Anonymous Referee #1

RW1: This paper presents new data from 4.2ka from a part of the world where data from this time are lacking. The data collection (e.g. purification of diatom samples) and the treatment of uncertainty in the age model is thorough and allows us to have more confidence in the results. The introduction presents a good hypothesis based on the previously produced proxies to test in this paper with the d18Odiatom data. However, my main concern is regarding the interpretation of the (slight) increase in d18Odiatom around 4.2ka as primarily a water balance signal (i.e. indicating a shift to drier conditions).

But, and the authors acknowledge this at points, a change in precipitation source could also account for some of the isotope shift. In fact, potentially it could account for all of the isotope shift. Also, a decrease in snow (with its very low d18O) around 4.2ka with everything else staying the same could account for the d18Odiatom rise. While your argument about temperature not being the main driver if valid, more thought and caution needs to go in to your interpretation.

There are only a couple of modern day lake water isotope values, but even the summer one is fairly low, so how evaporatively-driven is the isotope system? While I agree that something definitely happened in the lake 4.2ka as the d18Odiatom changes are outside of uncertainty and other proxies show changes too, with so few d18Odiatom data points and the relatively small magnitude of the change means it is difficult to unequivocally say that a change to drier conditions, rather than a change in precipitation source, or decrease in snow, or a combination of these factors, was responsible for the d18Odiatom change.

Therefore, I think the argument of the driver(s) of d18Odiatom needs to be more cautious and more thought through.

Nevertheless, this is a valuable new dataset that is robustly analysed and adds to our knowledge of what was going on in the Mediterranean region around 4.2ka, so I support its publication if my points are addressed.

AC: We thank reviewer#1 for these very constructive and meaningful comments concerning the interpretation of the $\delta^{18}O$ record. The factors that may have controlled the $\delta^{18}O_{\text{lake water}}$ and $\delta^{18}O_{\text{diatom}}$ signatures at 4.2 ka cal. BP are reviewed more thoroughly by reorganizing the discussion section as follows:

1) **A statement on the parameters that may control the present day $\delta^{18}O_{\text{lake water}}$ is made:**

Water inflows to Lake Petit consist of direct precipitation (rain and snow) and intermittent streams that form during the spring snowmelt. There is no groundwater input into the lake and no glacier is present in the watershed, the last period of active glacier advances in the Maritimes Alps being recorded during the Little Ice Age (Ribolini et al., 2007).

The outlet of Lake Petit is an intermittent surface outlet and is non-active when the lake level drops by 1 meter. Therefore, the hydrological regime alternates between two states: an open system when the outlet is active during snow melt and a closed system during summer months when most water losses are due to evaporation. The 2011 one off $\delta^{18}O_{\text{lake water}}$ measurements indicate that from the beginning of the unfreezed season to the end, the lake water gets heavier by 1.1 ‰. This ^{18}O-enrichment may come from the inputs of heavy summer precipitation fed by the Mediterranean Sea (weighted annual mean of -4 ‰ in the Alps compared to -8‰ for precipitation originated from Atlantic) and from evaporation of the lake water. The decrease in water depth during the same time supports a strong evaporation. However, in a δD *vs* $\delta^{18}O$ diagram, the lake water samples plot on the regional meteoric water line, which suggests that evaporation has a limited effect on the isotope composition of the lake water. The 1.1‰ shift may also be explained by the drastic decrease of meltwater input at the end of spring. The oxygen isotope composition of meltwater is controlled by $\delta^{18}O$ precipitation, which is lower during winter as the water vapour originates above the Atlantic Ocean (weighted annual mean of -8 ‰ in the Alps), and post-depositional fractionating processes (including evaporation, sublimation, ablation, meltwater percolation and drifting) leading to ^{18}O enrichment of the snow. However, because the Lake Petit watershed is small (area of 6 km^2) and located under the mountain crest, these post-depositional processes are expected to be of minor importance on the $\delta^{18}O$ of meltwater (Stichler and Schotterer, 2000).

Finally, although only two $\delta^{18}O_{\text{lake water}}$ measurements are available, they suggest that in the context of current climate conditions, seasonal changes in precipitation sources (i.e. winter Atlantic source vs summer Mediterranean source) leading to significant changes in $\delta^{18}O$ precipitation may control the seasonal shift in $\delta^{18}O_{\text{lake water}}$.

2) The $\delta^{18}O_{\text{diatom}}$ record around 4.2 ka cal. BP is interpreted in light of i) the modern behavior of the lake, ii) the other climate proxy data from the same core (Cartier et al., 2015) and iii) previous climate reconstructions from the Mediterranean area.

The 4400 to 3900 cal. BP period is characterized by the highest $\delta^{18}O_{\text{diatom}}$ values recorded over the last 4800 years in Lake Petit sediments. These values are about 3 ‰ higher than the modern one (27.8 ‰ in 1986 AD) but correspond to a 1.6 ‰ increasing shift from 4800 to 4400 cal. BP and a 1.5 ‰ decreasing shift from 3900 cal. BP. $\delta^{18}O_{\text{diatom}}$ depends on the $\delta^{18}O_{\text{lake}}$ and the temperature at which silica polymerizes. The $\delta^{18}O_{\text{lake}}$ value is itself influenced by the $\delta^{18}O_{\text{precipitation}}$ (rainfall or snow). $\delta^{18}O_{\text{precipitation}}$ is controlled by the isotope composition of the vapour source and Rayleigh fractionation during the vapour transport (i.e. the continental and altitude effect) and air temperature at the locality where precipitation forms. Changes in these parameters may combine to account for the high $\delta^{18}O_{\text{diatom}}$ values observed from 4400 to 3900 cal. BP at lake Petit. They are reviewed below, in light of the other climate proxy data from the same core (Cartier et al., 2015) and previous climate reconstructions from the Mediterranean area.

Shift in lake water temperature

Polymerization of the siliceous frustule from the lake water occurs at equilibrium and the resulting isotope fractionation is thus thermo-dependent. Diatom blooms in alpine lakes occur mainly after the snowmelt in spring season and during autumn. However, sediment traps placed in a lake in Switzerland located at 2339 m a.s.l have evidence that some diatom species (e.g. *Achnanthes*, *Fragilaria* spp.) can continue to grow under the ice when the lake is frozen (Rautio et al., 2000; Lotter and Bigler, 2000). In the following discussion, we assume that the isotopic signal from Lake Petit sediments is an annual signal even if most of the diatom production most likely occur during the ice-free season.

The equilibrium fractionation coefficient previously measured for different silica-water couples range from -0.2 to -0.4 ‰/°C (synthesis in Alexandre et al., 2012; Sharp et al., 2016). According to this range, a 1.6 ‰ shift in $\delta^{18}O_{diatom}$ only controlled by a lake water temperature change would require a mean annual water temperature shift of 4 to 8°C. Reconstruction of temperature based on chironomids and pollen assemblages from the Swiss Alps and Europe suggest that air temperature variations (likely larger than water temperature variations) did not exceed 2 °C during the Holocene (Davis et al., 2003; Heiri et al., 2003).Thus, although a decrease in mean annual temperature may have contributed to the 4400/3900 cal. BP increase in $\delta^{18}O_{diatom}$, it cannot be the only factor explaining this change. According to studies on speleothems in central Italy (Isola et al., 2018), a cooling during the 4.2 ka BP event in response to a positive North Atlantic Oscillation (NAO) is plausible in central Mediterranean. The recent synthesis of Bini et al. 2018 also suggest the presence of a cooling anomaly but temperature data are sparse and not uniform. In the Alps, moraine dated around 4200 cal. BP showed moderate glacier advances in northern and central western Alps but not in the Maritime Alps (Le Roy, 2012; Ivy-Ochs et al., 2009).

Shift in $\delta^{18}O_{lake\ water}$

An increase in the contribution of ^{18}O-enriched Mediterranean precipitation during the ice-free season, or a ^{18}O-depleted winter snow deficit may explain an increase in $\delta^{18}O_{lake\ water}$ at Lake Petit at 4400 cal. BP. High terrigenous inputs from 4400 cal. BP support the increase of ^{18}O-enriched precipitation during the ice-free season. Sedimentological data from the same core (Brisset et al., 2013), allowed to reconstruct before 4400 cal. BP a period of low detrital supply and high chemical weathering from acid soils developed on the slopes. The terrigenous inputs were interpreted as resulting from the dismantling of these weathered soils. The high representation of very low-dispersal alpine meadow pollen (e.g. *Botrychium*) in the sediment additionally argued for an intensification of runoff on the catchment slopes. Similar detrital events were recorded between 4500 and 3000 cal. BP in the Alps, for example at Lake Bourget (Arnaud et al., 2005; 2012). Moreover, a cluster of dated landslide events in the Southern Alps around 4200 cal. BP was interpreted as increasing intense fall precipitation (Zerathe et al., 2014).

A winter ^{18}O-depleted winter snow deficit can also be suggested. But a oxygen isotope record from speleothems record in Italian Apenin, at Corchia Cave, suggest reduced advection of air masses from the Atlantic during winter from ca. 4.5 to 4.1 ka cal. BP.

An evaporation, higher than the modern one, may also account for a ^{18}O enrichment of the surficial water at Lake Petit. However, on an annual basis, the effect of the previous summer's evaporation might be partially or (greatly) offset by the runoff from snowmelt (Ito et al., 2018), as evidenced today.

At least, an increase of air temperature may have led to the increase of the $\delta^{18}O$ of precipitation feeding the lake water. However, as previously discussed, this is not in agreement with other reconstructions from the Mediterranean area that rather argue for a cooling anomaly, although data are scarce (Bini et al. 2018).

Finally, the shift in $\delta^{18}O_{diatom}$ between 4400 and 3900 cal. BP rather suggests an increase in the contribution of ^{18}O enriched Mediterranean precipitation to Lake Petit during the ice-free season. This is in line with increased erosion in the watershed and increased terrigenous inputs to the lake. This does not exclude winter snow deficit and/or summer evaporation and/or on an annual basis, general drier conditions as suggested by Isola et al. (2018). A decrease in annual temperature of the lake water may also have played concomitantly. However, the record from Lake Petit does not allow to further discuss the relative weight of these parameters.

References

Bini, M., Zanchetta, G., Persoiu, A., Cartier, R., Català, A., Cacho, I., Dean, J. R., Di Rita, F., Drysdale, R. N., Finnè, M., Isola, I., Jalali, B., Lirer, F., Magri, D., Masi, A., Marks, L., Mercuri, A. M., Peyron, O., Sadori, L., Sicre, M.-A., Welc, F., Zielhofer, C., and Brisset, E.: The 4.2 ka BP Event in the Mediterranean Region: an overview, Clim. Past Discuss., in review, 2018.

Isola, I., Zanchetta, G., Drysdale, R. N., Regattieri, E., Bini, M., Bajo, P., Hellstrom, J. C., Baneschi, I., Lionello, P., Woodhead, J., and Greig, A.: The 4.2 ka BP event in the Central Mediterranean: New data from Corchia speleothems (Apuan Alps, central Italy), Clim. Past Discuss., in review, 2018.

Ito, E., Yu, Z., Engstrom, D. R., & Fritz, S. C. (1998). Is paleoclimatic interpretation of oxygen isotope records from glaciated Great Plains possible. Abstracts, AMQUA, 15, 119.

Lotter, A. F., & Bigler, C. (2000). Do diatoms in the Swiss Alps reflect the length of ice-cover? Aquatic sciences, 62(2), 125-141.

Rautio, M., Sorvari, S., & Korhola, A. (2000). Diatom and crustacean zooplankton communities, their seasonal variability and representation in the sediments of subarctic Lake Saanajärvi. Journal of Limnology, 59(1s), 81-96.

Ribolini, A., Chelli, A., Guglielmin, M., & Pappalardo, M. (2007). Relationships between glacier and rock glacier in the Maritime Alps, Schiantala Valley, Italy. Quaternary Research, 68(3), 353-363.

Stichler, W., & Schotterer, U. (2000). From accumulation to discharge: modification of stable isotopes during glacial and post‐glacial processes. Hydrological Processes, 14(8), 1423-1438.

Anonymous Referee #2

RW2: Cartier et al. present a novel diatom ∂18O dataset spanning the past ~5000 yrs from Lake Petit in the SW French Alps. The focus of the study lies in the local to regional characterization of hydroclimate perturbations around the 4.2ka climatic event and is thus relevant within the scope of CP. The oxygen isotope data (4 data points for the time slice) show a clear excursion towards higher values, which the authors primarily interpret to be the result of drier conditions with increased evaporation in the Lake Petit watershed. By using already published data from a previous 'multiproxy' study of the Petit sediment record the authors further suggest that the period was characterized by precipitation induced flood events. While the interpretation of the oxygen isotope data appears mostly sound (detailed comments below) it is sometimes hard to follow the argumentation regarding the sedimentary indicators that suggest a higher frequency of flood events/catchment erosion during this period. Since this is quite a central statement for the hydrological reconstructions I would suggest the authors provide a complete lithostratigraphic account of the record (eg. Are there any discernible or identifiable flood layers?). In a broader sense the manuscript contributes an additional hydroclimatic dataset that will help to paint a regional picture of climate repercussions during the 4.2ka event in the Mediterranean borderlands. The manuscript is in most parts appropriately structured, in some parts appropriately illustrated, but suffers from a large number of spelling mistakes and grammatical flaws.

AC: We thanks the reviewer for its valuable comments to improve the quality of the manuscript. In general, the reviewer highlights the overall quality of the manuscript, the relevance of the dataset presented, and pertinence of the interpretations as a significant new contribution to draw a more precise picture of the 4.2 ka BP event. Also, the reviewer points out several needs for clarifying the manuscript:

- To better describe the previous published dataset on core PET09P2, in order to assist, and restrict, the interpretations of the $d^{18}O$ data;
- To improve the overall writing quality of the manuscript.

We fully agree the reviewer's comments (all details given below), and will modify the manuscript in accordance.

We particularly realized that the term "flood" is somewhat confusing in the manuscript, compared to the recent similar literature in paleolimnology. The term "flood" was mentioned twice in the manuscript (chapter 5.2, lines 6 and 17): first to designate a hydrological process (water overflow of a river channel); second to describe a sedimentological facies (minerogenic normal-graded layer). No "flood layers" are deposited in PET09P2 at the difference of some other lake sediment records of this region, noticeably in Lake Allos that has been the most recently investigated for that purpose (Brisset et al., 2017; Wilhelm et al., 2012). At Lake Allos, the flood layer facies correspond to 60% of the material deposited over the last 7000 yrs. Comparing those two records, Lake Petit and Lake Allos is not straightforward, and probably, has led to the confusions noted by the reviewer.

Those clarifications will be done in the manuscript by including a detailed description of the lithostratigraphy of the Lake Petit and sedimentation processes, referring more precisely to the complementary dataset published by Brisset et al. (2013).

RW2: Site settings - the seasonal distribution is quite important in this setting. If possible provide precipitation data for summer and winter months. Also, what controls winter snow depth in this setting? From the data presented it seems as if snow depth (by the end of the season?) varies largely from year to year.

AC: Based on the meteorological station of Malaussène (500 m a.s.l; the closest station to Lake Petit) that covers the period 1997-1998, the precipitation regime in this area is characterized by a marked intra-annual variability, because of the influence of the Mediterranean climate regime. Precipitation essentially occur in spring and autumn (an average of 80 % of the total precipitation volume of the year, corresponding to 758 mm). Snow cover duration is about 185 days at the altitude of Lake Petit from November to April (Durand et al., 2009).
The origin of precipitation vary along the year: while rainfall has a Mediterranean origin (54% of the rainfall events, Celle-Jeanton, 2001), winter snowfalls are essentially associated with northwest atmospheric flows (Durand et al., 2009).

An ombrothermic diagram will be added in the Fig. 1 to make it clear for readers.

RW2: p.4, l. 1-4. Temperature dependent fractionation of rainfall is suggested as the main driver of seasonal oxygen isotopic composition. However, ∂18O of precipitation at Malaussene is lower (by almost 1per mill) during summer and higher during winter-please explain.

AC: Thanks to have point out this mistake. According to the GNIP database, the mean $\delta^{18}O_p$ at the meteorological station of Malaussène is of -4.9 ‰ in summer and of -5.8 ‰ in winter.

RW2: Material and methods - please provide a more complete description of the lithology of the record. Are there any discernible flood layers present? If so, does the frequency and/or the flood layer thickness increase during the respective time interval?
- have event layers (e.g. flood layers) been removed prior to the construction of the age model? - a new age-modelling algorithm has been applied to the Lake Petit core please provide an age-model figure.

AC: The sediments of the core PET09P2 consist in changes in the relative abundance of a biogenic silica lacustrine production (diatoms), an organic production (essentially algal, e.g. Hydrogen-index comprised between 450 and 575 HC/TOC), and a terrigenous minerogenic clay fraction (Brisset et al., 2012; 2013). The sediments deposited during the period at 4.2 ka are characterized by a higher proportion (80%) and a higher flux of the terrigenous fraction (Brisset

et al., 2013), while the diatom-organic component drop to lower but still significant concentrations (20%).
This unit does not correspond to one or to a cluster of "flood layers", as defined by sedimentological criteria (e.g. Mulder and Chapron, 2011; Gilli et al., 2013): grain-supported sediments, having a distinct – possibly erosional - contact with the previously deposited sediments, and characterized by a normal-graded grain-size sequence. No "flood layers" are deposited in PET09P2 at the difference of some other lake sediment records of this region, noticeably in Lake Allos that is the most recently investigated one on that topic (Brisset et al., 2017; Wilhelm et al., 2012); at Lake Allos, flood layer sedimentological facies, corresponds to 60% of the material deposited over the last 7000 yrs. Characteristics of the lake catchment likely explain the total absence of flood layers. Catchment slopes of Lake Petit are smoothly eroded (morphologies inherited of glacier abrasion processes shaping the glacial step in resistant crystalline rocks), and the gradient of the main river stream is relatively low (10°). These topographic characteristics do not favor surface water concentration to generate a sufficient-water discharge to carry coarse particle.
To clarify those points, the detailed lithological information will be added in the manuscript and the Fig. 4 will be complemented of the lithostratigraphic log.

The age-depth model presented in this study is indeed a new algorithm not published yet, and part of the present paper. The value of the algorithm "bacon" developed by Blaauw and Christen (2011) is to calculate the age probability density function of the data proxy. In the present paper, applying this approach is necessary to demonstrate that the 4.2 event is well constrained in the PET09P2 core (that is a minimum), and interestingly plus: the event cannot be instantaneous in time, and its time range is at a confidence interval of 95% of probability of > 25 years and < 660 years. Given these valuable results, we decided to recalculate the model (done using the "clam" R package in Brisset et al., 2013) by a model calculated using the 'bacon' R package (Blaauw and Christen, 2011).
We agree that adding the all details of this new model in the manuscript will contribute to a better understanding of the overall dataset and include those information in the revised manuscript.

RW2: Discussion - p. 6 l. 3-6: Why start with human impacts if you can rule those out for the respective time interval? Emphasizing the different factors influencing the hydrological setting is more important in the context of the study- I suggest to start the discussion with those.

AC: Following the comment of the reviewer, the first sentences concerning human impacts have been removed. The discussion starts with a description of the rise in $\delta^{18}O_{diatom}$ during the 4.2 ka BP event and the main factors influencing oxygen isotopes (changes in water temperature and $\delta^{18}O_{lake\ water}$).

RW2: Somewhere in the discussion (and in the site description section) it would be worth noting that the water residence time is short.

AC: We will add in the site settings that according to the size of Lake Petit the water residence time is expected to be short even if we don't have a quantitative estimate.

RW2: P. 6, L. 27-28: 'Today, Mediterranean precipitation favours runoff and erosion in steep areas (Kosmas et al., 2002)'. Please specify more precisely what type of precipitation favours (intense) runoff and flooding. Also the seasonal distribution of this type of precipitation is important here.

AC: According to a synthesis of floods and flash flood events in Mediterranean countries different types of precipitation favour intense runoff: short and local summer flash flood event, autumn high-rainfall event and extended rainfall event affecting more than one country (Llasat et al., 2010). In this study 185 flood events (daily accumulated precipitation over 60 mm) on the period 1990-2006 were distributed as follows: 54.7 % of the annual total occurred in autumn (September, October and November) while the summer months have 17.2 % and winter 15.3 %. In addition, Descroix et al. (2010) has shown that soil erosion is higher after long periods of drought.
These more detailed information will be inserted in the manuscript.

RW2: P. 6, L. 28-31: 'Geochemical data showing high terrigenous inputs to Petit Lake between 4400 and 4000 cal. BP (Fig. 4), interpreted as an increase of runoff in the watershed (Brisset et al., 2013), are thus consistent with a greater seasonal variability of the Mediterranean climate characterised by intense precipitation occurring in fall and spring and significantly drier periods in the summer months (Durand et al., 2009)'.
The statement of changes in seasonality is not supported by the data. Wouldn't an increase in convective precipitation during summer with Mediterranean moisture sourcing also explain both an increase in @18O and catchment erosion induced by heavy precipitation events. Also, snow cover in early spring would probably inhibit catchment erosion, leaving only heavy precipitation events in summer and early fall to explain an increased erosion pulse.

AC: Higher terrigenous inputs to Lake Petit during the 4.2 ka BP event highlighted the presence of intense precipitation events during the ice-free season which last in average from April to October. Therefore, we support the hypothesis that the precipitation regime has changed during this period of the year to produce the changes in erosion processes. According to Durand et al. (2009), precipitation in southern Alps occur mainly in Spring and Autumn. At the scale of the Mediterranean region, 54.7 % of heavy precipitation occur in Autumn (Llasat et al., 2010). Convective precipitation events from Mediterranean moisture sourcing are of higher occurrence during these months when air masses from the Mediterranean, still warm and humid meet the cold air masses from the Atlantic.

We agree with the reviewer that this sentence is mixing several ideas and that changes in seasonality can't be assessed precisely during the ice-free season. For this purpose, we have improved the discussion on the isotopic interpretation by adding sub-sections for each factor of interest including changing in snow contribution, precipitation regime and sourcing (refer to the answer to the reviewer 1).

RW2: P.7, l. 6-8: 'In summary, the rapid increase in $\delta^{18}O$ diatom from 4400 to 3900 cal. BP is most likely the result of an increase in water evaporation possibly associated with a shift in precipitation origin and distribution over the year. This state lasted for ca. 500 years'. I am not sure I can follow the reasoning here entirely as it is also in part contradictory to the statements made earlier on in the discussion. For example, on page 6 you explain the increase in catchment erosion by an increase in spring and fall precipitation (that is similar compared to today), now here you propose 'a shift in distribution over the year'. Also stronger evaporation is suggested as the main cause for the observed $\delta^{18}O$ signal. However, the increase in erosion is probably best explained by more frequent and intense summer precipitation events and/or local expansion of glaciers/icefields (glacial cirque just above the lake). I think this is not all wrong but I would suggest the authors to 1) take a look at other records aiming at heavy precipitation reconstructions in nearby sites for the respective time interval, what do the authors of those studies suggest in terms of precipitation type and seasonal distribution? 2) some studies have suggested moderate glacier advances during this period. Wouldn't persistence of snow/ice throughout the summer also influence the hydrological budget of the lake? And at the same time deliver erodible substrates to the lake? The lake is located just below a glacial cirque which appears to have been active not too long ago. I suggest expanding on this somewhat as this is central to the interpretation of the dataset presented.

AC: According to the geochemical data, the signature of the alumino-silicate fraction indicates high cation fractionation characteristic of pedogenetic origin. At Lake Allos (close to Lake Petit), no evidence of increasing flood frequency has been recorded around 4.2 ka BP but it has been shown that erosion was inhibited prior to deforestation and dismantling of soils by human activities at ca. 1700 cal. BP (Brisset et al., 2017). A synthesis of flood frequency across the Central Alps has shown evidence of increasing flood frequency from 4.2 ka BP to 2.4 ka BP and during the Little Ice Age certainly linked to a southerly position of the N-Atlantic circulation (Wirth et al., 2013). In their study sites, they interpreted flood records to be mainly a record of spring and fall events. These general wetter conditions across the Alps might have been a factor of decreasing $\delta^{18}O_{diatom}$ after the 4.2 ka BP event and during the Little Ice Age (fig. 3). During the 4.2 ka event at Lake Petit, we argue that the intensity of precipitation increased during the ice-free season but not necessarily the occurrence of events. $\delta^{18}O_{diatom}$ values suggest a higher contribution of ^{18}O enriched precipitation of Mediterranean origin to the lake water balance (refer to the answer to reviewer 1).

We agree with the reviewer that some studies have recorded moderate glacier advances in central western Alps and in the northern Alps but not, for now, in the Mediterranean Alps (Le Roy, 2012; Ivy-Ochs et al., 2009). According to the last review for the Mediterranean Alps (Brisset et al., 2015) the Holocene re-activation of glaciers has been dated 2720-2360 cal. BP (Ribolini et al., 2007). Rock glacier activities are also recorded later during the Little Ice Age which can explain why the glacier cirque appears to have been active not too long ago

(Federici and Stefanini, 2001). By looking at the isotopic record, the lowest value of $\delta^{18}O_{diatom}$ is during the Little Ice Age possibly due to wetter conditions during this period associated with higher snow contribution from the Atlantic. A persistence of snow during summer which has a low $\delta^{18}O$ signature would most likely lowered $\delta^{18}O_{diatom}$ contrary to what is observed during the 4.2 ka BP event. We will add more reference in the manuscript to reconstructions of glacier advances and heavy precipitation in the Southern Alps.

RW2: P. 7, l. 27-28: Based on the interpretation suggestions above chemical weathering of soils is unlikely to intensify during the proposed climate conditions. Rather soils that formed during wetter and warmer climate phases prior to the 4.2ka event were subject to erosion, resulting in the input of more weathered soil material into Lake Petit. Please revise.

AC: In the paper of Brisset et al., 2013 sedimentological data have been interpreted as follows: from 4700 to 4200 cal. BP a period of low detrital supply, high fractionation of cations suggesting the presence of developed acid soils in the watershed and high chemical weathering; during the 4.2 ka BP event: a maximum of clay detrital supply and high fractionation of alumino-silicates highlighting a dismantling of the former developed weathered soils.
We will revise this sentence to say that the high fraction of alumino-silicates during the 4.2 ka BP event is more likely the result of dismantling weathered soils formed during the previous period. A decrease of chemical weathering during the 4.2 ka BP event is possible due to drier conditions.

RW2: P. 8, l. 12-29: This paragraph is simply a listing of quotes from references. Please integrate these with your data in a discussion style.

AC: We will improve this part of the manuscript to follow the suggestion of the reviewer.

RW2: p. 9, l. 10-11: 'The new 18Odiatom record for Petit Lake was used to reconstruct past hydrological changes and decipher climatic implications from local human impacts around 4200 cal. BP.'
The study focuses on reconstructing hydrological changes, it does not touch upon human impacts. Please revise.

AC: This publication is following several papers on Lake Petit (Brisset et al., 2012; Brisset et al., 2013; Cartier et al.,2015) we wanted to highlight the fact that the use of oxygen isotopes from diatoms allowed us to confirm the effect of climate on the environmental change observed at Lake Petit at that time.

RW2: p.9, l. 23-25: 'This isotopic record at Petit Lake has revealed the implication of the 4.2 kyrs event in abrupt ecosystem changes in the Southern Alps and is useful to better understand the intensity and geographical extent of this climatic event in the Mediterranean region.'
Again, this study, as is, focuses almost exclusively on hydrological changes. If the authors would like to include impacts of hydrological change on ecosystem changes

than this part has to be developed throughout the manuscript and not only in the conclusions.

AC: We will change this sentence by “This isotopic record confirms the implication of the 4.2 ka BP event in the environmental responses observed at Lake Petit in previous studies (Brisset et al., 2013; Cartier et al., 2015)“. The summary of environmental changes during the 4.2 ka event is present in part 5.2. The detailed results of environmental responses are presented in previous papers.

References

Brisset, E., Guiter, F., Miramont, C., Delhon, C., Arnaud, F., Disnar, J.-R., Poulenard, J., Anthony, E., Meunier, J.-D., Wilhelm, B., Pailles, C., 2012. Approche multidisciplinaire d’une séquence lacustre holocène dans les alpes du sud au Lac Petit (Mercantour, alt. 2 200 m, France) : histoire d’un géosystème dégradé. Quaternaire. Revue de l’Association française pour l’étude du Quaternaire 23, 309–319.

Brisset, E., Miramont, C., Guiter, F., Anthony, E.J., Tachikawa, K., Poulenard, J., Arnaud, F., Delhon, C., Meunier, J.-D., Bard, E., Suméra, F., 2013. Non-reversible geosystem destabilisation at 4200 cal. BP: Sedimentological, geochemical and botanical markers of soil erosion recorded in a Mediterranean alpine lake. The Holocene 23, 1863–1874.

Brisset, E., Guiter, F., Miramont, C., Troussier, T., Sabatier, P., Poher, Y., Cartier, R., Arnaud, F., Malet, E., Anthony, E.J., 2017. The overlooked human influence in historic and prehistoric floods in the European Alps. Geology 45, 347–350.

Descroix, L. (2003). Les conséquences hydrologiques de l'évolution des usages des sols, 78 pp. Université Joseph Fourier, Grenoble Mémoire d'Habilitation à Diriger des Recherches (HDR).

Federici, P. R., & Stefanini, M. C. (2001). ABHANDLUNGEN-Evidence and chronology of the Little Ice Age in the Argentera Massif (italian maritime alps). With 7 figures. *Zeitschrift fur Gletscherkunde und Glazialgeologie*, *37*(1), 35-48.

Gilli, A., Anselmetti, F.S., Glur, L., Wirth, S.B., 2013. Lake Sediments as Archives of Recurrence Rates and Intensities of Past Flood Events, in: Schneuwly-Bollschweiler.

Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P. W., & Schlüchter, C. (2009). Latest Pleistocene and Holocene glacier variations in the European Alps. *Quaternary Science Reviews*, *28*(21-22), 2137-2149.

Le Roy, Melaine. *Reconstitution des fluctuations glaciaires holocènes dans les Alpes occidentales: apports de la dendrochronologie et de la datation par isotopes cosmogéniques produits in situ*. Diss. Grenoble, 2012.

M., Stoffel, M., Rudolf-Miklau, F. (Eds.), Dating Torrential Processes on Fans and Cones, Advances in Global Change Research. Springer Netherlands, pp. 225–242.

Llasat, M. C., Llasat-Botija, M., Prat, M. A., Porcu, F., Price, C., Mugnai, A., ... & Yair, Y. (2010). High-impact floods and flash floods in Mediterranean countries: the FLASH preliminary database. *Advances in Geosciences*, *23*, 47-55.

Mulder, T., Chapron, E., 2011. Flood deposits in continental and marine environments: Character and significance, Sediment Transfer from Shelf to Deep Water: Revisiting the Delivery System, AAPG Studies in Geology. Slatt M. et Zavala C.

Ribolini, A., Chelli, A., Guglielmin, M., & Pappalardo, M. (2007). Relationships between glacier and rock glacier in the Maritime Alps, Schiantala Valley, Italy. *Quaternary Research*, *68*(3), 353-363.

Wilhelm, B., Arnaud, F., Sabatier, P., Crouzet, C., Brisset, E., Chaumillon, E., Disnar, J.-R., Guiter, F., Malet, E., Reyss, J.-L., Tachikawa, K., Bard, E., Delannoy, J.-J., 2012. 1400 years of extreme precipitation patterns over the Mediterranean French Alps and possible forcing mechanisms. Quaternary Research 78, 1–12.

Wirth, S. B., Glur, L., Gilli, A., & Anselmetti, F. S. (2013). Holocene flood frequency across the Central Alps–solar forcing and evidence for variations in North Atlantic atmospheric circulation. *Quaternary Science Reviews*, *80*, 112-128.

Diatom-oxygen isotope record from high-altitude Lake Petit (2200 m a.s.l) in the Mediterranean Alps: shedding light on a climatic pulse at 4.2 ka BP

Rosine Cartier[1,2], Florence Sylvestre[1], Christine Paillès[1], Corinne Sonzogni[1], Martine Couapel[1], Anne Alexandre[1], Jean-Charles Mazur[1], Elodie Brisset[3,4], Cécile Miramont[2], Frédéric Guiter[2]

[1] Aix-Marseille University, CNRS, IRD, Collège de France, INRA. CEREGE, Europôle de l'Arbois, 13545 Aix-en-Provence, France

[2] Aix-Marseille University, CNRS, IRD, Avignon University, IMBE, Europôle de l'Arbois, 13545 Aix-en-Provence, France

[3] IPHES, Institut Català de Paleoecologia Humana i Evolució Social, Tarragona, Spain

[4] Àrea de Prehistòria, Universitat Rovira i Virgili, Tarragona, Spain

Correspondence to: Rosine Cartier (rosine.cartier@geol.lu.se)

Abstract. In the Mediterranean area, the 4.2 ka BP event is recorded with contrasted expressions between regions. In the Southern Alps, the high-altitude Lake Petit (Mercantour Massif, France, 2200 m a.s.l) offers pollen and diatom-rich sediments covering the last 4800 years. A multiproxy analysis recently revealed a detrital pulse around 4200 cal. BP due to increasing erosion in the lake catchment. Involvement of a rapid climate change leading to increasing runoff and soil erosion was proposed. Here, in order to clarify this hypothesis, we measured the oxygen isotope composition of diatom silica frustules ($\delta^{18}O_{diatom}$) from the same sedimentary core. Diatoms were analyzed by laser-fluorination-isotope ratio mass spectrometry after an inert gas flow dehydration. We additionally enhanced the accuracy of the age-depth model using the Bacon R package. The $\delta^{18}O_{diatom}$ record allows to identify a 500-year time lapse, from 4400 to 3900 cal. PB, where $\delta^{18}O_{diatom}$ reached its highest values (> 31 ‰). $\delta^{18}O_{diatom}$ were about 3 ‰ higher than the modern ones and the shifts at 4400 and 3900 cal BP were of similar amplitude as the seasonal $\delta^{18}O_{diatom}$ shifts occurring today. This period of high $\delta^{18}O_{diatom}$ values can be explained by the intensification of ^{18}O enriched Mediterranean precipitation events feeding the lake during the ice-free season. This agrees with other records from the Southern Alps suggesting runoff intensification around 4200 cal. BP. Possible changes in other climatic parameters may have played concomitantly, including a decrease in the contribution of ^{18}O depleted Atlantic winter precipitation to the lake water due to snow deficit. Data recording the 4.2 ka BP event in the North-Western Mediterranean area are still sparse. In the Lake Petit watershed, the 4.2 ka BP event translated into a change in precipitation regime from 4400 to 3900 cal. PB. This record participates to the recent efforts to characterize and investigate the geographical extent of the 4.2 ka BP event in the Mediterranean area.

1 Introduction

Since the last glaciation, several abrupt climatic changes, with large environmental effects, were identified from palaeoclimatic records (Berger and Guilaine, 2009; Magny et al., 2009), such as the Younger Dryas (13.500-11.500 cal. BP) at the end of the Late Glacial, and the 8.2 ka BP event at the beginning of the Holocene (Alley et al., 1997; Brauer et al., 1999; Tinner and Lotter, 2001), for the coldest ones. Other Holocene climatic events were described as less intense or regionally limited but may have triggered substantial impacts on the environment at the local scale. One of them, the "4.2 ka BP event", was recognised as an abrupt climate change (Bond et al., 2001; Booth et al., 2005; Huang et al. 2011; Thompson et al., 2002; Staubwasser et al. 2003) and is now commonly used as a marker of Holocene stratigraphy (Walker et al., 2012). In the Mediterranean area, the 4.2 ka BP event is recorded with contrasted expressions between regions (Bruneton et al., 2002; Digerfeldt et al., 1997; Drysdale et al., 2006; Kharbouch, 2000; Magny et al., 2009; Miramont et al., 2008; Zanchetta et al., 2011). In the Eastern Mediterranean area, this climatic event is assumed to have been responsible for severe droughts and involved in the fall of the Akkadian civilisation (Weiss, 1993; Cullen et al., 2000; Dean et al., 2015). In the Central Mediterranean area, speleothem isotope records suggest a reduction in cave recharges from ca. 4500 cal. BP to 4100 cal. BP at Corchia Cave (Isola et al., 2019) and ca. 4500 cal. BP to 4100 cal. BP at Renella Cave (Zanchetta et al., 2016), linked to annual and/or winter dry conditions. In the Alps (northern Italy), an opposite trend has been described, annual cool and wet conditions being assigned to the period around 4.2 ka BP (Magny et al., 2012; Zanchetta et al., 2016). Sedimentary records of past lake levels also mirror different climatic expression between regions. At Lake Ledro and Lake Accesa, in Italy, the transition from mid to late Holocene surrounding 4.2 ka BP shows a shift from low to high lake levels. Pollen-based precipitation reconstructions, although showing high variability from 5000 to 3000 cal. BP, suggest no significant change in the amount of annual precipitation but increasing summer precipitation (Peyron et al., 2013). The high-resolution record from Lake Accesa (Italy) allowed to interpret the 4.2 ka BP climatic event as a tripartite climatic oscillation with a phase of drier conditions from 4100 to 3950 cal. BP bracketed by two phases of wetter conditions (Magny et al., 2009). Overall, palaeoclimatic records from the Mediterranean area highlight climatic features spatially heterogeneous around 4200 cal. BP which makes it difficult to assign a general pattern. Further studies from different geomorphological contexts are required for a better characterization of the 4.2 ka BP climatic event in the area.

In the Southern Alps, the high-altitude Lake Petit (Mercantour Massif, France, 2200 m a.s.l) offers pollen and diatom-rich sediments covering the last 5000 years. A multiproxy analysis, including sedimentological and geochemical measurements, pollen and diatom morphological analyses, revealed a detrital pulse around 4200 cal. BP due to increasing erosion in the lake catchment (Brisset et al., 2012; 2013), followed by an abrupt change in diatom assemblages. The replacement of the dominant diatom *Staurosirella pinnata* by *Pseudostaurosira* spp. responded to a change in lacustrine living conditions (e.g. nutrient availability, turbidity) following the detrital input (Cartier et al., 2015). The hypothesis of a massive deforestation in the catchment to explain the detrital pulse was rejected as the vegetation surrounding the lake stayed open over the last 5000 years. Therefore, involvement of a rapid change either in precipitation regime or temperature, leading to increasing soil erosion and runoff around 4200 cal. BP was proposed (Brisset et al., 2012, 2013; Cartier et al., 2015).

Here, in order to clarify this hypothesis, we measured the oxygen isotope composition of diatom silica frustules ($\delta^{18}O_{diatom}$) from the Lake Petit-last 5000 years sedimentary core previously used for the multiproxy analyses (Brisset et al., 2013). $\delta^{18}O_{diatom}$ records are commonly used for paleoclimatic reconstructions (e.g. Barker et al., 2001; Leng et al., 2006; Quesada et al., 2015). The $\delta^{18}O_{diatom}$ value is controlled by the lake water isotope composition ($\delta^{18}O_{lake}$) and the temperature of silica polymerization. The $\delta^{18}O_{lake}$ value is itself influenced by the $\delta^{18}O$ signatures of precipitation ($\delta^{18}O_{precipitation}$) and other waters reaching and leaving the lake (groundwater, surface water), and the extent of the lake water evaporation. Lastly, the $\delta^{18}O_{precipitation}$ is controlled by the isotope composition of its water vapour source and Rayleigh fractionation processes occurring during the vapour transport and rain drop formation. Changes in Lake Petit $\delta^{18}O_{diatom}$ values are discussed according to these parameters, and assumptions characterizing the abrupt climatic change that may have occurred around 4200 cal. BP in the lake catchment area, and more broadly in the Southern Alps, are presented.

2 Site settings

Lake Petit (2200 m a.s.l; N 44°06.789; E 7°11.342) is a small circular body of water,150 m in diameter, located in the Southern French Alps about 60 km from the Mediterranean Sea. The 6 km^2 lake catchment culminates at 2600 m a.s.l.. It is composed of crystalline bedrock (gneiss and migmatites) and is largely covered by alpine meadows. The upper tree line (*Larix* sp.) is located at about 2100 m a.s.l. Lake Petit is at the lowest elevation of a chain of five lakes that were partly formed by glacier retreat (fig. 1). The five lakes are connected in spring during meltwater but remain unconnected for the rest of the year. The lake surface is usually frozen from October to April. The water depth of Lake Petit reaches 7 m in the wake of the snowmelt and is about 1 meter lower at the end of summer. The lake is open during snowmelt but has no outlet during summer. Water inputs are thus represented by snowmelt in spring and precipitation during the ice-free season. Water outputs mainly consist in evaporation, infiltration being likely very low due to the geological characteristics of the catchment. Today, diatoms are mainly benthic but tychoplanktonic diatoms are also present. These diatoms develop mainly during the ice-free season, even if some species (e.g. *Achnanthes*, *Fragilaria spp.*) are expected to continue to grow under the ice during winter as observed in other alpine lakes (Lotter and Bigler, 2000).

In the Mercantour Massif, alpine and mediterranean influences produce a climate marked by mild winters and dry summers. Mean annual air temperature at 1800 m a.s.l. is 5 °C, varying from 0.3 °C in winter to 9.9 °C in summer. Mean annual precipitation is 1340 mm at 1800 m a.s.l. Snow depths in winter are relatively important (150 to 250 cm at 2400 m a.s.l.) and snow cover duration is about 185 days at 2100 m a.s.l. mainly from November to April (Durand et al., 2009a,b). Because it is located in the extreme south-western part of the Alps, Lake Petit is strongly influenced by precipitation originating from the Mediterranean region during the summer, while winter snowfalls are essentially associated with northwest Atlantic atmospheric flows (Bolle, 2003; Lionello et al., 2006, 2012). In Southern France, precipitation is mostly generated by the clash between the warm, humid air of Mediterranean or mixed Atlantic-Mediterranean origin and cool air masses coming from the North. Nowadays, 54 % of precipitation in southern France (average for 6 meteorological stations) strictly come from the Mediterranean area, 12 % from the Atlantic and 34 % have a mixed Mediterranean-Atlantic influence (Celle-Jeanton, 2001). In spring and autumn advection of air masses from the Mediterranean can produce strong storms. Altogether, the Mediterranean influence remains predominant today, with high Mediterranean $\delta^{18}O_{precipitation}$ values compared to Atlantic $\delta^{18}O_{precipitation}$ values: from April 1997 to March 1999, at Avignon (IAEA/WMO, N 43°57) precipitation of Mediterranean origin had a weighted annual mean $\delta^{18}O_{precipitation}$ of −4.33 ‰ (σ=1.72 ‰), whereas precipitation from the Atlantic had a $\delta^{18}O_{precipitation}$ of −8.48 ‰ (σ=3.51 ‰) (Celle-Jeanton et al., 2004). Added to changes in temperature, changes in precipitation sources explain the current seasonal weighted $\delta^{18}O_{precipitation}$ values in the Alps, lower from October to March than from April to September (fig. 1, period 1960-2001; IAEA/WMO, 2018; Terzer et al., 2013). Different precipitation sources also explain the $\delta^{18}O_{precipitation}$ values obtained for the same period, at the meteorological stations close to Lake Petit (fig. 2a, IAEA/WMO, 2018).

3 Material and methods

Sediment core PET09P2 (144 cm-long) was sampled in 2009 in the deepest part of the lake using a UWITEC gravity corer. Core PET09P2 is organic-rich (total organic carbon represents 9 % of the dry weight on average) and biogenic silica is abundant (averaging 65 % of the dry weight) (Brisset et al., 2013). The core is composed of homogeneous yellow to greenish diatomaceous sediments with millimetre-thick brownish diatom-clay laminations. The sediments consist in biogenic silica (diatoms), organic compounds (essentially algal as the hydrogen-index comprised between 450 and 575 HC/TOC), and a terrigenous clay fraction (Brisset et al., 2012, 2013). The different lithological units are presented in fig. 4. Diatoms (D) represent the major contribution of biogenic silica in the sedimentary record. Only a few cysts of Chrysophyceae (C) were identified (C/D ratio = 0.01). The age-depth model covering the last 4800 years is based on short-lived ^{210}Pb and ^{137}Cs radionuclides data and seven ^{14}C ages obtained from terrestrial macro-remains (Brisset et al., 2013 for further details). For this study, we recalculated the age-depth model using the Bacon R package (Blaauw and Christen, 2011) and implemented the function “proxy.ghost” (square resolution:200) in order to highlight the chronological uncertainties of the age/depth model, and to estimate the duration “of the 4.2 ka BP event” recorded at Lake Petit. Figure 3 shows a range of possible ages for each sample depth.

Twenty diatom samples (1 cm^3) were sub-sampled from core PET09P2. Each diatom sample includes on average 36 years (min: 11 years; max: 55 years) of sedimentation according to the age-depth model. Diatom samples were weighed after drying at 50 °C. To remove carbonates and organic matter, the samples were first treated using standard procedures (bathed in a 1:1 mixture of H_2O_2 33%: water, a 1:1 mixture of HCl 10%: water, and repeatedly rinsed in distilled water). Following these steps, the identification and counting of diatom species for palaeoenvironmental reconstruction were performed. The data were reported in Cartier et al. (2015). Then, diatom silica frustules were cleaned from remaining detrital particles by following a protocol based on chemical oxidation and densimetric separation previously detailed in Crespin et al. (2008). The purity of each sample was checked using optical and scanning electron microscopy (SEM). Micro-X-ray fluorescence (XRF) measurements (5 measurements per sample) were additionally made using a HORIBA XGT-5000177 microscope equipped with an X-ray guide tube capable of producing a focused, high-intensity beam having a 100 µm spot size (detection limit: 2 ppm). The following compounds were detected via XRF: SiO_2, Al_2O_3, K_2O, CaO, TiO_2, Fe_2O_3, and Br_2O. The samples are on average composed of 97.2 % (s.d.=1.8 %) of SiO_2.

Measurements of oxygen isotopes from diatoms were performed at the CEREGE Stable Isotope laboratory (Aix-en-Provence, France). The samples were dehydrated and dehydroxylated under a flow of N_2 (Chapligin et al., 2010). Oxygen extraction was performed using the IR Laser-Heating Fluorination Technique (Alexandre et al., 2006; Crespin et al., 2008). No ejection occurred during the analysis. The oxygen gas samples were sent directly to and analysed by a dual-inlet mass spectrometer (ThermoQuest Finnigan Delta Plus). Measured $\delta^{18}O$ values were corrected on a daily basis using a quartz lab standard ($\delta^{18}O_{\text{Boulangé 50-100 µm}}$) calibrated on NBS28 (9.6 ± 0.3 ‰; n=11). The values are expressed in the standard δ-notation relative to V-SMOW. The long-term precision of the quartz lab standard is ± 0.2 ‰ (1s; *n*=50). The $\delta^{18}O_{diatom}$ values presented here are averages of two replicates. The reproducibility was better than ± 0.2 ‰.

Two surficial lake water samples were collected in the first meter depth in spring (May 17th, 2011) after the snowmelt, and at the end of the summer (September 17th, 2011). They were analysed in $\delta^{18}O$ and δD by Isotope Ratio Mass Spectrometry (IRMS) and the data were normalized on the VSMOW/SLAP scale. The values are expressed in the standard δ-notation relative to V-SMOW. Temperature in the water column was measured in spring (May 17th, 2012) at two locations (N 44°1133, E 7°1894; N 44°1134, E 7°1889), every 25 cm depth, down to the bottom of the lake.

4 Results

The $\delta^{18}O$ and δD compositions of the sampled lake water were -11.35 ‰ and -80.36 ‰, respectively, after the snowmelt and -10.19 ‰ and -72.6 ‰, respectively, at the end of summer 2011. They plot on the regional meteoric water line (fig. 2a). The distribution of precipitation over the year at the closest meteorological station to Lake Petit is presented in fig. 2b (station Malaussène, period 1997-1998; IAEA/WMO, 2018). Water temperature measured at two points of Lake Petit in May 17th, 2012 varied from 5.4 to 4.9°C and from 6.8 to 5°C (from surface to bottom) (fig. 2c).

Because dissolution of the diatom frustules during sedimentation may occur and induce kinetic isotope fractionation (Dodd et al., 2017) the samples were checked under SEM. The diatoms themselves were very well preserved. No significant dissolution features were observed, as shown in fig. 3c.

$\delta^{18}O_{diatom}$ values measured on the 20 sedimentary diatom samples (table 1) are plotted against ages (cal. BP) and presented in fig. 3a. $\delta^{18}O_{diatom}$ values range from 26.6 to 32 ‰ with a mean standard deviation (s.d.) of 0.18 ‰. From the bottom of the core (4800 cal. BP) to 4400 cal. BP, the $\delta^{18}O_{diatom}$ average value is 30.3 ‰ ± 0.14 ‰ and the lowest value (28.97 ‰) occurs at 4750 cal. BP. Then, a period stands out of the record with the highest values of $\delta^{18}O_{diatom}$ for the last 4800 years. At 4400 cal. BP, $\delta^{18}O_{diatom}$ increases quickly and reaches its maximum value of 31 ‰. $\delta^{18}O_{diatom}$ remains high (in average 31.3 ‰ ± 0.21 ‰) between 4400 and 3900 cal. BP, and decreases, afterwards, to values below those observed at the base of the core. The period from 3900 to 700 cal. BP shows low amplitude variations in $\delta^{18}O_{diatom}$ with an average value of 29.6 ‰ ± 0.13 ‰. After 700 cal. BP, the $\delta^{18}O_{diatom}$ falls sharply to its lowest value over the study period (26.6 ‰ at 309 cal. BP). At 1986 AD $\delta^{18}O_{diatom}$ increases again to reach 27.8 ‰ (fig. 3a).

The new age-depth model performed with the BACON R package is presented in supplementary material 1. A zoom on the 4800 to 3000 cal. BP period is presented in fig. 3b. Four ^{14}C ages (fig. 3a) obtained for this time interval, yield an age-depth model precision of ca. 320 years. It supports that at Lake Petit the 4.2 ka BP event is actually a 500-year period that occurred from 4400 to 3900 ca. BP. According to age uncertainties, the 4.2 ka BP event cannot be instantaneous in time, and its time range is at a confidence interval of 95 % of probability of a minimum of 117 years and a maximum of 755 years.

5 Discussion

The 4400 to 3900 cal. BP $\delta^{18}O_{diatom}$ values are about 3 ‰ higher than the modern one (27.8 ‰ in 1986 AD) and correspond to a 1.6 ‰ increase from 4800 to 4400 cal. BP and a 1.5 ‰ decrease from 3900 cal. BP. Figure 4 shows that the high $\delta^{18}O_{diatom}$ period is contemporaneous with the detrital pulse followed by a shift in diatom species previously evidenced (Brisset et al., 2013; Cartier et al., 2015). This suggest the occurrence of a climatic pulse that impacted the whole catchment. This climatic pulse can be further characterized by comparing the $\delta^{18}O_{diatom}$ signal to the present isotope composition of the lake water ($\delta^{18}O_{lake\ water}$) and by assessing the physical parameters possibly responsible of an increase in $\delta^{18}O_{diatom}$.

5.1 Present $\delta^{18}O_{lake\ water}$

The hydrological regime of Lake Petit alternates between two states: an open system when the outlet is active during snow melt, and a closed system the remaining time. The 2011 one off $\delta^{18}O_{lake\ water}$ measurements indicate that from the beginning of the unfreezed season to the end, the lake water gets heavier by 1.1 ‰. The decrease in water depth at the same time can be interpreted as a signal of evaporation. However, in the δD *vs* $\delta^{18}O$ diagram presented on figure 2a, the lake water samples plot on the regional meteoric water line which suggests that evaporation has a limited effect on $\delta^{18}O_{lake\ water}$. The 1.1‰ shift may rather be explained by the drastic decrease of meltwater input at the end of spring. The oxygen isotope composition of meltwater fed by winter precipitation is expected to be lower than $\delta^{18}O_{precipitation}$ during summer, due to its Atlantic origin and the low temperature at which snow forms. Post-depositional fractionating processes affecting the snow (including evaporation, sublimation, ablation, meltwater percolation and drifting) that may lead to ^{18}O-enrichment of meltwaters are likely limited. Indeed, the Lake Petit catchment is small and located under the mountain crest without any glacier supplying the watershed (Stichler and Schotterer, 2000). The seasonal shift occurring today in $\delta^{18}O_{\text{lake water}}$ has a similar amplitude as the $\delta^{18}O_{\text{diatom}}$ shift at 4200 cal. BP, which suggests similar controls.

5.2 Paleo-climatic interpretation of the $\delta^{18}O_{\text{diatom}}$ record

Diatom blooms in alpine lakes occur mainly after the snowmelt in spring season and during autumn. However, sediment traps placed in a lake in Switzerland located at 2339 m a.s.l evidence that some diatom species (e.g. *Achnanthes*, *Fragilaria* spp.) can continue to grow under the ice when the lake is frozen (Rautio et al., 2000; Lotter and Bigler, 2000). With the omnipresence of *Fragilaria* spp. in the sedimentary record and the absence of any detailed dynamic of the population over the year, the isotope signal from Lake Petit is considered to be an annual signal mostly influenced by diatoms growing during the ice-free season.

Polymerization of the siliceous frustule from the lake water occurs at equilibrium and the resulting isotope fractionation is thus thermo-dependent. The equilibrium fractionation coefficient previously measured for different silica-water couples range from -0.2 to -0.4 ‰/°C (synthesis in Alexandre et al., 2012; Sharp et al., 2016). According to this range, if the 1.6 ‰ positive shift in $\delta^{18}O_{\text{diatom}}$ around 4400 cal BP was only controlled by the lake water temperature change, this would require a negative shift in water temperature of 4 to 8°C during the ice-free season, when most of diatoms grow. A very high contribution of snowmelt water may lead to a drastic decrease of the lake water temperature. However, snowmelt is fed by winter precipitation that is ^{18}O depleted, which would counterbalance the effect of low water temperature on $\delta^{18}O_{\text{diatom}}$. Air cooling during the ice-free season may also be invoked. Air cooling during the 4.2 ka BP event in response to a positive North Atlantic Oscillation (NAO) was previously suggested for central Italy (Isola et al., 2019). In the Alps, moraine dating showed moderate glacier advances in northern and western Alps but not in the Mediterranean Alps (Federici and Stefanini, 2001; Ribolini et al., 2007; Ivy-Ochs et al., 2009; Le Roy, 2012, 2017; Brisset et al., 2015). The recent synthesis of Bini et al. (2018) for the Mediterranean region also suggests a possible cooling anomaly in some sites but temperature data are sparse and not uniform. Moreover, reconstruction of temperature based on chironomids and pollen assemblages from the Swiss Alps and Europe suggest that air temperature variations (likely larger than water temperature variations) did not exceed 2 °C during the Holocene (Davis et al., 2003; Heiri et al., 2003). At least, a decrease in air temperature would decrease $\delta^{18}O_{\text{precipitation}}$ and $\delta^{18}O_{\text{lake water}}$ during the ice-free period, which would counterbalance the temperature effect on $\delta^{18}O_{\text{diatom}}$. Therefore, a decrease in air and/or lake water temperature cannot be referred to as the dominant control in the increase of $\delta^{18}O_{\text{diatom}}$ over the 4400-3900 cal period.

An increase in the contribution of ^{18}O enriched Mediterranean precipitation during the ice-free season or, inversely, a decrease in the contribution of ^{18}O depleted Atlantic winter precipitation (due to winter snow deficit) to the lake water may explain an increase in $\delta^{18}O_{\text{lake water}}$ at Lake Petit around 4400 cal. BP. The other proxies analysed from the studied core rather support the first hypothesis as developed below.

From 4800 to 4350 cal. BP, low detrital supply and high chemical weathering suggest the presence of developed acid soils on the catchment slopes (Brisset et al., 2013). From 4350 to 4000, a maximum of clay detrital supply highlights the dismantling of the former developed weathered soils. The sediments deposited during this period are characterised by high terrigenous fluxes, while the diatom-organic component drop to lower but still significant concentrations (20%). Added to the over-representation of low-dispersal alpine meadow plants, these features argue for an intensification of runoff on the catchment slopes during the ice-free season (Brisset et al., 2013, fig. 4). For the same period, high percentages of grassland pollen were recorded in Lake Grenouilles (Southern Alps) located close to Lake Petit (Kharbouch, 2000) and detrital events occurred in other sites of the Alps, for example at Lake Bourget (Arnaud et al., 2005; 2012). In addition, a cluster of landslide events was identified in the Southern Alps around 4200 cal. BP (Zerathe et al., 2014). All these features suggest that runoff intensified in the Southern Alps around 4200 cal. BP, likely due to increasing intense precipitation events, today occurring in fall (Llasat et al., 2010). At a broader scale, records are less in agreement. Reconstructions of past lake levels suggest wetter conditions from 4500 to 3000 cal. BP at Lake Saint Léger (Alpes-de-Haute-Provence, Digerfeldt et al., 1997), Lake Ledro (southern Alps) and Lake Accesa (central Italy) (Magny et al., 2013) (fig. 5). High lake level was also reconstructed at Lake Cerin (Jura massif). However, to the contrary, a trend towards aridification has been suggested at Lake Preola in Sicily (Magny et al., 2012) or at Renella and Corchia cave in Italia (Drysdale et al., 2006; Zanchetta et al., 2016) (fig. 5).

A winter snow deficit might have been superimposed to an increase in intense precipitation events during the ice-free season at Lake Petit. In the Italian Apennine, oxygen isotope records from speleothems at Corchia Cave suggested a reduced water cave recharge from ca. 4500 to 4100 cal. BP (Isola et al., 2019). This was interpreted as a weakening of the cyclone centre located in the Gulf of Genoa in response to reduced advection in air masses from Atlantic during winter.

At least, evaporation higher than the modern one, may also be considered to explain the ^{18}O enrichment of the Lake Petit water around 4.2 cal BP. However, at a yearly scale, the effect of the previous summer's evaporation is expected to be partially or (greatly) offset by the runoff from snowmelt (Ito et al., 1998), as what may happen today. Moreover, this would contradict the assumption of higher precipitation amount during the ice-free season.

In summary, at Lake Petit, the high $\delta^{18}O_{\text{lake water}}$ values recorded from 4400 to 3900 cal. BP support an increase in intense ^{18}O enriched Mediterranean precipitation events during the ice-free season, in agreement with other proxies from the same core and other records from the Southern Alps. A reduction of snow may have been superimposed. However additional evidences are needed to further assess this hypothesis.

At 3900 cal. BP, $\delta^{18}O_{\text{diatom}}$ values decreased and remained relatively constant for 3300 years during the Neoglacial period. Although the low resolution of the record limits the determination of short-term events, a 2.7 ‰ decrease in the $\delta^{18}O_{\text{diatom}}$ values can be identified around 310 cal. BP (fig. 3a). This is concomitant with a strong decrease in $\delta^{18}O$ measured on ostracods from Lake Allos sediments (Cartier, 2016) suggesting a regional climate change. Conversely to what may have happened during the time interval 4400-3900 cal. BP, an increase of snowmelt contributing to the lake may have triggered a decrease in $\delta^{18}O_{\text{lake water}}$ and $\delta^{18}O_{\text{diatom}}$. This time span falls within the Little Ice Age (450-50 cal. BP). The Little Ice Age is recorded as a cold and humid period in the Southern Alps as shown in tree-ring records (Corona et al., 2010), fluvial activity reconstructions (Miramont et al., 1998) and glacial tongue advances (Holzhauser et al., 2005; Ivy-ochs et al., 2009). These records are thus in agreement with an increase of snowmelt water contribution to Lake Petit.

6 Conclusion

The location of Lake Petit above the local tree line, at the head of a small Alpine watershed, as well as its semi-closed lacustrine system, lead to the high responsiveness of the lake to changes in precipitation regime. Thanks to a robust and accurate age model, the last-4800-years $\delta^{18}O_{\text{diatom}}$ record allowed to identify a 500-year time lapse, from 4400 to 3900 cal PB, where $\delta^{18}O_{\text{diatom}}$ reached its highest values. This period of high $\delta^{18}O_{\text{diatom}}$ values can be explained by intense ^{18}O enriched Mediterranean precipitation events feeding the lake during the ice-free season. This agrees with previous reconstructions from the same core (Brisset et al., 2012; 2013) and other records from the Southern Alps suggesting runoff intensification around 4200 cal. BP. Possible changes in other climatic parameters may have played concomitantly, including a decrease in the contribution of ^{18}O depleted Atlantic winter precipitation to the lake water due to snow deficit. However additional evidences are needed to further assess this hypothesis.

Data recording the 4.2 ka BP event in the North-Western Mediterranean area are still sparse. In the Lake Petit watershed, a climatic pulse translated into a change in precipitation regime occurred from 4400 to 3900 cal PB. This record participates to the recent efforts to characterise and investigate the geographical extent of the 4.2 ka BP event in the Mediterranean area.

7 Author contribution

Rosine Cartier wrote the manuscript and performed analysis with Florence Sylvestre. Christine Paillès, Frédéric Guiter and Cécile Miramont provided funding support and material. Anne Alexandre, Elodie Brisset, Frédéric Guiter helped improving the manuscript. Corinne Sonzogni, Martine Couapel and Jean-Charles Mazur worked in analysing samples. All the co-authors gave their comments and agreement during the writing process.

8 Competing interests

The authors declare that they have no conflict of interest.

9 Acknowledgements

This work was supported by the ECCOREV research federation (HOMERE program led by F. Guiter and C. Paillès). The PhD thesis work of R. Cartier (Aix-Marseille University) was funded by the French Ministry of Education.

We thank C. Vallet-Coulomb (CEREGE, France) for the isotope analysis of modern Lake Petit waters and P. Chaurand (CEREGE, France) for providing help with the micro-XRF measurements. Thanks to A. Tonetto (Aix-Marseille University) for managing the SEM in Marseille. Coring of Lake Petit (in 2009 and 2012) was made possible thanks to F. Arnaud (EDYTEM), C. Giguet-Covex (EDYTEM), E. Malet (EDYTEM), J. Pansu (Princeton University), J. Poulenard (EDYTEM) and B. Wilhelm (LTHE).

10 References

Alexandre A., Basile-Doelsch I., Sonzogni C., Sylvestre F., Parron C., Meunier J. D., Colin F.: Oxygen isotope analyses of fine silica grains using laser-extraction technique: Comparison with oxygen isotope data obtained from ion microprobe analyses and application to quartzite and silcrete cement investigation. Geochim. Cosmochim. Ac. 70(11): 2827–2835, 2006.

Alexandre A., Crespin J., Sylvestre F., Sonzogni C. and Hilbert D. W.: The oxygen isotopic composition of phytolith assemblages from tropical rainforest soil tops (Queensland, Australia): validation of a new paleoenvironmental tool. Climate of the Past 8(1): 307–324, 2012.

Alley R. B., Mayewski P. A., Sowers T., Stuiver M., Taylor K. C. and Clark P. U.: Holocene climatic instability: A prominent, widespread event 8200 yr ago. Geology 25(6): 483–486, 1997.

Arnaud F., Revel M., Chapron E., Desmet M., Tribovillard, N.: 7200 years of Rhone river flooding activity in Lake Le Bourget, France: a high-resolution sediment record of NW Alps hydrology. The Holocene, 15(3), 420-428, 2005.

Arnaud F., Révillon S., Debret M., Revel M., Chapron E., Jacob J., Giguet-Covex C., Poulenard J., Magny, M.: Lake Bourget regional erosion patterns reconstruction reveals Holocene NW European Alps soil evolution and paleohydrology. Quaternary Sci. Rev., 51, 81-92, 2012.

Barker P. A., Street-Perrott F. A., Leng M. J., Greenwood P. B., Swain D. L., Perrott R. A., Telford P. J., Ficken K. J.: A 14,000-year oxygen isotope record from diatom silica in two alpine lakes on Mt. Kenya. Science 292(5525): 2307–2310, 2001.

Berger, J. F., Guilaine, J.: The 8200 cal. BP abrupt environmental change and the Neolithic transition: A Mediterranean perspective. Quatern. Int. 200, 31–49, 2009.

Bini, M., Zanchetta, G., Persoiu, A., Cartier, R., Català, A., Cacho, I., Dean, J. R., Di Rita, F., Drysdale, R. N., Finnè, M., Isola, I., Jalali, B., Lirer, F., Magri, D., Masi, A., Marks, L., Mercuri, A. M., Peyron, O., Sadori, L., Sicre, M.-A., Welc, F., Zielhofer, C., and Brisset, E.: The 4.2 ka BP Event in the Mediterranean Region: an overview, Clim. Past Discuss., https://doi.org/10.5194/cp-2018-147, in review, 2018.

Blaauw, M., Christen, J.A., Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Anal. 6, no. 3, 457–474. https://projecteuclid.org/ download/pdf_1/euclid.ba/1339616472, 2011.

Bolle, H. J.: Climate, climate variability, and impacts in the Mediterranean area: an overview. In Mediterranean Climate (pp. 5-86). Springer, Berlin, Heidelberg, 2003.

Bond G., Showers W., Cheseby M., Lotti R., Almasi P., deMenocal P., Priore P., Cullen H., Hajdas I., Bonani G.: A Pervasive Millennial-Scale Cycle in North Atlantic Holocene and Glacial Climates. Science 278(5341): 1257–1266, 1997.

Booth R. K., Jackson S. T., Forman S. L., Kutzbach J. E., Bettis E. A., Kreigs J., Wright D. K.: A severe centennial-scale drought in midcontinental North America 4200 years ago and apparent global linkages. The Holocene 15(3): 321–328, 2005.

Brauer A., Endres C., Günter C., Litt T., Stebich M. and Negendank J. F. W.: Highresolution sediment and vegetation responses to Younger Dryas climate change in varved lake sediments from Meerfelder Maar, Germany. Quaternary Sci. Rev. 18(3): 321–329, 1999.

Brisset, E., Guiter, F., Miramont, C., Revel, M., Anthony, E. J., Delhon, C., ... & de Beaulieu, J. L.: Lateglacial/Holocene environmental changes in the Mediterranean Alps inferred from lacustrine sediments. *Quaternary Science Reviews*, *110*, 49-71, 2015.

Brisset E., Guiter F., Miramont C., Delhon C., Arnaud F., Disnar J. R., Poulenard J., Anthony E., Meunier J. D., Wilhelm B., Paillès C.: Approche multidisciplinaire d'une séquence lacustre holocène dans les alpes du sud au Lac Petit (Mercantour, alt. 2 200 m, France) : histoire d'un géosystème dégradé. *Quaternaire. Revue de l'Association française pour l'étude du Quaternaire* (vol. 23/4): 309–319, 2012.

Brisset E., Miramont C., Guiter F., Anthony E. J., Tachikawa K., Poulenard J., Arnaud F., Delhon C., Meunier J. D., Bard E., Suméra F.: Non-reversible geosystem destabilisation at 4200 cal. BP: Sedimentological, geochemical and botanical markers of soil erosion recorded in a Mediterranean alpine lake. The Holocene. vol.: 23 issue: 12, page(s): 1863-1874, 2013.

Bruneton H., Provensal M., Devillers B., Jorda C., Ollivier V., Miramont C., Leveau P.: Relations entre paléohydrologie et morphogenèse holocènes des petits et moyens bassin-versants en basse Provence et Languedoc oriental. Les fleuves ont une histoire: paléo-environnement des rivières et des lacs français depuis 15 000 ans. In: Bravard J-P and Magny M (Dir.) Histoire des rivières et des lacs de Lascaux à nos jours. Paris: Errance, pp. 259–267, 2002.

Cartier R.: Trajectoires des écosystèmes lacustres alpins depuis 13500 ans dans les Alpes méditerranéennes (Massif du Mercantour, France). Ph.D thesis Aix-Marseille University, 235 pp, 2016.

Cartier R., Brisset E., Paillès C., Guiter F., Sylvestre F., Ruaudel F., Anthony E. J., Miramont C.: 5000 years of lacustrine ecosystem changes from Lake Petit (Southern Alps, 2200 m asl): Regime shift and resilience of algal communities. The Holocene 25(8): 1231–1245, 2015.

Celle-Jeanton, H., Travi, Y., Blavoux, B.: Isotopic typology of the precipitation in the Western Mediterranean region at three different time scales. Geophysical Research Letters, 28(7), 1215-1218, 2001.

Celle-Jeanton H., Gonfiantini R., Travi Y., Sol B.: Oxygen-18 variations of rainwater during precipitation: application of the Rayleigh model to selected rainfalls in Southern France. Journal of Hydrology 289(1–4): 165–177, 2004.

Chapligin B., Meyer H., Friedrichsen H., Marent A., Sohns E., Hubberten H. W.: A high-performance, safer and semi-automated approach for the δ18O analysis of diatom silica and new methods for removing exchangeable oxygen. Rapid Communications in Mass Spectrometry 24(17): 2655–2664, 2010.

Corona C., Guiot J., Edouard J. L., Chalie F., Buntgen U., Nola P., Urbinati C.: Millennium-long summer temperature variations in the European Alps as reconstructed from tree rings. Clim. Past, 6(3), 379-400, 2010.

Crespin J., Alexandre A., Sylvestre F., Sonzogni C., Pailles C., Garreta V.: IR laser extraction technique applied to oxygen isotope analysis of small biogenic silica samples. Analytical chemistry 80(7): 2372–2378, 2008.

Cullen H. M., deMenocal P. B., Hemming S., Hemming G., Brown F. H., Guilderson T., Sirocko F.: Climate change and the collapse of the Akkadian empire: Evidence from the deep sea. Geology 28, 379–382, 2000.

Dansgaard, W.: Stable isotopes in precipitation. Tellus, 16(4), 436-468, 1964.

Davis B. A., Brewer S., Stevenson A. C., Guiot J.: The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Sci. Rev., 22(15-17), 1701-1716, 2003.

Dean J. R., Jones M. D., Leng M. J., Noble S. R., Metcalfe S. E., Sloane H. J., Sahy D., Eastwood W. J., Roberts C. N.: Eastern Mediterranean hydroclimate over the late glacial and Holocene, reconstructed from the sediments of Nar lake, central Turkey, using stable isotopes and carbonate mineralogy. Quaternary Sci. Rev. 124, 162–174, 2015.

Digerfeldt G., de Beaulieu J. L., Guiot J., & Mouthon J.: Reconstruction and paleoclimatic interpretation of Holocene lake-level changes in Lac de Saint-Léger, Haute-Provence, southeast France. Palaeogeogr. Palaeocl., 136(1-4), 231-258, 1997.

Dodd J. P., Wiedenheft W., Schwartz J. M.: Dehydroxylation and diagenetic variations in diatom oxygen isotope values. Geochim. et Cosmochim. Ac., 199, 185-195, 2017.

Drysdale R., Zanchetta G., Hellstrom J., Maas R., Fallick A., Pickett M., Cartwright I., Piccini L.: Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone. Geology 34(2): 101–104, 2006.

Durand Y., Giraud G., Laternser M., Etchevers P., Mérindol L. and Lesaffre B.: Reanalysis of 47 Years of Climate in the French Alps (1958–2005): Climatology and Trends for Snow Cover. Journal of Applied Meteorology and Climatology 48(12): 2487–2512, 2009a.

Durand Y., Laternser M., Giraud G., Etchevers P., Lesaffre B. and Mérindol L.: Reanalysis of 44 Yr of Climate in the French Alps (1958–2002): Methodology, Model Validation, Climatology, and Trends for Air Temperature and Precipitation. Journal of Applied Meteorology and Climatology 48(3): 429–449, 2009b.

Federici, P. R. and Stefanini, M. C.: ABHANDLUNGEN-Evidence and chronology of the Little Ice Age in the Argentera Massif (italian maritime alps). With 7 figures. *Zeitschrift fur Gletscherkunde und Glazialgeologie*, *37*(1), 35-48, 2001.

Gat, J. R.: Oxygen and hydrogen isotopes in the hydrologic cycle. Annual Review of Earth and Planetary Sciences, 24(1), 225-262, 1996.

Heiri O., Lotter A. F., Hausmann S., Kienast F.: A chironomid-based Holocene summer air temperature reconstruction from the Swiss Alps. The Holocene, 13(4), 477-484, 2003.

Holzhauser H., Magny M., Zumbuühl H. J.: Glacier and lake-level variations in west-central Europe over the last 3500 years. The Holocene 15(6): 789–801, 2005.

Huang C. C., Pang J., Zha X., Su H., Jia Y.: Extraordinary floods related to the climatic event at 4200 cal. BP on the Qishuihe River, middle reaches of the Yellow River, China. Quaternary Sci. Rev. 30(3): 460–468, 2011.

IAEA/WMO: Global Network of Isotopes in Precipitation. The GNIP Database. Accessible at: http://www.iaea.org/water, 2018.

Isola, I., Zanchetta, G., Drysdale, R. N., Regattieri, E., Bini, M., Bajo, P., Hellstrom, J. C., Baneschi, I., Lionello, P., Woodhead, J., and Greig, A.: The 4.2 ka event in the central Mediterranean: new data from a Corchia speleothem (Apuan Alps, central Italy), Clim. Past, 15, 135-151, https://doi.org/10.5194/cp-15-135-2019, 2019.

Ito, E., Yu, Z., Engstrom, D. R., & Fritz, S. C.: Is paleoclimatic interpretation of oxygen isotope records from glaciated Great Plains possible. *Abstracts, AMQUA*, *15*, 119, 1998.

Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P. W., & Schlüchter, C.: Latest Pleistocene and Holocene glacier variations in the European Alps. *Quaternary Science Reviews*, *28*(21-22), 2137-2149, 2009.

Kharbouch M.: L'homme et la végétation dans la région du mont Bego (Tende, Alpes-Maritimes) depuis des millénaires. Comptes Rendus de l'Académie des Sciences – Series IIA: Earth. Planet. Sc. 330(12): 889–894, 2000.

Llasat, M. C., Llasat-Botija, M., Prat, M. A., Porcu, F., Price, C., Mugnai, A., ... & Yair, Y.: High-impact floods and flash floods in Mediterranean countries: the FLASH preliminary database. *Advances in Geosciences*, *23*, 47-55, 2010.

Leng M. J. and Barker P. A. : A review of the oxygen isotope composition of lacustrine diatom silica for palaeoclimate reconstruction. *Earth-Science Reviews* 75(1): 5–27, 2006.

Le Roy M., Deline P., Carcaillet J., Schimmelpfennig I., Ermini M., & ASTER Team : ^{10}Be exposure dating of the timing of Neoglacial glacier advances in the Ecrins-Pelvoux massif, southern French Alps. Quaternary Sci. Rev., 178, 118-138, 2017.

Le Roy, Melaine. *Reconstitution des fluctuations glaciaires holocènes dans les Alpes occidentales: apports de la dendrochronologie et de la datation par isotopes cosmogéniques produits in situ*. Diss. Grenoble, 2012.

Lotter, A. F., & Bigler, C.: Do diatoms in the Swiss Alps reflect the length of ice-cover?. *Aquatic sciences*, *62*(2), 125-141, 2000.

Magny M., Combourieu-Nebout N., de Beaulieu J. L., Bout-Roumazeilles V., Colombaroli D., Desprat S., et al. : North–south palaeohydrological contrasts in the central Mediterranean during the Holocene : tentative synthesis and working hypotheses. Clim. Past 9(5): 2043–2071, 2013.

Magny M., Joannin S., Galop D., Vannière B., Haas J. N., Bassetti M., Bellintani P., Scandolari R., Desmet M.: Holocene palaeohydrological changes in the northern Mediterranean borderlands as reflected by the lake-level record of Lake Ledro, northeastern Italy. Quaternary Research 77(3): 382–396, 2012.

Magny M., Vannière B., Zanchetta G., Fouache E., Touchais G., Petrika L., Croussot C., Walter-Simonnet A. V., Arnaud F.: Possible complexity of the climatic event around 4300-3800 cal. BP in the central and western Mediterranean. The Holocene 19(6), 2009.

McQueen D. J., Johannes M. R. S., Post J. R., Stewart T. J., Lean D. R. S.: Bottom-Up and Top-Down Impacts on Freshwater Pelagic Community Structure. Ecological Monographs 59(3): 289–309, 1989.

Miramont C., Boutterin C., Sivan O., Bruneton H., Mantran M.: Grandes séquences et principales ruptures morphogéniques en haute Provence les complexes sédimentaires des petits organismes torrentiels de moyenne Durance. Cahiers de Paléoenvironnement (Collection Edytem), pp.145-154, 2008.

Miramont C., Jorda M., Pichard G. : Évolution historique de la morphogenèse et de la dynamique fluviale d'une rivière méditerranéenne : l'exemple de la moyenne durance (France du sud-est). Géographie physique et Quaternaire 52(3): 381, 1998.

Mocci F., Walsh K., Richer S. : Archéologie et paléoenvironnement dans les Alpes méridionales françaises: hauts massifs de l'Argentiérois, du Champsaur et de l'Ubaye, Hautes-Alpes et Alpes-de-Haute-Provence. Néolithique final et début de l'Antiquité 6, 253e272, 2008.

Moschen R., Lucke A., Schleser G.H. : Sensitivity of biogenic silica oxygen isotopes to changes in surface water temperature and palaeoclimatology. Geophys. Res. Lett., 32, 2005.

Nearing M. A., Pruski F. F., O'neal M. R. : Expected climate change impacts on soil erosion rates: a review. Journal of soil and water conservation, 59(1), 43-50, 2004.

Peyron, O., Magny, M., Goring, S., Joannin, S., Beaulieu, J. L. D., Brugiapaglia, E., ... & Combourieu-Nebout, N. (2013). Contrasting patterns of climatic changes during the Holocene across the Italian Peninsula reconstructed from pollen data. *Climate of the Past*, *9*(3), 1233-1252.

Quesada B., Sylvestre F., Vimeux F., Black J., Pailles C., Sonzogni C., Alexandre A., Blard P. H., Tonetto A., Mazur J. C., Bruneton H.: Impact of Bolivian paleolake evaporation on the δ 18 O of the Andean glaciers during the last deglaciation (18.5–11.7 ka): diatom-inferred δ 18 O values and hydro-isotopic modeling. Quaternary Sci. Rev. 120: 93–106, 2015.

Ribolini, A., Chelli, A., Guglielmin, M., & Pappalardo, M. (2007). Relationships between glacier and rock glacier in the Maritime Alps, Schiantala Valley, Italy. *Quaternary Research*, *68*(3), 353-363.

Roberts N., Jones M. D., Benkaddour A., Eastwood W. J., Filippi M. L., Frogley M. R., Lamb H. F., Leng M. J., Reed J. M., Stein M., Stevens, L., Valero-Garcés B., Zanchetta G.: Stable isotope records of Late Quaternary climate and hydrology from Mediterranean lakes: the ISOMED synthesis. Quaternary Sci. Rev., *27*(25-26), 2426-2441, 2008.

Roberts C. N., Zanchetta G. and Jones M. D.: Oxygen isotopes as tracers of Mediterranean climate variability: An introduction. Global. Planet. Change 71(3–4): 135–140, 2010.

Roberts N., Eastwood W. J., Kuzucuoğlu C., Fiorentino G., Caracuta V.: Climatic, vegetation and cultural change in the eastern Mediterranean during the mid-Holocene environmental transition. The Holocene, 21(1), 147-162, 2011.

Sharp, Z. D., Gibbons, J. A., Maltsev, O., Atudorei, V., Pack, A., Sengupta, S., ... & Knauth, L. P.: A calibration of the triple oxygen isotope fractionation in the SiO 2–H 2 O system and applications to natural samples. Geochimica et Cosmochimica Acta, 186, 105-119, 2016.

Staubwasser M., Sirocko F., Grootes P. M., Segl M.: Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability. Geophysical Research Letters 30(8), 2003.

Stichler, W. and Schotterer, U.: From accumulation to discharge: modification of stable isotopes during glacial and post-glacial processes. Hydrological Processes, 14(8), 1423-1438, 2000.

S. Terzer, L. I. Wassenaar, L. J. Araguás-Araguás, and P. K. Aggarwal: Global isoscapes for $\delta^{18}O$ and $\delta^{2}H$ in precipitation: improved prediction using regionalized climatic regression models. Hydrol. Earth Syst. Sci. Discuss., 10, 7351-7393, 2013.

Thompson L. G., Mosley-Thompson E., Davis M. E., Henderson K. A., Brecher H. H., Zagorodnov V. S., Mashiotta T. A., Lin P. N., Mikhalenko V. N., Hardy D. R., Beer J.: Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa. science 298(5593): 589–593, 2002.

Tinner W. and Lotter A. F.: Central European vegetation response to abrupt climate change at 8.2 ka. Geology 29(6): 551–554, 2001.

Walker M. J. C., Berkelhammer M., Bj€orck S., Cwynar L. C., Fisher D. A., Long A. J., Lowe J. J., Newnham R. M., Rasmussen S. O., Weiss H.: Formal subdivision of the Holocene series/epoch: a discussion paper by a working group of INTIMATE (integration of ice-core, marine and terrestrial records) and the subcommission on quaternary stratigraphy (international commission on stratigraphy). J. Quat. Sci. 27, 649e659, 2012.

Rautio, M., Sorvari, S., & Korhola, A.: Diatom and crustacean zooplankton communities, their seasonal variability and representation in the sediments of subarctic Lake Saanajärvi. *Journal of Limnology*, *59*(1s), 81-96, 2000.

Walsh K.J., Mocci F.: Driving forces and variability in the exploitation of a high-altitude landscape from the Neolithic to Medieval Periods in the southern French Alps. In: Collis, J.R., Nicolis, F., Pearce, M. (Eds.), Summer Farms: Seasonal Exploitation of the Uplands from Prehistory to the Present, vol 16. J.R. Collis Publications, Sheffield, pp. 183e201, 2016.

Walsh K., Mocci F., Palet-Martinez J.: Nine thousand years of human/landscape dynamics in a high-altitude zone in the southern French Alps (Parc National des Ecrins, Hautes-Alpes). Preistoria alpina, 42, 9-22, 2007.

Weiss H., Courty M. A., Wetterstrom W., Guichard F., Senior L., Meadow R., Curnow A.: The genesis and collapse of third millennium north Mesopotamian civilization. Science 261(5124): 995–1004, 1993.

Yaalon, D. H.: Soils in the Mediterranean region: what makes them different?. Catena, 28(3-4), 157-169, 1997.

Zanchetta G., Sulpizio R., Roberts N., Cioni R., Eastwood W.J., Siani G., Caron B., Paterne M., Santacroce R.: Tephrostratigraphy, chronology and climatic events of the Mediterranean basin during the Holocene: An overview. The Holocene 21, 33–52, 2011.

Zanchetta G., Regattieri E., Isola I., Drysdale R. N., Bini M., Baneschi I., & Hellstrom J. C.: The so-called “4.2 event” in the central Mediterranean and its climatic teleconnections. Alp. Mediterr. Quat., 29, 5-17, 2016.

Zerathe S., Lebourg T., Braucher R., Bourlès D.: Mid-Holocene cluster of large-scale landslides revealed in the Southwestern Alps by 36Cl dating. Insight on an Alpine-scale landslide activity. Quaternary Sci. Rev., 90, 106-127, 2014.

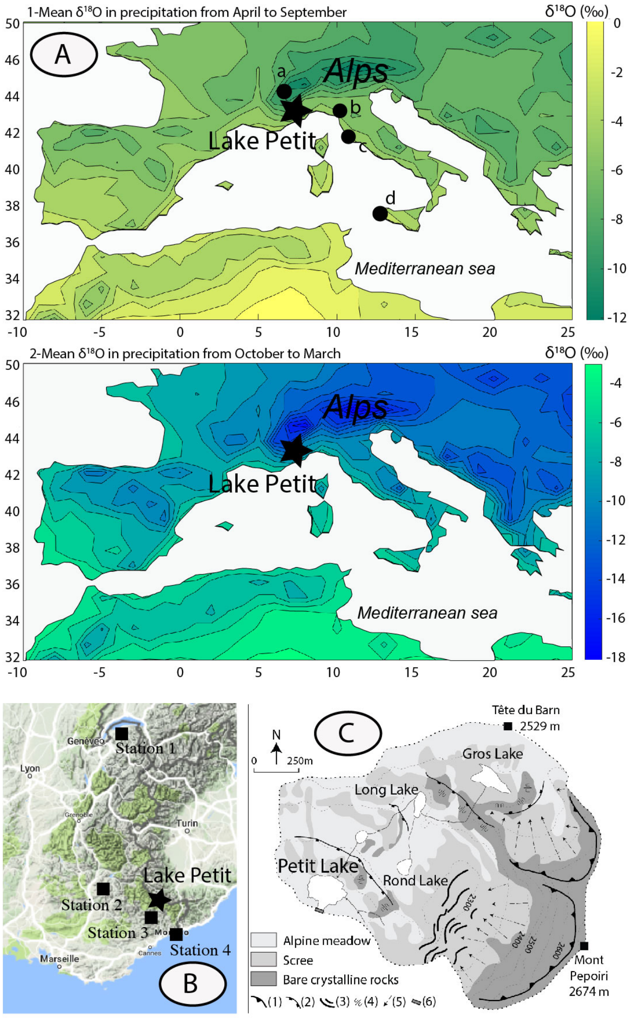


Figure 1: localisation map of Lake Petit: A) mean δ^{18}O in precipitation (δ^{18}O*p*) (in ‰ vs VSMOW) in the western Mediterranean region (IAEA/WMO, 2018; period 1960-2009) and selected palaeoclimatic studies (a: Ecrins-Pelvoux Massif (Le Roy et al., 2017), b: Buca della Renella (Zanchetta et al., 2016), c: Accesa Lake (Magny et al., 2009), d: Preola Lake (Magny et al., 2012); B) GNIP stations (IAEA/WMO, 2018) in black squares: 1) Thonon-les-bains, 2) Draix, 3) Malaussène, 4) Monaco; C) watershed characteristics: 1) glacial cirque, 2) glacial step, 3) moraine, 4) polished bedrock, 5) active debris slope, 6) dam built in 1947.

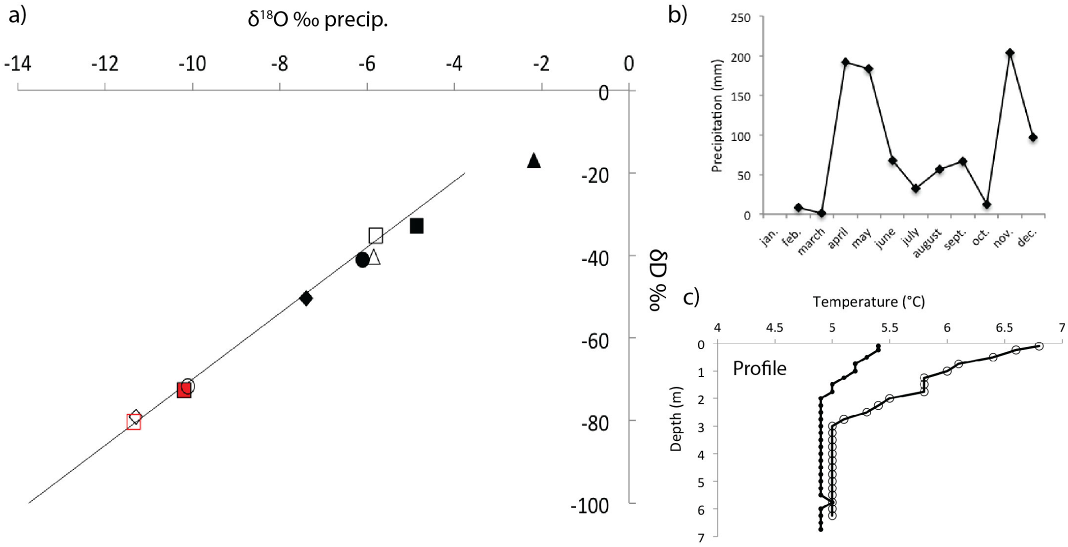


Figure 2: a) δ^{18}O*p* (in ‰ vs VSMOW) from GNIP stations (IAEA/WMO, 2018) and from Lake Petit (in red) at two key times of the year (❑- May 17th 2011, ■- September 17th 2011) plotted across the global meteoric water line (black line). Locations of GNIP stations are shown in Figure 1. Mean weighted average of δ^{18}O*p* for each station is represented by black filled markers for summer months (April to September) and black empty markers for winter months (October to March): Thonon-les-bains (◆), Malaussène (□), Monaco (▲), Draix (●). b) Average annual distribution of precipitation (mm) at the meteorological station Malaussène by month for the year 1997 and 1998, no data for the month of January (IAEA/WMO, 2018). c) Profile of water temperature (˚C) in function of water depth (m) in Lake Petit at two locations the May 17th, 2012.

Table 1: oxygen isotope measurements in diatoms (in ‰ vs V-SMOW) for the core PET09P2

Sample	Depth (cm)	Age (cal. BP)	$\delta^{18}O_{diatom}$	s.d.
PET2.5	2.5	-36	27.85	0.58
PET13	13	309	26.55	0.10
PET 21.5	21.5	744	29.31	0.07
PET29	29	1118	30.06	0.11
PET37	37	1436	29.13	0.19
PET45	45	1666	29.74	0.12
PET55	55	1930	29.23	0.05
PET68	68	2464	30.17	0.24
PET78	78	2996	29.07	0.35
PET85	85	3372	29.96	0.02
PET94	94	3798	29.86	0.05
PET100	100	4018	31.34	0.35
PET108	108	4241	31.03	0.24
PET109.5	109.5	4275	31.97	0.23
PET115	115	4386	30.73	0.03
PET120	120	4471	30.35	0.52
PET127	127	4570	30.36	0.05
PET135	135	4667	30.48	0.05
PET142	142	4747	28.97	0.05
PET144	144	4770	30.73	0.12

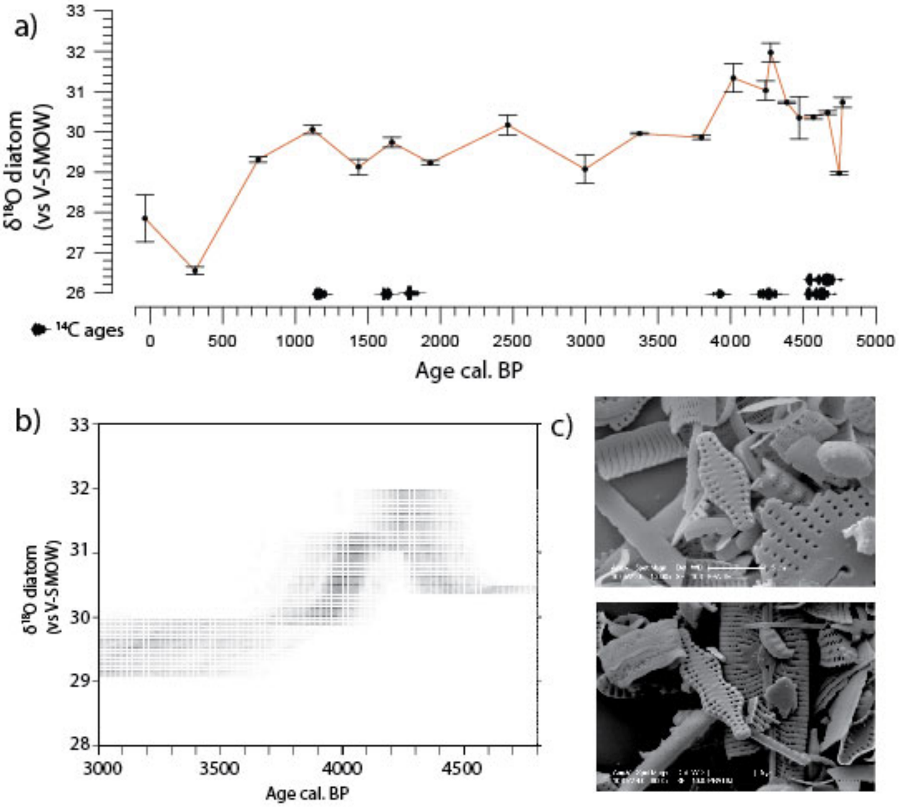


Figure 3: a) Oxygen isotope composition of diatoms (δ^{18}Odiatom expressed in ‰ vs V-SMOW) from Lake Petit sediments; b) δ^{18}O diatom (vs-VSMOW) taking into account the age uncertainties (the darkest grey is assigned to the most likely value within the entire core (normalised to 1), lower age probabilities are coloured in lighter grey); c) SEM image of a cleaned diatom sample from 127 cm depth using a Scanning Electron Microscope.

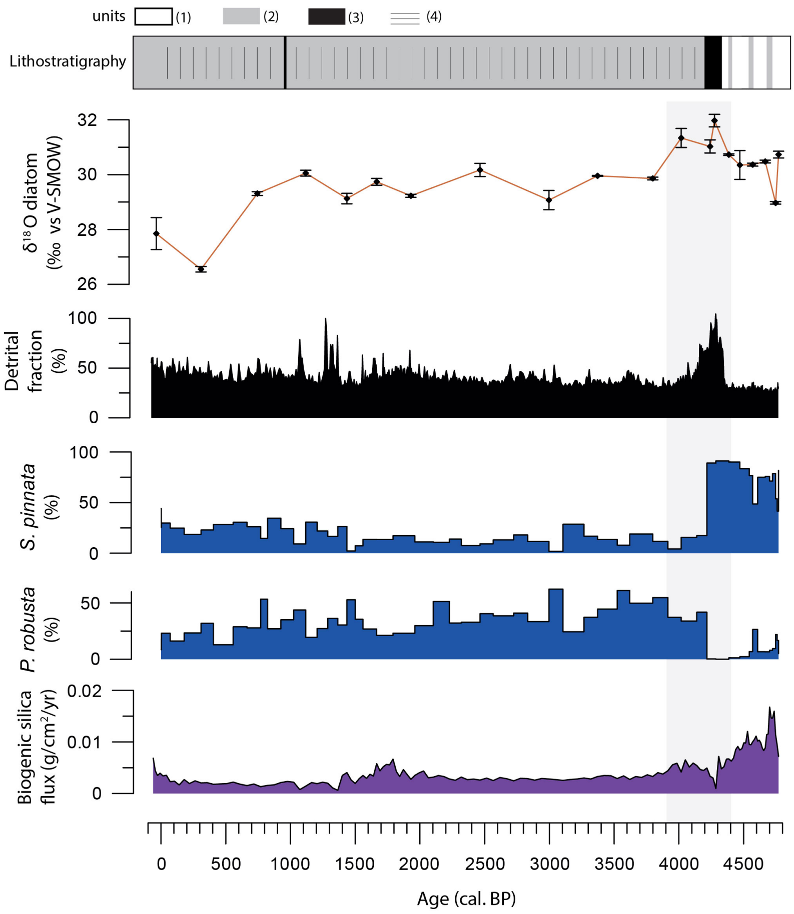


Figure 4: Multiproxy comparison of environmental responses to the 4.2 ka BP event at Lake Petit including the lithological units (1: pure diatomaceous sediments; 2: diatomaceous-clay sediments ; 3: clay-diatomaceous sediments ; 4: diffuse laminations, Brisset et al., 2013), oxygen isotope measurements on diatoms (δ^{18}O diatom, ‰ vs V-SMOW, this study), the
5 detrital fraction (% dry weight; Brisset et al., 2013), biogenic silica fluxes (g.cm^{2}.yr) and dominant diatom species (relative abundance (%) of *Staurosirella Pinnata*, *Pseudostaurosira robusta*) (Cartier et al., 2015).

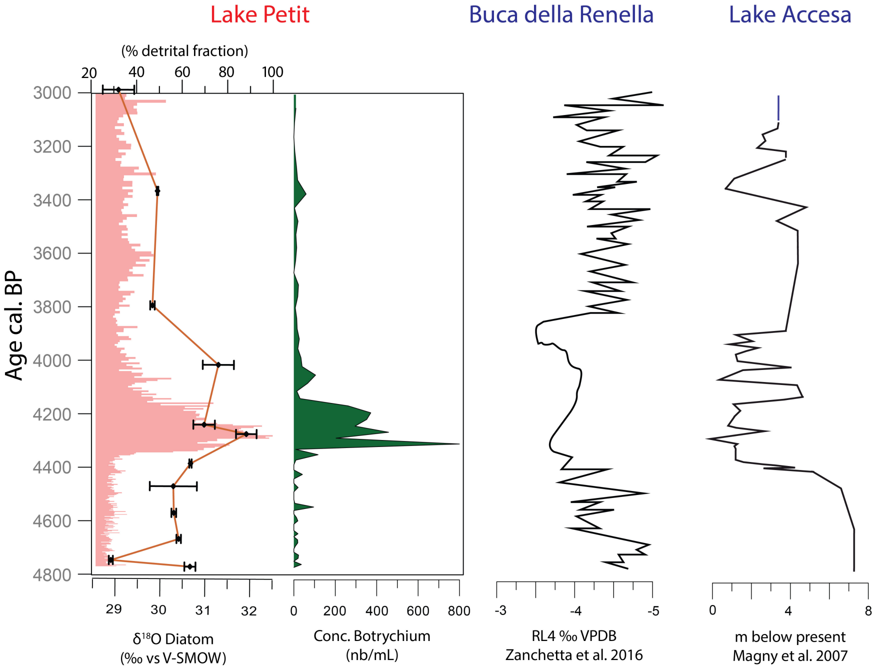
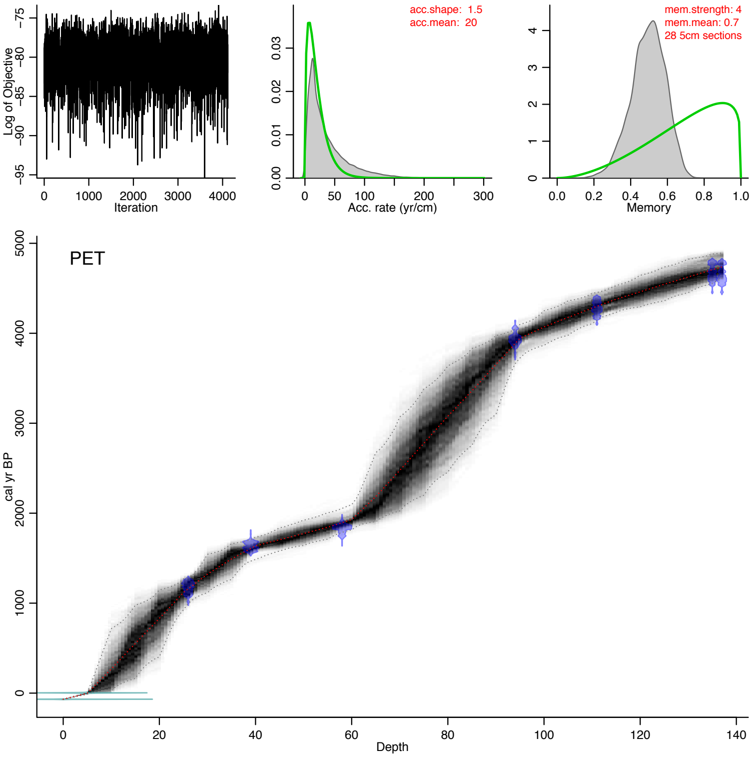


Figure 5: Oxygen isotope measurements in diatoms ($\delta^{18}O_{diatoms}$ ‰ vs V-SMOW; this work), detrital fraction (%) and conc. *Botrychium* (nb/mL) (Brisset et al., 2015) at Lake Petit compared to the palaeoclimatic record at Buca della Renella (northern Italy, Drysdale et al., 2006) and Lake level at Accesa (central Italy, Magny et al. 2007).



Supplementary material 1: Age-depth model for PET09P2 using the BACON R package from Blaauw and Christen, 2011. Radiocarbon ages are presented in Brisset et al., 2013.