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Palaeoenvironmental changes recorded by speleothems of the southern Alps (Piani Eterni, Belluno, Italy) during four interglacial to glacial climate transitions

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ABSTRACT

Three stalagmites, which grew in the high altitude (~1800 m a.s.l.) Piani Eterni karst system (northern Italy), represent the longest speleothem palaeoclimate-environmental record from the southern Alps. U-Th dating shows their discontinuous formation during Marine Isotope Stage (MIS) 10, 8, 7d, 6 and 5d–b, with carbonate deposition prevented during both full interglacial and full glacial stages. Speleothem formation was inhibited during interglacial peaks because local base level rise, connected to global climate changes, caused the alluviation of the main epiphreatic levels of the cave system. Drainage of the hydrological pathways, caused by the progressive decrease of rainfall and the accumulation of a perennial snow pack, stopped carbonate deposition during glacials. Thus, Piani Eterni speleothems function as indicators of transitional interglacial to glacial (IG–G) climate periods over the last ~400 thousand years (kyrs). Analysis of $\delta^{18}O$ and $\delta^{13}C$ suggest that: i) seasonal snow melt occurred in these high altitude terrains during IG–G times, allowing meteoric water to efficiently penetrate the karst network; ii) soils were restored during MIS 5c–b, but absent during MIS 10, 8, 7d and 6 due to denudation of the karst surfaces; and iii) rainfall perturbations modulated the IG–G shifts in the southern Alps. Rainfall variation is connected to solar radiation changes at orbital timescales during MIS 5c–b, and mimics Dansgaard-Oeschger (DO) cycle variability during DO 23 and 22. DO cycle-like variability is also suspected during MIS 10, 8 and 6. The most important result is that, from a geochemical perspective, this study demonstrates that drivers of $\delta^{18}O$ in southern alpine speleothems are similar to Mediterranean, Middle Eastern and Asian speleothems in that they are prevalently controlled by the rainfall amount effect. This contrasts with speleothem records from the more continental northern alpine sector where the air temperature effect on $\delta^{18}O$ of precipitation dominates.

1. Introduction

Interglacial to glacial (IG–G) climate transitions are characterised by high instability (Barker et al., 2011; Zhang et al., 2014). Interhemispheric reorganisation of atmospheric and ocean circulation, variations in ice-sheet size, and changes in orbital parameters and their attendant effects on the seasonal distribution of solar radiation are among the main causes of such climate fluctuations (Clark et al., 2001; Claussen et al., 2003; Braun et al., 2005, 2008; Arz et al., 2007). The deterioration of climate between the Last Interglacial (Marine Isotope Stage – MIS 5e, ~128 kilo-years before present, hereafter ka) and the Last Glacial Maximum (MIS 2, 26–18 ka) has been studied in great detail (Allen et al., 1999; Genty et al., 2003; NGRIP project members, 2004; Clement and Peterson, 2008; Brauer et al., 2007; Drysdale et al., 2007; Capron et al., 2012;

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Rasmussen et al., 2014; Regattieri et al., 2015; Fankhauser et al., 2016; Cheng et al., 2016; Arienzo et al., 2017). Greenland ice cores record this last progression as characterised by quasi-periodic occurrences of twenty-five warm vs cold pulses (Bond et al., 1997), called Dansgaard-Oeschger (DO) cycles (Dansgaard et al., 1993; Grootes et al., 1993), where rapid shifts toward the warm phases – Greenland Interstadials (GI) – are followed by gradual cooling trends leading to the cold stages – Greenland Stadials (GS). Evidence of this cyclicity is also found in sediments and foraminiferal assemblages from the North Atlantic (McManus et al., 1999). At higher resolution, sub millennial intra-DO changes have been identified in ice-cores (Capron et al., 2010), and, using terrestrial archives, in alpine and Mediterranean latitudes (Boch et al., 2011; Columbu et al., 2017a).

IG–G transitions prior to MIS 5e have been less explored, and the scarcity of information progressively increases further back in time. The Greenland ice record only covers the last ~125 kyrs reliably (NGRIP project members, 2004), so other archives must be sought as the foundation upon which to study the dynamics of DO-cycle-like oscillations prior to 125 ka, such as Antarctic ice cores (Jouzel et al., 2007), North Atlantic Ocean records (Lisiecki and Raymo, 2005; Martrat et al., 2007; Hodell et al., 2013), or the long Chinese speleothem records (Cheng et al., 2012). However, terrestrial records of pre-MIS 5e climate from Europe, especially from the Mediterranean region, are scarce; they are mostly reported from lacustrine sediments (Tzedakis et al., 2003; Giaccio et al., 2015; Francke et al., 2016; Regattieri et al., 2016; Stockhecke et al., 2016), while the few published speleothem records only cover non-contiguous periods of time (i.e., Ayalon et al., 2002; Bar-Matthews et al., 2003; Drysdale et al., 2004; Vaks et al., 2010; Regattieri et al., 2014, 2018). The lack of speleothems is noteworthy, considering that these archives may yield reliable time series (Henderson, 2006) by which palaeoclimate proxy data can be independently compared with other absolutely dated and/or relatively dated records (McDermott, 2004; Fairchild and Treble, 2009; Fairchild and Baker, 2012). Although less susceptible than many other terrestrial archives, speleothems are subject to increasing natural attrition from weathering and re-crystallization over such long time periods (~500 kyrs) (Scroxton et al., 2016); thus, well-dated, pre-MIS 5e stalagmites that preserve the original climate-driven geochemical and physical properties, are invaluable.

The Alps are highly sensitive to climate changes (Casty et al., 2005; Spötl et al., 2007), with several speleothem palaeoclimate reconstructions of the more recent cycles recording the local/regional responses to DO oscillations (Spötl and Mangini, 2002; Spötl et al., 2002, 2006; 2007, 2008; Frisia et al., 2003, 2005; Holzkämper et al., 2004, 2005; Mangini et al., 2005; Vollweiler et al., 2006; Meyer et al., 2008, 2009; Boch et al., 2011; Scholz et al., 2012; Belli et al., 2013; Luetscher et al., 2015; Moseley et al., 2015). However, these studies are prevalently from the northern Alps, with only a few from the southern side (Frisia et al., 2003, 2005; Scholz et al., 2012; Belli et al., 2013). The two regions are not directly comparable because the main alpine chain divide separates two climatologically distinct sub-regions along the northern Italian border: the northern and the southern Alps (Efthymiadis et al., 2007) (Fig. 1). The first is predominantly exposed to Atlantic climate, whereas the second experiences a strong Mediterranean influence.

In this work, we present three speleothem palaeoclimate proxy records from the Piani Eterni karst system in the Dolomiti Bellunesi National Park (Belluno, Italy, southern Alps) (Fig. 1), which grew in four different phases of IG–G transitions over the last ~400,000 years. Deposition was interrupted during both interglacial and glacial maxima. Their oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) stable isotope variations, and growth pattern through time appear to be influenced by climate fluctuations characterising these transient periods, when compared to glacial, marine and other terrestrial archives. Thus, these palaeoclimatic proxies enrich our knowledge about the last four IG–G transitions in the southern Alps. Our record is compared with those from the northern Alps to highlight the differences between the two climatologically distinct sub-regions. In doing so, we discuss: i) the palaeoclimate and palaeoenvironmental conditions allowing speleothem deposition in the Piani Eterni karst system; ii) the climate evolution of the long DO-23 event that affected the southern Alps climate, from inter-millennial to intramillennial timescales, and in comparison with the northern Alps and other records; and iii) IG–G transitions before MIS 5e, especially regarding variations in temperature, rainfall and environmental conditions at the surface. The results of this work further affirm speleothems as fundamental tools for the comprehension of palaeoclimate in climatically sensitive regions across different climate stages and regimes.

2. Study site and stalagmites

The Piani Eterni (11.99° N, 46.16° E) area belongs to the south-western Alps climate domain (Efthymiadis et al., 2007), subjected to subalpine temperate humid weather (Lionello, 2012). According to the meteorological station of Arabba (1642 m a.s.l.), from 2010 to 2017 annual rainfall varied from 850 to 1550 mm/year (average: 1180 mm/year), while annual average temperatures ranged between 3.7 °C and 6.3 °C (average: 5.2 °C) (Sup. Fig. 1). Rain mostly occurs from May to September (>100 mm/month), while average monthly temperatures are always above 10 °C during summers (Sup. Fig. 1). Snow cover typically lasts up to 4 months during winters (data from www.arpa.veneto.it). Because of the snow cover, and the annual distribution of rain, the Piani Eterni karst system recharge mostly occurs in the warm season. This area lacks adequate IAEA records for the isotopic composition of rainfall (from https://nucleus.iaea.org/wiser/index.aspx). In Trieste (the nearest IAEA station), where annual rainfall is around 900 mm, but monthly temperatures can be up to 23 °C in summer, annual $\delta^{18}O$ of rainfall is around −6.9‰ SMOW ($\delta D = 42.7$), −5.8‰ during the warmer seasons. Trieste is located, however, on the Adriatic coast, thus the maritime-influenced climate, affecting the composition of rainfall, is not directly comparable to the Piani Eterni. According to Longinelli and Selmo (2003), our study area would fit into the macro region where annual $\delta^{18}O$ rainfall can range between −8.0‰ and −9.0‰.

The Piani Eterni karst system lies in the Erera-Brendol plateau within the *Parco Nazionale delle Dolomiti Bellunesi* (Fig. 1). Explored caves extend for 36 km in length and 1052 m in depth from the highest entrance (1893 m a.sl.). Several interconnected caves constitute the karst system, with deep shafts accessible from the glacio-karstic cirques located at the top of the massif, and some horizontal caves accessible from the eastern flank of the plateau (Salogni, 2007) along the side of the Mis Valley at 1640 m a.s.l. (Fig. 1). The caves have developed within limestones/dolomitised limestones (upper to middle levels, ~1900–1300 m a.s.l.) and dolostones (lower levels, 1500–900 m a.s.l.) belonging respectively to the *Calcari Grigi* and *Dolomia Principale* formations (Costa et al., 1996) (Fig. 1). Part of the middle levels is also excavated into a bituminous dolomitic unit, rich in sulphides, that has not yet been officially named (Riva et al., 2008).

The cave system is characterised by palaeo-epiphreatic levels distributed along three main altitude ranges (Sauro et al., 2013, 2017). The deepest level explored so far is developed at 880 m a.s.l., which is 100–150 m above the actual water table, corresponding to the main karst resurgence of the area (Bus del Caoron, 750 m a.s.l.), a vauclusian resurgence explored by cave divers along flooded conduits up to 645 m a.s.l. (Sauro et al., 2013). The palaeo-