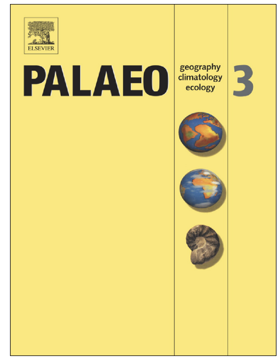

Speleothem U/Th age constraints for the last Glacial conditions in the Apuan Alps, northwestern Italy

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Speleothem U/Th age constraints for the Last Glacial conditions in the Apuan Alps, northwestern Italy.

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Abstract

During the Quaternary several glaciations occurred in the mountain regions around the Mediterranean and, in recent years, new ages have better constrained their timing. However, this is not the case for the Apuan Alps, a high-rainfall mountain chain adjacent to the Mediterranean Sea. Here, in spite of the widespread evidence for glaciers, the complete lack of geochronological information hinders our understanding of glaciation history. In this paper, we utilize speleothem ages to better constrain the timing of these glacial features. We re-examine 293 uranium-thorium ages from 19 speleothems collected in five caves at different elevations. After a period of very low growth between 160 and ~~135~~ 132 ka, the analysed speleothems grew almost continuously to ~75 ka, this period was followed by intermittent growth with lower deposition rate and presence of hiatuses until ~12.5 /12 ka. This is consistent with an ice coverage persisting over the Apuan Alps, inhibiting or interrupting the growth of speleothems via the limited availability of groundwater and the scarcity/absence of soils. This interval is much greater than the time interval that has previously been attributed to the existence of glaciers on the Apuan Alps, which has been assumed to be restricted to Marine Isotope Stage (MIS) 2. Instead, ice cover probably also appeared in the Apuan Alps during MIS 4. The phase of restarting of growth, which may implies the definitive or substantial glacier melts seem to predate the Holocene.

Keywords: Glacier; Pleniglacial; MIS2; MIS3; MIS4; Italy

1. Introduction

Speleothems (i.e. cave carbonate deposits) are multi-proxy paleoclimate archives, which can be accurately dated back to several hundred thousand years before present thanks to U-Th isotope systematic (Edwards et al. 1987; Hellstrom, 2006). Most of the paleoclimate research conducted using speleothems focused on the interpretation of stable isotope and trace element proxy records (e.g. Dykoski et al., 2005; Bar-Matthews et al., 1996; Wang et al., 2008; Regattieri et al., 2016). However, speleothems need certain conditions to grow continuously, such as the presence of liquid water, CO_2 and high Ca concentrations in drip waters (e.g. Atkinson et al., 1986; Gascoyne 1992; Genty et al., 2001). This generally implies relatively wet climate conditions, surface temperature above 0 °C and a well-developed soil above the cave (Gordon et al., 1989; Genty et al., 2001,2005). For instance, in desert environments, phases of speleothem growth are important indicators of past humid periods (Burns et al., 2001; Fleitmann et al., 2011; Vaks et al., 2006, 2007, 2010), as well as tufa, which occurrence significantly correlates with wetter phases (Smith et al., 2004; Cremaschi et al., 2015a). Similarly, the growth of speleothems in permafrost or glacier-dominated environments, often marks interruptions of cold conditions (i.e. Berstad et al., 2002; Spötl and Mangini, 2006; Pons-Branchu et al., 2010; Vaks et al., 2013). This is potentially consistent with degradation of permafrost and the formation of large ice-free surfaces, favoring water infiltration and soil ~~development~~ formation (Varks et al., 2013). Growth hiatuses within a single or multiple speleothems have been interpreted as evidences of particularly dry and/or cold conditions (e.g. Hodges et al., 2008; Genty et al., 2003, Baldini, 2002; Moreno et al., 2010; Mayer et al. 2012, Stoll et al., 2013), even if the nature and duration of hiatuses in speleothems cannot be unambiguously correlated to climatic conditions. However, stacking multiple speleothem records can give more robust information about the relationship between growth cessations and climate (e.g. Stoll et al., 2013).

During glacial periods, depressed external air temperatures at high latitudes and/or high altitudes sites may cause extensive freezing at the surface above a cave, strongly limiting water infiltration (Berstad et al., 2002; Genty et al., 2003,2005; Ayalon et al., 2013) and totally inhibiting soil activity (McDermott, 2004). This implies a strong reduction in the CO_2 transfer to the epikarst, a prerequisite for bedrock dissolution and speleothem growth. Therefore, development of glacial conditions (i.e. the presence of glaciers) in the water-infiltering area over a cave (catchment area from here onwards) would be a factor for reduced or ceased speleothem growth. In such conditions, the only possibility for the deposition of calcite can be related to sulphide oxidation if liquid water is present (Atkinson 1983; Gascoyne and Nelson, 1983; Spötl and Mangini, 2007).

In the Mediterranean region there are numerous mountains where geomorphological and geological evidence for the presence of glaciers has been dated (Baroni et al., 2018; Finsinger and Ribolini 2001; Perez-Alberti et al., 2004; Federici et al., 2008; 2012; 2017; Kuhlemann et al., 2008; Hughes et al., 2004, 2011, 2013; Giraudi et al., 2011 Giraudi and Giaccio, 2017; Ribolini al., 2011, 2018; Serrano et al. 2012; Hughes and Woodward, 2017 and references therein, Gromig et al., 2018; Hannah et al., 2017; Akçar et al., 2017; Çiner et al., 2017; Sarikaya and Çiner, 2017). However, for some regions, it is still challenging to identify the glacial cycles to which this evidence belongs. This is particularly true for the Apuan Alps, a mid-latitude (44°N) mountain chain in northwestern Italy where, despite the recognition of numerous glacial features, no precise chronological data exist so far.

In this paper, we use periods of speleothem deposition as an indicator of ice-free conditions in cave catchment areas, and periods of very low or absent stalagmite growth as proxy for constraining the chronology of glacier presence in the Apuan Alps. To achieve this, we use previously published and new U/Th ages of speleothems from five different caves located at different altitudes (Fig. 1).

2. Site description

The Apuan Alps is a NW-SE-oriented mountain range rising abruptly to about 2000 m a.s.l. from the narrow coastal plain bordered by the Ligurian Sea (Fig. 1). The atmospheric circulation is dominated by the important cyclogenesis centre of the Gulf of Genoa (Trigo et al., 2002) and by the humid westerly air masses of North Atlantic provenance (e.g. Reale and Lionello, 2013~~2014~~; Fig. 1). These sources of moisture impact on the Apuan Alps mountain chain, which acts as a natural barrier by forcing an adiabatic rise of air masses, resulting in high precipitation (> 2,500 mm/yr Rapetti and Vittorini, 1994; Piccini et al., 2008). As with most of the Apennine chain, winter rainfall amount, which is the main period of recharge of Apuan caves (Piccini et al., 2008), is strongly regulated by the North Atlantic Oscillation (NAO), with a negative correlations observed between NAO index and winter precipitation (López-Moreno et al., 2011).

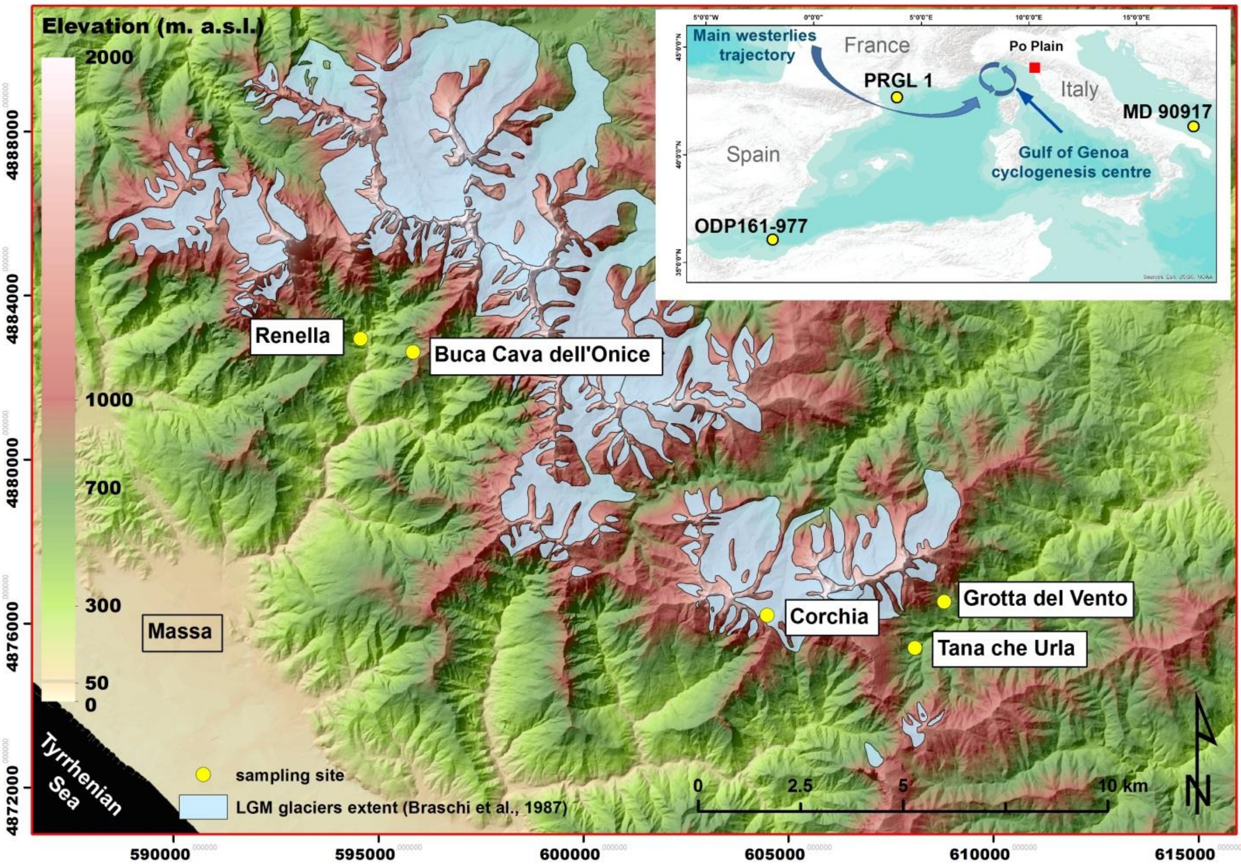


Fig. 1. Glacier extent (light blue) during the LGM according to the reconstruction of Braschi et al. (2001). Sampled sites are shown in yellow.

Two main tectono-metamorphic regional events have determined the structural setting of the Apuan Alps (e.g. Carmignani and Kligfield, 1990; Molli and Vaselli, 2006), where extensive areas of carbonate lithologies outcrop (Mesozoic marbles and metadolostones). The actions of glacial, fluvial and karst processes led to an Alpine-like landscape, where exokarst landforms and Quaternary cave systems are particularly developed (Piccini, 1998, 2003, 2011).

The Apuan Alps is one of the first places amongst the larger Apennine chain where glacial landforms have been described (Cocchi, 1872; Stopani, 1872). Following these pioneering studies, in the second half of nineteenth and throughout the twentieth century, further qualitative evidence of glacial landforms were reported (De Stefani, 1874,1875,1890; Merciai, 1912; Paci, 1935; Zaccagna, 1937; Tongiorgi and Trevisan, 1940; Beneo, 1945; Masini, 1970; Federici, 1981; 2005; Braschi al., 1987; Putzolu, 1995, Baroni et al. 2013; 2015). Most of these glacial features are now under risk of destruction due to marble quarrying (Bini, 2005). Despite only traces of small glaciers have been reported on the seaward side of the mountain chain (i.e. erosional landforms and a few scattered glacial deposits, Federici, 1981), features associated with at least nine glaciers have been identified on the northern side. These include lateral and terminal moraines, cirques and polished surfaces. Different phases of expansion have been described and, in some cases, the glacier termini reached exceptionally low elevations (~600 a.s.l.) considering the latitude (Braschi et al., 1987; Jaurand, 1998). The best-preserved glacial features, with relatively unweathered, incoherent detrital materials, are traditionally attributed to the Last Glacial Maximum (LGM) by all previous authors on the basis of their fresh appearance and by analogy with the Apennines and Alpine landforms. The temporal definition of LGM itself is not univocal, depending on the considered references, e.g. Clark at al. (2009) defined the LGM as the duration of sea-level lowstand during the interval 26.5-20/19 ka, while Hughes and Gibbard (2015) as the event between the top (end) of Greenland Interstadial 3 and the base (onset) of Greenland Interstadial 2, spanning the interval 27.540-23.340 ka (Greenland Stadial 3). In both cases within MIS2.

Inner terminal moraines have been interpreted as the Late-Glacial readvance/stillstand phases (Braschi et al., 1987; Federici, 2005). Cemented glacial deposits, rarely outcropping, have been attributed to a pre-LGM glacial event according to their appearance, altitude and stratigraphic position (Braschi et al. 1987). The presence of these older, cemented deposits, attributed to “Riss glaciation” (i.e. penultimate glaciation), has long been debated but no conclusive results have been forthcoming due to the absence of chronological constraints (Federici, 2005), moreover, Kotarba et al. (2001) have dated in the Apennines, similar types of older cemented moraines to the Riss, using U-series.

3. Cave descriptions

In the Apuan Alps karst massif, about 2000 cave entrances are now mapped with a composite length of cave development of ~500 km (http://www.speleotoscana.it). About 80 caves are carved below the areas potentially covered by glaciers during the Last Glacial expansion, as reconstructed by Braschi et al. (1987). Despite most of the Apuan caves are mainly vertical with active drainage systems, many kilometres of passages are relict and nowadays host carbonate (usually calcite) concretions. Here we focus on speleothems from five caves located at different elevations (Fig. 1).

The largest and highest cave is Antro del Corchia (CC), a large complex cave system (~60 km long ~1200 m deep) mainly developed in the Upper Triassic-Liassic marble, dolomitic marble and metadolostone of the Mt Corchia syncline confined by the non-karstifiable, low-permeable rocks of the Paleozoic basement (Piccini et al., 2008).

Tana che Urla (TCU) is a small resurgence cave with a permanent stream (~600 m of total length of which almost half is submerged; +45 m of total difference in height), developed at the contact between Paleozoic schist basement and Triassic metadolostone (Regattieri et al., 2012). The entrance is located at ~620 m a.s.l. on the south-eastern side of Panie Massif and functions as an overflow spring during intense rainfall and snowmelt.

Grotta Del Vento (GDV) is an almost fossil phreatic cave (~4.5 km total length and over 450 m of elevation change) developed at the contact between the Paleozoic schist basement and Triassic metadolostone. The entrance is located at ~630 m a.s.l. on the south-eastern side of the Panie Massif (Piccini et al., 2003).

Buca della Renella (RL) is a small, shallow cave at the confluence of Canale Regolo and the Frigido River (Drysdale et al. 2006; Zhornyak et al., 2011). The entrance is located at ~275 m a.s.l., only a few metres above the stream confluence. The cave, predominantly horizontal (~200 m length), is carved in Triassic metadolostone close to the contact with the Paleozoic phyllite.

Buca Cava dell’Onice (BCO) is a fossil small cave (85 m long and 65 m deep), carved in Lower Jurassic cherty metalimestone. The entrance is located in the northwest side of Mt. Castagnolo at ~700 m a.s.l.

4. Methods

We consider 19 speleothems (ages in supplementary material, Table 1), collected from the five caves described above. Nine stalagmites and two cores drilled from flowstones have been collected from the "Galleria delle Stalattiti" of the Corchia Cave. This part of the cave is a near-horizontal chamber carved at ~840 m a.s.l., vertically overlain by ~400 m of rock. The chamber lies hundreds of metres above the present groundwater table and is characterised by a mean annual air temperature of 7.8 °C (Piccini et al., 2008). Five speleothems have already been described in previous papers (CC1, CC5, CC7, CC26, CC27 and CC28, Drysdale et al., 2004, 2005, 2007, 2009; Zanchetta et al., 2007; Bajo et al., 2017; Isola et al., 2018). We present new ages for stalagmites CC4, CC7, CC22, CC27, CC53, and two flowstone cores CD4 and CD20.

At TCU two cores have been drilled from the same flowstone in the main gallery, about 100 m from the entrance. The mean air temperature is 10.2 °C (Regattieri et al., 2014a). Speleothem stratigraphy, chronology and geochemistry have been discussed by Regattieri et al. (2012, 2014a, 2016).

Two cores have been drilled from different flowstones located in the middle level of GDV (Piccini et al., 2003).

At RL, three samples have been collected in different stratigraphic levels from a fan-like flowstone deposited at the margin of an epiphreatic passage in the inner part of the cave (average air temperature ca. 12 °C) and their stratigraphy and chronology have been discussed by Drysdale et al. (2006) and Zhornyak et al. (2011).

Only one stalagmite (BCO1) has been collected in BCO, in a fossil gently dipping gallery, about 30 m from the entrance.

All ages from Corchia, Tana Che Urla and Renella have been obtained following the same procedure at the University of Melbourne (Victoria, Australia). Briefly, uranium and thorium isotopes were analysed using a Nu Instruments Multicollector Inductively Coupled Plasma–Mass Spectrometer (MC-ICP-MS), according to the analytical method and corrections (where necessary) described by Hellstrom (2003, 2006).

Age-depth models and speleothems growth rates were obtained from a Monte Carlo-derived method (described in Drysdale et al. 2005 and Scholz et al. 2012). Dating methods for Grotta del Vento are discussed by Piccini et al. (2003).

BCO1 $^{230}Th/^{234}U$ ages were determined at LSCE from 9 subsamples collected along the growth axis of the stalagmite. Subsamples were crushed in an agate pestle and aliquots of typically ~400 mg were rinsed twice with MilliQ, dissolved in diluted HCl (~10%) and equilibrated with a mixed ^{236}U-^{233}U-^{229}Th spike that was calibrated against a Harwell Uraninite solution (HU-1) assumed to be at secular equilibrium. Uranium and thorium were purified and separated using Eichrom UTEVA® and pre-filter resins in nitric media following a procedure modified from Pons-Branchu et al. (2005) and Douville et al. (2010). The isotopes of uranium and thorium were analysed by solution multi-collector ICPMS using a ThermoScientific Neptune^{Plus} hosted at the Laboratoire des Sciences du Climat et de l'Environnement (LSCE, Gif-sur-Yvette, France) following the procedure described by Pons-Branchu et al. (2014). Based on the measured atomic ratios, the $^{230}Th/^{234}U$ ages were calculated through iterative age estimation (Ludwig and Titterington, 1994) using the ^{230}Th, ^{234}U and ^{238}U decay constants of Cheng et al. (2013) and Jaffey et al. (1971). An initial $^{230}Th/^{232}Th$ activity ratio of 0.9±50% was used for correction of the non-radiogenic, detrital ^{230}Th fraction.

In order to highlight the higher and lower periods of speleothems deposition rate, we calculate the growth rate for all the considered speleothems from Corchia Cave and for speleothems from lower altitude caves, cumulated at 1000-yr intervals. Uncertainties in the growth rates were obtained using the standard errors propagation.

It is worth estimating potential changes in air temperature at the altitude of the different infiltration areas of the four caves (we ignore BCO because the sole sampled stalagmite covers only

MIS 5), in order to understand causes of any leads and lags in speleothem growth phases in the context of likely glacier development. The following calculations represent a first-order estimate that can be used to underpin the interpretations proposed below.

Speleothem growth patterns described above were compared with sea-surface temperature (SST) series from three Mediterranean cores: ODP 161-977 (Martrat et al., 2014) spanning all over the considered period; PRGL1 (Cortina et al., 2015), the nearest core to the Apuan Alps; and MD 90917 (Siani et al 2013), a high-resolution dataset covering the last ~25 kyr (cores locations are shown in Fig. 1). As these cores (ODP 161-977, PRGL1) provide SST data based on Alkenone unsaturation indices (Müller at al., 1998; Conte et al., 2006) and planktonic foraminifera assemblages (Siani et al 2013), they do not reflect exactly the same temperature signal. SST records in the Alboran Sea (ODP191-977) are more related to spring-summer conditions (Martrat et al., 2004, 2014), while the SST records from the Gulf of Lyon reflects a winter-spring temperature signal showing a colder imprint than other more southern SST records (Rigual-Hernández et al., 2013, Cortina et al., 2015). Finally, planktonic foraminifera assemblages coincide with the most productive period during the spring and the synchronous bloom of *G. bulloides* in the Mediterranean Sea (Pujol and Vergnaud-Grazzini, 1995; Siani et al., 2013). In performing the ocean-cave comparisons, we make several assumptions. First, we assume that the difference in mean annual SST (MASST) between the selected marine cores and the MASST offshore of the Apuan Alps (Locarnini et al., 2010) was constant through time; second, that the difference between the MASST and the Mean Annual Air Temperature (MAAT) measured along the coast facing the Apuan Alps (http://www.autorita.bacinoserchio.it/) was constant through time; third, we adopt an air temperature lapse rate of 0.6 °C/100 m (as calculated for the area by Rapetti and Vittorini, 2012) to estimate the MAAT in the speleothem catchment areas of four of the studied caves. For the elevations of the water recharge area feeding the caves, two values are considered: the elevation of the surface above the cave on the vertical of the sampling sites (C1, supplementary material Table 2) and the average between this point and the highest point of the drainage basin (C2, supplementary material 2). The first is the most conservative value representing the minimum elevation of recharge area while the second is probably more realistic because takes into account the whole hydrographic basin upvalley the cave. A more refined estimate of MAAT could incorporate also the effects of sea-level lowering during glaciations and tectonic uplift (estimates to be 0.6 mm/yr; Fellin et al. 2007; Piccini 2011) of the Apuan Alps. However, both effects introduce negligible temperature variations. Indeed, the maximum increase in relative elevation of the infiltration area above the contemporary sea level is during the LGM (e.g. ca. 100-120 m for the LGM, Lambeck and Bard 2000; Lambeck et al., 2014), corresponding to a total temperature variation (ΔT) of about -0.6°C, while the lowest, during MIS6, corresponds to ΔT of about +0.1°C.

5. Results

For the 19 speleothems considered, the dataset comprises 293 U/Th ages (supplementary material Table 1). In Figure 2, the ages are plotted vs the elevation of the sampling sites.

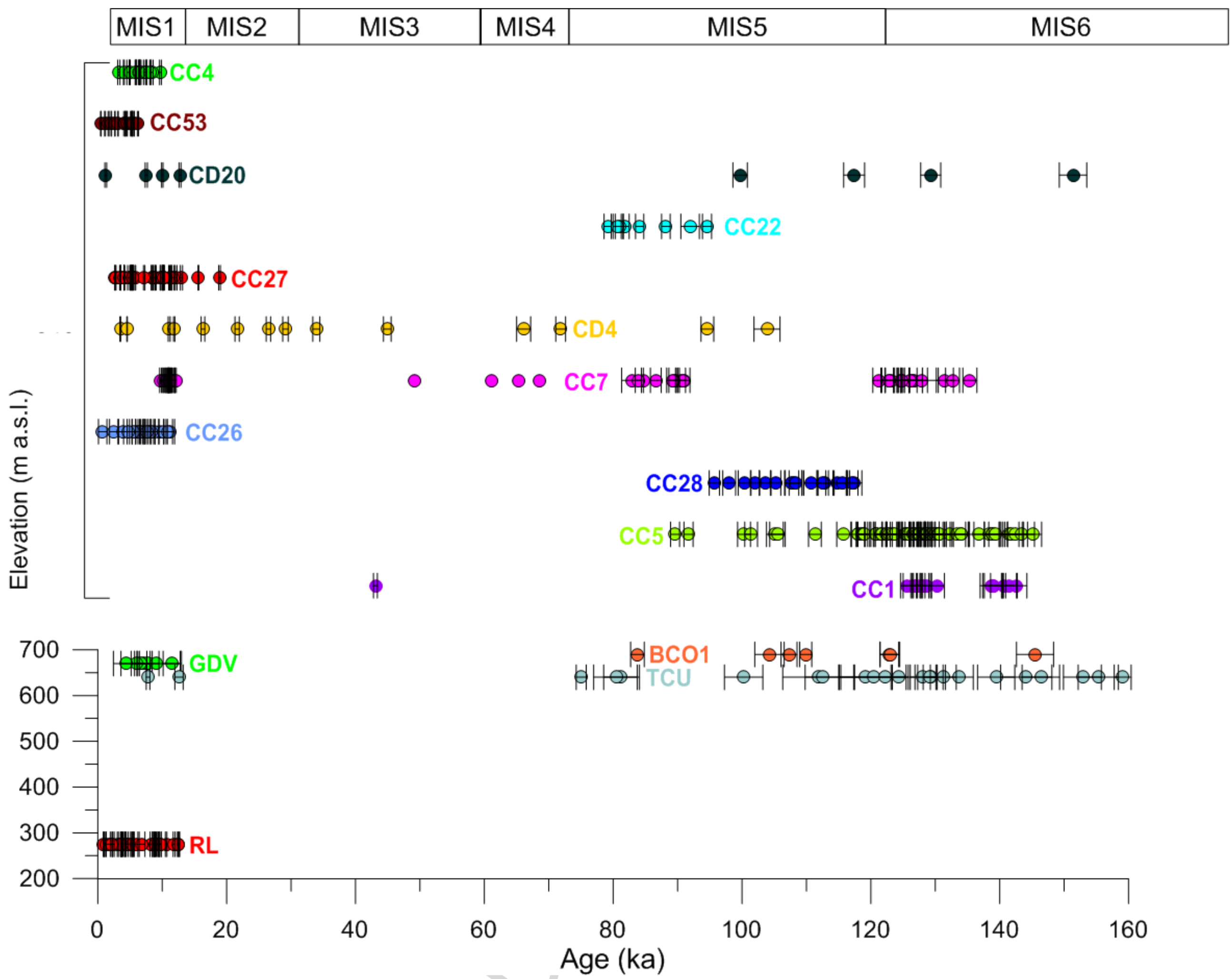


Fig. 2. 293 U/Th ages from 19 Apuan speleothems over the past 160 ka (2σ error bars) vs the elevation of sampling sites. Details on dating can be found in the original papers (Drysdale et al., 2004; 2009; Regattieri et al., 2012, 2014a, 2014b; Piccini et al, 2003; Drysdale et al., 2006; Zhornyak et al 2011, Isola et al., 2018). ~~The Holocene is shown in light blue shading.~~

Despite some differences, there are many common features. All caves show a major episodes of calcite deposition during the Holocene and the latest Late Glacial. Available samples from RL and GDV do not show phases of growth older than this period and the studied concretions cover, or are stratigraphically located over, thick fluvial deposits. TCU shows continuous deposition between ca. 160 and 121 ka (Regattieri et al., 2014a), followed by a discontinuous deposition to ca. 75 ka, after which there is a long hiatus from ca. 75 to 12.5 ka. The most relevant record is represented by

Corchia Cave, showing almost continuous calcite deposition from ca. 145 to 79 ka. A long lag of growth, with only very reduced phases of calcite deposition is evident during the Pleniglacial. The stalagmite from BCO has an intermittent growth phase throughout MIS 5, confirming a speleothems deposition phase during this period in the Apuan Alps. No information about other periods including the Holocene are available for this site until now, but we cannot exclude further growing phases, in fact, a single speleothem cannot be considered representative of the whole speleothems growth history of this cave.

More interesting than the simple ages distribution is the cumulative growth curve which takes into account the propagation of age errors for Corchia cave speleothems and for the other studied caves located at lower altitudes (Fig. 3). It is evident that speleothem growth at Corchia, after a period of low values, becomes significant between ca.132 and 80 ka (curve b in figure 3), after which it decreases abruptly until ca. 60 ka, and then almost stops for ca. 44 kyr. Continuous growth resumes at ca. 15 ka and increases later at ca. 12 ka.

The growth of speleothems belonging to the lower-altitude caves evidently decreases after 130 ka, reaching a local minimum at ca. 100 ka. An increase of composite growth rate is then observed around 80 ka, followed by an interruption in calcite deposition up to 13 ka.

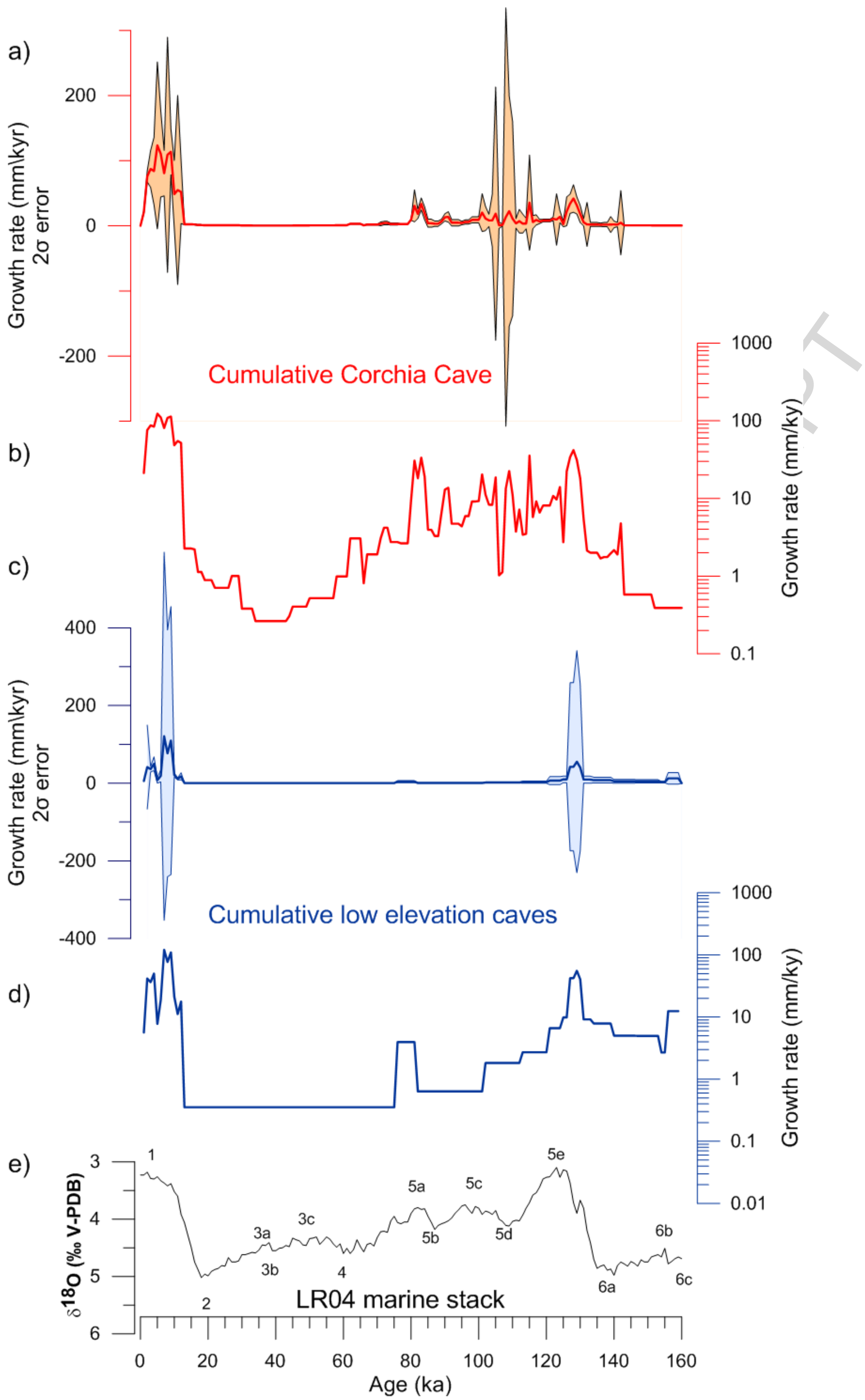


Fig. 3. Cumulative growth curves (i.e. the total speleothem growth calculated for all the considered speleothems and binned into 1000-yr intervals) for Corchia Cave speleothems (red lines a and b) and for the caves located at lower altitude (blue lines, c and d), the associated errors in shaded

strips. Note the linear (b and d) and the logarithmic (a and c) scales in the vertical axes. Shown in black (e) is the LR04 stack (Lisiecki and Raymo 2005) from benthic foraminifera $\delta^{18}O$ data. Numbers indicate Marine Isotope Substages.

Figure 4 shows the estimation of MAAT as described above. Due to the very similar geographic location (fig. 1), GDV and TCU temperature estimates are almost indistinguishable in all the reconstructions (blue and black lines in Fig. 4). The MAAT curves obtained for each cave using MD90917 data (~ 0.6 - 24 ka interval), including the two different infiltrating elevations (C1 and C2), are shown respectively in Figure 4a and b. The MAAT curves obtained using ODP 161-977 data (~ 0.06 - 120 ka interval) are shown respectively in figure 4c and d. The MAAT curves obtained using PRGL1 data (~ 29 - 120 ka interval) are shown respectively in Figure 4e and f. In the C1 cases (Fig. 4a, c, e) only the CC series displays excursions where MAAT is <0°C. In the C2 scenario (Fig. 4b, d, f), GDV and TCU areas also show periods when MAAT is <0°C. As expected, the temperature above RL is the mildest.

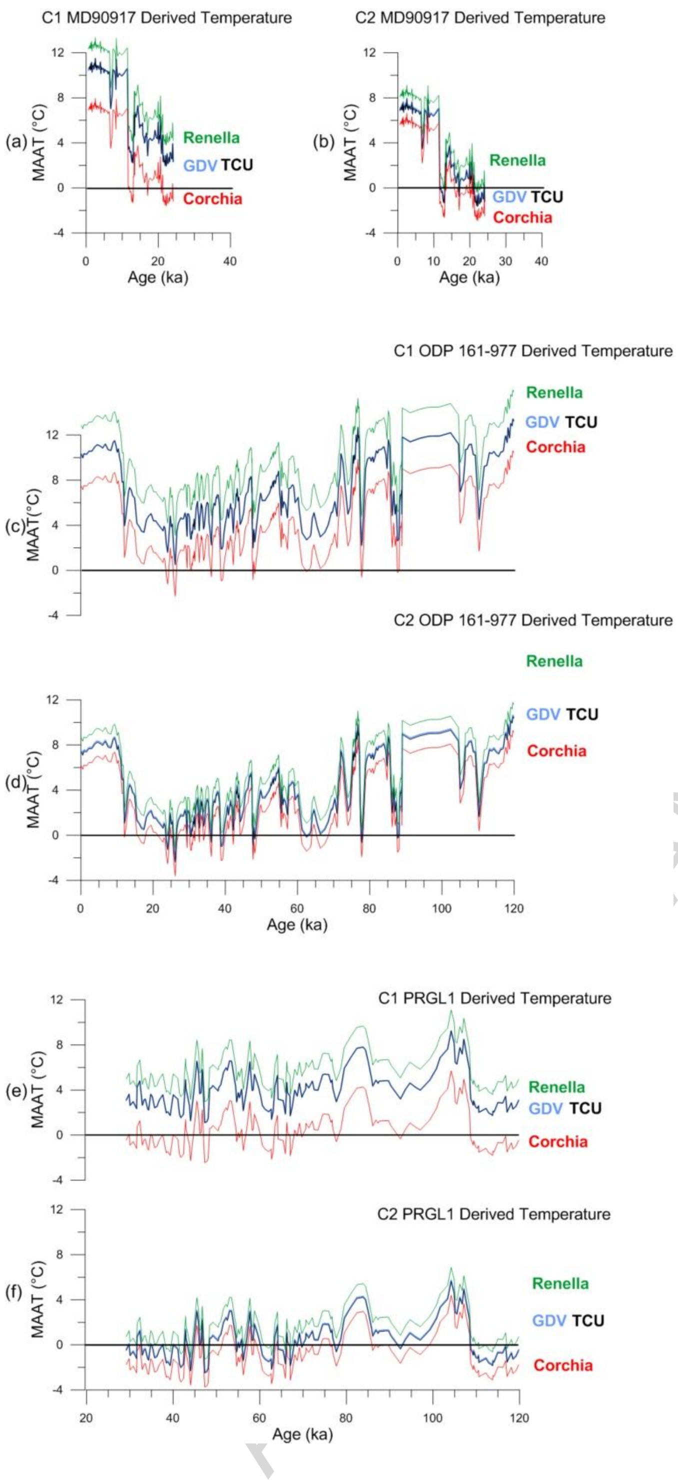


Fig. 4. MAAT curves derived for all the caves from MD90917: (a) C1 (see the text for explanation), (b) C2; from ODP 161-977, (c) C1 and (d) C2 ; and from PRGL1, (e) C1 and (f) C2. Black horizontal lines indicate the 0°C MAAT.

6. Discussion

According to the presented data, there is a long interval during the Pleniglacial where calcite deposition at CC and TCU caves slows down or is absent (fig. 3). This interval roughly corresponds to an extensive loess deposition in the Po Plain (Fig. 1 and 5; Cremaschi et al., 2015b; Zarboni et al., 2015). This marks a wide phase of aridity in northern Italy that might have involved also the Apuan Alps, but probably with different effects. Nowadays the mean annual precipitation in Po Plain does not exceed 1000 mm (www.arpalombardia.it), while the Apuan Alps are characterized by higher precipitations exceeding 2500mm/yr (Rapetti and Vittorini, 1994; Piccini et al., 2008). The different geographic position underpinning the actual rainfall regime, certainly played a role in the past too, mitigating the drought effect in the Apuan Alps. Moreover, it is very difficult to explain in a dry regime, the strong fluvial activity suggested, in the low elevation caves, by the presence of thick fluvial deposits, stratigraphically older than the phase of speleothems regrowth (about 12.5 ka). The resumption of calcite deposition is ~~instead,~~ almost coeval in all caves, with evidence of sustained growth slightly preceding the beginning of the Holocene, instead, the period of deposition decrease, at the end of MIS5, is not coeval between TCU and CC. However, the CC dataset is more extensive because the number of analyzed speleothems.

Moreover, this cave is very close to areas of the catchment occupied by glaciers in the Last Glacial (Fig.1). Specifically, the recharge basin of the “Galleria delle Stalattiti”, mainly consisting of the higher slopes of the northern side of Monte Corchia, was covered by a glacier according to Braschi et al. (1987). The most obvious process responsible for the strong reduction of speleothem growth at the “Galleria delle Stalattiti” would thus be a persistent ice cover. This long interval of extremely reduced or absent calcite deposition covers most of MIS4-MIS2, a time span more extensive than the classical attribution of Apuan glacial activity to the only Last Glacial Maximum (Federici, 2005; Jaurand 1998). This hypothesis is supported by evidence of moraines formed during MIS3 and MIS4 glacier expansions in the Central Apennines (Giraudi et al. 2011; Giraudi and Giaccio, 2015, 2017). In this regard, the Corchia speleothems cumulative growth curve delimits for the first time the temporal interval of possible glacier existence over the Apuan Alps or temperature lower enough to inhibit speleothem growth at higher altitudes. Although the chronological constraints are indirect because they do not refer to moraine ages, there is considerable robustness in the speleothem-age dataset. However, cessation of speleothem growth can be related to combined effect of low air temperature, soil-CO_2 deficiency and reduction of dripping. These conditions might have been present without invoking continuous ice covering of the slopes, i.e. where permafrost inhibits water infiltration and following dryer cave conditions. In the nearby Apennine chain, landforms diagnostic of permanently frozen ground are rare and essentially limited to the southern latitudes, where higher elevations are reached (Kotarba et al., 2001; Giraudi et al., 2011; Oliva et al., 2018).

The absence of speleothem growth in the other caves during the glacial period cannot be directly related to the reconstructed ice cover (Braschi et al. 1987) because of their lower altitudes. A recent geomorphology synthesis of the Apuan Alps (Baroni et al., 2015) does not report glacial deposits indicative of a glacial cover of the lower caves.

At RL and GDV, the presence of thick fluvial deposits stratigraphically older than the phase of speleothem growth (about 12.5 ka) suggests strong fluvial activity during the glacial period, which would inhibit speleothem growth (Zhornyak et al., 2011). This strong activity might be related to seasonal snow/ice melting and abundant availability of loose material coming from physical weathering. A similar explanation is also valid for the long deposition hiatus at TCU (about 12.6-75 ka). A continuous glacier cover nearby is unlikely throughout this period.

~~Speleothem growth, which was possible for most of MIS5, decreases or ceases during MIS4 (Fig. 3)~~

It is noteworthy that both CC and TCU show speleothem deposition during part of MIS6, suggesting that temperatures over the Apuan Alps during this period were not as low as those for MIS2-4. The transition between the penultimate glacial and the last interglacial, is marked by the abrupt increase of speleothems growth about 132 ka, as already described for CC by Drysdale et al., (2009) and for TCU by Regattieri et al. (2014a) and in agreement with other proxies like the more umid-temperate vegetation in Southern Europe (Sanchez –Goñi et al., 1999), or the high level in Ioannina Lake (Wilson et al., 2015). Then, speleothem growth, which was possible for most of MIS5, decreases or ceases during the interval MIS2-4 (Fig. 3).

The almost coeval resumption of calcite deposition in all the investigated caves requires further discussion. At CC, some U/Th ages indicate that a small growth phase also occurs at the beginning of the Late Glacial, but significant growth did not occur before ca. 12 ka. However, given the southern latitude and the relatively low altitude of the Apuan Alps, it is hard to argue that glaciers still existed during the middle part of the Lateglacial (Hughes ~~et al~~and Gibbard, 2015). Based on deglacial trends in CC speleothem carbon isotope composition, Drysdale et al. (2004) and Zanchetta et al. (2007) have suggested that soil development at CC is delayed after glacial periods due to intense erosive processes active at high altitudes during the first phases of climatic amelioration, under conditions of increasing rainfall. After the definitive ice melting at the end of MIS2, cold but ice-free conditions and delayed soil development would have retarded significant speleothem growth, which did not accelerate until ca. 12 ka. The fundamental elements of this hypothesis are supported by Bajo et al. (2017), who also invoked near-closed-system conditions and sulphuric-acid dissolution as additional processes to carbonate-acid dissolution (from soil-sourced CO_2) to explain the unusually high carbon isotope composition of CC26 stalagmite during late Late Glacial and the beginning of Holocene. However, an implication of this study is that growth was unsuitable before ca. 12 ka, in spite of the possibility of sulphuric-acid dissolution substituting for carbonic-acid dissolution, thus suggesting that speleothem growth was inhibited by cold climate conditions. From the same stalagmite, Regattieri et al. (2014b) concluded, based on the presence of an aragonite layer at the base of the CC26 succession and on trace element/Ca ratios (Ba, Sr, Mg) changes, that the start of growth of CC26 was related to a re-opening of a dripping point due to the replenishing of the cave plumbing system previously interrupted by reduced recharge.

Whilst we cannot detail the point at which resumption of speleothem growth occurred in CC during the Late Glacial, conditions generally favoring speleothem growth seem to have occurred when the plumbing system was newly recharged significantly even if ice cover should have already disappeared. It is probably not obvious that these conditions did not concomitantly occur in upper and lower altitude caves. Studying the transition between MIS6 and MIS5 at TCU Regattieri et al. (2014a) suggested that the delay in soil development as inferred for CC is not supported for TCU, due to its lower altitude. This may suggest that an earlier resumption of speleothem growth would be anticipated at lower altitude compared to CC. Data collected until now agree with this hypothesis (Fig. 3). We suggest that significant resumption of calcite deposition at CC can occur only when soil development and drip recharge are restored to a certain level.

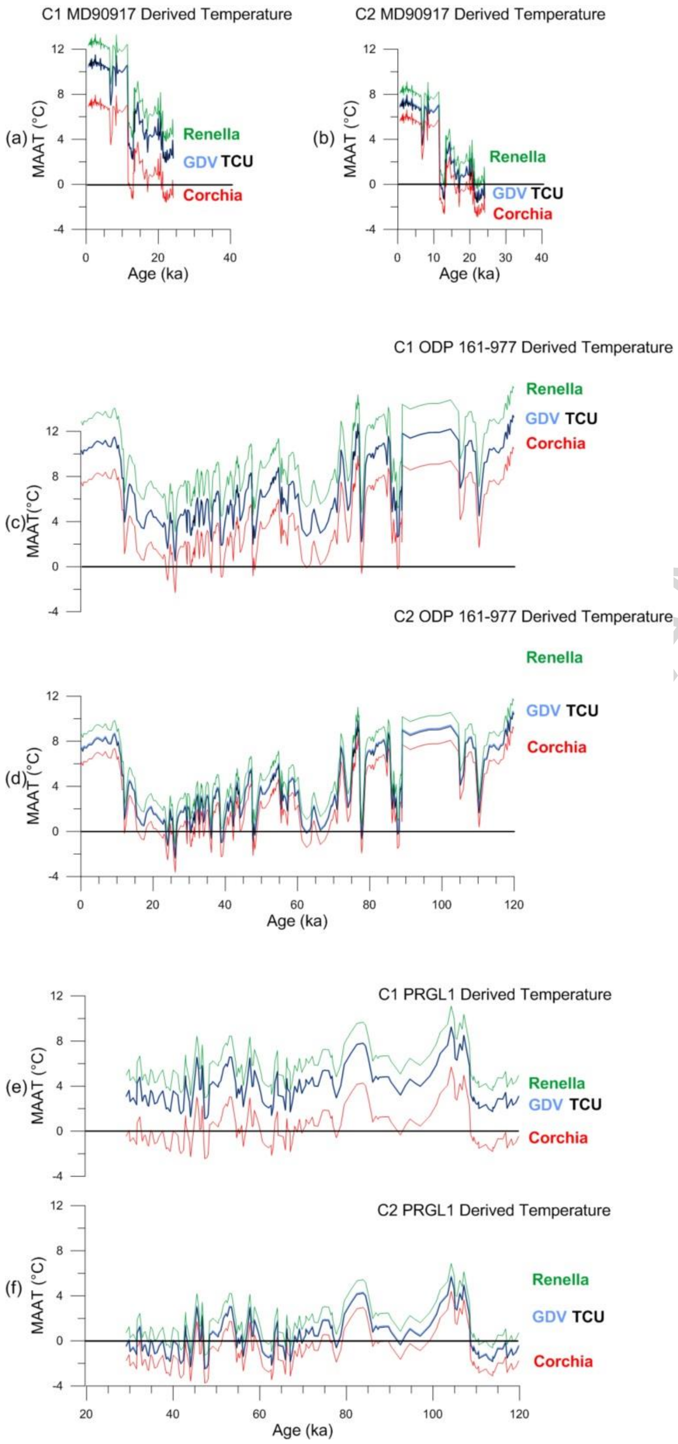
~~. It is worth estimating potential changes in air temperature at the altitude of the different infiltration areas of the four caves (we ignore BCO because the sole sampled stalagmite covers only MIS 5), in order to understand causes of any leads and lags in speleothem growth phases in the context of likely glacier development. The following calculations represent a first-order estimate that can be used to underpin the interpretations proposed below.~~

~~Speleothem growth patterns described above were compared with sea-surface temperature (SST) series from three Mediterranean cores: ODP 161-977 (Martrat et al., 2014) spanning all over the considered period; PRGL1 (Cortina et al., 2015), the nearest core to the Apuan Alps; and MD 90917 (Siani et al 2013), a high-resolution dataset covering the last ~25 kyr (cores locations are shown in Fig. 1). As these cores (ODP 161-977, PRGL1) provide SST data based on Alkenone unsaturation indices (Müller at al., 1998; Conte et al., 2006) and planktonic foraminifera assemblages (Siani et al 2013), they do not reflect exactly the same temperature signal. SST records in the Alboran Sea (ODP191-977) are more related to spring-summer conditions (Martrat et al., 2004, 2014), while the SST records from the Gulf of Lyon reflects a winter-spring temperature signal showing a colder imprint than other more southern SST records (Rigual-Hernández et al., 2013, Cortina et al., 2015). Finally, planktonic foraminifera assemblages coincide with the most productive period during the spring and the synchronous bloom of *G. bulloides* in the Mediterranean Sea (Pujol and Vergnaud-Grazzini, 1995; Siani et al., 2013). In performing the~~

~~ocean-cave comparisons, we make several assumptions. First, we assume that the difference in mean annual SST (MASST) between the selected marine cores and the MASST offshore of the Apuan Alps (Locarnini et al., 2010) was constant through time; second, that the difference between the MASST and the Mean Annual Air Temperature (MAAT) measured along the coast facing the Apuan Alps (http://www.autorita.bacinoserchio.it/) was constant through time; third, we adopt an air temperature lapse rate of 0.6 °C/100 m (as calculated for the area by Rapetti and Vittorini, 2012) to estimate the MAAT in the speleothem catchment areas of four of the studied caves. For the elevations of the water recharge area feeding the caves, two values are considered: the elevation of the surface above the cave on the vertical of the sampling sites (C1, supplementary material Table 2) and the average between this point and the highest point of the drainage basin (C2, supplementary material 2). The first is the most conservative value representing the minimum elevation of recharge area while the second is probably more realistic because takes into account the whole hydrographic basin upvalley the cave. A more refined estimate of MAAT could incorporate also the effects of sea-level lowering during glaciations and tectonic uplift (estimates to be 0.6 mm/yr; Fellin et al. 2007; Piccini 2011) of the Apuan Alps. However, both effects introduce negligible temperature variations. Indeed, the maximum increase in relative elevation of the infiltration area above the contemporary sea level is during the LGM (e.g. ca. 100-120 m for the LGM, Lambeck and Bard 2000; Lambeck et al., 2014), corresponding to a total temperature variation (ΔT) of about -0.6°C, while the lowest, during MIS6, corresponds to ΔT of about +0.1°C.~~

~~Figure 4 shows the estimation of MAAT as described above. Due to the very similar geographic location (fig. 1), GDV and TCU temperature estimates are almost indistinguishable in all the reconstructions (blue and black lines in Fig. 4). The MAAT curves obtained for each cave using MD90917 data (~ 0.6 - 24 ka interval), including the two different infiltrating elevations (C1 and C2), are shown respectively in Figure 4a and b. The MAAT curves obtained using ODP 161-977 data (~ 0.06 - 120 ka interval) are shown respectively in figure 4c and d. The MAAT curves obtained using PRGL1 data (~ 29 - 120 ka interval) are shown respectively in Figure 4e and f. In~~

~~the C1 cases (Fig. 4a, c, e) only the CC series displays excursions where MAAT is <0°C. In the C2 scenario (Fig. 4b, d, f), GDV and TCU areas also show periods when MAAT is <0°C. As expected, the temperature above RL is the mildest.~~



~~Fig. 4. MAAT curves derived for all the caves from MD90917: (a) C1 (see the text for explanation), (b) C2; from ODP 161-977, (c) C1 and (d) C2 ; and from PRGL1, (e) C1 and (f) C2. Black horizontal lines indicate the 0°C MAAT.~~

According to the timing of speleothem growth and MAAT estimations, it can be seen that above CC both the C1 and C2 MAAT reconstructions experienced a number of long-lasting sub-zero periods. Indeed, the Equilibrium Line Altitude (ELA) of 1200-1300 m a.s.l. in the Apuan Alps during the MIS 2 (Merciai, 1912; Braschi et al., 1987; Jaurand, 1998) supports the hypothesis that in the CC catchments (both C1 1240 m a.s.l. and C2 1460m a.s.l.) glaciers were existing. These unfavorable conditions for speleothem deposition (MAAT subzero or near 0 °C) persisted, discontinuously, above CC not only during the MIS 2, but also during MIS 4 (Fig. 4). This is consistent with evidence of a phase of glaciation during MIS 4 from the Alps and other peri-Mediterranean mountain ranges (Hughes et al. 2013; 2018; Sarikya et al., 2014; Pope et al., 2017) (blue bars in Fig. 5~~b~~a). There are evidences of very small growth phases during MIS4-MIS2 (Fig. 2, 3, 5~~c~~d) that may have occurred during warming reversals, most likely associated with the millennia-scale interstadials observed in the Greenland ice-core records (i.e. Dansgaard-Oeschger events, Dansgaard et al., 1993; Fig. 5~~f~~e), but also indicated by SST changes in the western Mediterranean (Cacho et al., 1999).

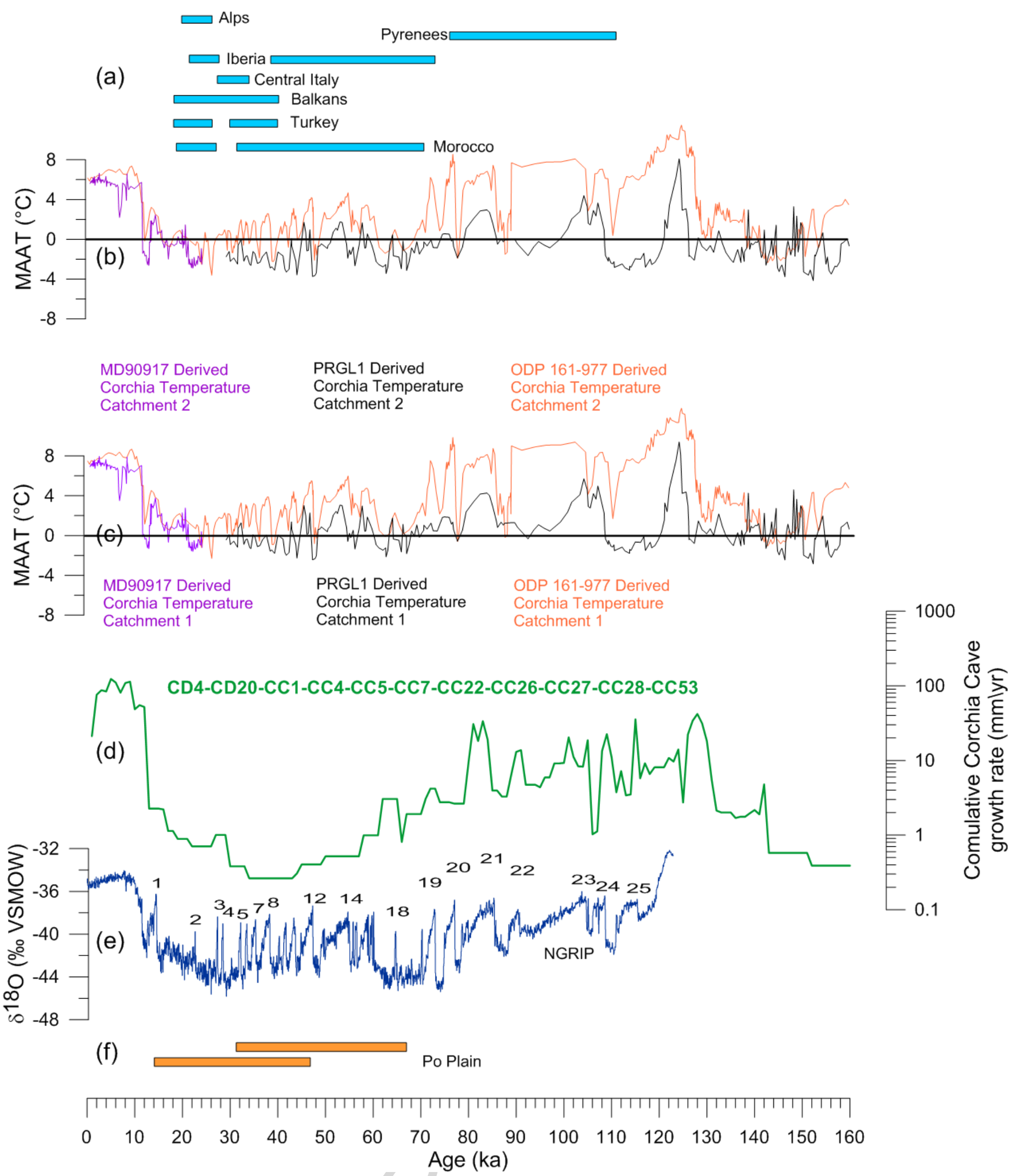


Fig. 5. Northern Hemisphere proxies for the Pleniglaciation~~: a) summer insolation curve at 65°N (Berger and Loutre, 1991); b~~a) the approximate timing of maximum extent of glaciers in the Mediterranean mountains (after Hughes et al., 2013; 2018; Sarikya et al., 2014; Pope et al., 2017); ~~c~~b) the derived MAAT curves in the C2 case above the Galleria delle Stalattiti: red curve is derived from ODP 161-977, purple curve from MD90917 data, black curve is derived from PRGL1 data. Horizontal black line indicates the 0°C MAAT; ~~d~~c) the derived MAAT curves in the C1 case above the Galleria delle Stalattiti: red curve is derived from ODP 161-977, purple curve from MD90917 data, black curve is derived from PRGL1 data and horizontal black line indicates the 0°C MAAT; ~~e~~d) Cumulative growth curve calculated for interval of 1000 yr for Corchia cave speleothems (green

line); ~~f~~e) NGRIP $\delta^{18}O$ values from North Greenland Ice Core (North Greenland Ice Core Project members, 2004). Numbers over the graph mark the position of the Dansgaard-Oeschger interstadials (Dansgaard et al., 1993); f) approximate interval of extensive loess accumulation in Po Plain (after Cremaschi et al., 2015b; Zerboni et al., 2015).

In general, pollen data from the western Mediterranean show that cold SSTs characteristic of Greenland stadials were contemporaneous with the expansion of semi-desert or steppic vegetation. On the contrary, Greenland interstadials were synchronous with the expansion of open forests (Sánchez-Goñi et al., 2008). Presumably, phases of forest expansion prompted the development of deeper soils. However, the very limited speleothem growth and the available ages prevent a precise correlation with the warmer intervals. On the other hand, according to Atkinson (1983) and Spötl et al. (2007), speleothems may form, although with a lower rate of growth, in caves overlain by temperate glaciers with available glacial meltwater infiltrating the karst system. The very low partial pressure of CO_2 in such water due to the absence of soil can be balanced by pyrite oxidation during the flow paths through fractures, providing the dissolved carbonate necessary for speleothem deposition. This process is demonstrably present at Corchia (Piccini et al., 2008; Bajo et al., 2017) and can be responsible of the very thin deposition layers included between two hiatus.

Summing up, growth histories and temperature estimation support the hypothesis that interruptions or strong reductions in speleothem growth at Corchia could have been due to a combination of glaciation and/or ice-free but cold temperatures with low or absent soil activity.

Glacial phases occurring in this period in the mountain regions around the Mediterranean are confirmed by multi-proxy analyses carried out on the glacial lacustrine sequences, as evidenced by a maximum of glacier expansion of Pyrenean glaciers before 30 ka (Garcia-Riuz at al., 2003) and in Picos de Europa dated at about 40 ka (Moreno et al. 2010; Serrano et al., 2012). Consistently in the central Apennines, tephra layers in lacustrine sediments bracket the maximum glacier extent between 33-27 ka, not a period of maximum cold conditions but one that was humid (Giraudi, 2012). Regarding the Alps there is a controversial discussion about glaciers extent before MIS 2 when the maximum expansion was reached (Ivy-Ochs et al. 2008; Preusser et al. 2011; Hughes et al. 2013). The uncertainties mainly derive from the fact that the majority of terrestrial records (i.e. glacial deposit, pro-glacial outwash, river terrace, lake deposit) were eroded, or at least remoulded or reworked, when MIS 2 glaciers invaded the valleys and in many cases spread out in piedmont lowlands. Indeed, while in the Eastern Alps no evidence for the presence of pre-MIS 2 glaciers are clearly found (Ivy-Ochs et al., 2008), an important glaciation reaching the lowlands of the Western Alps during MIS 4 is documented by OSL dating of pro-glacial outwash (Preusser et al. 2007) and lake sediments (Link and Preusser 2006).

~~This~~ The above described asynchronicity is not contradictory a priori, because it may be explained by the short reaction times of small glaciers (like those of most of the Mediterranean mountains) to changes in precipitation and/or temperature. Further sampling may reveal sporadic or very slow episodes of growth during this time interval, allowing better and more precise interpretations of MIS 3 climatic oscillations.

7. Conclusions

Speleothems in the Apuan Alps grew near-continuously during most of MIS5 (from ca. 130 ka to about 75 ka), then experienced a long period of absent to very low deposition covering the MIS4 to MIS2 interval, until ~12.5 ka. This growth history can be explained as the result of development of glaciers at high elevations, not necessarily continuously existent for the whole considered period, and/or low soil development and near-zero temperatures. The speleothem growth curves may suggest that glacial expansion in the Apuan Alps was not only limited to the LGM (MIS2) but also to MIS3 and MIS4, analogous to other peri-Mediterranean mountains.

During spring and summer ice-melting periods, high water discharges occurred and caves located at lower altitudes were flooded, resulting in phreatic conditions, inhibiting speleothem deposition and infilling caves with thick fluvial deposits.

There is no evidence of significant growth during interstadials within MIS3, which supports the fact that no particularly warm conditions occurred in the Apuan Alps during those climatic events.

Sustained speleothem growth resumed close to the beginning of the Holocene both at lower and high-altitude caves. This can be interpreted as the result of a definitive melting of ice cover and the consequent progressive soil development at high altitude, and the stabilisation of loose glacial debris and reduced flooding for lower altitude caves.

These data indicate the potential for cumulative speleothems growth curve to chronologically constrain large-scale geomorphological processes, like the timing of glaciers presence. However, other processes can locally bias the speleothem growth (i.e. cold-non glacial conditions, absence/limited soils), suggesting that this approach is restricted to a first-order approximation which should be followed by a direct dating of glacial features. Moreover, the adoption of speleothem growth curves needs to be verified in other mountain ranges, where U/Th dating can be used for constraining glacial events.

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Highlights

speleothem growth curves used to better constrain the timing of glacial features

293 U\Th ages from 19 speleothems collected in five caves at different elevations

glacial expansion in the Apuan Alps was not only limited to the MIS2