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

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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 marine isotope record. 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. In this paper, we demonstrate how the use of different tie points can affect cyclostratigraphy and orbital tuning for the period between ca. 140 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 obtained shows consistent differences with that proposed by Francke et al. (2015) for the same interval, in particular at the level of the MIS6-5e transition. According to this 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 important a detailed study of independent chronological tie points is for synchronizing different records and to highlight asynchronisms of climate events.

1 Introduction

Since the demonstration of a strong astronomical control on δ^{18}O signal 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 reference for chronological tuning of continental successions (Tzedakis et al., 1997) and infers, for instance, the response of regional vegetation to climate forcing on a global scale. δ^{18}O reference records are often based on benthic foraminifera, with appropriate species

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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 et al., 2003), and by translation the records can also be used for inferring sea-level oscillations (Shackleton et al., 1987; Woolbreak et al., 2002).

However, when marine records are used for tuning terrestrial archives there is an implicit assumption of synchronicity between marine and terrestrial events. Under scrutiny such a relationship may not be sustainable, as the proxies used could indicate different processes at local and global scales. For instance, marine pollen studies indicate that broad land–sea correlations and average ages of respective stages are generally correct, but there may be significant offsets in the precise timing of terrestrial and marine stage boundaries (e.g. Shackleton et al., 2003; Tzedakis et al., 2004). 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).

The recent development of U/Th-based speleothem studies may bypass the necessity to synchronise continental archives with marine records for supporting terrestrial chronologies, especially if similar proxies are used and considering that marine archive chronologies, beyond the limit of radiocarbon dating methods, are often based on astronomical assumptions. 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. Conversely, it is now also popular 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; 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 so 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).

A large literature is now devoted to the use of tephra layers for correlation and archives synchronization (Lowe, 2011 for 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 archives (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 date archives which lack an independent chronology. However, tephrostratigraphic and tephrochronological work also depends on the accuracy of existing data, and absolute ages provided for proximal and distal deposition of the same tephra can vary by up to several thousand years, such as for the Y-3 tephra, which indicates ages of 31–30 ka of supposed proximal deposits (e.g. Zanchetta et al., 2008) but challenged by Albert et al. (2015) to 28.7–29.4 ka starting from re-analyses of distal deposits.

In this paper we attempt to compare different proxy series and tephra layers from Marine Isotope Stage (MIS) 5 (ca. 130–80 ka; Railsback et al., 2015) in the "DEEP" core composite profile, drilled at 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. The major aims are to understand (1) which proxies are most useful for correlating different archives during specific intervals of time, (2) which proxies 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. Our approach is different from that previously used to produce a chronology for the DEEP site composite record, which is based on tephrostratigraphy, cyclostratigraphy and/or orbital tuning through the marine isotope record (Baumgarten et al., 2015; Francke et al., 2015). In contrast, our approach provides important, more detailed insights into the chronological framework of discrete time periods, which is a fundamental contribution for 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 Galicica and Suva Gora mountain ranges. Karst springs depleted in nutrients and minerogenic load represent the primary hydrologic inputs to 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., 2006). 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

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(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. 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 (41°02′57″ N and 020°42′54″ E, 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., 2015). 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., 2015). 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 m core composite depth or the period from ca. 140 to 70 ka according to the age model proposed by Francke et al. (2015).

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Proxy data used in this paper comprise total inorganic carbon (TIC), total organic carbon (TOC), and biogenic silica (B-SiO_2) from Francke et al. (2015), stable isotope composition from inorganic endogenic lacustrine carbonates ($\delta^{18}O_{TIC}$ and $\delta^{13}C_{TIC}$) from Lacey et al. (2015), pollen data from Sadori et al. (2015), and $\delta^{13}C$ of organic matter from Zanchetta et al. (2015). Analytical procedure and related errors, in addition to individual sampling resolutions, are extensively discussed in the quoted papers. $\delta^{18}O_{TIC}$ and $\delta^{13}C_{TIC}$ are present only between 128 and 78 ka, where there was sufficient TIC for precise measurements (Lacey et al., 2015). The investigated interval includes three prominent tephra layers, which were visually identified after opening the cores and are characterized by prominent peaks in XRF-scanning data (Francke et al., 2015). A detailed description of these tephra layers, as well as analytical procedures for their geochemical fingerprinting, can be found in Leicher et al. (2015). Most of these tephras were already described for other cores from Lake Ohrid and nearby Lake Prespa (Lézine et al., 2010; Wagner et al., 2008; Sulpizio et al., 2010; Vogel et al., 2010; Damaschke et al., 2013). In Fig. 2 all Lake Ohrid data are plotted vs. the age according to the model established by Francke et al. (2015). Other Mediterranean records are plotted using their own published age model. Correlation with MISs is given but acknowledged to be in a general context, 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), as the definition of "termination" is based on benthic isotopic records and should be reserved for this definition.

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 special issue (Francke et al., 2015, Lacey et al., 2015, Just et al., 2015). 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., 2015). 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. Based on the age model used for the DEEP site and taking an age of 129 ± 6 ka for the P11 tephra (Rotolo et al., 2013; Leicher et al., 2015) as independent chronological tie point of 1 st order (cf., Francke et al., 2015), all the proxy records indeed show a prominent rate of change, which starts at ca. 124–125 ka (Fig. 2). However, $\delta^{18}O_{TIC}$ shows a first step of decreasing values starting at ca. 128 ka, followed by a second, more pronounced step from ca. 124–125 ka. 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). The behavior of these three proxies can be explained by a first 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 seems to be 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, both 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 variability in DEEP proxy data at 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 Ohrid and may represent an interesting starting point for tuning consideration. Most 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 reported data from site ODP-975 compiled by Marino et al. (2015). In this work, 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 and 3). LC21 had previously been chronologically anchored to Soreq cave U/Th speleothem chronology (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) (Figs. 1 and 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 speleothem records 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). Potential tie points for tuning between these records are represented by small inflections visible in $\delta^{18}O_{TIC}$ in the DEEP site record (green line in Fig. 3), as similar inversions are observed in other Mediterranean isotopic records (green dots in Fig. 3). The end of this inflection point is easily identifiable and robustly U/Th dated at Tana che Urla at 129.6 ka (Regattieri et al., 2014). The use of this tie point for the DEEP core would have several important implications. Firstly, the current DEEP age model would underestimate 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 of Martrat et al. (2014) (Figs. 3 and 4; Marino et al., 2015). Therefore, moving the Ohrid chronology by ca. 4–5 ka, indicates that the rapid temperature increase observed at ca. 129–128 ka in the SST of ODP-976 is almost coincident with the sharp increase in TIC %, TOC %, AP %, and B-SiO_2 values and the sharp decrease in $\delta^{13}C_{TIC}$ and $\delta^{13}C_{TOC}$.

To strengthen the proposed correlation of events during the MIS6-5e transition, we 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) correlated with the tephra layer OH-DP-0499 recognized in the DEEP core (Leicher et al., 2015, Fig. 2). As shown in Fig. 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* δ^{18}O (Fig. 3). This also corresponds to the position of P-11 in the δ^{18}O *G. bulloides* record from core KET82-22 in 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 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 still within the error range) compared to the age reported from the Unit *P* at Pantelleria (ca. 129 ± 6 ka, Rotolo et al., 2013), which is usually regarded as proximal counter part of this tephra layer (Paterne et al., 2008) and was used for the age model of the DEEP core (Francke et al., 2015). However, this age is an average over different sets of dating, and thus bears 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. 2015).

Taking these considerations into account, it seems a fairly well alternative to shift the age model for the MIS6-MIS5e transition at the DEEP site by ca. 4 ka. 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.

In the 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 mainly interpreted in terms of "amount of precipitation", with lower/higher values related to increasing/decreasing precipitation (Bard et al., 2002; Drysdale et al., 2004, 2007, 2009; Zanchetta et al., 2007, 2014; Regattieri et al., 2014, 2015). Changes in precipitation amount, and thus in $\delta^{18}O$ speleothem values, 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). This also found equivalents in lake $\delta^{18}O$ records (Regattieri et al., 2015; Giaccio et al., 2015). Based on such evidence from the central Mediterranean speleothem $\delta^{18}O$ records, the first step in $\delta^{18}O_{TIC}$ of the DEEP record may also be related to increasing precipitation. However, according to Marino et al. (2015), the first $\delta^{18}O$ decrease in both Mediterranean planktonic foraminifera and of speleothems is most likely related to a decreasing sea surface salinity (SSS), due to massive iceberg discharge related to Heinrich event 11, a major deglacial meltwater pulse that may account for about 70 % of the glacial–interglacial sea-level rise. In this view, most of the prominent shift in the $\delta^{18}O_{TIC}$ in the DEEP record at beginning of the transition is probably related to the progressive lowering of sea surface isotopic composition due to decreasing SSS (i.e. source effect) and not to hydrological changes (e.g. increasing of precipitation).

The designation of additional target points for tuning during the Interglacial is 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. However, we suggest that a good correlation point would be the sharp increase in $\delta^{18}O$ record at the transition between GI24 and GS23 visible at Popoli, Corchia and DEEP site (Fig. 3, green dots and green line). This point is set at ca. 105.1 ka on CC28 stalagmite record from Corchia Cave (Drysdale et al., 2007) and chronologically in agreement with data of POP section from the Sulmona basin (Figs. 1 and 3, Regattieri et al., 2015) and NALPS speleothem records from NE Alps (Boch et al., 2011). However, the increase in $\delta^{18}O$ record slightly precedes the TIC, TOC, and B-SiO_2 decrease. We are not able to give a detailed explanation for this interesting difference, however it is perhaps more appropriate to use $\delta^{18}O_{TIC}$ in conjunction with other Mediterranean isotope records.

Two robust target correlation points are represented by the tephra layers OH-DP-0404 and OH-DP-0435 (Fig. 2), which are independently dated in other records (Table 1). Particularly, both tephras occur in the Popoli 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) as tie point thanks to the good $^{40}Ar/^{39}Ar$ radiometric age (Iorio et al., 2014).

An alternative age model can be proposed for the MIS 5 DEEP record (Fig. 4) using the tie points shown in Fig. 3 and detailed in Table 1. This new age model and corresponding 95 % confidence limits (Fig. 4) were calculated by StalAge (Scholz and Hoffmann, 2011), an algorithm written in the open-source statistical software R. StalAge was originally designed for speleothems, but can also be applied to other palaeoclimatic archives with similar constraints (i.e. monotonic depth–age behaviour, with age increasing with distance from the top; Scholz and Hoffmann, 2011, and see for instance Regattieri et al., 2015). The depth–time series and corresponding 95 % confidence limits are calculated by a Monte Carlo simulation, which fits ensembles of straight lines to subsets of the age data. It results in a large number of fits describing the age–depth relationship for individual sections. The best age estimate at a particular depth is then calculated as the median of these fits. The 95 % confidence limits of the age model are calculated from the distribution of the simulated fits (Scholz and Hoffmann, 2011). The simulation is limited to the chronological interval for which tie points are available (ca. 140–70 ka).

The most significant differences are in the timing of the whole glacial/interglacial transition. There is a good fit between 115 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.

The proposed correlation exercise can potentially be extended in the future to other sections of the DEEP record. The $\delta^{18}O_{TIC}$ and TIC records seem to contain interesting points for tuning, even if correlations with regional records are not always obvious. However, both have limitation because TIC is particularly low, if not absent during most of the glacial periods (Lacey et al., 2015; Francke et al., 2015) and seems to be affected by dissolution once a critical threshold is exceeded. Because of preservation/dissolution processes during glacial periods (Lacey et al., 2015; Francke et al., 2015) the selection of correlation points at the beginning of the glacial/interglacial transition would be complex. Moreover, the interglacial seems the more appropriate periods for applying this kind of approaches. 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 to utilize different sources of tuning and dating.

As last point, it is important to remember that Francke et al. (2015) 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. As higher the resolution is, as more important become changes in sedimentation rates. On the long-term scale, and using the chronological tie points of the 9 tephras and from orbital tuning used in the Francke et al. (2015) age model, more or less constant sedimentation rates are inferred in the DEEP site record. In a closer view, however, there might be significant changes, particularly at the MIS6-5e transition, as it is highly unlikely that a decrease in clastic matter input from the catchment (prevailing during glacials and indicated in the lithofacies 3 by Francke et al., 2015) is completely, simultaneously and equally compensated by an increase in carbonate precipitation reaching content to $> 80\,\%$ during the interglacial (MIS 5e peak). This means that it is highly

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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 paper.

5 Conclusions

Regional proxy records that have been independently dated support a more detailed chronology for the Lake Ohrid DEEP site record in the interval covering the MIS6/5 transition and part of MIS5. In particular, we have shown that the MIS6-MIS5 glacial/interglacial transition can be by up to 4 ka older than in the age model proposed by Francke et al., (2015), if using different chronological tie points. The synchronization 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 and 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 important tephra layers allows a relatively good anchoring of the chronology.

It is important to remark that the approach proposed in this paper 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). Therefore, the approach proposed by Baumgarten et al. (2015) and Francke et al. (2015) appear the most suitable for the definition of general chronology of the long record.

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Table 1. Tie points used for the new age model.

Point type	DEEP mc depth (m)	DEEP age (ka)	Name	New used age (ka)	Age differences (ka)
tephra	49.9	129.4	LC21(10.345)/P11 OH-DP-0499	133.5 (2.0)[a]	4.01
visual	48.4	124.3	TII inflection	129.6 (2.0)[b]	5.03
tephra	43.5	109.8	POP4/X6 OH-DP-0435	109.0 (1.5)[c]	−0.8
visual	41.7	103.1	end of GI24	105.1 (0.7)	2
tephra	40.7	98.8	POP2 OH-DP-0404	102.0 (2.4)[c]	3.2

[a] From Satow et al., 2015 (after Grant et al., 2012).
[B] From Tana che Urla record (Regattieri et al., 2014).
[c] From Popoli section record (Regattieri et al., 2015).
[d] From Corchia Cave CC28 record (Drysdale et al., 2007).

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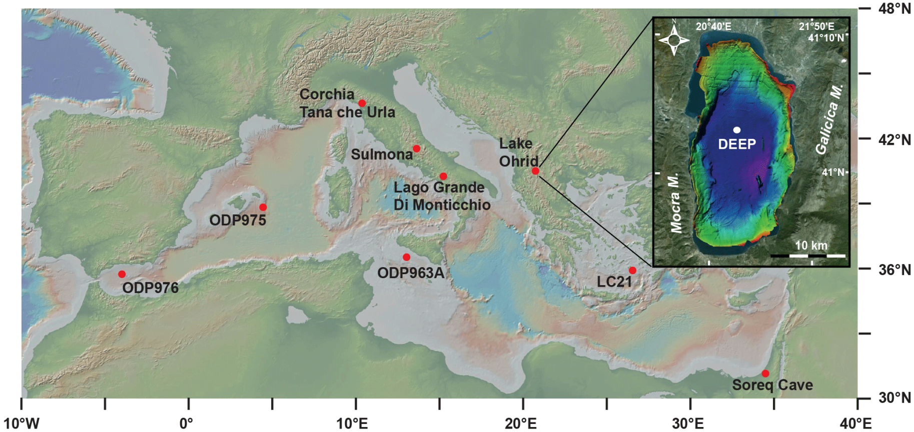

Figure 1. (a) site quoted in the text; **(b)** DEEP Sites drilling location within lake Ohrid.

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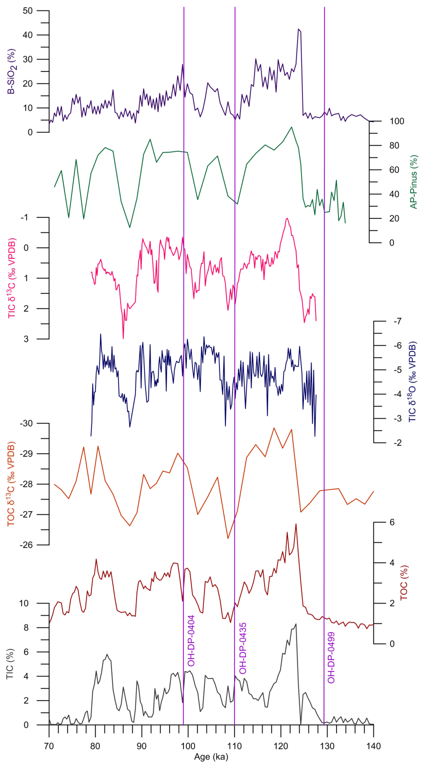

Figure 2. Proxy record from DEEP site. From top: B-SiO_2 after Francke et al. (2015), AP% (without considering Pinus spp. Pollen grains) after Sadori et al. 2015; TIC δ^{13}C after Lacey et al. (2015); TIC δ^{18}O after Lacey et al. (2015); TOC δ^{13}C after Zanchetta et al., 2015; TOC and TIC % after Francke et al. (2015). Violet lines tephra layers.

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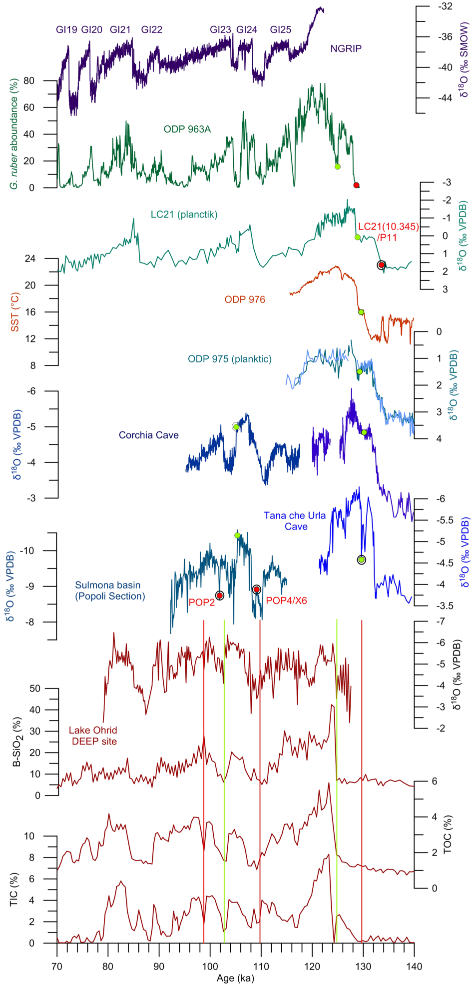

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Figure 3. Comparison of selected DEEP proxies (TIC $\delta^{18}O$ after Lacey et al. (2015), B-SiO_2 after Francke et al. (2015), TOC and TIC % after Francke et al. 2015) with regional to extra regional record. From the bottom $\delta^{18}O$ from Sulmona paleolake (Regattieri et al., 2015); $\delta^{18}O$ 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 $\delta^{18}O$ (*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). Red 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. Black circles on other records and lines (red = tephras, green = tuning point) on Ohird Deep proxies indicates age tuning points. See text and Table 1 for details.

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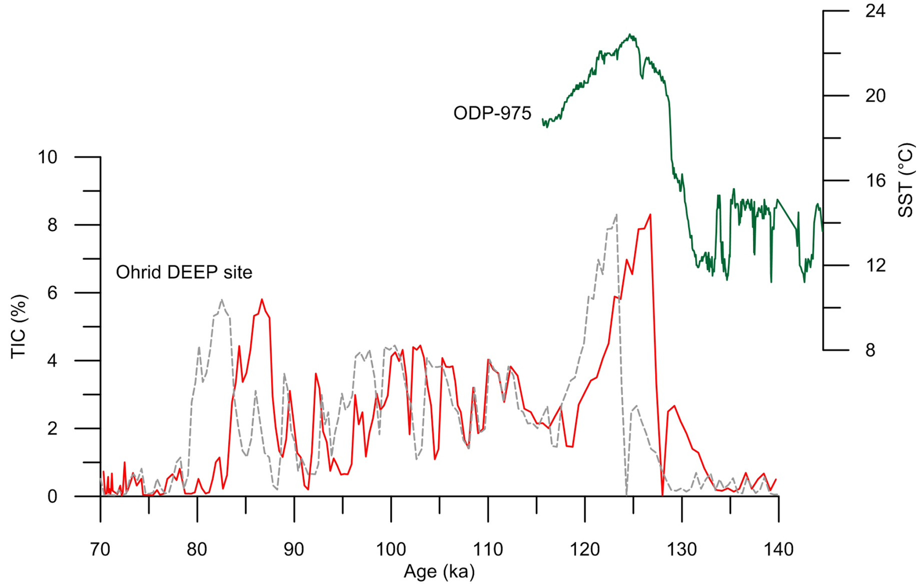

Figure 4. TIC % from Ohrid DEEP site plotted on original (grey dashed line) and new age model (red line) compared to alkenone SST from core ODP-975 (Martrat et al., 2014 on Marino et al., 2015 chronology).

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