

Response to Dr. Combourieu-Nebout

Thank you very much for handling our manuscript. We have carefully revised the manuscript to take into account all the comments. We respond to all points item by item bellow with the comments in black and our responses in blue fonts.

Editor Decision: Publish subject to minor revisions (review by Editor) (09 Nov 2015)
by Dr Nathalie Combourieu Nebout

Comments to the Author:

Dear authors,

Thank you for your responses to the reviewer comments posted on CPD site. After examining the reviews and your replies it is obvious that both reviewers are generally favourable to the publication of your paper in *Climate of the Past*. I will therefore encourage you to submit a revised version taking into account carefully all the comments.

Moreover, I have a small additional remark regarding the naming of the different climate episodes shown in the speleothem record. Could you replace the term “climate stage” by “climate event” or “climate period”. The term “climate stage” is confusing here because ‘Stage 1, 2, 3 and 4’ are generally used for the climate periods defined in the marine isotope records of the Pleistocene and not in the Holocene that also corresponds to stage 1. In fact the climate period 4 is not labelled in the figures. Why? We expect that it corresponds to the upper part of the record but it is necessary to point it on the figure as it is defined in the text and table. If not why do you defined a fourth event?

We agree. The term “climate stage” was replaced by “climate period” in revised manuscript. Climate period 4 was added in Figure 7.

Waiting after seeing your revised manuscript.

Sincerely yours

Nathalie Combourieu-Nebout

Response to the interactive comment by anonymous referee # 1

We thank the anonymous referee for his/her positive comments on our work. We also appreciate his/her thorough comments about our discussion on speleothem record that helped to improve the manuscript. He/she raises four detailed considerations, relating to: (1) the Hendy test, (2) the open nature of the cave and its impact on isotope values (modern - paleo isotope comparison); (3) the difference of the isotopic signal of two speleothems; and (4) the caution of climatic interpretation from growth phase/rate variability. We have carefully revised the manuscript to take into account these comments. We respond to all points item by item below with the comments in black and our responses in blue fonts.

Interactive comment on “Evidence of a prolonged drought ca. 4200 yr BP correlated with prehistoric settlement abandonment from the Gueldaman GLD1 Cave, N-Algeria” by J. Ruan et al.

Anonymous Referee #1

Received and published: 3 August 2015

The manuscript is interesting and adds more to the understanding that major climatic events during the Holocene in larger part of the Mediterranean basin are synchronized and that there is a possible link between climatic events and human occupation. The manuscript deals with climate reconstruction based on 2 speleothems from the open Gueldaman cave, in N-Algeria _60 km from the Northern Mediterranean Sea, where well dated speleothems and archeological remains co-exist. The isotopic record of the speleothems was correlated to speleothems from central and eastern Mediterranean Sea. The major conclusions from the comparison of the isotopic record from N. Al-geria with speleothems from Italy and Israel is that synchronicity with major drying at ca. 5600, ca. 5200 and ca.4200 yr BP occur across the Mediterranean basin. The archeological findings in the cave supports their conclusions. The weaker part of the manuscript is the discussion of the speleothems record. This section needs more clarification and re-organization. Hendy tests need to be shown as a figure, and need explanation if they were performed along single laminae or across lamination.

We have significantly revised and re-structured the Discussions part of the manuscript. We added the figure of Hendy tests as Supplement in revised manuscript (Figure 1, below). Our strategy for Hendy tests was to determine the isotopic compositions along visible single lamina, from the apex toward the edge, at the depths of 52 mm, 172 mm and 292 mm. Since the diameter of the drill we used is 0.6 mm and the growth rate at these depths vary from ca. 0.1 mm to 0.3 mm per year, each data point may contain information for ca. 2-6 years. The result shows that the carbon and oxygen isotope values significantly correlate and increase by up to ~1‰ from the apex toward the edge, which suggests non-equilibrium isotopic precipitation.

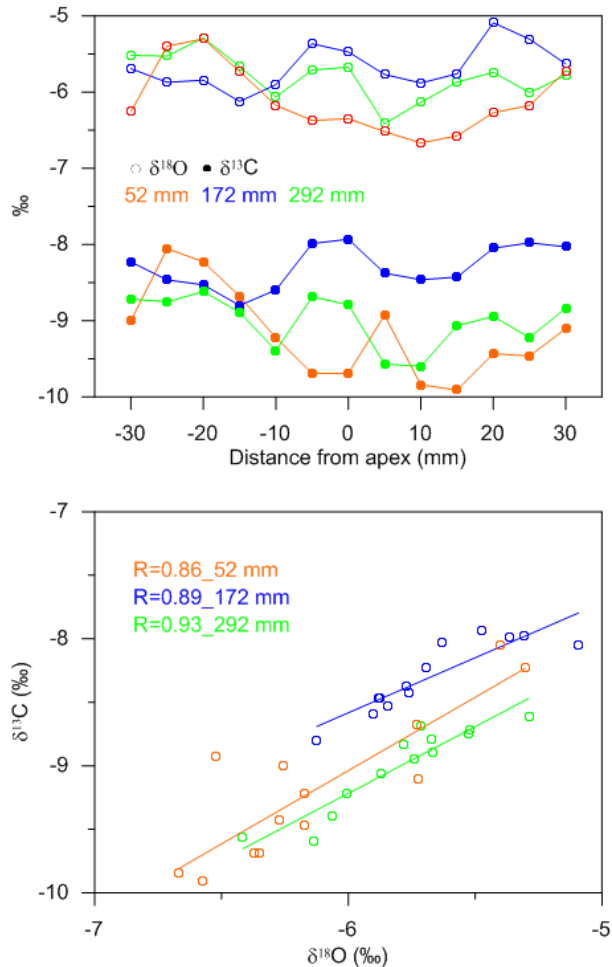


Figure 1. The Hendy test from stalagmite GLD1-stm2.

A more in depth discussion is needed regarding the fact that the cave is open and how this can modify the isotopic record? The authors show the present-day values of the speleothems d18O and d13C but they don't discuss why the values fit more the speleothems value pre _5000ka. Is it due to climate change? Can it be associated with the opening of the cave? When was the cave opened?

We agree with the reviewer. It would be helpful to further discuss the impact of open cave on speleothem isotopic values. More comments were added in the Discussions 4.1 of revised manuscript. Briefly, the open cave allows evaporative and kinetic isotopic fractionations, which would amplify the climatic signal imprinted in speleothem isotopes. First of all, variations in Gueldaman GLD1 speleothem isotope are negatively correlated to rainfall to a certain degree. Evaporation and kinetic fractionation processes, due to the open nature and short extension of the cave, further modify speleothem isotope values with an overall increasing effect, which is prolonged/diminished during drier (low rainfall) /wetter (high rainfall) period. In the manuscript, we compared the present-day isotope values to the paleo-records. We agree that the modern values fit better to the values of pre-5000 yr in stalagmite GLD1-stm4, but this is less clear when comparing them to stalagmite GLD1-stm2. We therefore only suggested (Discussions 4.1) that the current humidity condition is

within the range of its Mid-Holocene variability, based on the observation that the present-day isotope values fall in the range of two stalagmites variations. Radiocarbon dating and archaeological evidence argue that the Gueldaman GLD1 Cave was occupied by ancient human since at least ca 7 ka ago. Besides, there is no clear evidence from previous field investigation of changes in cave geomorphology. These suggest that the cave has probably been open in the last 7 ka. More information was added in the Study Site 2.1 of revised manuscript.

The isotopic events are well observed in GLD1-stm4 whereas in speleothem GLD1-stm2 the record hardly shows any significant change. It is impossible to compare the 4500 Ka event recorded in sample 4, to sample stm-2. The enrichment isotopic trend well observed from 4800-4600 yr BP in sample 4, but is hardly seen in sample 2. The authors need to explain why the isotopic profiles of two speleothems growing close to each other are so different.

Although two stalagmites broadly show similar isotopic variations and the isotopic events discussed in the manuscript (ca.3800-4400 yr, ca.5200 yr and ca.5400-5600 yr) are identical in both stalagmites, we admit that their isotopic profiles significantly differ in regards of the amplitude and stalagmite GLD1-stm2 record shows less clear changes during these events (Fig. 5). The absolute isotopic changes in stalagmite GLD1-stm2 usually are 1/3-1/2 as small as these in stalagmite GLD1-stm4 across these events. Albeit these we notice that the amplitude of stalagmite GLD1-stm2 is more comparable to those of Soreq and Corchia cave stalagmites (Fig. 5). The relatively ambiguous change of stalagmite GLD1-stm2 isotopic profile may suggest that the reservoir feeding GLD1-stm2 is so large that smooths significantly the rainfall signal and/or other site-specific factors also play an important role in controlling the isotope value. On the other hand, the isotopic events are clearly seen in stalagmite GLD1-stm4 possibly because: (1) the reservoir feeding GLD1-stm4 is small and smooths the rainfall signal to a lesser degree; and/or (2) the rainfall signal in GLD1-stm4 is amplified significantly by being suffered from prolonged evaporative and kinetic fractionations. These explanations were added in the Discussion 4.1 of revised manuscript.

As is clearly seen in Fig. 4, there is NO relation between the growth rate and the isotopic profile. Sample 2 shows a striking change in the growth rate at 4800-4600, which is more than twice that of the time periods before and after. This major fast "growth-rate" occurs before the major increase in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ in stm4. It does not seem to be related to changes in the isotopic composition, so maybe there is no connection with climate change? Changes in growth rate based on 1 or 2 speleothems are sometimes misleading because they can be associated with internal processes of water dripping mode.

We agree that caution should be taken when interpreting stalagmite growth rate. Because it is likely that two stalagmites have different reservoirs, their growth rate variations would be difficult to compare and their relationships to the isotope profiles might be non-stationary. However, we do not fully agree that there is no relationship

between stalagmite growth rate and its isotopic profile. The major fast growth rate in stalagmite GLD1-stm2 ca. 4800–4600 yr BP broadly corresponds to the most negative isotope values; both of which argue for wet conditions.

Sample 4 shows significant isotopic variations at 5800–5500 yr BP, 4600–4400 yr BP, etc. None of these events is reflected in the growth rate which is more or less constant at this period. The authors argue for a wetter period ca. 4800–4500 yr BP based on the high growth rates of stalagmite GLD1-stm2 and they say that it is not seen in the growth rate change of stalagmite GLD1-stm4 probably due to the lack of dating between 5023 and 4197 yr BP. This is a strange argument. Maybe another dating point is required to solve this inconsistency, or maybe the age model is not absolutely correct.

We agree that the growth rate of stalagmite GLD1-stm4 is relatively constant and its variability seems less sensitive to the isotope change. This may suggest that changes in GLD1-stm4 growth rate might have been affected by other climatic/hydrological processes than those closely associated with isotope variability. We would also like to suggest that the growth rate curve, stimulated from limited U/Th dates by the StalAge program, is less precise and resolved comparing to the isotope profile. This is most apparent for the period of pre-4197 yr BP in stalagmite GLD1-stm4, where was argued by the referee for the lack of isotope-growth rate relationship.

The authors don't give good explanation to why sample 2, though being the thicker speleothem, ceased to grow at 4100 yr, whereas speleothem 4 continued to grow. They try to suggest a phase of increased aridity, and this explanation fails to explain the continuous growth of speleothem 4. A possible explanation is that sample 2 ceased to grow due to local variations in the dripping position, rather than major climate change. The authors claim that the larger amplitudes of isotopic variations in stalagmite GLD1-stm4 (Fig. 4) can be explained by the likelihood of more evaporative and non-equilibrium enrichments due to lower drip rates, being indicated by its smaller diameters (Fig. 2), but in such case, shouldn't we expect a significant relation between the isotopic composition and growth rate?

We agree with this comment and give more detailed explanations in the Discussion 4.1 of revised manuscript. We suggest that the discrepancy in growth cessation of two stalagmites may be due to different sensitivities of their growths responding to climates, but we do not exclude the possibility that the growth cessation of stalagmite GLD1-stm2 have been caused by shifts in dripping position which eventually might also be linked to deteriorating climates. We also suggest that a significant growth rate – isotope/climate relationship may be blurred due to the lack of substantial U/Th dating from stalagmite GLD1-stm4. Additional dates will help refine the growth rate curve and prove this hypothesis.

Despite these inconsistency between the two speleothems and lack of good explanation for the reasons, one speleothems show a good match with the timing of major drying events in central and Eastern Mediterranean speleothems.

Response to the interactive comment by G. Zanchetta

We thank Dr. Zanchetta for his positive comments on our work. We also appreciate his detailed comments on our reference list which helped to improve the manuscript. We have revised the manuscript to take into account these comments. We respond to all points item by item bellow, with the comments in black and our responses in blue fonts.

Interactive comment on “Evidence of a prolonged drought ca. 4200 yr BP correlated with prehistoric settlement abandonment from the Gueldaman GLD1 Cave, N-Algeria” by J. Ruan et al.

G. Zanchetta (Referee)

Received and published: 3 August 2015

Dear Editor,

I have now completed my review of the manuscript by Ruan et al. “Evidence of a prolonged drought ca. 4200 yr BP...” The manuscript is clear and well written and robustly discussed. I have just one general comment, which concerns the fact that some important references on the 4.2 event in the Mediterranean are missing. Some are just to improve the reference list like: Dixit Y., Hodell D.A., Petrie C.A. 2014. Abrupt weakening of the summer monsoon in northwest India _4100 yr ago. *Geology*, 42, 339–342.

The reference Dixit et al (2014) was added into the Introduction of revised manuscript.

Others are more specific of central Mediterranean and need to be discussed and/or inserted in a general figures. For instances:

Finn éM., 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.

This interesting reference Finn é et al (2011) examined the climate history of E-Mediterranean over the last 6000 yr and concluded with much evidence of drying conditions across ca. 4200 yr BP, which is consistent with our discussions in the manuscript. We added it with our comments into the Discussion 4.2 of revised manuscript. We presented, to the best of our knowledge, most well-dated and high-resolution Soreq stalagmite records from E-Mediterranean and compared them with our records and others from Central Mediterranean in Fig. 5, thus, no more curve was added.

More specific are:

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

This paper is also important because at corchia cave the 4.2 event is not so clear expressed in the oxygen isotope curve but very well expressed using other proxies. Other short events are here reported more robustly.

We agree that this reference is also an important study from Corchia Cave showing additional evidence of dryness around 4200 yr BP. We added it in discussion 4.2 of revised manuscript. We noticed that the authors' climatic interpretations from the elemental proxy were rather consistent with those from the isotopic proxy. Considering the proxy consistency and potential modelling tests in future, we preferred to present detailed comparisons of stalagmite oxygen isotopes from different parts of Mediterranean in Fig. 5.

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

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

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

In these last three papers the event is well defined and constrained using tephra layers. The references Zanchetta et al (2012a; 2012) also discussed climate change around the event. We added them with our comments in the Discussion 4.2 of revised manuscript. We prefer not to include Zanchetta et al (2000) because of its limited relevance to present study.

Roland T.P., Caseldine C.J., Charman D.J., Turney C.S.M., Amesbury M.J. (2014) - Was there a '4.2 ka event' in Great Britain and Ireland? Evidence from the peatland record. *Quaternary Science Reviews* 83, 11-27.

Wanner H., Solomina O., Grosjean M., Ritz S.P., Jetel M. (2011) - Structure and origin of Holocene cold events. *Quaternary Science Reviews*, 30, 3109-3123.

In these last two papers is strongly challenged the idea that 4.2 event is a prominent signal in many part of the globe.

These two references are interesting, however, we do not agree that they strongly challenge the 4200 yr event. Actually we are in favour of the conclusion of Wanner et al (2011) that the Holocene climate change including "the 4200 yr event" show high spatiotemporal variability in a global scale. The 4200 yr climate anomaly has been widely identified around the world, but this does not necessarily mean that every signal archive can record it (Roland et al 2014). This may depend on the location and/or the sensitivity of each archive or sample, which need to be considered on a case-by-case basis and has long been in debate. In this study we focus on discussing the new record and available evidence from the Mediterranean basin. It is believed

that more high resolution absolute dated records, as we show here, are essential to help clarify this issue.

Magny M., Vanniere B., Zanchetta G., Fouache E., Touchias G., Petrika L., Cousot C., Walter-Simonnet A-V., Arnoud F. 2009. Possible complexity of the climatic event around 4300-3800 cal. BP in the central and western Mediterranean. *The Holocene*, 19, 1-11. Magny et al., 2009 showed that around 4.2 to 3.8 ka there is a succession of events in many Mediterranean record. Can the authors suggest some also for their record (e.g. some part more drier/wetter than the other?)

We indeed observed intra variations within the isotopically shifted period ca. 4400-3800 yr BP in stalagmite GLD1-stm4. It can be roughly divided into three successions: two significant isotopic enrichments (dry) at ca. 4400-4200 yr BP and ca. 4000-3800 yr BP are separated by a mild isotopic depletion (wetter) at 4200-4000 yr BP. Relevant descriptions were added in the Result 3.1 of revised manuscript.

Minor point along the text.

Like Pag. 2732 when for the first time a species is quoted this must be completely Reported

Modified as suggested

Pag. 2736 lines 5-10. It is unclear to me, looking also at table 1 why in the interval between 4900 and 4200 the error is so high.

The age model was developed and checked using the StalAge program, where a linear interpolation between depth and age was made through each progressive triplet of adjacent U-series dates. The large errors between 4900 and 4200 yr may be partly due to the relatively large errors of measured U/Th dates and/or inappropriate hypotheses applied in the algorithm. This comment was added in revised manuscript.

Suggestions: Calcite precipitation out of equilibrium: the data reported to sustain deposition out of equilibrium are probably convincing, then the authors should convince the reader that the climatic signal is preserved. In this case a good argument is that the record is replicated in two different stalagmites?

We agree that replication of two stalagmite records would be a good argument for preserving climatic signals. Albeit different amplitudes the similarity in isotopic profiles of two stalagmites were observed and discussed in the manuscript. It has been known based on studies over the last years that stalagmite oxygen composition preserves climate signal even when it precipitates out of isotopic equilibrium.

Actually in our study site, multiple lines of evidence indicates that the rainfall signal imprinted in stalagmite oxygen isotope (negatively correlated) is probably amplified by disequilibrium processes: longer residence time during drier (lower rainfall) period would allow extended disequilibrium processes which forces stalagmite isotope values further higher. We added more discussions in revised manuscript to further illustrate and better clarify the disequilibrium effect on stalagmite isotope record.

Pag. 2740 lines 18-20. “Thus the current climate in N-Algeria appears to be within : : : : :” This sentence is not very clear and probably wrong. Isotopic composition of modern calcite is too low compared to GLD1-stm4.

We agree that the meaning of this sentence might have been ambiguous. We re-phased the sentence in revised manuscript.

Pag. 2741 line 22 flowstone instead of flow stone.

Corrected

Pag. 2742 line 26 4400

Corrected

Pag.2743. Line 10-11 It is unclear the reference to Irish stalagmite, please add citation and eventually insert the curve in some figure.

The cave names (Soreq) were added to clarify in revised manuscript. The references and curves had already been shown in the text and Fig. 5.

Note that several archives seem to suggest that 4.2 event is not evident at northern latitudes (see reference suggested). Overall I think that the manuscript needs moderate revision before final acceptance. It is important to discuss in more detail available literature in the central Mediterranean and to consider other quotations which suggest (and may support) the view that this event is not strongly represented in the N-Atlantic region as correctly stated by the authors.

Although climate anomaly around ca. 4200 yr BP has been identified globally, this does not necessarily mean that every signal archive can record it and indeed there are archives showing ambiguous change across the event. This may depend on the location of studied archive/sample, because the event shows variable climatic expression and high spatiotemporal variability. This may also depend on the sensitivity of the archive to climates, which has always been debated. In this study we highlight presenting our new record and comparing it with evidence from other parts of the Mediterranean basin. Suggested references were added and discussed in revised manuscript. We believe that more high resolution absolute dated records, as we present here, are essential to clarify this event.

Sincerely

Gianni Zanchetta

Followed by

the marked-up manuscript with our corrections in blue fonts

1 **Evidence of a prolonged drought ca. 4200 yr BP**
2 **correlated with prehistoric settlement abandonment**
3 **from the Gueldaman GLD1 Cave, N-Algeria**

4

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14

15 **Abstract**

16 Middle Holocene cultures have been widely studied around the E-Mediterranean
17 basin in the last 30 years and past cultural activities have been commonly linked with
18 regional climate changes. However, in many cases such linkage is equivocal, in part
19 due to existing climatic evidence that has been derived from areas outside the
20 distribution of ancient settlements, leading to uncertainty from complex spatial
21 heterogeneity in both climate and demography. A few high-resolution well-dated
22 paleoclimate records were recently established using speleothems in the Central and
23 E-Mediterranean basin, however, the scarcity of such records in the western part of
24 the Mediterranean prevents us from correlating past climate evolutions across the
25 basin and deciphering climate-culture relation at fine time scales.

1 Here we report the first decadal-resolved Mid-Holocene climate proxy records from
2 the W-Mediterranean basin based on the stable carbon and oxygen isotopes analyses
3 of two U/Th dated stalagmites from the Gueldaman GLD1 Cave in N-Algeria.
4 Comparison of our records with those from Italy and Israel reveals synchronous
5 (multi) centennial dry phases centered at ca. 5600 yr BP, ca. 5200 yr BP and ca. 4200
6 yr BP across the Mediterranean basin. New calibrated radiocarbon dating constrains
7 reasonably well the age of rich anthropogenic deposits (e.g., faunal remains, pottery,
8 charcoal) excavated inside the cave, which allows the comparison between in situ
9 evidence of human occupation and of climate change. This approach shows that the
10 timing of a prolonged drought at ca. 4400-3800 yr BP blankets the onset of cave
11 abandonment shortly after ca. 4403 cal yr BP, supporting the hypothesis that a climate
12 anomaly may have played a role in this cultural disruption.

1 **1 Introduction**

2 As drought in NW-Africa is a recurring phenomenon and prolonged dry conditions
3 exert a significant impact on local social systems, it becomes important to accurately
4 document the role of drought conditions on the area. For instance, the most recent
5 drought in Algeria began in 1998, as part of a widespread pattern of drying in the
6 N-Hemisphere, and brought considerable loss in regards to water resource and
7 agricultural yields (Hoerling and Kumar, 2003). Increasingly dry sub-tropical
8 conditions are predicted as one potential consequence of anthropogenic climate
9 change, but current general circulation models do not completely capture the
10 magnitude and spatial extent of observed drought conditions (Seager et al., 2007). To
11 help understand recent climate anomalies, paleoclimate studies are crucial to
12 characterize the range of potential natural variability in the past and to improve our
13 understanding of the links between regional drought and large scale forcing.
14 Instrumental data from weather stations in NW-Africa report less than one hundred
15 years. Tree ring based drought reconstructions in Algeria and Tunisia have been
16 extended back to the last nine centuries, which reveals large spatial heterogeneity of
17 past climate evolutions in NW-Africa and concludes that the climate anomaly
18 1998-2002 appears to be the most severe in the last millennium (Touchan et al., 2008;
19 Touchan et al., 2011). Holocene paleoclimate studies in other regions, however, have
20 suggested larger oscillations at centennial to millennial time scales highlighting the
21 need for new records from this area (Mayewski et al., 2004; Wanner et al., 2008).

22 A significant climate excursion ca. 4200 yr BP has been widely reported and is
23 considered as an ideal case to study the causes and effects of a large-scale climate
24 anomaly that occurred against background conditions similar to those of today
25 (Berkelhammer et al., 2013; Booth et al., 2005; [Dixit et al., 2014](#); Roland, 2012). The
26 climatic expression of the 4200 yr BP event differs around the world. For example, it
27 has been documented as droughts in much of mid-to-low latitudes, across Africa, Asia
28 and N-America, wet and stormy in N-Europe and cooler in N-Atlantic (Booth et al.,

1 2005; Roland, 2012). More recently, this climatic anomaly was characterized by
2 extreme dry conditions on high-resolved speleothem isotope records from the Central
3 (Drysedale et al., 2006; Zanchetta et al., 2014) and E-Mediterranean basin
4 (Bar-Matthews and Ayalon, 2011), but, until now, such records have not available in
5 the W-Mediterranean which prevents us the correlation of past climate anomalies
6 across the basin.

7 Aside from its climatic interest, such an episode likely influenced numerous human
8 cultures. Major societal changes have been observed across the Mediterranean basin
9 during the Mid-Holocene, and in particular, a catastrophic desiccation ca. 4200 yr BP
10 has been suggested to trigger the collapse of the Akkadian Empire in Mesopotamia,
11 the Old Kingdom in Egypt and the Early Bronze Age civilizations of Greece and
12 Crete (Weiss and Bradley, 2000; Weiss et al., 1993; Wiener, 2014). These studies
13 have been stimulating an increasing number of debates on climate-culture relationship
14 (e.g., Coombes and Barber, 2005). Uncertainty regarding the societal impact of such
15 an event is still large, due in part that climatic evidence, in many cases, has been
16 derived from regions far from the distribution of ancient settlements (e.g., Cullen et
17 al., 2000). Although the 4200 yr BP dry event has been observed in several mid
18 latitude sites, the database remains incomplete and conflicting observations of
19 climatic conditions between seemingly adjacent regions exist (Magny et al., 2013;
20 Staubwasser and Weiss, 2006). Additionally, a recent study demonstrated that the
21 climatic impact on many agricultural settlements in ancient Near East was diverse
22 even within spatially limited cultural units (Riehla et al., 2014).

23 In N-Algeria, the extinction of large mammal species (e.g., *Syncerus antiquus*) during
24 the Mid-Holocene was correlated with regional climate aridity, likely due to the
25 competition with pastoralists and livestock for increasingly scarce water (Faith, 2014).
26 Similarly, the evidence of the aridity (i.e., the termination of the African Humid
27 Period) that provoked this extinction has been derived from the Sahara and its
28 surroundings (deMenocal et al., 2000), which is several hundred kilometres away,

1 leaving this assertion ambiguous and stimulating the search for new high resolution
2 paleoclimate records in the area.

3 In this study, we document the Mid-Holocene climate history in the Western
4 Mediterranean by decadal-resolved stable carbon and oxygen isotopes analyses of two
5 U/Th dated stalagmites from the Gueldaman GLD1 Cave of N-Algeria. We compare
6 the records with those established earlier in the Central and E-Mediterranean basin. In
7 addition, we describe archaeological deposits layers inside the cave whose ages have
8 been reasonably well constrained due to new radiocarbon dating. Finally we test the
9 links between cultural changes and climate anomalies with a particular emphasis on
10 the 4200 yr BP event.

11

12 **2 Samples and Methods**

13 **2.1. Study Site**

14 Gueldaman GLD1 Cave is one of a series of karstic caves formed within the SE-ward
15 slope of the Adrar Gueldaman ridge, western part of Babor mountains in N-Algeria
16 (Kherbouche et al., 2014). It is located close to the large Soummam River, 5-6 km
17 from the Akbou town, and approximately 65 km southern inland from the
18 W-Mediterranean Sea (36°26'N, 4°34'E, 507 m asl) (Fig. 1). Gueldaman GLD1 is a
19 relatively short cave (total extension of ~80 m) that developed in Jurassic limestone.
20 The entrance, facing to the SE, is a semi-circular ~6 m large arch, leading to a
21 dome-shaped ~10 m high and 6 m wide corridor which ends with the main chamber
22 “Grande Salle” at a depth of 30-40 m. [Previous archaeological excavation and field](#)
23 [investigation suggest that Gueldaman GLD1 Cave has probably been open since at](#)
24 [least ca. 7 ka ago \(Kherbouche et al., 2014\).](#) The area is covered by a thin layer (< 10
25 cm) of soil derived from the limestone bedrock, wind-blown silicate dust, and organic
26 matter from local vegetation such as *Pistacia lentiscus*, *Quercus ilex*, *Buxus*
27 *sempervirens*, typical Mediterranean *Garrigue* type plant assemblage (C3 dominated).

1 Local climate is Mediterranean semi-arid type, characterized by hot-dry summers and
2 mild-wetter winters. From the ERA-interim reanalysis data between 1979 and 2013
3 (<http://apps.ecmwf.int/datasets/>) the annual total rainfall is 516 mm, and the annual
4 mean temperature is 17.2 °C. Rainfall occurs rarely in the summer (37 mm) but
5 relatively evenly through the autumn (155 mm), winter (178 mm) and spring (147
6 mm). Gueldaman GLD1 Cave is well ventilated with the outside atmosphere due to its
7 larger opening and shorter extension. Hobo logger data at 10 min resolution from
8 November 2013 to April 2015 shows significant variations in cave temperature
9 ranging from 13.7 °C to 19.5 °C. The relative humidity varies from 56% to 94%.
10 Carbon dioxide has not been measured, but it is likely to be close to the atmospheric
11 value.

12 **2.2. Stalagmites Analyses**

13 Two stalagmites and three modern calcites samples were collected in 2012 and 2013
14 from the main chamber of Gueldaman GLD1 Cave. Both stalagmites were laid on the
15 cave floor during collection. Stalagmite GLD1-stm2 is 350 mm long and 100-200 mm
16 wide; stalagmite GLD1-stm4 is 203 mm long with a diameter of 50-120 mm (Fig. 2).
17 They were halved and polished along the longitudinal axis. It was noticed from the
18 sectioned sample that stalagmite GLD1-stm2 was broken at the depth of 5 mm/top
19 and covered by the calcite deposited at certain time after that point. The top 5 mm was
20 not analyzed in this study. Both stalagmites show well-marked laminae with several
21 shifts in the drip apex of the lower parts (Fig. 2). Black bandings, with visible
22 incorporations of charcoal particles, are found throughout both stalagmite profiles.

23 **U/Th dating** - Seventeen powder samples were drilled from the two stalagmites and
24 dated by a multi-collector inductively coupled plasma mass spectrometer. The
25 procedure to separate uranium and thorium were referred to Edwards et al. (1987) and
26 Cheng et al. (2013). The dating work was carried out at the University of Minnesota
27 (USA) and the Xi'an Jiaotong University (China). One dating from the base part of

1 stalagmite GLD1-stm2, for the exploration of preliminary age frame, was done at the
2 Laboratoire des Sciences du Climat et de l'Environnement (LSCE, France). The U/Th
3 dates were reported in years before 2000 AD. (Fig. 2, Table 1). The age model for
4 both stalagmites was developed using the StalAge program (Scholz and Hoffmann,
5 2011) where a linear interpolation between depth and age is made through each
6 progressive triplet of adjacent U/Th dates (Fig. 3). This procedure provides a
7 quantitative estimate of age uncertainty continuously along the record despite having
8 analytical constraints only at locations where the U/Th dates exist. Stalagmite growth
9 rates were calculated based on the StalAge age model (Fig. 4).

10 **Stable isotopes** - Four hundred and thirty samples were drilled every 1 to 2 mm along
11 the stalagmite central growth axis (Fig. 2). Stable carbon and oxygen isotopes
12 compositions of both stalagmites and modern calcites were measured using a
13 VG-OPTIMA mass spectrometer at the LSCE. For each analysis, 60 to 80 μg calcite
14 powder is reacted with phosphoric acid at 90 °C, and the resultant CO_2 is measured
15 relative to a reference gas that has been calibrated against a series of isotopic
16 standards. Duplicates were run every 10 to 20 samples to check replicability. All
17 values are reported in ‰ relative to the V-PDB (Fig. 4). The error is 0.08‰ for $\delta^{18}\text{O}$
18 and 0.05 ‰ for $\delta^{13}\text{C}$.

19 **2.3. Archaeological analyses**

20 Archaeological excavations were carried out at two sectors S2 and S3 inside the
21 Gueldaman GLD1 Cave during the 2010-2012 campaign (Fig. 1). This work consisted
22 mainly in collecting, identifying, and referencing the archaeological materials found
23 in stratigraphic layers (refer to Kherbouche et al. (2014) for details). More than 7000
24 anthropogenic remains were collected, consisting mainly of faunal remains, ceramic,
25 and lithic and bone tools. Besides, all sediments were water screened through 1.5 mm
26 and 4 mm mesh and subjected systematically to flotation with collection in a 250 μm
27 mesh yielding a huge amount of charcoals. Initial radiocarbon dating of upper

1 stratigraphic sequences from S2 and S3 gave the median ages ranging from ca. 6800
2 to 1500 cal yr BP (Kherbouche et al., 2014). In order to refine the chronology of these
3 deposits, in this study, six new charcoal samples were collected from the key
4 archaeological layers in excavation area MN 47/48 of S2. These samples were dated
5 using the AMS radiocarbon method at the CEA Saclay (France). Detailed procedures
6 of the chemical preparation and the dating in the lab were referred to Cottureau et al.
7 (2007). The dates were calibrated using the IntCal13 dataset (Reimer et al., 2013) and
8 reported in years before 2000 AD (Table 2).

9

10 **3 Results**

11 **3.1. Stalagmites U/Th dates and growth rates**

12 The uranium contents of measured stalagmites samples are relatively high ranging
13 from 95 to 225 ppb (Table 1). The 2 sigma U/Th errors vary from 20 to 210 years with
14 an average of 77 years (1.6%). The U/Th date (5070 ± 194 yr BP) of sample
15 GLD1-stm4-47 was detected as a major outlier by the StalAge program, thus, it was
16 not used to calculate the final age model. Calculated StalAge age model for stalagmite
17 GLD1-stm4 shows large errors up to 500 years during ca. 4900-4200 yr BP (Fig. 3).
18 This may partly be due to relatively large errors of adjacent U-series dates and/or
19 inappropriate hypotheses applied in the algorithm. Based on individual StalAge age
20 model, stalagmite GLD1-stm2 grew from ca. 6200 to 4000 yr BP (4100 yr BP if
21 excluding the top 5 mm), whereas stalagmite GLD1-stm4 grew from ca. 5800 to 3200
22 yr BP (Fig. 3).

23 Stalagmite GLD1-stm2 shows high and variable growth rates (mean = $180 \mu\text{m yr}^{-1}$)
24 with higher values $\sim 400 \mu\text{m yr}^{-1}$ at ca. 4800-4600 yr BP; whereas stalagmite
25 GLD1-stm4 shows relatively lower and less variable growth rates (mean = 120
26 $\mu\text{m yr}^{-1}$) with higher values $\sim 200 \mu\text{m yr}^{-1}$ at ca. 3800-3200 yr BP (Fig. 4).

1 **3.2. Stable carbon and oxygen isotopes**

2 The isotopic compositions of modern calcite vary from -5.40‰ to -5.56‰ for the
3 $\delta^{18}\text{O}$ and from -8.43‰ to -10.34‰ for the $\delta^{13}\text{C}$. The $\delta^{18}\text{O}$ values from stalagmites
4 GLD1-stm2 and GLD1-stm4 range from -7.8‰ to -2.8‰ and from -7.3‰ to -0.6‰,
5 respectively; the $\delta^{13}\text{C}$ values range from -10.6‰ to -3.3‰ and from -11.9‰ to -0.6‰,
6 respectively. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ significantly correlate in both stalagmites: $R = 0.87$, P
7 < 0.01 for GLD1-stm2 and $R = 0.92$, $P < 0.01$ for GLD1-stm4. Albeit the different
8 amplitudes, the isotopic profiles of the two stalagmites show similarities during their
9 common development of ca. 5800-4000 yr BP: relatively elevated isotope values are
10 found at ca. 5700-5400 yr BP, ca. 5200 yr BP, and ca. 4500 yr BP (Fig. 4). Two other
11 isotopically enriched periods in stalagmite GLD-stm2 are found at ca. 6200 yr BP and
12 ca. 4900 yr BP (Fig. 4). There is a common isotopic enrichment trend since ca.
13 4800-4600 yr BP (depending on individual age model; abrupt in stalagmite
14 GLD1-stm4 whereas more gradual in GLD1-stm2). Toward the end of this trend, the
15 most prominent anomaly occurs in stalagmite GLD1-stm4 at ca. 4400-3800 yr BP
16 during which the $\delta^{18}\text{O}$ values are enriched by approximately 3.5‰ relative to the
17 background values of that time as well as the modern calcite values for a period of
18 ~500 years (Fig. 4). Specifically within this anomalous period, there is a mild isotopic
19 depletion at ca. 4200-4000 yr BP, blanketed by two significant enrichments at ca.
20 4400-4200 yr BP and ca. 4000-3800 yr BP (Fig. 4). The last part, ca. 3800-3200 yr BP,
21 of GLD1-stm4, is characterized by a $\delta^{18}\text{O}$ recovery of about -3‰, synchronous with
22 increased growth rates (Fig. 4).

23 **3.3. Anthropogenic deposits and 14C dates**

24 Excavations inside Gueldaman GLD1 Cave revealed a large variety of archeological
25 remains and, among them, are numerous precious macro charcoals that have been
26 used for establishing the chronology of the deposits. In the ~7 m² total excavated area
27 of S2, more than 7000 archaeological objects were identified and consisted of faunal

1 remains, lithic artifacts and grinding equipment, potteries, bone tools, ornaments, and
2 ochre. In addition, a fragment of a human mandible and two isolated teeth were found
3 during the excavation 2010-2012 in Gueldaman GLD1 Cave (Kherbouche et al.,
4 2014). These deposits belong mainly to the Neolithic; only the top level of the
5 sequence contains potsherds of the historic period. In the lower Neolithic levels,
6 identified domestic species (i.e. sheep and goats) represented ~25% of total faunal
7 assemblages (N = 2378) suggesting a partly pastoral based economy. The potteries (N
8 = 825) are mostly related to cooking vessels of 25-40 cm rim diameter. Hundreds of
9 black charcoals (>1 cm) were found and always associated with ceramic
10 concentrations suggesting evidence of cooking activities.

11 Determined radiocarbon dates give the median ages of the sequence between 7002
12 and 1482 cal yr BP, with their 2σ -error intervals varying from 132 to 374 years (Table
13 2). These dates provide a first chronology for the archaeological deposits excavated
14 from sector S2 (Fig. 6) (Kherbouche et al., 2014): anthropogenic remains (i.e.
15 charcoals, bones, teeth and potteries) are numerous during ca. 7002-6003 cal yr BP
16 (depths of ~150-120 cm), decreased at ca. 6003-4918 cal yr BP (depths of ~120-105
17 cm), most abundant in the period of ca. 4918-4403 cal yr BP (depths of 105-75 cm),
18 significantly diminished during the long interval of ca. 4403-1484 cal yr BP (depths
19 of 75-60 cm), and finally, numerous again from ca. 1484 cal yr BP (depths of ~60-50
20 cm). With an overall decrease in archeological materials, there are two levels clearly
21 marked by their poverty in charcoal and pottery during the periods of ca. 6003-4918
22 cal yr BP and ca. 4403-1484 cal yr BP (Fig. 6).

23

24 **4 Discussions**

25 **4.1. Climatic significance of stalagmites proxies**

26 Under isotopic equilibrium precipitation, stalagmite calcite $\delta^{18}\text{O}$ depends mainly on
27 the temperature of calcite-water fractionation and on the $\delta^{18}\text{O}$ of drip water that is

1 controlled by local rainfall $\delta^{18}\text{O}$ (Genty et al., 2014; Lachniet, 2009). Observations
2 from the IAEA network show that the rainfall $\delta^{18}\text{O}$ at many Mediterranean stations
3 (including one in Algiers, Algeria) are partly controlled by the amount of rainfall
4 (IAEA, 2005), which is coherent with previous studies that stalagmite $\delta^{18}\text{O}$ records
5 from the Mediterranean regions were interpreted to primarily reflect changes in
6 rainfall amount (inversely correlated) (e.g., Bar-Matthews and Ayalon, 2011;
7 Bar-Matthews et al., 2003; Bar-Matthews et al., 1997; Drysdale et al., 2006;
8 Drysdale et al., 2004; Zanchetta et al., 2014). Therefore, higher stalagmite $\delta^{18}\text{O}$
9 values are expected during periods of decrease in rainfall (drier). The temperature
10 effect on calcite-water fractionation, on the other hand, is partly counteracted by the
11 condensation temperature effect on rainfall $\delta^{18}\text{O}$ (Drysdale et al., 2006). We notice
12 that this interpretation may particularly hold true for the present study because the
13 regional temperature seems to have been relatively constant since the Mid-Holocene
14 (Martrat et al., 2004).

15 Stalagmite $\delta^{13}\text{C}$ variations have several potential causes, the most likely, considering
16 the studied location and time interval, being variations in soil CO_2 input and water
17 flow rate (Genty et al., 2001a; McDermott, 2004). Despite the fact that soil biogenic
18 CO_2 production varies according to both temperature and moisture level, moisture is
19 likely to be a major controlling factor due to low temperature variability of the
20 considered time interval and limited water availability under semiarid climates.
21 Moisture also influences water flow rate and thus the CO_2 loss during the prior calcite
22 precipitation (Fairchild et al., 2000). Longer residence time due to lower flow rate,
23 under diminished moisture condition, enhances CO_2 loss and preferential ^{12}C removal
24 from solution causing enrichments in stalagmite $\delta^{13}\text{C}$ (Johnson et al., 2006; Mickler et
25 al., 2004). Eventually, atmospheric rainfall largely determines the moisture level and
26 controls the $\delta^{13}\text{C}$ variations. Therefore, the significant correlation of stalagmite $\delta^{13}\text{C}$
27 and $\delta^{18}\text{O}$ may suggest a common control of rainfall.

28 The rainfall signal imprinted in the Gueldaman stalagmite isotopes (inversely

1 correlated) is probably amplified by two other processes - evaporation and
2 disequilibrium isotopic fractionation (Mickler, 2006) that are very likely to have
3 occurred at the Gueldaman GLD1 Cave due to its large entrance. Longer residence
4 time during drier (lower rainfall) periods would allow extended evaporative and
5 non-equilibrium fractionations, which drives stalagmite isotopes further higher
6 (Mickler et al., 2004). It has recently been observed that evaporation in semiarid caves
7 could cause 4-5‰ $\delta^{18}\text{O}$ enrichments of a wide range of drip waters (Cuthbert et al.,
8 2014). The Hendy test (i.e. studying the isotopic variation in contemporaneous
9 laminae (Hendy, 1971)) made on three different depths in stalagmite GLD1-stm2
10 show that the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ correlate and increase by up to ~1‰ from the apex
11 toward the edge, suggesting that the stalagmite forms out of isotopic equilibrium
12 (Supplement). These two processes may partly account for the significant correlation
13 of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ profiles in both stalagmites (R=0.87 for GLD-stm2; R=0.92 for
14 GLD1-stm4). Comparison of two stalagmites shows different amplitudes in their
15 isotopic profiles. This might be due to: 1) having been fed by reservoirs that smooth
16 rainfall signal differently, and 2) having been suffered from variable evaporative and
17 kinetic enrichments associated with different recharge features. Albeit this
18 discrepancy the isotopic profiles of two stalagmites broadly show similar patterns.
19 Consequently, synchronous $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ variations in the two stalagmites can be
20 interpreted in terms of humidity change. A prolonged severe drought is inferred from
21 the most elevated isotopes values during ca. 4400-3800 yr BP together with drier
22 periods from higher values at ca. 6200 yr BP, ca. 5700-5400 yr BP, ca. 5200 yr BP,
23 and ca. 4500 yr BP (Fig. 4), while wetter periods are suggested from depleted isotopes
24 at ca. 4600-5100 yr BP and ca. 5300 yr BP.

25 Moreover, stalagmite growth phase has long been regarded as an environmental
26 indicator (e.g., Genty et al., 2001b; Stoll et al., 2013) and could be used to
27 complement and/or test the climatic interpretation from isotope records. Water
28 availability is an essential factor for stalagmite growth in arid-to-semiarid areas, as

1 shown by Vaks et al. (2013) who correlated growth periods well with periods of
2 effective rainfall regimes. The growth cessation of stalagmite GLD1-stm2 at ca. 4000
3 yr BP may suggest a phase of increased aridity, which is consistent with the dryness
4 inferred from elevated isotopes (Fig. 4). However, the continuous growth of
5 stalagmite GLD1-stm4 at that time suggests that the growth cessation might also have
6 been caused by shifts in dripping position under deteriorating climates (Fairchild and
7 Baker, 2012). Moreover, fast stalagmite growths together with wide diameters usually
8 are associated with high drip rates suggesting humid conditions. A wet period ca.
9 4800-4600 yr BP is indicated by the high growth rates of stalagmite GLD1-stm2,
10 which is broadly in line with the humid period inferred from depleted isotopes (Fig. 4).
11 Another wetter period ca. 3800-3200 yr BP is suggested by faster growths and
12 relatively depleted isotopes of stalagmite GLD1-stm4 (Fig. 4). The discrepancy in the
13 growth rate profiles of the two stalagmites is possibly due in part to 1) the lack of
14 substantial U/Th dating especially for stalagmite GLD1-stm4 between 5023 and 4197
15 yr BP, and/or 2) site-specific processes due to different reservoirs play a key role in
16 controlling stalagmite growth.

17 Finally, the modern calcite isotopic values fall in the range of two stalagmite records
18 (Fig. 4), which suggests that the current humidity condition in N-Algeria seems to be
19 within the range of its Mid-Holocene variability. The average $\delta^{18}\text{O}$ value during ca.
20 4400-3800 yr BP in stalagmite GLD1-stm4 is more enriched by about 3.5‰ relative
21 to the modern values (Fig. 4), therefore, the 4400-3800 yr BP climate anomaly may be
22 considered analogous to end numbers of the most recent and ongoing drying.

23 **4.2. Mid-Holocene climate anomalies across the Mediterranean basin** 24 **and their dynamic implications**

25 High-resolution absolute-dated Mid-Holocene climate records are rare in the
26 W-Mediterranean basin, however, there are number of paleoenvironment studies using
27 sediment cores that documented large oscillations in vegetation ecology and indicated

1 climate anomalies during the Mid-Holocene. A drying trend from ca. 4600 cal yr BP
2 onwards was inferred, based on the decreasing pollen ratio of deciduous broad-leaf
3 *versus* evergreen sclerophyllous taxa at Capestang in the Mediterranean S-France
4 (Jalut et al., 2000). At a nearby site in NE-Spain, the Mid-Holocene most arid
5 condition at ca. 4800-4000 cal yr BP was interpreted using maximum salinity values,
6 more positive organic carbon isotope values, and decreased algal productivity in
7 Estanya Lake (Morrellon et al., 2009). In the Mediterranean S-Spain, desertification
8 phases at ca. 5200 cal yr BP and ca. 4100 cal yr BP were inferred using multiple
9 palaeoecological indicators including pollen, microcharcoal, spores of terrestrial
10 plants, fungi, non-siliceous algae, and other microfossils in Siles Lake (Carrión, 2002).
11 Similar environment changes have also been observed in the Central Mediterranean
12 basin, as shown by a synthesis study of lacustrine palynological data which suggested
13 a dryness peaking at ca. 4000 cal yr BP (Sadori et al., 2011). [Evaluated carbonate
14 oxygen isotopes from Lake Shkodra was argued to an indicator of drier condition at
15 ca. 4100-4000 cal yr BP \(Zanchetta et al., 2012b\)](#). Increasing aridity at ca. 5000-4000
16 cal yr BP was suggested to explain the increases in non-tree pollen percentage and
17 micro charcoal content in the Lago di Pergusa Lake, Sicily (Roberts et al., 2011;
18 Sadori and Giardini, 2007; Sadori and Narcisi, 2001). Close to our site, a study at
19 Preola Lake, E-Sicily, documented a significant low stand lake level at ca. 4500-4000
20 cal yr BP suggesting extreme aridity (Magny et al., 2011). [Moreover, six tephra layers
21 were carefully studied to correlate the climate event at ca. 4500-3800 cal yr BP from
22 different archives in central Mediterranean \(Zanchetta et al., 2012a\)](#). In the east, Finné
23 et al. (2011) reviewed the climate history of E-Mediterranean over the last 6000 years
24 and concluded with much evidence of drying conditions at ca. 4600-3800 yr BP.
25 Although the sampling and dating resolutions in most of the above studies are low,
26 they are in good agreement with the present study regarding the 5200 yr BP dry event,
27 the drying trend from 4800-4600 yr BP onward, and the 4400-3800 yr BP drought.
28 Recently, evidence of detailed Mid-Holocene climate change has been shown in

1 high-resolution U/Th-dated speleothem records from the Central and E-Mediterranean
2 basin. Drysdale et al. (2006) demonstrated a severe Mid-Holocene drought through
3 multiproxy analysis on a [flowstone](#) from Renella Cave, Central Italy. The following
4 work at nearby Corchia Cave by Zanchetta et al. (2007) and [Regattieri et al. \(2014\)](#)
5 revealed similar climatic condition during the Mid-Holocene (Fig. 5). In the
6 E-Mediterranean, Bar-Matthews and Ayalon (2011) explicitly discussed the
7 Mid-Holocene climate by high-resolution dating and isotopic analysis on speleothems
8 from Soreq Cave in Israel (Fig. 5). Zanchetta et al. (2014) made comparisons between
9 records from the Central and E-Mediterranean; they identified coeval dry events at ca.
10 5600 yr BP and ca. 5200 yr BP based on comparable enrichments in speleothem $\delta^{18}\text{O}$
11 from Corchia Cave and Soreq Cave. Detailed comparisons of these speleothem
12 records with the Gueldaman GLD1 stalagmite records reveal similar variations. In
13 particular, elevated $\delta^{18}\text{O}$ values in the Gueldaman GLD1 stalagmites at ca. 5700-5400
14 yr BP, ca. 5200 yr BP and ca. 4400-3800 yr BP are all identified in speleothems from
15 the Renella, Corchia and Soreq suggesting that anomalous dry conditions
16 synchronously developed across the Mediterranean basin (Fig. 5). These observations
17 indicate that climates across the Mediterranean might have been under an identical
18 regional scale climate regime during the Mid-Holocene.

19 It has been suggested that climate change in mid-latitude Europe and Mediterranean
20 might arise from a perturbation of the Westerlies from a high-latitude trigger (i.e. the
21 North Atlantic Ocean) (Bond et al., 2001; Drysdale et al., 2006; Zanchetta et al., 2014)
22 or from dynamics within the tropics (Booth et al., 2005; Hoerling and Kumar, 2003).
23 The three dry periods in the Mediterranean are broadly in phase with the ice rafting
24 events in the subpolar North Atlantic (Bond et al., 2001), which suggests some links
25 with the N-Atlantic circulation. Based on the coincidence with the elevated wind
26 strength in Iceland (Jackson et al., 2005), Zanchetta et al. (2014) argued that the dry
27 events at ca. 5700-5400 and ca. 5200 yr BP might be caused by reduction of vapor
28 advection into the Mediterranean, due to the intensification and northward

1 displacement of the N-Atlantic Westerlies. However, lacking evidence of strengthened
2 wind in the fourth millennium BP argues for a different forcing of the 4400-3800 yr
3 BP drought. The considerably lower amplitude of the Bond ice rafting event at ca.
4 4200 yr BP than at the fifth millennium BP also indicates a varied ocean-atmosphere
5 circulation state. The modern mid-latitude droughts (1998-2002) have been linked to
6 the increased warmth in equatorial oceans (Booth et al., 2005). During this event, SST
7 changes lead to persistent high pressure over the Northern Hemisphere's mid-latitudes,
8 causing widespread synchronous drought (Hoerling and Kumar, 2003). However, the
9 challenge in applying the dynamics under the 1988-2002 drought toward an
10 understanding of the 4400-3800 yr BP climate anomaly is that while the mechanism
11 operate effectively on short time scales, it has never been tested as to whether they
12 could produce an anomalous climate mode for several centuries (Berkelhammer et al.,
13 2013). General circulation model simulations that begin with realistic boundary
14 conditions and are perturbed with a variety of forcings have been successfully
15 undertaken to understand potential mechanisms that lead to the 8200 yr BP event
16 (Tindall and Valdes, 2011). Similar efforts would be a useful starting point to produce
17 hypotheses for the dynamical underpinnings of the 4200 yr BP event.

18 **4.3. Possible relations between climate anomaly and cultural change**

19 A regional drought ca. 4200 yr BP has been widely linked to ancient cultural changes
20 in the E-Mediterranean and the Asia (Staubwasser and Weiss, 2006), though, in many
21 cases, climatic inferences have been derived from sites that are distant to these human
22 settlements. For instance, evidence of reduced precipitation from elevated $\delta^{18}\text{O}$ of
23 [Soreq stalagmites \(Israel\)](#) and increased dust input into the Gulf of Oman sediment
24 core has been suggested to contribute to the collapse of the Akkadian imperial in
25 Mesopotamia (Bar-Matthews and Ayalon, 2011; Cullen et al., 2000; Weiss et al.,
26 1993). Similarly, a dry period inferred from reduced discharge of the Indus river and
27 elevated $\delta^{18}\text{O}$ of a NE-Indian stalagmite has been linked with the Indus Valley

1 de-urbanization (Berkelhammer et al., 2013; Staubwasser et al., 2003; Staubwasser
2 and Weiss, 2006). A recent study in ancient Near East, however, revealed that the
3 regional impact of the drought on ancient civilizations, being influenced by
4 geographic factors and human technology, were highly diverse even within spatially
5 limited cultural units (Riehla et al., 2014). This highlights the need for caution when
6 linking evidence of human activities from a site to evidence of climate oscillations
7 from another one.

8 The present study in the Gueldaman GLD1 Cave provides an opportunity to test
9 climate-culture relations by comparing in situ archeological sequences and high
10 resolution paleoclimate records, thereby avoiding the uncertainty of inter-site
11 correlation arising from complex spatial heterogeneity in climate and demography.

12 To facilitate the comparison, stalagmite-inferred climate changes at the cave site
13 during ca. 6200-3200 yr BP are separated into four **periods** 1-4 (Table 3):

- 14 - **Period 1** (~6200-5100 yr BP): wet, superimposed by several centennial-scale
15 drier events;
- 16 - **Period 2** (~5100-4400 yr BP): wettest, ending with a ~200-yr-long shift from
17 the wettest to extreme dry conditions;
- 18 - **Period 3** (~4400-3800 yr BP): a drought-like climatic anomaly;
- 19 - **Period 4** (~3800-3200 yr BP): relatively wetter.

20 In parallel, from the abundance of archaeological remains (especially bone, charcoal
21 and pottery) (Fig. 6), the temporal evolution of past cave occupations can be separated
22 into five phases 0-4 (Table 3):

- 23 - **Phase 0** (~7002-6003 cal yr BP): permanent and intensive occupation;
- 24 - **Phase 1** (~6003-4918 cal yr BP): permanent but less intensive occupation;
- 25 - **Phase 2** (~4918-4403 cal yr BP): permanent and most intensive occupation;
- 26 - **Phase 3** (~4403-1484 cal yr BP): abandonment of the cave/occasional visits;
- 27 - **Phase 4** (~1484 cal yr BP-): re-occupation of the cave.

1 Correlations can be identified when comparing the climatic and archaeological
2 records, though this does not necessarily mean that occupation of the cave depends
3 merely on climate (Table 3; Fig. 7). When the climate was wet and variable ca.
4 6200-5100 yr BP (Period 1), the Gueldaman GLD1 Cave preserved a few bones and
5 rare charcoals and potteries (Phase 1) (Fig. 7). When the climate was wettest ca.
6 5100-4400 yr BP (Period 2), the most abundance of bones, charcoals and potteries
7 suggests a permanent and more intensive occupation of the cave (Phase 2) (Fig. 7).
8 More striking is the drought-like climate anomaly that has been establishing ca.
9 4400-3800 yr BP (Period 3), from which the cave was abandoned for ca. 3000 years
10 (indicated by a dramatic decrease in anthropogenic remains, especially charcoal and
11 pottery) (Phase 3) (Fig. 7). The rarer bones seen in this period imply that the cave
12 might have been occasionally visited until its re-occupation at ca. 1484 cal yr BP (Fig.
13 7). These observations argue for links between climate and settlement activity
14 especially during the 4200 yr BP climate anomaly. Water availability was likely
15 crucial to maintain the Neolithic community at Gueldaman, N-Algeria and the
16 prolonged severe drought ca. 4400-3800 yr BP might have played a role in triggering
17 the settlement abandonment, indicating that the pastoral economy may not be as
18 resistant, as commonly assumed, to climate anomaly in semiarid area.

19 Moreover, the sole piece of the bone from large ungulate (supposed to be elephant or
20 rhinoceros) found at the depth of ~110 cm (Kherbouche et al., 2014) was anchored by
21 two calibrated ^{14}C dates from present study between 6003 and 4913 cal yr BP, which
22 is in line with the latest survival of large mammal species (e.g., *S. antiquus*) at the
23 proximate sites of N-Algeria during the Mid-Holocene (Faith, 2014 and references
24 wherein). The extinction of the Mid-Holocene large mammal in N-Algeria was
25 attributed to the competition with pastoralists and livestock for increasingly scarce
26 water, corresponding with an abrupt climatic shift toward extreme aridity in the
27 Sahara region ca. 5500 cal yr BP (i.e. the end of the Humid Africa Period (deMenocal
28 et al., 2000) (Faith, 2014). Recently, the timing of this climatic transition was refined

1 to ca. 4900 yr BP \pm 200 yrs (McGee et al., 2013). In addition, a paleoenvironmental
2 study in the Sahara revealed that the Mid-Holocene deteriorations of terrestrial
3 ecosystem and climate culminated at ca. 4200-3900 cal yr BP (e.g., Kröpelin et al.,
4 2006). Therefore, it is more likely based on evidence from the Gueldaman GLD1
5 Cave and the proximate sites (Faith, 2014) that extinction of large mammal/ungulate
6 in N-Algeria occurred during the prolonged drought ca. 4400-3800 yr BP.

7

8 **5 Conclusions**

9 It is increasingly clear based on a growing number of records spanning across much
10 of mid-to-low latitudes, N-Europe, and the Atlantic ocean that there was a significant
11 large scale climate anomaly at around 4200 yr BP (Booth et al., 2005). The 4200 yr
12 BP aridity that had been suggested to affect the Early Bronze Age populations from
13 the Aegean to ancient Near East was recently characterized by high-resolution
14 speleothem records from the Central and E-Mediterranean basin (Bar-Matthews and
15 Ayalon, 2011; Drysdale et al., 2006; Zanchetta et al., 2014). The new record presented
16 here from the Gueldaman GLD1 Cave in N-Algeria provides increased evidence of a
17 prolonged severe drought ca. 4400-3800 yr BP, which suggests that the Mid-Holocene
18 dryness spread to the W-Mediterranean of N-Africa.

19 Radiocarbon dating made on charcoals constrains reasonably well the age of
20 archaeological deposits excavated inside the cave (Kherbouche et al., 2014) and
21 reveals significant changes in human occupation during the last ca. 7000 years.
22 Comparison of the stalagmite record with in situ archaeological sequence suggests
23 synchronicity between climate and settlement activity. Relatively wet/dry periods
24 coincide with the periods of more/less intensive human occupation. Particularly, the
25 timing of the prolonged drought at ca. 4400-3800 yr BP blanket the onset of the cave
26 abandonment event shortly after ca. 4403 cal yr BP, which argues a possible role of
27 climate anomaly in this societal disruption. Further work on pollen-based
28 reconstruction of vegetation/environment change from the excavation sequence and

1 on refinement of the chronology of transitions between different occupation phases
2 would potentially uncover the intrinsic relations among climate, environment and
3 settlement. It is suggested that the methodology and the findings from the present
4 study at the Gueldaman GLD1 Cave be applied and tested at other sites.

5

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17

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1 Table 1. U/Th dates from MC-ICP-MS analyses of stalagmites GLD1-stm2 and GLD1-stm4 from the Gueldaman GLD1 Cave. Analytical errors
2 are 2σ of the mean. U decay constants: $\lambda_{238} = 1.55125 \times 10^{-10}$ (Jaffey et al., 1971) and $\lambda_{234} = 2.82206 \times 10^{-6}$ (Cheng et al., 2013). Th decay constant:
3 $\lambda_{230} = 9.1705 \times 10^{-6}$ (Cheng et al., 2013). * $\delta^{234}\text{U} = ([^{234}\text{U}/^{238}\text{U}]_{\text{activity}} - 1) \times 1000$. ** $\delta^{234}\text{U}_{\text{initial}}$ was calculated based on ^{230}Th age (T), i.e., δ
4 $^{234}\text{U}_{\text{initial}} = \delta^{234}\text{U}_{\text{measured}} \times e^{\lambda_{234} \times T}$. Corrected ^{230}Th ages assume the initial $^{230}\text{Th}/^{232}\text{Th}$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. Those are the values for a
5 material at secular equilibrium, with the bulk earth $^{232}\text{Th}/^{238}\text{U}$ value of 3.8. The errors are arbitrarily assumed to be 50%. ***BP stands for
6 “Before Present” where the “Present” is defined as the year 2000 AD.

Sample	^{238}U		^{232}Th		$^{230}\text{Th}/^{232}\text{Th}$		$d^{234}\text{U}^*$		$^{230}\text{Th}/^{238}\text{U}$		^{230}Th Age		^{230}Th Age		$d^{234}\text{U}_{\text{Initial}}^{**}$		^{230}Th Age		Laboratory
Number	(ppb)		(ppt)		(atomic $\times 10^{-6}$)		(measured)		(activity)		(uncorrected) (yr)		(corrected) (yr)		(corrected)		(corrected) (yr BP)***		
GLD1-stm2-7	169	± 0.1	396	± 0	136	± 1	863	± 2.3	0.105	± 0.001	6297	± 40	6228	± 72	863	± 2.3	6228	± 72	LSCE
GLD1-stm2-36	154	± 0.2	1922	± 39	137	± 3	910	± 2.2	0.103	± 0.000	6036	± 29	5848	± 136	925	± 2.3	5835	± 136	UM
GLD1-stm2-98	150	± 0.2	69	± 2	3077	± 73	776	± 2.4	0.086	± 0.000	5374	± 29	5366	± 29	788	± 2.5	5353	± 29	UM
GLD1-stm2-180	152	± 0.2	161	± 3	1157	± 25	644	± 2.0	0.074	± 0.000	5036	± 30	5018	± 33	653	± 2.1	5005	± 33	UM
GLD1-stm2-192	162	± 0.1	182	± 4	1158	± 24	807	± 1.7	0.079	± 0.000	4858	± 16	4840	± 20	818	± 1.7	4827	± 20	UM
GLD1-stm2-213	175	± 0.2	547	± 11	390	± 8	697	± 2.0	0.074	± 0.000	4841	± 33	4788	± 50	707	± 2.1	4775	± 50	UM

GLD1-stm2-286	169	±0.2	207	±4	980	±21	756	±1.8	0.073	±0.000	4601	±25	4581	±28	765	±1.9	4568	±28	UM
GLD1-stm2-320	195	±0.3	384	±8	575	±12	759	±2.2	0.069	±0.000	4321	±26	4288	±34	769	±2.2	4276	±34	Xi'an U
GLD1-stm2-340	194	±0.3	354	±7	612	±13	800	±2.9	0.068	±0.000	4172	±20	4142	±29	809	±2.9	4129	±29	UM
GLD1-stm4-10	105	±0.1	283	±6	415	±11	322	±1.5	0.068	±0.001	5734	±90	5675	±99	327	±1.6	5662	±99	UM
GLD1-stm4-24	126	±0.1	983	±20	135	±3	347	±1.9	0.064	±0.001	5311	±49	5143	±128	352	±1.9	5131	±128	Xi'an U
GLD1-stm4-30	106	±0.1	1362	±27	80	±2	298	±1.9	0.062	±0.001	5321	±57	5035	±210	302	±1.9	5023	±210	Xi'an U
GLD1-stm4-47	96	±0.1	1104	±22	88	±2	290	±1.9	0.062	±0.001	5341	±63	5082	±194	294	±1.9	5070	±194	Xi'an U
GLD1-stm4-70	224	±0.4	749	±15	254	±5	334	±2.5	0.051	±0.000	4282	±27	4210	±58	338	±2.6	4197	±58	UM
GLD1-stm4-113	155	±0.2	130	±3	910	±20	363	±2.1	0.046	±0.000	3761	±29	3743	±32	367	±2.1	3730	±32	UM
GLD1-stm4-152	180	±0.3	582	±12	226	±5	373	±2.0	0.045	±0.000	3590	±25	3521	±54	376	±2.0	3508	±54	UM
GLD1-stm4-195	175	±0.1	929	±19	131	±4	369	±1.7	0.042	±0.001	3403	±74	3290	±108	372	±1.8	3277	±108	UM

1 Table 2. Radiocarbon dates from AMS analyses of charcoals from excavation sector S2
 2 inside the Gueldaman GLD1 Cave. * Kherbouche et al. (2014). Ages are reported in
 3 years before 2000 AD.

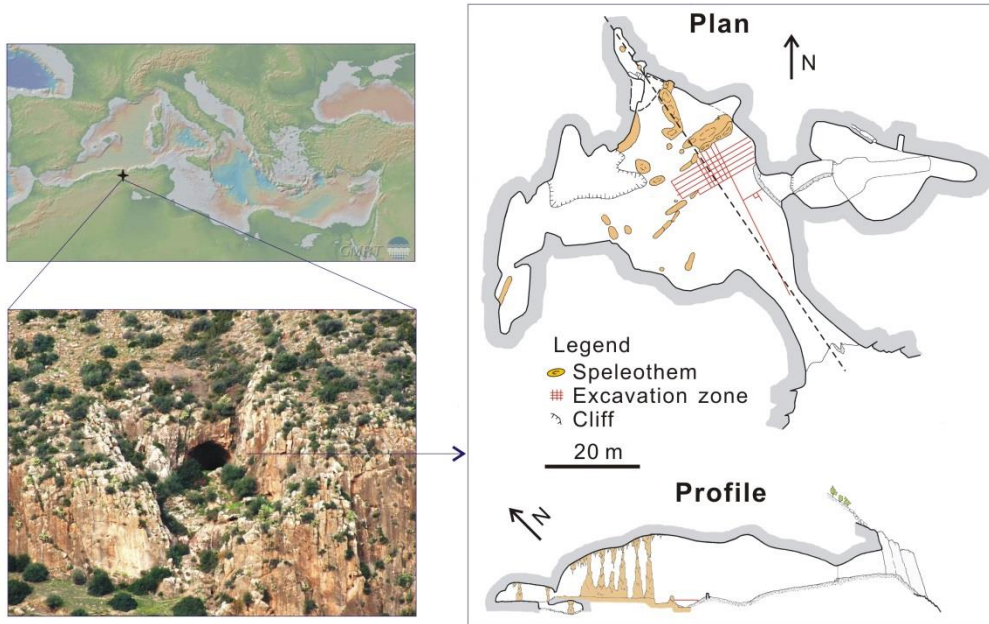
Depth Z (cm)	Square	Lab No. (SacA#)	Material	14C Age ($\pm 2\sigma$; yr)	Median Age (yr)	Cal. Interval (2σ ; yr)	Note
60	M48	39408	Charcoal	1600 \pm 30	1482	1385 - 1604	This study
65	N48	29731	Charcoal	1610 \pm 25	1484	1415 - 1547	*
84	N48	39410	Charcoal	4020 \pm 30	4495	4411 - 4785	This study
86	N48	39411	Charcoal	3975 \pm 30	4416	4290 - 4569	This study
91	M48	39409	Charcoal	3945 \pm 30	4403	4244 - 4522	This study
108	N47	36982	Charcoal	4355 \pm 30	4918	4851 - 5032	This study
124	L48	23883	Charcoal	5250 \pm 35	6003	5924 - 6178	*
132	L48	23884	Charcoal	4260 \pm 30	6025	5933 - 6178	*
147	M47	36981	Charcoal	6120 \pm 35	7002	6907 - 7157	This study

4

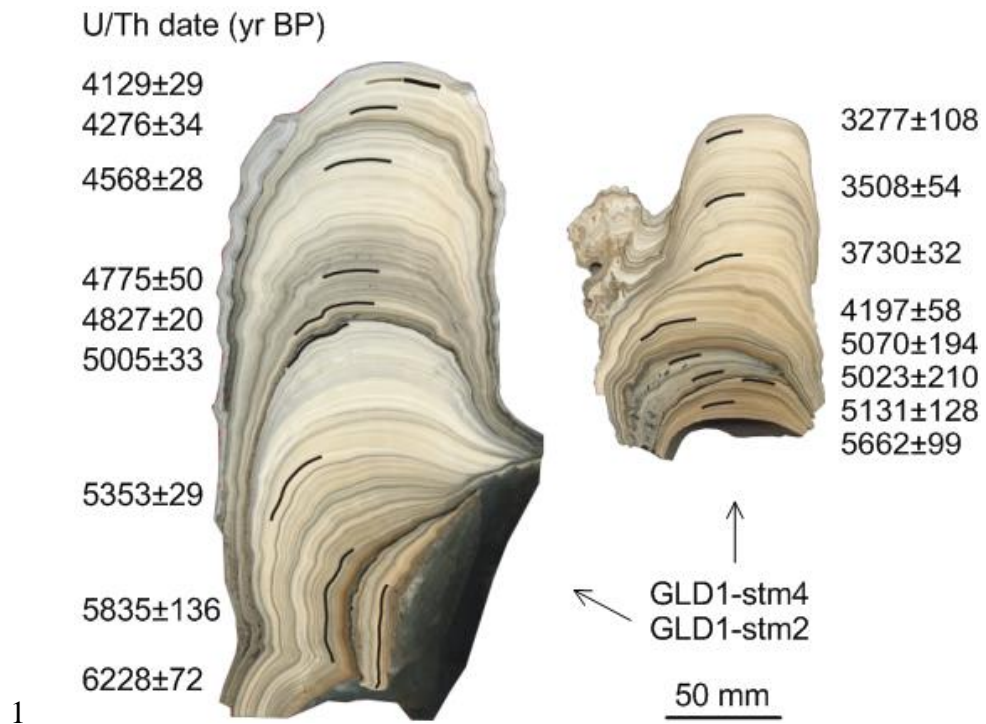
1 Table 3. Summary of the features of climate and human activity in different [climate](#)
 2 [periods](#) and occupation phases.

Climate period	Age (^{230}Th yr)	Climate condition	Occupation phase	Age (^{14}C cal yr)	Human activity
/	/	/	0	~7002-6003	Permanent and intensive occupation
1	~6200-5100	Wet & oscillatory	1	~6003-4918	Permanent but less intensive occupation
2	~5100-4400	Wettest, ending with a dramatic shift in the last ~200 years	2	~4918-4403	Permanent and most intensive occupation
3	~4400-3800	Extremely dry	3	~4403-1484	Abandonment of the cave/occasional visit
4	~3800-3200	Relatively wetter	4	~1484-	Re-occupation of the cave

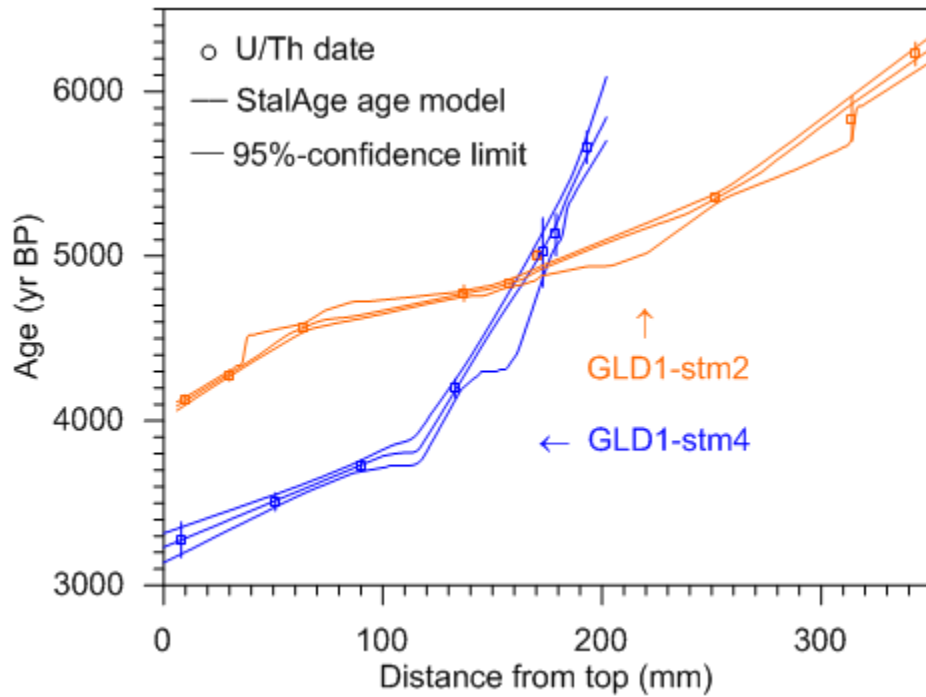
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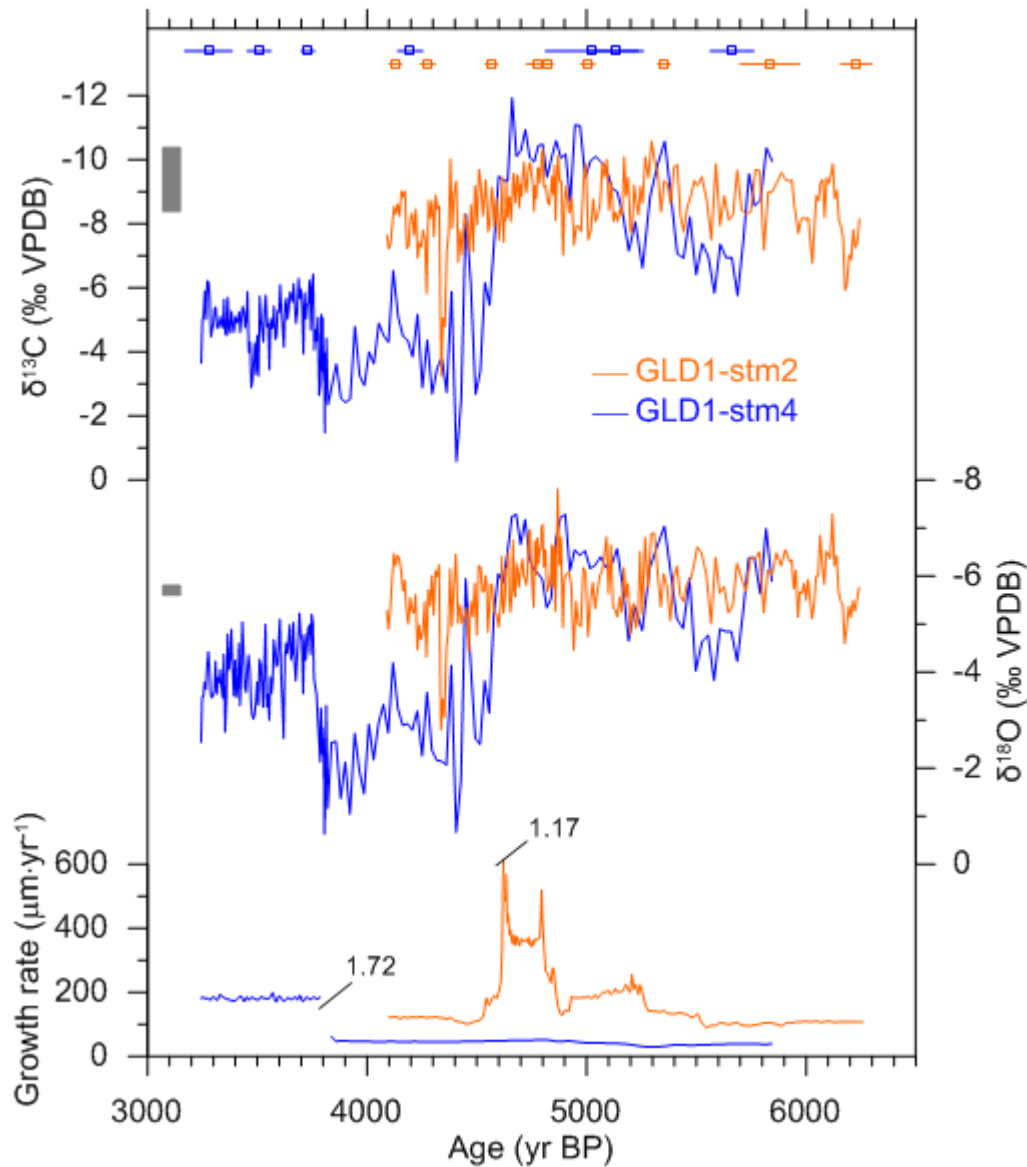
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 2 Figure 1. The Gueldaman GLD1 Cave (36°26'N, 4°34'E, 507 m asl). The top left
 3 shows the location of the Gueldaman GLD1 Cave, in the N-Algeria of
 4 W-Mediterranean basin; the low left shows a photo of cave entrance and local
 5 vegetation cover; the right panel shows maps of inner cave where stalagmites and
 6 archaeological deposits are collected.



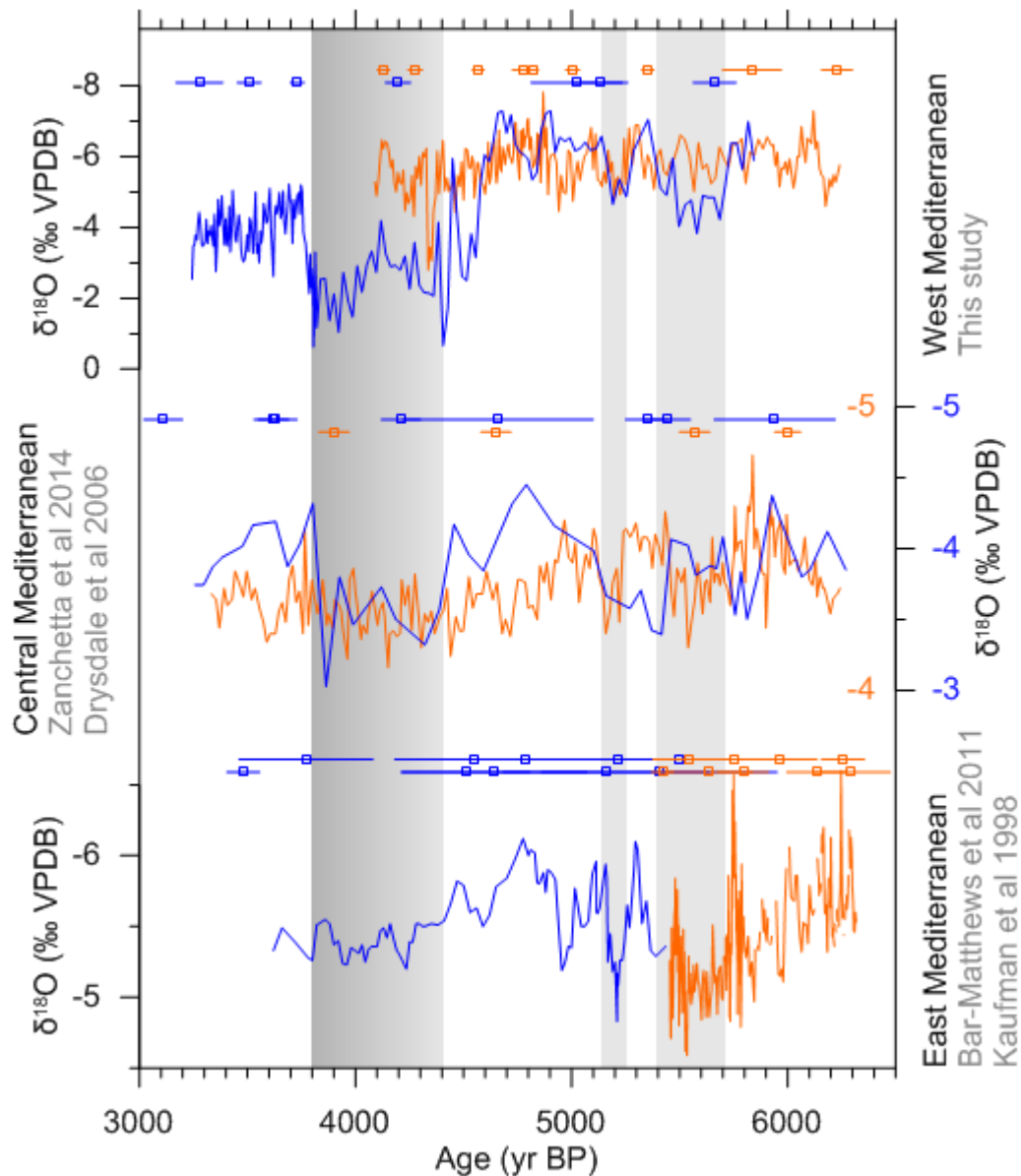
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2 Figure 2. U/Th dating of stalagmites GLD1-stm2 and GLD1-stm4 from the Gueldaman
3 GLD1 Cave. U/Th dates and 2σ errors are shown next to sampling positions.



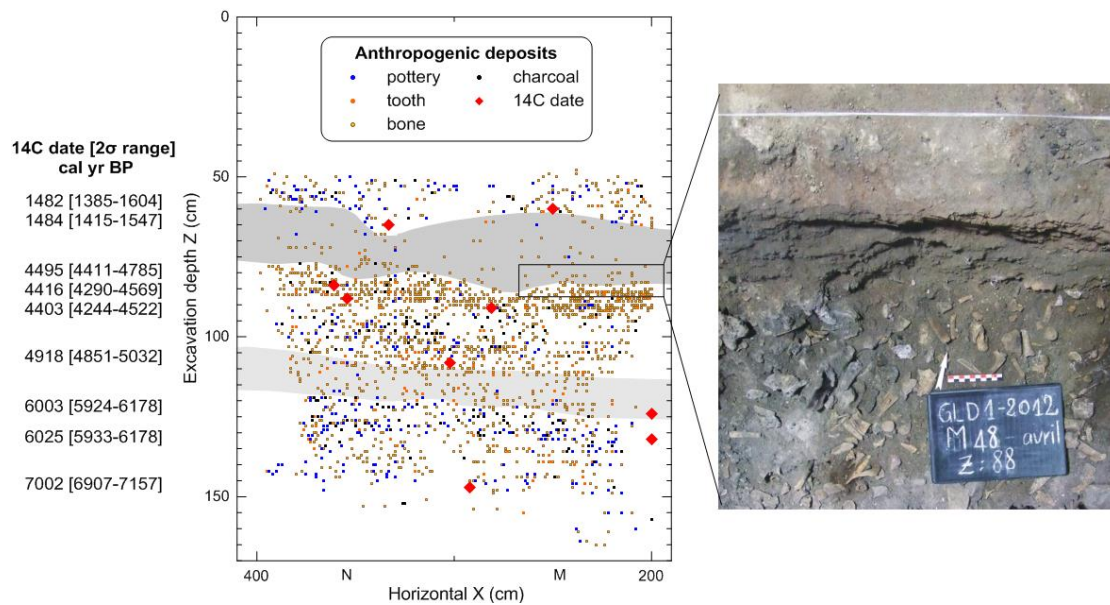
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 2 Figure 3. Age models of stalagmites GLD1-stm2 and GLD1-stm4 from the Gueldaman
 3 GLD1 Cave. The age models were calculated using the StalAge program (Scholz and
 4 Hoffmann, 2011). Note that the U/Th date of sample GLD1-stm4-47 was detected as a
 5 major outlier and not used in the final age model of stalagmite GLD1-stm4. The 2σ
 6 analytical uncertainty of each U/Th date (dot) is represented by the error bars,
 7 whereas the 95% uncertainty assessed from the model simulation is represented by
 8 thin curves.



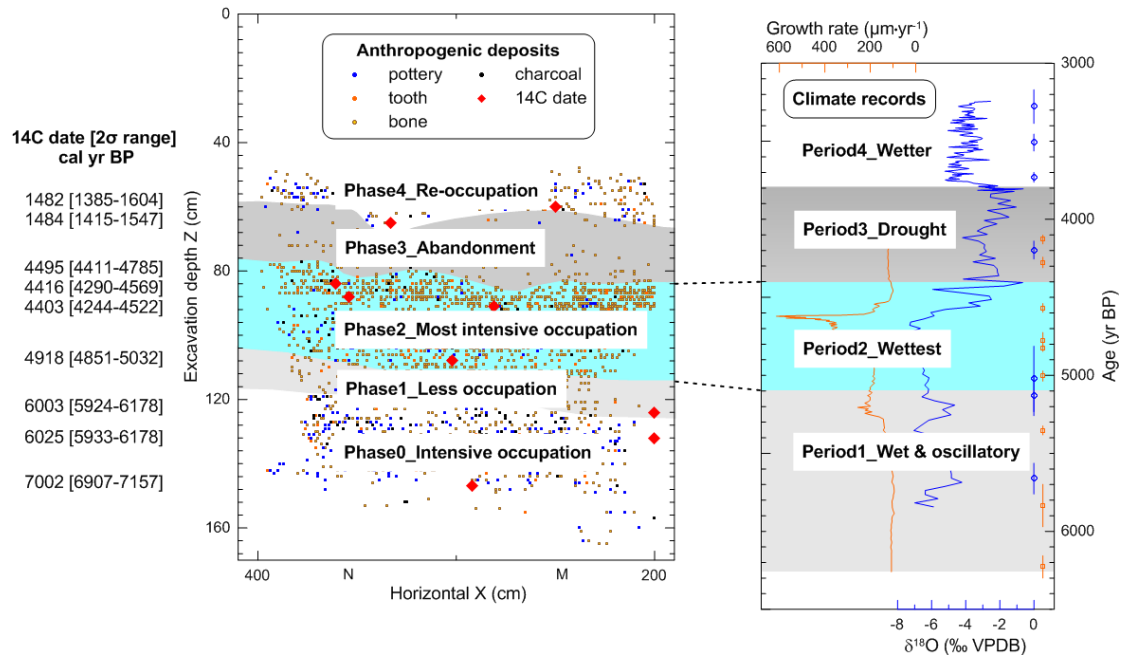
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2 Figure 4. The $\delta^{18}\text{O}$, $\delta^{13}\text{C}$ and growth rate of stalagmites GLD1-stm2 and GLD1-stm4
3 from the Gueldaman GLD1 Cave. U/Th dates with 2σ errors are presented at the top.
4 The isotopic ranges of modern calcites are also shown on the left (rectangles). Growth
5 rates are calculated from the StalAge age model. Note that the extraordinarily high
6 growth at ca. 4600 yr BP in stalagmite GLD1-stm2 and ca. 3800 yr BP in stalagmite
7 GLD1-stm4 are likely attributed to artificial simulations by the StalAge program and
8 thus are not fully discussed in terms of climate in the text.



1
 2 Figure 5. Comparison of high-resolution Mid-Holocene stalagmite $\delta^{18}\text{O}$ records across
 3 the Mediterranean basin. From the top to bottom are stalagmite records from the
 4 Gueldaman GLD1 Cave in N-Algeria of W-Mediterranean basin (this study), the
 5 Corchia Cave (Zanchetta et al., 2014) and the Renella Cave (Drysdale et al., 2006) in
 6 Central Italy of Central Mediterranean basin, and the Soreq Cave (Bar-Matthews and
 7 Ayalon, 2011; Kaufman et al., 1998) in Israel of E-Mediterranean basin. Different
 8 stalagmites from each area are represented in distinct colors. U/Th dates with 2σ
 9 errors are shown at the top of each curve. Ages are reported in years before 2000 AD.



1
 2 Figure 6. Radiocarbon dating of anthropogenic deposits layers in excavation sector S2
 3 inside the Gueldaman GLD1 Cave. From the left to right are ^{14}C dates of charcoal
 4 samples, anthropogenic deposit distribution, and a photo at depth across ~75-88 cm
 5 showing a transition of layer from rich to rare anthropogenic deposits. The gray
 6 colours highlight two phases with diminished anthropogenic remains (especially
 7 pottery and charcoal) at ca. 4403-1484 cal yr BP (depths of ~75-60 cm) and ca.
 8 6003-4918 cal yr BP (depths of ~120-105 cm).



1
 2 Figure 7. Comparison between evidence of ancient human occupation and of past
 3 climate change from the Gueldaman GLD1 Cave. The definition of occupation phases
 4 0-4 and climate periods 1-4 are referred to the text. The periods/phases 1-3 are
 5 highlighted by different colours.