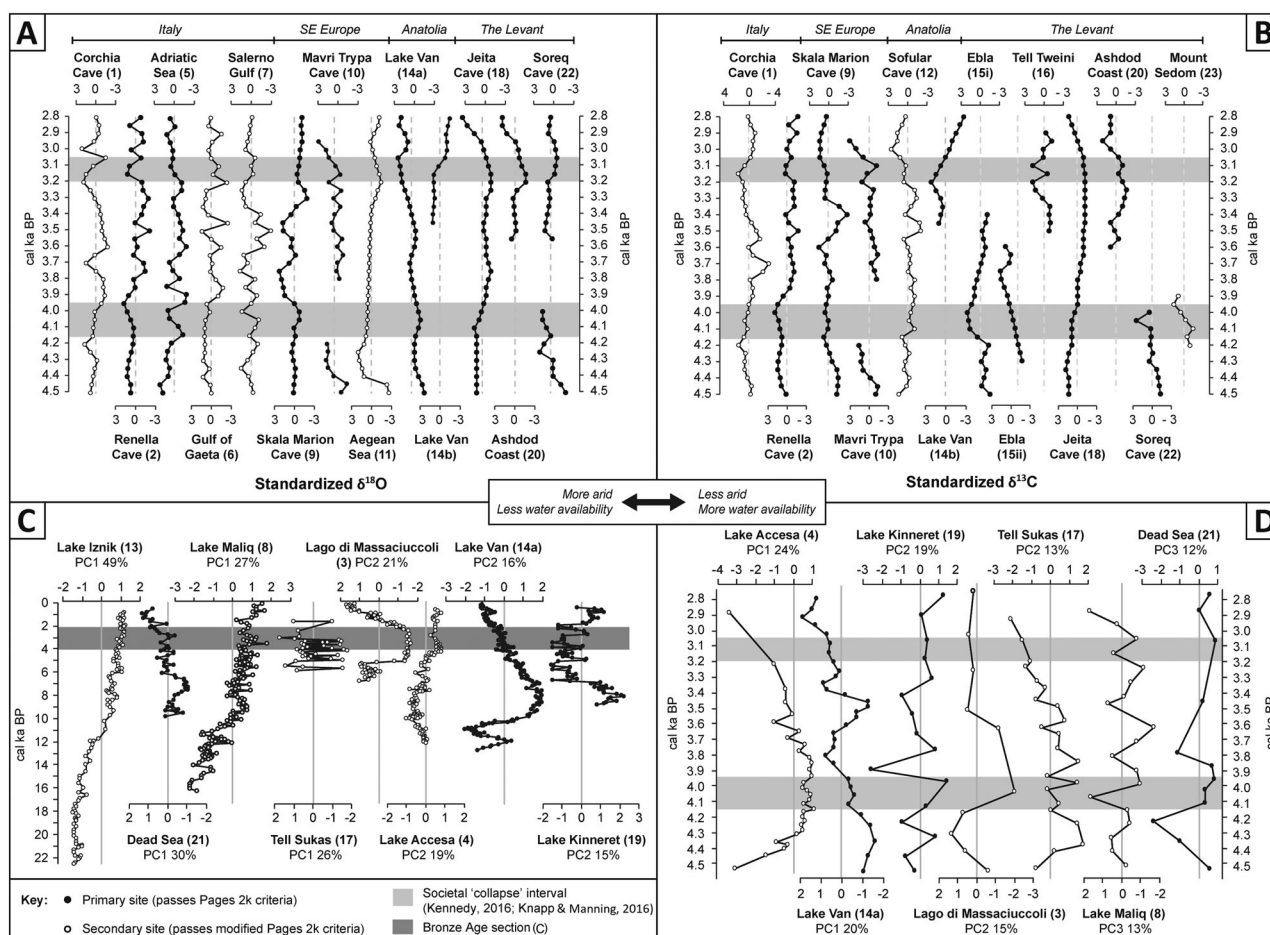
### 2.2.1. Lacustrine sediment cores

Pollen preserved in lake sediments enables assessment of vegetation changes linked to past climatic shifts (Wick et al. 2003; Colombaroli et al. 2007; Bordon et al. 2009; Peyron et al. 2011; Litt et al. 2012; Miebach et al. 2016; Schiebel and Litt 2018). One lake site also provides an oxygen isotope record (Şimşek and Çağatay 2018). The varying ratio of oxygen isotopes  $^{18}\text{O}$  and  $^{16}\text{O}$  (herein referred to as  $\delta^{18}\text{O}$ ) recorded in autochthonous lacustrine carbonates reflects the balance of precipitation and evaporation (Bar-Matthews et al. 1998; Wick et al. 2003; Roberts et al. 2011). Following Roberts et al. (2011), all stable isotope datasets were statistically transformed to standardised normal values (i.e. the standard deviation about the record's mean) to overcome site-specific factors such as elevation or absolute precipitation, highlight climatic shifts of more rapid onset, and facilitate inter-site comparability. A trend towards more positive standardised isotope values indicates increasing aridity, while a trend towards more negative standardised isotope values indicates decreasing aridity (Roberts et al. 2011).

### 2.2.2. Marine sediment cores

$\delta^{18}\text{O}$  records from marine cores (Schilman et al. 2001; Rohling et al. 2002; Piva et al. 2008; Lirer et al. 2013; Lirer et al. 2014; Margaritelli et al. 2016) again reflect the balance of precipitation and evaporation, this time recorded in planktic foraminifera tests (Schilman et al. 2001; Schilman et al. 2002). One marine core also provides a carbon isotope record (Schilman et al. 2001). The varying ratio of carbon isotopes  $^{13}\text{C}$  and  $^{12}\text{C}$  (herein referred to as  $\delta^{13}\text{C}$ ) measured in foraminifera tests reflects changes in inorganic carbonate runoff of terrestrial origin, and therefore land-based precipitation rates (Schilman et al. 2001; Bar-Matthews and Ayalon





2011). One core also provides pollen data (Table 1; Sorrel and Mathis 2016).

### 2.2.3. Terrestrial organic matter

$\delta^{13}\text{C}$  records within terrestrial buried organic matter (Fiorentino et al. 2008; Frumkin 2009; Kaniewski et al. 2011) are used to infer drought intervals, as during droughts plants close their stomata to retain moisture, thereby taking on less  $^{12}\text{C}$  (Ferrio et al. 2005; Roberts et al. 2011).

### 2.2.4. Speleothems

Cave deposits including stalagmites, stalactites and flowstones (collectively termed speleothems) contain reservoirs of calcium carbonate that is precipitated by dripping porewaters seeping through to the cave systems from rainfall. The oxygen within these often annually resolvable speleothems has been fractionated by the evaporation–precipitation balance, therefore  $\delta^{18}\text{O}$  can be used to infer this balance around the cave. Variations in  $\delta^{13}\text{C}$  also reflect precipitation levels (as described above) (Lauritzen and

Lundberg 1999; McDermott 2004). Combined  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  records come from six speleothems (Schilman et al. 2002; Verheyden et al. 2008; Bar-Matthews and Ayalon 2011; Regattieri et al. 2014; Zanchetta et al. 2016; Finné et al. 2017; Psomiadis et al. 2018), and one speleothem provides  $\delta^{13}\text{C}$  only (Göktürk et al. 2011).

### 2.3. Pollen

Pollen data were normalised using Box-Cox transformation in PAST version 3.17 (Hammer et al. 2001), excluding aquatics and taxa below 1%. This method normalises percentage data not only at a site level but also between sites, allowing for greater inter-site comparability. Following normalisation, two iterations of PCA were conducted in PAST to assess controls on pollen assemblages first on the full record, and then on the Bronze Age interval. The Bronze Age interval was defined for each core as the closest sample depths before 4.50 and after 2.80 cal ka BP. PCA is a standard method of pollen analysis, and was specifically chosen in this case to identify key environmental drivers of trends in the pollen dataset that

could be related to climate and environmental change (Shi 1993; Nguyen et al. 2013; Strother et al. 2015). PCA rotates pollen percentage abundance data through multidimensional space to define and separate the uncorrelated variables controlling assemblage makeup (Delile et al. 2015). These variables, known as principal components, were assigned a statistical weighting for assemblage control within each sample and those inferred to record water availability fluctuations are graphically displayed as a principal component axis against time (Figure 3). Although not necessarily independent from the others, a single principal component axis can be used to infer specific environmental parameters based on the relationship between the taxa at either end of each axis (Enzel et al. 2003; Colombaroli et al. 2009; Zhao et al. 2009; Kaniewski et al. 2015). Full details of these taxa and environmental parameters are provided in Supplementary 2. Strother et al. (2015) considered meaningful variance on a Principal Component axis as at least 14%, however during the Bronze Age five principal component axes account for between 12% and 14% variance. Due to this, only principal component axes accounting for a variance of greater than 12% are examined for possible proxy inferences within the Bronze Age.

### 3. Results

We present standardised results in Figure 3: oxygen (a) and carbon (b) isotopes, and pollen PCA scores (c, d).

#### 3.1. The Levant

##### 3.1.1. Stable isotopes

Ebla and Mount Sedom  $\delta^{13}\text{C}$  profiles (Figure 3(b)) and the Soreq Cave  $\delta^{18}\text{O}$  (Figure 3(a)) record suggest a general trend of increasing aridity through the EBAC. However, this trend is not observed during the EBAC at Jeita Cave (Figure 3(a,b)) or in the  $\delta^{13}\text{C}$  record from Soreq Cave (Figure 3(b)). Prior to the LBAC, the Jeita Cave and Ashdod Coast isotope records suggest decreasing aridity, followed by a reversal in isotope values indicative of increasing aridity (Figure 3(a,b)). Three  $\delta^{18}\text{O}$  records (Figure 3(a)) suggest the onset of less arid conditions within a 100-year interval; at 3.30 cal ka BP at Jeita Cave and Ashdod Coast, and at 3.20 cal ka BP at Soreq Cave. The timing of subsequent increasing aridity varies between 3.25 cal ka BP (Ashdod Coast  $\delta^{13}\text{C}$ ; Figure 3(b)), 3.20 cal ka BP (Jeita Cave and Ashdod Coast  $\delta^{18}\text{O}$ ; Figure 3(a)), and 3.05 cal ka BP (Soreq Cave  $\delta^{18}\text{O}$ ; Figure 3(a), and Jeita Cave  $\delta^{13}\text{C}$ ; Figure 3(b)). By contrast, the Tell Tweini  $\delta^{13}\text{C}$  record (Figure 3(b)) suggests increasing aridity 3.35–3.20 cal ka BP, when other sites record decreasing aridity.

##### 3.1.2. Pollen

Long-term records from the Dead Sea and Lake Kinneret (Figure 3(c)) show that prior to the Bronze Age, water availability decreased from ca. 7.00 cal ka BP. After the Bronze Age, water availability continued to decrease in the Dead

Sea, but increased at Lake Kinneret (Figure 3(c)). The long-term Tell Sukas record is highly oscillatory (Figure 3(c)).

Increasing water availability is suggested at Lake Kinneret and the Dead Sea preceding and during the EBAC, followed by a sharp decrease after the EBAC (3.95 cal ka BP at Lake Kinneret and 3.80 cal ka BP at the Dead Sea) (Figure 3(d)). Early Bronze Age water availability fluctuates at Tell Sukas, with a long-term decline from 3.60 to 2.90 cal ka BP that is not observed at the other sites (Figure 3(d)).

#### 3.2. Anatolia

##### 3.2.1. Stable isotopes

Both the early Bronze Age  $\delta^{13}\text{C}$  record from Sofular Cave, northwest Turkey (Figure 3(b)), and  $\delta^{18}\text{O}$  record from Lake Van, eastern Turkey (Figure 3(a)), show no significant trends. By contrast, greater shifts in isotope values occurred in the late Bronze Age. Sofular Cave  $\delta^{13}\text{C}$  records increasing aridity 3.30–3.00 cal ka BP (Figure 3(b)), and one Lake Van  $\delta^{18}\text{O}$  record suggests increasing aridity 3.50–3.05 cal ka BP (Figure 3(a)), followed by a short interval of decreasing aridity. However, a second late Bronze Age Lake Van  $\delta^{18}\text{O}$  record and corresponding  $\delta^{13}\text{C}$  record from the same study, offer contrasting evidence of no large changes between 3.45 and 3.15 cal ka BP ( $\delta^{18}\text{O}$ ; Figure 3(a)), and increasing aridity 3.35–3.20 cal ka BP ( $\delta^{13}\text{C}$ ; Figure 3(b)), followed by decreasing aridity.

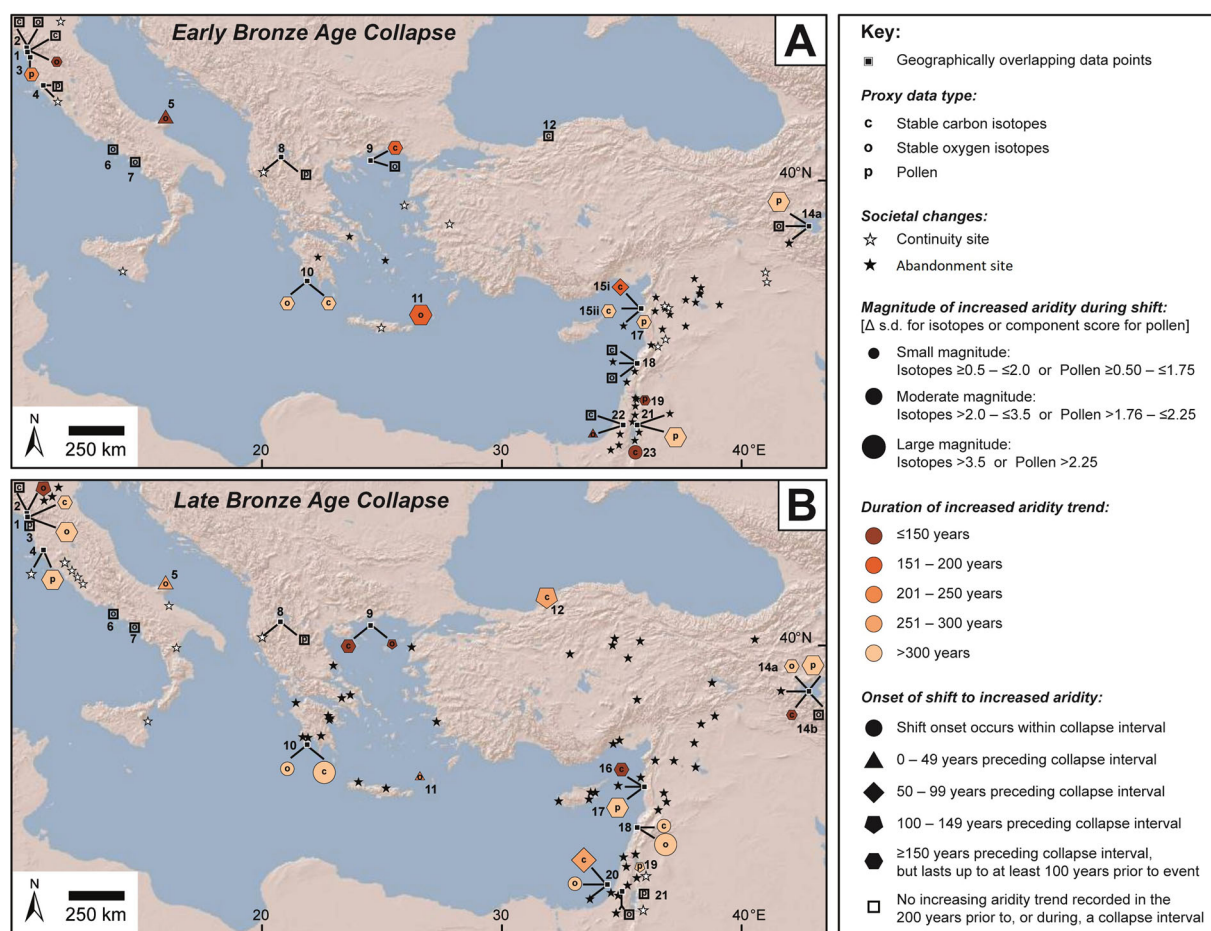
##### 3.2.2. Pollen

Within the full core profiles, the observed variance within the pollen records from Lakes Iznik and Van controlled by water variability are ~49.2% (PC1) and ~15.8% (PC2) respectively (Figure 3(c)). While pollen taxa at Lake Iznik infer gradually increasing water availability throughout the full core, at Lake Van water availability is inferred to gradually decrease from 7 cal ka BP (Figure 3(c)), as well as during the Bronze Age interval (Figure 3(d)). Water availability starts to decline 200 years before the onset of the EBAC and there is a sharp decline 250 years before the LBAC (Figure 3(d)).

#### 3.3. Southeast Europe

##### 3.3.1. Stable isotopes

Carbon and oxygen isotopes from Mavri Trypa (Figure 3(a,b)) and carbon isotopes from Skala Marion Cave (Figure 3(b)) suggest increasing aridity preceding the EBAC. This is not reflected in oxygen isotopes from Skala Marion (Figure 3(a)). By contrast, the Aegean Sea  $\delta^{18}\text{O}$  record (Figure 3(a)) indicates a large shift towards increasing aridity at 4.45 cal ka BP, before  $\delta^{18}\text{O}$  values stabilised at 4.15 cal ka BP (onset of the EBAC) until 3.35 cal ka BP. Following a 150-year trend of decreasing aridity, the Skala Marion  $\delta^{18}\text{O}$  record (Figure 3(a)) suggests increasing aridity in the 100 years before the LBAC. Both Mavri Trypa and Aegean Sea  $\delta^{18}\text{O}$  records (Figure 3(a)) show aridity increased later, after the onset of the LBAC. Carbon isotopes from Skala Marion Cave (Figure 3(b)) record increasing aridity 3.40–3.30 ka cal. BP, whilst Mavri Trypa  $\delta^{13}\text{C}$  values (Figure 3(b)) are oscillatory through the LBAC and consistent increasing aridity only occurs from 3.10 cal ka BP.



**Figure 4.** Regional distribution of climate proxy records analysed in this section and the nature of climatic trends preceding and during the EBAC (a) and LBAC (b) intervals. Site markers used to indicate magnitude of change in the proxy record (size of marker), duration of shift towards increased aridity (shading), closeness of the onset of increasing aridity to the collapse interval (shape), and record type (letter). Hollow squares indicate no shift towards increased aridity is recorded in the 200 years prior to, or during, a collapse interval. Archaeological records are shown by stars, with white stars marking sites displaying societal expansion or unrestricted continuity. Black stars indicate major regions that experienced destruction/abandonment/contraction or a mixture of these events at the transition from the (a) early to mid Bronze Age (ca. 4.00 ka BP) (Prag 1986; Whitelaw 2000; Kennedy 2016) or (b) late Bronze Age to the Iron Age (ca. 3.18–3.13 ka BP) (Wilson 1995; Nur and Cline 2000; Issar 2003; Mercuri et al. 2006; Valsecchi et al. 2006; Knapp and Manning 2016).

### 3.3.2. Pollen

Only one high resolution pollen record exists from this region, Lake Maliq in Albania, where water availability only accounts for 12.5% of the variance (Figure 3(c)). There is a trend of gradually increasing water availability through the Holocene (Figure 3(c)), but no consistent trends during the Bronze Age (Figure 3(d)).

## 3.4. Italy

### 3.4.1. Stable isotopes

Early Bronze Age Italian isotope records show no consistent shifts, with significant inter-site variability (Figure 3(a,b)). Corchia and Renella Cave  $\delta^{13}\text{C}$  profiles (Figure 3(b)), and Renella Cave and Gulf of Gaeta  $\delta^{18}\text{O}$  profiles (Figure 3(a)) all suggest relative stability throughout the early Bronze Age. Corchia Cave  $\delta^{18}\text{O}$  values (Figure 3(a)) are also relatively stable, with only a small oscillation ( $\sim 1$  standard deviation from the record mean) between 4.30 and 4.15 cal ka BP. By contrast, the Adriatic Sea  $\delta^{18}\text{O}$  record (Figure 3(a)) suggests decreasing aridity 4.45–4.15 cal ka BP, before aridity increases until 4.00 cal ka BP.

Isotope records from all sites suggest large oscillations throughout the middle Bronze Age (Figure 3(a,b)). Notable excursions from record means occurred at 3.80–3.60 cal ka BP at Corchia Cave ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ; Figure 3(a,b)) and 3.65–3.35 cal ka BP at Salerno Gulf ( $\delta^{18}\text{O}$ ; Figure 3(a)). Increasing aridity is inferred at Corchia Cave immediately before the LBAC 3.55–3.15 ( $\delta^{13}\text{C}$ ; Figure 3(b)) and 3.60–3.20 ( $\delta^{18}\text{O}$ ; Figure 3(a)) cal ka BP, followed by decreasing aridity 3.15–3.05 ( $\delta^{13}\text{C}$ ; Figure 3(b)) and 3.20–3.05 ( $\delta^{18}\text{O}$ ; Figure 3(a)) cal ka BP. The  $\delta^{18}\text{O}$  profile from nearby Renella Cave (Figure 3(a)) also suggests increasing aridity 3.30–3.15 cal ka BP, followed by decreasing aridity 3.15–3.05 cal ka BP, but there are no consistent trends in  $\delta^{13}\text{C}$  values (Figure 3(b)). Similarly, no consistent directional trends are present in  $\delta^{18}\text{O}$  profiles from Tyrrhenian Sea cores (Gulf of Gaeta/Salerno Gulf) around the time of the LBAC (Figure 3(a)).

### 3.4.2. Pollen

Both full core records from Italy, Lago di Massaciuccoli and Lake Accesa, show the Bronze Age interval was the wettest of the Holocene (Figure 3(c)). The early Bronze Age was wetter than the late Bronze Age, with the trend towards



decreasing water availability starting at both sites at 3.65 cal ka BP (Figure 3(d)).

#### 4. Discussion

Previous research has attempted to relate events such as climate shifts or earthquakes to societal fluctuations, often relying on spatially or temporally broad events that occur far from archaeological sites (Cullen et al. 2000; Arz et al. 2006; Drysdale et al. 2006; Drake 2012; Kaniewski et al. 2013; Cline 2014; Psomiadis et al. 2018). Recent reviews have suggested that in order to infer direct causation between a climatic shift and specific archaeological event, a precise correlation must be demonstrated at a single site (Kennedy 2016; Knapp and Manning 2016; Homsher and Cradic 2017; Riehl 2017; Jones et al. 2019). Therefore, the synthesis of palaeoclimate records will be compared with archaeological evidence from nearby sites, to assess the potential correlation of climate change with societal shifts and changes. The regional distribution of climate proxy and archaeological records and the nature of climatic/anthropogenic trends preceding and during the EBAC and LBAC intervals are displayed in Figure 4.

Within Figure 4, the magnitude of increased aridity is defined by the categorised (Figure 4), quantitative change in the x-axis scales from the respective graph in Figure 3 for any single, consistent shift in proxy data. Specifically, for isotope data that is a shift in standard deviation plotted as excursions from the site-specific mean, and for pollen data that is a shift in the principal component axis score. The duration and onset of each shift is variable, and defined in Figure 4 by the shade and the shape of the symbology, respectively.

The inclusion of societal 'Abandonment Sites' was achieved by reviewing the published archaeological literature discussing Bronze Age societal shifts, and regions are identified that are reported to have experienced destruction, abandonment, contraction or a mixture of these events at the transitions from the early to mid Bronze Age (ca. 4.00 ka BP) (Prag 1986; Whitelaw 2000; Kennedy 2016) and the late Bronze Age to the Iron Age (ca. 3.18–3.13 ka BP) (Wilson 1995; Nur and Cline 2000; Issar 2003; Valsecchi et al. 2006; Mercuri et al. 2006; Knapp and Manning 2016). In this primary archaeological literature, societal decline or abandonment is often inferred where there is a clear change in the sorts of artefacts and material culture being recovered or a complete cessation of such artefacts, a decrease in the number, size, or complexity of archaeological sites in a region at a specific moment in time, ash layers in the sedimentary record and signs of conflagration, an increase in the quantity of battle artefacts such as arrow heads, the construction of mass graves, an apparent decline in elite cultural markers such as expensively adorned burials and the construction or discontinued use of large religious structures and temples (Whitelaw 2000; Kaniewski et al. 2013; Kennedy 2016; Knapp and Manning 2016).

It is important to note that the archaeological chronologies used for making the following comparisons between our palaeoclimate dataset and societal shifts during the

Bronze Age have not been examined, recalibrated, or manipulated in anyway during the review and resynthesis of the proxy datasets. In a similar fashion to accepting the previously established archaeological wisdom of where societies declined, contracted, or abandoned sites, here we are relying on the established and widely accepted floating chronologies and relative timescales utilised by the relevant archaeological literature when discussing specific sites and societies. While this is in contrast to the highly selective criteria for the inclusion of radiocarbon chronologies and the subsequent efforts to recalibrate and standardise those temporal datasets, it is the opinion of the authors that any attempt to re-establish or 'refine' the well researched and highly scrutinised archaeological interval boundaries would be well beyond the scope of this paper or our expertise. While in the discussion and Figure 4 of this publication we thought it important to use the local archaeological intervals and relative chronologies as stated in the literature for comparison with the resynthesized palaeoclimate dataset, it must be acknowledged that there is a serious limitation in the accuracy and reliability of directly comparing even well-dated climate proxy records to individual societal shifts inferred from specific archaeological horizons. This is because, in a field where the formation and understanding of temporal boundaries and societal shifts is constantly evolving, the revision of archaeological intervals is a commonplace occurrence. As such, it is the primary goal of this paper to provide a synthesis of the highest resolution palaeoclimate data with the highest resolution dating, compare as best we can these results with current archaeological understanding, and then allow future archaeological, and even palaeoclimate research, to use the dataset as a contextual record for their own findings. If, at any given site, there is any future alteration to the archaeological interval boundaries as they are currently defined, it will still be possible to compare such advancements to this contextual palaeoclimate dataset.

#### 4.1. Northern Levant

##### 4.1.1. Early Bronze Age

Archaeological sites at Ebla display two phases of destruction towards the end of the early Bronze Age dated to ca. 2300 BC (ca. 4.25 ka BP) and ca. 2000 BC (ca. 3.95 ka BP) (Fiorentino et al. 2008; Kennedy 2016), which follow increasingly arid conditions inferred from Ebla  $\delta^{13}\text{C}$  records. The nearby site of Ras Shamra also displays two phases of destruction at ca. 2400 and 2300 BC (ca. 4.35–4.25 ka BP and 4.15–4.05 ka BP) (Kennedy 2016), coincident with decreasing water availability (ca. 4.39–4.03 cal ka BP) inferred from pollen at Tell Sukas, 35 km south of Ras Shamra.

However, evidence for climate causation of societal 'collapse' is far from equivocal. Inter-site variability between proxy records and in the timing of societal shifts from archaeological records results in a complex picture, and some proxy records contradict archaeological evidence. For example, early Bronze Age settlement decline at Tell Fadous-Kfarabida (ca. 2500–2000 BC; ca. 4.45–3.95 cal ka BP) (Genz 2017) occurs when crops nearby and isotopes at Jeita Cave

(~30 km to the south) showed no signs of drought (Riehl 2017). Two further archaeological sites close to Jeita Cave (Byblos, 20 km north, and Sidon, 50 km south) suggest continued occupation during the early Bronze Age (Genz 2010, 2017), with sudden abandonment later at the early Bronze Age termination coincident with a thick (50–140 cm) fine-sand layer interpreted as a tsunami deposit (Kennedy 2016). Evidence for earthquakes in the early Bronze Age has also been found in archaeological excavations at Ebla (Pinnock 2009; Kennedy 2016) and Ras Shamra (Schaeffer 1948; Schaeffer 1968; Nur and Cline 2000; Kennedy 2016). In addition, whilst there is evidence for abandonment of individual sites, multiple sites in the northern Levant show social continuity through the early and middle Bronze Age, including Tell Nebi Mend, Qatna, Tell Tuqan and Tell Afis (Kennedy 2016). Expansion of northern palace economies during the early Bronze Age (ca. 2500–2000 BC; ca. 4.45–3.95 cal ka BP) (Schloen 2017) also provides further evidence suggesting that in many locations, correlated climate change was not extreme enough to cause so-called societal ‘collapse’.

#### 4.1.2. Late Bronze Age

There is evidence for increasing aridity preceding the LBAC at Jeita Cave, Tell Sukas and Tell Tweini, as well as archaeological evidence for subsequent societal destruction at ca. 3.15 cal ka BP from both tell sites (Knapp and Manning 2016). Previous interpretations were of destruction by fire (Kaniewski et al. 2011; Knapp and Manning 2016), but it is unclear whether settlements were destroyed by fire during an invasion (Kaniewski et al. 2011), or whether they were abandoned due to deteriorating climate and then subsequently burnt. The correlation with an abrupt increase in aridity at Jeita Cave following the more prolonged increasing aridity trend, may also have influenced the societal response (Riehl 2017). From 3.10 to 3.00 ka BP, the Assyrian Empire experienced crop failure, famines and repeated nomad incursions into built up settlements (Neumann and Parpola 1987).

### 4.2. Southern Levant

#### 4.2.1. Early Bronze Age

Multiple southern Levant sites record increasing aridity preceding and during the early Bronze Age (Mount Sedom, Soreq Cave, Lake Kinneret, Dead Sea). Pollen evidence suggests water availability declined ca. 4.53–4.23 cal ka BP in the Dead Sea, and ca. 4.55–4.45 and ca. 4.33–4.23 cal ka BP at Lake Kinneret, concurrent with an interval of increasing aridity inferred from the Soreq Cave oxygen isotopes (4.50–4.25 cal ka BP). Subsequent intervals of increasing aridity are also suggested at 4.15–4.00 cal ka BP at Soreq Cave and 4.10–3.95 cal ka BP at Mount Sedom. During this interval of increasing aridity, there is widespread agreement that previously well-established early Bronze Age (ca. 2500–2000 BC; ca. 4.45–3.95 cal ka BP) walled-town structures in the southern Levant declined (Kennedy 2016; Genz 2017; Schloen 2017) and virtually all medium and large settlements were abandoned or greatly reduced in size (Harrison 2012).

Evidence for abandonment is recorded at multiple sites proximal to Lake Kinneret and the Dead Sea, including Tyre (~56 km northwest of Lake Kinneret), Sha’ar Har-Golan (~4 km south of Lake Kinneret), Jerico (~15 km northeast of the Dead Sea), Tell Iktanu (~7 km northeast of the Dead Sea), Khirbat Iskandar (~14 km east of the Dead Sea) and Bâb edh-Dhrâ’ (~11 km south of the Dead Sea) (Kennedy 2016; Genz 2017). More broadly, the northward shift to the southern boundary of inland urban centres between the early and middle Bronze Age has been suggested to represent a withdrawal from areas with lower annual rainfall (Finkelstein and Langgut 2014).

Compared to the north, the southern Levant features a more consistent spread of both societal abandonment and short ( $\leq 150$  year) increasingly arid climate shifts during the early Bronze Age (Figure 4). It is plausible that the duration of the climatic shifts was important in ultimately determining societal resilience and adaptability, with aridity events generally being of shorter duration in the southern Levant compared to the north. Where increasingly arid climatic events are longer and more gradual in their onset and escalation, such as during the early Bronze Age in the northern Levant (Figure 4), it has been proposed that elite classes responded to the slowly mounting crises by reorganizing their societal structures (Genz 2012; Harrison 2012; Höflmayer 2017a), whereas southern Levant early Bronze Age communities either attempted to sustain established strategies by opting for urban dissolution (Harrison 2012) or were simply unable to adapt (Rosen 1995) to the shorter, more rapid, increasing aridity (Figure 4).

#### 4.2.2. Late Bronze Age

There is limited evidence for increasing aridity before, and at the onset of, the LBAC in the southern Levant. In fact, proxy records suggest increasing water availability at Ashdod Coast (3.45–3.25 cal ka BP from  $\delta^{13}\text{C}$  and 3.30–3.20 cal ka BP from  $\delta^{18}\text{O}$ ), Soreq Cave (3.20–3.05 cal ka BP), Lake Kinneret (ca. 3.41–3.30 cal ka BP) and the Dead Sea (ca. 3.80–3.10 cal ka BP). Only at Ashdod Coast, does a shift towards increased aridity coincide with the LBAC interval, beginning around 3.25–3.20 cal ka BP. This overlaps with an interval of partial destruction between 1225 and 1175 BC (ca. 3.18–3.13 ka BP) at the nearby sites of Ashdod and Ashkelon (Nur and Cline 2000). However, collapsed buildings may provide evidence for seismic activity at this time, and therefore the correlation with increased aridity may be coincidental or of secondary importance (Drews 1993; Nur and Cline 2000). Whilst all presented proxy records satisfy the Pages 2k criteria overall, the late Bronze Age sections are not all of the same resolution. For example, the Dead Sea pollen record is limited due to sand bank deposition ca. 1400–1200 BC (ca. 3.35–3.15 ka BP) (Enzel et al. 2003; Bookman et al. 2004; Neumann et al. 2007; Langgut et al. 2014; Kagan et al. 2015), which hinders preservation of pollen.

In concordance with a lack of evidence for palaeoclimate deterioration before and during the late Bronze Age, there is also archaeological evidence for settlement continuity. In the Negev and southern Trans-Jordan highlands, both bordering



the Dead Sea, more permanent archaeological settlements are observed from ca. 3.40 ka BP (Issar 2003). Agriculture also expanded around the central Negev between 1500 and 1000 BC (3.45–2.95 ka BP) into areas that today have rainfall below the 200 mm isohyet (Rosen 2017). To the northeast in Gilead, the number of archaeological sites also displays relative continuity, with 24 and 20 in the middle and late Bronze Age respectively (Finkelstein 1995). Furthermore, across the late Bronze Age–Iron Age transition, the Trans-Jordan, Gilead and Galilee mountains (bordering the Dead Sea and Lake Kinneret) underwent rapid and intensive settlement (Issar 2003), with evidence for late Bronze Age settlement decline or destruction being restricted only to sites in central Judea, the Trans-Jordan plateau (Finkelstein 1995), and west of the River Jordan (Knapp and Manning 2016) (Figure 4), where precise dating is uncertain (Cline 2014; Knapp and Manning 2016).

Unlike climate shifts in the northern Levant that were either relatively rapid ( $\leq 150$  years), large magnitude, or featured an abrupt onset during the so-called ‘collapse’ interval, late Bronze Age climate records from the southern Levant reconstruct either no increasing aridity, longer duration ( $> 250$  year), or smaller magnitude shifts to aridity (Figure 4). Late Bronze Age settlement continuity in areas of the southern Levant and the more gradual transition into the middle Bronze Age observed there in the archaeological record (Kennedy 2016), may therefore reflect effective societal resilience aided by the absence of rapid changes in aridity at this time, as in the northern Levant during the EBAC. In summary, it appears there was not a widespread climate change event that acted as a primary driver for widespread societal transformation in the southern Levant during the late Bronze Age. Rather, localised or potentially adaptable long-term changes in aridity may have contributed to an increase in highland settlements in the more southerly regions and a southward shift to the agricultural exploitation boundary.

### 4.3. Anatolia and Southeast Europe

#### 4.3.1. Early Bronze Age

Four climate reconstructions across Anatolia and Southeast Europe suggest no increase in aridity before or during the EBAC interval, while three more records suggest a long-term ( $> 300$  year) trend of increasing aridity beginning  $\geq 150$  years before the EBAC interval, and two final records suggest a shorter (151–200 year) trend of increasing aridity that began  $\geq 150$  years before the EBAC interval (Figure 4).

Around the eastern Anatolian Lake Van basin, there is pollen evidence for a prolonged interval of decreasing water availability 4.36–3.81 cal ka BP, as well as for reduced human occupation in archaeological excavations (Marro and Özfirat 2005). However, this decrease in water availability is not mirrored in the Lake Van oxygen isotope record. Similar inconsistencies exist between different proxy records and between sites throughout Anatolia and southeast Europe. The carbon isotope record from Skala Marion Cave suggests a 200-year interval of increasing aridity leading into the EBAC, but the oxygen isotope record from the same site and carbon

isotopes from Sofular Cave both suggest aridity did not increase before or during the EBAC interval. At this time, there is evidence for continued human occupation during the early Bronze Age at Thasos and Skala Sotiros, coastal sites 10 km from Skala Marion Cave (Papadopoulos and Malamidou 2008; Nerantzis et al. 2016).

Finally, oxygen isotopes from the southeast Aegean Sea initially indicate increasing aridity, however this trend reverses 100 years before the onset of the EBAC interval. On the island of Crete, located  $\sim 50$  km southwest of this marine core, there is evidence for urbanisation towards the end of the early Bronze Age, before the number and complexity of sites expanded dramatically throughout the middle Bronze Age (Manning 1994; Whitelaw 2000). The correlation with less arid conditions experienced from ca. 4.30 cal ka BP, could have been a contributing factor to this interval of urbanisation.

In summary, archaeological and palaeoenvironmental records do not provide clear consensus of climate change impacts on early Bronze Age societies, although the relative lack of joint archaeological and high-resolution climate archives for this interval from this region limits discussion. It would appear however, that evidence is not found for widespread climate change in Anatolia and southeast Europe in the early Bronze Age, and there is evidence for societal continuity and even expansion at many sites. For Greece specifically, this conclusion supports similar findings in previous research reviews (Weiberg et al. 2016; Weiberg and Finné 2018)

#### 4.3.2. Late Bronze Age

There is evidence for a stepped increase in aridity from Sofular Cave, northwestern Anatolia, from 3.30 to 3.00 cal ka BP. In archaeological records, the sites of Alaca Höyük and Hattuşa ( $\sim 265$  km from Sofular) and Maşat Höyük ( $\sim 350$  km from Sofular) feature destruction layers and at least temporary abandonment at the end of the late Bronze Age, though precise timing is not well-established (Knapp and Manning 2016). Furthermore, textual evidence from the Hittite Empire records severe dry years in the last decade preceding its disbandment at 3.13 ka BP (Akurgal 2015), while the Beyşehir Occupancy of southwestern Turkey is typically dated from ca. 3.00 ka BP (Eastwood et al. 1998) to 2.50 ka BP (Vermoere et al. 2002), the latter date coinciding with a change from arid to wetter conditions (Vermoere et al. 2002). While the timing of the observed increasing aridity trends may tempt suggestions of a climatic contribution to societal disruption, distances between Sofular Cave and the archaeological sites means any inferences would be highly tenuous. It is also not possible to rule out alternative causes of abandonment that have been suggested, including internal disruption (Knapp and Manning 2016) or external invasion (Bryce 2005).

Archaeological evidence from Lake Van suggests the late Bronze Age interval ended between 1300 and 1200 BC (3.25–3.15 ka BP) at this site following the continuation of a shift from lowland habitation to highland pastoralism that began in the middle Bronze Age (Marro and Özfirat 2005). Water availability inferences from the Lake Van pollen record

suggest broadly decreasing values ca. 3.46–2.91 ka BP, and carbon isotope and one oxygen isotope (14a) record indicates increasing aridity from at least 3.35 to 3.20 ka BP. However, a duplicate oxygen isotope record from the same site (14b) shows the opposite trend, providing no clear consensus on if or how aridity changed in the late Bronze Age and if this correlates with decreased lowland settlement. Likewise, at Lake Maliq, water availability only explains 12.5% of variance in the pollen record, leading to a fluctuating late Bronze Age record which cannot be used as evidence for clear palaeoclimatic change. At this time, abundant artefacts testify to continued societal occupation at Sovjan on the shore of Lake Maliq until the Iron Age (Fouache et al. 2001; Lafe 2004). Archaeological sites in the region of the Struma River valley to the north reveal a dramatic increase in the number of settlements throughout the region featuring an eastern Mediterranean influence from 3.35 to 3.15 ka BP (Marinova et al. 2012). This may suggest an influx of migrants from farther east (Marinova et al. 2012), to an area which records no increased aridity prior or during the LBAC.

In Greece and the Aegean Sea region, proxy records again do not provide clear consensus on palaeoclimate conditions. In southern Greece, oxygen and carbon isotopes from Mavri Trypa suggest increasing aridity from 3.15 and 3.10 ka BP respectively. However, isotope records from Skala Marion Cave and the Aegean Sea do not show the same clear aridity trends. Whilst there is a small shift inferred from oxygen isotopes at Skala Marion towards increasing aridity immediately preceding the LBAC interval (3.30–3.20 ka BP), this is much smaller than preceding isotopic shifts that do not correlate with known societal declines. During this interval of inconsistent palaeoclimate evidence, there is much clearer evidence for a regional societal shift in the archaeological record, with societal destruction across Crete at the end of the late Minoan interval, 1315 and 1190 BC (ca. 3.27–3.14 ka BP) (Manning 1994; Drake 2012). Reasons for this disparity suggest either a non-climatic cause for societal changes (Weiberg et al. 2016; Weiberg and Finné 2018) or a sub-decadal climate trigger (Carpenter 1966; Bryson et al. 1974; Weiss 1982) which is not resolvable in current proxy records that highlights the need for a high resolution terrestrial palaeoclimate record from Crete, rather than a marine core.

#### 4.4. Italy

##### 4.4.1. Early Bronze Age

We infer short duration increasing aridity trends from oxygen isotopes in Corchia Cave preceding the EBAC and the Adriatic Sea during the EBAC, but carbon isotopes from Corchia Cave, and oxygen and carbon isotope records from all other Italian sites, do not suggest clear continuous shifts towards aridity before/during the EBAC interval. At Lago di Massaciuccoli, a rapid increase in water availability is inferred from 150 years before the EBAC onset, following a decline 4.55–4.31 ka BP. By contrast, less than 100 km south, a far higher resolution pollen record from Lake Accesa suggests continuously increasing water availability leading up to the EBAC (4.53–4.15 ka BP). Therefore, any patterns of

palaeoclimate change appear to be highly site-specific. This conclusion is consistent with a recent review of pollen datasets, which does not report any significant vegetation change in response to the 4.20 ka BP climatic event at Italian sites between 43° and 45°N (Di Rita and Magri 2019). Of greater significance in the early Bronze Age is that archaeological evidence suggests sedentary human occupation of central and southern Italy did not occur until around 1600 BC (ca. 3.55 ka BP) (Bernabò Brea et al. 1997; Mercuri et al. 2006). Stationary open-air sites (as opposed to cave dwellings) were rare during the early Bronze Age (Attema et al. 2010), and permanent dwellings were located only near Lake Garda (De Marinis 1999; De Marinis 2009) and on Sicily (Leonard 1980; Castellana 1987; McConnell 1992) at this time.

##### 4.4.2. Late Bronze Age

Isotope records from Corchia and Renella Caves suggest increasing aridity leading up to 3.20–3.15 ka BP. This trend is shorter in duration at Renella Cave ( $\leq 150$  years) than Corchia Cave ( $> 300$  years). Water availability reconstructed from pollen at Lago di Massaciuccoli and Lake Accesa ( $\sim 30$  and  $\sim 125$  km south of the caves respectively) also declines from around 3.63 ka BP. Archaeological evidence suggests the Terramare culture from this region expanded during the middle and late Bronze Age between ca. 1600 and 1175 BC (ca. 3.55–3.13 ka BP) (Bernabò Brea et al. 1997; De Marinis 1999), before many central Po Valley villages were abandoned at the end of the late Bronze Age (ca. 1175 BC; 3.13 ka BP), bringing an end to the Terramare civilisation (Bernabò Brea et al. 1997; Mercuri et al. 2006; Mercuri et al. 2012; Cremaschi et al. 2016). It has been observed that a clear drop in the water table occurred in the water management systems (wells and interconnecting ditches) at the Terramare di Santa Rosa of the Po Plain coincident with a short decrease in aquatic plants (Mercuri et al. 2012). Whereas the general trend towards increasing aridity recorded at Corchia Cave and in the lake cores corroborate previous suggestions that a prolonged climatic deterioration may have contributed to the decline of the Terramare civilisation (Bernabò Brea et al. 1997; Mercuri et al. 2006; Cremaschi et al. 2016), the fact that societal decline closely follows the abrupt aridity shift reconstructed from Renella Cave suggests that a more rapid and intense aridity event may have ultimately triggered the societal response. This conclusion would support the suggestion of a pronounced dry peak coincident with the Terramare societal decline described in (Cremaschi et al. 2016). The Terramare di Montale pollen record strongly suggests local over-exploitation may have amplified the effects of the water crisis (Mercuri et al. 2012), however potential causes driving this over-exploitation are not discussed in the paper. The lack of significant climate change in the Gulf of Gaeta record correlates with recent pollen evidence potentially suggesting continued landscape management and exploitation from 3.40 to 3.00 ka BP (Di Rita et al. 2018).

## 5. Conclusions

### 5.1. Early Bronze Age

- Levant: variability in northern Levantine palaeoclimate records and evidence for impacts of seismic hazards in archaeological records prevent correlation between climate change and so-called societal 'collapse' in this region in the early Bronze Age and emphasises the need for contextual site-by-site evaluations (Holmgren et al. 2016; Riehl 2017). By contrast, in the southern Levant there is a more ubiquitous spread of both societal 'collapse' sites and concurrent short ( $\leq 150$  year) periods of increasingly arid climate conditions, which may suggest a more causal link between climatic and societal change.
- Anatolia and Southeast Europe: there is neither consistent evidence for widespread climate change, nor evidence of concurrent societal 'collapse' from archaeological sites.
- Italy: palaeoclimate records are highly site-specific, and only one record reveals a change in aridity that occurs in the EBAC interval. Societies on mainland Italy were mainly nomadic throughout the early Bronze Age, and therefore archaeological remains are infrequent.

### 5.2. Late Bronze Age

- Levant: northern Levantine sites of so-called societal 'collapse' may correlate to aridity changes, which are often rapid ( $\leq 150$  years), large magnitude, and/or onset during the 'collapse' interval. However, inconsistent palaeoclimate and archaeological evidence from southern Levant prevents this correlation being established for the entire Levantine region.
- Anatolia and Southeast Europe: proxy records provide no clear consensus on regional palaeoclimate, suggesting observed societal changes are either not climate-related or proxy records are of insufficient resolution to resolve a climate trigger.
- Italy: as the climate became increasingly arid in the northernmost regions, a congruent societal 'collapse' in these regions may have been triggered by an intense aridity event. Middle and southern Italian sites do not record significant increases in aridity or evidence of decreased agricultural activity in pollen derived archaeo-demographic records.

Overall, this synthesis of palaeoclimate records, focussing on those with the highest temporal and sampling resolutions, does not support the over-simplified hypothesis that climate change and increased aridity across the entire eastern Mediterranean were the sole cause for either the EBAC or LBAC events. Instead, the results present a more nuanced view; aridity does not always correlate with so-called societal 'collapse' and vice versa. It is likely that societal resilience to climate change, the severity and speed of any change, how this translated to local level water availability and how widely these climate effects influenced their trade/social network, combined to create complexity in archaeological records of societal change. This synthesis clearly demonstrates a need for more high-resolution multi-proxy records,

proximal to archaeological sites for providing societal response context, in order to better understand the role, if any, of climate change in the dynamics of eastern Mediterranean Bronze Age societies.

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## ORCID

Calian J. Hazell  <http://orcid.org/0000-0002-9310-6087>  
 Matthew J. Pound  <http://orcid.org/0000-0001-8029-9548>  
 Emma P. Hocking  <http://orcid.org/0000-0002-8925-1695>

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