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Middle-to-late Holocene palaeoenvironmental reconstruction from the A294 ice-cave record (Central Pyrenees, northern Spain)

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ABSTRACT

Perennial ice deposits in caves represent unique, but underexplored, terrestrial sequences that potentially contain outstanding palaeoclimatic records. Here, we present a pioneer palaeoenvironmental study of an ice deposit preserved in a small sag-type cave (A294) in the Central Pyrenees (northern Iberian Peninsula). The 9.25-m-thick sequence, which is dated from 6100 ± 107 to 1888 ± 64 cal BP, represents the oldest known firn ice record worldwide. The stratigraphy (detrital layers, unconformities, and cross stratification), plant macrofossils, and isotopic signature (similarity between the ice linear distribution, $\delta^2H = 7.83\delta^{18}O + 8.4$, and the Global Meteoric Water Line) of the ice point to the diagenesis of snow introduced to the cave by winter snowstorms. Four phases of rapid ice accumulation (6100–5515, 4945–4250, 3810–3155, and 2450–1890 cal BP) are related to wetter and colder winters. Comparison of the isotopic composition ($\delta^{18}O$ and deuterium excess) of the ice with other paleoclimate records show that both source effects and the North Atlantic Oscillation (NAO) mechanism exert a dominant influence on the ice cave record. The NAO signal may be a combination of source effects and rainfall amount. Three intervals with low ice accumulation occurred between the phases of rapid accumulation and were related to drier, and possibly warmer, winters. These centennial-scale episodes appear to be in-phase with regional arid events, as established from high altitude lacustrine records and can be correlated to global Rapid Climate Change events. The current warming trend has dramatically decreased the volume of the ice deposit in cave A294.

1. Introduction

Ice caves are rock cavities that host perennial ice resulting from the diagenesis of snow and/or freezing of infiltrated water (Perşoiu and Onac, 2012). Ice cave deposits are unique cryospheric archives with high palaeoenvironmental potential, based on geochemical and biological variables associated with changes in climate, vegetation, and hydrology of mid-high altitude and latitude areas (Luetscher et al., 2005; Stoffel et al., 2009; Feurdean et al., 2011; Kern and Perşoiu, 2013; Perşoiu et al., 2017). However, cave ice archives have been poorly exploited as palaeoclimatic records because of a lack of robust chronologies, difficulties in interpreting isotopic signals and detection of ablation periods in ice sequences (Luetscher et al., 2007; Stoffel et al., 2009; Hercman et al., 2010; Feurdean et al., 2011; Spötl et al., 2014; Perşoiu et al., 2017).

In this study, we address the palaeoenvironmental significance of ice cave A294, located on the Cotiella Massif in the Southern Pyrenees. The Pyrenees form the highest calcareous mountain belt in Western Europe and ice cave A294 is the southernmost studied in Europe. The occurrence of ice caves in northern Spain has been well known since pioneering reconnaissance work in the Monte Perdido Massif (Central Pyrenees) in the mid-twentieth century. Subsequent studies of ice caves mainly focused on characterising current environmental conditions in the Pyrenees (ice cave A294) (Belmonte-Ribas et al., 2014) and Cantabrian Mountains (Peña Castil ice cave) (Gómez-Lende et al., 2014), but there has been no systematic palaeoclimatic analysis of cave ice deposits from the northern Iberian Peninsula.

Here, we present a palaeoclimatic reconstruction based on a firn ice profile in ice cave A294 which encompasses the mid- to late Holocene and is framed by a reliable radiocarbon age model. In addition, the stratigraphic architecture of the ice sequence and

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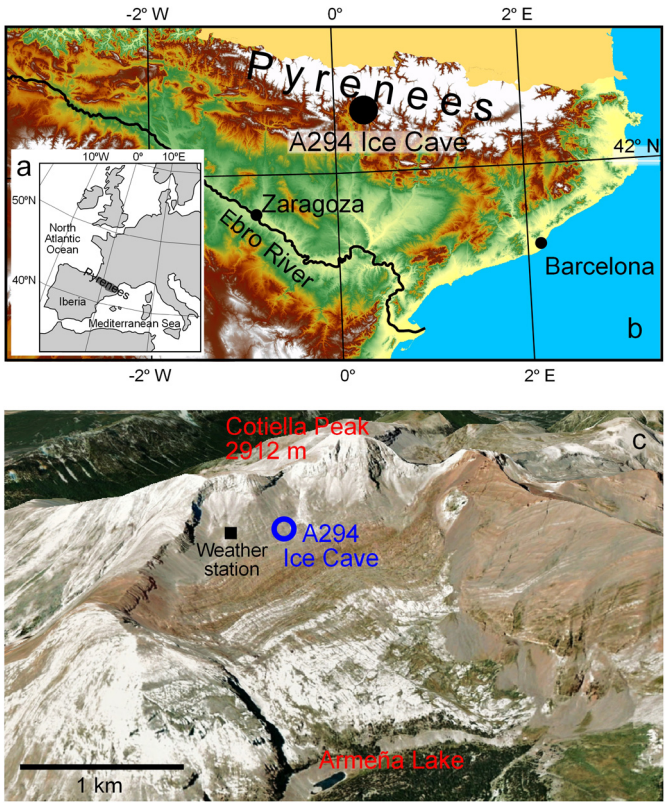

Fig. 1. Location of the A294 ice cave in northeastern Iberia (a), the Central Pyrenees (b) and the Cotiella Massif (Huesca province) (image Landsat from Google Earth 2015) (c).

its stable isotopic composition are discussed in terms of Holocene palaeoenvironmental variations.

2. Setting of cave A294

Ice cave A294 (42°30′52″N; 0°20′10″E, 2238 m asl) is located in Cotiella, a deglaciated calcareous massif of the south-central Pyrenees (Huesca province, Northern Spain) (Fig. 1). This alpine mountain is mainly composed of Upper Cretaceous and Eocene carbonate rocks arranged in a thrust system. The cave is part of a large karst system encompassing more than 8 km of cave passages and up to 600 m deep.

Ice cave A294 opens at the bottom of a large glacial cirque and is positioned between a set of Last Glacial Maximum moraines (about 1920 m elevation) and a huge moraine complex of Younger Dryas age (2400 m). Above the moraines (2500 m), there is an active rock glacier that originated during the Little Ice Age (LIA). Periglacial activity is limited to ice-thaw processes, with remarkably little evidence of solifluction and associated morphologies (Belmonte-Ribas, 2014).

The study area experiences a mountain climate, and is situated in an air mass transition zone, with precipitation derived from both North Atlantic (Jódar et al., 2016) and Mediterranean (Araguás-Araguás and Diaz Teijeiro, 2005) systems. Meteorological observations from summer 2011 to summer 2016 were obtained from a weather station located 400 m from the cave at an altitude of 2180 m. A mean annual temperature of 1.5 °C was recorded over the period, with strong seasonal contrasts (mean winter and summer temperatures of −5 °C and 9.5 °C, respectively). Annual precipitation of ca. 1700 mm mostly occurred as snow events, with >60 per year, concentrated between October and May, and a snow mantle thickness of up to 250 cm in March–April. Snow precipitation in winter months is usually associated with the arrival of Atlantic fronts.

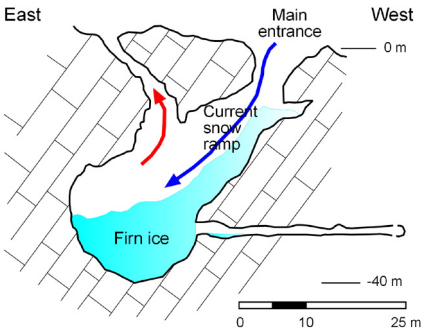

Fig. 2. Vertical cross-section of the A294 ice cave showing the ice deposit. The current air circulation pattern during winter (descending and ascending arrows are cold and warm air flows, respectively) is also shown.

There is a strong altitudinal vegetation gradient in the study area, from valley bottom (1300 m) to Cotiella Peak (2912 m). Well-developed deciduous forests occur up to 1700 m, with species such as *Betula pendula*, *Corylus avellana*, and *Fagus sylvatica* that mix with conifers, such as *Pinus sylvestris*. Between 1700–2000 m, the forest is mainly composed of *Pinus uncinata* and shrubs, such as *Juniperus communis*, *Rhododendron ferrugineum*, and *Arctostaphylos uva-ursi*. Ice cave A294 is located above the present day treeline (established by *P. uncinata*) of ca. 2000 m, in a zone of patchy alpine vegetation.

A294 is a small sag-type cave (Fig. 2) with a circular entrance of approximately 30 m^2 and another smaller entrance. The chamber is triangular in plan, approximately 40 m wide and 22 m high, and hosts an ice deposit with a volume of nearly 250 m^3. Currently, a snow ramp connects the main entrance with the top of the ice deposit, indicating that snow is blown directly into the cave (Fig. 3a). An ice wall front (ca. 10 m high) provides excellent exposures of ice stratigraphy (Fig. 4a).

The temperature and relative humidity of ice cave A294 were recorded over one annual cycle from May 2011 to May 2012 (Belmonte-Ribas et al., 2014) and show four environmental phases in terms of the relationships between climatic conditions inside and outside the cave. First, open conditions, preceded by a chimney effect (Fig. 2), occur in the cave during the winter phase (November–May), with a mean temperature of −0.77 °C inside the cave. Ventilation takes place through the main shaft and out of the second smaller shaft (Fig. 2). This connection is reversed during the summer phase (June–October), and the cave acts as a thermal trap, reaching a mean temperature of 0.26 °C. Transitional cooling and warming phases have also been recognized. Therefore, A294 can be considered a statodynamic ice cave following the classification of Luetscher and Jeannin (2004). The cave is currently experiencing an annual ice loss of approximately 12 m^3, based on estimates during the years 2008–2012 (Belmonte-Ribas et al., 2014), and the ice deposit is in danger of being lost in ca. 20 years.

3. Materials and methods

Detailed logging of the well-exposed front wall of the ice deposit in cave A294 allowed us to characterize the stratigraphy. Internal stratigraphic features and unconformities were identified and described. The stratigraphic column was subsequently sampled for radiocarbon dating, using plant macro remains, and isotopic analysis.

AMS ^{14}C dating was undertaken on 22 plant macro samples, of which 5 were replicates taken from 2 horizons to assess reproducibility. Analyses were carried out at the Radiocarbon Laboratory of the University of Zürich, Switzerland, and the Radiocarbon Dating Service, Seattle, Washington, USA. Radiocarbon dates were