Climate in the eastern Mediterranean during the Holocene and beyond – A Peloponnesian perspective

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Abstract

This thesis contributes increased knowledge about climate variability during the late Quaternary in the eastern Mediterranean. Results from a paleoclimate review reveal that regional wetter conditions from 6000 to 5400 years BP were replaced by a less wet period from 5400 to 4600 years BP and to fully arid conditions around 4600 years BP. The data available, however, show that there is not enough evidence to support the notion of a widespread climate event with rapidly drying conditions in the region around 4200 years ago. The review further highlights the lack of paleoclimate data from the archaeologically rich Peloponnese Peninsula. This gap is addressed in this thesis by the provision of new paleoclimate records from the Peloponnese. One stalagmite from Kapsia Cave and two stalagmites from Glyfada Cave were dated and analyzed for stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes. The Glyfada record covers a period from ~78 ka to ~37 ka and shows that the climate in this region responded rapidly to changes in temperatures over Greenland. During Greenland stadial (interstadial) conditions colder (warmer) and drier (wetter) conditions are reflected by depleted (enriched) $\delta^{13}C$-values in the speleothems. The Kapsia record covers a period from ~2900 to ~1100 years BP. A comparison between the modern stalagmite top isotopes and meteorological data shows that a main control on stalagmite $\delta^{18}O$ is wet season precipitation amount. The $\delta^{18}O$ record from Kapsia indicates cyclical humidity changes of close to 500 years, with rapid shifts toward wetter conditions followed by slowly developing aridity. Superimposed on this signal is a centennial signal of precipitation variability. A second speleothem from Kapsia with multiple horizons of fine sediments from past flood events intercalated with the calcite is used to develop a new, quick and non-destructive method for tracing flood events in speleothems by analyzing a thick section with an XRF core scanner.

Keywords: Stable isotopes; U-Th dating; stalagmites; climate variability; flooding history; eastern Mediterranean; southern Greece; Holocene; Pleistocene

Sammanfattning

Människans historia i östra medelhavsområdet sträcker sig tiotusentals år tillbaka i tiden. Under hela denna period har klimatet och dess variationer varit en faktor som påverkat människors liv. Efter den senaste istiden, som tog slut för cirka 11 500 år sedan, utvecklades jordbruk och befolkning kom att öka och organisera sig i allt mer komplexa samhällen i östra medelhavsområdet. Människans långa historia i området betyder att det finns mängder med lämningar från människor och svunna samhällen. Denna rikedom av arkeologiska och historiska lämningar gör östra Medelhavet till en bra plats att undersöka hur klimatförändringar påverkat människan och hennes samhällen genom historien. Genom att jämföra arkeologiska data med information om hur klimatet har varierat kan man försöka förstå sambanden mellan människa och klimat. Detta kräver att det finns bra och tillförlitliga klimatdata och arkeologiska data. Avsaknaden av klimatdata från ett antal platser med rika och välundersökta arkeologiska lämningar, exempelvis Egypten och Peloponnesos, gör att dessa jämförelser inte går att genomföra. Denna avhandling syftar till att 1) undersöka vilka platser som saknar klimatdata samt att 2) försöka bidra med information och data om klimatets variabilitet genom historien från en sådan plats.

I avhandlingens första del granskas ingående publicerad kunskap om klimatet i östra medelhavsområdet under de senaste 6000 åren. Denna granskning visar att klimatet i östra Medelhavet var fuktigare än nu under perioden 6000 till 5400 år före nutid (alltså före AD1950). Den följande perioden från 5400 till 4800 år före nutid var torrare än nu, men fortfarande fuktigare än den tidigare perioden. En övergång mot ett torrare klimat än nu inleddes kring 4800 år och omkring 4600 år före nutid dominerade ett torrare klimat det östra medelhavsområdet. Antalet studier minskar kraftigt efter cirka 1400 år före nutid vilket gör att det inte går att dra några slutsatser om klimatet. Inom arkeologin har man länge debatterat hur så kallade klimatevent påverkat människor och samhällen. Klimatevent är snabba förändringar i klimatet som sker under en kort period vilken efter klimatet går tillbaka till något som liknar ursprungsläget. Det har föreslagits, baserat på olika typer av klimatdata, att ett antal klimatevent inträffat efter den senaste istiden. I östra medelhavsområdet har det föreslagits att utbredd och svår torka inträffat 4200 och 3200 år före nutid (de så kallade 4.2 och 3.2-eventen) vilket skulle ha fått samhällen att kollapsa och gå under. Utifrån resultaten av granskningen av klimatdata kan man se att det rådde omfattande torka kring dessa båda event, men också att det för närvarande saknas tydliga bevis för en snabb och kortvarig försämring i klimatet just kring dessa två tider.

I avhandlingens andra del analyseras stabila isotoper av syre och kol ($\delta^{18}O$ och $\delta^{13}C$) i droppstenar (stalagmiter) från två grottor på Peloponnesos: Kapsia och Glyfada. Datering med hjälp av uran-torium metoden visar att stalagmiterna i Glyfadagrottan växte under en period från cirka 78 000 år före nutid till cirka 37 000 år före nutid, det vill säga under den senaste istiden. De stabila isotoperna från Glyfada visar att klimatet över Peloponnesos varierade i takt med temperaturförändringar över Grönland. När klimatet var varmare över Grönland var det fuktigare över Peloponnesos, och när klimatet var kallare över Grönland var det torrare över Peloponnesos. Analysen av stalagmiterna från Glyfada visar att stalagmiterna slutade växa när isarna på norra halvklotet var som störst. Detta beror sannolikt på att lågtryckssystemen som förser Peloponnesos med nederbörd försköts söderut.

Från Kapsiagrottan analyserades en stalagmit som växte under en period från cirka 2900 år före nutid till cirka 1100 år före nutid. Dateringen av denna stalagmit skedde genom en kombination av uran-torium datering och kol-14-datering. Toppen av stalagmiten har vuxit under de senaste cirka 20 åren och genom att jämföra $\delta^{18}O$-värden från toppen med meteorologiska data går det att visa att nederbördsmängden mellan oktober och april till stor del kontrollerar $\delta^{18}O$-signalen i stalagmiten. Genom denna kunskap går det att med större säkerhet tolka $\delta^{18}O$-signalen för perioden 2900–1100 år före nutid. Under denna period visar $\delta^{18}O$-signalen på ett cykliskt mönster hos nederbördsmängden med ungefär 500 år långa perioder där ett snabbt skifte mot fuktigare klimat följs av en långsam förändring mot torrare. En variabilitet på sekelskala går också att urskönja, den visar att klimatet var fuktigare kring 2800, 2650, 2450, 2350–2050, 1790–1650 och 1180 år före nutid och torrare runt 2400, 1850–1800 och 1300 år före nutid.

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List of papers

This doctoral thesis consists of this summary and the following four papers, which are referred to by their Roman numerals in the text.

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

Paper II
Finné, M., Bar-Matthews, M., Holmgren, K., Sundqvist, H.S., Liakopoulos, I., Zhang, Q., 2014.
Speleothem evidence for late Holocene climate variability and floods in Southern Greece. Quaternary Research 81, 213-227.

Paper III
Finné, M., Holmgren, K., Bar-Matthews, M. Rapid climatic shifts in southern Greece during MIS 5a–3 evidence from speleothems. Manuscript submitted to Palaeogeography, Palaeoclimatology, Palaeoecology.

Paper IV
Finné, M., Kylander, M., Boyd, M., Sundqvist, H.S., Löwemark, L. Can XRF scanning of speleothems be used as a non-destructive method to identify paleoflood events in caves? Accepted for publication in International Journal of Speleology.

Author contributions
Paper I: Review performed and written by MF in close collaboration with KH and HSS (mainly statistical analyses). EW and ML provided archaeological expertise and editing.

Paper II: Conceived and designed by MF and KH. MF wrote the paper and designed figures. KH was involved in the interpretations and age model building as well as commenting and editing of the manuscript. MBM contributed with U-Th dating and discussions around age-model building and general discussions around interpretations. HSS contributed interpretation of monitoring data and discussions around isotopic equilibrium and interpretations. IL contributed archaeological expertise on the cave and the area in general. QZ performed wavelet analysis and helped with interpretations.

Paper III: Conceived and designed by MF and KH. MF wrote the paper and designed figures with the help of KH. KH was also involved in the interpretations and age model building. MBM contributed U-Th dating and discussions around age-model building and general discussions around interpretations.

Paper IV: Conceived and designed by MF, MB, HSS, MK and LL. MF wrote the paper and designed figures after discussions with MK. MB, HSS and LL contributed to discussions around interpretations and commented on the manuscript.

Introduction

The eastern Mediterranean region has a long history of human presence. The region is one of the cradles of agriculture and it has seen the development and demise of numerous state formations. During the course of human history the climate has always varied and played an important role in the broad interplay between humans and their environment. The long presence of humans has left innumerous traces in the form of archaeological and historical remains. Exploration and excavation of these remains have created a wealth of long and detailed archaeological and historical records from the region. The richness of archaeological data from the eastern Mediterranean region offers an opportunity to investigate how climate variability has affected human societies and activities over long periods of time. However, there is a lack of paleoclimate data from many archaeologically rich areas of the eastern Mediterranean, hampering investigations about climate-society interactions. This knowledge gap is a main motivation behind this thesis.

With the onset of the Holocene epoch, around 11 500 years ago, climate conditions rapidly improved from the cooler and more arid conditions that prevailed during the last ice age. At roughly the same time the development of agriculture and a sedentary life-style during the Neolithic revolution led to more people coming to inhabit the eastern Mediterranean region and forming more complex societies. The Holocene is therefore highly relevant to study in closer detail, in order to understand the interrelations between climatological and archaeological-historical perspectives (e.g. Caseldine and Turney, 2010; Sinclair et al., 2010; Roberts et al., 2011). To critically investigate such interrelations may offer new ways of interpreting archaeological and historical records. This can yield new and deeper understandings of processes behind cultural change, avoiding over-simplifications when discussing cause and effect behind for example climate changes and societal changes (Caseldine and Turney, 2010; Weiberg and Finné, 2013).

The Holocene climate includes a number of rapid climate changes, so-called climate events, some of the better known occuring around 8200 years BP[1] (the so-called 8.2-event), around 4200 years BP (the 4.2-event), and around 3200 years BP (the 3.2-event) (Alley et al., 1997; Mayewski et al., 2004; Kaniewski et al., 2010). During all three events the climate is suggested to have become rapidly cooler and more arid around much of the globe, including the eastern Mediterranean. Evidence for a climate deterioration during the 8.2-event is quite strong from the Mediterranean region and the negative impacts of this event on the Neolithic, and last Mesolithic societies, have been shown by for example Berger and Guilaine (2009). The 4.2-event is perhaps the best known and most debated climate event of the three (e.g. Mayewski et al., 2004; Wanner et al., 2008). In archaeology, the possible impact of the 4.2-event on societies is much discussed, for instance the decline of the Akkadian state in the Near East around this time has been explained by rapidly increasing aridity (Weiss et al., 1993; Cullen et al., 2000). Recently the 3.2-climate event and its archaeological impacts have been investigated in for instance Syria and Cyprus (Kaniewski et al., 2010; 2013) and southern Greece (Drake, 2012).

There are many examples of proposed connections between climate deterioration and societal change from the eastern Mediterranean (e.g. Weiss, 1982; Weiss et al., 1993; Barker et al., 1996, 2007; Tainter, 2000; Whitelaw, 2000; Weiss and Bradley, 2001; Issar, 2003; Diamond, 2005; Shennan, 2005; Staubwasser and Weiss, 2006). However, these examples are often based on spatially dispersed data sets with climate data from one region

[1]All ages in this thesis are reported as either years before present (BP), i.e. years before AD1950, or as ka (b2k), i.e. kilo years before AD2000

and evidence of societal upheaval from another. The applicability of regionally scattered data has recently been questioned in the Mediterranean region because of strong local differences (Roberts et al., 2011). Further, limitations in dating accuracy and resolution, both in paleoclimatology and archaeology often impair and/or limit comparisons and discussions around for example cause and effect (Caseldine and Turney, 2010). Although records addressing the problems of spatial variability, by extracting paleoclimate data from archives located in close proximity to archaeological sites, have begun to appear (Unkel et al., 2014; Kaniewski et al., 2010; 2013) there is still a great need for improved coverage and quality of data sets from both a climatic, environmental and a societal viewpoint in order to better understand social-environmental-climate conditions and interactions. What is needed from the paleoclimate community is higher resolution, more precise dating and proxies that can be interpreted unambiguously. By employing modern paleoclimate methods in new areas, there is the potential for the development of a denser network of sites for regional comparisons and to investigate the climate at multiple levels of scales.

Project background

This PhD-project developed in the wake of a Mistra (Foundation for Strategic Environmental Research) funded research project The Urban Mind - Cultural and Environmental Dynamics. The project was a joint venture between scientists mainly from the fields of humanities and natural science, from Uppsala and Stockholm universities. The overall aim of the project was to develop an understanding of cultural and environmental factors behind urban development, both prosperity and decline, in the eastern Mediterranean region. The outcome of the project is presented in the volume The Urban Mind - Cultural and Environmental Dynamics, edited by Sinclair et al. (2010).

One of the results from the Urban Mind project was an indication of areas that lack paleoclimate data but are rich in archaeological findings and thus are highly interesting for studies on how climate can have impacted on people and societies in the past, given that climate data can be retrieved (Finné and Holmgren, 2010). One of these identified areas was the Peloponnese which is the focus area of this PhD-project.

Speleothems

Speleothems is a general term for mineral deposits growing in caves. The term is derived from the Greek words spelaion which means cave and thema which means deposit. Speleothems in limestone areas most commonly occur in karstic caves (i.e. formed in limestone by dissolution) all around the world and in a variety of shapes for instance stalagmites, stalactites, straws, flowstones, curtains, columns etc. In paleoclimatology primarily two types of calcareous speleothems (i.e. made of mainly calcium carbonate $CaCO_3$) are used: 1) stalactites, growing from the ceiling towards the floor, and more commonly 2) stalagmites, growing from the floor towards the ceiling (Fairchild et al., 2006a). The formation of speleothems is essentially a function of carbonate dissolution in the soil and epikarst and precipitation (deposition) in the underlying cave zone. Dissolution of the carbonate bedrock in the soil and epikarst is controlled by high carbon dioxide levels (high pCO_2) in the soil, a result of biological respiration and decomposition (Ford and Williams, 1989; Fairchild and Baker, 2012). The carbon dioxide dissolves in percolating meteoric water to form carbonic acid. The slightly acidic water can then dissolve the bedrock and the calcium concentration of the water increases. The water then descends into the karst system through cracks and joints in the bedrock. During its course through the bedrock the water may enter a void, for example a cave, with a lower pCO_2 compared with what the water had previously encountered. This will lead to degassing of CO_2 from the solution and in turn to precipitation of $CaCO_3$ and the formation of speleothems (Ford and Williams, 1989; Fairchild and Baker, 2012).

Speleothems have been widely applied in paleoclimate studies mainly because they can be precisely dated and because they can record and preserve a climate signal for a long time (McDermott, 2004; Fairchild et al., 2006a; Lachniet, 2009). The range of climate proxies analyzed to recover information about past climate variability from speleothems include for instance lamina thickness, luminescence, trace element analysis and, most commonly, stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes (for a comprehensive review see e.g. Fairchild et al., 2006a).

Dating of speleothems is most commonly done by uranium-thorium dating (U-Th dating). The *basic idea* behind the method is that uranium which, in contrast to thorium, can dissolve in water and be transported into a cave where it is subsequently incorporated into depositing calcite (Richards and Dorale, 2003; Dorale et al., 2004). After deposition the uranium begins to decay into one of its daughter nuclides thorium, through time a ratio that can be measured between the two nuclides evolves. From this ratio the age of the sample can be worked out by applying the known decay rates for the nuclides.

In parallel with the development and application of U-Th dating, other possibilities for providing chronological control for speleothems have also progressed with the, perhaps, most promising being the counting of laminae. Since the first demonstrations of laminae forming annually in stalagmites the usefulness of these for chronological control, as well as for climatic interpretations, has begun to be explored in recent years (for reviews see e.g. Tan et al., 2006; Baker et al., 2008). Comparisons between radiometric dating and chronologies based on lamina counting have shown the potential of this method for providing highly precise and accurate chronologies (e.g. Baker et al., 1993; Genty and Deflandre, 1998; Linge et al., 2009; Mattey et al., 2008; Jex et al., 2010; Tan et al., 2013).

Stable oxygen and carbon isotopes in speleothems

Stable isotopes in carbonates ($\delta^{18}O$ and $\delta^{13}C$), and in water ($\delta^{18}O$ and δD), have been used in paleoclimate studies for more than 50 years (e.g. Urey et al., 1948; Craig, 1953). Systematic studies of $\delta^{18}O$ and $\delta^{13}C$ in speleothems have been conducted during the past 40 years, but it was not until around 20 years ago smaller sample sizes allowed the field to grow substantially (e.g. Hendy and Wilson, 1968; Schwarcz, 1986; McDermott, 2004).

Isotope ratios in carbonates are expressed in the δ notation in parts per mille (‰) relative to V-PDB (Vienna Pee Dee Belemnite):

$\delta^{18}O$ V-PDB = $(R_{sample}/R_{standard}-1)\times1000$ where R = $^{18}O/^{16}O$

and similarly,

$\delta^{13}C$ V-PDB = $(R_{sample}/R_{standard}-1)\times1000$ where R = $^{13}C/^{12}C$

(Water samples are also in the δ notation in parts per mille but relative to V-SMOW (Vienna Standard Mean Ocean Water)

There is an intimate link between climate parameters and the composition of $\delta^{18}O$ in precipitation (Rozanski et al., 1993; Gat, 1996). The amount of ^{18}O in precipitation is mainly controlled by the following factors: 1) condensation temperature, 2) latitude effect, 3) altitude effect, 4) distance from source or continentality effect, 5) seasonal effect, and 6) amount effect (see e.g. Rozanski et al., 1993; Gat, 1996; Sharp, 2007). After pioneering work in the 1950s and 1960s revealing the potential of $\delta^{18}O$ as a climate recorder the number of studies utilizing this method is almost endless. The $\delta^{18}O$ signal of the precipitation, reflecting variations in the climate affecting the hydrological cycle, can be recorded in various types of natural archives, for example speleothems, ice cores, lake sediments, peat bogs (Gat, 1996; see e.g. Leng, 2006 for a comprehensive list of applications). In caves, the drip water derives from meteoric water from the surface which means that the $\delta^{18}O$ signal in precipitation falling outside of a cave can be recorded in the cave. If conditions are favorable, i.e. in equilibrium or near equilibrium, during the formation of a stalagmite, the $\delta^{18}O$ value of the drip water feeding the speleothem will be reflected in the precipitated calcium carbonate (Hendy, 1971; McDermott, 2004; Fairchild et al., 2006a; Lachniet, 2009). The idea of deposition of speleothems under true equilibrium conditions have been discussed in recent years and it is becoming evident that most speleothems do not form under equilibrium conditions and that kinetic effects are important (Lachniet, 2009; McDermott et al., 2011). Additionally processes in the soil zone and the epikarst may affect the $\delta^{18}O$ of the drip water and it is pointed out by Lachniet (2009, and references therein) that a good understanding of the relationship between modern climate and $\delta^{18}O$ is an important complement to paleoclimate studies.

Carbon isotopes in speleothems have been less utilized compared with $\delta^{18}O$ because of the complexity of carbon transport and isotope fractionation in the karst system. The $\delta^{13}C$ in speleothems is mainly controlled by: 1) carbon source for groundwater, 2) open or closed system dissolution of bedrock, 3) disequilibrium between soil water and soil CO_2, 4) rate of degassing in the cave controlled by pCO_2 and drip rate, 5) prior calcite precipitation in the epikarst, and 6) evaporation in the cave (Cosford et al., 2009). It has been estimated that around 80–90% of the carbon in cave drip water derives from biological processes in the soil zone with the remaining part coming from the atmosphere and bedrock dissolution (Genty et al., 1998; Cosford et al., 2009; Lambert and Aharon, 2011). Soil carbon is relatively depleted in ^{13}C compared with the atmosphere because kinetic fractionation of biological processes favors the use of ^{12}C. Vegetation type (C_3 or C_4) is also an important control on soil $\delta^{13}C$, a higher proportion of plants following the C_3 photosynthetic pathway will lead to more depleted $\delta^{13}C$. Increased biological productivity (including soil microbial activity) and a higher proportion of C_3 vegetation will therefore lead to more depleted values of $\delta^{13}C$ as the input of biogenic light carbon is increased (Baldini et al., 2005; Cosford et at., 2009). Other factors that can influence the speleothem $\delta^{13}C$, such as reduced dripping, facilitating increased de-gassing and increased prior calcite precipitation drive the $\delta^{13}C$ signal in the same directions as do the biological processes, i.e. drier conditions lead to more enriched $\delta^{13}C$ values (Fairchild et al., 2006a).

Aim of the thesis

The overall aim of this thesis is to increase knowledge about past climate variability in the eastern Mediterranean region during the Holocene and the Pleistocene, i.e. the late Quaternary. The thesis is broadly laid out in two stages.

1. Assessing current knowledge. Paper I explores current knowledge about the climate in the eastern Mediterranean during the past 6000 years. Based on the results of Paper I the second part of the project was designed.

2. Bridging the gap. This stage forms the main part of the thesis. Papers II–IV, together with additional results presented for the first time in this thesis summary, are the results of empirical investigations of speleothems and cave environments from the Peloponnese. To achieve the aim of the thesis the following questions were defined

- How has the climate in the eastern Mediterranean varied in space and time during the late Quaternary?
- What uncertainties are associated with absolute paleoclimate reconstructions of temperature and precipitation from the region?
- What were the characteristics and the spatial extent of the so-called 4.2-event in the eastern Mediterranean region based on the currently available data?
- Can speleothems from karstic caves be used to provide information about past climate variability on the Peloponnese for the late Quaternary period?
- How did the climate vary on the Peloponnese during the late Quaternary and what were the characteristics of this variability?

Study area

The eastern Mediterranean region together with adjacent areas are explored in Paper I and is defined as an area covering parts of southeastern Europe and southwestern Asia (Fig. 1). The area extends beyond the area of classic Mediterranean climate in order to enhance coverage of archaeological and historical sites. The defined area generally sustains a pronounced period of summer drought and is influenced by the proximity of the Mediterranean Sea. Winter precipitation in the region is mainly controlled by eastward tracking cyclones originating over the Mediterranean.

The Peloponnese peninsula makes up the southern part of mainland Greece and is the focus area for Papers II–IV (Fig. 1). The peninsula is topographically variable with a core of a high-altitude mountainous area, with narrow and elongated areas of river valleys, grabens and lowland along the coast. The peninsula is rich in archaeological remains reflecting its long history of human activity which extends back to, at least, the Paleolithic age (e.g. Runnels, 1995; Shelmerdine, 1997; Bintliff, 2012). During this long history the Peloponnese has been the home of for example the Mycenaean civilization and the Spartan city state (for a concise overview, see e.g. Bintliff, 2012).

Modern climate in the eastern Mediterranean

The Mediterranean type of climate is highly distinct with hot and dry summers and mild and wet winters. The Mediterranean region lies between the subtropical high pres-

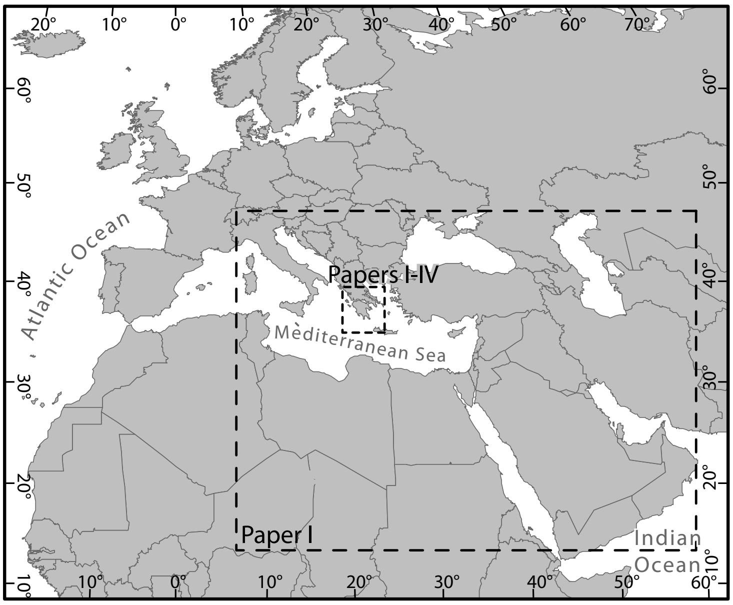


Figure 1. The location of the study area. Large dashed rectangle shows the area covered in Paper I. Small dashed square shows the focus area of papers I–IV, see Fig. 2 for details.

sure systems to the south and the belt of westerly winds to the north. During summer the region is under the influence of the subtropical high pressure systems creating hot and dry conditions. In winter the subtropical high pressure systems shift southward and the westerly wind belt influences the region, creating mild and wet conditions. Globally, the climate type is comparatively rare and occurs in relatively narrow coastal zones in, for instance, central California, the Cape Province in South Africa and in SW Australia.

In the Mediterranean region the presence of the Mediterranean Sea means that the influence of the Mediterranean type of climate can extend further into a landmass than elsewhere. The climate in the western basin is influenced by the proximity to the Atlantic Ocean and is generally more maritime with more rainfall and milder temperatures throughout the year whereas the eastern basin is more continental with a drier climate and hotter summer temperatures and colder winters.

In the eastern Mediterranean, mean annual precipitation ranges from >2000 mm, for example in parts of SW Turkey to less than 120 mm in North Africa (Rohling et al., 2009). Summer rainfall is very low and winter precipitation accounts for around 90% of the annual total (Xoplaki, 2002). During summer the northward shift of the subtropical high pressure systems causes air to subside over the eastern Mediterranean minimizing cloud formation and thus precipitation (Trigo et al., 1999; Raicich et al., 2003; Ziv et al., 2004). In winter the southward displacement of the subtropical high pressure systems allows depressions of Atlantic origin to enter the region strengthening local cyclogenesis and moisture transport (Cullen et al., 2002; Rohling et al., 2009). Cyclones affecting the eastern basin are mainly formed over the Gulf of Genoa, south of Italy, the Aegean Sea and Cyprus (Harding et al., 2009). Most activity takes place in the Gulf of Genoa during winter from which cyclones tend to track SE-ward. Cyclogenesis is triggered by the passage of remnant North Atlantic synoptic systems and local topography, and cyclones can form consecutively at multiple centers as a single North Atlantic system passes (Trigo et al., 2002). These mainly eastward moving cyclones deliver the majority of the precipitation in the eastern basin.

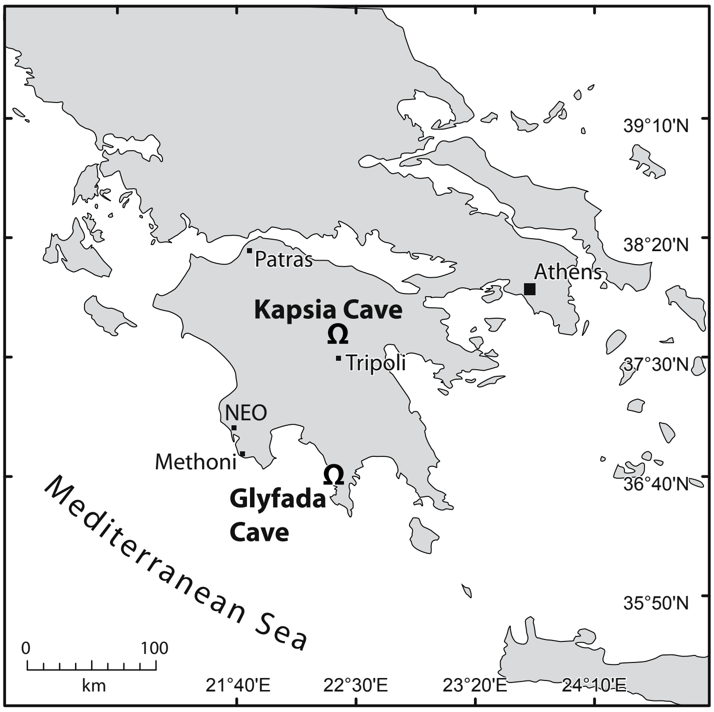


Figure 2. The location of Kapsia Cave and Glyfada Cave on the Peloponnese peninsula.

The climate in the eastern Mediterranean is spatially variable and local differences caused by for instances topography and local winds occur (Harding et al., 2009). Elevation impacts on temperatures and on precipitation and some of the wettest areas are west-facing coastal mountains (Harding et al., 2009). Some areas also receive summer precipitation such as the north coast of Turkey (Fleitmann et al., 2009).

The North Atlantic Oscillation (NAO) influences the winter precipitation and temperature of the eastern Mediterranean (Cullen and deMenocal, 2000; Türkeş and Erlat, 2003; Feidas et al., 2004). Positive (negative) NAO will create cooler and drier (warmer and wetter) conditions as less air from the North Atlantic penetrates into the region. Rainfall and temperature variability depends further on the pressure difference between the North Sea and the Caspian Sea, the so-called North Sea – Caspian Pattern Index (NCPI) (Kutiel et al., 2002; Kutiel and Benaroch, 2002). During a positive phase of the NCPI, an anomalous circulation pattern forms in the eastern Mediterranean and the Aegean Sea with a stronger component of northeasterly winds bringing cool and dry continental air into many parts of the region. During negative NCPI, circulation tends to be stronger from the southwest favoring higher temperatures and wetter conditions (Kutiel and Benaroch, 2002; Kutiel et al., 2002). Another important control on winter temperature variability is the Mediterranean Oscillation (MO), calculated from the differences in pressure between for example Cairo and Algiers (Dünkeloh and Jacobeit, 2003; Feidas, 2004; Harding et al., 2009). It has been shown that a southerly flow over the western basin causing higher temperatures is associated with opposite conditions, i.e. northerly flow of air and cooler temperatures in the eastern part, creating a seesaw like pattern in the Mediterranean region (Maheras and Kutiel, 1999). During positive MO a southward flow of cool air over Greece can be facilitated in connection with enhanced frequency and persistence of low pressures over the central Mediterranean (Feidas et al., 2004).

Figure 3. Photos from Kapsia Cave. Clockwise from top left: 1) photo showing high water mark (flood mark) in the ceiling of Kapsia Cave and speleothem formations. Brown areas have been inundated by sediment rich flood water. 2) Abundant speleothem growth in Kapsia. Flood mark is visible on the column. 3) Stalagmite GK02 in original growth position. 4) Water collection set up at drip site GK02 the former growth location for stalagmite GK02. In photo the collection bucket with the drip counter can be seen, the silicone tube leads to the larger collection vessel. All photos by Joylon Desmarchelier.

Kapsia Cave

Kapsia cave (N37.623°, E22.354°) is situated in the center of the Peloponnese close to the village Kapsia in the Arcadia prefecture (Fig. 2). The cave entrance is located approximately 700 m a.s.l., where the Mantinea Plain meets the Mainalo Mountains. The cave is formed in a small limestone hill rising approximately 50 m above the surface of the Mantinea Plain, and it is beautifully decorated with numerous speleothem formations such as flow stones, curtains, stalactites, stalagmites and columns. An artificial entrance was opened up in 2004 and since 2010 parts of the cave have been open to tourists. The limestones belong to the Triassic to Eocene Gavrovo–Tripolitza zone formed in shallow marine conditions (Thiébault et al., 1994; Faupl et al., 2002). Bedrock thickness above the cave is 20–30 m.

The hill above the cave is covered with vegetation dominated by oak shrubs (mainly Quercus coccifera) c. 2 m high, different grass species and herbaceous plants including various Lamiaceae species and Euphorbia sp. Within the vegetation cover there are patches of bare soil and outcropping bedrock. A stand of burnt, dead, tree trunks, most likely Juniperus sp., indicates that wild fires disturb the vegetation at times. The latest major fire on the hill occurred in August 1997.

The Mantinea Plain, an important agricultural area, is a large structural polje drained by 5 sinkholes (Higgins and Higgins, 1996). One sinkhole is located adjacent to the natural entrance to Kapsia Cave. This sink hole is active during winter with large amounts of water draining through it. When surface water input exceeds the draining capacity of the

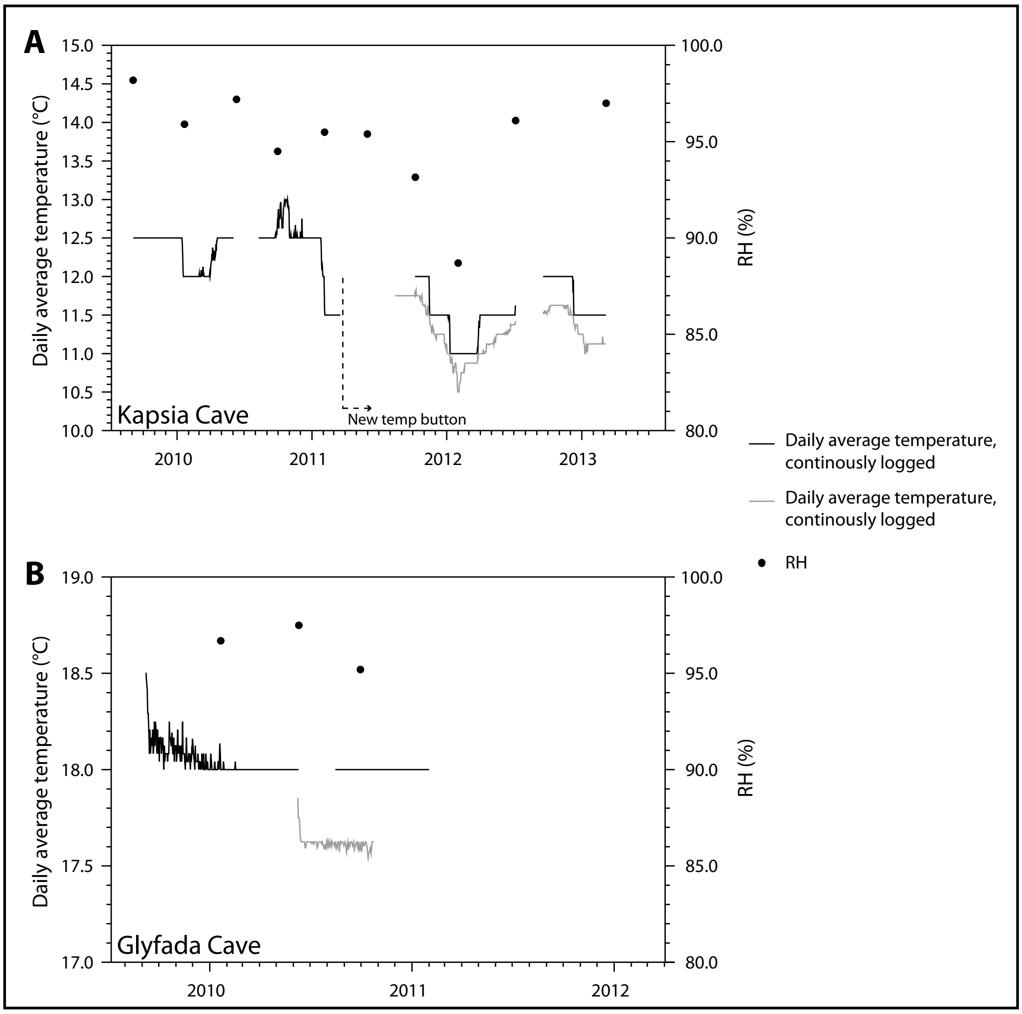


Figure 4. A: Monitored cave air temperature and relative humidity (RH) in Kapsia Cave. Black and gray lines show daily average temperature as recorded by continuous logging. Differences in the temperature data are within measurement uncertainties. Black circles show the relative humidity of the cave air as measured by a hand-held device.
B: Monitored cave air temperature and relative humidity (RH) in Glyfada Cave. Black and gray lines show daily average temperatures. Differences in the temperature data are within measurement uncertainties. Black circles show the relative humidity of the cave air as measured by a hand-held device.
Note the differences in scale on the x-axes between A and B.

sinkholes, parts of the plain, and sometimes also the cave, are flooded. The cave has been flooded both in recent times and in the past, as is clear from meter-thick clay-layers on the cave floor, distinct color changes (flood marks) on the cave walls and speleothem surfaces and horizons of clayey sediments in sliced stalagmites (Fig. 3). The latest recorded flooding of the cave was in 2001 (pers. comm. Grigoris Rousiotis).

The cave is rich in archaeological remains. Close to the natural entrance Neolithic remains have been found. Deeper in the cave sherds, dated to Hellenistic times (323–31 BC), have been found along with sherds and terracotta lamps dated to a period of 4th–6th century AD and bronze coins and two bronze fibulae, dated to the 2nd half of the 6th century AD. Bones and skulls from around 50 human individuals, of all ages, have been found

Figure 5. Photos from Glyfada Cave showing the abundant decorations and the sea surface in the cave. The pure white stalagmite in upper left photo is currently forming. All photos by Joylon Desmarchelier.

scattered around the deep part of the cave. Since the bones are scattered there is a debate about how this can have happened. Two possible explanations have been presented by archaeologists: 1) the people drowned in a flood, or starved to death when a flood sealed the natural entrance, or 2) the cave used to be a burial ground and a place for worshipping the dead and the bones found in the cave originate from already deceased persons (Merdenisianos, 2005).

The cave environment in Kapsia has been continuously monitored since September 2009 as part of this PhD study. During the monitoring period the average temperature of the cave air was around 11.9 ± 0.52°C (Fig. 4). Typically temperatures drop around 1.0–0.5°C during winters most likely related to air circulation. The relative humidity in the cave is normally ≥95% (Fig. 4). The lowest recorded relative humidity value is 89% and was recorded in the winter of 2012 when the rains started late (Fig. 4).

The climate outside the cave can be characterized by data from the nearest meteorological station in Tripoli (approximately 10 km to the south, elevation 650 m) (Fig. 6). The annual average precipitation amount in Tripoli is 768 ± 393 mm for the period 1951–2008, with a great deal of year-to-year variability. Around 70–80% of the precipitation falls in the period from October to April (wet season) and in higher terrain snowfall usually occurs. Annual average temperature is 14.1 ± 1.4°C for the period 1951–2004. Winters (DFJ) are cool with a recorded annual average temperature of 5.8°C for the period 1951–2008. High summer (MJJAS) temperatures (1951–2008 average is 21.6 ± 3.2°C) and low summer precipitation lead to a negative water balance, i.e. evaporation from soil and vegetation exceeds precipitation, for the period May to September (Fig. 6). During the period of negative water balance no, or very little, recharge to the karstic aquifer is likely to occur. The prevailing wind direction is southwesterly in November and December and from February to June and northerly in January and from July to October.

Glyfada Cave

Glyfada Cave (N36.638°, E22.380°), one of the best known show caves in Greece, is located on the west side of the Mani Peninsula in the Laconia prefecture, southern Peloponnese (Fig. 2). The cave is formed in a promontory, approximately 2 km wide and extending c. 200 m a.s.l. at its highest point, overlooking the Ionian Sea. The cave is located close to the present day sea level and parts of the cave are located under the sea surface. The cave is formed in crystalline limestone belonging to the Plattenkalk unit of Mesozoic–Eocene age (Bassiakos, 1993; Giannopoulos, 2000; Robertson, 2006; van Hinsbergen and Schmid, 2012). In the year 2000 some 10 000 m of passageways had been explored in the cave of which almost 2000 m was underwater (Giannopoulos, 2000). The cave system is heavily decorated with different types of speleothems (Fig. 5). Two previous studies carried out in the cave mainly focused on the environment of the cave and the abundance of paleontological material found in the cave (Bassiakos, 1993; Giannopoulos, 2000). Bones belonging to a range of mammal families including: Bovidae, Hippotamidae and Felidae, have been found indicating that the cave communicated with the external environment in prehistoric times (Giannopoulos, 2000).

Just inland of the cave the southern end of the Taygetos Mountains extends as a central ridge on the Mani peninsula with peaks of around 1000 m a.s.l. 4 km east of the cave entrance. The topography of the region promotes orographically induced precipitation to fall on the west-facing side of the peninsula. The vegetation above the cave is typically Mediterranean. It is sparse on the promontory, especially on the steep sides where bedrock outcropping is extensive. Most of the flat top surface is covered by olive groves.

Continuous temperature logging during the period September 2009 to February 2011 indicates stable temperatures around 18.0 ± 0.1°C in Glyfada Cave (Fig. 4). Relative humidity was measured to be around 96% on three different occasions during 2010 (Fig. 4). The stable conditions follow the relative isolation of the chamber in Glyfada Cave. Dripping occurs throughout the cave, including the sampling sites. Deposition of calcite was recorded to occur at some sites but not on the sampling sites.

From data from the meteorological station in Methoni (located approximately 64 km to the east, elevation 53 m) the climate in the area of Glyfada Cave can be described (Fig. 6). Annual average air temperature is 18.0 ± 0.4°C for the period 1951–2008. Summer (MJJAS) temperature average is 23.2 ± 2.5°C and winter (DJF) average temperature is 11.9 ± 1.4°C for the period 1951–2008. The annual average precipitation amount in Methoni is 698 ± 151 mm for the period 1951–2008. Normally >90% of the precipitation falls between October and April. The prevailing wind direction, in Methoni, is west-northwest to south bringing in moist air from the Mediterranean. Similarly as in Kapsia the water balance in the area is negative from May to September (Fig. 6).

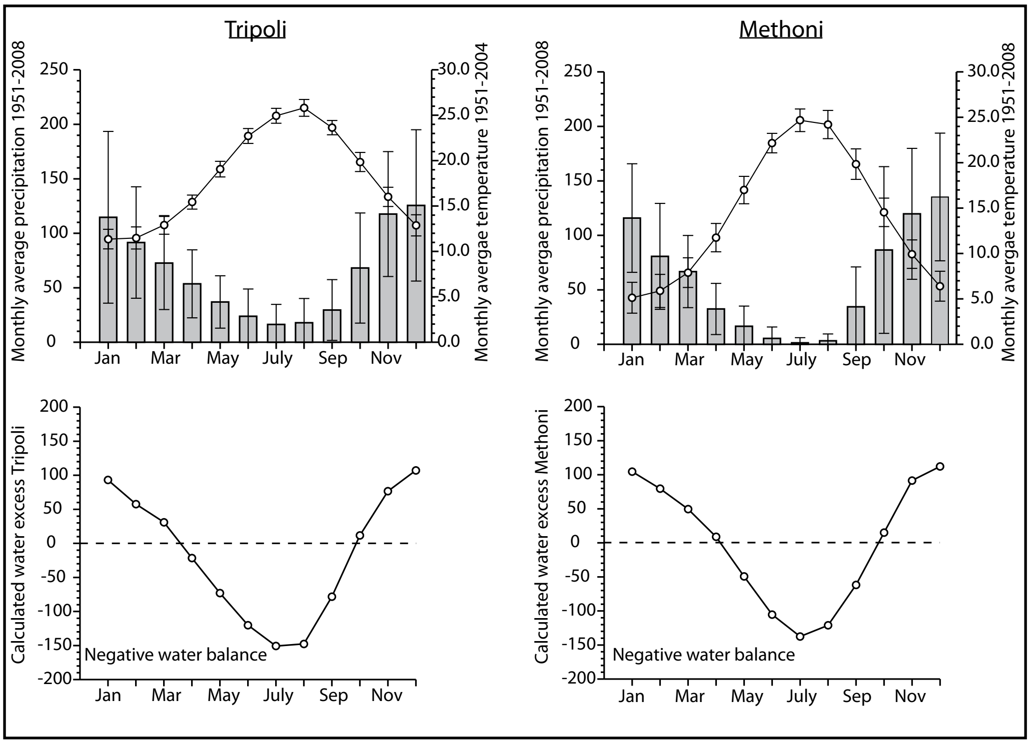


Figure 6. Modern climate (precipitation and temperature) at the meteorological stations in Tripoli (upper left) and Methoni (upper right) showing the pronounced dry and hot conditions during summer and milder and wetter conditions during winter. The climate situation leads to a negative water balance from May to September at both places as indicated by the calculated water excess (lower left and right). During times of negative water balance evapotranspiration is greater than precipitation which means that no, or very little, water can enter the limestone aquifers above the caves. Calculations for water excess follow Thornthwaite (1954) as applied by Genty and Deflandre (1998). Error bars show 1 standard deviation.

Material and Methods

Paper I

In the literature review process information regarding dating technique(s) and reliability, time-span covered, resolution, proxy type, uncertainties (e.g. measurement uncertainty), and suggested climate interpretations, was recorded for proxy records published in peer-reviewed articles. From this list of records an essentially qualitative selection, based on a set of criteria including high dating reliability, high time resolution, small levels of uncertainties, and one or preferably several unambiguous proxy(ies) was made. Preference was given to records fulfilling these criteria and which covered the whole Holocene. Following this first step, 18 records complying with the defined criteria were selected for a closer analysis.

For each of the 18 records the average value of the proxy was calculated for the period 6000–0 years BP, or as late into the Holocene as the record allowed. The 6000-year period was then divided into 30 time slices of 200 years each. The proxy records and the average values were plotted on graphs and divided into three classes: proxy values below average, average, and above average, in each of the 30 time slices. Based on the three classes spatial and temporal analyses were undertaken to investigate climate variability in the eastern Mediterranean geographically and over time.

Additionally, 15 records with reconstructed absolute values of temperature were used to illustrate the inherent uncertainties in paleoclimate reconstructions. For each of the 15 records the average values were calculated and the uncertainties of the average values were estimated for three selected time periods, *viz*. 6000 ± 100 years BP, 4200 ± 100 years BP, and 2400 ± 100 years BP. The uncertainties were estimated by using a so-called calibration uncertainty (σ_c) as an approximation of minimum uncertainties. The size of the calibration uncertainty comprises, for instance: 1) the incapability of the proxy to perfectly portray past variations of the climate variable, and 2) measurement errors but does not include for instance dating uncertainties. The calibration uncertainty is presented in absolute values of the climate variable, in this case °C.

Papers II–IV and ongoing studies

The stalagmites

In September 2009 two stalagmites from Kapsia Cave and two stalagmites from Glyfada Cave were collected from their growth positions. In Kapsia Cave both stalagmites were growing in the same part of the cave well away from the artificial and natural entrances and in a section of the cave where tourists are not allowed. One stalagmite (GK01 - referred to as GK0901 in Paper IV) was collected from a low part of the cave and the other one (GK02 - referred to as GK-09-02 in Paper II) from an elevated shelf around 2–3 m above the first one (Fig. 3). Both stalagmites were slightly cone shaped. Dripping occurred at both collection sites.

In Glyfada Cave two candle-stick-shaped stalagmites (GG1 and GG2) growing approximately 2 m apart and around 1.5 m above the current sea level were collected. The stalagmites were growing in a smaller chamber attached to a large room in an isolated part of the cave not accessible to tourists. As in Kapsia, dripping occurred at both sampling locations in Glyfada.

From all collected stalagmites a one centimeter thick central slab was extracted by cutting along the growth axis using a diamond coated saw to expose the inner part (Fig. 7). All central slabs were polished with wet sanding paper. Both stalagmites from Kapsia were visibly laminated with translucent thin dark layers and thicker milky white, opaque calcite. In some areas the stalagmites from Kapsia were porous. In the stalagmite growing in a lower position (GK01), numerous thin horizons of clayey sediments were intercalated in the calcite matrix. The stalagmites from Glyfada Cave consist of compact translucent calcite with areas of milky white, opaque calcite.

Petrographic thin sections and visible lamina

For all collected stalagmites one of the sides facing the central slab was used to produce petrographic thin sections (30 μm thick). Thin sections were produced along the full growth axis of all stalagmites. The thin sections were analyzed to 1) investigate the stalagmites for depositional hiatuses, and 2) to investigate the presence of visible laminae. Information about the presence and position of depositional hiatuses is crucial for the age-depth model building. Visible laminae in speleothems can, if present, be observed using transmission or reflection light microscopy. The formation of visible laminae requires a change in the spatial arrangement of calcite crystals with a well-defined morphology and often occurs on a seasonal basis (Tan et al., 2006 and references therein). Petrographic

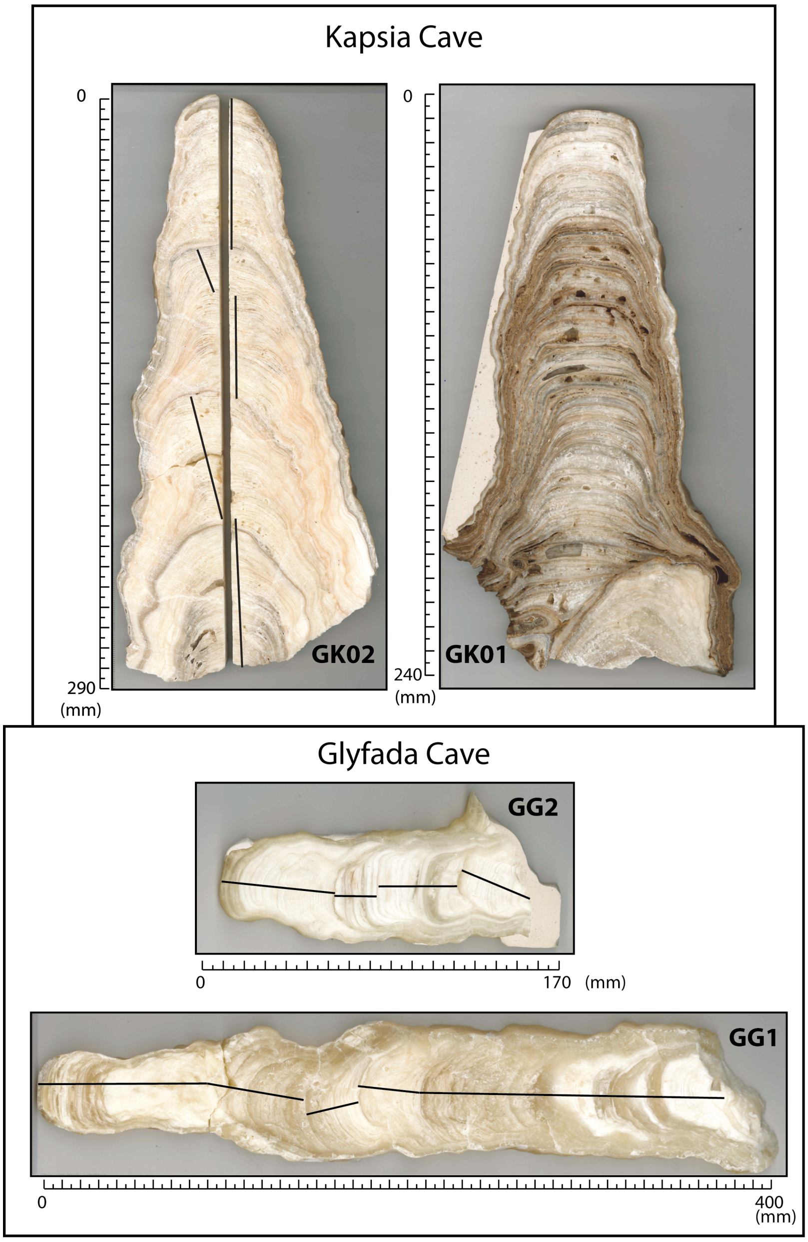


Figure 7. The stalagmites investigated in this thesis. Stalagmites GK01 and GK02 from Kapsia Cave (top) and stalagmites GG1 and GG2 from Glyfada Cave (bottom). Shown in the figure is the extracted, polished, central slab from each stalagmite, revealing the inner part of the samples.

analyses of all thin sections were performed under a Nikon Optiphot2-Pol microscope equipped with a camera under ×25 and ×100 magnification. For the top part of stalagmite GK02 lamina counting was performed by two persons, independently of each other, and using the same microscope and magnification as above. Lamina thickness was also measured using the microscope. The thin sections were photographed under the microscope and photos were further inspected for lamina using image processing software.

Table 1. List of monitored drip sites in Kapsia Cave and period covered by monitoring. The water collection column gives information about the type of water samples that were collected from the drip site. Continuous samples were collected in plastic jars between visits. Instant drip water samples were typically collected over 24 hours.

Drip site ID	Water collection	Period covered	Remark
GK01	Continuous and instant	Jan 2010–present	Collection site of stalagmite GK01
GK02	Continuous and instant	Sept 2009–present	Collection site of stalagmite GK02
KD1	Instant	Sept 2009–March 2013 (latest visit)	~0.5 m from site GK02
KD2	Instant	Jan 2010–March 2013 (latest visit)	~1 m from site GK02

Cave monitoring

Cave monitoring is an important tool for understanding the hydrology of the karst system and how this affects the formation of speleothems and the stable isotope signal in them. Cave monitoring was initiated in September 2009 in both Kapsia and Glyfada Caves. The monitoring in Glyfada Cave was terminated in February 2011, subsequently the main monitoring focus has been on Kapsia Cave and the drip sites listed in Table 1.

Monitoring of the cave environment includes continuous logging of discharge rate, or drip rate, and temperature as well as continuous collection of drip water and growth of calcite on an artificial substrate (Table 2). For continuous collection of drip water, a simple water collection system was installed in both caves, which connected the drip counter via a silicone tube to a plastic jar for collection (Fig. 3). However, this system was more often than not disrupted by hungry, or curious, mice chewing off the tubes.

During the monitoring period the caves were visited three times per year. During these visits cave air temperature, relative humidity, air pressure and pCO_2 were measured with hand-held meters (Table 2). Raw cave air pCO_2 values were corrected for changes in air pressure (P, in hPa) using:

$$CO_2(\text{ppmv}) = CO_2(\text{raw}) \times 1013/P,$$

following Riechelmann et al. (2011). Additionally, instant drip water was collected as well as a sample of the continuously collected drip water for chemical analyses. Analyses carried out directly in the cave include: pH, electrical conductivity and alkalinity (Table 2) and, analyses carried out in the lab include: $\delta^{18}O$, δD, cations and anions. The possibilities of continuously logging pCO_2, air pressure and relative humidity were explored with two different logger types but without success. Problems encountered mainly include condensation on sensors and short circuits due to condensation drops within the loggers.

Table 2. List of parameters monitored in Kapsia Cave and type of equipment used with accuracy. Accuracy of equipment as stated from the manufacturers.

Monitored parameter	Equipment	Accuracy	Remark
Discharge rate (or drip rate)	Driptych Stalagmate		Type: Stalagmate Plus Mk2b. Mattey and Collister (2008)
Cave air temperature – continuous	Maxim Thermochron ibutton	± 1°C	Type DS1921Z resolution 0.125°C Type DS1921G resolution 0.5°C
Relative humidity of cave air	Vaisala HM70	± 1.7%	HMP75 probe
Cave air temperature – discrete	Vaisala HM70	± 0.2°C	HMP75 probe
Cave air CO_2	Vaisala GM70	± 1.5% of range and ± 2% of reading	GMP222 probe
Air pressure	Sunartis BKT380 barometer		Mechanical
Electrical conductivity of water	WTW 340i multimeter	± 0.5% of measured value ± 1 digit	TetraCon 325 probe
pH of water	WTW 340i multimeter	± 0.01 ± 1 digit	SenTix 21-1 probe
Water temperature	WTW 340i multimeter	± 0.05°K ± 1 digit	SenTix 21-1 probe
Alkalinity of water	AQUAMERCK® kit	± 5 mg/L HCO^-_3	

Analytical methods

Calcite $\delta^{18}O$ and $\delta^{13}C$

For analyzing $\delta^{13}C$ and $\delta^{18}O$ in the stalagmites samples were drilled with 1 mm resolution along the growth axis of the stalagmites using a hand-held diamond coated drill-bit. For the uppermost part of stalagmite GK02 a micromiller was used to achieve a resolution of 0.3 mm. The collected carbonate samples (around 0.2 mg) were flushed with argon gas in a septum-seal glass vial and 100 µL of 99% H_3PO_4 was added to each sample for reacting to carbon dioxide. Analyses were performed using a Gasbench II coupled to a Finnigan MAT 252 mass spectrometer. Reproducibility and accuracy were monitored by replicate analysis of laboratory standards calibrated to NBS19 and LSVEC and proved to be better than 0.07‰ for $\delta^{13}C$ and 0.15‰ for $\delta^{18}O$ (2σ). Analyses were performed at the Stable Isotope Laboratory (SIL), Department of Geological Sciences, Stockholm University and at the Stable isotope laboratory of Friedrich-Alexander University, Erlangen-Nürnberg.

Radiocarbon

Powder for radiocarbon analysis was also drilled using a hand-held diamond coated drill-bit. The collected samples (around 2 mg) were washed in de-ionized water in an ultrasonic bath before analysis. Samples were leached stepwise in 0.5 HCl to investigate possible contamination. The evolved CO_2 gas was converted into graphite using Fe-catalyst before being inserted into the accelerator mass-spectrometer. Radiocarbon analyses were performed at The Ångström Laboratory, Uppsala University, Sweden.

U-Th

The hand held diamond coated drill-bit was also used to extract samples for U-Th dating (0.5 g). U-Th dating was performed at the Geological Survey of Israel (GSI) using a Nu Instruments Ltd (UK) MC-ICP-MS. All samples were dissolved, with a combination of 7 M HNO_3 and HF, and equilibrated with a mixed $^{229}Th/^{236}U$ spike. Samples were loaded onto minicolumns containing 2 mL of Bio-Rad AG 1X8 200–400 mesh resin. U was eluted by 1 M HBr and Th with 6 M HCl. U and Th solutions were evaporated to dryness and the residues dissolved in 2 mL and 5 mL of 0.1 M HNO_3, respectively. Analytical details are described in Bar-Matthews and Ayalon (2011) and in Grant et al. (2012).

Water $\delta^{18}O$ and δD

Collected water samples were stored in airtight containers in 4°C until analysis. Drip water $\delta^{18}O$ and δD were analyzed by a Laser Water Isotope Analyzer from Los Gatos Research located at SIL, Stockholm University. The reproducibility was calculated to be better than 0.6‰ for δD and 0.15‰ for $\delta^{18}O$.

Cations and anions

Water samples for cation analysis were acidified upon collection with extra pure HNO_3. Water samples were stored in 4°C until analysis. Cations (e.g. Ca^{2+}, Mg^{2+}, Sr^{2+}, K^+) were analyzed on two different ICP-OES instruments: a Varian Vista Ax and a Thermo ICAP 6500 duo, both with a reproducibility of ± 5%. Anions (F^-, Cl^-, NO^{3-}, SO_4^{2-}) were analyzed on a Dionex IC20, equipped with an IonPac AS22 column and an AERS 500 suppressor, injection volume was 10 µL and the eluent was 4.5 mM Na_2CO_3/1.4 mM $NaHCO_3$. Measurement uncertainties are for: F^-: 22%, for Cl^-: 15%, and for SO_4^{2-}: 11%. All instruments are located at SIL, Stockholm University.

The calcite saturation index was calculated using PHREEQ (Parkhurst and Apello, 2013).

ITRAX XRF core scanner

A polished stalagmite thick section was scanned using an ITRAX XRF core scanner from Cox Analytical Systems (Gothenburg, Sweden) located at the Department of Geological Sciences, Stockholm University. A Molybdenum tube set at 30 kV and 30 mA was used and the scanning was done with a step size of 200 µm and an exposure time of 40 s along the growth axis.

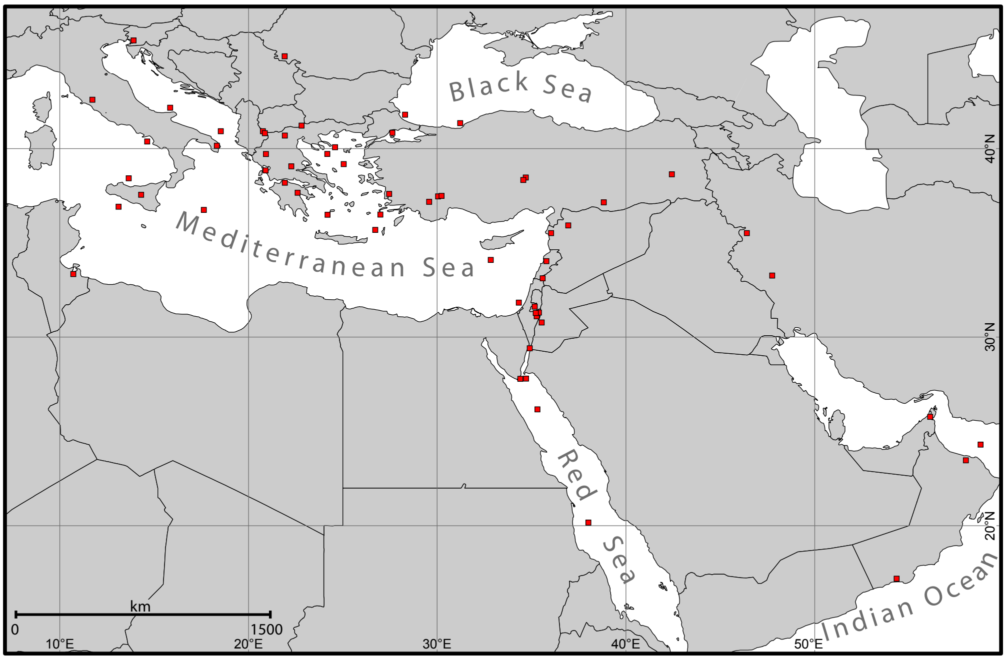


Figure 8. Map of the eastern Mediterranean with the location of published paleoclimate records (red squares). Note the lack of records from the dry areas in the Middle East and North Africa. The paucity of paleoclimate data from the archaeologically rich and relatively well documented southern Greece can also be discerned.

Results

The major results from this thesis are presented as a summary of papers followed by preliminary results from an ongoing project.

Assessing the current knowledge

Paper I: Climate in the eastern Mediterranean, and adjacent regions, during the past 6000 years - A review

Paper I reviews current knowledge of climate variability during the past 6000 years in the eastern Mediterranean region. The review is based on 80 papers with proxy-based paleoclimate information. The 80 papers include 18 paleoclimate proxy records that are analyzed in more detail and 15 paleoclimate reconstructions presenting temperature variability in absolute numbers. In the paper a more classical literature review is complemented with spatial and temporal analyses of the 18 proxy records as well as a statistical analysis of the 15 temperature reconstructions. Analyzing the distribution of the sites covered by the 80 papers, there are a number of areas that have little or no paleoclimate data, for instance S Greece and Egypt (Fig. 8).

The temporal analysis shows evidence of generally wetter conditions in the region in the period from 6000 to 5400 years BP (Fig. 9). The wetter conditions are most likely associated with the early Holocene, northern hemisphere, insolation maximum. In the following period from 5400 to 4600 years BP, conditions become drier but still remain wetter than average for the period. A wet period around 5000 years BP is clearly manifested in

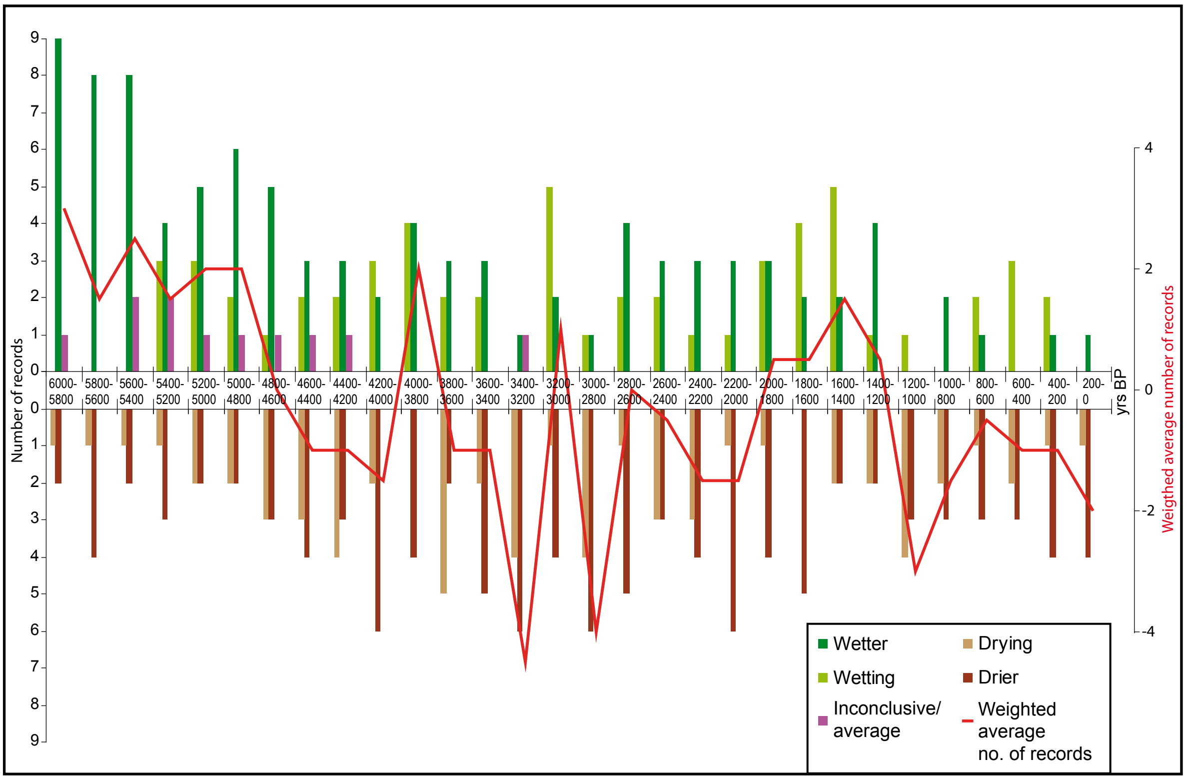


Figure 9. The results from the temporal analysis of paleoclimate records showing wetter and drier conditions from the eastern Mediterranean. Each bar represents the number of records in each 200-year time slice that show either above (wetter) or below (drier) than average conditions, or going from either drier to wetter (wetting) or from wetter to drier (drying) conditions. Average line (red) is calculated as follows: dark green bars were assigned a value of +2, light green bars were assigned a value of +1, dark brown bars were assigned a value of -2 and light brown bars were assigned a value of -1. For each 200-year period an average value was calculated based on the assigned values.

the temporal analysis. After a transitional period from 4800 to 4400, drier conditions come to dominate in the eastern Mediterranean in the period from 4600 to 1400 years BP (Fig. 9). For the last part of the period covered (i.e. after 1400 years BP) the number of proxy records are too few to draw any firm conclusions from. From our analysis it is clear that dry conditions prevail in the region around 4200 years BP, the time of the proposed 4.2-event, however, there is little unequivocal evidence of a rapid climate deterioration in the region. Rather, the evidence from the review suggests that it is masked or mediated by the overall climatic change that started around 4600 years BP.

From the spatial analysis of proxy data a regional heterogeneity in climate variability in the eastern Mediterranean becomes evident. For instance, the spatial analysis suggests that the onset of generally more arid conditions was earlier in the Levant and the southern part of the eastern Mediterranean compared to the northern part.

The compilation and analysis of absolute temperature records generally shows little fluctuation in sea surface temperatures (SST) during the past 6000 years. The lack of consistency between different SST records renders it difficult to describe regional spatial patterns in terms of sea surface temperature change. It is clear that the large uncertainties associated with temperature reconstructions inhibit straightforward conclusions about the relatively minor temperature shifts during the last 6000 years.

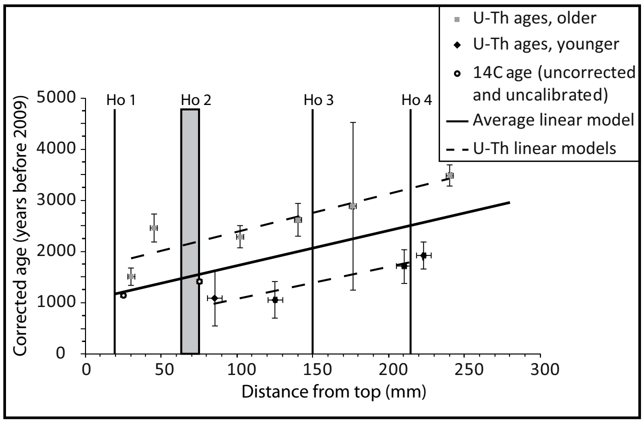


Figure 10. Linear age-depth model for stalagmite GK02 based on the average ages of the 10 cleanest U-Th ages. Errors on individual U-Th ages are 2σ multiplied by a factor of 3 to account for uncertainties involved in the corrections. The average line provides the best fit with the two radiocarbon ages. Ho1 marks the end of the older deposition phase whereas Ho2 to Ho4 indicates the position of flood horizons in the stalagmite.

Moving on from Paper I

Paper I reveals that the southern part of mainland Greece, and the Peloponnese in particular, contains little paleoclimate data compared with many other places in the eastern Mediterranean region (Fig. 8). Available paleoclimate data, from the Peloponnese, include geographically scattered, chronologically poorly constrained palynological (pollen) data (e.g. Sheehan, 1979; Kraft et al., 1980; Bottema, 1990; Atherden et al., 1993; Jahns, 1993; Zangger et al., 1997; Kontopolous and Avramidis, 2003; Urban and Fuchs, 2005, Papazisimou et al., 2005; Engel et al., 2009; Lazarova et al., 2012). The usefulness of palynological data alone for climate interpretations, is hampered by the fact that not only climate but also human activities, for example agriculture and logging, affect natural vegetation. The paucity of climate data from the archaeologically rich and relatively well explored Peloponnese region hampers local comparisons and discussions of how past climate variability has affected and impacted on human societies. The dry conditions in the area and the active draining by humans, since at least Mycenaean times (Knauss, 1991), prevent the formation and preservation of many natural archives, for example peat bogs and wet-lands, which excludes the use of many paleoclimate research methods commonly employed. However, the limestone bedrock in the region is ideal for the formation of caves and speleothems with the possibility of recording valuable information about past climate variability. Considering the availability of speleothems the second part of this project explores the potential to use them as recorders of past climate on the Peloponnese. A number of caves in the Arcadia, Laconia and Argolis prefectures on the Peloponnese were visited during the spring and summer of 2009 in search of suitable stalagmites. Kapsia Cave and Glyfada Cave were assessed to have the best potential, hence, they were chosen for detailed investigations.

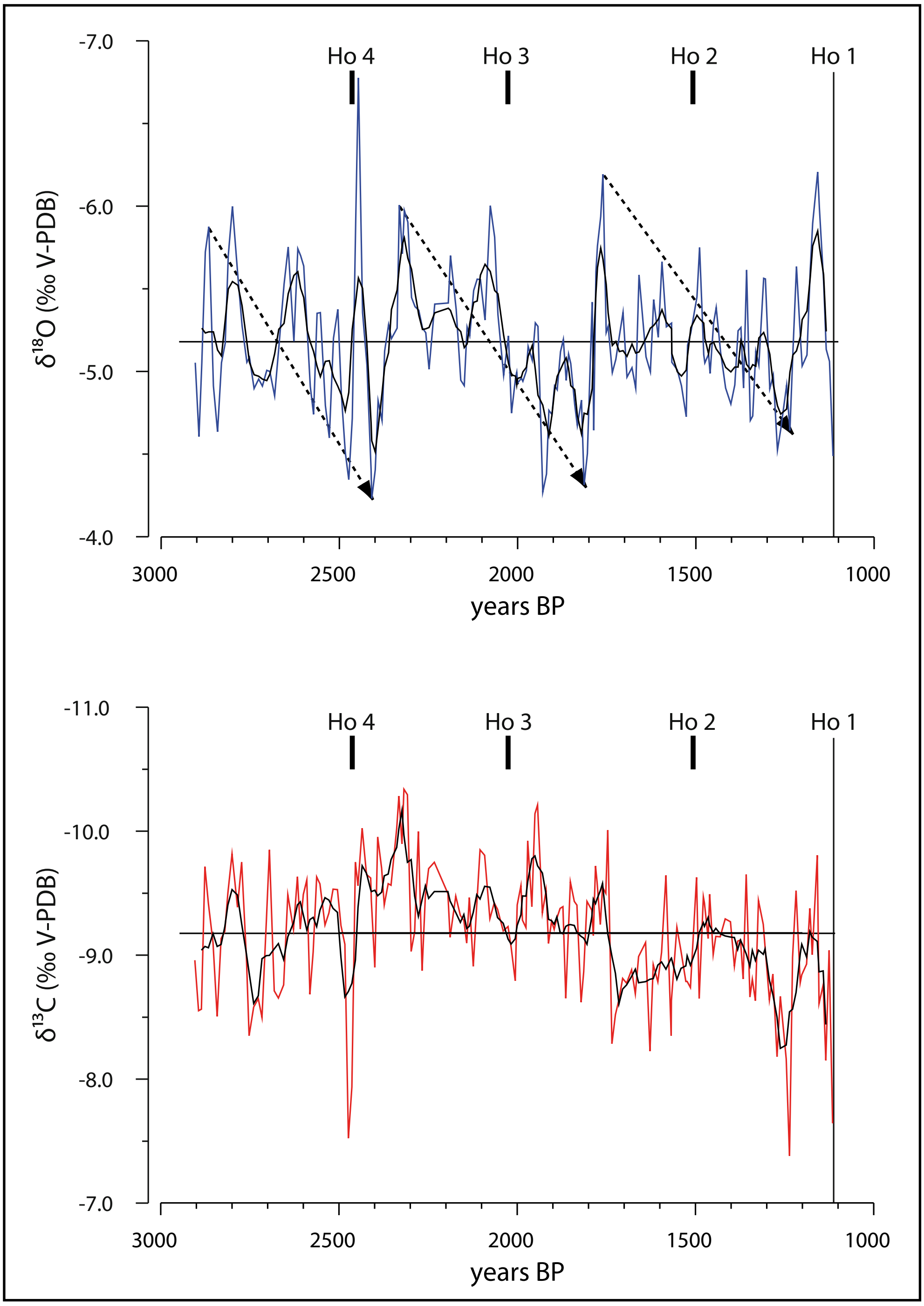


Figure 11. $\delta^{18}O$ (upper) and $\delta^{13}C$ (lower) results from Kapsia Cave plotted vs. age. Black line represents 5 point average. $\delta^{18}O$ is interpreted as being controlled by precipitation amount with more depleted (enriched) values showing more (less) precipitation. $\delta^{13}C$ is interpreted to be controlled by biological activity with more (less) activity indicated by depleted (enriched) values. Note inverted y-axes.
Ho1 marks the end of the older deposition phase whereas Ho2 to Ho4 indicates the position of flood horizons in the stalagmite. Dashed arrows indicate periods of slowly developing aridity.

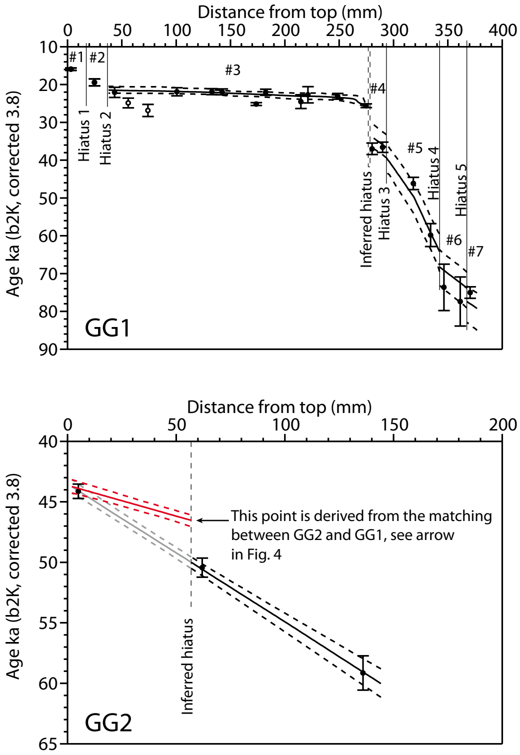


Figure 12. Age-depth models for stalagmites GG1 (upper) and GG2 (lower) based on U-Th ages and information from petrographic analysis. Age-depth model for stalagmite GG1 constructed using StalAge (period #3) and Bacon (periods #4–7). Hiatuses 1–5 are identified in petrographic thin section analysis whereas the hiatus between growth periods #3 and #4 was inferred from U-Th dating. Open circles indicate samples omitted from the age model building. Age-depth model for GG2 constructed using StalAge (black and grey line). The red line shows the age-depth model after the matching with GG1 (see text and Fig. 11 for details about the matching). Errors on individual U-Th ages are 2σ. Dashed lines show 95% confidence intervals. The uncertainties in the interval following the adjustment (red line) in GG2 might be larger than depicted in the figure.

Bridging the gap – Papers II–IV

Paper II: Speleothem evidence for late Holocene climate variability and floods in Southern Greece

In Paper II stable isotope records ($\delta^{18}O$ and $\delta^{13}C$) from detrital rich stalagmite GK02 from Kapsia Cave is presented. The record covers an almost 1800 year long period between c. 2900 and 1100 years BP. The high detrital content of the stalagmite meant that the U-Th ages (n = 26) had to be corrected for input of non-authigenic thorium before an age-depth model could be created. Following a systematic scheme for selection of the least contaminated U-Th samples, a combination of U-Th dating and radiocarbon dating was used to constrain a site specific correction factor for ($^{232}Th/^{238}U$) detrital molar ratio. Based on the remaining, cleanest, U-Th ages (n = 10) a linear age-depth model was created (Fig. 10).

The stable oxygen record is interpreted to reflect precipitation amount, meaning that increased precipitation leads to more depleted values of $\delta^{18}O$ in the stalagmite and vice versa. The record from Kapsia indicates that cyclical changes of close to 500 years in precipitation amount, with rapid shifts towards wetter conditions followed by slowly developing aridity, took place during the growth period (Fig. 11). Superimposed on this low-frequency signal, centennial-scale variability in hydroclimatic conditions with wetter and drier periods is evident. Wetter conditions are inferred around 2800, 2650, 2450, 2350–2050, 1790–1650 and 1180 years BP whereas the driest conditions are inferred to have occurred around 2400, 1850–1800 and 1300 years BP (Fig. 11).

The stable carbon isotope record is interpreted to reflect changes in biological activity as a result of both climate variability and changes in the intensity of human activities. More biological activity is reflected in the stalagmite calcite as more depleted values of $\delta^{13}C$. The $\delta^{13}C$ signal from Kapsia shows that biological activity was generally higher in the older part of the record and that after a rapid decline around 1790 years BP a lower level of activity was reached and maintained (Fig. 11). The rapid set-back in biological activity without recovery could possibly be related to a sustained increase in human activity and impact on the landscape.

Three detrital horizons in the stalagmite indicate that three major floods have occurred in the cave. These have been dated to have taken place 2450, 2020 and 1500 years BP (Fig. 10 and Fig. 11). The latest flood concurs with evidence of human activity from the cave and it is possible that this flood directly influenced human activities in the cave.

Paper III: Rapid climatic shifts in southern Greece during MIS 5a–3 evidence from speleothems

In paper III stable isotope records ($\delta^{13}C$ and $\delta^{18}O$) from Glyfada Cave are presented. The records cover a period from 78 ± 5 to 37 ± 3.6, i.e. the end of Marine Isotope Stage (MIS) 5a and large parts of MIS 4 and MIS 3. The final stable isotope record is based on the results from stalagmites GG1 and GG2 and is the first U-Th dated speleothem record from this area covering the time period in question.

Age-depth models, based on U-Th ages, were developed for each of the two stalagmites separately (Fig. 12). In stalagmite GG1 five depositional perturbations, disclosed by the petrographic analyzes of thin sections, meant that age-depth model building had to be undertaken in chronologically separated periods (denoted #1–7). For periods #4–7 (covering the period of interest for this paper) the age-depth model was created using Bacon (v.2.2) employing a Bayesian statistical approach (Blaauw and Christen, 2011). For stalagmite GG2 no depositional perturbations were revealed in the thin sections so a near linear age-depth model assuming continuous growth was created using StalAge (v.1.0) (Scholz and Hoffmann, 2011). The assumption of continuous growth for GG2, however, proved not to be correct. There is an overlap in growth between stalagmites GG2 and GG1 between ~60 and ~44 ka (Fig. 13A). Generally the $\delta^{18}O$ and $\delta^{13}C$ trends are similar in the two stalagmites, however, judging from the main isotopic peaks there is a chronological offset between them (Fig. 13A). To compensate for this the timing of the most depleted isotopic event in the overlapping part in stalagmite GG2 were adjusted to fit the most depleted isotopic event in the overlapping part in stalagmite GG1, which in turn fits the timing of GIS 12 in NGRIP (arrow in Fig. 13A). This adjustment, of 3.6 ka, creates a break in the GG2 record between 50.1 ± 0.5 ka and 46.5 ± 0.5 ka (Fig. 12 and Fig. 13B). This suggested hiatus corresponds in time with Heinrich event 5 (H5) that occurred ~48 ka following Bond et al. (1993) and the latest NGRIP age model (Wolff et al., 2010). Following the adjustment a one common time-scale for our two stalagmite isotope records is created (Fig. 13B).

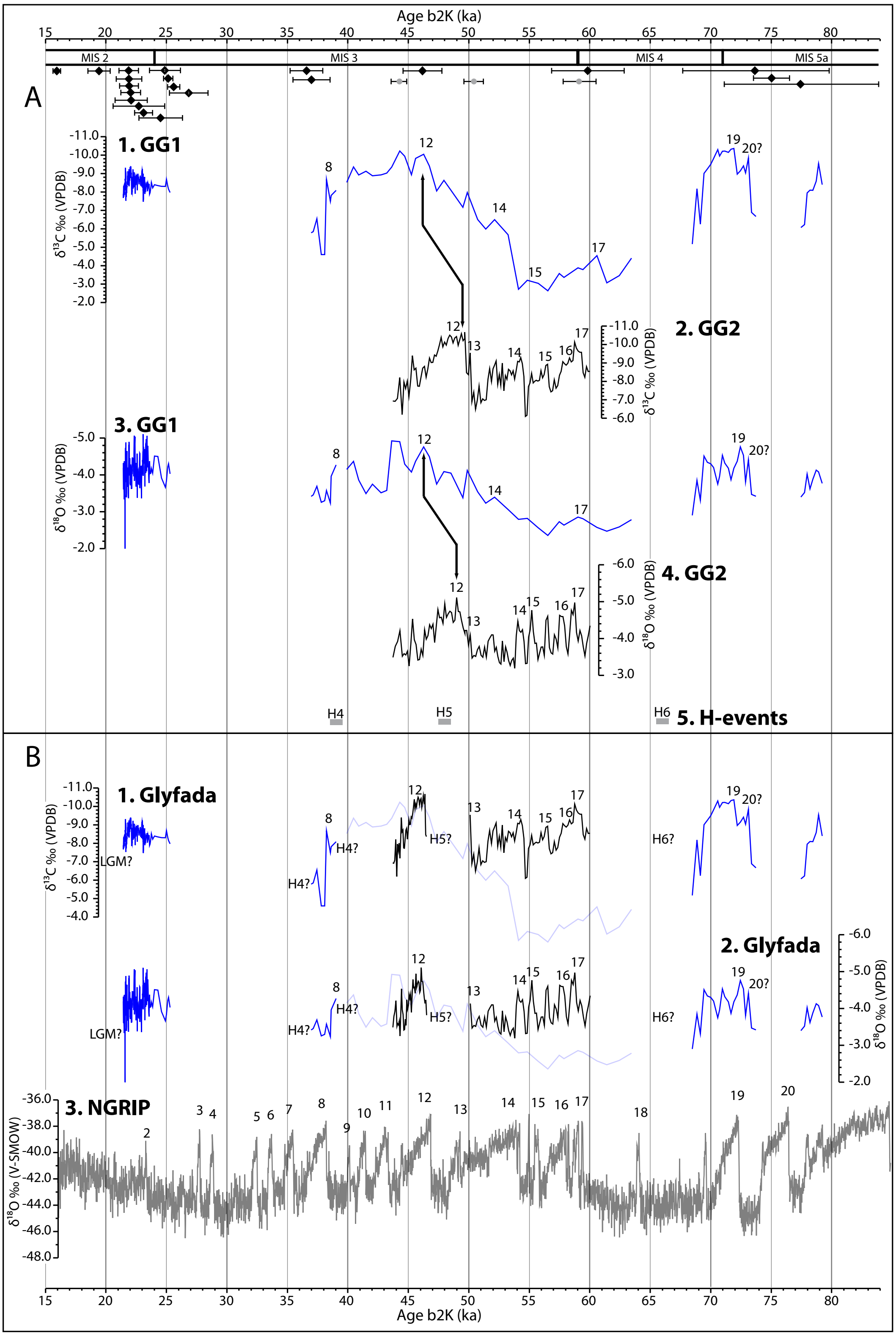
The record from Glyfada Cave shows that the climate over the Peloponnese rapidly responded to interstadial and stadial conditions over Greenland. During stadial (interstadial) conditions colder (warmer) and drier (wetter) conditions are reflected by depleted (enriched) $\delta^{13}C$ values in the speleothems from Glyfada Cave. The depositional hiatuses in Glyfada Cave stalagmites correspond to periods of severe cold conditions in the northern Hemisphere and reduced precipitation over the Peloponnese, most likely forced by a southward displacement of Mediterranean cyclone tracks due to expanding northern ice sheets and increased snow cover over the European continent. The Glyfada Cave record generally supports previously published stalagmite records from the Mediterranean region (Genty et al., 2003; 2010; Fleitmann et al., 2009) and pollen studies from Greece. The comparison between our record and the pollen records from Ioannina (Tzedakis et al., 2002; 2004) and Megali Limni (Margari et al., 2009) revealed a time lag during the first half of MIS 3 which is larger than can be explained by dating uncertainties. When compared with the record from Tenaghi Philippon (Müller et al., 2011) a stronger match in the timing of climatic change is evident suggesting that the tuning to NGRIP is precise.

Paper IV: Can XRF scanning of speleothems be used as a non-destructive method to identify paleoflood events in caves?

In Paper IV a novel, quick and non-destructive method for tracing flood events in caves by analyzing a stalagmite thick section, using an ITRAX XRF core scanner is developed. The analyzed stalagmite (GK01) has multiple horizons of fine sediments from past flood events intercalated with areas of cleaner calcite. Scanning along the non-uniform growth axis shows considerable variability in a number of elements for example Fe, Si, Ti and Ca. When comparing elemental data from the stalagmite with data from a scan of three clay samples from the cave, it is evident that: 1) visually clean areas of the stalagmite consisting of mainly white opaque and/or translucent darker calcite show small peak area values of elements associated with clays, and 2) in areas where clay horizons are present, elevated peak areas of clay elements are recorded (Fig. 14).

Flood events detected from the elemental XRF core scanning data show good agreement with the position of flood horizons identified in petrographic thin sections. Discrepancies between the methods can be explained by 3 factors (where 1 and 2 account for the majority): 1) a washing effect which is related to loss of clay material while cutting the sample using a diamond saw cooled and lubricated by water. In this case the XRF-core scanner integrated a signal across a less cohesive material causing more scattered secondary X-rays to be emitted. 2) A bleeding effect which is the result when the X-ray beam hits a boundary between calcite and clay at an angle and records the signal of both. Because the detection footprint is about 8 mm wide and 0.2 mm thick, any oblique layers may be "smeared" and almost disappear from the record if they are thin enough. 3) In two instances in this study a peak is evident in the elemental data but no corresponding flood horizon is found in the petrographic thin sections. This could be a result of multiple clay

Figure 13. A. $\delta^{13}C$ and $\delta^{18}O$ results for the full sequences of stalagmites GG1 (blue graphs 1 and 3) and GG2 (black graphs 2 and 4) plotted against age. Arrows shows the matching between GG1 and GG2 to construct the Glyfada master curve. Diamonds indicate U-Th ages derived from GG1. Open diamonds indicate samples omitted from age-depth model. Filled grey circles indicate U-Th ages from GG2. Error bars are 2σ. Grey bars (5): timing of Heinrich events (H-events) following Bond et al. (1993) and the latest age model for NGRIP (Wolff et al., 2010).
B. The constructed Glyfada Cave master curve for $\delta^{18}O$ (1) and $\delta^{13}C$ (2) compared with $\delta^{18}O$ from NGRIP (3) (NGRIP Members, 2004, age model GICC05modelext (Wolff et al., 2010)). LGM stands for last glacial maximum.


Age b2K (ka)
MIS 2
MIS 3
MIS 4
MIS 5a
A
1. GG1
δ13C ‰ (VPDB)
2. GG2
3. GG1
δ18O ‰ (VPDB)
4. GG2
H4
H5
H6
5. H-events
B
1. Glyfada
LGM?
H4?
H5?
H6?
2. Glyfada
3. NGRIP
δ18O ‰ (V-SMOW)

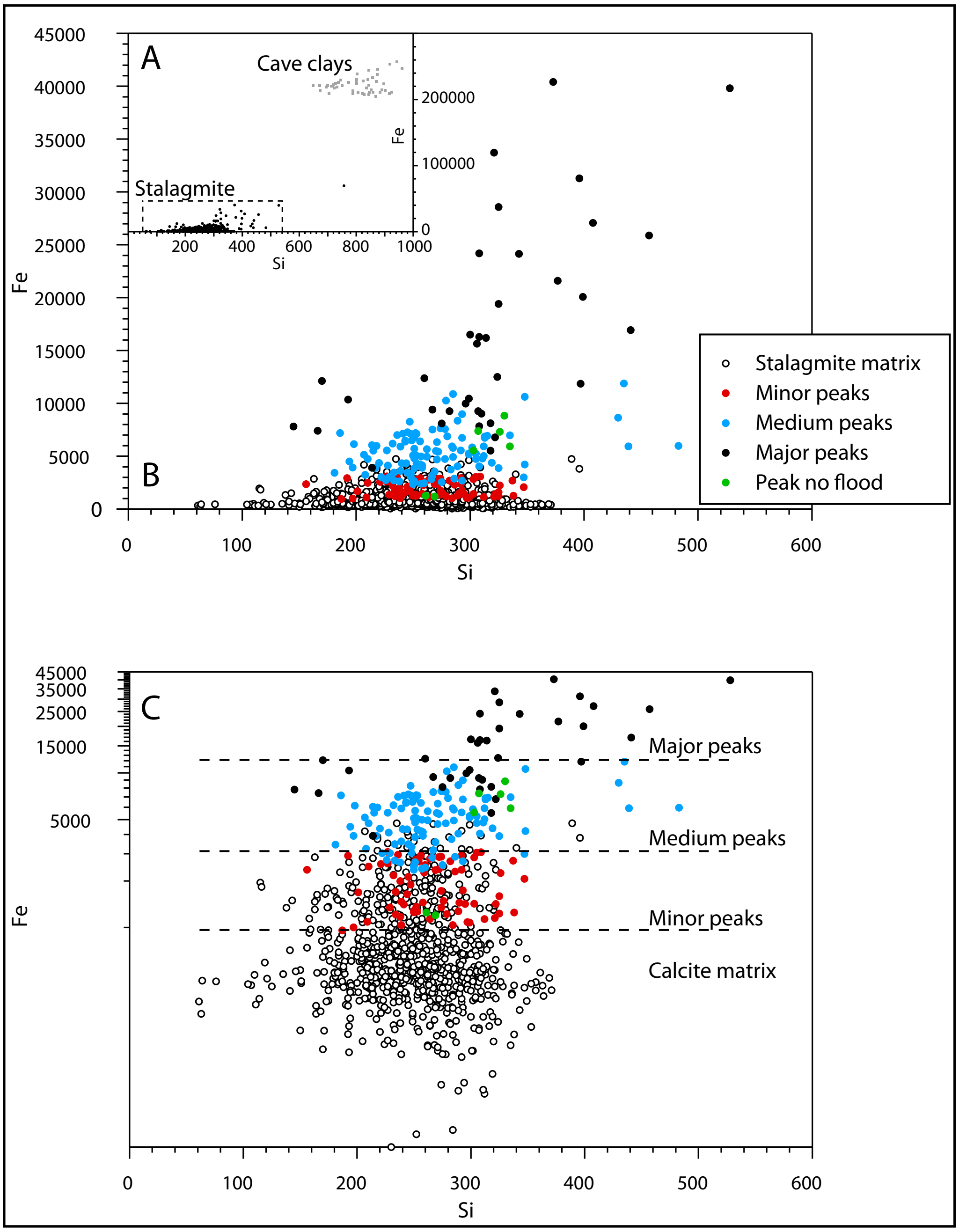


Figure 14. A: Biplots (Fe vs. Si) of cave clays together with stalagmite values (both clayey layers and matrix) showing the difference in the signal between cave clay samples and the stalagmite. Dashed box indicates area of zoom in B and C. B: Biplots (Fe vs. Si) of stalagmite clays and calcite matrix, revealing a clustering that closely follows the different peak types (major, medium and minor peaks) defined in Paper IV. All values in peak areas. C: Biplots (Fe vs. Si) of stalagmite clays and calcite matrix same as in B but on a logarithmic y-axis highlighting how close the clustering follows the different identified peak types (major, medium and minor peaks). Intervals, marked by horizontal black bars, follow values established in Paper IV. It can also be seen that the calcite matrix values are distinctly different from the clayey horizons. All values in peak areas.

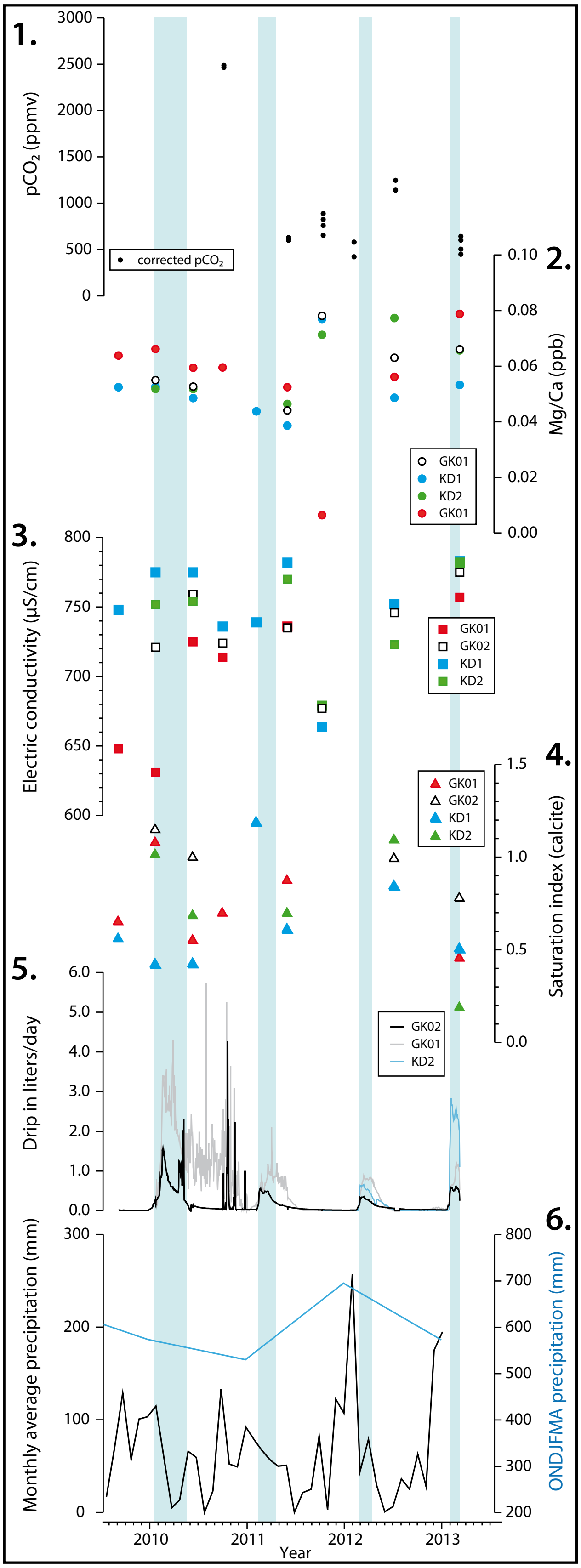


Figure 15. Results from monitoring of Kapsia Cave from September 2009 until March 2013. From the top: 1. Corrected cave air pC0$_2$ in Kapsia Cave measured with a hand held meter. 2. Drip water Mg/Ca ratio. 3. Drip water electric conductivity (µS/cm). 4. Calculated saturation index for calcite in drip water. 5. Drip rate at drip sites GK01, GK02 and KD2 in Kapsia in liters per day. The noisy signal (highly scattered and large amplitude variations) in the period January 2010 to December 2010 for GK01 and June 2011 for GK02 is due to erroneously working drip counters. The exact values for these periods are not correctly recorded but the overall trend can be traced. 6. Monthly average precipitation (black line) and precipitation amount for period with positive water balance (i.e. wet season - ONDJFMA) both in mm.
Blue vertical bars indicate periods of high drip rate.

horizons in close proximity to the Fe peak, making it difficult to exactly match this peak to a certain flood level or impurities on the surface of the sample.

The washing effect will cause the number of peaks in the elemental data to overestimate the actual number of flood events whereas the bleeding effect can explain why a flood horizon visible in the thin sections is not recorded by the XRF scanner.

The geochemical composition of the individual flood layers shows that in certain cases the clay horizons had a distinct geochemical fingerprint suggesting that it is possible to distinguish individual flood layers based on their geochemistry. This implies that there is a possibility of using flood events as marker horizons to chronologically tie different speleothems in a cave to each other, much in a similar way as tephra layers may be utilized for sediments.

Processes behind speleothem formation and interpretations of geochemical data in Kapsia Cave

During the monitoring period of Kapsia Cave the drip rate (or discharge) in the cave followed a seasonal pattern with a pronounced, relatively short, fast drip period with noticeable variability and an extended period of slow steady dripping (Fig. 15). The drip rate at the drip sites in the cave can be classified as a seasonal drip - based on discharge mean and variability over the year (Fairchild et al., 2006b). The period with a fast drip rate in the cave is intimately connected with the onset, extension and amount of wet season precipitation (Fig. 15). The response time of the drip rate in the cave is around 2–3 months, i.e. it takes around 2–3 months for dripping in the cave to respond to the wet season precipitation. During spring and early summer the drip rate gradually declines until a base line drip rate is reached.

During the periods of faster dripping in winter and spring the electrical conductivity is higher, indicating that the availability of Ca to form speleothems is maintained during the high discharge periods (Fig. 15). During the periods of slow dripping electrical conductivity is lower and the Mg/Ca ratio is higher. Higher values of Mg/Ca could be an indicator of increased prior calcite precipitation in the aquifer during summer and fall which would also lead to lower electrical conductivity (Fairchild et al., 2006a).

Drip water at the four monitored drip sites in Kapsia Cave are always oversaturated as indicated by the calculated saturation index (SI) allowing formation of speleothems year around (Fig. 15). Throughout the monitoring period calcite precipitated on the monitoring equipment at all drip sites. Another important factor for the rate of speleothem formation is the levels of cave air CO_2 (pCO_2). In Kapsia Cave, the measured pCO_2 is lower during the winter compared to the summer (Fig. 15). A reduction in pCO_2 means that degassing from water entering the cave will be faster and that the water will become more oversaturated. Under these conditions precipitation of calcite can be enhanced. Considering the above results from the monitoring of Kapsia Cave it is concluded that speleothem formation is more pronounced during the high discharge period (typically JFM) when building material (Ca^{2+} and HCO_3^-) is abundant and pCO_2 is lower.

The measured $\delta^{18}O$ values in the drip water collected during the monitoring period range from -7.10 to -4.58‰ with an average of -6.25 ± 0.44‰ (Fig. 16). Generally, the variability of $\delta^{18}O$ in the drip water from drip sites GK02, KD1 and KD2 is low. In the drip water from site GK01 there is more variability with more depleted values just after the fast drip period potentially indicating that this site at times is more directly connected to the surface via fractures and that less mixing occurs in the aquifer (Fig. 16).

Stable isotope values ($\delta^{18}O$ and $\delta^{13}C$) in modern calcite precipitated on the plastic film wrapped drip counters show relatively stable values with an average of -4.07 ± 0.40‰ (n = 13) for the period October 2010 to July 2012, with one exception (Fig. 16). The calcite forming between October 2011 and February 2012 is significantly enriched compared to the other periods (Fig. 16). The enrichment during this period could be a result of the very dry conditions that prevailed in the cave during this period. In the period October 2011 and February 2012 relative humidity in the cave was low, in October 2011 around 93% and in February 2012 a low of 89% was measured (Fig. 4). The low RH in combination with low pCO_2 most likely caused increased evaporation and fast degassing which in turn caused increased kinetic fractionation to occur, driving both $\delta^{18}O$ and $\delta^{13}C$ towards enrichment.

Meteorological data, speleothem $\delta^{18}O$ and annual lamina – enhancing the interpretations

The top part of stalagmite GK02 from Kapsia Cave, shown to be modern in Paper II, was investigated for annually forming visible laminae and a stable isotope analysis at high resolution (0.3 mm) was performed. The aim of this work was to enable comparison between meteorological data and modern speleothem $\delta^{18}O$ and $\delta^{13}C$ values in order to test previous interpretations of stable isotopes (Paper II).

The strong seasonal differences in the weather situation around Kapsia with a negative water balance from May to September (Fig. 6) suggest that there is a potential for forming annual laminae in stalagmites in this cave (Tan et al., 2006; Baker et al., 2008; Mattey et al., 2008; Jex et al., 2010; Tan et al., 2013).

In the petrographic thin sections a total of 38 couplets, forming 19 complete lamina, and 2 single couplets were counted from the top of the stalagmite to the hiatus at ~17 mm from the top (reported at 19 mm in Paper II) (Fig. 17). Average lamina thickness in the upper part is 0.75 ± 0.44 mm (± 1σ). In an area from c. 12 mm to 12.4 mm, from the top, two unusually thin laminae, labelled 12 and 13, (0.13 and 0.32 mm respectively) with two thin adjoining couplets on each side are visible (Fig. 17). This area is discerned in the thick section as a narrow brownish layer. From the top to just above the thin laminae a total of 25 couplets (12.5 laminae) were counted. Assuming that the stalagmite was actively forming at collection and that laminae are annual, the upper 17 mm of the stalagmite covers a period of around 20 years.

The results from the high resolution stable isotope analysis (n = 55) show that $\delta^{18}O$ range from -5.50‰ to -4.03‰ (V-PDB) and $\delta^{13}C$ range from -10.76‰ to -7.14‰ (V-PDB) in the upper 17 mm of the stalagmite. To transfer the depths of the stable isotope samples to absolute ages, an age-depth model was created using the results from the lamina counting. The age-depth model was created in StalAge (v. 1.0) to produce an easily replicable age-depth model that includes age error. For the age-depth modeling an age uncertainty of ± 1 year for the lamina counting was assumed. The calculated age-depth model shows that the top part of the stalagmite was formed during a period from 1989 to 2009 (Fig. 18). The growth rate ranges from c. 0.64 mm/year to 1.0 mm/year and is slower in the top 2 mm of the stalagmite (Fig. 18).

The $\delta^{18}O$ and $\delta^{13}C$ values from the stalagmite are compared with the wet season precipitation amount (ONDJFMA - corresponding to the period of positive water balance for the area, see Paper II) and temperature from the nearby meteorological station in Tripoli (ONDJFMA precipitation shown in Fig. 19). The comparison reveals a similar pattern between stalagmite $\delta^{18}O$ values and wet season precipitation amount for the whole period covered by the upper part of the stalagmite. A similar finding is reported from Akçakale

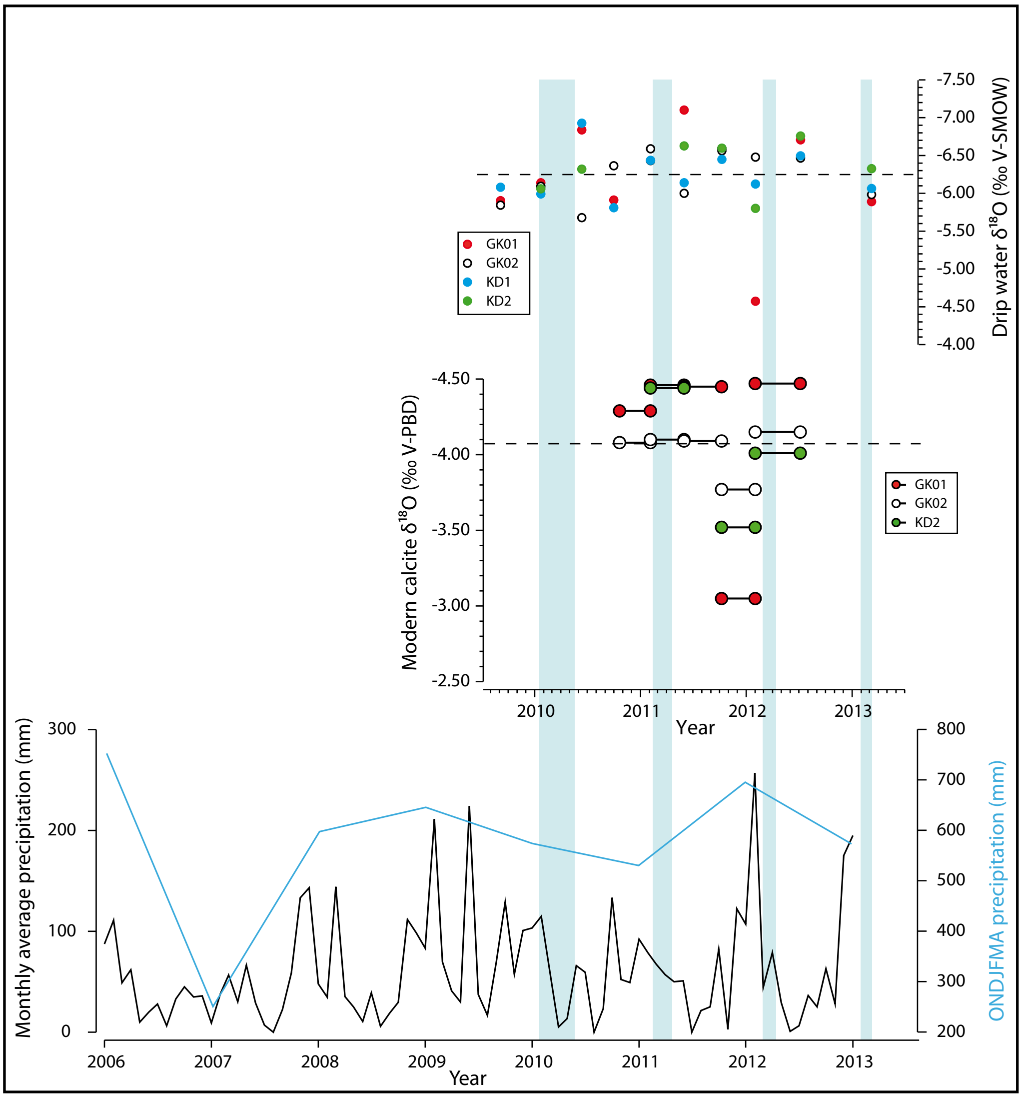


Figure 16. Drip water and modern calcite (i.e. calcite precipitated on plastic substrates) $\delta^{18}O$ values during the period September 2009 to March 2013 compared to precipitation. From the top: Drip water $\delta^{18}O$ for drip water from drip sites GK01, GK02, KD1 and KD2. Modern calcite $\delta^{18}O$ values for different periods. Dashed horizontal lines indicate average $\delta^{18}O$ values for the measured periods. Monthly average precipitation (black line) and precipitation amount for period with positive water balance (wet season - ONDJFMA) both in mm. Blue vertical bars indicate periods of high drip rate (see Fig. 15 for details).

Cave in NE Turkey (Jex et al., 2010). A stable 1–2 year lag between precipitation amount and stalagmite $\delta^{18}O$ values can be observed in the most recent part of the record (until the area of unusually thin lamina around 1995 according to our age-depth model) (Fig. 19). The time lag between precipitation amount and $\delta^{18}O$ values of drip water or stalagmite $\delta^{18}O$ gives an estimate of the residence time, or the transit time, of water in the vadose zone (Ayalon et al., 1998; Lachniet, 2009). In the older part, below the area of unusually thin lamina, a longer lag of 5–6 years is evident. The possibility of ceased or much reduced dripping, and thus stalagmite formation, in the period of low precipitation from 1989 to 1993 should be considered. Therefore the older part of the $\delta^{18}O$ record is adjusted

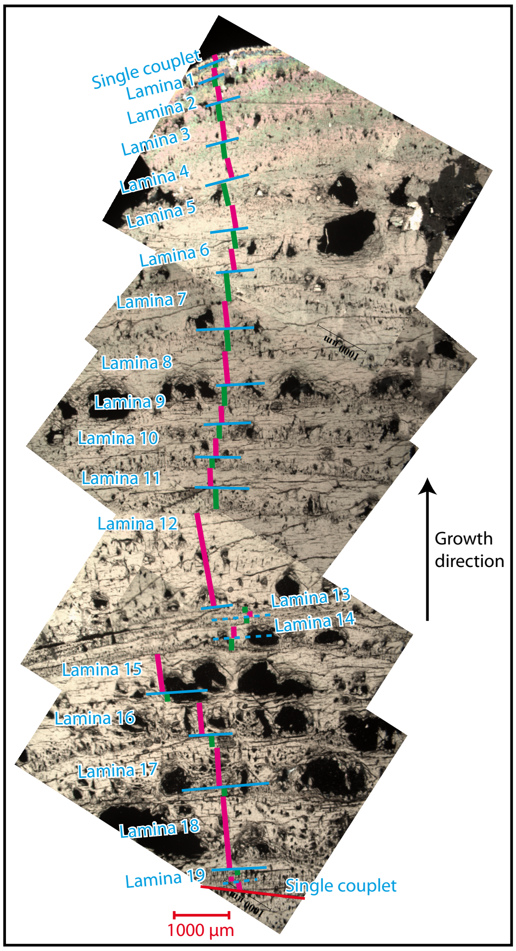


Figure 17. Thin section of the upper 17 mm of stalagmite GK02. Visible laminae can be seen throughout the top. Each lamina consists of two sub-annual couplets consisting of more porous, open columnar calcite and less porous, compact columnar calcite. Sub-annual couplets are indicated by alternating pink (compact columnar) and green (open columnar) bars. Upper most single couplet most likely represents the summer/fall deposition formed before sampling in September 2009. Note area of thin laminae (lamina 12 and 13).

so that the lag was of a similar length as in the younger part (Fig. 20). From the comparison it is evident that more depleted $\delta^{18}O$ values are connected with larger amounts of wet season precipitation and vice versa. The results support the interpretation in Paper II that the $\delta^{18}O$ in the stalagmite from Kapsia Cave reflects precipitation amount. The relationship between $\delta^{13}C$ and precipitation amount is not as clear as for $\delta^{18}O$. No clear relationship between temperature and $\delta^{18}O$ and $\delta^{13}C$ was detected.

Considering the results from this analysis it is suggested that:

- Formation of visible lamina in the stalagmite from Kapsia Cave is annual with sub-annually forming couplets.
- The amount effect has been a major control on $\delta^{18}O$ values in speleothems in Kapsia Cave, at least for the last 20 years.
- The residence, or transit, time for water in the aquifer above Kapsia Cave has been around 2 years, at least for the last 14 years.

Discussion

The literature review (Paper I) forming the basis of this thesis high-lighted the need for more high-resolution paleoclimate records, in order to (1) better understand regional patterns and trends versus local climate variability and to (2) fill the data gap from some regions. Further, the compilation of available data showed that there is not enough evidence to support the notion of a widespread climate event 4200 years BP with rapidly drying conditions in this region. Subsequent studies of speleothems from Kapsia Cave and Glyfada Cave, did not shed more light on the climate around the 4.2-event because this time period was not covered by any of the speleothems analyzed. However, the speleothem results from Kapsia Cave yielded new information about regional climate variability for the late Holocene period 2900–1100 years BP, which is also a period of interest from a human society perspective (Paper II). Furthermore, results from Glyfada Cave, contribute to the understanding of regional climate variability and hemispheric-scale teleconnections during the late Pleistocene (Paper III). The studies also demonstrate the potential and limitations of classical speleothem studies, where U-Th dating in theory is an excellent

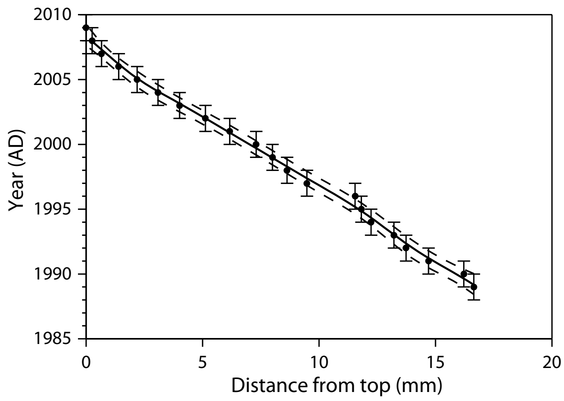


Figure 18. Age-depth model for the top of stalagmite GK02 based on lamina counting created using StalAge. Each data point represents a lamina. Uncertainty is assumed to be ± 1 year.

method but in practice can be rather complicated, and where the multiple processes behind stable isotope records can sometimes be hard to disentangle. Paper IV and on-going studies indicate ways to address these problems by additional approaches.

Speleothems from the Peloponnese as paleoclimate recorders

Cave monitoring and analysis of a modern stalagmite – implications for interpretations of the past

Nature of stalagmite laminae in Kapsia Cave

The formation of visible laminae in speleothems requires a change in the spatial arrangement of calcite crystals with a well-defined morphology often on a seasonal basis (Tan et al., 2006 and references therein). Processes behind the formation of visible laminae might include one or both of the following: 1) seasonal variations in drip rate and 2) seasonal variations in drip water supersaturation and or cave climate (e.g. pCO_2 or relative humidity) (Baker et al., 2008). Generally the growth rate of speleothems increases in a cave system with increasing supersaturation and flow, and if discharge rates are variable it is common to find compact columnar and open columnar fabrics in different parts of the same speleothem (Frisia and Borsato, 2010).

The petrographic thin section analysis of the uppermost part of stalagmite GK02 shows how more compact columnar calcite layers are followed by more porous layers consisting of open columnar calcite (Fig. 17). Considering the strong seasonal variations in the cave revealed by monitoring, e.g. in the discharge rate and variations in cave air pCO_2 (Fig. 15), it is proposed that sub-annual layers are forming. It can be hypothesized that, during the summer/fall period when discharge is slow and steady and pCO_2 high, the more compact layers are slowly formed and that during the winter/wet season when the drip rate is higher and more variable and pCO_2 lower rapid growth forms the more porous type of calcite layers.

The monitoring results

The monitoring results from Kapsia Cave yield information about the seasonal variation in growth and how the system responds to external variability and change. During the monitoring period the amount of wet season precipitation has been fairly stable (Fig. 16), which means that there should be little variations in $\delta^{18}O$ of calcite forming during this period, if our hypotheses about residence time and control of $\delta^{18}O$ signal are correct. The results from the analysis of $\delta^{18}O$ in the modern calcite support this assumption, showing very little change, except for the period October 2011 and February 2012, which is affected by kinetic fractionation (Fig. 16). A problem with the monitoring in Kapsia Cave, which may affect how well the present conditions represent the past, is the opening of the artificial entrance in 2004. This must have meant that air circulation in the cave was altered, especially before the two-door-airlock system was in place (unknown when). Most likely the opening of the artificial entrance led to more ventilation, potentially lowering pCO_2 levels and reducing RH, making the problems of kinetic fractionation more pronounced. Lower pCO_2 of the cave air leads to faster degassing of CO_2 from the drip water driving $\delta^{13}C$ values towards enrichment, and low RH leads to increased evaporation causing enrichment in the $\delta^{18}O$ of the drip (Mickler et al., 2004; Lachniet, 2009). Even with the doors installed this is, most likely, still occurring since the doors are opened several times per day for visitors. When looking at the results from the stalagmite top, forming both before and after the opening of the artificial entrance, the enhanced kinetic fractionation can be tentatively demonstrated. In the period after the year 2004 there is a higher correlation between $\delta^{18}O$ and $\delta^{13}C$ ($r^2 = 0.58$) ($n = 11$, significant at 95%) compared to the period before the year 2004 when r^2 is 0.26 ($n = 44$, significant at 95%). The number of samples in the period after the year 2004 is small and the results should be interpreted with caution but they give an indication of the types of alterations that have occurred in the cave recently.

While there are clear indications of kinetic fractionation in the modern calcite samples precipitated on plastic substrates, it can be noted that the kinetic fractionation is driving the isotopic values in the same direction as does the amount effect, i.e. during periods of drier conditions increased kinetic fractionation and the amount effect will both drive the $\delta^{18}O$ signal towards enrichment. The same also holds for the Kapsia paleo-record, and even if the Hendy tests show no clear indications of kinetic fractionation in the past, most likely some kinetics did occur (Mickler et al., 2004). Although speleothem growth occurs all year round, the drip water is mainly influenced by water from the wet season (ONDJFMA), since this is the time when the aquifer is recharging. It is thus this isotope signal that is incorporated into the speleothems (Lachniet, 2009). However, high frequency noise in the signal can be a result of differences in for example kinetic effect between summer and winter/wet season growth.

Stable isotopes in speleothems from the Peloponnese

The usefulness of speleothems as recorders of past climate and environments mainly depends on 1) whether the proxies, here $\delta^{18}O$ and $\delta^{13}C$, can be interpreted with confidence and 2) how well they can be dated. There are multiple ways of interpreting $\delta^{18}O$ and $\delta^{13}C$ in speleothems, as outlined in the thesis introduction. The comparison between meteorological data and $\delta^{18}O$ from the modern speleothem top from Kapsia reveals that there is a strong connection between increased precipitation amount during winter and spring and $\delta^{18}O$ depletion in the stalagmite, a so-called amount effect. This effect is also evident in studies of meteoric water in Greece, where precipitation amounts of up to 100 mm per month show an amount effect with more depleted $\delta^{18}O$ values with increasing precipitation (Argiriou and Lykodis, 2006), supporting our interpretation. Our interpretation is also in line with the interpretations of $\delta^{18}O$ values in speleothems, from southern Europe and the eastern Mediterranean for the Holocene in general (Bard et al., 2002; Bar-Matthews et al., 2003; Verheyden et al., 2008; Drysdale et al., 2005, 2006; Zanchetta et al., 2007; Frisia et al., 2006; Couchoud et al., 2009; Orland et al., 2009; Jex et al., 2010, 2011). The interpretation of the $\delta^{18}O$ signal on longer time scales is more complex. In the late Holocene Kapsia record, the $\delta^{18}O$ signal is controlled by the amount effect and although this interpretation is also, to some extent, true for the Glyfada record there are a number of other factors operating on longer time scales that affect the $\delta^{18}O$ signal, complicating the interpretation of $\delta^{18}O$ in Glyfada. In the long-term the $\delta^{18}O$ is affected by for example global ice volume and changes in $\delta^{18}O$ of the source, changes in storm tracks, surface and cave temperature and seasonality of precipitation (Genty et al., 2003; 2010, Kolodny et al., 2005; Fleitmann et al., 2009). Change in source $\delta^{18}O$, due to global ice volume, is a well-known factor to consider when analyzing records covering the last glacial period. In a study on carbonates from Israel the source effect during the last glacial period was shown to be even larger than what is to be expected from the ice volume effect only (Kolodny et al., 2005), highlighting the complexity of the $\delta^{18}O$ fractionation on long-term time scales. Studies from Israel, however, have demonstrated a strong negative correlation between $\delta^{18}O$ and the annual rainfall amount when sea surface conditions remain almost constant, indicating that the amount effect is also a strong control in the region (e.g. Bar-Matthews et al., 2000; Bar-Matthews et al., 2003; Vaks et al., 2006; Almogi-Labin et al., 2009). The issue of the source effect is highly important if comparisons between a Holocene part and a Pleistocene part of a record are to be performed, which not the case in Glyfada is. Instead the similarities between the $\delta^{18}O$ and the $\delta^{13}C$ signals in Glyfada support a common control on the two isotopes, therefore it is inferred that rainfall amount is one important control, among others, on $\delta^{18}O$ values in Glyfada.

The interpretation of the $\delta^{13}C$ signal in the stalagmites from Kapsia Cave is more complicated compared to the signal from Glyfada, since biological activity is likely to have been heavily affected by human activities during their formation. The small limestone hill in which Kapsia Cave is formed is located geographically very close to the ancient polis of Mantinea which existed during much of the time stalagmite GK02 grew (Pretzler, 2012). The proximity of the cave to Mantinea, which was one of the larger *poleis* on the Peloponnese, must have meant that humans were present and used the landscape in this area in ways that affected the biological activity. In Kapsia this can be seen as the $\delta^{13}C$ signal does not closely follow the $\delta^{18}O$ signal, indicating that agents other than the climate are important for the biological activity above the cave. In Glyfada, although humans may have been present when the speleothems formed they are not likely to have impacted on the landscape in such a way as would substantially alter that the biological activity above

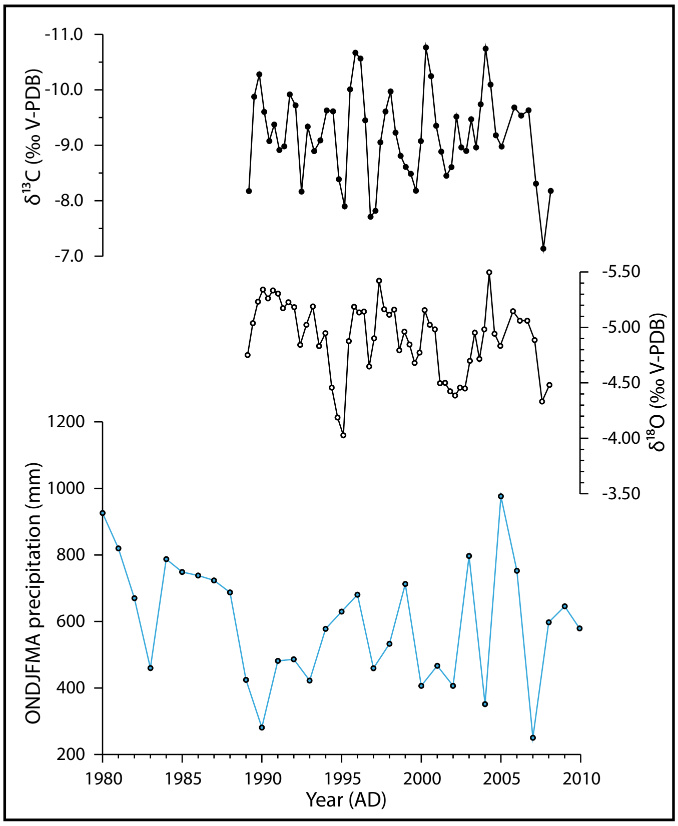


Figure 19. Comparison between $\delta^{18}O$ and $\delta^{13}C$ values from stalagmite GK02 (plotted against age-depth model based on lamina counting) and wet season (ONDJFMA) precipitation in Tripoli. The comparison shows a good agreement between higher precipitation and more depleted $\delta^{18}O$ values. In the period from 2009 to 1995 a lag of 1 to 2 years is evident between precipitation and $\delta^{18}O$. In the part from 1995 to 1989 the lag is around 5 years.

the cave since they would mostly have been involved in hunting and gathering. Instead the main control on the biological activity above Glyfada during the Pleistocene would have been the climate. Warmer, and thus also wetter, winter conditions should have had a positive effect on the vegetation over the Peloponnese during the late Quaternary. Considering the various climate-related factors that can influence the $\delta^{18}O$ signal on long time scales the use of $\delta^{13}C$ when interpreting the Glyfada record is favored, similarly as Genty et al. (2003; 2010) and Fleitmann et al. (2009). The above discussion highlights the need to consider the time scales when interpreting $\delta^{18}O$ and $\delta^{13}C$ signals in speleothems from the eastern Mediterranean region.

Dating of speleothems from the Peloponnese

High quality U-Th dating of speleothems requires no, or very little, input of non-authigenic thorium (or detrital thorium) into the sample so that the basic assumption that only uranium is deposited in the speleothem and all thorium measured in a sample derives from the decay of uranium is valid. In the case of Kapsia Cave relatively large amounts of detrital thorium are incorporated into the speleothems, as shown by low ($^{230}Th/^{232}Th$), thus violating the basic assumption behind the U-Th dating technique. Detrital thorium is commonly transported into speleothems with organic matter, colloids or fine dust (Kaufman et

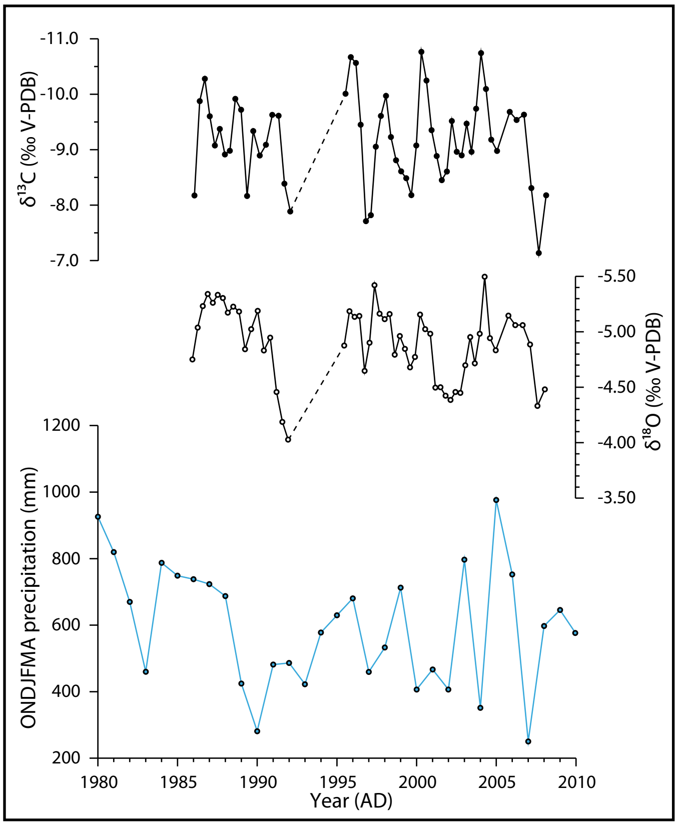


Figure 20. Comparison between the shifted $\delta^{18}O$ and $\delta^{13}C$ values from stalagmite GK02 and wet season (ONDJFMA) precipitation in Tripoli. The shift is based on the idea that there may have been very slow or no growth following the dry years 1990–1994.

al., 1998; Fairchild and Baker, 2012). In Kapsia detrital thorium is most likely transported with colloids or organic matter in the drip water since newly precipitated calcite also is rich in detrital thorium. Another potential source of detrital thorium is clay particles deposited on speleothems during floods. The substantial and variable input of detrital thorium has made it difficult to yield reliable ages from Kapsia Cave with small uncertainties in turn making it troublesome to construct precise chronologies. In a broader sense, the work with the less than perfect, speleothems from Kapsia Cave have provided an opportunity to test the limitations of the U-Th dating method.

In Glyfada Cave input of detrital thorium is smaller and better quality U-Th ages could be produced. However, the presence of multiple depositional hiatuses in the speleothems from Glyfada made it difficult to create accurate age-depth models. The application of Bacon allowed the employment of a Bayesian statistical approach for stalagmite GG1 incorporating information about hiatuses retrieved from the analysis of petrographic thin section. The importance of using petrographic thin sections to detect hiatuses cannot be underestimated and it is very unfortunate that one thin section in stalagmite GG2 was uninterpretable. This led to the inability to confirm the presence of a hiatus in GG2 and that the age-depth model building, in this part of the stalagmite, had to rely on isotope matching with stalagmite GG1 only. However, analyzing the central slab of GG2 visually there are indications of a perturbation in the growth where the hiatus is suggested to be located. Before the hiatus the shape of the stalagmite is narrow, indicative of drier conditions, and just after the hiatus it is wide, the angle of the growth axis changes and the visual appearance of the speleothem fabrics change supporting the suggestion of a hiatus. One way around the problems encountered in Glyfada Cave, although expensive, material and time consuming, is to perform more U-Th dating.

The bedrock on the Peloponnese Peninsula consists mainly of limestone bedrock and caves are abundant. The potential to find new speleothems that cover other time periods and that are better than the current ones regarding the dating issue, is very good (work in progress). In comparison to radiocarbon dating of, for example sediments, speleothems from the Peloponnese can contribute high quality chronologies based on U-Th ages. The radiocarbon ages on material from the peninsula can be affected by a hard water effect, i.e. the incorporation of old carbon from the limestone bedrock into organic matter, leading to inaccurate ages. However, the development of AMS radiocarbon dating, allowing the use of small amounts of terrestrial material, means that the problem of the hard water effect can be avoided. This may open up new potential for better comparisons between U-Th dated speleothems and radiocarbon dated sediments, leading to both the formation of a denser network of paleoclimate sites and enhanced interpretations when different proxies can be compared.

Late Quaternary climate variability in the eastern Mediterranean

Long-term perspective – beyond the Holocene

During the last glacial period rapid shifts in the climate have been revealed by the study of polar ice cores. Temperatures in Greenland went through abrupt shifts from colder Greenland stadials (GS) to warmer Greenland interstadials (GIS) following a cyclic pattern, known as Dansgaard-Oeschger (DO) cycles (Dansgaard et al., 1993; NGRIP Members 2004; Svensson et al., 2008). Additionally, at the end of a series of DO cycles GS episodes of extremely cold and dry conditions occurred regularly during the last glacial period. These episodes, known as Heinrich (H) events, were initially discovered as horizons of ice rafted debris in marine sediment cores from the North Atlantic (Heinrich, 1988; Bond et al., 1993; Broecker, 1994). Subsequent studies have shown the impact of GIS and GS conditions and H events also at lower latitudes. The rapid shifts in temperatures over Greenland during the late Pleistocene with warmer stadials (GS) and colder interstadials (GIS) are repeated over much of the European continent and the Mediterranean Sea and surroundings (e.g. Cacho et al., 1999, 2006; Sánchez Goñi et al., 2000, 2002, 2008; Bar-Matthews et al., 2003; Bar-Matthews, 2014; Bartov et al., 2003; Genty et al., 2003; 2005; 2010; Martrat et al., 2004; Spötl et al., 2006; Drysdale et al., 2007; Ampel et al., 2008; Wohlfarth et al., 2008; Fleitmann et al., 2009; Langgut et al., 2011; Rowe et al., 2012; Torfstein et al., 2013). During GS conditions, especially those associated with Heinrich events, conditions were cold and dry as a result of the shutdown of the North Atlantic meridional overturning circulation, in concert with an expansion of the polar vortex, causing outbreaks of polar or continental air (Allen et al., 1999; Sanchez Goñi et al., 2002; Tzedakis et al., 2002, 2004; Margari et al., 2009; Fletcher et al., 2010; Müller et al., 2011).

Growth in Glyfada occurred during the relatively warmer late Marine Isotope Stage (MIS) 5a and early MIS3 recording climatic shifts concurring with GIS and GS conditions. During full glacial conditions (e.g. MIS 4 and MIS 2) when extensive ice sheets covered much of the northern hemisphere, a southward displacement of Mediterranean cyclone tracks leading to increased precipitation in the Levant have been proposed (Bartov et al., 2003; Vaks et al., 2006; Frumkin et al., 2011; Torfstein et al., 2013). This southward shift of the cyclone tracks led to reduced precipitation over the Peloponnese and thus to very arid conditions. This is suggested to be recorded as depositional hiatuses in in Glyfada Cave from 68 ± 4.9 ka to 60.0 ± 1.2 ka and after 37 ± 3.6 ka. However, there is also a possibility that the depositional hiatuses are sample-specific, due to for instance rerouting of water. More work is needed in Glyfada Cave to investigate whether the hiatuses actually represent periods of no, or little, growth in the whole system due to for example reduced precipitation in response to climate change. Interestingly there is a period of growth in Glyfada Cave between 25.3 ± 0.6 and 21.5 ± 1.0 ka indicating wetter conditions (Fig. 13), however, the full climatic meaning of this growth period and the stable isotope sequences have not yet been fully explored. The early part of this growth period coincides with high levels in Lake Lisan in Israel and beach deposits also indicating higher lake levels in Kastritsa (Ioannina) as well as increased numbers of temperate tree pollen from Ioannina and Kopais (Galanidou and Tzedakis, 2001; Tzedakis et al., 2002; Tzedakis, 2009). The need for high resolution records for the time period between 27 and 24 ka was pointed out recently by Tzedakis (2009). Hopefully, more in-depth studies of this well-dated, high resolution growth interval in Glyfada can reveal more detailed knowledge about the climate in the very late MIS 3 and early MIS 2 leading into the LGM.

During Heinrich events, conditions in the Mediterranean region were very cold and arid (Allen, 1999; Sanchez Goñi et al., 2002; Margari et al., 2009; Müller et al., 2011). At the time of H5 (occurring around 45 ka, see Langgut et al. (2011) for a list of ages for H5) arid and cold conditions prevailed in the eastern Mediterranean region as indicated by contractions in tree populations and periodic lowering of lake levels in Lake Lisan (Tzedakis et al., 2002, 2004; Bartov et al., 2003; Margari et al., 2009; Müller et al., 2011; Langgut et al., 2011; Torfstein et al., 2013). A recent study on lake levels in Lake Lisan suggest that increasing winds causing more evaporation from the lake surface could explain the lowering of the lake during H-events (Rohling, 2013). H5 is also recorded in Soreq Cave as a period of drier climate (Bar-Matthews et al., 1999). In Glyfada Cave it is inferred that a depositional hiatus occurred corresponding in time with H5, although not confirmed by thin section analysis there are visual indications of a perturbation in growth. Stalagmite growth also seems to have ceased around the time of H4 but the uncertainties in the age-depth model makes it impossible to know if the growth period between 39 ± 3.4 and 37 ± 3.6 ka preceded or succeeded the hiatus.

The Glyfada $\delta^{13}C$ record shows how the biological activity above the cave controlled by precipitation and temperatures over the Peloponnese rapidly responded to changing temperatures over Greenland. During GS conditions, more enriched $\delta^{13}C$ values signal a reduction in vegetation and microbial activity in the soil zone and the opposite during GIS conditions. This interpretation is supported by local pollen data from Ioannina in NW Greece, Tenaghi Philippon in NE Greece and Megali Limni in E Greece which all show contractions in tree populations and increases in plants adapted to cooler and drier conditions during GS.

Short-term perspective, the Holocene

In the early and Mid-Holocene the climate in the eastern Mediterranean was generally wetter and cooler than in the late Holocene (e.g. Robinson et al., 2006; Roberts et al., 2008; Paper I). During the early Holocene insolation was stronger in the Northern Hemisphere (Berger and Loutre, 1991) which caused a northward shift of the climate system and more convective precipitation to fall over the Sahara which was then a savanna (Kuper and

Kröpelin 2006; Kröpelin et al., 2008). There is also evidence of more precipitation over the Mediterranean Sea itself and over the northern borderlands (e.g. Kotthoff et al., 2008; Roberts et al., 2008). The stronger insolation also caused cooler conditions in the eastern Mediterranean (Davis et al., 2003) which could potentially have an effect on moisture availability as evapotranspiration was reduced. Regionally drier conditions began to develop during a transitional phase between 4800 and 4600 years BP. The onset of drier conditions seems to have been earlier in the Levant and in the southern part of the eastern Mediterranean than in the northern part. Around 4200 years BP, i.e. at the time of the 4.2-event, dry conditions prevailed in much of the eastern Mediterranean. However, there are very few records that indicate anything chronologically well-constrained or unique in amplitude as would be expected from a substantial dry event (Fig. 9). It is possible that the evidence is masked by the transition into drier conditions that began to dominate in the period 4400 to 4000 years BP. More precisely dated and high resolution proxy data are needed to further investigate the extent and precise character of the suggested 4.2-event. From the Peloponnese (or S Greece) there is very little direct evidence of pronounced aridity or an event-like shift around this time.

Around 3200 years BP, i.e. around the time of the proposed 3.2-event, the regional climate in the eastern Mediterranean was much drier and here the literature review (Paper I) indicates that this event was much more abrupt and distinct in the region in comparison to the 4.2 event (Fig. 9). Recent studies from Cyprus and Syria have also revealed rapidly developing arid conditions around 3200 years BP lasting around 400 years. This dry event is in turn tied to socio-economic crises in these areas (Kaniewski et al., 2010, 2013). Similarly, Drake (2012) inferred that reduced precipitation over southern Greece following lowered sea surface temperatures during the late Bronze Age (i.e. around 3200 years BP) led to the breakdown of social institutions. However, the Asea Valley record (central Peloponnese) displays stable conditions of a wetter and cooler climate during this period (Unkel et al., 2014). Considering the lack of evidence of a 4.2-drying event and the conflicting evidence for the 3.2-event, it is not a straightforward operation to infer significant climate change on the Peloponnese for any of the two climate events, at this stage. This is especially the case when considering the past and present heterogeneity in the regional climate (Brayshaw et al., 2011; Roberts et al., 2011). Viewing the results from the literature review the period around 3000–2800 years BP also seems to have a drying excursion, more distinct than the 4.2-event (Fig. 9), and could be an interesting period for further investigations.

Stalagmite GK02 in Kapsia began to grow 2950 years BP. The period from 2950 to 1100 years BP covered by stalagmite GK02 from Kapsia Cave is, on a regional scale, one going from drier conditions towards wetter conditions and back to drier again. The initiation of growth in Kapsia Cave is unknown and may not have been related to the climate but could be a result of the opening of new cracks and fissures in the bedrock following for example tectonic movement or be related to the properties of the cave atmosphere. What may be noted is that the period when stalagmite GK02 grew is a period when a record from Lake Gölhisar in SW Turkey indicates wetter conditions (Eastwood et al., 2007). The location of the Gölhisar record is in a setting which responds climatically in a similar way as western and central Peloponnese (Kutiel et al., 2002). On a local scale the Kapsia record is supported by the two nearby records from Asea Valley and Lake Ioannina. The initial trend of drying conditions in Kapsia is similar to the sediment record from Asea Valley (c. 30 km from Kapsia) that shows wetter conditions lasting until 1200 years BP followed by a transition into a period of dry conditions reaching its apex around 2300 years BP (Unkel et al., 2014). In Ioannina, NW Greece, dry conditions are recorded between 2000 and 1800 years BP and wetter conditions between 1800 and 1600 years BP which is similar to the dry interval recorded in Kapsia between 2050 and 1800 years BP followed by the wet spell at 1800 to 1650 years BP (Frogley et al., 2001; Roberts et al., 2008). Cyclical precipitation variations recorded in Kapsia are most likely controlled by shifts in the relative dominance between the North Atlantic Oscillation and the North Sea–Caspian Pattern Index. One of the mechanisms behind this control could be the position of the jet stream and the intensity of the polar vortex. It has been illustrated how millennial scale shifts in the position of the jet stream affect precipitation amounts over the Mediterranean region in the period from 3000 to 1000 years BP. When the zonal jet stream is pushed northward the polar vortex is more intense and conditions are drier over Turkey and the central Mediterranean area and vice versa (Dermody et al., 2012). Dermody et al. (2005) suggest that in the period between 3000 and 1800 years BP conditions became gradually drier in Turkey and the central Mediterranean and, although, the Kapsia record does not show this exact trend the dry conditions around 2050–1800 years BP fits well with their suggestion. Similarly wet conditions in Kapsia around 1180 years BP is in line with wet climate conditions in Turkey and the central Mediterranean (Dermody et al., 2012).

A good understanding of the climate during the last 1000 years is hampered by the small number of proxy based paleoclimate records (Paper I). There are a few records enabling local interpretations, but regional suggestions are less reliable due to the small and scattered sample. It can be noted that a number of tree ring records are available from this region and for this time period. Many of these records are listed in Paper I however, they were omitted from the analysis in Paper I because they usually cover short time spans and the very high resolution of this type of record is difficult to compare with other proxy records. However, recent work covering the last 2000 years BP have substantially added knowledge about the climate and its variability in the eastern Mediterranean (Luterbacher et al., 2012).

From a temperature perspective there is proxy evidence of a cooler Mid-Holocene compared to the Late Holocene and a warm period between 2400 and 1800 years BP, often referred to as the Roman Warm Period. On the other hand from the absolute temperature reconstructions large uncertainties inhibit straightforward conclusions about the relatively minor fluctuations that have occurred during the Holocene complicating the picture of temperature variability during the Holocene.

Future perspectives

More work lies ahead with the sequence from Glyfada Cave. Primarily, the well dated period between 25.3 ± 0.6 and 21.5 ± 1.0 ka needs to be investigated in close detail. Hopefully, additional stalagmites from the cave can shed more light on reasons for depositional hiatuses and also strengthen the interpretations of the $\delta^{18}O$ and $\delta^{13}C$ signals.

Despite the dating difficulties encountered in Kapsia additional stalagmites from Kapsia Cave have been collected and are in the process of being dated. Continued monitoring of the cave environment will provide further insights into how the outside climate signal is transferred to, and modified in, the speleothems in Kapsia. This in combination with the recent results suggesting a strong amount effect on the $\delta^{18}O$ signal in speleothems from Kapsia makes the cave an interesting place for continued work.

The abundant availability of caves on the Peloponnese means that the potential to find additional caves and new and better speleothems, to achieve a better understanding of climate variability and the timing of climate change over the Peloponnese is good. It is, for example, highly desirable to find speleothems covering all of the Holocene including the time periods around the proposed climate events, especially the ones occurring at 4200 years ago and at 3200 years ago.

With the emergence of new paleoclimate data from the Peloponnese, both from this project and other ongoing research projects, new possibilities for inter-disciplinary efforts to integrate locally based archaeological and historical records with locally based climate and environmental data, have opened up. This will hopefully facilitate future analysis and a deeper understanding of the impacts of climate variability on human societies in this archaeologically rich region. Additionally, future work in the field of paleoclimatology from the Peloponnese should make efforts to develop paleoclimate datasets that are directly integrated with archaeological and historical evidence. Instrumental here will be to design research projects that are inter-disciplinary from the very beginning and to develop paleoclimate datasets in close proximity to archaeological and historical sites.

Conclusions

This thesis contributes to an improved understanding of speleothems from the Peloponnese as climate archives and of the climate in the eastern Mediterranean during the late Quaternary. The literature review of the Mid- and late Holocene climate variability in the eastern Mediterranean, published in Journal of Archaeological Science, provides a valuable review easily accessible for the historical and archeological communities as well as for the paleoclimate science community. Following this detailed review the first speleothem-based stable isotope records ($\delta^{18}O$ and $\delta^{13}C$) from the Peloponnese reveal changes in the climate and the environment of the peninsula during the periods of speleothem growth. The main conclusions from this thesis are:

- Speleothems from the Peloponnese can provide valuable contributions to the general understanding of the climate on the Peloponnese in particular, but also in the eastern Mediterranean in general. Speleothems can also be used as recorders of past local flood events as has been shown by the development and employment of a novel, quick and non-destructive method for analyzing speleothems for traces of past floods using an XRF core scanner.
- This thesis provides the two first speleothem based $\delta^{18}O$ and $\delta^{13}C$ records from the Peloponnese. The records provide information about the climate on Holocene time scales and they offer opportunities to investigate the timing of late Pleistocene climate variability. The locally derived U-Th chronologies can also be used for comparisons with previously published long-term pollen records from Greece. Further, the location of the Peloponnesian Peninsula means that the records from this area provide an improved understanding of the Atlantic influence and the position of Mediterranean cyclone tracks in the region during the last glacial period.
- In Kapsia Cave the major control on speleothem $\delta^{18}O$ values, at least, for the last 20 years has been the wet season (ONDJFMA) precipitation amount, the so-called amount effect. Comparisons between Kapsia and other paleoclimate records support the hypothesis that the amount effect is a major control on stalagmite $\delta^{18}O$ also for the late Holocene.
- During the last glacial period (Marine Isotope Stages 5a–3) the climate over the Peloponnese rapidly responded to Greenland interstadials and stadials. During warmer (colder) interstadial (stadial) conditions vegetation and soil microbial activity responded rapidly reflected by depleted (enriched) $\delta^{13}C$ of the speleothems from Glyfada Cave. Depositional hiatuses occurring in Glyfada during MIS 4 and

the latter part of MIS 3 reflect dry conditions corresponding to a southward shift of Mediterranean cyclone tracks brought about by large and/or expanding ice volumes in the Northern Hemisphere.

- During the last 6000 years three main climate periods have been identified in the eastern Mediterranean: 1) From 6000 to 5400 years BP conditions were mainly wetter than average, 2) in the period 5400 to 4600 years BP conditions remained mainly wetter but less so than the previous period, and 3) 4600 to 1400 years BP drier conditions came to dominate the regional picture. However, there are periods of increased moisture.
- Around 4200 and 3200 years BP aridity was widespread and pronounced in much of the eastern Mediterranean. However, considering the lack of unambiguous evidence of a widespread and distinct event at 4200 year BP and the conflicting evidence from the Peloponnese around 3200 years BP, it is difficult to make firm conclusions about the character and the impact of these two climate events.
- From the Peloponnese there is local evidence of changes in precipitation amount with rapid shifts toward wetter conditions followed by slowly developing aridity following a cyclical pattern of close to 500 years in the period from 2950 to 1100 years BP. Wetter conditions are inferred around 2800, 2650, 2450, 2350–2050, 1790–1650 and 1180 years BP. Driest conditions are inferred to have occurred around 2400, 1850–1800 and 1300 years BP.

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