Dear Editor,

Please find here the reply to the reviewers comments on the manuscript: "*Aligning MIS5 proxy records from Lake Ohrid (FYROM) with independently dated Mediterranean archives: implications for core chronology*" by Zanchetta et al. (published in BGD). We thank both reviewers for their comments, which we feel have been largely addressed. **The corrections has been reported in red along the manuscript. The new figures are also inserted at the end of this pdf.**

Firstly, it is important to note that the revised Francke et al. (2016) manuscript (scheduled for the same issue) based on the interactive discussion and the referees suggestions produced a modified age model, which is now substantially different from the age model published in Francke et al. (2015 BGD). The Francke et al. (2016) final age model now includes a revised chronology for a time-control point for the tephra layer OH-DP-0499, which derives from our manuscript (Zanchetta et al., 2015) in BGD. This is an excellent example of how open reviewing can permit real-time integration and revision of research. The introduction of this point strongly reduced the differences between the age models of Francke et al. (2015) and Zanchetta et al. (2015) during the last glacial/interglacial transition.

Nevertheless, we feel the discussion of the effects of using different age models is an important contribution to better evaluate the reliability of age models. Therefore, our revised manuscript will discuss the use of the different age models from the original version of the Francke et al. (2015, BGD) time series alongside the new time series (Francke et al. 2015, and this manuscript).

Below there is a point by point reply to the referees comments.

Reviewer #1

Setting up a sound chronology is essential for discussing the relative timing of paleoenvironmental changes in the terrestrial and marine realms – especially considering the dramatic changes occurring during glacial terminations. Therefore, the paper of Zanchetta et al. is a timely contribution for improving the fine-tuning of the MIS 5 stratigraphy from Lake Ohrid. Setting up a reliable chronostratigraphy for Termination II and MIS 5 has furthermore implications for adjusting the time-frame of the earlier glacials/interglacial cycles and glacial terminations.

In general, the authors present good arguments for revising the timing of Termination II. The shape of the $\delta^{18}O$ *signal as well as its amplitude (approx. 4‰ decrease during T II) match these of the other presented archives (marine records, speleothems and lake records) quite well – also with respect to the location of the P-11 tephra. However, there are some issues that should be considered before publication, especially concerning the later stages of MIS 5. My major points of concern are listed below:*

1) *I would like to see the TIC-δ¹⁸O record being extended in order to fully cover the proposed duration of T II. This might be even more important because the TIC-δ¹⁸O record is essentially the foundation of the revised tuning! These are only a few measurements but would certainly strengthen the case of the authors.*

Unfortunately, the TIC and δ^{18}O records by Lacey et al. (2016; this volume) and Francke et al. (2016; this volume) are restricted to the interval between 128 and 78 ka. Lake Ohrid sediments comprise abundant endogenic calcite only during the interglacials, and the availability of isotope data is intrinsically linked to the presence of TIC. Carbonate is almost absent during the glacials, apart from discrete and discontinuous bands of early diagenetic authigenic siderite. The calcite and siderite therefore formed at different times in different parts of the lake (Lacey et al., 2016), and the record cannot be extended.

2) *The tuning of the younger part of MIS 5 is not convincing. On first sight it seems plausible to tune the marked δ^{18}O increase between the POP2 and POP4/X6 tephra with the respective δ^{18}O increase in the Popoli section and Corchia Cave. However, the location of the tephra within the isotope record of the Popoli section is different from that of the tephra within the DEEP Site (presuming these are the same tephra). It is therefore doubtful if the tuning point (green dot) between both tephra is robust.*

Chemical data supporting the correlation between OH-DP-043 & POP4 and OH-DP-0404 & POP2 are provided in Leicher et al. (2016; this volume), so these tie points of correlation between the Sulmona and Ohrid record are independent of climate interpretation. However, of note the position of the two tephras when compared to the δ^{18}O data from Sulmona is perfectly aligned with the δ^{18}O data from Ohrid. Both POP4 tephra and OH-DP-043 occur just after a “negative” spike in δ^{18}O within the GS24 stadial, whereas POP2 and OH-DP-0404 are precisely placed at the beginning of a well pronounced positive δ^{18}O spike within the GI23. This δ^{18}O spike in the Ohrid record is also replicated in the TIC and TOC time series data. Therefore, both the chemistry and the fine-scale “climatostratigraphic” position of the two tephra layers are quite convincing, we have improved Figure 3 accordingly.

3) *I wonder why there is no comparison of the DEEP data to established pollen records from the Mediterranean realm: For the classical Tenaghi Philippon (T.P.) site, high resolution pollen records are available for MIS 5 (e.g. Milner et al., 2012; Milner et al., 2013; Pross et al., 2015). This record has been tuned to the speleotheme-dated MIS 5 pollen record of Iberian Margin core MD95-2042 (original data by Sánchez-Goñi et al., 1999). Hence, a similar timing as the Lake Ochrid record should be expected for Termination II and MIS 5. Interestingly, comparison of the Iberian Margin pollen record to the planktonic foraminifera δ^{18}O data from the same core show a lag of approx. 4 kyrs by the terrestrial biomes to temperature change, similar to the lake Ochrid data set – another argument for the revised stratigraphy. A similar shortcoming is that no attempt was made to compare the Lake Ochrid record to the Monticchio sequence of the last Interglacial (Brauer et al., 2007) which is independently dated based on varve counting and tephrochronology. While tuning pollen records naturally includes the assumption of*

synchronous paleoenvironmental changes, a comparison of the DEEP data to these archives should be included for a thorough discussion of the stratigraphy.

Yes, we agree with both reviewer#1 and reviewer#2 that using pollen data would improve the discussion. In the Zanchetta et al. (2015; BGD), we aimed to provide suggestions of ways to improve the chronology, allowing the proxy data to be presented in other papers of the special issue. In the revised version we have added a figure (Figure 5) showing the Ohrid pollen record for MIS5 (Sadori et al., 2016) with the new age model proposed here, and have compared this to Monticchio (after Brauer at al. 2007) and Tenaghi pollen records (after Milner et al. 2012 and 2013). We now also discuss this new figure in the text but avoid an in depth discussion of pollen from the Mediterranean region as this is irrelevant for this paper. We have added the following sentences:

"With this new age model it is also possible to attempt a more precise regional correlation of pollen records. In Figure 5 pollen records from Tenaghi Philippon, (Fig. 1, Milne et al. 2012, 2013; Pross et al. 2015) and Monticchio (Fig. 1; Brauer et al. 2007) are plotted against the DEEP site pollen record (Sadori et al. 2016). The sharp increases in the AP percentages at ca. 130 ka is almost synchronous in all the mentioned records, and simultaneous to the highest rate of SST increase in the western Mediterranean (Fig. 4). A comparison of the chronology from different records after the end of the Eemian forest phase is more problematic, since the first clear forest opening coincides with the C24 cold event in North Atlantic (Sánchez-Goñi et al. 1999). In the DEEP core, two tephra layers and a robust alignment point at the end of GI24 probably make this chronology the most reliable even if in the younger part of the record there are no further alignment points."

4) A comparison to summer insolation at 42° N might be helpful as well – note that the TIC peak at MIS 5e coincides with maximum summer insolation in the revised stratigraphy. While this makes sense in terms of climate forcing, this relation breaks down for late MIS 5 in the new stratigraphy. Here the original stratigraphy with the pronounced TIC peak at ca. 82 ka fits better to summer insolation than in the revised version (c.f. figure attached). This offset is odd and should be discussed, if the revised stratigraphy remains as is.

We have added insolation data to Figure 4 and associated text. We would like to point out that when we are building an independent chronology it is necessary to avoid the use of the "tuning insolation paradigm" (which was not completely the case for Francke et al. (2015; BGD)), because it can become a circular argument. When looking for leads and lags within a climate system it is necessary to only deal with independent chronologies. For instance we note that the maximum warming in the SST temperature of Martrat et al. (2014) tuned with Marino chronology (Marino et al. 2015), occurs later than the maximum insolation (the Marino et al. (2015) record is supported by tuning with speleothems). Alternatively, in the

Sulmona basin the end of GI24 (or rather its isotope expression) corresponds precisely to the insolation maxima/precession minima (Regattieri et al. 2015). This is very similar to that indicated by TIC data for the DEEP core in Lake Ohrid for the subsequent insolation maxima at ca. 80 ka. Without doubt, insolation is the general pace-maker of glacial to interglacial alternation, but we would like to point out that seasonality and reorganization of the climatic system can produce leads and lags between different system which advise against simple tuning with insolation, especially when proxy records are examined in detail.

4) No sedimentation rates are discussed, I would also suggest to show them in Fig. 4. How do the sedimentation rates compare between the old and new chronologies?

Sedimentation rates are now included in the new Figure 4 and discussed in more detail.

"Figure 4 also illustrates the change in sedimentation rate in the different age models. It is possible to see that increasing the number of aligning points make the sedimentation rate significantly different, suggesting a faster decrease at the time of the interglacial inception. Sedimentation rate increased again around ca. 120 ka, and then remained stable since ca.105 ka. We note that the Francke et al. (2015; this volume) age model (and most other age models too) are based on the assumption of gradually changing sedimentation rates. This might be true, if studying long sequences and on a low resolution. However, changes in sedimentation rates become more important when examining a sequence at higher resolution. On the long-term scale, and using the chronological tie points of the 9 tephras from the orbital tuning used in the Francke et al. (2015; this volume) age model, relatively constant sedimentation rates are inferred for the DEEP core site record. On closer inspection, however, there might be significant changes, particularly at the MIS6-5e transition, as inferred for the new age model, as it is highly unlikely that a decrease in clastic matter input from the catchment (prevailing during glacials, even if partially compensated by a reduced input of organic matter, and indicated in lithofacies 3 of Francke et al. 2016) is completely, simultaneously and equally compensated by an increase in carbonate precipitation reaching > 80% during the interglacial (MIS 5e peak, Fig. 4). This means that it is highly likely that there are significant changes in sedimentation rates, which can only be detected by high resolution studies and by a detailed comparison of different records as indicated in this study".

Specific comments

p. 16981, lines 23-24: “the marine isotope signal: infers: ” this wording is odd because the isotope signal itself cannot infer something. Rephrase to e.g. “The marine isotope signal has been used to infer……”

Done.

p. 16982, l. 6: “Woolbreak” – I guess this should read “Waelbroeck”?

Yes, done.

p. 16982, l. 9-10. “could indicate different processes” is quite a vague statement. Marine and terrestrial proxies naturally report different processes. Please specify what is meant here.

We have rephrased this sentence to make it clearer, this is also a comment of reviewer #2. The sentence now reads:

“However, when marine records are used for tuning terrestrial archives there is an implicit assumption of synchronicity between climatic events recognized in marine proxies and those in terrestrial archives often identified using different proxies. Under scrutiny such a relationship may not be sustainable, as terrestrial and marine proxies could indicate different processes at local and global scales with different responses to climatic forcing.”

p. 16982, l. 25-27: a reference to (Hodell et al., 2013) might be useful. This citation refers to the speleotheme-based tuning of Iberian Margin Sites MD01-2443/2444 via the synthetic Greenland ice core by (Barker et al., 2011). As suggested earlier, the comparison to the pollen records from the

Iberian Margin might be of use for this study as well.

We have added this reference.

p. 16991, l. 14: there are no 95% confidence limits given in Fig. 4

We have corrected this sentence.

p. 16992, l. 18: it should read “that the Francke…” (add “the”)

Done.

Table 1: What do the number in brackets denote in the column with the new age control points? If this is the 95% confidence interval, please note if this is 1 or 2 sigma.

We have corrected Table 1.

Fig. 1: Why is Lago Grande di Monticchio shown if no data is presented from this location (although I encourage inclusion of the Monticchio data)?

The new Figure 5 includes Monticchio data. Figure 1 includes the Tenaghi data.

Figs. 2 + 3: Both figures are too small, the text is hardly readable in print-out.

We have enlarged the text in both figures.

Fig. 3: the y axis for the Corchia Cave does only reach to -3 ‰ it does not cover the full range of values.

We have corrected the axis on both figures.

Fig. 3 Caption: Add a ":" after "From the bottom". Please write all species names in italics. Pre-last sentence: correct "Ohrid" to "Ochrid"

We made the first two corrections. The official name is Lake Ohrid.

Fig. 4: *It might be useful to plot the other target records used for tuning here as well in order to judge how well the new stratigraphy fits to the other records (especially the Popoli section, Corchia, possibly Tenaghi Philippon, Monticchio)*

In Figure 4 we have now included the sedimentation rates based on the new age model of Franke et al.(2016; this volume) the old age model of Francke et al. (2015; BGD), and that obtained from our age modelling. Moreover, we have plotted the TIC data alongside the different age models and insolation. As an external proxy we also show the proposed SST from Martrat et al. (2014) on the Marino et al. (2015) chronology. The comparison with pollen is now given in the new Figure 5 and discussed in the text. Figure 4 is now complete without adding further proxies.

References:

Barker, S., Knorr, G., Edwards, R.L., Parrenin, F., Putnam, A.E., Skinner, L.C., Wolff, E. and Ziegler, M., 2011. 800,000 Years of Abrupt Climate Variability. Science, 334(6054): 347-351.

Brauer, A., Allen, J.R.M., Mingram, J., Dulski, P., Wulf, S. and Huntleyyâ˘Aa¸, B., 2007. Evidence for last interglacial chronology and environmental change from Southern Europe. Proceedings of the National Academy of Science of the USA, 104(2): 450-455.

Hodell, D., Crowhurst, S., Skinner, L., Tzedakis, P.C., Margari, V., Channell, J.E., Kamenov, G., Maclachlan, S. and Rothwell, G., 2013. Response of Iberian Margin sediments to orbital and suborbital forcing over the past 420 ka. Paleoceanography, 28(1): 185-199.

Milner, A.M., Collier, R.E.L., Roucoux, K.H., Müller, U.C., Pross, J., Kalaitzidis, S., Christanis, K. and Tzedakis, P.C., 2012. Enhanced seasonality of precipitation in the Mediterranean during the early part of the Last Interglacial. Geology, 40(10): 919-922.

Milner, A.M., Müller, U.C., Roucoux, K.H., Collier, R.E.L., Pross, J., Kalaitzidis, S., Christanis, K. and Tzedakis, P.C., 2013. Environmental variability during the Last Interglacial: A new high-resolution pollen record from Tenaghi Philippon, Greece. Journal of Quaternary Science, 28: 113-117.

Pross, J., Koutsodendris, A., Christanis, K., Fischer, T., Fletcher, W.J., Hardiman, M., Kalaitzidis, S., Knipping, M., Kotthoff, U., Milner, A.M., Müller, U.C., Schmiedl, G., Siavalas, G., Tzedakis, P.C. and Wulf, A.S., 2015. The 1.35-Ma-long terrestrial climate archive of Tenaghi Philippon, northeastern Greece: Evolution, exploration, and perspectives for future research. Newsletter on Stratigraphy, 48(3): 253-276.

Sánchez-Goñi, M., Eynaud, F., Turon, J. and Shackleton, N., 1999. High resolution palynological record off the Iberian margin: direct land-sea correlation for the LastInterglacial complex. Earth and Planetary Science Letters, 171(1): 123-137.

Anonymous Reviewer #2

General comments: The question how the age models for records for the interval preceding, during and after the MIS 5 can be generated is a very interesting topic, particularly for the terrestrial realm. This is a generally well-written manuscript which discusses different approaches for age models for a very important terrestrial site from the central Mediterranean region. I thus think it is worth publishing. What I immediately wondered when reading the manuscript was why there is no comparison with the Tenaghi Philippon record and other important records from the region (e.g. Monticchio) – as I have just seen, reviewer 1 takes a similar view and mentions recent publications in this context. Generally, while introduced in the method section, the DEEP site pollen record is then only mentioned once again at the beginning of the "Results and discussion" section and shortly in the conclusions – I think the authors waste potential here (see also remark to conclusions), and I would have expected in the discussion the implications of the new chronology for vegetation development in the Mediterranean region.

This is a similar comment to reviewer#1 and has been addressed (see above).

In the last figure of the manuscript, the authors show how the newly introduced age model shifts the DEEP total inorganic carbon curve and compare this with the ODP-975 SST record (Martrat et al., 2014 using Marino et al., 2015; see below). Such a figure I would have expected for interesting terrestrial proxies from, e.g., Monticchio, Tenaghi Philippon and Lake Ohrid. This is the more important since Sadori et al. (2015) use the medium-resolution pollen record from Wijmstra (1969) for comparison between Lake Ohrid and Tenaghi Philippon, while there are now records in higher resolution available as mentioned by reviewer 1.

As requested by reviewer#1 we have added a new figure and the discussion has been expanded.

Concerning language: I am not a native speaker myself, but I am sure that the English could be slightly improved. What I particularly noted is the frequent unnecessary use of the word 'however' in the "Results and discussion" section (see below for detailed remarks).

Two co-authors are native English speakers, they have now improved the language throughout the text.

Detailed remarks:

1 Introduction

Page 16982, Lines 2 and following: The whole paragraph is difficult to understand. Of course, one can guess what the authors mean, but it is imprecisely stated. For example, "assumption of synchronicity between marine and terrestrial events": What is regarded as a marine event? An event restricted to the marine realm, or a signal in a marine proxy (which might be caused by an event taking place in the terrestrial realm!), or an event reflected by a terrestrial proxy transported into the marine realm (sediments, pollen etc.)?

We have improved this sentences including also the observation of reviewer#1 (see above)

Page 16983, Line 4: "A large literature:" Not sure if this is grammatically correct, though the expression can be found in other publications.

We have change it thus:

"An increasing number of studies are now devoted to the use of tephra layers for correlation and synchronization of archives (see e.g. Lowe (2011) for an extensive review)."

Line 19 (and later): The term "paper" appears like scientist colloquial language to me. Why not "publication"?

Changed.

4 Results and discussion

Page 16989, Lines 20 and following; and Page 16991, Lines 2 and following: These are sections where "However: : :" is used in two subsequent sentences, and I would suggest to avoid phrases like ": : : we have to note: : :"

Correction made.

Page 16992, Lines 18 and following: Even though I understand that this is not a high resolution study, I wonder why, if they are discussed, sedimentation rates are not shown in a figure.

The sedimentation rate is now included in Figure 4.

Same line (Page 16992, Lines 18): It is probably a matter of personal taste, but phrases like "As last point, it is important to remember: : :" waste place and are unnecessary. If it was not important, you would not write it, I guess.

Correction made.

5 Conclusions

Page 16993, Line 11: While AP % has been introduced in the text, I wondered here if it would be better not to use the abbreviation since arboreal pollen are only mentioned in one other section. Since you claim the concomitance with increasing temperatures here, I wonder if you should not show at least another pollen curve for thermophilous species. The AP % curve could as well be tied to an increase in precipitation.

Pollen data are now discussed . AP was introduced and is a widely accepted term in the International literature.

Line 21: "It is important to remark: : :" Again, a matter of personal taste: Would you remark this if it was not important?

Yes, personal taste, but we have made the change.

Figures: Please increase the size of almost all figures in the final manuscript (perhaps this is just a problem of the upload process?). Apart from the size, I think the figures are generally well-made.

Done.

Figure 2: What is used as pollen reference sum? Why is only Pinus removed from AP? (In Sadori et al., 2015 it is mentioned that this is due to over-representation of Pinus, but if so, should the reasons for over-representation not as well be immanent for Abies, Picea, and, if occurring, other bisaccate pollen?) Please write "Pinus" in italics.

(Ironically, I am not sure how to use italics in the comment form...) The abbreviation "AP" is not explained in the figure text. Even if this is from already published records:

Figures and figure text together should provide all necessary information! (And Sadori et al (2015) is a discussion paper!) I would even consider explaining "TIC" and "TOC" – though I guess everybody interested in the topic knows these abbreviations, it would still be appreciated by readers who do not often work with carbon content.

We have checked all the text in detail to be sure that all the acronyms are correctly quoted at their first mention. The full explanation for pollen data are from Sadori et al. (2016), but are not discussed in this paper.

Figure 3: Change "LC21 planctik" to "LC 21 planktic"; change "Ohird" to "Ohrid".

Done.

Figure 4: Compare general comments.

Done.

Finally, we hope in the details above we have satisfied all the changes that the reviewers suggested. The final text will include all their comments as discussed. We thank them for their great efforts in improving the manuscript. Below the two completely new figures and the new table 1 with related captions.

Aligning and synchronization of MIS5 proxy records from Lake Ohrid (FYROM) with independently dated Mediterranean archives: implications for DEEP core chronology

G. Zanchetta[1], E. Regattieri[2], B. Giaccio[2], B. Wagner[3], R. Sulpizio[4], A. Francke[3], H. Vogel[5], L. Sadori[6], A. Masi[6], G. Sinopoli[6], J. H. Lacey[7,8], M. J. Leng[7,8], N. Leicher[3]

[1]{Dipartimento di Scienze della Terra, University of Pisa, Pisa, Italy}

[2]{Institute of Environmental Geology and Geoengineering, IGAG-CNR, Montelibretti, Rome, Italy}

[3]{Institute of Geology and Mineralogy, University of Cologne, Cologne, Germany}

[4]{Dipartimento di Scienze della Terra e Geoambientali, University of Bari, Bari, Italy}

[5]{Institute of Geological Sciences & Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland)}

[6]{Dipartimento di Biologia Ambientale, University of Roma "La Sapienza" Roma, Italy}

[7]{Centre for Environmental Geochemistry, School of Geography, University of Nottingham, Nottingham, UK}

[8]{ NERC Isotope Geosciences Facilities, British Geological Survey, Keyworth, Nottingham, UK}

Correspondence to: G. Zanchetta (zanchetta@dst.unipi.it)

Abstract

The DEEP site sediment sequence obtained during the ICDP SCOPSCO project at Lake Ohrid was dated using tephrostratigraphic information, cyclostratigraphy, and orbital tuning through the marine isotope stages (MIS) 15-1. Although this approach is suitable for the generation of a general chronological framework of the long succession, it is insufficient to resolve more detailed paleoclimatological questions, such as leads and lags of climate events between marine and terrestrial records or between different regions. Here, we demonstrate how the use of different tie points can affect cyclostratigraphy and orbital tuning for the period between ca. 140 ka and 70 ka and how the results can be correlated with directly/indirectly radiometrically-dated Mediterranean marine and continental proxy records. The alternative age model presented here shows consistent differences with that initially

proposed by Francke et al. (2015) for the same interval, in particular at the level of the MIS6-5e transition. According to this new age model, different proxies from the DEEP site sediment record support an increase of temperatures between glacial to interglacial conditions, which is almost synchronous with a rapid increase in sea surface temperature observed in the western Mediterranean. The results show how a detailed study of independent chronological tie points is important to align different records and to highlight asynchronisms of climate events. Moreover, Francke et al (2016) have incorporated the new chronology proposed for tephra OH-DP-0499 in the final DEEP age model. This has reduced substantially the chronological discrepancies between the DEEP site age model and the model proposed here for the last Glacial-Interglacial transition.

1 Introduction

Since the demonstration of a strong astronomical control on the oxygen isotope composition ($\delta^{18}O$) preserved in the shells of foraminifera collected from marine sediments (e.g. Hays et al., 1978) and the construction of composite reference records (e.g. Martinson et al., 1987; Lisiecki and Raymo, 2005), the marine isotope signal has been extensively used as a reference for chronological tuning of continental successions (e.g Tzedakis et al., 1997) and to infer, for instance, the response of regional vegetation to climate forcing on a global scale. $\delta^{18}O$ reference records are often based on benthic foraminifera, with appropriate species offset corrections, and are primarily interpreted as first order indicators of global ice-volume. Therefore, these records can provide information on glacial-interglacial variations in Earth's climate conditions, even if heavily contaminated by the effect of deep-water temperature variability (e.g. Shackleton, 2000; Skinner and Shackleton, 2006), and by translation these records can also be used for inferring sea-level oscillations (Shackleton, 1987; Waelbroeck et al., 2002).

However, when marine records are used for tuning terrestrial archives there is an implicit assumption of synchronicity between climatic events recognized in marine proxies and those in terrestrial archives, often identified using different proxies. Under scrutiny such a relationship may not be sustainable, as terrestrial and marine proxies could indicate different processes at local and global scales, with different responses to climatic forcing. For instance, marine pollen studies indicate that broad land-sea correlations and average ages of respective stages are generally correct, but that there may be significant offsets in the precise timing of terrestrial and marine stage boundaries (e.g. Shackleton et al., 2002, 2003; Tzedakis et al., 2004) when, e.g., pollen and benthic foraminifera $\delta^{18}O$ were directly compared. These offsets can offer complementary information, which will not be recognized and understood if tuning is the only tool used for chronological control (Blaauw, 2012; Sanchez-Goni et al., 2013). However, correlation between the terrestrial and marine realm is a fundamental task for understanding how climate systems work at different time-scales and the nature of climate change impacts on the Earth system.

The development of U/Th-based speleothem studies in the last 20 yrs may bypass the necessity to synchronise continental archives with marine records for supporting terrestrial chronologies, especially if similar proxies are used (e.g. stable isotopes, Regattieri et al., 2014). Considering that marine chronologies, beyond the limit of radiocarbon dating methods, are often based on astronomical assumptions, it is now also common to transfer independently dated speleothems chronologies to marine records (Bar-Matthews et al., 2000; Almogi-Labin et al., 2009; Drysdale et al., 2007; 2009; Grant et al., 2012; Ziegler et al., 2010; Hodell et al., 2013; Marino et al., 2015; Jiménez-Amat and Zahn, 2015). This can be somewhat problematic, as the assumption of synchronicity between speleothem and marine proxy records is not necessarily straightforward (e.g. Zhornyak et al., 2011). Moreover, different approaches to correlate chronologies from speleothem-based proxy records and marine proxies have been proposed (e.g. Drysdale et al., 2009; Ziegler et al., 2010; Grant et al., 2012; Marino et al., 2015; Jiménez-Amat and Zahn, 2015).

An increasing number of studies are now devoted to the use of tephra layers for correlation and synchronization of archives (see e.g. Lowe, 2011 for an extensive review). In the Mediterranean region, the use of tephra layers as chronological and stratigraphic markers (Wulf et al., 2004; 2008; Zanchetta et al., 2011; 2012ab; Blockley et al., 2014; Albert et al., 2015; Giaccio et al., 2015) has largely improved our ability to synchronize archives and proxies, and to recognize leads and lags between different paleoclimate records (e.g. Regattieri et al., 2015). Therefore, the parsimonious use of tuning based on independently dated archives, along with the strong stratigraphic constraint afforded by tephra layers is perhaps the most rigorous way to provide a chronological reference for archives which lack an independent chronology (e.g. Regattieri et al., 2016). However, tephrostratigraphic and tephrochronological work also depends on the accuracy of existing data, and radiometric ages provided for proximal and distal deposition of the same tephra can vary by up to several thousand years. For example the Y-3 tephra is a widespread marker in the central Mediterranean (Zanchetta et al., 2008), for which an age range of ca. 31-30 ka has been proposed for the supposed proximal deposits (e.g. Zanchetta et al., 2008) but this age range has been recently challenged by Albert et al. (2015) who dated distal Y-3 deposits to be between 28.7-29.4 ka.

Here, we attempt to compare different proxy series from MIS 5 (ca. 130-80 ka; cf. Railsback et al., 2015) from the 'DEEP' core composite profile, drilled in Lake Ohrid (Fig. 1) within the framework of the ICDP-SCOPSCO project (Wagner et al., 2014a, b), with recent radiometrically-dated continental records in the central Mediterranean, to further constrain the age model of the DEEP record for this period. The major aims are to understand: (1) which proxies are most useful for correlating different archives during specific intervals of time, (2) which proxies can provide fundamental information on time-lag relationships between specific environments, and (3) which proxies can be confidently considered as an expression of local-to-regional climatic change. The approach employed here is different from that previously used to produce a chronology for the DEEP site composite long record, which is based on tephrostratigraphy, cyclostratigraphy and/or orbital tuning through the marine isotope record (Baumgarten et al., 2015; Francke et al., 2015, 2016). In contrast, our approach provides more detailed insights into the chronological framework of a discrete time period, and aims to contribute to the synchronization of paleoclimate records in the Mediterranean region.

2 Site description

Lake Ohrid originated in a tectonic graben and formed during the latest phases of uplift of the Alps (Stankovic, 1960). It is located on the border between Macedonia (FYROM) and Albania and covers an area of 358 km^2 at an altitude of 693 m a.s.l. (Fig. 1). It is about 30 km long and 15 km wide, with a maximum water depth of 293 m (Lindhorst et al., 2015). The topographic watershed of Lake Ohrid comprises an area of 2393 km^2 incorporating Lake Prespa, which is situated 10 km to the east of Lake Ohrid at an altitude of 848 m a.s.l. (Popovska and Bonacci, 2007). The two lakes are connected via karst aquifers that pass through the Galičica and Suva Gora mountain ranges. Karst springs depleted in nutrients and minerogenic load represent the primary hydrologic inputs to Lake Ohrid (55%) and up to 50% of these karst waters originate from Lake Prespa (Anovski et al., 1992; Matzinger et al., 2007). Direct precipitation on the lake surface, river and direct surface runoff account for the remaining 45% of the hydrologic input into Lake Ohrid. The surface outflow (60%) through the river Crn Drim in the northern corner and evaporation (40%) represent the main hydrologic outputs (Matzinger et al., 2006a). The theoretical hydraulic water residence time is estimated to be ca. 70 years (Matzinger et al., 2006a). Due to its sheltered position in a relatively deep basin surrounded by high mountain ranges and to the proximity of the Adriatic Sea, the climate of the Lake Ohrid watershed shows both Mediterranean and continental characteristics (Watzin et al., 2002). The average annual air temperature for the period between 1961 and 1990 is +11.1°C, with a maximum temperature of +31.5°C and a minimum temperature of –5.7°C. The average annual precipitation amounts to 800–900 mm (Popovska and Bonacci, 2007), and the prevailing wind directions follow the N–S axis of the Ohrid valley.

The lake is thought to be the oldest lake in continuous existence in Europe, with current age estimates varying between ca. 1.2 and 5 million years from geological investigations and between 1.5 and 3.0 Ma from molecular clock analyses of endemic taxa (Trajanovski et al., 2010). Preliminary analyses from SCOPSCO DEEP core sediments confirm a limnological age for Lake Ohrid of > 1.2 Ma (Wagner et al., 2014a, b; Baumgarten et al., 2015). The peculiar hydrological conditions of the lake and the presence of >300 endemic species make Lake Ohrid a hotspot of biodiversity and site of global significance (Albrecht and Wilke, 2008; Föller et al., 2015).

3 Material and Methods

The “DEEP” core was retrieved in the central basin of Lake Ohrid (N 41°02’57’’ and E 020°42’54", Fig. 1) at 243 m water depth, in a basement depression with an estimated maximum thickness of sediment fill of 680 m (Lindhorst et al., 2015). Seismic data show that the upper ~400 m comprises undisturbed sediments without unconformities or erosional features, thus supporting a continuous sediment record (Wagner et al., 2014a, b). At the DEEP site (ICDP label 5045-1), six parallel holes were drilled to a maximum sediment depth of 569 m below lake floor (blf). Pelagic or hemi-pelagic sediments characterize the uppermost 430 m of the sediment column (Francke et al., 2016). Below 430 m blf, shallow water facies became increasingly dominant, including peaty layers, coarser sediments with shell remains, and distinct sandy layers. The correlation of the core segments of the individual holes revealed an overall recovery of almost 100% for the upper ca 248 m (Francke et al., 2016). Mass movement deposits have thicknesses of < 3 cm, are not erosive, and are very rare in the section studied here, which spans from ca. 53 to 29 meters core composite depth or the period from ca. 140 to 70 ka according to the age model proposed by Francke et al. (2016).

Proxy data used here comprise total inorganic carbon (TIC), total organic carbon (TOC), and biogenic silica (B-SiO_2) from Francke et al. (2016), the stable isotope composition of total inorganic carbonate ($\delta^{18}O_{TIC}$ and $\delta^{13}C_{TIC}$) from Lacey et al. (2016) and pollen data from Sadori et al. (2016). Analytical procedure and related errors, in addition to individual sampling resolutions, are discussed in the cited papers. $\delta^{18}O_{TIC}$ and $\delta^{13}C_{TIC}$ data are present only between 128 and 78 ka, where there was sufficient TIC for isotope analysis (Lacey et al., 2016). The investigated interval includes three prominent tephra layers, which were visually identified after core opening and are characterized by prominent peaks in XRF-scanning data (Francke et al., 2016). A detailed description of these tephra layers, as well as analytical procedures for their geochemical fingerprinting, can be found in Leicher et al. (2016). Most of these tephras have already been described for other cores from Lake Ohrid and nearby Lake Prespa (Lezine et al., 2010; Wagner et al., 2008; Sulpizio et al., 2010a; Vogel et al., 2010; Damaschke et al., 2013). In Figure 2 all Lake Ohrid data are plotted versus the age, according to the model established by Francke et al. (2016). Other Mediterranean records (Fig. 3) are plotted using their own published age models. Correlation with MISs is given but acknowledged to be likely inaccurate as there may not necessarily be an identical correspondence between marine and terrestrial proxies. Moreover, we use the term “transition” instead of “termination” for the passage between glacial and interglacial periods, as suggested by Kukla et al. (2002), because the definition of “termination” should be reserved for benthic isotopic records where it has been defined (e.g. Broecker and van Donk, 1970). Govin et al. (2015) have recently suggested to use the term “penultimate deglaciation” to refer to the climatic transition occurring between full glacial and interglacial conditions. The two terms are often used interchangeably. Following the definition of Govin et al. (2015) our approach is to align the $\delta^{18}O$ records at the regional scale. However, according to Govin et al. (2015), the term “synchronization” should be used when tephra layers are used. Therefore, in our tuning exercise here proposed, we align using regional proxies and we synchronise using tephra layers.

4 Results and discussion

Figure 2 shows the correlation of selected proxy series from the DEEP site. The general structure of the different proxies shows a relatively good agreement, as already discussed in other contributions of this themed issue (Francke et al., 2016; Lacey et al., 2016; Just et al., 2016). Interglacial sediments are typically characterized by calcareous and slightly calcareous silty clay, while clastic, silty clayey material dominates in the glacial periods (Francke et al., 2016). However, although orbital-scale sedimentological variability and sedimentation rates appear to remain fairly constant, differences are apparent when the cores are examined at higher resolution. The transition between MIS6 and the Last Interglacial (i.e., MIS5e) is of particular interest. In the original Biogeosciences Discussion paper by Francke et al. (2015) the age model used for the DEEP site assumed an age of 129 ± 6 ka for the tephra layer OH-DP-0499, which was correlated to P11 tephra (Rotolo et al., 2013, Leicher et al., 2015) and used as 1st order independent chronological tie point (cf., Francke et al., this 2016). Using this model, all the proxy data show a prominent change starting at ca. 124-125 ka (Fig. 2a). $\delta^{18}O_{TIC}$ shows decreasing values starting at ca. 128 ka, followed by a second, more pronounced step from ca. 124-125 ka (Fig. 2a). TIC percentage starts to increase almost synchronous to the first $\delta^{18}O_{TIC}$ step, but with a prominent rate of increase from ca. 125 ka. TOC shows a similar pattern, but with a slightly earlier and more gradual increase (Francke et al., 2015, 2016). The behavior of these three proxies can be explained by an initial step of warming at the end of the glaciation, with an increase of primary productivity possibly connected with a change in the efficiency of recycling of organic matter within the lake (e.g. burial vs. bottom oxygenation). This early signal of warmer temperature is also confirmed by $\delta^{13}C_{TIC}$, which shows a small decrease at the same time TIC percentage begins to increase, and by pollen data, which shows a synchronous small increase of arboreal pollen percentage (AP%) (Fig. 2). Interestingly, TIC percentage and isotopes show a short inversion just before the start of the second prominent step (Fig. 2). This second step is also well marked by strong increase in B-SiO_2, indicating a definite transition to interglacial conditions.

The comparison of DEEP proxy data during the MIS6-MIS5 transition with regional records (Fig. 3) shows some interesting features, which highlight the timing and evolution of the glacial/interglacial transition at Lake Ohrid and may represent the starting point for tuning consideration. A majority of Mediterranean $\delta^{18}O$ planktonic records show a two-stepped MIS6-MIS5 transition (e.g. Paterne et al., 2008; Grant et al., 2012; Martrat et al., 2014; Marino et al., 2015 and references therein). Figure 3 shows data from site ODP-975 compiled by Marino et al. (2015). In Marino et al. (2015), the well-documented intermediate-water connection between the eastern and western Mediterranean Sea allowed for the ODP-975 $\delta^{18}O$ planktonic record to be tuned with the $\delta^{18}O$ planktonic record of the LC21 core in

Eastern Mediterranean (Marino et al., 2015; Figs. 1, 3). LC21 had previously been chronologically anchored to Soreq cave U/Th speleothem chronology, based on the assumption that speleothem $\delta^{18}O$ from Soreq Cave strictly reflects changes in the isotopic composition of the eastern Mediterranean surface water (Bar-Matthews et al., 2003; Grant et al., 2012). Marino et al. (2015) subsequently propagated the ODP-975/LC21 chronology to the core ODP-976, producing an Alkenone Sea Surface Temperature (SST) record starting from the data obtained by Martrat et al. (2014) (Fig. 1, 3). Therefore, planktonic $\delta^{18}O$ records of LC21 and ODP-975 and SST from ODP-976 are all anchored to the same chronologies derived by tuning with Soreq Cave speleothems (Grant et al., 2012; Marino et al., 2015).

A similar two-stepped pattern for the MIS6-MIS5 transition is also observed in $\delta^{18}O$ of two well dated speleothems from the Apuan Alps in central Italy (Fig. 1) collected in the Corchia and Tana che Urla caves (Drysdale et al. 2009; Regattieri et al., 2014). A potential tie point for tuning between the DEEP site and these speleothem records is represented by a small inflection that is evident in the DEEP $\delta^{18}O_{TIC}$ data (green line in Fig. 3), in both speleothem $\delta^{18}O$ series (Tana Che Urla and Corchia) and in LC21 and ODP975 $\delta^{18}O$ planktonic records (green dots in Fig. 3). The end of this inflection is easily identifiable and robustly U/Th dated at Tana che Urla at 129.6±0.9 ka (Regattieri et al., 2014). The use of this tie point for the DEEP core would have several important implications. Firstly, the old DEEP age model of Francke et al. (2015) underestimated the chronology of the transition by ca. 4-5 ka. Secondly, the distinct step recorded by all the DEEP proxies at 124 ka (Fig. 2) would coincide with the phase of highest rate of rising temperature recorded in the Western Mediterranean, according to the new chronology for ODP-976 SST record (Marino et al., 2015) (Figs. 3, 4). Therefore, aligning the DEEP time-series with other Mediterranean chronologies, indicates that the rapid temperature increase observed at ca. 129-128 ka in the SST of ODP-976 is almost coincident to the sharp increase in TIC %, TOC %, AP %, and B-SiO_2 values and to the sharp decrease in $\delta^{13}C_{TIC}$ and $\delta^{13}C_{TOC}$ (Fig. 4).

To strengthen the proposed correlation of events during the MIS6-5e transition, we also consider the position of the tephra layer P-11 from Pantelleria Island in different records (Fig. 3, red dots; Paterne et al., 2008; Caron et al., 2010; Vogel et al., 2010), which is correlated with the tephra layer OH-DP-0499 recognized in the DEEP core (Leicher et al., 2016; Fig. 2). As shown in Figure 3, this tephra layer occurs at the base of the first small, but pronounced, increase of TIC in the Ohrid record. In the ODP-963A record from the central Mediterranean

(Fig. 3; Sprovieri et al., 2006; Tamburrino et al., 2012) this tephra layer (here correlated with ODP3 layer) corresponds to the first increase in the abundance of *Globigerinoides ruber* (a warm foraminifera taxa) after the end of MIS6. In core LC21 from the eastern Mediterranean, a pantelleritic tephra (Satow et al., 2015) was found at the beginning of the first decrease of *G. ruber* $\delta^{18}O$ (Fig. 3). This also corresponds to the position of P-11 in the $\delta^{18}O$ *G. bulloides* record from core KET82-22 in the Ionian Sea (Paterne et al., 2008), although this record has a low resolution compared to LC21. Overall, P-11 occupies the same "climatostratigraphic" position in every one of these records. According to the speleothem-based chronology proposed for core LC21, the Pantelleritic layer was dated at ca. 133.5±2 ka (Grant et al., 2012; Satow et al., 2015). This would be slightly older (although statistically indistinguishable) compared to the age reported from the Unit P at Pantelleria (ca. 129±6 ka, Rotolo et al., 2013), which is regarded as proximal counter part of this tephra layer (Paterne et al., 2008) and that was used for the first age model of the DEEP core (Francke et al., 2015). This age represents an average over different sets of dating, and thus has a large error (Rotolo et al., 2013). However, we have to note that even if the stratigraphic correlation between P-11 and the pantelleritic layer in LC21 is obvious, chemical data used for tephrostratigraphy are not unambiguous and could indicate a different dispersion of ash with different chemistry, as result of a zoned magma chamber (Leicher et al., 2016). Taking these considerations into account, it seems reasonable to shift the age model for the MIS6-MIS5e transition at the DEEP site by ca. 4 ka compared to Francke et al. (2015). This shift is supported by a marked increase in the abundance of *G. ruber* in ODP-963A, immediately following the P-11 tephra (Fig. 3), which is indicative of warming conditions and probably correlates with the initial TIC increase observed in the DEEP site record. Following the revision proposed here, which substantially differs from the approach used by Francke et al. (2015), Francke et al. (2016) changed the age of OH-DP-0499 tephra to that of Satow et al. (2015), which alleviated the discrepancies between the two age models for the period corresponding to the penultimate deglaciation (Fig. 4).

In the central Mediterranean, and specifically for Corchia and Tana che Urla caves, speleothem calcite $\delta^{18}O$ is principally seen as an indicator of local hydrology and interpreted in terms of "amount of precipitation", with lower/higher values related to increasing/decreasing precipitation (Bard et al., 2002; Drysdale et al., 2004, 2005, 2006, 2007, 2009; Zanchetta et al., 2007, 2014; Regattieri et al., 2014). Changes in precipitation amount, and thus in $\delta^{18}O$ of speleothem, have in turn been linked to North Atlantic conditions, with enhanced ocean evaporation and advection toward the Mediterranean (i.e. higher rainfall) during periods of higher ocean SST (e.g. Drysdale et al., 2004). Similar findings have also been found in lake $\delta^{18}O$ records (Regattieri et al., 2015, 2016; Giaccio et al., 2015). Based on such evidence, the first decreasing in the $\delta^{18}O_{TIC}$ values of the DEEP record may also be related to increasing precipitation. However, Marino et al. (2015) proposed that the first $\delta^{18}O$ decrease in both Mediterranean planktonic foraminifera and speleothems is instead related to a decreasing sea surface salinity (SSS), due to massive iceberg discharge related to Heinrich event 11 (H11), a major deglacial meltwater pulse that may account for about 70% of the glacial-interglacial sea-level rise. If this is correct then the prominent shift in the $\delta^{18}O_{TIC}$ of the DEEP record at the beginning of the transition is likely related to the progressive lowering of sea surface isotopic composition due to decreasing SSS (i.e. source effect) and not to hydrological changes (i.e., increasing of precipitation).

The designation of additional tuning points during the Interglacial appears more complicated. During the first part of MIS5e some common patterns are evident, like the prominent increase in TIC, TOC and B-SiO_2 between ca 124 and 120 ka. We suggest that a good correlation point would be the sharp increase in $\delta^{18}O$ at the transition between GI24 and GS23 visible at Corchia and the DEEP core (Fig. 3, green dots), as well as in the $\delta^{18}O$ record from lacustrine carbonate from the Sulmona basin (POP section, Regattieri et al., 2015). This point is set at ca. 105.1 ka in the CC28 stalagmite record from Corchia Cave (Drysdale et al., 2007) and it is chronologically in agreement with data from the POP section (Fig. 1, 3, Regattieri et al., 2015) and NALPS speleothem records from NE Alps (Boch et al., 2011). We note that the increase in $\delta^{18}O$ slightly precedes the TIC, TOC, and B-SiO_2 decrease. We are not able to give a detailed explanation for this, but we believe that it is more appropriate to use the $\delta^{18}O_{TIC}$ when tuning with other $\delta^{18}O$ records (speleothem and lacustrine). As discussed, we are aware by the fact that $\delta^{18}O$ in speleothems and lacustrine sediments can be affected by several local factors (e.g. Wilson et al., 2015) and unequivocal paleoclimatic interpretation may complicate the use of this proxy for "synchronization" studies (Govin et al., 2015), but the consistent nature of the $\delta^{18}O$ signal observed in different regional archives (e.g. speleothems and lacustrine carbonate) make the use of $\delta^{18}O$ of carbonate a good candidate for the alignment of the discussed records.

Two robust target points for synchronization are represented by the tephra layers OH-DP-0404 and OH-DP-0435 (Fig. 2), which were independently dated in other records (Table 1).

Particularly, both tephras occur in the POP section from the Sulmona Basin (Regattieri et al., 2015) and thus their recalculated ages can be obtained from this age model. Tephra OH-DP-0435 is also used in Francke et al. (2015, 2016) as tie point, and the ^{40}Ar/^{39}Ar radiometric age from Iorio et al. (2014) was used.

From the above discussion, we suggest an alternative age model for the MIS 5 DEEP record (Fig. 4) using the tie points shown in Figure 3 (green and purple arrows) and detailed in Table 1. This new age model was calculated using the Bacon software (Blaauw, 2011), using the same settings employed also for the construction of the DEEP site chronology by Francke at al. (2016). The simulation is limited to the chronological interval for which tie points are available (ca. 140-70 ka).

As noted before, the most significant differences are in the timing of the whole glacial/interglacial transition in the first age model of Francke et al. (2015). However, in the final version of the age model from Francke et al. (2016), incorporating the new age here proposed for the OH-DP-0499 tephra layer, the differences are less evident (Fig. 4). There is a good fit between ca. 115 ka and 108 ka and ca. 95-88 ka, whereas ages diverge again at the base of the record. Interestingly, the new model allows for comparison between the Ohrid record and with SST reconstructions from the Western Mediterranean (core ODP-975), which, as previously explained, is an indirectly, radiometrically dated record (Fig. 4). Despite a minor chronological offset, the pattern of TIC variability during the transition is consistent with that of SST.

Figure 4 also illustrates the change in sedimentation rate in the different age models. It is possible to see that by increasing the number of aligning points the sedimentation rate become significantly different, suggesting a faster decrease at the time of the interglacial inception. Sedimentation rate increased again around 120 ka, and then remained stable since ca.105 ka. We note that the Francke et al. (2016) age model (and most other age models too) are based on the assumption of gradually changing sedimentation rates. This might be true, if studying long sequences at low resolution. However, changes in sedimentation rates become more important when examining a sequence at higher resolution. On the long-term scale, and using the chronological tie points of the 11 tephras from the orbital tuning used in the Francke et al. (2015, 2016) age model, relatively constant sedimentation rates are inferred for the DEEP core site record. On closer inspection, however, there might be significant changes, particularly at the MIS6-5e transition, as inferred from the new age model (see also Francke et al., 2016), as it is highly unlikely that a decrease in clastic input from the catchment (prevailing during glacials, even if partially compensated by a reduced input of organic matter and calcite, and indicated in lithofacies 3 of Francke et al. 2016) is completely, simultaneously and equally compensated by an increase in carbonate precipitation reaching > 80% during the interglacial (MIS 5e peak, Fig. 4). This means that it is highly likely that there are significant changes in sedimentation rates, which can only be detected by high resolution studies and by a detailed comparison of different records, as indicated in this study.

From the Figure 4 is also possible to note that the strong increasing in SST and TIC occurred slightly before the maximum of summer insolation at 65°N; when the insolation reached its maximum TIC starts to decrease, whereas SST reach its maximum. A secondary maximum in TIC occurs at ca. 86 ka, ca. 4 ky before the maximum in insolation, whereas the decrease starts at the maximum of insolation.

With the new age model presented here it is also possible to attempt a more precise regional correlation of pollen records. In Figure 5 pollen records from Tenaghi Philippon, (Fig. 1, Milner et al. 2012, 2013; Pross et al. 2015) and Monticchio (Fig. 1; Brauer et al. 2007) are plotted against the DEEP site pollen record (Sadori et al., 2016). The sharp increase in the AP percentages at ca. 130 ka is almost synchronous in all the mentioned records, and simultaneous to the highest rate of SST increase in the western Mediterranean (Fig. 4). A comparison of the chronology from different records after the end of the Eemian forest phase is more problematic, since the first clear forest opening coincides with the C24 cold event in the North Atlantic (Sánchez-Goñi et al., 1999). In the DEEP core, two tephra layers and a robust alignment point at the end of GI24 probably make this chronology the most reliable, even if in the younger part of the record there are no further alignment points.

The proposed correlation exercise described here can potentially be extended in the future to other sections of the DEEP record. The $\delta^{18}O_{TIC}$ and TIC data contain interesting points for tuning, even if correlations with regional records are not always obvious. However, both have limitation because TIC is particularly low or absent during most of the glacial periods (Lacey et al., 2016; Francke et al., 2016) and seems to be affected by dissolution once a critical threshold is exceeded. Because of preservation/dissolution processes during glacial periods (Lacey et al., 2016; Francke et al., 2016) the selection of correlation points at the beginning of the glacial/interglacial transition would be complex. Moreover, the interglacial periods seem the more appropriate periods for applying the approach presented here. Therefore, a careful selection between proxy data is necessary, because leads and lags are evident when the fine scale is considered. However, the DEEP multiproxy record, along with the presence of regionally important tephra layers, allow us to apply a range of alignment and synchronization approaches.

4 Conclusions

Regional proxy records that have been independently dated support the development of a more detailed chronology for the Lake Ohrid DEEP site record in the interval covering the MIS6/5 transition and the first part of MIS5. The aligning with regional proxies indicates that the most prominent rate of increase of B-SiO$_2$, TIC, TOC, AP%, and $\delta^{13}C_{TOC}$ is concomitant with increasing in temperature in Western Mediterranean cores (Figs. 3, 4), whereas $\delta^{18}O_{TIC}$ and TIC seem also to record an early warming, probably connected with hydrological changes (increasing rainfall). $\delta^{18}O_{TIC}$ may also record a source change in the isotopic composition of oceanic surface waters due to a massive discharge of freshwater resulting from the H11 event (Marino et al., 2015).

During the MIS5 interglacial, different proxy records show generally similar patterns but with evident leads and lags, which can make the selection of the tuning points somewhat more complex. However, the presence of two regionally widespread tephra layers allows a relatively good anchoring of the chronology.

It is important to remark that the approach proposed here can be extended to relatively few intervals of the long DEEP record because independently radiometrically dated records in the Mediterranean region are rare for periods older than the MIS5 (e.g. Bar-Matthews et al., 2000; Drysdale et al., 2004; Giaccio et al., 2015; Regattieri et al., 2016). Therefore, the approach proposed by Baumgarten et al. (2015) and Francke et al. (2016) still appears the most suitable for the definition of general chronological framework of the long record.

Acknowledgements

The SCOPSCO Lake Ohrid drilling campaign was funded by ICDP, the German Ministry of Higher Education and Research, the German Research Foundation, the University of Cologne, the British Geological Survey, the INGV and CNR (both Italy), and the governments of the republics of Macedonia (FYROM) and Albania. Logistic support was provided by the

Hydrobiological Institute in Ohrid. Drilling was carried out by Drilling, Observation and Sampling of the Earth’s Continental Crust’s (DOSECC) and using the Deep Lake Drilling System (DLDS). Special thanks are due to Beau Marshall and the drilling team. Ali Skinner and Martin Melles provided immense help and advice during logistic preparation and the drilling operation. We thank two anonymous reviews for the constructive comments and criticisms, which improved the quality of the manuscript.

References

Albert, P. G., Hardiman, M., Keller, J., Tomlinson, E. L., Smith, V. C., Bourne, A. J., Wulf, S., Zanchetta, G., Sulpizio, R., Müller, U. C., Pross, J., Ottolini, L., Matthews, I.P., Blockley S. P. E., and Menzies, M. A.: Revisiting the Y-3 tephrostratigraphic marker: a new diagnostic glass geochemistry, age estimate, and details on its climatostratigraphical context, Quat. Sc. Rev., doi:10.1016/j.quascirev.2014.04.002, 2015.

Albrecht, C., and Wilke, T.: Lake Ohrid: Biodiversity and evolution, Hydrobiol., 615, 103–140, 2008.

Almogi-Labin, A., Bar-Matthews, M., Shriki, D., Kolosovsky, E., Paterne, M., Schilman, B., Ayalon, A., Aizenshtat, Z., and Matthews, A.: Climatic variability during the last 90 ka of the southern and northern Levantine Basin as evident from marine records and speleothems. Quat. Sc. Rev., 28, 2882-2896, 2009.

Anovski, T, Andonovski, B, and Minceva, B.: Study of the hydrological relationship between Lake Ohrid and Prespa. Proc Symp Isotope Techn Water Res Dev. IAEA, Vienna,

Austria, March 1991, 737-740 1992.

Bard, E., Delaygue, G., Rostek, F., Antonioli, F., Silenzi, S., and Schrag, D.: Hydrological conditions in the western Mediterranean basin during the deposition of Sapropel 6 (ca. 175 kyr). Earth Planet. Sc. Lett. 202, 481-494, 2002.

Bar-Matthews, M., Ayalon, A., and Kaufmann, A.: Timing and hydrological conditions of sapropel events in the eastern Mediterranean, as evident from speleothems, Soreq cave, Israel. Chem. Geol., 169, 145-156, 2000.

Bar-Matthews, M., Ayalon, A., Gilmor, M., Matthews, A.,Hawkeshworth, C.J.: Sea–land oxygen isotopic relationships from planktonic foraminifera and speleothems in the Eastern Mediterranean region and their implication for paleorainfall during interglacial intervals. Geochim. Cosmochim. Acta 67, 3181–3199, 2003.

Baumgarten, H., Wonik, T., Tanner, D. C., Francke, A., Wagner, B., Zanchetta, G., Sulpizio, R., Giaccio, B., and Nomade, S.: Age–depth model of the past 630 kyr for Lake Ohrid (FYROM/Albania) based on cyclostratigraphic analysis of downhole gamma ray data.Biogeosci., 12, 7453-7465, 2015.

Berger, A., and Loutre, M. F.: Insolation values for the climate of the last 10 million years. Quat. Sc. Rev., 10, 297-317, 1991.

Blaauw, M.: Out of tune: the dangers of aligning proxy archives. Quat. Sc. Rev., 36, 38-49, 2012.

Blockley, S., Rasmussen, S. O., Harding, P., Brauer, A., Davies, S., Hardiman, M., Lane, C., Macleod, A., Matthews, I., Wulf, S., and Zanchetta G.: Tephrochronology and the extended INTIMATE (Integration of ice-core, marine and terrestrial records) event stratigraphy 8-110 ka B2K. Quat. Sc. Rev. 106, 88-100, 2014.

Brauer, A., Allen, J.R.M., Mingram, J., Dulski, P., Wulf, S., Huntley, B.: Evidence for last interglacial chronology and environmental change from Southern Europe. PNAS, 104, 450-455, 2007.

Broecker, W.S., and van Donk J.: Insolation changes, ice volume, and the o18 record in deep-sea cores. Rev. Geophys. 8, 169-198, 1970.

Boch, R., Cheng, H., Spötl C., et al.: NALPS: a precisely dated European climate record 120–60 ka. Clim. Past 7, 1247–1259, 2011.

Caron, B., Sulpizio, R., Zanchetta, G., Siani, G., and Santacroce, R.: The Late Holocene to Pleistocene tephrostratigraphic record of lake Orhid (Albania). Comptes Ren. Geosc., 342, 453–466, 2010.

Damaschke, M., Sulpizio, R., Zanchetta, G., Wagner, B., Böhm, A., Nowaczyk, N., Rethemeyer, J., and Hilgers A.: Tephrostratigraphic studies on a sediment core from Lake Prespa in the Balkans. Clim. Past, 9, 267-287, 2013.

Drysdale, R.N., Zanchetta, G., Hellstrom, J. C., Fallick, A. E., McDonald, J., and Cartwright, I.: Stalagmite evidence for the precise timing of North Atlantic cold events during the early last glacial, Geology, 35, 77-80, 2007.

Drysdale, R.N., Hellstrom, J. C., Zanchetta, G., Fallick, A. E., Sánchez Goñi, M. F., Couchoud, I., McDonald, J., Maas, R., Lohmann, G., and Isola, I.: Evidence for Obliquity Forcing of Glacial Termination II, Science, 325, 1527-1531, 2009.

Föller, K., Stelbrink, B., Hauffe, T., Albrecht, C., and Wilke, T.: Constant diversification rates of endemic gastropods in ancient Lake Ohrid: Ecosystem resilience likely buffers environmental fluctuations, Biogeosci. 12, 7209-7222, 2015.

Francke, A., Wagner, B., Just, J., Leicher, N., Gromig, R., Vogel, H., Baumgarten, H., Lacey, J. H., Zanchetta, G., Sulpizio, R., Giacco, B., Wonik, T., and Leng, M. J.: Sedimentological processes and environmental variability at Lake Ohrid (Macedonia, Albania) between 640 ka and modern days, Biogeosci. Disc., this issue, submitted.

Francke, A., Wagner, B., Just, J., Leicher, N., Gromig, R., Baumgarten, H., Vogel, H., Lacey, J. H., Sadori, L., Wonik, T., Leng, M. J., Zanchetta, G., Sulpizio, R., and Giacco, B.: Sedimentological processes and environmental variability at Lake Ohrid (Macedonia, Albania) between 637 ka and the present. Biogeosci. 13, 1179-1196, 2016.

Giaccio, B., Regattieri, E., Zanchetta, G., Nomade, S., Renne, P. R., Sprain, C. J., Drysdale, R. N., Tzedakis, P. C., Messina, P., Scardia, G., Sposato, A., and Bassinot, F.: Duration and dynamics of the best orbital analogue to the present interglacial. Geology, 43, 603–606, 2015.

Govin, A., Capron, E., Tzedakis, P.C., Verheyden, S., Ghaleb, B., Hillaire-Marcel, C., St-Onge, G., Stoner, J.S., Bassinot, F., Bazin, L., Blunier, T., Combourieu-Nebout, N., El Ouahabi, A., Genty, D., Gersonde, R., Jimenez-Amat, P., Landais, A., Martrat, B., Masson-Delmotte, V., Parrenin, F., Seidenkrantz, M.-S., Veres, D., Waelbroeck, C., Zahn, R.: Sequence of events from the onset to the demise of the Lasdt Interglacial: Evaluating strnghts and limitations of chronologies used in climatic archives. Quat. Sc. Rev., 129, 1-36, 2015.

Grant, K. M., Rohling, E. J., Bar-Matthews M., Ayalon A., Medina-Elizalde, M., Bronk Ramsey, C., Satow, C., and Roberts A. P.: Rapid coupling between ice volume and polar temperature over the past 150,000 years. Nature, 491, 744-747, 2012.

Hays, J. D., Imbrie, J., Shackleton, N. J.: Variations in the Earth's Orbit: Pacemaker of the Ice Ages For 500,000 years, major climatic changes have followed variations in obliquity and precession. Science, 194, 1121-1132, 1976.

Hodell, D., Crowhurst, S., Skinner, L., Tzedakis, P.C., Margari, V., Channell, J.E., Kamenov, G., Maclachlan, S. and Rothwell, G.: Response of Iberian Margin sediments to orbital and suborbital forcing over the past 420 ka. Paleoceanography, 28, 185-199, 2013

Iorio, M., Liddicoat, J., Budillon, F., et al.: Combined palaeomagnetic secular variation and petrophysical records to time constrain geological and hazardous events: an example from the eastern Tyrrhenian Sea over the last 120 ka. Glob. Planet. Chang., 113, 91–109, 2014.

Jiménez-Amat, P., and Zahn, R.: Offset Timing of Climate Oscillations During the Last two Glacial-Interglacial Transitions Connected with Large-Scale Freshwater Perturbation. Paleoceanography, 30, 768-788, 2015.

Kukla, G. J., Bender, M. L., de Beaulieu, J.-L., Bond, G., Broecker, W. S., Cleveringa, P., Gavin, J.E., Herbert, T. D., Imbrie, J., Jouzel, J.. Keigwin, L. D., Knudsen, K.-L., McManus, J. F.; Merkt, J., Muhs, D. R., Muller, H., Poore, R. Z., Porter, S. C., Seret, G., Shackleton, N. J., Turner, C.; Tzedakis, P. C., and Winograd, I J.: Last Interglacial Climates. Quat. Res., 58, 2–13, 2002.

Just, J., Nowaczyk, N., Francke, A., Sagnotti L., and Wagner, B.: Climatic control on the occurrence of high-coercivity magnetic minerals and preservation of greigite in a 640 ka sediment sequence from Lake Ohrid (Balkans). Biogesc., 13, 2093-2109, 2016.

Lacey, J. H., Leng J. M., Francke, A., Sloane, H. J., Milodowski, A., Vogel, H., Baumgarten, H., Zanchetta, G., and Wagner, B.: Northern Mediterranean climate since the Middle Pleistocene: a 637 ka stable isotope record from Lake Ohrid (Albania/Macedonia). Biogesc. 13, 1801-1820, 2016.

Leicher, N., Zanchetta, G., Sulpizio, R., Giaccio, B., Wagner, B., Nomade, S., and Francke, A., Del Carlo P.; First tephrostratigraphic results of the DEEP site record in Lake Ohrid, Macedonia. Biogesc., 13, 2151-2178.

Lézine, A.-M., von Grafenstein, U., Andersen, N., Belmecheri, S., Bordon, A., Caron, J., Cazet, P., Erlenkeuser, H., Fouache, E., Grenier, C., Huntsman-Mapila, P., Hureau-Mazaudier, D., Manelli, D., Mazaud, A., Robert, C., Sulpizio, R., Tiercelin, J.-J., Zanchetta, G., and Zeqollari Z.: Lake Ohrid, Albania, provides an exceptional multi-proxy record of environmental changes during the last glacial-interglacial cycle. Palaeogeogr., Palaeoclimatol., Palaeoecol. 287, 116–127, 2010.

Lindhorst, K., Krastel, S., Reicherter, K., Stipp, M., Wagner, B., and Schwenk, T.: Sedimentary and tectonic evolution of Lake Ohrid (Macedonia/Albania), Basin Research, 27, 84-101, 10.1111/bre.12063, 2015.

Lisiecki L. E., and Raymo M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography, 20, PA1003, doi:10.1029/2004PA001071, 2005.

Lowe, D. L.: Tephrochronology and its application: a review. Quaternary Geochronology 6, 107–153, 2011

Marino, G., Rohling, E. J., Rodrìguez-Sanz, L., Grant, K.M., Heslop, D., Roberts, A. P., Stanford, J. D., and Yu, J.: Bipolar seesaw control on last interglacial sea level. Nature, 197, 197-201, 2015

Martinson, D. G., Pisias, N. G., Hays, J. D., Imbrie, J., Moore, Jr., T. C., and Shackleton, N. J.: Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy. Quat. Res., 27, 1-29, 1987.

Martrat, B., Jimenez-Amat, P., Zahn, R., and Grimaltm J. O.: Similarities and dissimilarities between the last two deglaciations and interglaciations in the North Atlantic region. Quat. Sc. Rev., 99, 122-134, 2014.

Matzinger, A., Spirkovski, Z., Patceva, S., and Wüest, A.: Sensitivity of ancient Lake Ohrid to local anthropogenic impacts and global warming. Journal of Great Lakes Research, 32:158–179, 2006.

Matzinger, A., Schmid, M., Veljanoska-Sarafiloska, E., Patceva, S., Guseska, D., Wagner, B., Müller, B., Sturm, M., and Wüest, A.: Eutrophication of ancient Lake Ohrid: global warming amplifies detrimental effects of increased nutrient inputs, Limnol. Oceanogr., 52, 338–353, 2007.

Milner, A.M., Collier, R.E.L., Roucoux, K.H., Müller, U.C., Pross, J., Kalaitzidis, S., Christanis, K. and Tzedakis, P.C.: Enhanced seasonality of precipitation in the Mediterranean during the early part of the Last Interglacial. Geology, 40, 919-922, 2012.

Milner, A.M., Müller, U.C., Roucoux, K.H., Collier, R.E.L., Pross, J., Kalaitzidis, S., Christanis, K. and Tzedakis, P.C.,. Environmental variability during the Last Interglacial: A new high-resolution pollen record from Tenaghi Philippon, Greece. J. Quat. Sc., 28, 113-117, 2013.

Paterne, M., Guichard, F., Duplessy, J.C., Siani, G., Sulpizio, R., and Labeyrie, J.: A 90,000–200,000 yrs marine tephra record of Italian volcanic activity in the Central Mediterranean Sea. J. Volcanol, Geoth. Res., 177, 187–196, 2008.

Popovska C., and Bonacci O.: Basic data on the hydrology of Lakes Ohrid and Prespa. Hydrol Process 21:658–664, 2007.

Pross, J., Koutsodendris, A., Christanis, K., Fischer, T., Fletcher, W.J., Hardiman, M., Kalaitzidis, S., Knipping, M., Kotthoff, U., Milner, A.M., Müller, U.C., Schmiedl, G., Siavalas, G., Tzedakis, P. C. and Wulf, S.: 2015. The 1.35-Ma-long terrestrial climate archive of Tenaghi Philippon, northeastern Greece: Evolution, exploration, and perspectives for future research. Newslett. Strat, 48(3): 253-276, 2015.

Railsback, R. B., Gibbard, P .L., Head, M. J., Voarintsoa, N. R. G., and Toucanne, S.: An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. Quat. Sc. Rev. 111, 94-106, 2015.

Regattieri, E., Giaccio, B., Galli, P., Nomade, S., Peronace, E., Messina P., Sposato, A., Boschi, C., and Gemelli, M.: A multi-proxy record of MIS 11-12 deglaciation and glacial MIS 12 instability from the Sulmona Basin (central Italy). Quat. Sc. Rev., 32, 129-145, 2016.

Regattieri, E., Zanchetta, G., Drysdale, R.N., Isola, I., Hellstrom, J.C., and Roncioni A.: A continuous stable isotope record from the penultimate glacial maximum to the Last Interglacial (159–121ka) from Tana Che Urla Cave (Apuan Alps, central Italy). Quat. Res. 82, 450–461, 2014.

Regattieri, E., Giaccio, B., Zanchetta, G., Drysdale, R. N., Galli, P., Nomade, S., Peronace, E., and Wulf, S.: Hydrological variability over the Apennines during the Early Last Glacial precession minimum, as revealed by a stable isotope record from Sulmona basin, Central Italy. J. Quat. Sc., 30, 19-31, 2015.

Rotolo, S. G., Scaillet, S., La Felice, S., Vita-Scaillet, G.: A revision of the structure and stratigraphy of pre-Green Tuff ingimbrites at Pantelleria (Strait of Sicily). Journal of Volcanology and Geothermal Research, 250, 61-74, 2013.

Sadori, L., Koutsodendris, A., Panagiotopoulus, K., Masi, A., Bertini, A., Combourieu-Nebout, N., Francke, A., Kouli, K., Joannin, S., Mercuri, A.M., Peyron, O., Torri, P., Wagner, B., Zanchetta, G., and Sinopoli G.: Pollen-based paleoenvironmental and paleoclimatic change at Lake Ohrid (south-eastern Europe) during the past 500 ka. Biogesc. 13, 1423-1437, 2016.

Sánchez-Goñi, M. F., Bard, E., Landais, A., Rossignol, L., and d’Errico F.: 2013 Air–sea temperature decoupling in western Europe during the last interglacial–glacial Transition. Nat. Geosc., 6, 837-841, 2013.

Sánchez-Goñi, M., Eynaud, F., Turon, J. and Shackleton, N.: High resolution palynological record off the Iberian margin: direct land-sea correlation for the Last Interglacial complex. E. Planet. Sc. Lett., 171, 123-137, 1999.

Satow, C., Tomlinson E. L., Grant, K. M., Albert, P.G., Smith V.C., Manning C.J., Ottolini L., Wulf S., Rohling E. J., Lowe J. J.,. Blockley S. P. E, and Menzies M.A.: A new contribution to the Late Quaternary tephrostratigraphy of the Mediterranean: Aegean Sea core LC21. Quat. Sc. Rev. 117, 96-112, 2015.

Shackleton, N. J.: Oxygen isotopes, ice volume and sea level. Quat. Sc. Rev. 6, 183–190, 1987.

Shackleton, N. J., 2000. The 100,000-Year Ice-Age Cycle Identified and Found to Lag Temperature, Carbon Dioxide, and Orbital Eccentricity. Science 289, 1897-1902, 2000.

Stankovic, S.: The Balkan Lake Ohrid and Its Living World, Uitgeverij Dr. W. Junk, Den Haag, 1960.

Skinner, L.C., Shackleton, N.J.: Deconstructing Terminations I and II: revisiting the glacioeustatic paradigm based on deep-water temperature estimates. Quat. Sc. Rev. 25, 3312–3321, 2006.

Sprovieri, R. Di Stefano, E., Incarbona, A., Oppo, D. W.: Suborbital climate variability during Marine Isotopic Stage 5 in the central Mediterranean basin: evidence from calcareous plankton record. Quat. Sc. Rev., 25, 2332-2342, 2006.

Sulpizio, R., van Welden, A., Caron, B., and Zanchetta, G.: The Holocene tephrostratigraphy of Lake Shkodra (Albania and Montenegro). J. Quat. Sc. 25, 633–650, 2010a.

Sulpizio R., Zanchetta G., D'Orazio M., Vogel H., and Wagner B.. Tephrostratigraphy and tephrochronology of the lakes Ohrid and Prespa, Balkans. Biogesciences, 7, 3273-3288, 2010b.

Tamburrino, S., Insinga, D., Sprovieri, M., Petrosino, P., and Tiepolo M.: Major and trace element characterization of tephra layers offshore Pantelleria Island: insights into the last 200 ka of volcanic activity and contribution to the Mediterranean tephrochronology. J. Quat. Sc., 27, 129-140, 2012.

Trajanovski, S., C. Albrecht, K., Schreiber, R. Schultheiß, T. Stadler, M. Benke, and Wilke T., Testing the spatial and temporal framework of speciation in an ancient lake species flock:The leech genus *Dina* (Hirudinea: Erpobdellidae) in Lake Ohrid. Biogeosciences, 7, 3387–3402, 2010.

Tzedakis, P. C., Hooghiemstra, H., and Pälike, H.: The last 1.35 million years at Tenaghi Philippon: revised chronostratigraphy and long-term vegetation trends. Quat. Sc. Rev., 25, 3416-3430, 2006.

Tzedakis, P. C., Andrieu, V., de Beaulieu, J.-L., Crowhurst, S., Follieri, M., Hooghiemstra, H., Magri, D., Reille, M., Sadori, L., Shackleton, N. J., and Wijmstra, T. A.: Comparison of terrestrial and marine records of changing climate of the last 500,000 years. E. Planet. Sc. Lett. 150, 171–176, 1997.

Tzedakis, P. C., Andrieu, V., Birks, H. J. B., de Beaulieu, J.-L., Crowhurst, S., Follieri, M., Hooghiemstra, H., Magri, D., Reille, M., Sadori, L., Shackleton, N. J., Wijmstra, T. A., Establishing a terrestrial chronological framework as a basis for biostratigraphical comparisons. Quat. Sc. Rev. 20, 1583–1592, 2001.

Vogel, H., Zanchetta, G., Sulpizio, R., Wagner, B., Nowaczyk, N.:. A tephrostratigraphic record for the last glacial-interglacial cycle from Lake Ohird, Albania and Macedonia. J. Quat. Sc., 25, 320-338, 2010.

Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J. F., Lambeck, K., Balbon, E., and Labracherie, M.: Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quat. Sc. Rev. 21, 295–305, 2002.

Wagner, B., Sulpizio, R., Zanchetta, G., Wulf, S., Wessels, M., Daut, G., Nowaczyk, N. 2008. The last 40 ka tephrostratigraphic record of Lake Ohrid, Albania and Macedonia: a very distal archive for ash dispersal from Italian volcanoes. J. Volcanol. Geoth. Res., 177, 71-80, 2008.

Wagner, B., Wilke, T., Krastel, S., Zanchetta, G., Sulpizio, R., Reicherter, K., Leng, M. J., Grazhdani, A., Trajanovski, S., Francke, A., Lindhorst, K., Levkov, Z., Cvetkoska, A., Reed, J. M., Zhang, X., Lacey, J. H., Wonik, T., Baumgarten, H., and Vogel, H.: The SCOPSCO drilling project recovers more than 1.2 million years of history from Lake Ohrid. Sc. Drill., 17, 19–29, 2014a.

Wagner, B., Wilke, T., Krastel, S., Zanchetta, G., Sulpizio, R., Reicherter, K., Leng, M., Grazhdani, A., Trajanovski, S., Levkovm Z., Reed, J., and Wonik T.: More than one Million years of History of Lake Ohrid cores. EOS, 95, 25-32, 2014b.

Watzin, M. C., Puka, V., and Naumoski, T.B.: Lake Ohrid and its Watershed, State of the Environment Report. Lake Ohrid Conservation Project. Tirana, Albania and Ohrid, Macedonia, 2002.

Wilson, G.P., Reed, J.R., Frogley, M.R., Hughes, P.D., Tzedakis, P.C.: Reconciling diverse lacustrine and terrestrial system response to penultimate deglacial warming in southern Europe. Geology, 43, 819-822. 2015.

Wulf, S, Keller, J, Paterne, M, et al.: The 100–133 ka record of Italian explosive volcanism and revised tephrochronology of Lago Grande di Monticchio. Quat, Sc. Rev., 58, 104–123, 2012.

Wulf, S., Kraml, M., Brauer, A., Keller, J., and Negendank, J. F. W., Tephrochronology of the 100 ka lacustrine sediment record of Lago Grande di Monticchio (southern Italy). Quat. Inter. 122, 7–30, 2004.

Wulf, S., Kraml, M., and Keller, J.: Towards a detailed distal tephrostratigraphy in the Central Mediterranean: the last 20,000 yrs record of Lago Grande di Monticchio. J. Volcanol. Geother. Res. 177, 118–132, 2008.

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

Zanchetta, G., Giraudi, C., Sulpizio, R., Magny, M., Drysdale, R. N., and Sadori L.: Constraining the onset of the Holocene “Neoglacial” over the central Italy using tephra layers. Quat. Res., 78, 236-247, 2012a.

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

Zhornyak, L.V., Zanchetta, G., Drysdale, R. N., Hellstrom, J. C., Isola, I., Regattieri, E., Piccini, L., and Baneschi I.: Stratigraphic evidence for a “pluvial phase” between ca. 8200-7100 ka from Renella Cave (Central Italy). Quat. Sc. Rev., 30, 409-417, 2011.

Ziegler, M, Tuenter, E, and Lourens, L. J.: The precession phase of the boreal summer monsoon as viewed from the eastern Mediterranean (ODP Site 968). Quat. Sc. Rev. 29: 1481–1490, 2010.

			DEEP core age model				This study					
tuning points		mcd depth	Final AM		Discussion AM		New used age		New modelled age		Age differences	
			Age (ka)	2σ (ka)	age	2σ (ka)	Age (ka)	2σ (ka)	Age (ka)	2σ (ka)	Final	Discussion
tephra	POP2	40.49	101.8	2.4	99.2	3.2	102.0^{+}	2.4	103.6	3	-1.8	-1.8
tuning	end GI24	41.63	104.8	4.2	103.1	3.6	$105.4^{\S}$	0.9	105.4	1.8	-0.6	-2.3
tephra	POP4	43.51	109.8	2.0	109.7	2	109	1.5	109.7	2.4	0.1	0
tuning	TII TCU	48.58	127.7	6.6	124.4	2.7	129.6**	0.9	129.4	2	-1.7	-5
tephra	P11	49.94	133.0	2.0	129.4	6	133.5*	2.0	132.7	2.7	0.3	-3.3

*from Satow et al., 2015 (after Grant et al., 2012),**from Tana che Urla record (Regattieri et al., 2014), §from Popoli section record (Regattieri et al., 2015), $^{+}$from Corchia Cave CC28 record (Drysdale et al., 2007)

Table 1- Chronological tie points discussed in this study. DEEP core ages and associated 2σ uncertainties are from Francke et al., 2015 (Discussion AM) and Francke et al., 2016 (Final AM) age models.

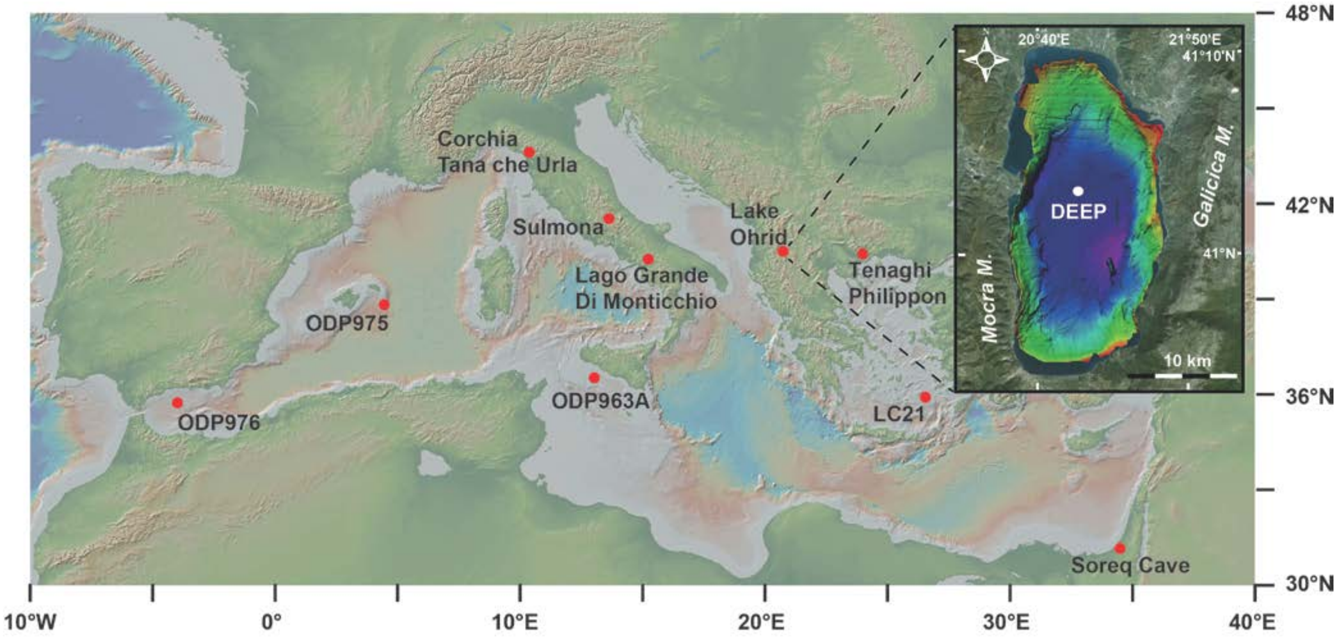

Figure 1. A) site quoted in the text; B) DEEP site drilling location within Lake Ohrid

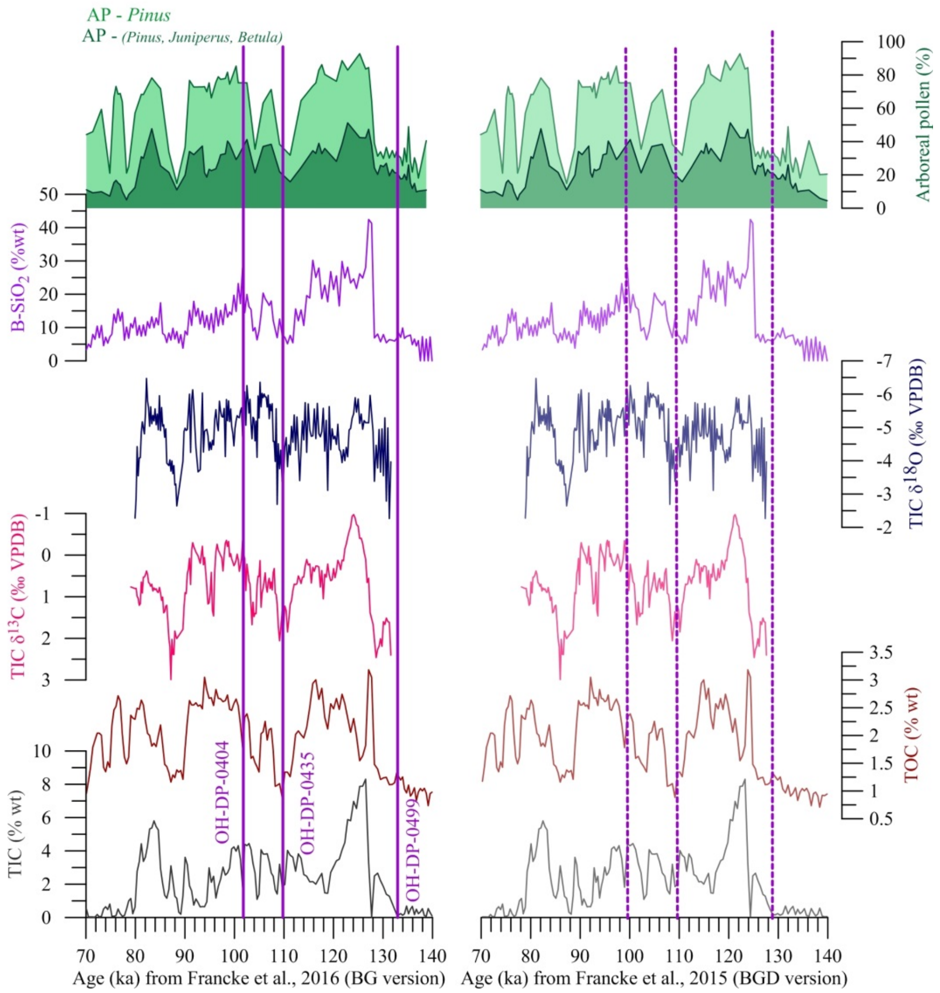

Figure 2- DEEP site proxy series plotted on age models from Francke et al., 2016 (left) and Francke et al. (2015, Discussion version) (right). From top: B-SiO$_2$ after Francke et al. 2016, AP% (Arboreal Pollen, without considering *Pinus* spp. pollen grains) after Sadori et al., 2016; TIC δ^{13}C after Lacey et al., 2016; TIC δ^{18}O after Lacey et al. (2016); TOC and TIC % after Francke et al. (2016). Violet lines indicate tephra layers.

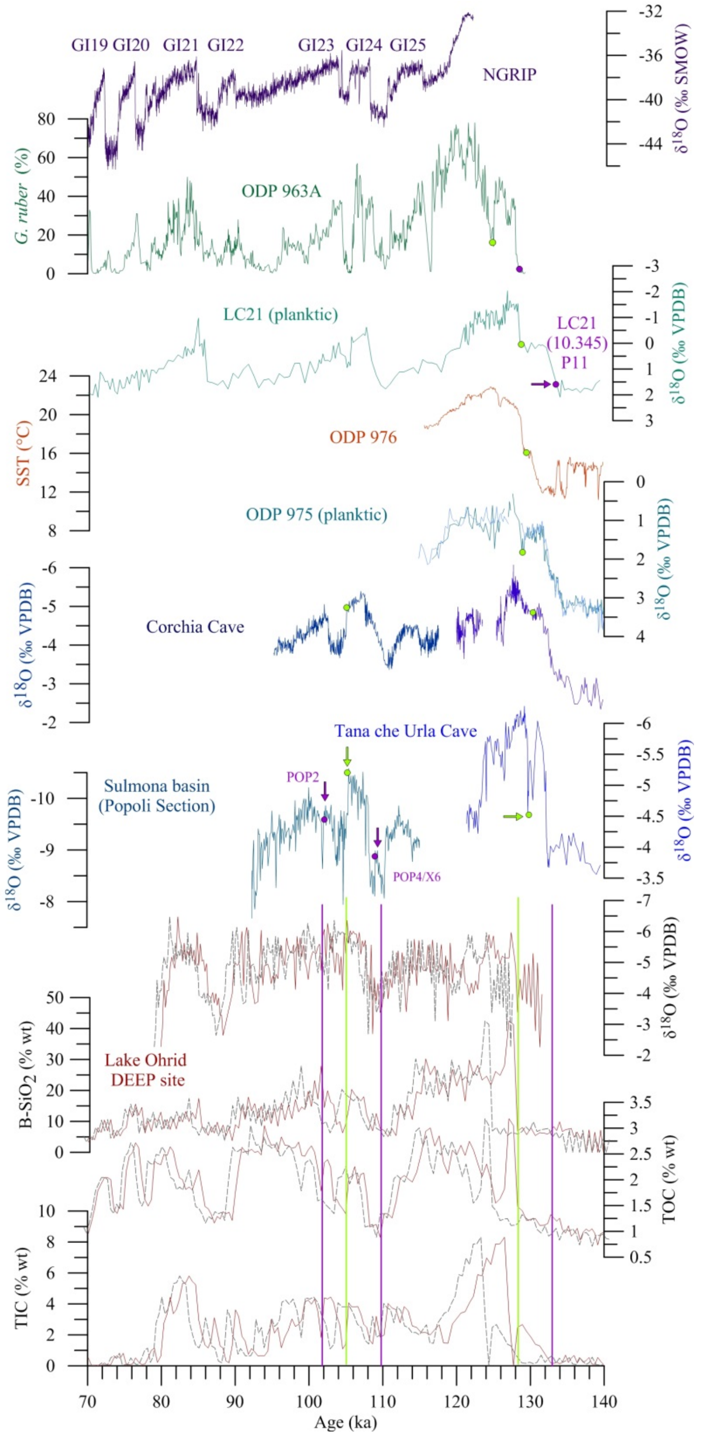

Figure 3. Comparison of selected DEEP proxies (TIC δ^{18}O after Lacey et al. (2016), B-SiO$_2$ after Francke et al. (2016), TOC and TIC % after Francke et al. 2016) with regional to extra regional record. From the bottom: δ^{18}O from Sulmona paleolake (POP section, Regattieri et al., 2015); δ^{18}O from Corchia Cave (CC5 Drysdale et al., 2009; CC28 Drysdale et al. 2007) and Tana che Urla Cave (Regattieri et al., 2014); ODP-975 planktic δ^{18}O (*G. ruber* darker; *G. bulloides*, lighter, after Marino et al., 2015); ODP-976 Alkenone SST (data from Martrat et

al., 2014 and age model after Marino et al., 2015); LC21 planktic $\delta^{18}O$ (*G. bulloides* Grant et al. 2012); ODP-963A *G. ruber* abundance (Sprovieri et al., 2006); $\delta^{18}O$ from NGRIP ice core (NGRIP member 2004). Violet dots indicates correlated tephra layers (LC21 10.345/P11 on core LC21 and ODP-963A, POP2 and POP4/X6 on Sulmona Basin $\delta^{18}O$ record, Regattieri et al., 2015); green dots indicate correlated points used for tuning. Arrows and lines (violet=tephras, green= tuning point) indicates age tuning points. See text and table 1 for details. Dotted lines are the same proxies, but plotted using the Franke et al 2015 age model.

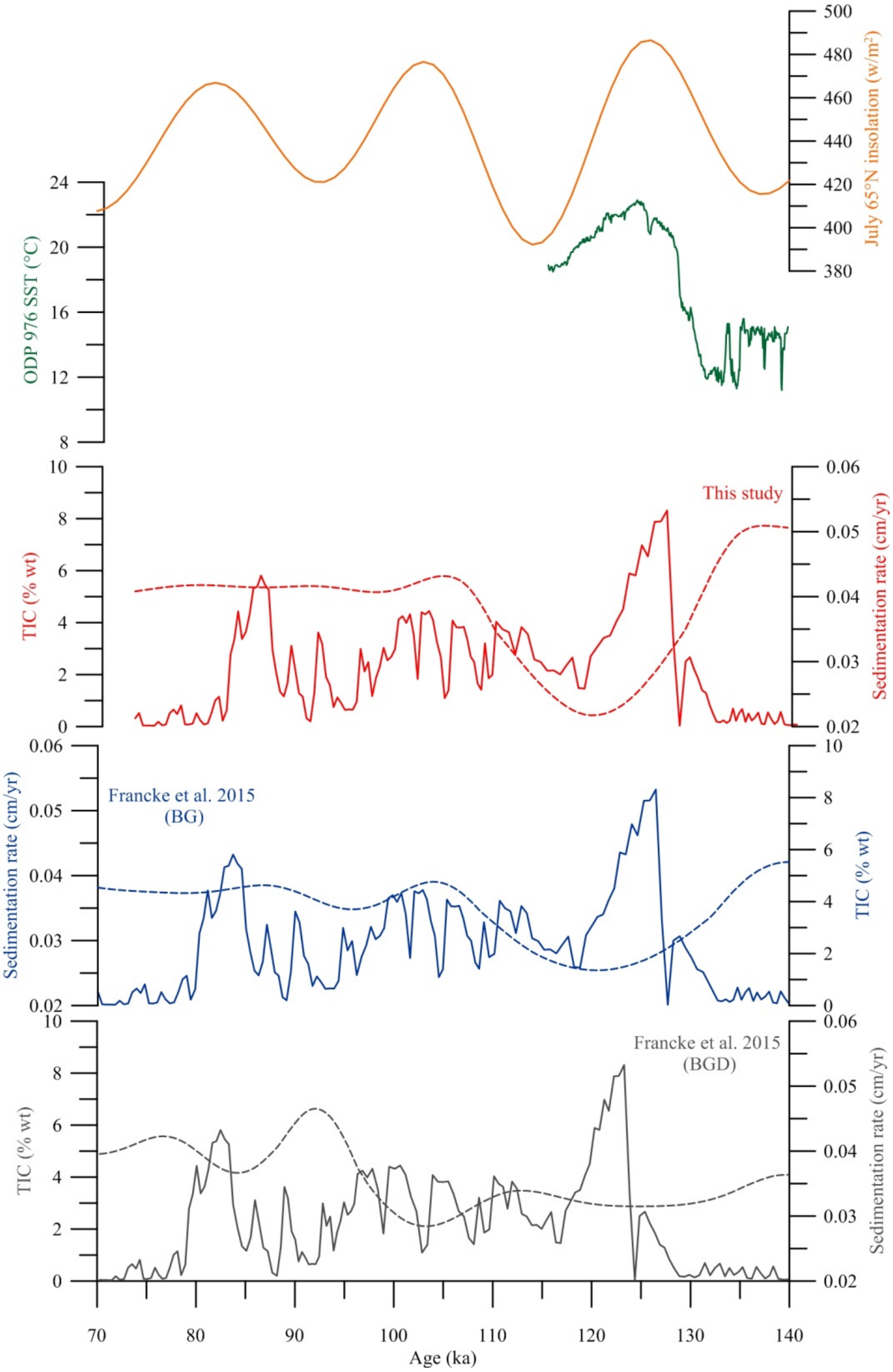

Figure 4- From bottom: TIC (%wt) and sedimentation rate of DEEP site plotted on age models from Francke et al., 2015, Discussion version, grey); Francke et al. (2016, blue); This study (red); Alkenone SST (°C) for core ODP-976 (Marino et al., 2015, green); Summer (July) insolation at 65°N (orange) (Berger and Loutre, 1991).

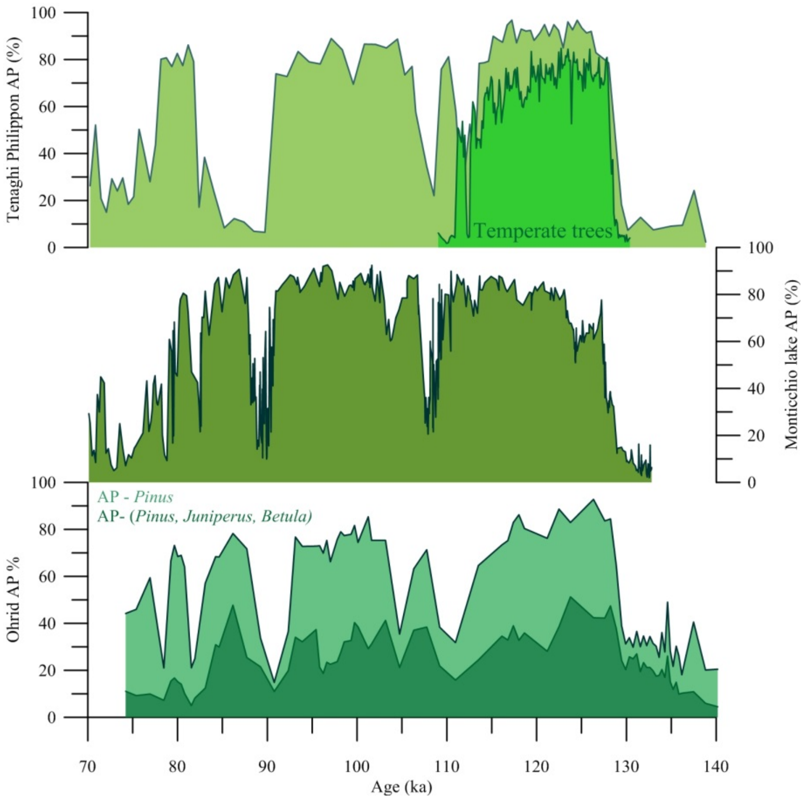

Figure 5- From bottom: DEEP site pollen record (AP- *Pinus* and AP- (*Pinus, Betula and Juniperus*), Sadori et al., 2016) plotted on chronology proposed in this study; Monticchio Lake arboreal pollen (Brauer et al., 2007); Tenaghi Philippon, % of temperate trees from Milner et al. (2012) and total AP from Tzedakis et al. (2006).