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Last Glacial central Mediterranean hydrology inferred from Lake Trasimeno's (Italy) calcium carbonate geochemistry

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There is still a paucity of hydrological data explaining the relationship between (rapid, millennial-scale) climate forcing and Mediterranean rainfall since the Last Glacial. We show that distinct lake-level fluctuations at Lake Trasimeno (Italy) are associated with changing aridity in the central Mediterranean during the last ~47 800 years. The lake-level fluctuations are reconstructed based on carbonate mineral content and carbonate mineral species, as well as the stable oxygen and carbon isotope ($\delta^{18}O$ and $\delta^{13}C$) geochemistry of endogenic carbonates. Low lake levels are linked to high carbonate, Mg-calcite and aragonite contents, and high $\delta^{18}O$ and $\delta^{13}C$ values. Inferred hydrological changes are linked to glacial–interglacial and, tentatively within the limitations of our chronology, to millennial-scale climate variability as well as the intensity of the Atlantic Meridional Overturning Circulation (AMOC). Prior to the Last Glacial Maximum (LGM), during intervals equivalent to Marine Isotope Stage 3 (MIS 3), a stronger AMOC associated with Greenland interstadial periods (Dansgaard/Oeschger (D/O) warm periods) and stronger Asian monsoon probably coincide with increased precipitation in central Italy as inferred from high lake levels at Lake Trasimeno. Periods of weak AMOC intensity such as during Greenland stadials (D/O cold periods), during Heinrich events, and weak Asian monsoons are correlated with lake level lowstands, which imply relatively dry conditions in central Italy. Lake Trasimeno's water level during the LGM and the Lateglacial (MIS 2) is relatively stable, with recorded changes showing distinct similarities to orbital configurations. Although muted, high latitude climate forcing is still evident in the data during peak glacial conditions. The transition from D/O-like hydrological variability at Lake Trasimeno during MIS 3 to orbitally controlled fluctuations during the Lateglacial to Holocene transition coincides with an increasing amplitude in local winter and summer insolation, probably indicating increasing seasonality and a larger temperature gradient between low- and high-latitude settings.

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Understanding controls of hydrological variability in the geological past has become crucial to better predict the amplitude and impact of future rainfall patterns (IPCC 2014). Information on hydrological variability is not only critical to improve the precision of global circulation models (GCMs), but also for the implementation of local to regional mitigation and/or adaptation management plans in response to potential future drought scenarios. This is particularly relevant in regions already characterized by (semi-)arid climates, such as the Mediterranean realm. A recent study has demonstrated the importance of low latitude orbital forcing on the hydrological variability in the central Mediterranean (Wagner *et al.* 2019). Further information is, however, still required to understand regional hydrological variability in response to rapid (millennial-scale) Northern Hemisphere (NH) climate forcing mechanisms. Rapid climate variability on millennial time scales during the Last Glacial period is widely recognized to comprise Dansgaard-Oeschger (D/O) cycles (Dansgaard *et al.* 1984) and Heinrich (H) events (Heinrich 1988). Similar millennial-scale climate variability is also noted in Chinese speleothem records as archives for Asian monsoon intensity (Cosford *et al.* 2008). D/O events, which occurred every 2000–3000 years, are finely resolved in the Greenland ice-core record and are associated with a rapid warming on the order of 8–15 °C (Greenland interstadials, GI; Steffensen *et al.* 2008), followed by a gradual cooling trend (Greenland stadials, GS; Rohling *et al.* 2003; NGRIP-members 2004). H events mark the deposition of ice rafted debris layers in the North Atlantic and are likely the result of enhanced iceberg

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discharge mainly from the Laurentide Ice Sheet (Bond & Lotti 1995). GI/GS climate variability has been shown to be closely connected to the strength of the Atlantic Meridional Overturning Circulation (AMOC, e.g. Gottschalk *et al*. 2015; Ng *et al*. 2018), which in turn modulates the westerly wind system, the Intertropical Convergence Zone (ITCZ), and the Asian monsoon (e.g. Cosford *et al*. 2008; Wilson *et al*. 2021).

The impact of D/O (or GI/GS)-like millennial-scale climate variability during the Last Glacial has been described in many terrestrial records across the world (e.g. Harrison & Sanchez Goñi 2010). Given its proximity to the North Atlantic and dominating westerly wind systems in the mid-latitudes, palaeorecords from the European continent provide the most robust terrestrial evidence of these millennial-scale oscillations. For example, several palynological studies from the central Mediterranean region have revealed that vegetation adapted quickly to centennial- and millennial-scale environmental modifications (e.g. Fletcher *et al*. 2010). The pollen records suggest that warmer and wetter conditions prevailed in the Mediterranean during GI periods, while cold and dry conditions dominated during GS periods (Follieri *et al*. 1998; Allen *et al*. 1999). However, there is a paucity of standalone hydrological data, decoupled from temperature-driven influences, but which is capable of capturing the environmental response to rapid millennial-scale climate change in the central Mediterranean region. Moreover, it remains to be determined if muted millennial-scale climate variability in this region during the coldest intervals of the Last Glacial is controlled by the expansion of a large, more stable NH ice sheet or by low latitude forcing.

Lake Trasimeno, central Italy, is of particular interest to study Mediterranean hydrological variability since it is located at a latitude of 43°N, which has frequently been described as a transition zone from temperate (to the north) to Mediterranean (to the south) climates (Magny *et al*. 2003, 2013; Fletcher *et al*. 2010). Previous studies have already revealed that distinct ecological shifts are recorded in the sediment of Lake Trasimeno, which are a response to NH climate forcing, providing detailed insights into Late Pleistocene and Holocene hydrological and temperature variability in the region (Marchegiano *et al*. 2019, 2020). These previous studies on the same core studied herein focused on chronological, sedimentary and ecological (ostracod) work. Marchegiano *et al*. (2020) used a modern calibration of 13 ostracod species to reconstruct Lateglacial to Holocene quantitative mean July and January temperatures by means of the mutual ostracod temperature range (MOTR) method. The data revealed that Lake Trasimeno experienced significant lake-level fluctuations in the geological past. Higher lake levels prevailed during the early- to mid-Last Glacial, associated with overall warmer phases recorded in the NH ice-core records, as well as during the Holocene. Shallow and/or ephemeral conditions have been inferred for the mid- to late-Last Glacial. Reconstructed summer and winter temperatures show strong similarities to NH millennial-scale climate variability.

Here, we provide new data that improve our understanding of the control mechanisms on lake-level changes, and thus, rainfall variability at Lake Trasimeno by using sedimentary geochemical, mineralogical, and stable isotope data. New elemental (inorganic carbon content, Ca intensities, Rb/Sr ratios), mineralogical, and stable isotope ($\delta^{18}O$ and $\delta^{13}C$) data are used to interrogate the lake-level-sensitive formation of endogenic calcium carbonate species in the lake. We also evaluate the impact of pre-aged soil organic matter input on radiocarbon dated bulk organic samples by means of lipid biomarker analyses to better constrain the uncertainties associated with previously published chronologies for the same record (Marchegiano *et al*. 2019, 2020). The MOTR reconstruction plotted against the radiocarbon-based chronology of Marchegiano *et al*. (2018) yields major peaks and minima that tentatively match with key peaks and minima of the NGRIP $\delta^{18}O$ record, a similarity that was used to 'tune' Lake Trasimeno's MOTR winter temperatures to the ice-core record (Marchegiano *et al*. 2020). Marchegiano *et al*. (2020) argue, considering the given limitations of this approach, that the Lake Trasimeno Co1320 record satisfies a key criterion necessary to justify the tuning exercise. This key criterion is that any tuning should be limited to within regions that have independently been shown to pertain the target climate signal (inhere: millennial-scale climate variability in central Italy) in a second, independently palaeoclimate record. D/O-like millennial-scale climate variability in Italy has been described previously (Fletcher *et al*. 2010), most prominently by the absolutely dated sediments of Lake Monticchio (Allen *et al*. 1999). Within the limitations of our (updated) chronology, we discuss Lateglacial climate variability recorded in ecological (Marchegiano *et al*. 2019, 2020) and geochemical data (this study) of Lake Trasimeno in comparison with NH ice-core records, AMOC intensities, monsoon intensities, and orbital configurations during the last ~47 800 years. The limitations of our chronology confine our focus to lake-level change and the general variability and trends in our proxy data across multiple D/O cycles only.

Site information

Lake Trasimeno (latitude 43°08′N, longitude 12°06′E, Fig. 1) is a tectonic lake located in the region of Umbria (Italy) at an altitude of ~250 m above sea level (a.s.l.). The lake basin developed from a marine gulf on the continental shelf of the Tyrrhenian Sea during the Early Pliocene via a wide fluvial plain phase to a freshwater lake during the Middle Pleistocene (Gasperini *et al*. 2010). Presently, the Lake Trasimeno basin is characterized by a gentle (2°) ENE dip that started to form in the Middle Pleistocene. The tectonic setting is controlled by a set of

SW dipping normal faults along the eastern shoreline (Gasperini *et al.* 2010). The progressive ENE dip is thought to be responsible for providing accommodation space for the deposition of Lake Trasimeno's >200-m-thick lacustrine sediments and prevents the lake from completely silting up (Gasperini *et al.* 2010).

Lake Trasimeno is one of the largest lakes in Italy and covers a surface area of 124.3 km^2 with a maximum diameter of ~14 km (Ambrosetti *et al.* 2003). The flat-bottom bathymetry has a maximum water depth of 6 m and an average depth of 4 m (Ambrosetti *et al.* 2003; Gasperini *et al.* 2010). The total water volume is 0.59 km^3. Seasonal, decadal and long-term lake-level fluctuations are common, although the lake level has been controlled by an artificial underground outlet since Etruscan and Roman times (Burzigotti *et al.* 2003; Ludovisi & Gaino 2010). Prior to anthropogenic influence, Lake Trasimeno was a closed lake (Burzigotti *et al.* 2003).

Lake-level fluctuations considerably influence the water quality of Lake Trasimeno (Taticchi 1992). Salinity and total alkalinity (measured as mg L^{-1} $CaCO_3$) vary on seasonal and decadal time scales, generally increasing with a higher E/P ratio and a lower lake level (Ludovisi & Gaino 2010). The lake is meso- to eutrophic today with a mean annual pH between 8.2 and 8.9 (Taticchi 1992; Ludovisi & Gaino 2010). Periods of low water transparency occur particularly when lake-level lowstands promote sediment re-suspension from the surface sediments, rather than being a product of higher algal biomass (Taticchi 1992). The shallow water depth and large surface area of Lake Trasimeno promote wind fetch and hamper thermal stratification even during prolonged hot summer months (Ludovisi & Gaino 2010).

The catchment area of Lake Trasimeno covers ~376 km^2. Whereas the topography to the west of the lake is characterized by a wide flat plain, high mountains (up to ~790 m a.s.l.) surround the lake to the north, east and south. These mountains predominantly consist of Oligocene to Miocene turbidites with marine sandstones, claystones and some marly claystones, which have negligible exposure in the catchment of Lake Trasimeno (Burzigotti *et al.* 2003; Fig. 1). The turbidite successions also form the three islands Maggiore, Polvese, and Minore in the northern and southeastern part of Lake Trasimeno (Gasperini *et al.* 2010). To the west of the lake, Pliocene marine sandstones and claystones crop out. The wide flat areas that surround the lake are covered by Pliocene to Holocene lacustrine and fluvial deposits (Burzigotti *et al.* 2003; Gasperini *et al.* 2010). The catchment area of Lake Trasimeno is drained by small rivers, which occasionally form prograding wedges into the lake basin (Fig. 1).

Mediterranean-type conditions with warm-dry summers and mild-humid winters characterize the climate regime at Lake Trasimeno. The mean annual air temperature averages at 13.3 °C, with the hottest and coldest months being July (mean temperature 22.4 °C) and January (4.7 °C), respectively. The mean annual precipitation is 783 mm.

Detailed lithological information for the ~8.6-m-long sediment core Co1320 (43°09.624′N, 12°03.491′E, Fig. 1 B) used in this study was previously published by Marchegiano *et al.* (2018) and Marchegiano *et al.* (2019, Fig. 2). The core was retrieved where hydroacoustic data indicated undisturbed, horizontally bedded sediments down to at least ~12 m sediment depth (see Fig. 2 for detailed information on sedimentary characteristics). The previously published chronological framework of core Co1320 is based on radiocarbon analysis (Marchegiano *et al.* 2018), and was subsequently further refined by tuning to ice-core records (Marchegiano *et al.* 2020).

Material and methods

X-ray fluorescence (XRF) core scanning (ITRAX core scanner, Cox Analytics, Sweden) was carried out at 2-mm resolution using a voltage and amperage of 30 kV and 55 mA, respectively. Inaccuracies compared to conventional XRF analyses on powdered sample material that arise due to variations in water content, grain size, mineralogy, porosity, and the surface structure of the core (Croudace *et al.* 2006).

Subsampling for further analyses was carried out at 2-cm resolution. The 2-cm-thick subsamples were freeze-dried, homogenized, and an aliquot of ~100 mg was ground to fine powder. The total inorganic carbon (TIC) content was determined using a DIMATOC 100 carbon analyser (Dimatec Corp., Germany) as released CO_2 after treatment with phosphoric acid (H_3PO_4) and combustion at 160 °C. Five samples were randomly selected across the core, sieved to <63 μm and re-analysed for TIC to detect the impact of biogenic carbonates on bulk TIC measurements.

In order to investigate the mineralogical composition of the lacustrine sediments as well as the origin of the TIC in the deposits of core Co1320, aliquots (1.5 g) of seven selected samples were ground to <63 μm and prepared for X-ray diffraction (XRD) analyses. XRD patterns were recorded using a PANalytical X'Pert PRO MPD Θ-Θ diffractometer (Co-Kα radiation generated at 40 kV and 40 mA), equipped with a variable divergence slit (20-mm irradiated length), primary and secondary soller, Scientific X´Celerator detector (active length 0.59°), and a sample changer (sample diameter 28 mm). The samples were investigated from 5° to 85° 2Θ with a step size of 0.0167° 2Θ and a total analysis time of 1 h. For specimen preparation, the back loading technique was used. Rietveld refinement of the experimental XRD data was conducted using the software BGMN (Bergmann & Kleeberg 1998). The coexisting calcium carbonates (low Mg-calcite, high Mg-calcite, aragonite) could be distinguished from each other by slightly different lattice

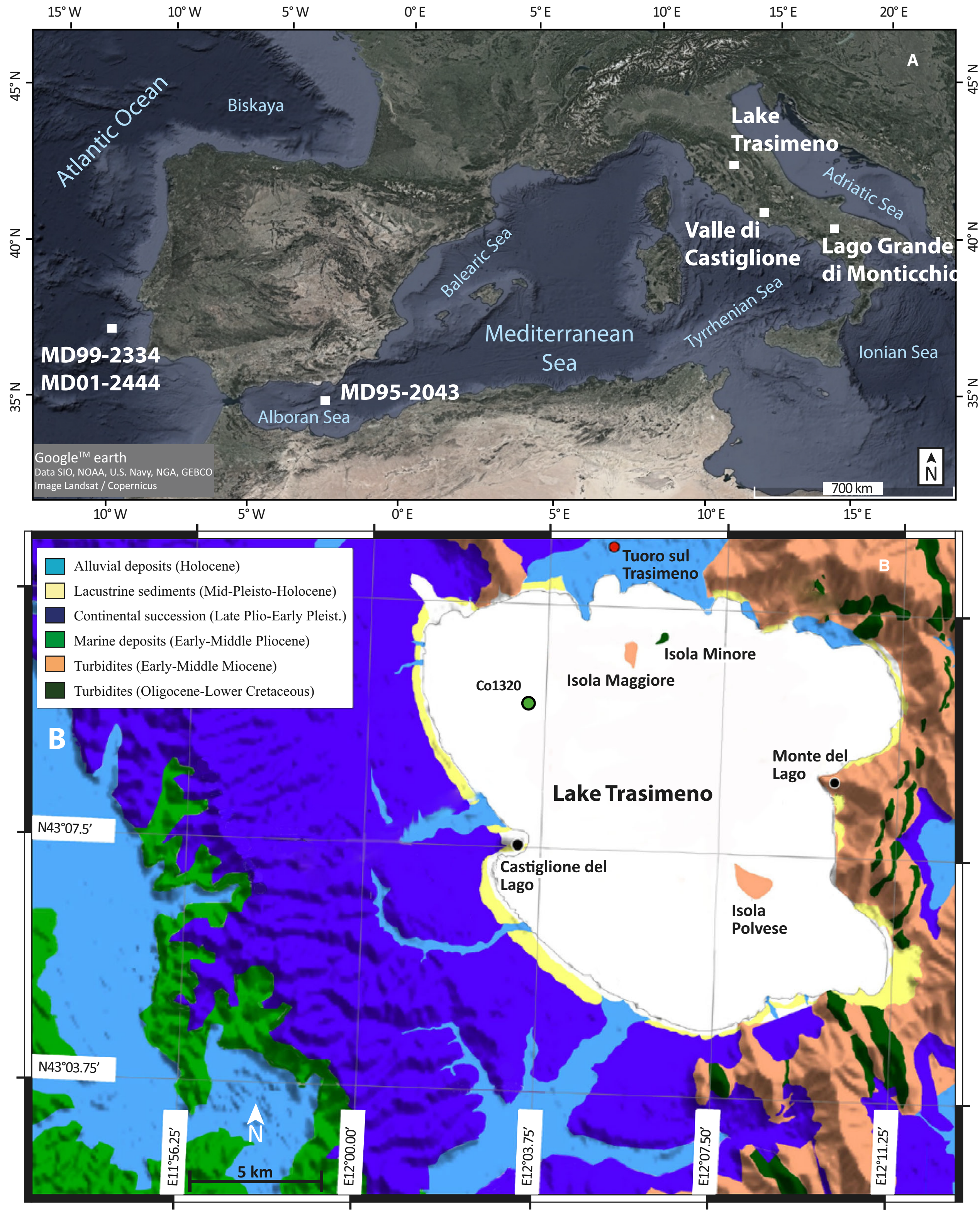

Fig. 1. Site information. A. Geographical map showing the location of Lake Trasimeno in central Italy. White squares indicate the location of cores MD99-2334/MD01-2444, and of Lago Grande di Monticchio and Valle di Castiglione. B. Geological map of the Lake Trasimeno area (Gasperini *et al.* 2010). The green circle marks the location of core Co1320.

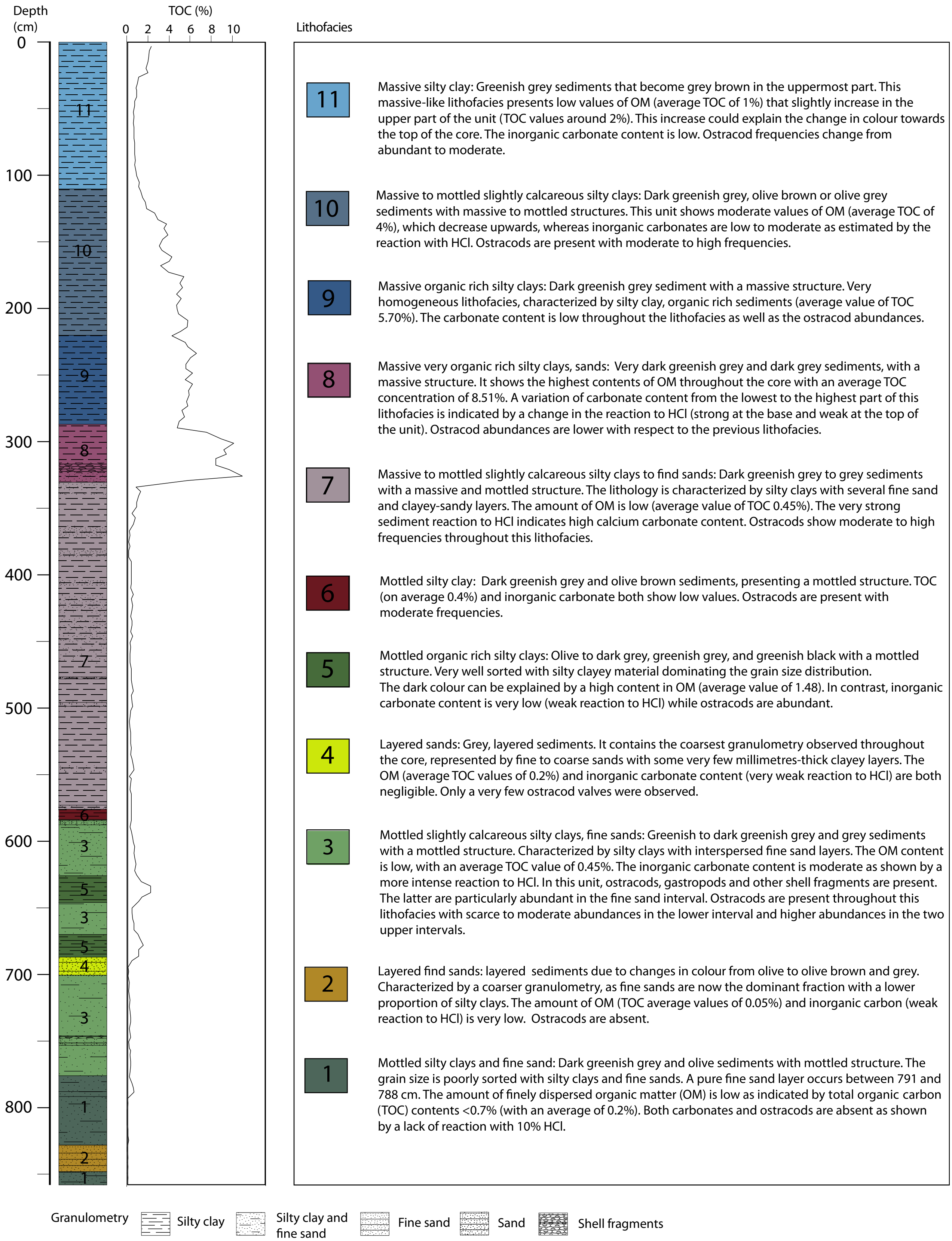

Fig. 2. Lithology and total organic carbon content of core Co1320. Modified from Marchegiano *et al.* (2018).

constants and hence different peak positions following the method described in detail by Bischoff *et al.* (1983).

Stable isotope analysis was carried out on core sections where TIC is >0.4%. For oxygen and carbon isotope analysis on carbonate ($\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$), between 30 and 300 mg of sediment (dependent on TIC %) was disaggregated in 5% sodium hypochlorite solution for 24 h to oxidize reactive organic material, following sieving to 63 μm to remove any biogenic carbonate. The <63-μm fraction was then rinsed in deionized water, dried at 40 °C, and ground in an agate mortar. The processed samples were reacted overnight *in vacuo* with anhydrous phosphoric acid at a constant 25 °C, cryogenically separated from water vapour *in vacuo*, and analysed using a VG Optima dual inlet mass spectrometer. The mineral-gas fractionation factor of 1.01025 (Friedman & O'Neil 1977) was used to account for isotopic fractionation during the reaction of carbonate with phosphoric acid. Unlike for other carbonate minerals, the mineral-gas fractionation factors for calcite and aragonite are not significantly different (Tarutani *et al.* 1969) and, therefore, the same correction was applied to all samples.

Lipid biomarkers were extracted from 1.0 to 5.2 g freeze-dried and homogenized sediments using accelerated solvent extraction (Dionex ASE 300) with 9:1 dichloromethane: methanol (v:v) maintained at 120 °C and 120 bar. The total lipid extract was dried using rotary evaporation and a C_{46} GDGT standard was added prior to filtering over PTFE filters (0.45 μm × 4 mm) using 95:5 hexane: isopropanol (v:v). GDGTs were analysed using an Agilent 1290 UHPLC connected to an Agilent 6460 QQQ equipped with an APCI ion source following the method of Schouten *et al.* (2007). GDGTs were analysed in SIM mode and quantified according to Huguet *et al.* (2006) including normalization to TOC. The br/(cren+cren′) ratio was defined as the sum of branched glycerol dialkyl glycerol tetraethers (brGDGTs) IIIa, IIIa′, IIIb, IIIb′, IIIc, IIIc′, IIa, IIa′, IIb, IIb′, IIc, IIc′, Ia, Ib and Ic over the sum of crenarchaeol and its isomer.

Marchegiano *et al.* (2018) used the R64-based software package clam2.2 (Blaauw 2010) and the IntCal13 calibration curve (Reimer *et al.* 2013) for age-depth modelling. To account for more variable sedimentation rates as implied by the clam2.2 derived chronology, we herein use Bayesian age-depth modelling embedded in the software Bacon 2.0 (Blaauw & Christen 2011; Blaauw *et al.* 2018), update the calibration of radiocarbon ages to IntCal 2020 (Reimer *et al.* 2013), and finally include newly introduced age-tie points of Marchegiano *et al.* (2020) to refine the chronology for core Co1320. Sedimentation rates were derived from the refined chronology. We exclude any significant bias by compaction during sediment recovery, since we applied a piston coring technique that minimizes disturbance during coring activities. This was confirmed in the laboratory by comparing sediment recovery with the drilled length of each core run.

Results and discussion

Chronology

The chronological framework for the sediments of core Co1320 has previously been published by Marchegiano *et al.* (2018) and Marchegiano *et al.* (2020) (Fig. 3, Table 1). Both chronologies are based on radiocarbon analysis of terrestrial plant materials recovered from the surface of core halves following opening and/or during subsampling, and five bulk organic carbon samples. Marchegiano *et al.* (2020) aimed at improving the radiocarbon-based chronology of Marchegiano *et al.* (2018) by aligning Co1320-derived January minimum temperatures (in °C, five-point running mean), inferred from the MOTR method, to the NGRIP oxygen isotope record (on the chronology of Rasmussen *et al.* 2014).

We herein aim to further evaluate the challenges and limitations of tuning based on a limited number of available independent age-tie points, which can introduce significant uncertainty to climate interpretations via circular reasoning and unrecognized chronological uncertainties (Blaauw 2012), by further investigating the impact of potential contributions of old carbon used for dating. The four radiocarbon ages derived from terrestrial plant remains and the age from the charcoal sample provide a robust basis for the chronological framework of core Co1320, since they are considered as being not affected by reservoir and/or hardwater effects or by redeposition (Fig. 3). Several studies have shown that bulk lacustrine OM ages can contain reservoir and/or hardwater effects, which also can vary significantly over time (Vogel *et al.* 2010b; Aufgebauer *et al.* 2012; Francke *et al.* 2013). Reservoir and/or hardwater effects for lacustrine OM are expected to be low for Lake Trasimeno as carbonate bedrock is not widespread in the catchment and the high lake surface to water volume ratio promotes rapid exchange with the atmosphere. Radiocarbon ages can also be biased if the analysed bulk OM sample includes a considerable amount of pre-aged or fossil soil organic matter (SOM, Martin & Johnson 1995). In order to estimate the contribution of (potentially pre-aged) SOM to Lake Trasimeno sediments, we analysed the relative contribution of brGDGTs and the isoprenoid GDGT crenarchaeol (cren and its isomer cren′) in 12 samples of core Co1320 (Table 2), out of which five were used for bulk OM radiocarbon analysis (Fig. 3, Table 2). BrGDGTs are bacterial membrane lipids predominantly found in soils, whereas crenarchaeol is primarily produced by (chemo-)autotrophic planktonic Thaumarchaeota (Schouten *et al.* 2013). Since the branched and isoprenoid tetraether (BIT) index, a proxy for SOM input (Hopmans *et al.* 2004), in core Co1320 is biased by variable crenarchaeol concentrations, we report the ratio

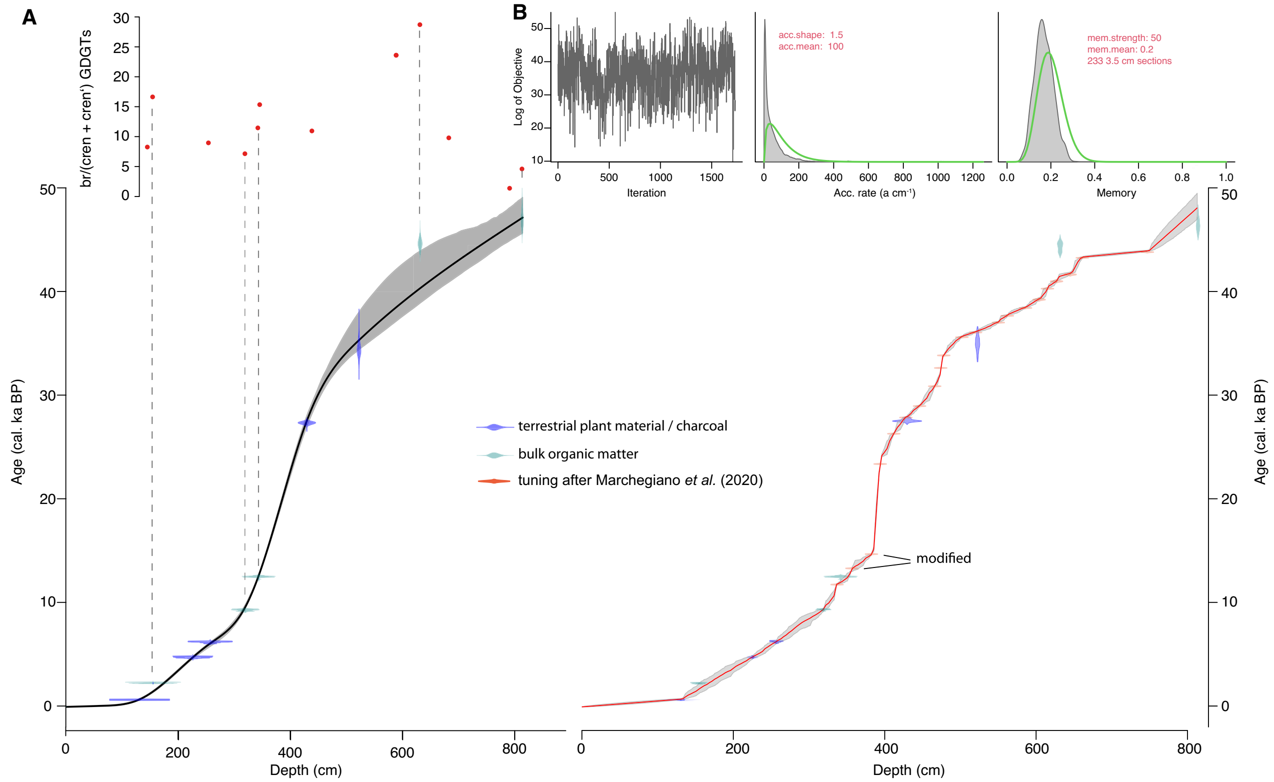

Fig. 3. A. Chronological framework as published by Marchegiano *et al.* (2018) and lipid biomarker (br/(cren+ cren′) GDGT ratio) data of core Co1320. Biomarker data were used to better assess potential biases in radiocarbon ages derived from bulk organic matter samples introduced by soil organic matter. B. New chronology based on radiocarbon ages from Marchegiano *et al.* (2018) and tuning points of Marchegiano *et al.* (2020), modelled with Bayesian statistics using the software Bacon 2.0 by Blaauw & Christen (2011).

of absolute branched GDGTs to the isoprenoid GDGT crenarchaeol cren and cren′ (br/(cren+ cren′) GDGT ratio) in order to identify those samples containing considerable amounts of SOM. Significant *in situ* production of brGDGTs was excluded based on the #rings$_{tetra}$ values (Sinninghe Damsté 2011), which average 0.4±0.2 and only exceed the 0.7 threshold value in the sample at 590 cm.

The low br/(cren+cren′) GDGT ratio implies that sample COL3666.1.1 at 827 cm and COL3663.1.1 at 319 cm do not incorporate a considerable amount of SOM. The bulk OM samples at 631 cm (COL3665.1.1), at 343 cm (COL3664.1.1) and at 154.5 cm (COL3662.1.1), however, yield higher br/(cren+cren′) GDGT ratios. This indicates a substantial SOM contribution, which we assume distorts the bulk ^{14}C age due to the incorporation of pre-aged SOM. Thus, all three samples were not included in the age-depth interpolation and some minor modifications of the tuning points provided by Marchegiano *et al.* (2020) at around 340-cm sediment depth were carried out. Assuming that sample COL3664.1.1 incorporates some pre-aged carbon allows

Table 1. Radiocarbon ages from core Co1320 (Lake Trasimeno).

AMS Lab. ID	Core depth (cm)	Material	C weight (μg)	$F^{14}C$	^{14}C age (a BP)
COL3171.1.1	130.5	Terrestrial plant	988	0.9180	685±35
COL3662.1.1	154.5	Bulk organic matter	995	0.7546	2260±40
COL3172.1.1	225.5	Charcoal	1000	0.5930	4190±40
COL3173.1.1	256.5	Terrestrial plant	575	0.5100	5410±50
COL3663.1.1	319	Bulk organic carbon	999	0.3564	8290±50
COL3664.1.1	343	Bulk organic carbon	993	0.2694	10 550±55
COL3174.1.1	429	Terrestrial plant	791	0.0570	23 000±100
COL3175.1.1	522	Terrestrial plant	320	0.0230	30 300±810
COL3665.1.1	631	Bulk organic carbon	999	0.0060	41 100±620
COL3666.1.1	827	Bulk organic carbon	992	0.0044	43 700±830

a better (younger) alignment of MOTR derived temperature reconstructions and ostracod assembly inferred lake water salinity variations, which indicates humidity at Trasimeno (Marchegiano *et al.* 2018), to local pollen records (Fletcher *et al.* 2010; Sadori 2018) and NGRIP (Rasmussen *et al.* 2014).

A comparison between the absolute-dated chronology of Marchegiano *et al.* (2018) and the updated chronology based on the tuning exercise of Marchegiano *et al.* (2020) reveals age model differences during the Holocene of less than 500 years. These changes are probably related to the different age-depth interpolation methods used, since we do not change Holocene age-tie points, and the updated IntCal20 calibration curve does not differ significantly from IntCal13 for the Holocene (Reimer *et al.* 2020). The predominant change to the age-depth model is for the Lateglacial to Holocene transition, where sediment ages are up to ~4900 years younger in the tuned chronology. Shifts on the order of ~1500 years result at around 35 000 cal. a BP and around 42 000 cal. a BP (Fig. 3). The chronology for the sediments of core Co1320 provide uncertainties related to the impact of old soil-carbon on bulk radiocarbon ages and the risk of circular reasoning for the tuning exercise against the NGRIP ice-core record. We attempted to obtain additional age-tie points via tephrochronology, including cryptotephra analyses, with sieving and counting of individual glass shards; however, thus far no reliable results have been obtained. The absence of (crypto)tephra is probably related to the northward location of Lake Trasimeno relative to most Italian volcanic fields and the shallow water depth most likely promoting sediment reworking, which may also be responsible for ambiguous results obtained from palaeomagnetic work (relative palaeointensity).

Carbonate mineralogy

The strong correlation of TIC contents, Ca and XRD results of core Co1320 implies that calcium carbonate ($CaCO_3$) is the dominant carbonate phase in the sediments of Lake Trasimeno ($R^2 = 0.85$, Fig. 4A). Minor contributions could come from other carbonates such as ankerite ($CaFe[CO_3]_2$). Rhodochrosite ($MnCO_3$) and siderite ($FeCO_3$) are not evident in the XRD data. Ca can additionally be incorporated in detrital feldspars (Ca-rich plagioclases), but XRD analyses suggest that ankerite is only present in one sample, whereas plagioclase occurs in all analysed samples at minor contributions only (Table 3). A limited impact of carbonate species other than calcium carbonate and/or a bias of the core scanning derived Ca intensities due to grain size and/or water content is supported by TIC/Ca ratios showing no systematic offset in core Co1320. A cross-plot of Ca and TIC shows two slightly different linear correlation lines, which characterize samples older and younger than ~4200 cal. a BP (Fig. 4A). It has been reported from

Table 2. GDGT concentrations (in ng/g TOC) of 12 selected samples from core Co1320, of which five correspond to samples used for bulk organic matter radiocarbon analysis (marked with an asterisk).

Depth	br/(cren+cren′)	brGDGTs									isoGDGTs					
		Ic	Ib	Ia	IIc+IIc’	IIb+IIb’	IIa+IIa’	IIIc+IIIc’	IIIb+IIIb’	IIIa+IIIa’	cren′	cren	GDGT-3	GDGT-2	GDGT-1	GDGT-0
146.5	8.3	972.9	3713.9	7860.3	779.5	6557.9	11 582.7	146.1	1001.2	7347.7	64.7	4726.3	280.6	1347.9	1852.7	18503
154.5*	16.7	3098	10 558	21 110.5	2635	20 477.5	31 171.5	591.9	3324.5	18 170.1	136.8	6501.4	1562.4	3823.7	6632.5	58 654.1
255	8.9	1794.6	6608.5	11 300	1236.4	9995.9	16 859.9	218.9	1590.4	11 272.6	80.8	6755.3	681.1	1757.3	4302	38 996.4
319*	7.2	1977.9	9192.8	29 059.2	1265.4	14 549.6	29 623.9	343.8	2190.7	18 316.6	231.3	14 654.1	1042.1	7526.5	8974.3	19 1529.5
343*	11.5	188.9	714.8	4173.4	88.8	875.3	4727.6	0	185.9	2376.7	62.6	1098	147	1167.8	911.6	26 421.8
347	15.4	132.4	467.6	2295.5	64.7	527.5	3235.7	0	111.1	1231.8	30.6	492	73.5	501.9	470	13 219.8
440	11	401.9	1120	2037.7	176.2	1544.4	2371.5	0	244.1	1424.7	24.5	824.9	72.8	362.8	466	7445.9
590	23.6	370	1004.2	857.7	117.7	858.9	807.9	0	62.2	420.2	6.3	184.2	30.1	73.8	80.2	663.2
631*	28.7	882.1	2818.8	7525.5	854	7309.1	14 894.6	250.9	1523	15 350.7	36.7	1757.1	215.1	572.2	1830.1	19 107.8
683	9.8	253.5	719.3	2992.2	101.9	1021.7	3708.3	0	283.4	1823.4	58.5	1052.4	113.1	677.2	1189	23 487.6
810	1.3	291.7	520.5	3695.1	99.4	432.8	1536.8	0	142.6	1084.2	121.3	5963.7	401.9	597.5	731	9457.2
858*	4.6	77.6	311.8	491.2	41.7	482	1044.3	0	71.9	708.5	88.4	607.4	120.6	229.9	195.8	360.1

other lakes in the Mediterranean region that Late Holocene human-induced wood clearance significantly enhanced clastic matter supply and runoff (Wagner *et al.* 2008; Vogel *et al.* 2010a; Aufgebauer *et al.* 2012; Francke *et al.* 2019). This could imply that human activity in the catchment had a considerable impact on the lake water chemistry and/or on the supply of detrital matter to the lake, which may have intensified following the construction of the Etruscan artificial outlet (Burzigotti *et al.* 2003). Excluding the Late Holocene samples younger than ~4200 cal. a BP, the correlation coefficient (R^2) between TIC and Ca increases to 0.88 (Fig. 3A), further supporting the robustness of our XRF-core scanning data.

Biogenic carbonates (bivalves, molluscs) may contribute to the $CaCO_3$ content in the sediments of Lake Trasimeno. Macroscopic shell fragments were carefully removed prior to TIC and stable isotope analyses. Selected samples were sieved to <63 μm and the fine fraction was analysed for TIC to test the impact of finely ground shell detritus and ostracod shells on calcium carbonate contents measured in the sediments (Fig. 6). The data imply that the majority of analysed TIC in the samples is not derived from shell fragments and/or ostracods. Further indications that ostracod-derived calcium carbonate is not the main control on TIC variability in the sediments come from the complementary mineralogical data, since ostracods incorporate low Mg-calcite into their shells (Cohen 2003) and XRD results shows that the Mg-calcite found in the sediments of Lake Trasimeno predominantly consists of high Mg-calcite (Table 3).

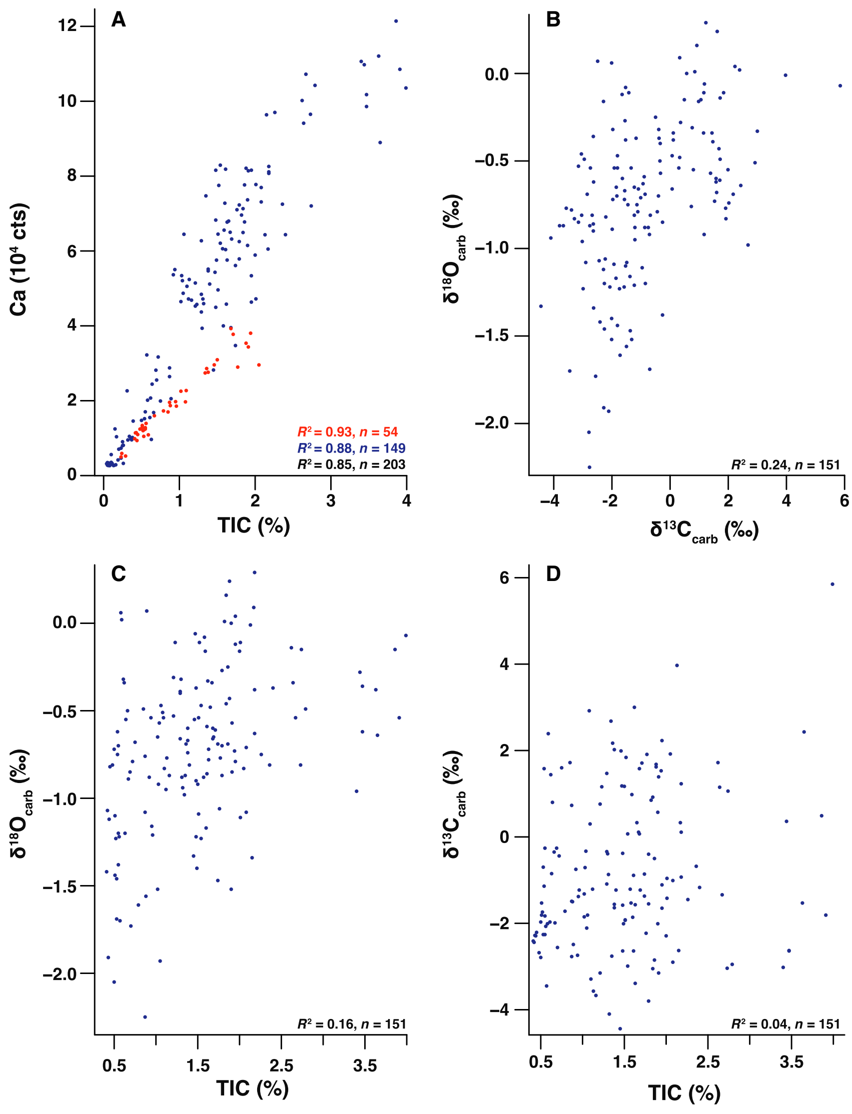

Fig. 4. Cross-plots of TIC content against Ca intensities. R^2 in red refers to the red-marked samples only (<4200 cal. a BP), in blue to the blue-marked samples only (>4200 cal. a BP), and in black to both red- and blue-marked samples (A), $\delta^{13}C_{carb}$ against $\delta^{18}O_{carb}$ (B), TIC against $\delta^{18}O_{carb}$ (C), and TIC against $\delta^{13}C_{carb}$ (D).

Table 3. Results of X-ray diffraction (XRD) analyses, TIC content, Ca intensities and Rb/Sr ratios from seven selected samples for core Co1320 reported as wt(%). wt(%) <1 indicates negligible amounts only, close to the detection limit

Age (cal. a BP)	Depth (cm)	Muscovite (2M1) (%)	Chlorite (%)	Kaolinite (%)	Plagioclase (%)	K-feldspar (%)	Quartz (%)	Rutile (%)	Anatase (%)	Gypsum (%)	Pyrite (%)	Ankerite (%)	Aragonite (%)	Mg-calcite (%)	Calcite (%)	Rb/Sr	Ca (cts)	TIC (%)
1120	146.5	33	11	6	6	6	16	<1	1		<1			10	10	0.65	38 039	1.9
13 200	347	27	6		9		16	<1	<1	<1	<1	6	22	4	6	0.12	108 530	3.9
29 000	440	25	7		16	6	36	<1	<1		1			3	4	0.72	53 417	1
38 500	590	30	9		14	6	27	<1	1					7	5	0.58	64 502	1.5
40 300	631	39	11		12	4	28	2	1		1				2	2.43	3270	0.1
42 400	683	31	12		8	5	16	1	2		1		13	6	5	0.31	82 578	2.2
46 300	810	25	8		17	7	41	1	1						<1	1.32	2749	0.1

Lake water monitoring at Lake Trasimeno has shown that dissolved ions (Cl^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, CO_3^-) and total dissolved solids (TDS) concentrations vary on decadal and seasonal time scales in response to fluctuations of the evaporation/precipitation (E/P) ratio and lake level (Ludovisi & Gaino 2010; Frondini *et al.* 2019). Trasimeno's lake water earth alkali concentrations are additionally controlled by carbonate mineral solubility, with $CaCO_3$ precipitation being promoted by (i) $pCO_{2(aq)}$ reduction during (summer) algae growth and photosynthesis, and (ii) Ca^{2+} concentration increase and oversaturation resulting from (summer) evaporation (Frondini *et al.* 2019). This implies a lake level and E/P-sensitive response of endogenic $CaCO_3$ formation at Lake Trasimeno. In high-Mg low-Ca lake water regimes such as Lake Trasimeno (Ludovisi & Gaino 2010), high Mg-calcite and aragonite can become the dominant carbonate species (Dean *et al.* 2006; De Choudens-Sanchez & Gonzalez 2009; Roeser *et al.* 2016). During dry periods in particular, a further reduction in lake level and ongoing calcite precipitation can cause Mg-calcite and aragonite formation due to the progressive depletion of Ca^{2+} in the lake water (De Choudens-Sanchez & Gonzalez 2009). High Ca^{2+} and HCO_3^- concentrations first promote calcite precipitation in the water column, whereas ongoing mineral formation (low lake level) and high Mg concentrations subsequently foster high Mg-calcite and finally aragonite formation in the lake water (De Choudens-Sanchez & Gonzalez 2009). XRD analyses on seven representative samples (Table 3) confirm the presence of calcite, high Mg-calcite and aragonite in the sediments of Lake Trasimeno. A scatterplot of Ca and Sr intensities highlights two linear correlation clusters, with lower Sr intensities (<850 cts) associated with calcite and Mg-calcite, and higher Sr intensities (>850 cts) with increasing abundance of aragonite (Fig. 5A). This is consistent with a preferential incorporation of Sr into the crystalline lattices of Mg-calcite and aragonite (Fig. 5A; Cohen 2003; De Choudens-Sanchez & Gonzalez 2009). The two linear clusters in the Ca-Sr scatterplot prevent the use of Ca/Sr ratios as a proxy for the amount of Mg-calcite and aragonite in the sediments of Lake Trasimeno, as previously reported from other sites (summarized in Davies *et al.* 2015). In the case of core Co1320, Low Ca/Sr ratios could be related to both low calcite or aragonite contents in the sediments, and the Ca/Sr ratio is thus an inaccurate indicator for the relative contribution of calcite and aragonite. We thus normalize Sr with the immobile element Rb, which is mainly associated with volcanic and clastic rocks, to account for any Sr bound to siliciclastic matter in the sediments. Mineral sorting and/or chemical alteration, which are frequently inferred from Rb/Sr ratios at other sites (summarized in Davies *et al.* 2015), have a minor control on Rb/Sr ratios in Lake Trasimeno's sediments. This is demonstrated by a weak positive relationship between (usually) Ca/Sr-rich plagioclase content and Rb/Sr (Table 3). Excess Sr in relation to Rb should consequently indicate the excessive incorporation of Sr into the different calcium carbonate species. Aragonite-bearing sediment successions were defined by Rb/Sr ratios <0.4 as XRD results suggest that samples with Rb/Sr >0.31 only contain calcite (Table 3).

In summary, Lake Trasimeno's sediment geochemical composition (Ca, TIC, Sr) is sensitive to changes in water geochemistry mainly controlled by E/P ratio and lake level. High (low) Ca and TIC are promoted by high (low) dissolved ion concentrations, and thus, by decreasing/low (increasing/high) lake levels. Hence, we use the absolute amounts of endogenic carbonates (TIC, Ca) and the relative contribution of Mg-calcite and aragonite (Rb/Sr) as proxies for lake-level fluctuations at Lake Trasimeno (Figs 5, 6).

Sediment accumulation and lake level

There is a positive relationship between high sedimentation rates and high/increasing lake levels at the coring site (low TIC, Fig. 6). Under present-day conditions, the maximum wind fetch of ~10 km at the coring location combined with moderate to strong winds (up to 30–40 knots wind speed) would allow wave heights not much higher than ~1 m, with the wave height being limited by the fetch distance (Goda 2003). A lower lake level at Trasimeno would simultaneously decrease wind fetch and, in addition, limit wave height due to the reduced water depth, which would restrict the maximum possible wave height at the coring location. Sedimentation rates have been shown to be increased by a factor of 25 due to wave action in other shallow lakes (Douglas & Rippey 2000); however, this is not observed at Lake Trasimeno, where sedimentation rates increase with increasing lake level and less wave action. High sedimentation rates at the coring location during high lake levels are consequently thought to be controlled by catchment erosion and enhanced sediment yield to Lake Trasimeno during wetter conditions, and a higher capacity of deeper waters for particle suspension and transportation of fine-grained detrital matter to the coring location. Catchment erosion has been shown to rapidly respond to wetter conditions in the Mediterranean, particularly during the glacial period when the landscape was covered by open woodland vegetation (Fletcher *et al*. 2010; Sadori 2018; Francke *et al*. 2019).

Stable isotope geochemistry

A moderate range of ~2.5‰ (−2.2 to +0.3‰; $\bar{x}$ = −0.7‰) in $\delta^{18}O_{carb}$ suggests that the lake has not experienced complete hydrological closure since ~47 800 cal. a BP (Fig. 6). Given the high surface area to water volume ratio of Lake Trasimeno and its sensitivity to hydroclimate, as well as average modern $\delta^{18}O_P$ in the area of ~ −7‰ (Giustini *et al*. 2016), changes in the E/P ratio are

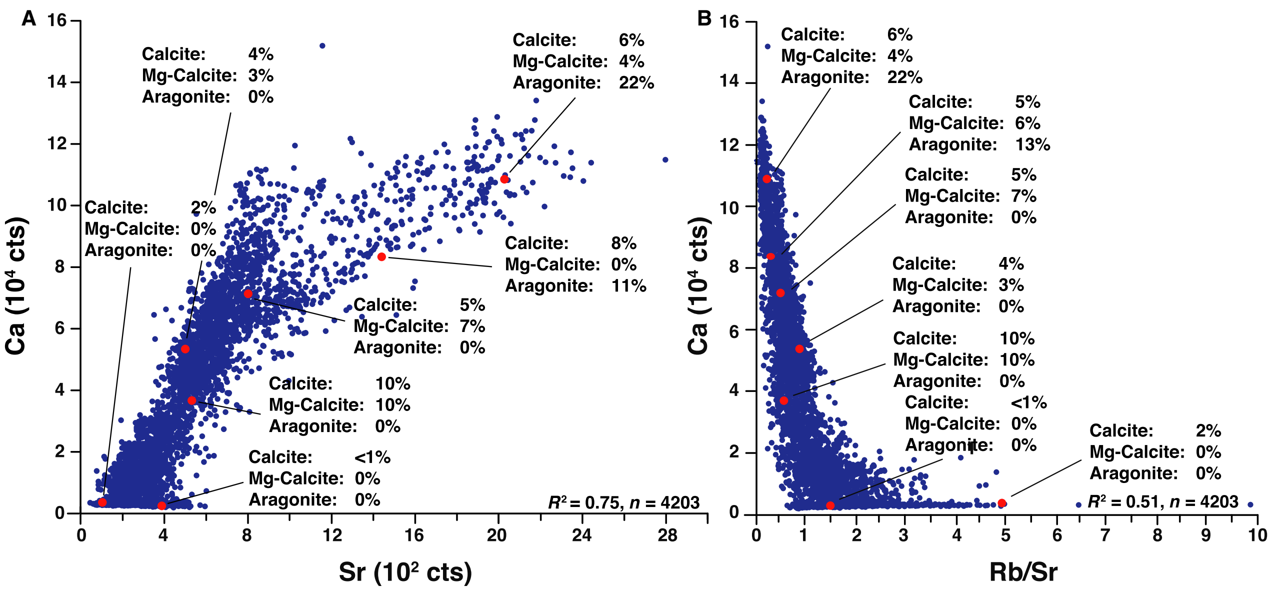

Fig. 5. Endogenic calcium carbonate in the sediments of Lake Trasimeno: A. Cross-plot of Ca and Sr intensities as derived from XRF core scanning. Marked in red are the samples selected for XRD analyses. Shown are the calcite, Mg-calcite, and aragonite concentrations as obtained from XRD analyses. This cross-plot shows that Mg-calcite and aragonite-bearing sediments show elevated Sr intensities as Mg-rich calcium carbonates preferentially incorporate Sr into their crystal lattice (cf. main text). B. Cross-plot of the Ca intensities and the Rb/Sr ratio. Calcite, Mg-calcite, and aragonite concentrations as obtained from XRD analyses are also displayed by red dots. The data imply that aragonite is dominant when Rb/Sr is <0.4 (cf. also Table 3).

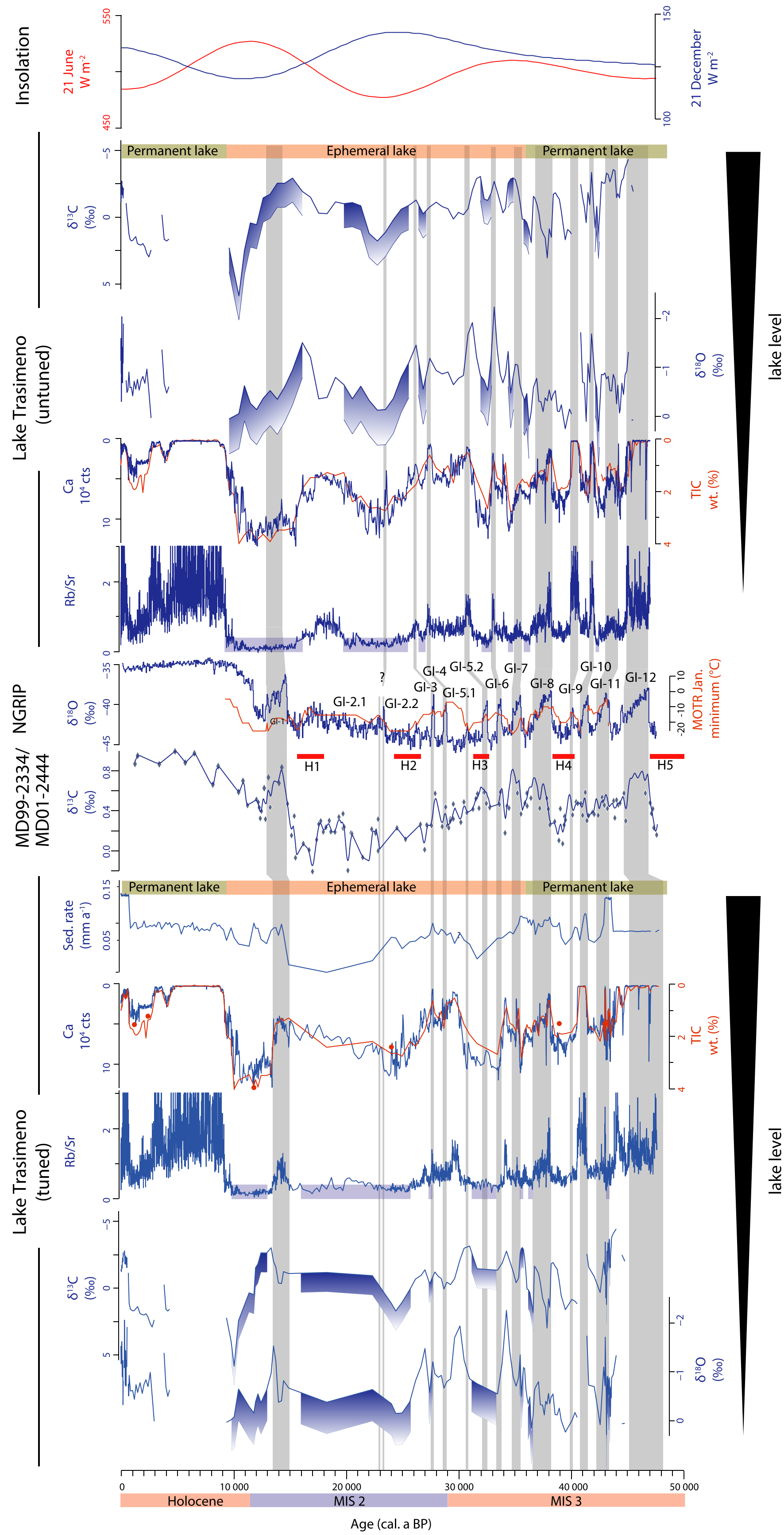
Insolation
21 June W m⁻²
21 December W m⁻²
Lake Trasimeno (untuned)
Permanent lake
Ephemeral lake
Permanent lake
δ13C (‰)
δ18O (‰)
Ca 10⁴ cts
TIC wt. (%)
Rb/Sr
lake level
NGRIP
MD99-2334/ MD01-2444
δ18O (‰)
MOTR Jan. minimum (°C)
GI-2.1
GI-2.2
GI-3
GI-4
GI-5.1
GI-5.2
GI-6
GI-7
GI-8
GI-9
GI-10
GI-11
GI-12
H1
H2
H3
H4
H5
δ13C (‰)
Lake Trasimeno (tuned)
Permanent lake
Ephemeral lake
Permanent lake
Sed. rate (mm a⁻¹)
Ca 10⁴ cts
TIC wt. (%)
Rb/Sr
δ13C (‰)
δ18O (‰)
lake level
Holocene
MIS 2
MIS 3
Age (cal. a BP)

Fig. 6. Lake Trasimeno proxy data: TIC content, Ca intensities, Rb/Sr ratio, $\delta^{18}O_{carb}$, and $\delta^{13}C_{carb}$ plotted against age (cal. a BP). Also shown are the summer and winter insolation at 43°N latitude (Lake Trasimeno), the NGRIP $\delta^{18}O$ ice-core record (NGRIP-members 2004) based on the chronology of the INTIMATE (Integration of Ice-core, Marine and Terrestrial records) working group (Rasmussen *et al.* 2014), and the MD99-2334/MD01-244 $\delta^{13}C_{benthic}$ record from the Iberian Margin (Skinner *et al.* 2013). Grey bars mark GI warm periods of the NGRIP ice-core record (Rasmussen *et al.* 2014). The ages for Heinrich events H5 to H1 are from Sanchez Goñi & Harrison (2010). Blue shaded areas define where Rb/Sr is <0.4 and depicts the uncertainty associated with mineral-water isotope fractionation effects between the carbonate phases. Ephemeral and permanent lake conditions are inferred from ostracod data (Marchegiano *et al.* 2018, 2019).

most likely the primary driver of $\delta^{18}O_{carb}$ variability in core Co1320 (Leng & Marshall 2004; Roberts *et al.* 2008). This is supported by lake water $\delta^{2}H$ and $\delta^{18}O$ data for Trasimeno (Frondini *et al.* 2019), which plot along a local evaporation line (LEL) that distinctly falls away from the Local Mediterranean Meteoric Water Line (LMWL). In the geological past, a predominant influence of E/P is supported by the good agreement of $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ (−4.4 to +5.9‰; $\overline{x} = -0.9‰$, Figs 4B, 6), which have a moderate positive correlation ($R^2 = 0.24$), as evaporation promotes isotopic exchange between the lake water and the atmosphere (Leng *et al.* 2013; Lacey *et al.* 2016). Supply of dissolved inorganic carbon (DIC) from the catchment as source for higher $\delta^{13}C_{carb}$ is unlikely for Lake Trasimeno due to the siliciclastic rich bedrock lithology having negligible carbonate amounts. Changes in $\delta^{13}C_{DIC}$ via increased primary productivity and the preferential uptake and burial of ^{12}C by algae (Lacey *et al.* 2016) could promote higher $\delta^{13}C_{carb}$ during wetter and warmer intervals when primary productivity at Trasimeno is enhanced. Lower $\delta^{13}C_{DIC}$ and $\delta^{13}C_{carb}$ are supported by a greater contribution of ^{12}C-rich soil-derived CO_2 from the catchment and/or by the decomposition and recycling of organic material in lacustrine surface sediments (Leng *et al.* 2010; Zanchetta *et al.* 2018).

Isotope analyses were carried out under the assumption that calcite is the dominant $CaCO_3$ species in the sediments of Lake Trasimeno. However, XRD analyses and the Rb/Sr ratio evidence the presence of aragonite in some intervals of core Co1320, which has to be considered during interpretations of Lake Trasimeno's stable isotope record as the isotopic fractionation between calcite and aragonite is +0.6‰ (Tarutani *et al.* 1969) for $\delta^{18}O_{carb}$ and +1.8‰ (Rubinson & Clayton 1969) for $\delta^{13}C_{carb}$. As aragonite-bearing sediment successions were defined by Rb/Sr ratios <0.4 only stable isotope ratios of sediments with Rb/Sr <0.4 may potentially be biased. Our XRD analyses show a mixture of calcite, Mg-calcite, and aragonite, with aragonite contributing ~70% of the total carbonate present in samples at 347 and 683 cm (Table 3). Thus, the relative enrichment of $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ values should be less than +0.6 and +1.8‰, respectively, due to the mixed nature of the carbonate polymorphs. Although the true error is likely lower, we depict these errors in Fig. 6 to provide conservative estimates. The mixture of $CaCO_3$ species in Lake Trasimeno sediments may also explain the limited correlation between $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ (due to the different fractionation factors, $R^2 = 0.24$), $\delta^{13}C_{carb}$ and TIC content ($R^2 = 0.04$), and $\delta^{18}O_{carb}$ and TIC content ($R^2 = 0.16$, Fig. 4) despite their overall similar trends (cf. Figs 4, 6).

High $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ correspond to aragonite-bearing sediment successions in core Co1320 with low Rb/Sr and high TIC, which implies that these intervals likely represent phases of low lake level and dry conditions at Lake Trasimeno. A low lake level and dry conditions are consistent with high E/P ratios as indicated by the $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$, even when the potential bias from different fractionation factors is not taken into account (Fig. 6). If the potential bias is considered, the amplitude of excursions in $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ that indicate high E/P ratios during lake-level lowstands is even higher, which supports the interpretation of the stable isotope record. A lake-level sensitive response of E/P ratios and $\delta^{18}O$ is also supported by modern lake water monitoring, which revealed consistently higher lake water $\delta^{18}O$ in response to lower lake levels between January 2006 and January 2014 (Frondini *et al.* 2019). The monthly variations of the isotope composition of lake water have furthermore been reported to be positively correlated to temperature and evaporation, and inversely correlated to precipitation (Frondini *et al.* 2019). A strong correlation between $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ and lake level has also been reported from Lake Ledro in northern Italy (Baneschi *et al.* 2020).

Lateglacial to Holocene hydrological variability in central Italy

Pre-LGM (47 800 to 29 000 cal. a BP, equivalent to MIS 3). – Sedimentary proxies from Lake Trasimeno show millennial-scale variability using both the tuned and untuned chronologies between 47 800 and 29 000 cal. a BP (Fig. 6). The millennial-scale climate variability overprints a general trend from permanent to more shallow/ephemeral lake conditions as inferred from ostracod data (Marchegiano *et al.* 2019; Fig. 6), irrespective of chronology. The observed millennial-scale variability indicates that Lake Trasimeno has experienced rapid lake-level fluctuations during this time interval that might potentially correspond to GI/GS variability in NGRIP. A precise alignment and chronological comparison to the ice-core records is, however, limited by our temperature-tuned and radiocarbon-based chronologies. Low Ca, $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ correspond to high Rb/Sr implying high lake levels and a low E/P ratio at Lake Trasimeno during periods tentatively aligned with GIs. Low lake levels, a high E/P ratio, and potential aragonite formation (Rb/Sr < 0.4) are associated with GS time periods and particularly with Heinrich events H4 and H3. These findings agree with previously published ostracod data recording higher (lower) lake water salinity, very shallow/temporary (high/permanent) water levels, and low (high) water temperatures during Last Glacial GS (GI) periods at Lake Trasimeno (Marchegiano *et al.* 2018, 2020), interpretations that are equally limited by uncertainties in the chronologies. Major tectonic events amplifying the wedge-shape depression hosting Lake Trasimeno (i.e. subsidence along the eastern shoreline) during the time interval investigated herein might also control deepening water levels and decreasing lake surface area. Nonetheless, tectonic events do not directly impact lake water geochemistry relevant for our geochemical proxy data (Ca, Rb/Sr). A lower lake surface area would restrict evaporation and might thus affect $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$; however, progressive ENE dipping of the Lake Trasimeno basin cannot account for millennial-scale lake level variability as recorded in the stable isotope data.

Periods of rapid aridification in central Italy might correspond to abrupt reductions of the Atlantic Meridional Overturning Circulation (AMOC). This relationship can be concluded from a comparison of the Lake Trasimeno proxy data to the AMOC intensity as inferred from the MD99-2334/MD01-244 record (Fig. 6), where low benthic foraminifer $\delta^{13}C$ values reflect the incursion of Antarctic bottom water towards the Iberian Margin correlated to a break-down of the AMOC (Skinner *et al.* 2013). A strengthening (weakening) of the AMOC during GI (GS) periods has recently been underpinned by Gottschalk *et al.* (2015), reporting that the majority of GI periods are accompanied by a rapid incursion of North Atlantic Deep Water into the South Atlantic. The potential co-variation between AMOC variability and Lake Trasimeno water level fluctuations would support a close link (teleconnection) of ocean circulation patterns and hydrological conditions in the central Mediterranean and, thus, between ocean and atmospheric circulation during the Last Glacial period. During GS periods and H events (weak AMOC), cooling is centred over Scandinavia but also spreads from Greenland and northern Europe to southern Europe, North Africa, and Asia, triggering a southward displacement of the atmospheric circulation pattern (Menviel *et al.* 2014). A southward displacement of atmospheric circulation particularly during autumn and winter could have promoted outbreaks of cold and dry polar air masses from northern and northeastern directions, explaining the low lake levels and the shift towards higher $\delta^{18}O_{carb}$ particularly during (tentative) H events H4 and H3. A synchronicity between Eastern Mediterranean aridification and enhanced freshwater discharge into the North Atlantic has also been inferred from Lake Van (Stockhecke *et al.* 2016) and the Dead Sea Basin (Torfstein *et al.* 2013). Furthermore, a reduction of autumn and winter rainfall could be promoted by persisting low NH summer–winter insolation (temperature) gradients during the pre-LGM (eccentricity minimum, Fig. 6) and a restricted northward migration of the ITCZ, which hampers local cyclogenesis in the Mediterranean (Wagner *et al.* 2019).

Enhanced rainfall across the Mediterranean region during warm GI intervals is mostly associated with enhanced storm track intensity and/or frequency in the Westerlies and the delivery of low $\delta^{18}O$ precipitation from the Atlantic (Chondrogianni *et al.* 2004; Zanchetta *et al.* 2007; Roberts *et al.* 2008), which would promote reduced E/P conditions and lower $\delta^{18}O_{carb}$ at Lake Trasimeno. The close connection between central Mediterranean precipitation amount and AMOC intensity implies an ocean–atmosphere coupling with intensified/more frequent (reduced/less frequent) mid-latitude cyclogenesis during GI (GS) boundary conditions. The strong relationship between (winter) precipitation, Mediterranean sea surface temperatures (SSTs), and the position of the ITCZ might, however, have additional control on millennial-scale climate variability in the Mediterranean realm. Associated millennial-scale northward (southward) displacement of the ITCZ identified in Asian speleothem records is likely linked to longitudinal equatorial heat transfer and AMOC and could foster higher (lower) Mediterranean SSTs, which might promote convective rainfall (Bosmans *et al.* 2015; Wagner *et al.* 2019; Wilson *et al.* 2021). It is still unclear whether the position of the northern ice sheet (high latitude forcing) or the orbital configuration (low latitude precessional forcing) has stronger influence on the amplitude of hydrological variability in the central Mediterranean region. Interestingly, we tentatively find highest lake levels (irrespective of chronology) for GI-12, GI-10 and GI-8, which occur prior to the precession minima (maximum in summer insolation, Fig. 6) typically coinciding with enhanced precipitation in the Mediterranean region (Kutzbach *et al.* 2013; Bosmans *et al.* 2015; Wagner *et al.* 2019). This implies a limited control of orbital forcing and can probably be attributed to the previously discussed low seasonal temperature (insolation) gradient under MIS 3 orbital configuration (eccentricity minima). Moreover, comparable lower lake levels after 35 000 cal. a BP (i.e. between GI-7 and GI-6, during the summer insolation maximum, cf. Fig. 6) occur during a time of lower variability of the AMOC intensity as suggested by benthic foraminifera $\delta^{13}C$ values at the Iberian Margin (cf. Fig. 6). This proposes a dominance of high-latitude forcing via AMOC variability at Lake Trasimeno at a latitude of 43°N, which is in good agreement with pollen records from Italy (Fletcher *et al.* 2010) and extends even as far east as the Balkan Peninsula (e.g. Panagiotopoulos *et al.* 2014), showing a stronger response of temperate forest taxa compared to Mediterranean-type taxa (and associated Mediterranean-type climate conditions) north of 40°N.

Pollen records from the central Mediterranean also imply increasing aridity over the course of longer interstadial periods (GI-12, GI-8, Fletcher *et al.* 2010), whereas it remains unclear if such trends can be observed during shorter GI intervals due to a delayed adaption of the vegetation belts to rapid climate change. Lake-level fluctuations of Lake Trasimeno likely responded much quicker to changes in moisture availability in central Italy compared to pollen records, but clear trends towards increasing aridity are evident for (tentative) GI-12 and GI-8 only. The opposite pattern with highest SSTs occurring at the end of GI periods has been reported from the Alboran Sea (MD95-2043, Fig. 1, Cacho *et al.* 1999). This observation supports the argument that the intensification and/or higher cyclone frequency in the Westerlies of Atlantic origin control the hydrological variability in central Italy rather than (regional) Mediterranean cyclones.

LGM and termination 1 (29 000 to 11 600 cal. a BP, equivalent to MIS 2). – The core Co1320 proxy data indicate more stable hydrological conditions at Lake Trasimeno between 29 000 and 11 600 cal. a BP (Fig. 6). Lowest lake level and driest conditions are identified in intervals with aragonite-bearing sediments (Fig. 6), which is supported by ostracod data indicating ephemeral lake conditions (Marchegiano *et al.* 2018, Fig. 6). The timing, however, contains larger uncertainties due to limited independent dating. The untuned chronology records these dry periods between 25 000 and 20 000 cal. a BP, and between 16 000 and 11 600 cal. a BP. In contrast, the tuned chronology implies dry conditions between 25 000 and 16 000 cal. a BP, and between 13 000 and 11 600 cal. a BP. Higher lake levels are indicated between 20 000 and 16 000 cal. a BP based on the untuned chronology, and between ~16 000 and ~13 000 cal. a BP based on the tuned chronology, respectively.

The onset of more stable and dry conditions at Lake Trasimeno after ~29 000 cal. a BP (as inferred from both chronologies) corresponds to the start of full glacial conditions, as recorded in marine sediment cores (MIS 2), concomitant with the expansion of global ice sheets (Lisiecki & Raymo 2005) and a weakening of the AMOC (Gottschalk *et al.* 2015). However, a precise correlation of the marine chronology to GI/GS climate variability in the Greenland ice-cores is still under debate. Recently, the onset of fully glacial conditions was placed between GI-4 and GI-3, at ~27 800 cal. a BP (Sanchez Goñi & Harrison 2010). A full glacial climate in the Mediterranean with very arid conditions, as inferred from pollen reconstructions from Lago Grande di Monticchio emerged after 25 900 cal. a BP, subsequent to GI-3 and contemporaneous with H2, similar to the onset recorded in core MD99-2334/MD01-2444 from the Iberian Margin and confirmed from the South Atlantic (Gottschalk *et al.* 2015). The rapidly increasing Ca and TIC contents following GI-3 in the sediments of Lake Trasimeno (irrespective of chronology) are in line with the findings from the two marine records. Simultaneously decreasing summer insolation is in excellent agreement with Lake Trasimeno's stable isotope record (Fig. 6), characterized by very high $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$ values corresponding to lower local summer insolation and peak glacial conditions culminating at around 22 000 cal. a BP. Low lake levels at Trasimeno may be explained by a weakening of the (humid) Westerlies along with an expansion of polar air bringing cold and dry air masses to central Italy, local Mediterranean anticyclones, a weak AMOC, and low summer–winter temperature gradients. Significant Last Glacial aridification associated with a weakening of westerly storm tracks has also been recorded from stable isotope records further eastward from the Balkan Peninsula (Lacey & Jones 2018).

The collapse of the AMOC associated with H1 (corresponding to the Oldest Dryas; Naughton *et al.* 2007) is well reflected in the Northeast Atlantic by low benthic foraminifera $\delta^{13}C$ in MD99-2334/MD01-2444 (Fig. 6) as well as $^{213}Pa/^{230}Th$ records from the subtropical to high latitude North Atlantic (Ng *et al.* 2018). Uncertainties in our chronology hamper a direct alignment of Lake Trasimeno's proxy data to H1 (Fig. 6). The untuned chronology suggests somewhat higher lake levels during H1, which is inconsistent with most other palaeoclimate records from central Italy (Fletcher *et al.* 2010). Broadly increasing lake level at Lake Trasimeno after the LGM (based on the tuned chronology), however, indeed matches increasing local summer insolation after the LGM, contemporaneous with increasing obliquity and higher insolation contrasts between low (35°) and high (65°) latitude insolation forcing (Laskar *et al.* 2004). Substantial low to high latitude temperature differences (Shaw *et al.* 2016), probably amplified by the post-LGM expanding northern ice sheet (Lisiecki & Raymo 2005), can amplify the Westerlies' intensity, thus, explaining increasing lake levels at Trasimeno despite a relatively weak AMOC (Fig. 6). This observation probably implies that increasing humidity at Lake Trasimeno after the LGM is controlled by orbital configuration rather than by millennial-scale NH climate forcing and AMOC intensity. Interestingly, the climate shift towards more humid conditions is not evident in Rb/Sr or the temperate pollen taxa from Lago Grande di Monticchio (Brauer *et al.* 2007; Fletcher *et al.* 2010) and Valle di Castiglione (Follieri *et al.* 1998; Fletcher *et al.* 2010), suggesting that precipitation increase was probably limited (Lake Trasimeno shows response in Ca only) with no or negligible impact of temperature.

The reinforcement of the AMOC associated with GI-1 (cf. Fig. 6), a climate oscillation correlated to the Bølling/Allerød interstadial (Naughton *et al.* 2007), and subsequent cold and dry conditions during the Younger Dryas until 11 700 cal. a BP, is only mirrored in our tuned chronology data. The untuned chronology, implying wetter conditions between 20 000 and 16 000 cal. a BP, is inconsistent with other palaeoclimate archives from the region (Fletcher *et al.* 2010). Rb/Sr and stable isotope data based on the tuned chronology in turn imply dry conditions and increasing evaporation (increasing $\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$) during the Younger Dryas. This denotes an overall low lake level at Lake Trasimeno despite a relatively strong AMOC and, thus, an overall low impact of glacial to Holocene deglaciation on moisture availability in central Italy. Dry conditions in this region during the Lateglacial period are also supported by data from Lago Grande di Monticchio, where pollen assemblages indicate a strong seasonality (Allen *et al.* 2000), and at Lago di Mezzano (Sadori 2018). This strong seasonality combined with dry winter conditions during the Lateglacial may be explained by a low winter insolation (Fig. 6) and a southward displacement of polar air during winter, but high insolation during summer. Low lake levels and high E/P ratios (stable isotopes) are then amplified by increasing summer temperatures in response to global warming, in agreement with the previously discussed strong seasonality. Cold and dry Lateglacial to Early Holocene conditions on the Balkan Peninsula have previously been attributed to (cold) polar air outbreaks (Vogel *et al.* 2010a; Panagiotopoulos *et al.* 2013).

Holocene (11 600 cal. a BP to present day). – During the Holocene, a relatively high lake level is inferred from low to negligible Ca and high Rb/Sr and from ostracod data (Marchegiano *et al.* 2019; Fig. 6). Higher moisture availability compared to glacial times is consistent with various palaeoclimate records in the Mediterranean region (Roberts *et al.* 2008). The data show a delayed lake-level increase during the Early Holocene, with the highest lake level after ~9000 cal. a BP. A delayed maximum in humidity compared to the onset of interglacial conditions has been reported for the Mediterranean region south of 40°N (Magny *et al.* 2013) and is explained by strong Hadley cell activity in response to enhanced summer insolation forcing (Tinner *et al.* 2009). A strong Hadley cell and an intensive African monsoon system block the westerly transport of wet air to the Mediterranean region (Magny *et al.* 2013). In addition, a low lake level at Lake Trasimeno during the first two millennia of the Holocene could have been amplified by enhanced evaporation due to high summer temperatures, which is consistent with increasing $\delta^{18}O_{carb}$, $\delta^{13}C_{carb}$ as well as ostracod assemblages (Marchegiano *et al.* 2019) until ~9000 cal. a BP.

The pattern of increasing aridity implies that Lake Trasimeno, located at a latitude of 43°N, shows higher similarities to Mediterranean-type palaeoclimate records located south (rather than north) of 40°N (Magny *et al.* 2003), which may imply that the 40°N climate boundary needs to be shifted further north (Marchegiano *et al.* 2019). The Mediterranean-type climate at Trasimeno during the Holocene implies a major shift in atmospheric circulation at 43°N. Holocene climate is mainly controlled by local cyclogenesis and orbital forcing (Wagner *et al.* 2019), in contrast to high latitude, Atlantic control on rainfall patterns prevailing during the pre-LGM. Marchegiano *et al.* (2018) report Holocene climate variability at Trasimeno lacks a distinct response to the 8.2-cooling event and records increasing aridity towards the Late Holocene. This interpretation is now also supported by Ca, TIC, and Rb/Sr from our study.

Conclusions

Major element (Ca, TIC, Rb/Sr) and stable isotope ($\delta^{18}O_{carb}$ and $\delta^{13}C_{carb}$) geochemical data show Last Glacial millennial-scale variability in lake-level fluctuations at Lake Trasimeno, which can tentatively be correlated to the intensity of westerly storm tracks penetrating into the central Mediterranean region (within the limitations of the age-depth models). In concert with marine proxy records off the Iberian Margin, our data imply that Trasimeno's lake-level fluctuations during the Last Glacial (MIS 3) period are probably connected to modifications of the AMOC (strength/intensity). Lateglacial (MIS 2) to Holocene hydrological change in central Italy, however, seems to be increasingly controlled by orbital forcing. MIS 2 lake-level fluctuations show good agreement with orbital forcing, corresponding to overall low lake levels particularly during the LGM, and (limited) increasing moisture availability afterwards. Low lake levels during the Lateglacial to Holocene transition are probably controlled by amplified seasonality (high summer and low winter insolation) with high evaporation during summer and cold and dry polar air outbreaks during winter, as supported by literature data.

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Author contributions. – AF conducted the research and carried out the interpretation of the geochemical proxy data. JHL conducted stable isotope analyses and provided their interpretation. MM, KK, IB and AF provided the lithology and the core correlation for core Co1320. KK

carried out biogeochemical analyses. BW provided the core material. DA, BW and GZ supported the interpretation of the geochemical proxy data and their climatic interpretation. SK carried out biomarker analyses and provided their interpretation. KU provided XRD analyses. AF wrote the text with contributions from all authors.

Data availability statement. – Element geochemical (TIC, TOC, Ca, Rb/Sr ratios), and stable isotope ($\delta^{13}C_{carb}$, $\delta^{18}O_{carb}$) are available at EARTHCHEM. The DOI is https://doi.org/10.26022/IEDA/112051.

References

Allen, J. R. M., Brandt, U., Brauer, A., Hubberten, H.-W., Huntley, B., Keller, J., Kraml, M., Mackensen, A., Mingram, J., Negendank, J. F. W., Nowaczyk, N. R., Oberhänsli, H., Watts, W. A., Wulf, S. & Zolitschka, B. 1999: Rapid environmental changes in southern Europe during the last glacial period. *Nature 400*, 740–743.

Allen, J. R. M., Watts, W. A. & Huntley, B. 2000: Weichselian palynostratigraphy, palaeovegetation and palaeoenvironment; the record from Lago Grande di Monticchio, southern Italy. *Quaternary International 73–74*, 91–110.

Ambrosetti, W., Barbanti, L. & Sala, N. 2003: Papers from Bolsena Conference (2002). Residence time and physical processes in lakes: sciences, management, education. *Journal of Limnology 62*, 1–15.

Aufgebauer, A., Panagiotopoulos, K., Wagner, B., Schaebitz, F., Viehberg, F. A., Vogel, H., Zanchetta, G., Sulpizio, R., Leng, M. J. & Damaschke, M. 2012: Climate and environmental change in the Balkans over the last 17 ka recorded in sediments from Lake Prespa (Albania/F.Y.R. of Macedonia/Greece). *Quaternary International 274*, 122–135.

Baneschi, I., Magny, M. & Zanchetta, G. 2020: Are stable isotopes of lacustrine carbonate a good tracer of lake hydrology and lake level variablity? The Lake Ledro case (Northern Italy). *Alpine and Mediterranean Quaternary 33*, 99–106.

Bergmann, J. & Kleeberg, R. 1998: Rietveld analysis of disordered layer silicates. *Materials Science Forum 278–281 part 1*, 300–305.

Bischoff, W. D., Bishop, F. C. & Mackenzie, F. T. 1983: Biogenically produced magnesian calcite; inhomogeneities in chemical and physical properties; comparison with synthetic phases. *American Mineralogist 68*, 1183–1188.

Blaauw, M. 2010: Methods and code for 'classical' age-modelling of radiocarbon sequences. *Quaternary Geochronology 5*, 512–518.

Blaauw, M. 2012: Out of tune: the dangers of aligning proxy archives. *Quaternary Science Reviews 36*, 38–49.

Blaauw, M. & Christen, J. A. 2011: Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis 6*, 457–474.

Blaauw, M., Christen, J. A., Bennett, K. D. & Reimer, P. J. 2018: Double the dates and go for Bayes — Impacts of model choice, dating density and quality on chronologies. *Quaternary Science Reviews 188*, 58–66.

Bond, G. C. & Lotti, R. 1995: Iceberg discharges into the North Atlantic on millennial time scales during the last deglaciation. *Science 267*, 1005–1010.

Bosmans, J. H. C., Drijfhout, S. S., Tuenter, E., Hilgen, F. J., Lourens, L. J. & Rohling, E. J. 2015: Precession and obliquity forcing of the freshwater budget over the Mediterranean. *Quaternary Science Reviews 123*, 16–30.

Brauer, A., Allen, J. R. M., Mingram, J., Dulski, P., Wulf, S. & Huntley, B. 2007: Evidence for last interglacial chronology and environmental change from Southern Europe. *Proceedings of the National Academy of Sciences 104*, 450–455.

Burzigotti, R., Dragoni, W., Evangelisti, C. & Gervasi, L. 2003: The Role of Lake Trasimeno (central Italy) in the History of Hydrology and Water Management. IWHA 3rd International Conference, Alexandria, Egypt.

Cacho, I., Grimalt, J. O., Pelejero, C., Canals, M., Sierro, F. J., Flores, J. A. & Shackleton, N. J. 1999: Dansgaard-Oeschger and Heinrich event imprints in Alboran Sea paleotemperatures. *Paleoceanography 14*, 698–705.

Chondrogianni, C., Ariztegui, D., Rolph, T., Juggins, S., Shemesh, A., Rietti-Shati, M., Niessen, F., Guilizzoni, P., Lami, A., McKenzie, J. A. & Oldfield, F. 2004: Millennial to interannual climate variability in the Mediterranean during the Last Glacial Maximum. *Quaternary International 122*, 31–41.

Cohen, A. S. 2003: *Paleolimnology: The History and Evolution of Lake Systems.* 525 pp. Oxford University Press, New York.

Cosford, J., Qing, H., Yuan, D., Zhang, M., Holmden, C., Patterson, W. & Hai, C. 2008: Millennial-scale variability in the Asian monsoon: evidence from oxygen isotope records from stalagmites in southeastern China. *Palaeogeography, Palaeoclimatology, Palaeoecology 266*, 3–12.

Croudace, I. W., Rindby, A. & Rothwell, R. G. 2006: ITRAX: description and evaluation of a new multi-function X-ray core scanner. *New Techniques in Sediment Core Analysis 267*, 51–63.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N., Hammer, C. U. & Oeschger, H. 1984: North Atlantic climatic oscillations revealed by deep Greenland ice cores. *Climate Processes and Climate Sensitivity 29*, 288–298.

Davies, S. J., Lamb, H. F. & Roberts, J. S. 2015: Micro-XRF core scanning in paleolimnology: recent developments. *In* Croudace, I. & Rothwell, R. G. (eds.): *Micro-XRF Studies of Sediment Cores*, 189–226, Springer, Dordrecht.

De Choudens-Sanchez, V. & Gonzalez, L. A. 2009: Calcite and aragonite precipitation under controlled instantaneous supersaturation: elucidating the role of $CaCO_3$ saturation state and Mg/Ca ratio on calcium carbonate polymorphism. *Journal of Sedimentary Research 79*, 363–376.

Dean, W., Rosenbaum, J., Skipp, G., Colman, S., Forester, R., Liu, A., Simmons, K. & Bischoff, J. 2006: Unusual Holocene and late Pleistocene carbonate sedimentation in Bear Lake, Utah and Idaho, USA. *Sedimentary Geology 185*, 93–112.

Douglas, R. W. & Rippey, B. 2000: The random redistribution of sediment by wind in a lake. *Limnology and Oceanography 45*, 686–694.

Fletcher, W. J., Sánchez Goñi, M. F., Allen, J. R. M., Cheddadi, R., Combourieu-Nebout, N., Huntley, B., Lawson, I., Londeix, L., Magri, D., Margari, V., Müller, U. C., Naughton, F., Novenko, E., Roucoux, K. & Tzedakis, P. C. 2010: Millennial-scale variability during the last glacial in vegetation records from Europe. *Quaternary Science Reviews 29*, 2839–2864.

Follieri, M., Giardini, M., Magri, D. & Sadori, L. 1998: Palynostratigraphy of the Last Glacial period in the volcanic region of central Italy. *Quaternary International 47*, 3–20.

Francke, A., Dosseto, A., Panagiotopoulos, K., Leicher, N., Lacey, J. H., Kyrikou, S., Wagner, B., Zanchetta, G., Kouli, K. & Leng, M. J. 2019: Sediment residence time reveals Holocene shift from climatic to vegetation control on catchment erosion in the Balkans. *Global and Planetary Change 177*, 186–200.

Francke, A., Wagner, B., Leng, M. J. & Rethemeyer, J. 2013: A Late Glacial to Holocene record of environmental change from Lake Dojran (Macedonia, Greece). *Climate of the Past 9*, 481–498.

Friedman, I. & O'Neil, J. R. 1977: Compilation of stable isotope fractionation factors of geochemical interest. *U.S. Geological Survey Professional Paper 440-KK*, https://doi.org/10.3133/pp440KK. U.S Government Printing Office, Washington.

Frondini, F., Dragoni, W., Morgantini, N., Donnini, M., Cardellini, C., Caliro, S., Melillo, M. & Chiodini, G. 2019: An endorheic lake in a changing climate: geochemical investigations at Lake Trasimeno (Italy). *Water 11*, 1319, https://doi.org/10.3390/w11071319.

Gasperini, L., Barchi, M. R., Bellucci, L. G., Bortoluzzi, G., Ligi, M. & Pauselli, C. 2010: Tectonostratigraphy of Lake Trasimeno (Italy) and the geological evolution of the Northern Apennines. *Tectonophysics 492*, 164–174.

Giustini, F., Brilli, M. & Patera, A. 2016: Mapping oxygen stable isotopes of precipitation in Italy. *Journal of Hydrology: Regional Studies 8*, 162–181.

Goda, Y. 2003: Revisiting Wilson's formulas for simplified wind-wave prediction. *Journal of Waterway, Port, Coastal, and Ocean Engineering 129*, 93–95.

Gottschalk, J., Skinner, L. C., Misra, S., Waelbroeck, C., Menviel, L. & Timmermann, A. 2015: Abrupt changes in the southern extent of

North Atlantic Deep Water during Dansgaard-Oeschger events. *Nature Geoscience 8*, 950–954.

Harrison, S. P. & Sanchez Goñi, M. F. 2010: Global patterns of vegetation response to millennial-scale variability and rapid climate change during the last glacial period. *Quaternary Science Reviews 29*, 2957–2980.

Heinrich, H. 1988: Origin and consequences of cyclic ice rafting in the Northeast Atlantic Ocean during the past 130,000 years. *Quaternary Research 29*, 142–152.

Hopmans, E. C., Weijers, J. W. H., Schefuß, E., Herfort, L., Sinninghe Damsté, J. S. & Schouten, S. 2004: A novel proxy for terrestrial organic matter in sediments based on branched and isoprenoid tetraether lipids. *Earth and Planetary Science Letters 224*, 107–116.

Huguet, C., Hopmans, E. C., Febo-Ayala, W., Thompson, D. H., Sinninghe Damsté, J. S. & Schouten, S. 2006: An improved method to determine the absolute abundance of glycerol dibiphytanyl glycerol tetraether lipids. *Organic Geochemistry 37*, 1036–1041.

IPCC 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. 169 pp. IPCC.

Kutzbach, J. E., Chen, G., Cheng, H., Edwards, R. L. & Liu, Z. 2013: Potential role of winter rainfall in explaining increased moisture in the Mediterranean and Middle East during periods of maximum orbitally-forced insolation seasonality. *Climate Dynamics 42*, 1079–1095.

Lacey, J. H. & Jones, M. D. 2018: Quantitative reconstruction of early Holocene and last glacial climate on the Balkan Peninsula using coupled hydrological and isotope mass balance modelling. *Quaternary Science Reviews 202*, 109–121.

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

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M. & Levrard, B. 2004: A long-term numerical solution for the insolation quantities of the Earth. *Astronomy & Astrophysics 428*, 261–285.

Leng, M. J. & Marshall, J. D. 2004: Palaeoclimate interpretation of stable isotope data from lake sediment archives. *Quaternary Science Reviews 23*, 811–831.

Leng, M. J., Baneschi, I., Zanchetta, G., Jex, C. N., Wagner, B. & Vogel, H. 2010: Late Quaternary palaeoenvironmental reconstruction from Lakes Ohrid and Prespa (Macedonia/Albania border) using stable isotopes. *Biogeosciences 7*, 3109–3122.

Leng, M. J., Wagner, B., Boehm, A., Panagiotopoulos, K., Vane, C. H., Snelling, A., Haidon, C., Woodley, E., Vogel, H., Zanchetta, G. & Baneschi, I. 2013: Understanding past climatic and hydrological variability in the Mediterranean from Lake Prespa sediment isotope and geochemical record over the Last Glacial cycle. *Quaternary Science Reviews 66*, 123–136.

Lisiecki, L. E. & Raymo, M. E. 2005: A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. *Paleoceanography 20*, PA1003, https://doi.org/10.1029/2004pa001071.

Ludovisi, A. & Gaino, E. 2010: Meteorological and water quality changes in Lake Trasimeno (Umbria, Italy) during the last fifty years. *Journal of Limnology 69*, 174–188.

Magny, M., Bégeot, C., Guiot, J. & Peyron, O. 2003: Contrasting patterns of hydrological changes in Europe in response to Holocene climate cooling phases. *Quaternary Science Reviews 22*, 1589–1596.

Magny, M., Combourieu-Nebout, N., de Beaulieu, J. L., Bout-Roumazeilles, V., Colombaroli, D., Desprat, S., Francke, A., Joannin, S., Ortu, E., Peyron, O., Revel, M., Sadori, L., Siani, G., Sicre, M. A., Samartin, S., Simonneau, A., Tinner, W., Vannière, B., Wagner, B., Zanchetta, G., Anselmetti, F., Brugiapaglia, E., Chapron, E., Debret, M., Desmet, M., Didier, J., Essallami, L., Galop, D., Gilli, A., Haas, J. N., Kallel, N., Millet, L., Stock, A., Turon, J. L. & Wirth, S. 2013: North-south palaeohydrological contrasts in the central Mediterranean during the Holocene: tentative synthesis and working hypotheses. *Climate of the Past 9*, 2043–2071.

Marchegiano, M., Francke, A., Gliozzi, E. & Ariztegui, D. 2018: Arid and humid phases in central Italy during the Late Pleistocene revealed by the Lake Trasimeno ostracod record. *Palaeogeography, Palaeoclimatology, Palaeoecology 490*, 55–69.

Marchegiano, M., Francke, A., Gliozzi, E., Wagner, B. & Ariztegui, D. 2019: High-resolution palaeohydrological reconstruction of central Italy during the Holocene. *The Holocene 29*, 481–492.

Marchegiano, M., Horne, D. J., Gliozzi, E., Francke, A., Wagner, B. & Ariztegui, D. 2020: Rapid Late Pleistocene climate change reconstructed from a lacustrine ostracod record in central Italy (Lake Trasimeno, Umbria). *Boreas 49*, 739–750.

Martin, C. W. & Johnson, W. C. 1995: Variation in radiocarbon ages of soil organic matter fractions from Late Quaternary buried soils. *Quaternary Research 43*, 232–237.

Menviel, L., Timmermann, A., Friedrich, T. & England, M. H. 2014: Hindcasting the continuum of Dansgaard-Oeschger variability: mechanisms, patterns and timing. *Climate of the Past 10*, 63–77.

Naughton, F., Sanchez Goñi, M. F., Desprat, S., Turon, J. L., Duprat, J., Malaizé, B., Joli, C., Cortijo, E., Drago, T. & Freitas, M. C. 2007: Present-day and past (last 25000 years) marine pollen signal off western Iberia. *Marine Micropaleontology 62*, 91–114.

Ng, H. C., Robinson, L. F., McManus, J. F., Mohamed, K. J., Jacobel, A. W., Ivanovic, R. F., Gregoire, L. J. & Chen, T. 2018: Coherent deglacial changes in western Atlantic Ocean circulation. *Nature Communications 9*, 2947, https://doi.org/10.1038/s41467-018-05312-3.

NGRIP-members 2004: High-resolution record of Northern Hemisphere climate extending into the last interglacial period. *Nature 431*, 147–151.

Panagiotopoulos, K., Aufgebauer, A., Schäbitz, F. & Wagner, B. 2013: Vegetation and climate history of the Lake Prespa region since the Late Glacial. *Quaternary International 292*, 157–169.

Panagiotopoulos, K., Böhm, A., Leng, M. J., Wagner, B. & Schäbitz, F. 2014: Climate variability over the last 92 ka in SW Balkans from analysis of sediments from Lake Prespa. *Climate of the Past 10*, 643–660.

Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchardt, S. L., Clausen, H. B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S. J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W. Z., Lowe, J. J., Pedro, J. B., Popp, T., Seierstad, I. K., Steffensen, J. P., Svensson, A. M., Vallelonga, P., Vinther, B. M., Walker, M. J. C., Wheatley, J. J. & Winstrup, M. 2014: A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quaternary Science Reviews 106*, 14–28.

Reimer, P. J. & 41 others 2020: The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon 62*, 725–757.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M. & van der Plicht, J. 2013: IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon 55*, 1869–1887.

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

Roeser, P., Franz, S. O. & Litt, T. 2016: Aragonite and calcite preservation in sediments from Lake Iznik related to bottom lake oxygenation and water column depth. *Sedimentology 63*, 2253–2277.

Rohling, E., Mayewski, P. & Challenor, P. 2003: On the timing and mechanism of millennial-scale climate variability during the last glacial cycle. *Climate Dynamics 20*, 257–267.

Rubinson, M. & Clayton, R. N. 1969: Carbon-13 fractionation between aragonite and calcite. *Geochimica et Cosmochimica Acta 33*, 997–1002.

Sadori, L. 2018: The Lateglacial and Holocene vegetation and climate history of Lago di Mezzano (central Italy). *Quaternary Science Reviews 202*, 30–44.

Sanchez Goñi, M. F. & Harrison, S. P. 2010: Millennial-scale climate variability and vegetation changes during the Last Glacial: concepts and terminology. *Quaternary Science Reviews 29*, 2823–2827.

Schouten, S., Hopmans, E. C. & Sinninghe Damsté, J. S. 2013: The organic geochemistry of glycerol dialkyl glycerol tetraether lipids: a review. *Organic Geochemistry 54*, 19–61.

Schouten, S., Huguet, C., Hopmans, E. C., Kienhuis, M. V. M. & Sinninghe Damsté, J. S. 2007: Analytical methodology for TEX86 paleothermometry by high-performance liquid chromatography/atmospheric pressure chemical ionization-mass spectrometry. *Analytical Chemistry 79*, 2940–2944.

Shaw, T. A., Baldwin, M., Barnes, E. A., Caballero, R., Garfinkel, C. I., Hwang, Y. T., Li, C., O'Gorman, P. A., Rivière, G., Simpson, I. R. & Voigt, A. 2016: Storm track processes and the opposing influences of climate change. *Nature Geoscience 9*, 656–664.

Sinninghe Damsté, J., Verschuren, D., Ossebaar, J., Blokker, J., van Houten, R., van der Meer, M. T. J., Plessen, B. & Schouten, S. 2011: A 25,000-year record of climate-induced changes in lowland vegetation of eastern equatorial Africa revealed by the stable carbon-isotopic composition of fossil plant leaf waxes. *Earth and Planetary Science Letters 302*, 236–246.

Skinner, L. C., Elderfield, H. & Hall, M. 2013: Phasing of millennial climate events and northeast Atlantic deep-water temperature change since 50 ka BP. *In* Schmittner, A., Chiang, J. C. H. & Hemming, S. R. (eds.): Ocean Circulation: Mechanisms and Impacts —Past and Future Changes of Meridional Overturning, 197-208. Geophysical Monograph Series 173.

Steffensen, J. P., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Fischer, H., Goto-Azuma, K., Hansson, M., Johnsen, S. J., Jouzel, J., Masson-Delmotte, V., Popp, T., Rasmussen, S. O., Röthlisberger, R., Ruth, U., Stauffer, B., Siggaard-Andersen, M.-L., Sveinbjörnsdóttir, Á. E., Svensson, A. & White, J. W. C. 2008: High-resolution Greenland ice core data show abrupt climate change happens in few years. *Science 321*, 680–684.

Stockhecke, M., Timmermann, A., Kipfer, R., Haug, G. H., Kwiecien, O., Friedrich, T., Menviel, L., Litt, T., Pickarski, N. & Anselmetti, F. S. 2016: Millennial to orbital-scale variations of drought intensity in the Eastern Mediterranean. *Quaternary Science Reviews 133*, 77–95.

Tarutani, T., Clayton, R. N. & Mayeda, T. K. 1969: The effect of polymorphism and magnesium substitution on oxygen isotope fractionation between calcium carbonate and water. *Geochimica et Cosmochimica Acta 33*, 987–996.

Taticchi, M. I. 1992: Studies on Lake Trasimeno and other water bodies in Umbria Region, Central Italy. *In* Tartari, G. & Giussani, G. (eds.): *Limnology in Italy*, 295–318. Memorie Dell´Istituto Italiano Di Idrobiologia, Perugia.

Tinner, W., van Leeuwen, J. F. N., Colombaroli, D., Vescovi, E., van der Knaap, W. O., Henne, P. D., Pasta, S., D'Angelo, S. & La Mantia, T. 2009: Holocene environmental and climatic changes at Gorgo Basso, a coastal lake in southern Sicily, Italy. *Quaternary Science Reviews 28*, 1498–1510.

Torfstein, A., Goldstein, S. L., Stein, M. & Enzel, Y. 2013: Impacts of abrupt climate changes in the Levant from Last Glacial Dead Sea levels. *Quaternary Science Reviews 69*, 1–7.

Verschuren, D., Ossebaar, J., Blokker, J., van Houten, R., van der Meer, M. T. J., Plessen, B. & Schouten, S. 2011: A 25,000-year record of climate-induced changes in lowland vegetation of eastern equatorial Africa revealed by the stable carbon-isotopic composition of fossil plant leaf waxes. *Earth and Planetary Science Letters 302*, 236–246.

Vogel, H., Wagner, B., Zanchetta, G., Sulpizio, R. & Rosén, P. 2010a: A paleoclimate record with tephrochronological age control for the last glacial-interglacial cycle from Lake Ohrid, Albania and Macedonia. *Journal of Paleolimnology 44*, 295–310.

Vogel, H., Zanchetta, G., Sulpizio, R., Wagner, B. & Nowaczyk, N. 2010b: A tephrostratigraphic record for the last glacial-interglacial cycle from Lake Ohrid, Albania and Macedonia. *Journal of Quaternary Science 25*, 320–338.

Wagner, B., & 47 others 2019: Mediterranean winter rainfall in phase with African monsoons during the past 1.36 million years. *Nature 573*, 256–260.

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. *Journal of Volcanology and Geothermal Research 177*, 71–80.

Wilson, G. P., Frogley, M. R., Hughes, P. D., Roucoux, K. H., Margari, V., Jones, T. D., Leng, M. J. & Tzedakis, P. C. 2021: Persistent millennial-scale climate variability in Southern Europe during Marine Isotope Stage 6. *Quaternary Science Advances 3*, 100016. https://doi.org/10.1016/j.qsa.2020.100016.

Zanchetta, G., Baneschi, I., Francke, A., Boschi, C., Regattieri, E., Wagner, B., Lacey, J. H., Leng, M. J., Vogel, H. & Sadori, L. 2018: Evidence for carbon cycling in a large freshwater lake in the Balkans over the last 0.5 million years using the isotopic composition of bulk organic matter. *Quaternary Science Reviews 202*, 154–165.

Zanchetta, G., Borghini, A., Fallick, A., Bonadonna, F. & Leone, G. 2007: Late Quaternary palaeohydrology of Lake Pergusa (Sicily, southern Italy) as inferred by stable isotopes of lacustrine carbonates. *Journal of Paleolimnology 38*, 227–239.