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Reconstructing high-resolution climate using CT scanning of unsectioned stalagmites: A case study identifying the mid-Holocene onset of the Mediterranean climate in southern Iberia

Izabela W. Walczak [a], [*], James U.L. Baldini [a], Lisa M. Baldini [a], Frank McDermott [b], [c], Stuart Marsden [d], Christopher D. Standish [e], David A. Richards [e], Bartolomé Andreo [f], Jonathan Slater [d]

[a] *Department of Earth Sciences, Durham University, Durham DH1 3LE, United Kingdom*
[b] *UCD School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland*
[c] *UCD Earth Institute, University College Dublin, Belfield, Dublin 4, Ireland*
[d] *Department of Clinical Radiology, University Hospital of North Durham, North Road, Durham DH1 5TW, United Kingdom*
[e] *School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, United Kingdom*
[f] *Departamento de Geología, Facultad de Ciencias, Universidad de Málaga, Calle Albert Einstein, 4, 29010 Málaga, Spain*

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ABSTRACT

The forcing mechanisms responsible for the mid-Holocene onset of the Mediterranean-type climate in south-western Europe are currently unclear, but understanding these is critical for accurate climate projections under future greenhouse gas warming. Additionally, regional studies that present conflicting patterns for the onset and advancement of Mediterranean climatic conditions complicate definitively ascribing causality. Here, we use a new high resolution stalagmite density record obtained non-destructively using Computed Tomography (CT scanning) to reconstruct southern Iberian climate between 9.3 and 2.9 ka BP. We suggest that stalagmite density can be used as a water-excess proxy, with lower densities associated with more variable drip rates, possibly reflecting increased seasonality consistent with expectations from previous studies of speleothem textures and crystal fabrics. Our results reveal an early Holocene humid interval and mid-Holocene year-round aridity that preceded the onset of Mediterranean climate at 5.3 ka BP in southern Iberia. Using this new dataset combined with previously published results, we link the gradual advancement of the Mediterranean climate to the southward migration of the North Atlantic Subtropical High induced by an orbitally driven decrease in Northern Hemisphere insolation. Future anthropogenic warming could result in a reversal of this trend, a northward migration of the North Atlantic Subtropical High, and a return to year-round aridity in south-western Europe.

1. Introduction

1.1. Stalagmite-derived climate proxies

Stalagmites are excellent climate archives because they yield multi-proxy information (e.g., stable isotope, trace element, and petrographic information) constrained by radiometric chronologies. Additionally, at relatively undisturbed sites they can complement palaeoclimate information from well-dated archives (e.g., sediment cores) (Fairchild et al., 2006; Henderson, 2006). High-resolution stalagmite climate reconstructions are usually based on information gleaned from a single plane cut through the sample, and typically attempt to follow the stalagmite's growth axis in two dimensions. However, this approach ignores possible growth axis shifts that could occur out of this plane which in turn could dramatically affect climate interpretations, for example through off-axis stable isotope kinetic enrichment (Mickler et al., 2004). To date, no high-resolution stalagmite climate proxy research has taken account of such three-dimensional growth axis shifts, which can occur due to changes in infiltration pathway,

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[*] Corresponding author.
E-mail address: i.w.walczak@durham.ac.uk (I.W. Walczak).

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lateral growth of soda straws, following subsidence of cave floors and/or seismic activity (Becker et al., 2006). Taking these potential shifts into account is particularly important in seismically active areas, like southern Iberia, which lies close to the convergence zone between the Eurasian and African Plates (Gràcia et al., 2010). X-ray computed tomography (CT scanning), a non-destructive technique commonly applied in medicine and also in the geosciences (Carlson et al., 2003; Ketcham and Carlson, 2001; Mees et al., 2003), uses internal three-dimensional density mapping of opaque objects to provide information about stalagmite growth axis shifts (Mickler et al., 2004) and internal porosity (Zisu et al., 2012). Moreover, CT scanning provides rapidly acquired quantitative information about stalagmite density, a variable that typically can only be obtained at low spatial resolution only through calculations based on the mass of cut stalagmite blocks (Zhang et al., 2010). Despite numerous studies using CT scanning to derive quantitative density data from sediment cores (Mees et al., 2003; Tanaka et al., 2011; Wirth et al., 2013), the technique has not previously been used to derive time-series data from stalagmites.

The relationship between stalagmite density and environmental factors such as meteoric precipitation, temperature, soil, and vegetation above a cave is complex. These factors directly control water flow dynamics, and consequently drip-water saturation state (with respect to calcium carbonate) that is the predominant determinant of stalagmite density (Dreybrodt, 2008; Frisia et al., 2000; Zhang et al., 2010). In addition, cave ventilation regimes also complicate it by affecting the intensity of CO_2 degassing from drip-water entering a cave (Boch et al., 2011; Mattey et al., 2010). However, because environmental change during stalagmite growth drives calcite density variability, stalagmite calcite density is interpretable in terms of climate (Zhang et al., 2010). In a study of the East Asian Monsoon, Zhang et al. (2010) demonstrated that rainfall amounts (inferred from stalagmite $\delta^{18}O$) and calcite density variations (derived by conventional non-CT scanning methods) were positively correlated, which is also consistent with studies of calcite textures (Frisia, 2015; Frisia et al., 2000). By calculating stalagmite density from the measured mass of stalagmite blocks cut every 5 mm, Zhang et al. (2010) achieved a resolution of 87 years. CT scanning therefore offers a novel means to produce comparable density data quickly and non-destructively, and at a considerably higher spatiotemporal resolution than is achievable using conventional density measurements.

1.2. *Holocene climate variability in the Mediterranean region*

The southern Iberian Peninsula is currently characterised by a Mediterranean climate (Csa in Köppen-Geiger classification, Peel et al. (2007)), with dry and hot summers and wet winters caused by the seasonal meridional migration of the North Atlantic Subtropical High (NASH) (Harding et al., 2009). The NASH (often also referred to as the Bermuda or Azores High (Davis et al., 1997)) is the semi-permanent subtropical anticyclone over the North Atlantic Ocean basin that forms at the descending limb of Hadley cell circulation. The NASH exerts a major influence on the present-day weather and climate of Iberia by controlling the latitude of North Atlantic westerlies (Marshall et al., 2001; Tzedakis et al., 2009). The contrast between winter and summer precipitation in Iberia is due largely to the tendency for the NASH to migrate northwards over Iberia in summer (resulting in hot, dry conditions) and to migrate southwards in winter (bringing increased rainfall with the westerlies) (Harding et al., 2009; Trigo et al., 2004). In the present day, interannual variability in the strength and position of the NASH is linked to the state of the North Atlantic Oscillation (NAO) (Souza and Cavalcanti, 2009).

Several studies suggest that the western Mediterranean region, located at critical geographic and atmospheric boundaries, has experienced abrupt climatic shifts over the Holocene (Anderson et al., 2011; Baldini, 2007; Carrión, 2002; Dorado Valiño et al., 2002; Fletcher et al., 2013; García-Alix et al., 2012; Jalut et al., 2009; Jambrina-Enríquez et al., 2014; Jiménez-Moreno and Anderson, 2012; Moreno et al., 2011; Pérez-Obiol et al., 2011; Roberts et al., 2011). Jalut et al. (2009) examined circum-Mediterranean pollen data to derive three climatic phases for the Holocene: i) the early Holocene (11.5–7 ka BP) characterised by increased rainfall, ii) the mid-Holocene (7–5.5 ka BP), characterised by increased variability, linked to decreasing Northern Hemisphere insolation, and iii) the late Holocene, characterised by the onset of a drying trend at ~5.5 ka BP. This drying trend may reflect decreased annual rainfall induced by substantially lower summer rainfall, with winters remaining cool and wet. Typically this transition into seasonal aridity is interpreted as the Holocene onset of the Mediterranean climate in Iberia. Existing Iberian pollen and lake sediment records (Fig. 1) reveal considerable variability in the timing and character of these phases, thereby impeding our understanding of Holocene climate in the region (Anderson et al., 2011; Carrión et al., 2010; Dorado Valiño et al., 2002; García-Alix et al., 2012; Jalut et al., 2009; Jambrina-Enríquez et al., 2014; Jiménez-Moreno and Anderson, 2012; Moreno et al., 2011; Pérez-Obiol et al., 2011; Roberts et al., 2011). Thus, the spatiotemporal pattern of Mediterranean climate advancement within the Iberian Peninsula has remained difficult to constrain. Studies along the Iberian eastern margin concluded that the Mediterranean climate advanced from the south (beginning at 10 ka BP) towards the north (between 3.3

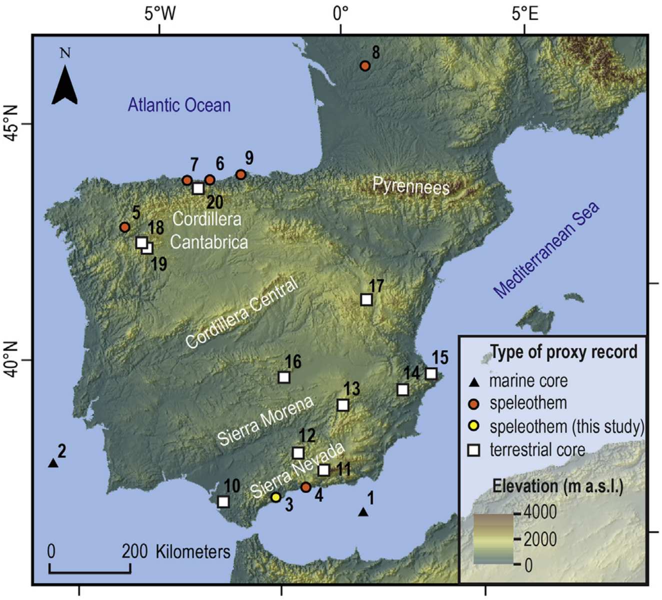

Fig. 1. Location of palaeoclimate proxy records mentioned in the text. Marine cores (black triangles): (1) MD95–2043 (Fletcher et al., 2013), (2) MD95–2042 (Chabaud et al., 2014); speleothems from (3) El Refugio Cave (this study, yellow circle); speleothems (red circle) from (4) Nerja Cave (McMillan, 2006), (5) Cova de Arcoia (Railsback et al., 2011), (6) Pindal (Stoll et al., 2013), (7) Cueva Rosa (Stoll et al., 2013), (8) Villars Cave (Genty et al., 2006) (9) La Garma Cave (Baldini, 2007; Baldini et al., 2015); terrestrial cores (white squares) from (10) Laguna de Medina (Reed et al., 2001), (11) Borreguiles de la Virgen (García-Alix et al., 2012), (12) Laguna de Rio Seco (Anderson et al., 2011), (13) Siles (Carrión, 2002), (14) Salinas (Burjachs and Riera, 1995), (15) Cabo de Gata (Jalut et al., 2000), (16) La Mancha Plain (Dorado Valiño et al., 2002), (17) Villarquemado (Aranbarri et al., 2014), (18) Sanabria Lake (Jambrina-Enríquez et al., 2014), (19) Laguna de la Roya (Allen et al., 1996), (20) Lago Enol (Moreno et al., 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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